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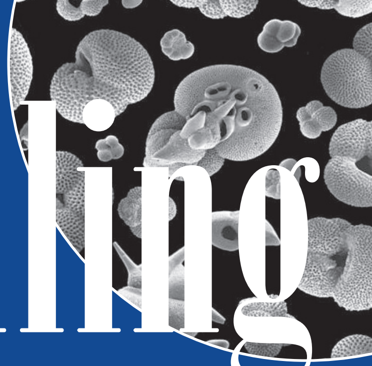

Reports on Deep Earth Sampling and Monitoring

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Editorial Preface

Dear Reader,

The Lima Climate Change Conference puts the world on track to a new climate agreement to reduce the output of greenhouse gases. There is urgent need for action towards the "stabilization of greenhouse gas atmosphere at a level that would prevent dangerous anthropogenic interferences with the climate system …", and Scientific Drilling contributes to improve our understanding of past and recent climatic and environmental change and offers solutions to provide clean, emission-free energy.

Improving the output of geothermal energy was the goal of a workshop in southern California (p. 34–42) to discuss the science and technology involved in developing high-enthalpy geothermal fields. The theme of the workshop – "**Investigating ultra high-enthalpy geothermal systems: a collaborative initiative to promote scientific opportunities**" – was to explore the feasibility and economic potential of increasing the power output of geothermal wells by an order of magnitude by drilling deeper to reach much higher pressures and temperatures.

As the planet begins to be affected by anthropogenic greenhouse gas emissions, it is important to understand climate forcing and response in Earth's past, especially greenhouse episodes. The "**Early Cenozoic tropical climate: report from the Tanzania Onshore Paleogene Integrated Coring (TOPIC)**" workshop (p. 13–17) served to develop a proposal for a new ICDP project. The aim is to recover Eocene hemipelagic sediments in southern Tanzania, a unique drilling target because of their extraordinary good preservation of fossils and a high potential for climate proxy studies.

Drilling in Antarctica can yield samples of rock that were influenced directly by glacial processes and which provide access to Antarctica's ice-covered geology. Fifty-four participants attended the "**Antarctic Geologic Drilling Workshop**" (AGDW) to discuss science objectives and develop key projects (p. 11).

Forces originating deep within the dynamic Earth can have a profound surface effect on human societies, and are addressed by scientific drilling. The workshop "**Drilling to investigate processes in active tectonics and magmatism**" (p. 19–33) was held in Park City, Utah. The objective of the meeting was to provide a road map of specific projects addressing the most pressing issues in research on earthquakes and volcanic eruptions.

An **ICDP workshop on Scientific Deep Drilling in the Koyna region** (p. 5–9) was held in western India at the most prominent site of artificial reservoir-triggered earthquakes, also known as reservoir-induced seismicity. The workshop served to discuss results from pre-site studies and pilot wells, to deliberate on the design of planned deep and ultradeep boreholes, to decide on the monitoring instrumentation to be deployed, and to prepare a full ICDP drilling proposal for investigation of induced seismicity.

Corganise is a software tool developed to simplify whole-round sampling for time-sensitive microbiology and geochemistry subsampling in scientific drilling. It is designed to work with a wide range of core and section configurations and can thus be used in future IODP and ICDP scientific drilling projects (p. 1–4).

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

Aims & Scope

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

Editorial Board

Additional Information

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Cover figures: Koyna workshop participants examine drill core from observation boreholes (Thomas Wiersberg, ICDP), Planktonic foraminifera from the Eocene/Oligocene Transition at the proposed TOPIC drill site (Paul Pearson, Cardiff University), Dry superheated stream from the high enthalpy IDDP-1 well (Kristján Einarsson, Landsvirkjun)

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Scientific Drilling
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Corganiser: a web-based software tool for planning time-sensitive sampling of whole rounds during scientific drilling

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Abstract. Corganiser is a software tool developed to simplify the process of preparing whole-round sampling plans for time-sensitive microbiology and geochemistry sampling during scientific drilling. It was developed during the Integrated Ocean Drilling Program (IODP) Expedition 347, but is designed to work with a wide range of core and section configurations and can thus be used in future drilling projects. Corganiser is written in the Python programming language and is implemented both as a graphical web interface and command-line interface. It can be accessed online at http://130.226.247.137/.

1 Introduction

Modern scientific drilling projects, such as those carried out by the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP), often have increasingly important microbiology and geochemistry components (D'Hondt et al., 2007; Orcutt et al., 2014). Microbiology and geochemistry samples collected from cores present special challenges for scientists carrying out this sampling, as samples are time sensitive, with properties that change rapidly following recovery as a consequence of surface temperature, atmospheric composition, pressure, and other properties, differing from in situ conditions (Lin et al., 2010; Mills et al., 2012). Samples must be removed from the core (generally as whole rounds), recorded, and preserved as quickly as possible following core recovery. In order to ensure that all sample requests are fulfilled and samples are preserved correctly while swiftly processing time-sensitive samples, a clear and straightforward sampling plan is vital. Such a sampling plan should clearly describe which samples need to be taken from each section expected from a given hole, so that when the core is ready for processing no time is wasted.

IODP Expedition 347 (Baltic Sea Paleoenvironment) included a significant microbiological shipboard sampling program. During the offshore phase, samples were collected for 27 separate sample requests for microbiological and geochemical analyses. Each of these sample requests had different handling instructions, including storage at −80 or −20 °C, storage under a nitrogen atmosphere, and mixing with various chemical preservatives, including formaldehyde and glycerol solutions. Several holes were drilled at each site, with the final hole dedicated to subsampling for microbiology, meaning that data collected while drilling the first holes were used to determine the optimal sampling frequencies for each unit in the microbiology hole. Time for developing the sampling plan was thus limited, and with 3 m cores arriving on deck at an average rate of one per hour, the time available for subsampling and preserving each core was tightly restricted. To meet these challenges, a software tool called Corganiser was developed to enable the rapid creation and modification of whole-round sampling plans. Corganiser was designed to be sufficiently flexible for use on other platforms and expeditions with core and section lengths other than those used during Expedition 347.

This paper describes the input parameters and algorithm used to place samples within the sampling plan as well as the two implementations of Corganiser: web-based and command line.

2 How Corganiser works

Corganiser is designed to produce a colour-coded diagram to guide processing of each core without the time-consuming, error-prone, and labour-intensive process of producing a diagram for each core manually.

2.1 Data input

To make a sampling plan for a hole, the user enters the length of the core to be sampled, the number of sections the core will be divided into, the unsampled length of the core (e.g. the length of the core catcher and any other depth intervals not sampled), and the total depth of the hole. For each sample request, the user can enter samples in two different ways: either as one-off samples taken at specific depths, or as a series of samples taken at regular intervals across a specific depth range. Each sample is given a length (i.e. 10 cm whole-round core) and a short text handling instruction (i.e. "$-80\,^{\circ}$C" or "anoxic $4\,^{\circ}$C"). The user can also specify a starting depth and starting core number, meaning that a sampling plan can be made to cover a portion of a hole's entire depth. This is useful if a change in core length or section length is planned in the course of drilling, as a different sampling plan can be made for each core/section length configuration.

2.2 Sample placement algorithm

Samples are placed at the next-deepest section interface following the depth specified by the user. Samples are prioritised by stacking outwards from each section interface in the order that the sample requests are entered to keep them as close to one another and thus as easily comparable to each other as possible. Sample requests under the same sample request number are placed adjacent to each other. Samples are generally not placed in Sect. 1, as the top of the core is usually the most disturbed part of the core. Samples are only placed in Sect. 1 when samples have a repeating depth interval equal to the length of one section or less, as decisions about the usefulness of these samples can be made on a case-by-case basis. Samples are not placed at the precise depth specified by the user's input for two reasons: (a) this would not avoid samples overlapping with one another and (b) whole-round cores are typically sampled from the section edges inwards to preserve the longest possible segments of each section for non-time-sensitive analyses. If too many samples are placed in a given target section (i.e. potentially overlapping samples) then an error message will be generated. It will be evident from the program's output which sample request was one too many for that particular section, allowing the operator to re-design the sampling plan with adjusted target depths.

2.3 Sampling plan output

The sampling plan is produced as a colour-coded diagram, with one or more pages for each core and at most three sections shown on each page. Each section has a centimetre ruler to its left to aid in slicing the section accurately. Handling instructions for each sample are listed down the right-hand side of each section. A different colour is used for each sample request number, with a key on the right-hand side of the page showing which sample request each colour corresponds to.

3 Implementation

Corganiser has been written in the Python programming language using the ReportLab package (ReportLab Europe Ltd, London, UK), for drawing diagrams in PDF format. Corganiser can be used in two different ways: via a graphical web-based implementation and a command-line-based implementation (Fig. 1).

3.1 Web-based implementation

In the web-based implementation, the user inputs data using an HTML form. This form is dynamically updated based on the user's inputs to include fields for as many sample requests and samples as necessary. Submitting the form produces two output files: the PDF sampling plan file in A4 format ready for printing and use, and a Corganiser file (a ".cor" file) in a custom text-based format containing all the information entered into the HTML form. The ".cor" file can be saved on the user's computer and re-uploaded to the server for editing at a future time. The web-based implementation is intended for users unfamiliar with using software tools from the command line and who have access to the internet during the drilling project. The Corganiser web application is currently hosted at Aarhus University in Denmark and can be accessed via the URL http://130.226.247.137/. The source code for this implementation is available at https://github.com/ianpgm/Corganiser.

3.2 Command-line implementation

Corganiser is also available in a command-line implementation. Here the user executes a Python script with a ".cor" input file to generate a PDF file output. The ".cor" file can be produced either by the web-based Corganiser service, modified from a file produced on the web, or created by the user themselves as a text file – the correct notation for writing a ".cor" file is included in the Corganiser manual. The command line implementation will work on any operating system with Python and ReportLab, including Windows, MacOS X, and GNU/Linux. It has the advantage of working independently of an internet connection, but the disadvantage of requiring an operator familiar with executing Python scripts from the command line. The scripts for the

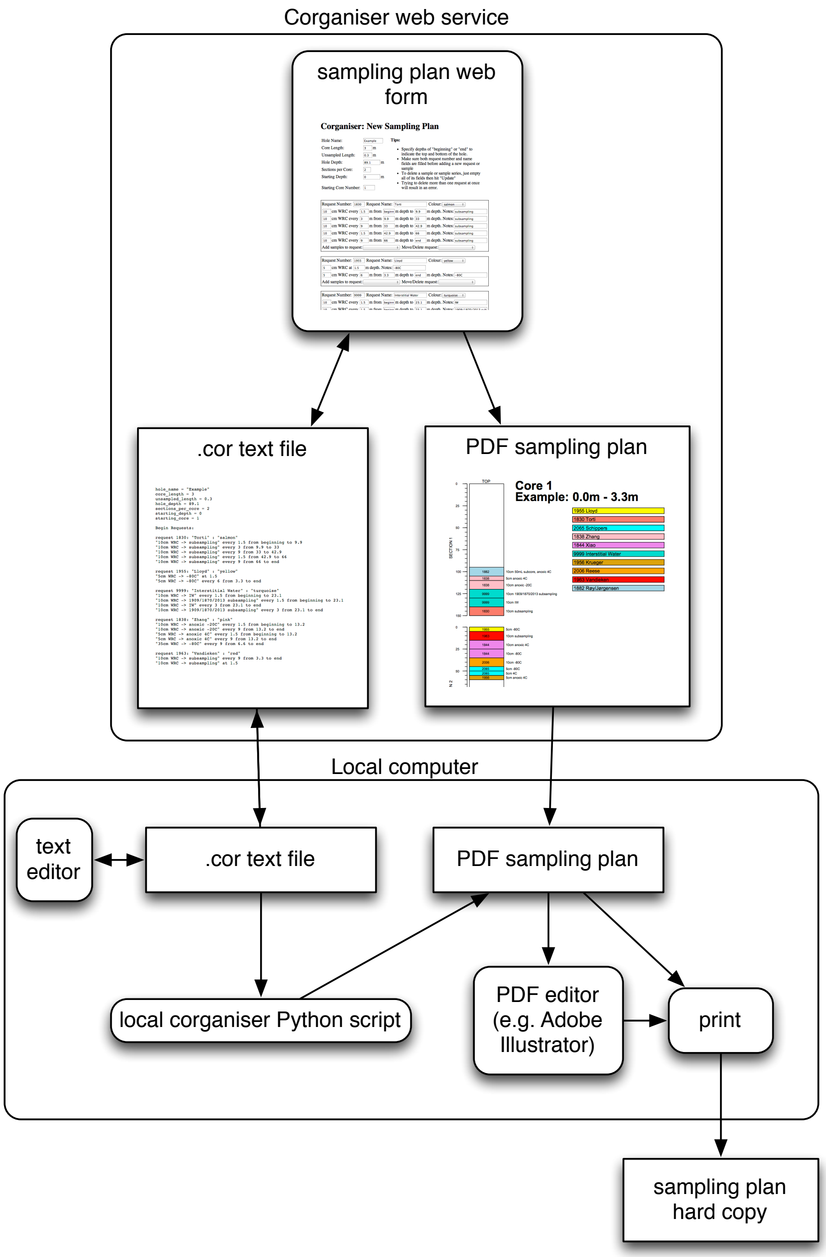

Figure 1. Diagram displaying how the web-based and desktop versions of Corganiser can be used to generate a sampling plan.

command-line implementation of Corganiser can be downloaded from https://github.com/ianpgm/Corganiser.

3.3 Further modification of Corganiser output

PDF files generated by Corganiser can be edited by any software capable of editing vector graphics in PDF files, such as Adobe Illustrator. Section diagrams can be modified and extra annotations can be added manually if sampling plans require changes beyond Corganiser's core capabilities.

4 Limitations

4.1 Cut-off syringe sampling

Corganiser does not plan the organisation of sampling with cut-off syringes, as the arrangement of such syringes in a core cross section is a much more complex problem and impacted by the individual needs of the researchers carrying out sampling, the nature of the sediment, and the tools available to the researchers. During IODP Expedition 347 syringe sampling was manually planned, with space made for syringe sampling in the Corganiser plan using a “syringe” sample requester spacer.

4.2 Maximum sampling frequency

For each sample type, Corganiser is designed to work with a maximum of one sample per section. Attempts to enter a higher sampling frequency (a sampling interval shorter than the section length) will result in samples from the same requester adjacent to one another. This is an intentional limitation, following the practice of sampling whole-round cores from section ends only. If a higher sampling frequency than once per section is required, then the simplest way of planning this is to increase the number of sections per core. For example, if a sample requester requests one sample every 0.5 m for a hole with planned section lengths of 1.5 m, the planned section length should be decreased to 0.5 m.

4.3 Changes to the plan following core collection

The sampling plan produced by Corganiser is of course an idealised view of how the samples will be taken. Suboptimal core recovery, disturbed cores, lithologies poorly suited to microbial/geochemical sampling, and a myriad of other factors will help determine the best sampling strategy. In such cases handwritten annotations to the printed sampling plan will help to keep data entry, label printing, and sampling organised.

5 Conclusions

Corganiser proved itself a useful tool during IODP Expedition 347, helping to streamline the collection of whole-round samples with a printed, colour-coded plan produced several hours before the drilling of each microbiology hole commenced. This short timespan for generating sampling plans meant that the plans could be guided by data generated offshore from other holes drilled at the same site. Corganiser is now available as an easy-to-use web application suitable for preparing sampling plans during future scientific drilling projects with extensive sampling of whole rounds for microbiological and geochemical analyses.

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Probing reservoir-triggered earthquakes in Koyna, India, through scientific deep drilling

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Abstract. We report here the salient features of the recently concluded International Continental Scientific Drilling Program (ICDP) workshop in Koyna, India. This workshop was a sequel to the earlier held ICDP workshop in Hyderabad and Koyna in 2011. A total of 49 experts (37 from India and 12 from 8 other countries) spent 3 days reviewing the work carried out during the last 3 years based on the recommendations of the 2011 workshop and suggesting the future course of action, including detailed planning for a full deep drilling proposal in Koyna, India. It was unanimously concluded that Koyna is one of the best sites anywhere in the world to investigate genesis of triggered earthquakes from near-field observations. A broad framework of the activities for the next phase leading to deep drilling has been worked out.

1 Introduction

During 16–18 May 2014, an International Continental Scientific Drilling Program (ICDP) workshop on Scientific Deep Drilling in the Koyna region of western India was held in Koyna. It was jointly organized by the Council of Scientific and Industrial Research (CSIR)-National Geophysical Research Institute (NGRI), Hyderabad and the National Center of Antarctic and Ocean Research (NCAOR), Goa on behalf of the Ministry of Earth Sciences (MoES). This was in continuation of an earlier ICDP workshop held in March 2011 (Gupta et al., 2011) where an exploratory phase of investigations involving compilation and improvement of the hypocentral parameters through operation of additional seismic stations; MT surveys; lidar; airborne geophysical surveys; core drilling at four sites, and modeling of hydraulic connectivity etc. were recommended to be undertaken prior to planning of the deep borehole(s). The purpose of the current workshop was to bring together key experts to discuss results of the exploratory phase, to deliberate on the design of the deep borehole(s), to decide on the instrumentation to be deployed, to build an international science team, and to provide necessary inputs for preparation of a full drilling proposal.

There were 49 participants: 37 from India and the remaining 12 from Canada, France, Germany, Japan, New Zealand, Norway, Spain, and USA. Participants included seismologists, geologists and drilling and instrumentation experts having experience in working on deep drilling sites globally.

The Koyna region, located in the ∼65 Ma old Deccan Traps of India (Fig. 1), is globally the most prominent site of artificial water-reservoir-triggered earthquakes, also known as reservoir-induced earthquakes (Gupta, 2011). Soon after the impoundment of the Shivaji Sagar Lake formed by the Koyna Dam in 1962, triggered earthquakes started occurring and have continued until now. This includes the $M = 6.3$ 10 December 1967 earthquake; 22 earthquakes of $M > 5$, and over 200 $M > 4$ earthquakes plus thousands of smaller

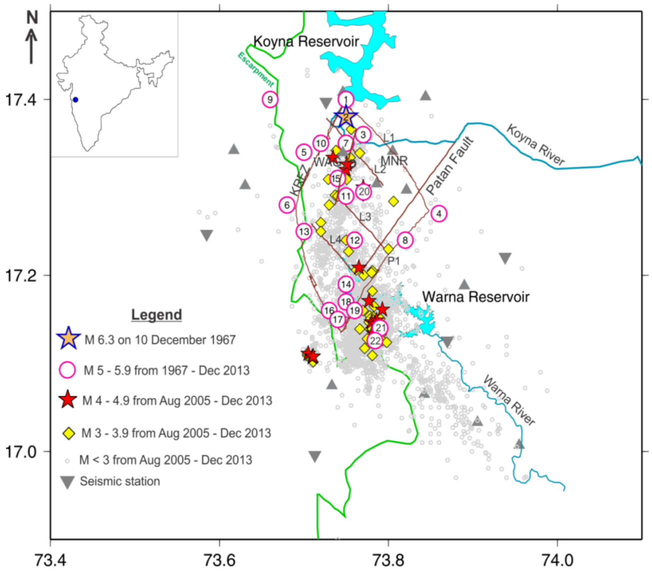

Figure 1. Seismic stations and earthquakes in Koyna–Warna region. KRFZ: Koyna River fault zone; D: Donichiwada Fault; P1: fault parallel to Patan Fault; L1, L2, L3, and L4: NW–SE trending fractures. Inset: Koyna on India's map.

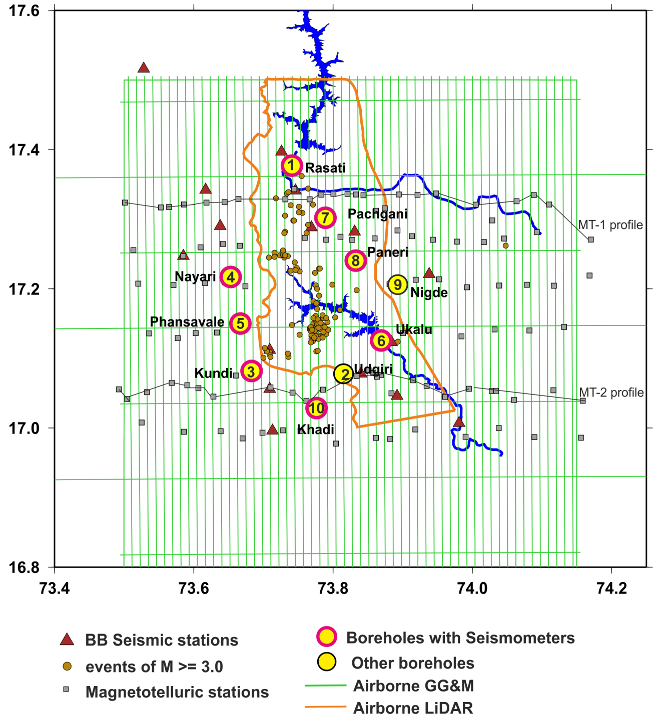

Figure 2. Map of the study area. Green lines indicate the airborne gravity gradiometry and magnetic data flight lines. An orange line encloses the airborne lidar acquisition area. Grey squares indicate MT sites. Red triangles are broadband seismological stations. Numbered circles indicate the locations of exploratory boreholes which are being drilled and logged. Borehole 2 could not be logged; 9 and 10 are planned. Boreholes in Rasati and Kundi have been instrumented with three component seismometers at depths of 1522 and 1134 m, respectively. The remaining six boreholes are to be instrumented in the next few months. Brown filled circles indicate earthquakes of magnitude greater than 3 for the period 2005 to 2013.

earthquakes. Filling of the nearby Warna Reservoir in 1985 caused further expansion of the triggered earthquake zone. A strong association of earthquake activity is observed with the annual loading and unloading cycles of the two reservoirs (Gupta, 2002). The entire earthquake activity is limited to an area of about 20 km $\times$ 30 km, with the focal depths of most of the earthquakes lying between 3 and 8 km. There is no other earthquake source within 50 km of the Koyna Dam. Accessibility to the epicentral zones makes the Koyna/Warna site well suited for earthquake-related near-field observations. An earthquake of $M = 3.2$ occurred on 15 May 2014 in the Koyna region, a day prior to the commencement of the workshop.

2 Proceedings of the workshop

The first day of the workshop was dedicated to discussing the scientific questions that need to be addressed. Several of these are taken from the SAFOD program (Zoback et al., 2011). These include the following:

1. What is the fluid pressure and permeability within and adjacent to the fault zone?
2. What are the composition and origin of fault-zone fluids and gases?
3. How do stress orientation and magnitude vary across fault zones?
4. How do earthquakes nucleate?
5. How do earthquake ruptures propagate?
6. How do earthquake source parameters scale with magnitude and depth?
7. What is the role of water reservoirs in triggering earthquakes?
8. What is the 3-D/4-D nature of the fault zone?

Although several studies have clearly established the association of continued triggered earthquakes in Koyna with the precipitation-driven loading and unloading of the Koyna and Warna reservoirs, the triggering mechanism is not well understood. Our knowledge about the physical properties of rocks and fluids in the fault zones and how they affect the buildup of stress for extended period is limited by the lack of data from the near-field region.

Existing geological, hydrological and geophysical studies in the region provide a good initial framework to study the regional tectonic setting but lack critical inputs needed to explore the physical mechanisms that connect the reservoir water level changes to the occurrence of earthquakes. The clear evidence provided by past seismic activity makes a compelling case for bringing new scientific tools to probe the triggered seismicity in the Koyna area. The proposed scientific deep drilling and setting up of a deep borehole observatory is aimed to study pre-seismic, co-seismic and post-seismic changes in physical properties in the "near-field" of earthquakes and provide answers to the abovementioned questions. By instrumenting the deep borehole for long-term monitoring of critical parameters such as seismicity, temperature, fluid/gas and pore pressure, it would be possible to obtain unprecedented new information on the temporal changes of those parameters in the near-field of earthquakes before, during and after an earthquake.

Studies carried out since 2011 in the preparatory phase were reviewed, including detailed airborne magnetic and gravity-gradient surveys, MT surveys, drilling and logging of six boreholes going to depths of ~ 1500 m, heat flow measurements, seismological investigations including the deployment of two borehole seismometers, and lidar surveys (Fig. 2).

Among the most significant results are those obtained from the six boreholes on the thickness of the Deccan Traps basalt and its relation to the basement and the geophysical environment to be encountered in deeper drilling. These holes were continuously cored and penetrate through the Deccan Traps into the Archean basement. It was found that the basal flows rest directly on basement with no intervening sedimentary layers. The basement contact is almost horizontal indicating very little topography of the basement across the Western Ghats escarpment. It was also inferred that the temperature at a depth of 5 km will be around 130 to 150 °C, confirming earlier estimates. Seismic waveform modeling and double difference approach to earthquake relocation have helped in better understanding the hypocentral distribution and fault geometry. To achieve desired accuracies of a few tens of meters, seismometers need to be placed below the basalt cover. This has led to the plan of putting eight borehole seismometers with good azimuthal coverage around the earthquake zone. Two of them are already in operation and six more are planned to be installed in the months to come.

As part of the workshop, talks were given addressing a deep borehole observatory plan, earthquake nucleation, geochemical control on fault reactivation, stress regime in the Indian subcontinent, borehole seismology, role of fluids in triggering earthquakes, temperature monitoring in boreholes, and physical properties from well logs and laboratory measurements. Posters on the investigations were displayed to encourage discussions throughout the 3 days of the workshop. The day ended with a visit to the Panchgani drilling site (Fig. 4).

The second day was dedicated to discussions in the following three breakout groups:

a. main hole(s) drilling, down hole measurements and sampling,

b. main hole(s) completion plan, observatory design and installation plan, and

c. sample management, distribution and laboratory studies.

Coordinators for each of these three groups led the discussions and managed to converge on practical plans. International collaboration was another issue that was discussed on the second day. The day ended with boating on Koyna Lake.

On the third day, a presentation was made on ICDP participation, training and equipment setup maintained by trained personnel of the Operational Support Group (OSG). Available facilities include the following:

- online gas monitoring while drilling
- Slim Wave™ Geophone Chain
- core scanning and logging
- data management system.

The schedule for the use of these facilities has to be made well in advance.

The coordinators of the three breakout groups presented their recommendations to the entire workshop, which were discussed in detail.

3 Outcome of the workshop

All the participants appreciated the progress made since the first ICDP workshop held in March 2011. The sites of the pilot hole(s) and the main bore hole(s) were tentatively agreed upon (Fig. 3). A broad framework for the future work was chalked out. It was concluded that Koyna is the best site for addressing the questions that need to be resolved for an improved understanding of reservoir-triggered earthquakes and that answers can be found through deep drilling. The major outcome of the workshop may be summarized as follows:

1. Details of geophysical, geological, airborne studies and borehole measurements carried out during the preparatory phase of the past 3 years and their broad results form a solid basis for upcoming investigations in this area. Based on gravity, magnetic, seismic and MT data, a 3-D structure of the region has been worked out, which has been validated from the information obtained from the six boreholes drilled down to ~ 1500 m depth and other geoinformation.

2. The results of recording of two borehole seismometers at depths of 1134 and 1522 m, several hundred meters into the basement, have been very encouraging. It is seen that earthquakes of $M < 1$, which are almost a part

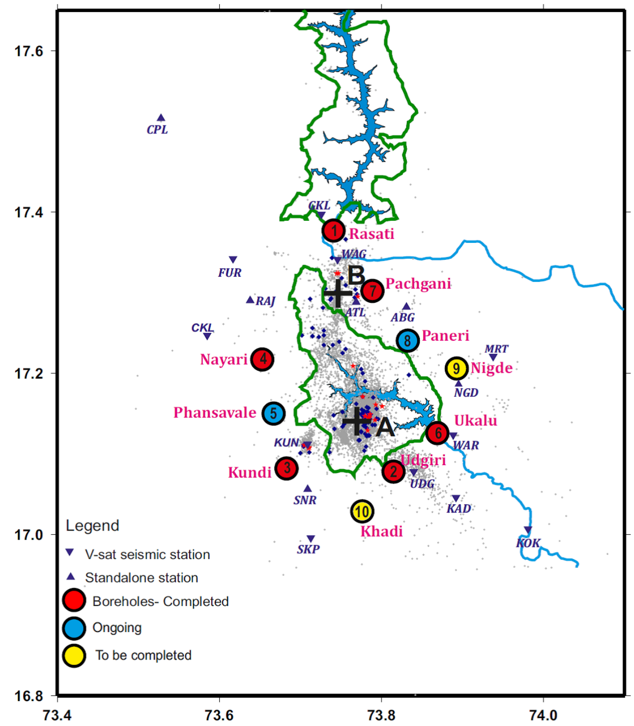

Figure 3. Locations of exploratory boreholes vis-à-vis seismic clusters. Black crosses mark proposed locations of pilot boreholes. The grey, blue and red dots represent epicenters of seismic activity over the last 9 years in increasing order of magnitude from 1.8 to 5.5. Green lines mark boundaries of reserve forest areas surrounding the Koyna (north) and Warna (south) reservoirs.

of the noise on the surface station, are clearly recorded by the borehole seismometers. Six additional borehole seismometers are suggested to be deployed to help to constrain the geometry of the active fault and provide information critical for fine-tuning the location of the pilot and main borehole(s).

3. For a better comprehension of the mechanism of earthquake occurrence and the part played by reservoirs in triggering earthquakes, it was recommended to have two pilot and two main boreholes, hosting comprehensive sets of monitoring instruments. Originally only one pilot bore hole and one main bore hole were planned (A in Fig. 3). However, an additional pilot bore hole and a main borehole (B in Fig. 3) located close to the second-most active seismic cluster in the Koyna region, were recommended. Operation of two bore well observatories would provide exceptional opportunities to address the questions posed earlier.

   The well scheme for the 3000 m deep pilot hole (Table 1) was proposed. The following is a suggested drilling approach:

   - pre-conditions
     - no high-pressure zone
     - no influx of gas, hydrocarbons, corrosive fluids
     - no mud-loss zone
     - no high temperature environment
     - anticipated rate of progress from core drilling 1–2 m h^{-1}
   - drilling objective
     - react to potential mud losses in and at the base of basalt; increase the drilling performance drastically over core drilling (3–4 m h^{-1}).
   - rig specification
     - 300 t hook-load capacity
     - 2× triplex mud pumps (1000 kW each)
     - top-drive desirable (else rotary table)
     - 3000 m of 5 in. DP+5 in. HWDP+6 1/4 in./8 1/4 in./9 1/2 in. DC
   - drilling techniques
     - classic rotary drilling: with mud motors or turbine, 3R-insert bits, polycrystalline
     - diamond bit (PDC) or impregnated bits
     - air hammer: fast, environmental issues (noise at surfaces > 80 db, plus air pollution). Rotary mud-drilling is less noisy.
     - having an option to switch any time over from air drilling to mud rotary drilling, logging, casing and cementation.
   - mud system: water-based polymer mud (SG = 1,2)
   - directional drilling: max tolerable verticality: ∼ 1.5° inclination.
   - coring: on-demand spot coring is possible any time, not needed in basalt, is not primary task in pilot hole, might be if penetrating fault zone

4. An outline of the logging and other measurements along with possible instrumentation for the pilot boreholes was discussed in detail. Commencement of drilling the pilot borehole(s) must be as early as possible. Necessary instrumentation and equipment also need to be procured.

5. International collaboration is welcome and will be established through bilateral agreements for investigation of specific research problems with approval of MoES and/or ICDP.

6. An Integrated Data Management System and GIS platform will be put in place to enable external participation and optimize interpretations.

Table 1. Well scheme.

Hole diameter	Casing size	Setting depth
17.5 in.	13.38 in.	400 m
12.25 in.	9.63 in.	1400 m*
8.5 in.	5.5 in.	3000 m

*Option of one contingency casing 7 in. liner after 9 5/8 in. casing to mitigate uncertainties/surprises. All casing, drill bits and other consumables are of API standards.

Figure 4. Participants at the Panchgani drill site.

7. Permissions necessary to put experiments and drilling in the reserve forest area should be obtained on a priority basis.

8. A full drilling proposal for the main borehole(s) is foreseen to be prepared in due time to meet the 15 January 2015 deadline of submission to the ICDP.

4 Broad schedule for the future work

– Submitting a proposal to ICDP for the main boreholes by 15 January 2015. Details need to be worked out.

– Drilling of two 3 km deep pilot boreholes by summer of 2015 (leap-frog with two rigs).

– Concurrent planning of deep main borehole(s), firming the specifications by the summer of 2015 and drilling from October 2015 through December 2017.

– Plan for an international meeting and visit of the facilities in December 2017 to coincide with 50 years of Koyna $M = 6.3$ earthquake of 10 December 1967.

The workshop provided an excellent opportunity to discuss with the global community the work carried out in the preparatory phase since the first ICDP workshop of March 2011 and to firm up the future plan of action. There was much appreciation of the work reported and concurrence on the future course of work.

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Scientific Drilling
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A way forward to discover Antarctica's past

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Antarctic Geologic Drilling Workshop – Houston, Texas, 7–8 November 2013

Fifty-four participants attended the Antarctic Geologic Drilling Workshop (AGDW) to discuss science objectives and develop key projects. The goal of the NSF-sponsored AGDW was specifically to discuss the interests of US-based scientists in Antarctic and Southern Ocean projects, foster interactions within the Antarctic geoscience community, and discuss top-priority scientific questions and technological requirements to advance outstanding scientific goals.

Antarctica, with its thick shroud of glacial ice and fringed belt of floating oceanic ice, offers challenges to unraveling the history of one of Earth's last frontiers. Rocks deposited in and around Antarctica, reachable through a wide-range of innovative geological drilling approaches, formed during times that witnessed climate and ice-sheet changes. Recovery of rocks through drilling expands the understanding of the interplay of Earth's dynamic processes that control and respond to the Antarctic cryosphere.

Much of our knowledge of past climate changes, and inferred ice-sheet history, has been obtained from drill cores taken in low-latitude settings. Such far-field proxies offer an outline of ice-sheet behavior, but cannot show which part of the ice sheet changed or what the ocean currents, temperatures, or other controlling parameters were in ice-proximal settings. Drilling in Antarctica can yield samples of rock that were influenced directly by glacial processes and which provide access to Antarctica's ice-covered geology. Limited outcrops, short gravity cores, and drill cores with partial recovery have been studied from many locations, but such records cannot give the continuous temporal record needed to determine the timing and rates of ice-sheet change or boundary conditions controlling that behavior. Spatially distributed records, including transects from onshore to distal records from each major ice drainage basin, are needed to resolve the individual histories of each area. Seismic data linking drill sites can increase the impact of individual sites by extending the details over a broader area and tightening the time constraints at each site. New over-ice seismic data acquisition through systems like Vibroseis will identify new subglacial drilling targets. New methods to sample bedrock and measure conditions beneath the ice will help refine basal-bed boundary conditions that are vital to reconstructions of ice-sheet behavior. Numerical modeling can test data-driven hypotheses and evaluate forcing mechanisms under different atmospheric boundary conditions.

Within the workshop discussions, two general themes rose to highest priority. One is on late Quaternary interglacials, when Earth and ocean conditions were similar to today and ice retreated landward of its current position. The other priority is the study of mid-Cenozoic ice-sheet history during times when boundary conditions of high atmospheric CO_2 approached those estimated for the next century, but when Earth and ocean conditions were different from today. Combining records of ice-sheet behavior during these two time intervals and these two sets of conditions that are converging in our future will yield information needed to advance the development of computer simulations for studies of near-term future behavior of Antarctica's ice sheets.

The full report is available at http://agdw.uh.edu/.

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Early Cenozoic tropical climate: report from the Tanzania Onshore Paleogene Integrated Coring (TOPIC) workshop

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Abstract. We are currently developing a proposal for a new International Continental Scientific Drilling Program (ICDP) project to recover a stratigraphic and paleoclimatic record from the full succession of Eocene hemipelagic sediments that are now exposed on land in southern Tanzania. Funding for a workshop was provided by ICDP, and the project was advertised in the normal way. A group of about 30 delegates assembled in Dar-es-Salaam for 3 intensive days of discussion, project development, and proposal writing. The event was hosted by the Tanzania Petroleum Development Corporation (TPDC) and was attended by several geologists, geochemists, geophysicists, and micropaleontologists from TPDC and the University of Dar-es-Salaam. International delegates were from Canada, Germany, India, Ireland, Italy, the Netherlands, United Kingdom, and United States (and we also have project partners from Australia, Belgium, and Sweden who were not able to attend). Some of the scientists are veterans of previous scientific drilling in the area, but over half are new on the scene, mostly having been attracted by Tanzania's reputation for world-class paleoclimate archives. Here we outline the broad aims of the proposed drilling and give a flavor of the discussions and the way our proposal developed during the workshop. A video of the workshop with an introduction to the scientific goals and interviews of many of the participants is available at http://vimeo.com/107911777.

1 Scientific rationale

The current atmospheric CO_2 concentration (about 400 ppm) is similar to that of the Pliocene, and in the coming century we may see levels comparable to those of the early Paleogene (IPCC, 2013). As the planet begins to be affected by anthropogenic greenhouse gas emissions, it is important to understand climate forcing and response in Earth's past, especially greenhouse episodes. In particular we need to know

– to what extent atmospheric CO_2 and global temperature co-varied during previous intervals of global warmth.

– how extreme climatic conditions were in the tropics, both in the ocean and on land.

– what the response was of the marine and terrestrial biota to extreme climate states and intervals of climate change.

– whether the paleoclimate forcings and responses we infer from the sediment record are consistent with the predictions of general circulation models (GCMs)?

The hemipelagic tropical marine clays of the Kilwa Group, now uplifted and exposed onshore Tanzania (Fig. 1), are uniquely placed to help answer these questions because of their extraordinary potential for climate proxy work including temperature and $p\mathrm{CO_2}$ proxies (e.g., Pearson et al., 2007, 2009). Carbonate microfossils (foraminifera and nannofossils) are extremely well preserved through the entire Paleogene (Pearson et al., 2001, 2007; Wade and Pearson, 2008; Bown et al., 2008) (Fig. 2). Oxygen isotope ratios of planktonic foraminifera have been widely used to estimate sea surface temperatures in the past, but in deep-sea carbonates they are usually diagenetically altered, resulting in an artificially high oxygen isotope signal (i.e., low temperature), thereby biasing temperature reconstructions. This is the primary rea-

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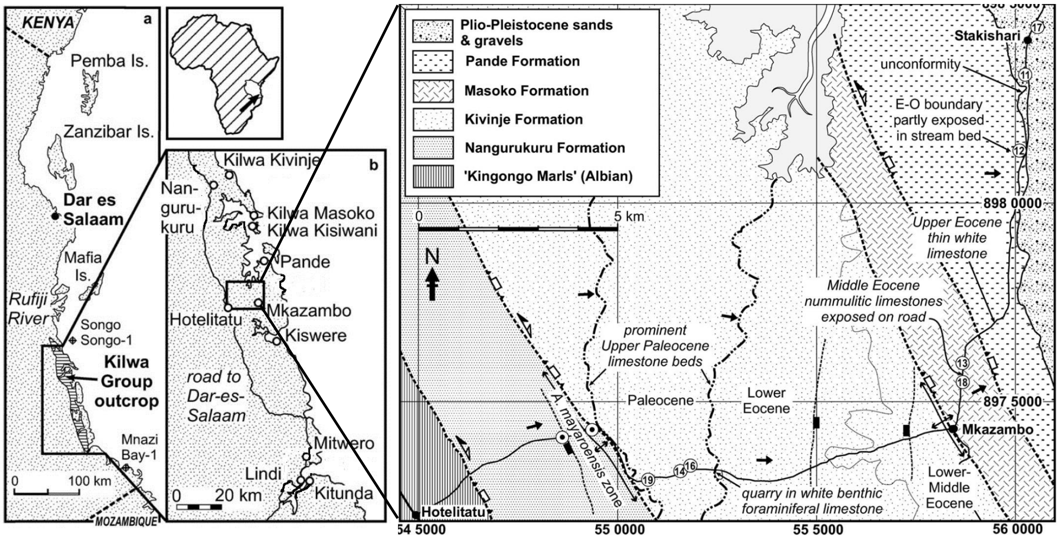

Figure 1. Location map. **(a)** Coastal Tanzania; **(b)** detail of Kilwa Group outcrop; **(c)** geological map showing principal faults and sites of several Tanzania Drilling Project drill cores (circled numbers). The proposed TOPIC drill site is at TDP site 12 as highlighted by the circle in the northeastern corner of the geological map. Note: the Pande through Nangurukuru formations comprise the Kilwa Group. Modified from Nicholas et al. (2006).

son why deep-sea drilling has so far not been able to provide a consistent tropical paleotemperature record for the Eocene; hence it is central to our plan for Tanzania. The development of a calcareous microfossil "Konservat-Lagerstätte" onshore and offshore Tanzania appears to be related to clay-rich sediments that act as a relatively impermeable medium, isolating microfossils from chemical and physical processes of diagenetic alteration (Pearson et al., 2001; Bown et al., 2008). The Tanzania hemipelagic sediments also contain exceptionally well-preserved organic matter, including terrestrial pollen and spores, marine dinoflagellate cysts (Pearson et al., 2004), and organic biomarkers (Van Dongen et al., 2006), suitable for reconstructions of both marine and terrestrial environments.

The Tanzania Onshore Paleogene Integrated Coring (TOPIC) consortium plans to core the entire Eocene succession (from about 56 to 33 million years ago) at one site. The Eocene epoch was characterized by globally warm climate states and a series of climate perturbations and trends. These include the Paleocene–Eocene thermal maximum, several other short hyperthermal events, the extended super-warm phase known as the Early Eocene Climate Optimum, and the long-term global cooling that eventually led to the Eocene–Oligocene transition and the development of a continental-scale ice cap on Antarctica. This rich history of climatic change provides us with a wide range of questions to address. Understanding climate change in Earth's past is societally important and well aligned to ICDP's science plan.

The planned drilling will produce a standard reference section for Eocene stratigraphic correlation, including high-resolution magneto- and cyclostratigraphy and integrated biostratigraphy using calcareous and organic microfossils. The detailed stratigraphic framework and information on basin evolution will be of great interest regarding hydrocarbon exploration in Tanzania, which hosts major gas fields offshore in Eocene age reservoirs. The drill site also provides an exceptionally interesting opportunity to study the biomass and activity of the deep biosphere in a homogeneous clay-rich formation down to a depth of 1000 m.

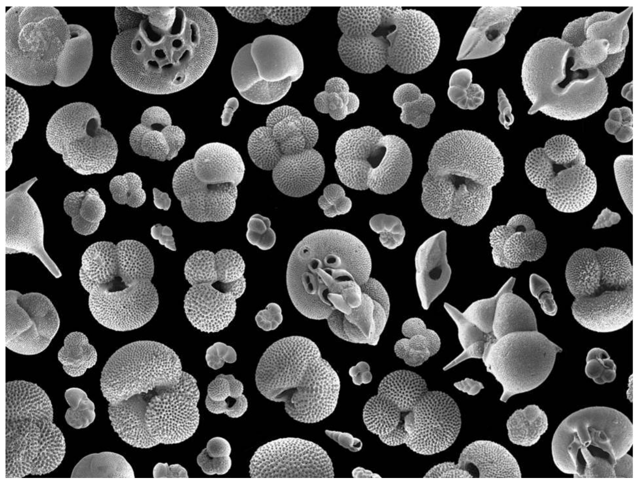

Figure 2. Planktonic foraminifera from the Eocene–Oligocene transition at the proposed drill site. The exquisite preservation is typical of the Tanzanian Kilwa Group and allows for high-quality biostratigraphy as well as reliable geochemical proxy work including oxygen isotope paleotemperatures and boron isotope palaeo-pCO_2 estimation. Organic biomarkers are also extremely well preserved.

Figure 3. The workshop participants. Photo: Ishka Michoka, Plastic Buddha Productions.

2 The workshop

The workshop was held from 9 to 11 September at a hotel on the outskirts of Dar-es-Salaam (Fig. 3).

The meeting was preceded by some informal discussions with potential drilling contractors to establish the capacity and availability of potential drill rigs and consider various logistical aspects. This helped us to clarify the likely rate of progress and cost of operations. The drilling itself is relatively straightforward for an ICDP project (continuous coring to a depth of about 1000 m in two holes), but the site is fairly remote, so operations will need to be completed within the long dry season. A plentiful supply of freshwater is one of the more significant challenges and would require on-site storage and frequent trucking. Seawater would be much easier to source, and delegates at the workshop highlighted the potential benefits of using seawater, especially for easy detection of possible contamination of pore waters by drilling fluid, which is an important concern for the microbiological objectives.

The first day was largely devoted to a series of presentations setting out the main scientific themes in the context of past work, most notably the Tanzania Drilling Project (funded by successive research grants from the UK Natural Environment Research Council and US National Science Foundation). This program ran from 2002 to 2009, during which time a total of 40 shallow drill sites were cored to a maximum depth of about 150 m using small truck-mounted rigs. This drilling has produced over 40 peer-reviewed papers to date but also has a series of limitations inherent in the technology, including relatively low maximum penetration depth, unexceptional recovery and core quality, narrow diameter cores, and no downhole logging. Only about half the total stratigraphy was recovered despite these intensive efforts; hence the need for deeper penetration and a much more continuous record via ICDP is very clear.

Links to IODP Full Proposal 778 (Tanzania Offshore Paleoclimate; TOP) were discussed. That project has similar and complementary aims but with a greater focus on the Neogene, which is only poorly represented onshore. Together IODP–TOP and ICDP–TOPIC will produce an onshore–offshore transect and recovery of almost the entire Cenozoic (from the Holocene down to the top Paleocene). IODP–TOP has been graded as "excellent" by the IODP Proposal Evaluation Panel but has so far not been scheduled because of perceived piracy risk, although this has diminished greatly in recent years; hence we are optimistic that it will be available for scheduling soon. We note that successful completion of ICDP–TOPIC would allow IODP–TOP to reduce the proposed deep drilling at one site without compromising its scientific objectives, and so allow more ship time for triple coring and drilling of an alternative site.

One area of science that is new to the proposal at this stage is the study of the deep subsurface biosphere. The TOPIC project provides an exceptionally interesting opportunity to study prokaryotic activity and biomass in a homogeneous clay-rich environment down to a depth of 1 km. Clay-rich sediments occur over large areas and are attractive targets for subsurface waste disposal, including nuclear waste, but knowledge of prokaryotic activity in such environments is very limited (Parkes et al., 2014). The Kilwa Group sediments have exceptional preservation of micro- and nannofossils, indicating limited diagenesis and pore fluid activity, which in turn suggests that prokaryotic activity and populations may be much more limited than in other sediment types at similar depths. It has been suggested that subsurface bacteria require interconnected pore throats greater than 0.2 µm in diameter for sustained activity (Fredrickson et al., 1997). If that is so, then in Tanzania the prokaryotes may be "entombed" in the clays and therefore more representative of the original marine sedimented population than more active subsurface populations. Hence the proposed drilling will help us answer some fundamental unknowns in the field.

Other scientific areas discussed include the challenges of modeling Eocene climate, linkages between continental and marine climate, fundamental questions of controls on evolution and ecology in a changing environment, and what we may be able to learn in this location about the late Eocene impact events. Having refined our scientific aims, we then moved on to develop details of the sampling strategy for the full range of analyses and proxies and a collaboration plan to ensure those aims can be realized.

Also of importance is how to maximize the benefit for Tanzania. The country is experiencing a boom in exploration thanks to recent large gas discoveries offshore. Knowledge of the Eocene stratigraphy and environments and basin evolution will be important in the search for new discoveries. To help build scientific capacity in the area, the University of Dar-es-Salaam is currently initiating a master's level degree program with an emphasis on petroleum geology. The TOPIC project will provide a major opportunity for students

Figure 4. One of 40 shallow penetration boreholes drilled by the Tanzania Drilling Project (2002–2009). This is TDP site 12, the proposed TOPIC drill site (see Fig. 1 for location).

to engage with a cutting-edge science project and international scientists from many countries. We discussed ways of funding master's projects and involving students on site, possibly with an ICDP training course.

It is also important to engage with the public across Tanzania and in the area of drilling. Tanzania has experienced unprecedented extremes of weather recently that have been linked to climate change, and there is a growing awareness of the need to protect the natural environment. The goals and strategy of a national outreach program were discussed, including interaction with government science agencies, universities, and schools. The drilling will be an opportunity to inspire future Earth scientists and raise awareness of problems associated with climate change.

3 Scope of the proposed drilling

Days 2 and 3 of the workshop were focused on intensive discussions on the optimum location for the drill site (which will be near a previous Tanzania Drilling Project site – Fig. 4), scope of the proposed drilling, sampling requirements, and collaborative development of the full proposal. Progress was accelerated via a series of breakout groups tackling issues as disparate as education and outreach, recording the continental climate signal, organic geochemistry, biotic evolution, seismic interpretation, and operational logistics. Delegates contributed to a growing communal draft full proposal.

With reference to our feedback from ICDP, delegates were reminded not to feel overly constrained by the focus presented in the workshop proposal and that there was scope for expanding the scientific aims if desirable. In particular, and in response to the review comments, considerable discussion focused on the possibility of drilling deeper or adding a second site lower in the stratigraphy. The desirability of obtaining a Cretaceous–Paleogene boundary was discussed, as well as significant deeper targets such as the Cenomanian–Turonian boundary interval. However in the end a consensus was reached that, given current knowledge and seismic information, the proposal should for now focus on a single site to recover the entire Eocene more or less as originally envisaged. A follow-on proposal or industry support may allow the project to develop further into the deeper objectives when better seismic data become available.

The available seismic data for the proposed Eocene drill site were discussed, and consideration was given to moving the location along strike to coincide exactly with a seismic line. The deep structure is relatively simple with a gentle ocean-ward dip. The risk of encountering hydrocarbon pockets at the proposed depths and location of drilling is considered low.

Our plan is to accomplish all the drilling within the 10 weeks of the long dry season in the area. Rates of likely drilling progress mean we can expect to drill two holes to approximately 1000 m, which will enable penetration from the lower Oligocene to upper Paleocene. We will use the maximum possible diameter of pipe to allow maximum core recovery. Two holes will be drilled to fill in coring gaps in a composite section and to increase the material available for destructive sampling. On-site biostratigraphy in real time will allow us to monitor the rate of drilling progress and help determine the optimum point for termination of drilling. Sampling for deep biosphere and pore fluid geochemistry will also be done on site, as will basic core description, and cores will be scanned by a multi-sensor core logger. Cores in plastic liners will then be shipped to a suitable core laboratory and repository for intensive sampling.

4 Project development

Delegates left the workshop with a clear understanding of the aims of the drilling and the current extent of collaboration. Each participating country will now develop its own research plan within the context of the project as a whole. It now remains for us to finish the full proposal, including an operations plan, responsibility matrix, and detailed costings. In summary, the TOPIC project has enormous scientific potential and is relatively straightforward from a logistical perspective; hence we plan to have a full proposal submitted to ICDP within 4 months of the workshop. More details of the project are available at http://www.icdp-online.org/projects/world/africa/tanzania/.

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Drilling to investigate processes in active tectonics and magmatism

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Abstract. Coordinated drilling efforts are an important method to investigate active tectonics and magmatic processes related to faults and volcanoes. The US National Science Foundation (NSF) recently sponsored a series of workshops to define the nature of future continental drilling efforts. As part of this series, we convened a workshop to explore how continental scientific drilling can be used to better understand active tectonic and magmatic processes. The workshop, held in Park City, Utah, in May 2013, was attended by 41 investigators from seven countries. Participants were asked to define compelling scientific justifications for examining problems that can be addressed by coordinated programs of continental scientific drilling and related site investigations. They were also asked to evaluate a wide range of proposed drilling projects, based on white papers submitted prior to the workshop.

Participants working on faults and fault zone processes highlighted two overarching topics with exciting potential for future scientific drilling research: (1) the seismic cycle and (2) the mechanics and architecture of fault zones. Recommended projects target fundamental mechanical processes and controls on faulting, and range from induced earthquakes and earthquake initiation to investigations of detachment fault mechanics and fluid flow in fault zones. Participants working on active volcanism identified five themes: the volcano eruption cycle; eruption sustainability, near-field stresses, and system recovery; eruption hazards; verification of geophysical models; and interactions with other Earth systems. Recommended projects address problems that are transferrable to other volcanic systems, such as improved methods for identifying eruption history and constraining the rheological structure of shallow caldera regions. Participants working on chemical geodynamics identified four major themes: large igneous provinces (LIPs), ocean islands, continental hotspot tracks and rifts, and convergent plate margins (subduction zones).

This workshop brought together a diverse group of scientists with a broad range of scientific experience and interests. A particular strength was the involvement of both early-career scientists, who will initiate and carry out these new research programs, and more senior researchers with many years of experience in scientific drilling and active tectonics research. Each of the themes and questions outlined above has direct benefits to society, including improving hazard assessment, direct monitoring of active systems for early warning, renewable and non-renewable resource and energy exploitation, and predicting the environmental impacts of natural hazards, emphasizing the central role that scientific drilling will play in future scientific and societal developments.

1 Introduction

Forces originating deep within the active Earth are expressed at Earth's surface, where they have a profound effect on human societies. On a global scale, these effects include the development of mountain ranges, rift valleys and subduction zones. On a local scale, they are expressed as active faults (with slip ranging from a few meters to hundreds of kilometers) and volcanoes (ranging from individual volcanoes to large volcanic chains or fields). Both earthquakes and volcanic eruptions have caused significant loss of life and economic losses in recent times. Key measurements of the forces and energy driving these dynamic systems are missing, hindering progress towards physically based models that can be used to predict natural system behavior.

Understanding how fault systems and volcanoes operate is therefore crucial to mitigating these hazards. Unfortunately, studying active systems is difficult because earthquake nucleation and propagation, as well as crucial magmatic processes, take place at depth, obscured from simple observational techniques. Although deeper parts of faults and volcanic plumbing systems may be exposed by erosion in older terranes, information on active processes can only be inferred because critical relationships are still hidden beneath the Earth's surface. Deep scientific drilling is established as one of the most powerful techniques for investigating these active fault zones and magmatic systems (Harms et al., 2007).

To establish ways in which continental scientific drilling (CSD) can be used to address these critical societal issues, a workshop was held in Park City, Utah, in May 2013, sponsored by the US National Science Foundation (NSF), and attended by 41 investigators in active tectonics and magmatism. Although emphasis was placed on our goal of helping to define a US-based program of continental scientific drilling, participants included representatives from Canada, India, Italy, Japan, Great Britain, and New Zealand, who are actively engaged in international research efforts in cooperation with US-based investigators. Here, we summarize the key findings from the workshop, and present a series of investigator-driven ideas for future research. We hope that the results from this workshop can act both as a guide and source of motivation for renewed community interest in scientific drilling.

1.1 Workshop organization

Participants were asked to define significant scientific questions related to active tectonics and magmatic processes that can only be addressed by a coordinated program of continental scientific drilling and related site investigations. Workshop participants were also asked to prioritize these ideas, and to propose specific faults and volcanoes that would be targeted by these efforts.

Our goal for this workshop was to provide a road map of specific science projects and objectives that address the most pressing issues in active tectonics and magmatism that can be addressed by drilling.

White papers on specific drilling targets and projects submitted prior to the meeting focused discussions on particular locations where major problems could be addressed (white papers can be accessed at http://digitalcommons.usu.edu/geology_facpub/386/). At the workshop, participants discussed the scientific motivations for these proposed projects and their corresponding target sites, and attempted to prioritize them based on the strength of the science drivers, and on their readiness for formal review. Many of these proposed efforts are interdisciplinary, are directly related to ongoing NSF programs and consortia (e.g., Geodynamic Processes at Rifting and Subducting Margins: GeoPRISMS; Incorporated Research Institutions for Seismology: IRIS; Earthscope), and apply to a range of scales, from localized fault systems to plate boundary faults, and from small monogenetic vents to super-volcanoes. Some projects are being supported in part by other US federal agencies, e.g., US Geological Survey and US Department of Energy, or internationally (e.g., drilling in the Deccan Traps, as discussed below). All of the white papers propose to interrogate fundamental processes in geosciences and so are transferable globally.

The workshop spanned two full days of meetings. On the first morning, keynote speakers presented talks on "Trends and Topics" in scientific drilling of faults and volcanoes (see Table 1 and Fig. 1). This was followed in the afternoon and on the morning of day two by short talks (5–10 min) by workshop participants highlighting their white papers. The remainder of day two was devoted to breakout groups on faults, fault processes, active volcanism, and chemical geodynamics as expressed by volcanic terranes. At the end of day two, scribes from each breakout group presented summaries of their findings. The summary of this work is provided in Shervais et al. (2013a).

1.2 Building on past success

Deep continental drilling has successfully addressed longstanding problems in active tectonics, and some of continental drilling's most successful projects have grown out of issues related to active processes in faults and volcanoes, and those related to chemical geodynamics of the Earth. The success of these projects demonstrates the effectiveness of continental scientific drilling, and these projects formed the basis for some of the new projects proposed and discussed at this workshop. Drilling projects that have addressed the mechanics of faulting and fault zone processes include the San Andreas Fault Observatory at Depth (SAFOD: Zoback et al., 2010, 2011); the Chelungpu Fault (Taiwan) Drilling Project (Ma et al., 2006, 2012); the Alpine Fault (New Zealand) Deep Fault Drilling Project (Towend et al., 2009); the Nojima Fault Drilling Project (Ando, 2001); the Wenchuan, China Project (Xu et al., 2009); and (within the oceanic realm) the NanTroSeize project to drill faults within

Table 1. List of white papers prepared for the workshop, and published through USU Digital Commons portal: http://digitalcommons.usu.edu/geology_facpub/386/.

Evolution of fault zone geology in an active continental rift: scientific drilling opportunities along the Sangre de Cristo fault system, northern Rio Grande rift, Colorado	L. B. Ball, J. S. Caine, V. J. S. Grauch, C. A. Ruleman
Capturing the seismic cycle: sampling and instrumenting an earthquake nucleation patch	B. Carpenter, J. Chester, and S. Hickman
Reconstructing an "A-type" silicic magma system along the track of the Yellowstone Hotspot, central Snake River Plain, Idaho	E. H. Christiansen and the Hotspot Science Team
Testing the extensional detachment paradigm: a borehole observatory in the Sevier Desert Basin	N. Christie-Blick, M. H. Anders, G. Manatschal, and B. P. Wernicke
Understanding the evolution of a back-arc bimodal shield volcano, Newberry Volcano, Oregon	Z. Frone
Volcano structure and Hawaiian plume heterogeneity based on new drilling of Mauna Kea	M. Garcia, D. Depaolo, E. Haskins, N. Lautze, J. M. Rhodes, and D. Thomas
Coring and studying clay gouges from mature active fault zones	J. Hadizadeh, T. Candela, J. C. White, and F. Renard
Isotope geochemistry and mantle source regions for plume-lithosphere interaction	B. B. Hanan
A proposal to drill active faults and magmatism in a major intracontinental fault zone, Mono Lake Basin, Walker Lane, western Great Basin, USA	A. S. Jayko and S. Martel
Koyna – Warna Seismic Zone, Western India: a unique intraplate setting for drilling for an active fault zone underlying a basaltic pile	Vivek S. Kale
Geological CO_2 Storage: constraints from scientific drilling of natural CO_2 reservoirs, leaky faults and travertine deposits of the Colorado Plateau	N. Kampman, M. Bickle, J. Evans, D. Condon, C. Ballentine, G. Holland, Z. Zhou, Z. Shipton, M. Schaller, C. Rochelle, and J. Harrington
Enhancing data management for continental scientific drilling	K. Lehnert and A. Noren
Mechanics of normal fault systems	S. J. Martel
Sampling and *in-situ* Observations of Okmok (SINOOK)	T. Masterlark, J. Eichelberger, J. Freymueller, M. Haney, S. Hurwitz, P. Izbekov, J. Larsen, S. Nakada, C. Neal, W. Roggenthen, and C. Thurber
Study of the thermo-mechanical aspects of extensional fault systems by shallow continental scientific drilling into paleo brittle-ductile transition zones and top of channel flow in the Basin and Range Province, USA	E. Miller and J. Lee
Large igneous provinces (LIPs) and the IODP connection	C. R. Neal
Drilling investigations on the mechanics of faults: downhole measurements to detect time variation of in-situ stress	K. Omura
Project HOTSPOT: investigating subsurface basalt using wireline logs	K. Potter
Proposal to drill into the Puysegur Subduction Zone: investigating the complex role of peridotite and serpentinite in the seismicity of the subduction zone interface	L. A. Reinen and V. G. Toy
Mauna Loa: drilling the other side of the Hawaiian plume	J. M. Rhodes, F A. Trusdell, and M. O. Garcia
Earthquake triggering and fault zone drilling	H. Savage, N. Van Der Elst, and J. Kirkpatrick
Borehole geophysics – applications and limitations in extreme environments	D. R. Schmitt and M. D. Lee
Drilling the Josephine Ophiolite – direct observation of a subduction zone mantle wedge	J. W. Shervais and H. J. B. Dick
Tracking the Yellowstone Hotspot through space and time	J. W. Shervais, B. B. Hanan, E. H. Christiansen, S. R. Schmitt, and the Hotspot Science Team
Alpine Fault – Deep Fault Drilling Project (DFDP), New Zealand: current and future opportunities for active US participation in an international continental fault zone drilling project	V. G. Toy, J. Townend, and R. Sutherland
Magmatic-hydrothermal transitions in active extensional regimes of the western U.S.: the need for drilling to assess physico-chemical state	P. Wannamaker

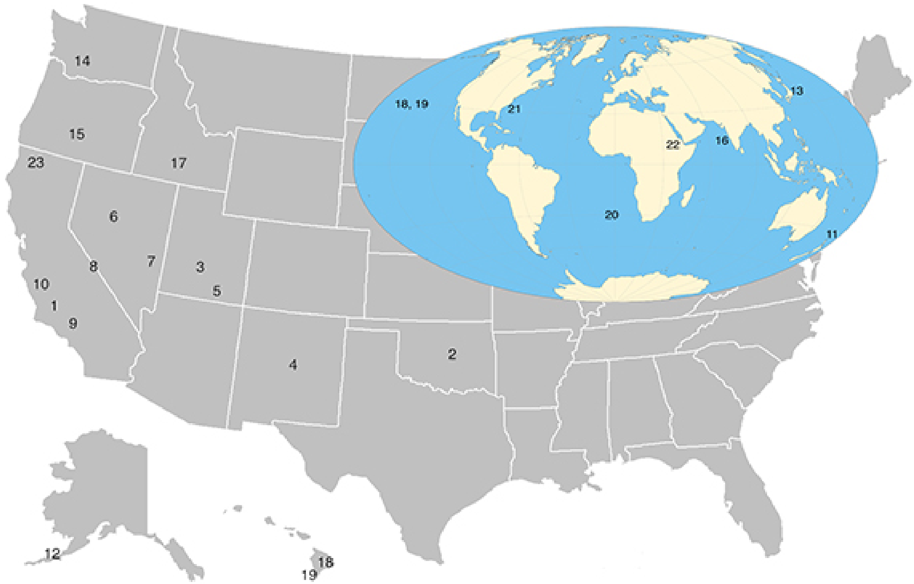

Figure 1. Map of USA and inset map of the world with recommended projects and alternate projects marked (Table 2). Projects 1–11 relate to fault zone drilling, projects 12–15 to active volcanic systems, and projects 16–23 to chemical geodynamics.

an accretionary prism (Tobin et al., 2006, 2009) and the Japan Trench Fast Drilling Project (JFAST) that sampled the seismically active plate boundary at the Japan trench (Chester et al., 2013). Drilling projects that addressed the origin, evolution, or eruptive mechanisms of volcanoes or young active volcanic terranes include the Mt. Unzen Scientific Drilling Project (Nakada et al., 2005) and the Iceland Deep Drilling Project (IDDP: Friðleifssona et al., 2014; Elders et al., 2014). Projects focusing on chemical geodynamics include the Hawai'i Scientific Drilling Project (DePaolo et al., 1996, 2007) and Hotspot: the Snake River Drilling Project (Shervais et al., 2006, 2013b).

2 Broader context

Continental scientific drilling is a tool for studying processes that cannot be accessed through normal surface-based investigations. In the US, it complements existing NSF programs such as GeoPRISMS, Earthscope, Frontiers in Earth System Dynamics (FESD), Integrated Earth Systems (IES), Critical Zone Observatory (CZO), Petrology and Geochemistry, Tectonics, and Paleo Perspectives on Climate Change (P2C2). Scientific drilling is also an important component of other agency programs, such as the U.S. Geological Survey (USGS: e.g., fault zone drilling, geothermal energy, oil and gas assessments, water resources research), the Department of Energy (DOE: e.g., geothermal energy, CO_2 sequestration, oil and gas research) and the Department of Defense (DOD: e.g., geothermal energy). As a result, the science drivers for continental scientific drilling overlap with the science objectives in these other agencies.

2.1 Science drivers for continental scientific drilling

Scientific drilling provides unique access to dynamic tectonic environments and samples, and allows us to examine active processes before they are overprinted or altered during exhumation (e.g., Ito et al., 2007; Zoback et al., 2011; Eichelberger and Uto, 2007). Installation of borehole observatories enables monitoring of in situ geophysical, geochemical, mechanical, physical, and hydrological conditions, and their evolution over time. Drilling, sampling, and downhole measurements, in concert with surface-based geophysical imaging, make it possible to characterize variations in geologic structure, rock and fluid composition, and rock physical properties in three dimensions around fault zones and volcanoes. Further, it is often possible to sample rock that is actively deforming at conditions not found in the near surface (e.g., those with a temperature-dependent rheology), and then study the deformational behavior of these samples in the laboratory at realistic conditions of temperature, pressure, and fluid chemistry.

Active magmatic systems (volcanoes) are extremely challenging environments for drilling. They are characterized by high temperatures, corrosive gasses and fluids, and wide variations in physical rock properties. Nonetheless, drilling into active volcanoes can be highly rewarding scientifically. The motivations for scientific drilling into active volcanic systems have been discussed by Eichelberger and Ito (2007). These include (a) sampling of deep uncontaminated materials (rocks, fluids, and gases); (b) studying hydrothermal alteration; (c) sampling quenched magmas; (d) measuring state of stress associated with magmatic systems; (e) delineating the geometry and thermal regime of magmatic and hydrothermal

Table 2. Potential projects recommended by the participants, and other potential projects. Author(s) of relevant white paper listed in parentheses.

Faults and fault mechanics
A. Understanding the seismic cycle
1. *Reoccupying and extending the SAFOD site (Carpenter et al.)* 2. *Triggering earthquakes for science (Savage et al.)*
B. 4-dimensional mechanics and architecture of fault zones
3. *Mechanics of the Sevier detachment (Christie-Blick et al.)* 4. *Tectonic evolution and mechanics of the Rio Grande rift (Ball et al.)* 5. *Fluid flow and supercritical fluid–rock interactions in the Little Grand Wash fault (Kampman et al.)*
C. Faults: other potential targets
6. *Dixie Valley (Wannamaker)* 7. *The Snake Range Detachment fault zone (Miller and Lee)* 8. *Mono Basin (Jayko et al.)* 9. *The San Andreas fault near Little Rock* 10. *The San Andreas fault at San Juan Bautista (Hadizadeh et al.)* 11. *The Puysegur Subduction Zone (Reinen and Toy)*
Active magmatic systems
12. *Okmok Volcano, Alaska, USA (Masterlink et al.)* 13. *Aso Caldera, Japan (Nakada)* 14. *Mount St. Helens, Washington, USA* 15. *Newberry Volcanic Monument, Oregon, USA (Frone)*
Geodynamic and geochemical evolution of earth
16. *Deccan Traps, India: US Participation in the Indian Koyna Drilling Project and Joint ICDP–IODP Drilling of the Deccan–Reunion Hotspot track (Kale and Neal)* 17. *Snake River Plain Continental Plume Track (Christiansen et al., Shervais et al., Hanan et al., Potter et al., Schmitt and Lee)* 18. *Mauna Kea PTA Project (Garcia et al.)* 19. *Mauna Loa Project (Rhodes et al.)*
Other potential geodynamic targets
20. *Etendeka–Walvis Ridge* 21. *CAMP: The Central Atlantic Magmatic Province, On-shore and Off-shore* 22. *Ethiopian Traps* 23. *Josephine Ophiolite –Direct Observation of a Subduction Zone Mantle Wedge (Shervais and Dick)*

plumbing systems; (f) measuring physical properties in zones of active deformation and seismicity associated with magma intrusion and volatile release; and (g) determining variations in temperature, deformation, and fluid composition over time, which may require installation of borehole observatories.

Chemical geodynamics of the mantle (i.e., the creation of physically distinct mantle reservoirs with different geochemical and isotopic compositions) may be investigated in part by studying hotspots, subduction zones, and rifts. The connection between deep-seated mantle plumes, ocean island basalts, and large igneous provinces (LIPs) is now supported by new techniques in mantle tomography that establish visible connections between hotspot volcanoes and deep thermal anomalies (DePaolo and Weiss, 2007). The formation of LIPs may also have significant impact on short-term climate change, which can affect biotic evolution and extinctions, and in some cases may be tied to Ocean Anoxic Events (Tejada et al., 2009; Erba et al., 2010). Scientific drilling can provide long-term stratigraphic records that record the evolution of these magmatic systems over time, their precise age ranges and duration, and evidence for biotic overturn, providing direct linkages to climatic records. The recovery of unweathered samples through continuous coring is critical for resolving many of the questions discussed in detail below.

2.2 Integration with IODP

Active tectonic and volcanic processes affect oceanic crust continental crust, and drive the processes at plate boundaries.

Because of this, participants concluded that better integration is needed between CSD worldwide and the International Ocean Discovery Program (IODP). Although some fault zone processes projects already involve onshore and offshore components (e.g., NantroSEIZE, Alpine Fault – DFDP, proposed Hikurangi margin drilling; see also Ito et al., 2007), there is little coordination between IODP and continental drilling projects that address active magmatism or chemical geodynamics. The close genetic relationship among continental flood basalts (CFBs), LIPs, and ocean island chains presents a unique opportunity for linkages between CSD and IODP. These linkages were highlighted at an NSF-IODP workshop held in Colraine, Northern Ireland, in 2006 (Neal et al., 2008). They include onshore–offshore linkages between CFBs and their related "plume tail" oceanic tracks, the onset of continental rifting, and syn-LIP sedimentation (which preserves the onset of LIP eruptions).

2.3 Integration with other drilling programs

Continental scientific drilling projects are commonly conducted through collaborations among multiple agencies. In some cases, these agencies prioritize drilling projects that address fundamental science objectives (e.g., IODP; International Continental Scientific Drilling Program: ICDP; USGS). Other agencies fund drilling projects that have more practical, applied science objectives, but which have collateral benefits for pure science investigations (e.g., US Department of Energy, US Department of Defense). Funding from these other agencies can be critical for many drilling projects, and may comprise the main or only funding for some projects. These projects have presented, and will continue to present, significant opportunities. An example of the opportunities provided by alternative funding sources is the Snake River Geothermal Drilling Project, funded by US Department of Energy, which produced ∼ 5.3 km of core (Shervais et al., 2013b).

3 Fault zone processes and geomechanics

The following three sections summarize the conclusions of the workshop regarding the key scientific objectives that are best addressed with CSD, and present specific project proposals that were prioritized by the attendees. Workshop participants discussed a wide range of proposed scientific drilling projects in all areas of active tectonics and magmatic systems. Of the projects presented in the white papers, some of these project proposals were deemed to be mature enough to proceed through the formal proposal process. Other proposals were judged to need more development before moving forward as formal proposals. The following assessment discusses both mature proposals and those deemed worthy of consideration but which require more development to move forward. Although certainly not an exhaustive list, several sites have been suggested as possibly fruitful drilling targets. Several of the white papers represent mature proposals for which much of the preliminary site survey work is either in progress or has already been largely completed.

3.1 Scientific objectives

Workshop participants interested in active faulting recognized that the key scientific questions and hypotheses proposed in the white papers submitted to the workshop, and also those that are most topical among this research community at present, fall into two major topics: (1) understanding the seismic cycle and (2) long-term mechanical and structural evolution of fault zones. Scientific questions on understanding the seismic cycle include

1. How and why do earthquakes initiate? (white papers by Carpenter, and Savage)

2. What physico-chemical mechanisms control earthquake triggering and interaction? (white papers by Carpenter, Omura, Savage, and Singh)

3. What controls variations in faulting style and slip rates? (white papers by Carpenter, Hadizadeh, Reinen and Toy, and Lee)

4. Are there clear textural and mineralogical records that are diagnostic of the spectrum of faulting styles and slip rates? (white papers by Carpenter, Hadizadeh, Reinen and Toy, and Schleicher)

5. How do permeability, temperature, fluid pressure and flow, the stress field, and fault strength vary over the seismic cycle, and how are these controlled? (white papers by Carpenter, Christie-Blick, Kale, Kampman, Omura, Savage, Fulton, and Lee)

Scientific questions on long-term mechanical and structural evolution of fault zones include

1. How do faults act as barriers and conduits for fluids? How does this influence mineralization, heat transport, generation of damage zones, and migration and storage of multi-phase fluids (H_2O, CO_2, CH_4, H_2, He, and magma) (white papers by Ball and Kampman)

2. How do the mantle, the lower crust, and upper crust interact? What are the avenues and rates of mass, heat, and fluid transport? (white papers by Ball, Kampman, Martel, Miller, and Lee)

3. How do geometry, composition, stress, deformation, and mechanical properties of fault zones evolve over geologic timescales? (white papers by Ball, Christie-Blick, Hadizadeh, Martel, Miller, and Lee)

The active faulting group prioritized several future drilling projects that propose to address the key topics outlined above. The first two of these fall into the understanding the seismic cycle topic and the last three are closely aligned with the long-term mechanical and structural evolution of fault zones topic. However, we emphasize that there are significant potential overlaps between all of the projects outlined below.

3.2 Recommended projects: understanding the seismic cycle

3.2.1 Reoccupying and extending the SAFOD site (white papers by Carpenter et al. and Hadizadeh et al.)

This project proposes to drill an additional multi-lateral borehole off the existing SAFOD main hole, to penetrate a repeating M2 earthquake patch (the Hawaii, HI, patch), for comparison with results already obtained within the creeping San Andreas Fault by SAFOD. Opportunities presented by these proposals include analyses of microstructure, physical properties, and deformational behavior of fault rocks from the seismically active fault zone, sampling of liquids and gases, and measuring physical conditions within the rupture patch of the recurring HI earthquake. This would include instrumenting the San Andreas Fault zone for long-term monitoring of seismicity, fluid pressure, temperature, and deformation during multiple cycles of the M2 repeating HI earthquake.

3.2.2 Triggering earthquakes for science (white paper by Savage et al.)

The physics of earthquake nucleation, propagation, and arrest, as well as the triggering of earthquakes both by distant earthquakes and by human activities, are important outstanding topics of current research. This project proposes to design and install an observatory consisting of surficial and borehole seismometers, as well as down-hole temperature, strain, and pore pressure sensors to make in situ measurements of variations in stress, strain, and fluid pressure in and near an active earthquake source. An earthquake occurring in the near field of this borehole observatory is critical to the success of this project. To increase the likelihood of recording an earthquake with this observatory, the project will trigger an earthquake within the observatory by pumping water into a fault at depth. Stimulating an earthquake within a certain area will mean the project does not need to penetrate a fault at natural nucleation depths, and therefore several fault-penetrating holes could be possible. The spatial coverage of the instrumental array would allow us to closely monitor all stages of the earthquake rupture process. Although no specific fault has been proposed at this time, several faults were suggested, mostly within the Basin and Range.

3.3 Recommended projects: long-term mechanical and structural evolution of fault zones

3.3.1 Tectonic evolution and mechanics of the Rio Grande rift (white paper by Ball et al. and Martel)

The Sangre de Cristo Fault (SCF) system accommodated late Quaternary extension in the northern Rio Grande rift. However, analysis of surficial geology and a wealth of geophysical data show that this structure is complex and has a long tectonic history. Scientific drilling through multiple and representative elements of the SCF presents opportunities to better understand the processes of fault system evolution within an intracontinental rift and provide an analog to other extensional systems. In situ fault zone characterization, rock sampling, hydraulic and thermal experimentation, and stress measurements would provide the subsurface ground truth and monitoring necessary to evaluate hypotheses on tectonic evolution, modern strain accommodation, and physical heterogeneity created by faults. Significantly, this project will develop results that address seismic hazard and groundwater resource exploitation in the wider Rio Grande rift region. Other sites within actively deforming regions of the Basin and Range, or the San Andreas Fault, could examine similar questions.

3.3.2 Fluid flow and supercritical fluid–rock interactions in the Little Grand Wash fault (white paper by Kampman et al.)

Geological carbon dioxide sequestration is an important target of ongoing research to which continental drilling can make a significant contribution. Degassing normal faults at Green River, Utah, are important analogs to seal bypass for engineered geological CO_2 storage. Surface studies have provided important constraints on the CO_2 source and the Quaternary degassing history of these faults, which imply large temporal variations in fault hydraulic behavior. Recent drilling at the site provided core and fluid samples that constrain fluid flow and fluid–rock reaction in the shallow subsurface (~ 300 m). Deep drilling at depths > 800 m, where the CO_2 is supercritical, presents an opportunity to investigate how these mantle-derived volatiles react both within a fault damage zone and with the surrounding reservoir rocks and impermeable seals. In situ hydrological tests combined with geophysical imaging and geochemical monitoring would provide important constraints on the nature and rates of fracture-hosted two-phase flow. Mineralogical and petrophysical observations of the recovered core, combined with geochronological studies of fracture mineralization, would allow the long-term transmissivity of the faults to be assessed.

3.3.3 Mechanics of the Sevier detachment (white paper by Christie-Blick et al.)

The Sevier Desert Detachment (SDD) accommodates normal slip of < 47 km, with movement as recent as the Holocene (< 8 ka). It has been proposed that the SDD initiated at a dip of $\sim 11°$, implying it has very low effective frictional strength, but the kinematics of the deformation remains controversial and the initiation of the fault obscure (Christie-Blick et al., 2009). Drilling aims to better characterize fault zone geometry, and to elucidate the mechanism(s) or physical conditions that result in weakness, providing insight into the formation of low-angle normal faults more generally. Magnetotelluric studies demonstrate fluids interact with the structure at depth, so this project also addresses fault–fluid interactions. An ICDP workshop has already been held to define both scientific objectives and a preliminary drilling plan, and this workshop group considers that pursuing the project further will address the aims of fault zone processes and geomechanics.

3.4 Additional targets

The following target sites and project ideas were also agreed to have significant scientific merit by the workshop participants. However, these proposals were considered less mature than those discussed above, and will require more development before they should move forward as full proposals.

- The interest in active basin and range deformation and fault mechanics in general (white papers by Martel; Omura; Miller and Lee; Savage et al.; Schmitt et al.; Toy et al.; Wannamaker et al.) suggests the need for collaborative teams to work on drilling projects that examine the mechanics of fault development, as well as earthquake rupture dynamics, the latter including rapid-response drilling and determining post-slip temperature measurements within fault zones (e.g., Fulton et al., 2013).

- Dixie Valley (white paper by Wannamaker): an active Basin and Range fault with hydrothermal–magmatic interactions, possibly also induced seismicity. The fault is already being drilled in a project funded by US DOE, and it makes sense to take advantage of this campaign. However, slightly lower priority was assigned to this site because the same scientific questions are able to be addressed through drilling at the Rio Grande rift.

- The Snake Range Detachment fault zone (white paper by Miller and Lee) provides the opportunity to investigate the mechanical coupling between brittle and ductile crust – in particular, whether or not the footwall was rigid or experienced a form of channel flow/stretching during large-scale extension. A major question is, "how do the thermal structure of the crust and rates of extension control the formation and evolution of this and similar deeply rooted detachment faults?"

- Mono Basin (white paper by Jayko et al.): drilling the tectonically and volcanically active Mono Basin to measure the stress field and evaluate the role of the Eastern Sierran frontal fault system in controlling the timing, location, and rates of magmatism and volcanism. These issues are crucial for defining the tectonics of the Walker Lane fault system, assessing the role of faults as conduits for magma, and for evaluating the geothermal energy potential in the area.

- The Puysegur Subduction Zone (white paper by Reinen and Toy): the young (< 11 Ma) crust of the incoming Australian Plate at this seismically active subduction zone has morphology indicating it may have peridotite at or very near the surface. Thus, it is very likely that the subduction thrust interface is within ultramafic rock containing serpentine. Serpentine has peculiar mechanical properties allowing it to slip seismically, or creep aseismically, depending on the imposed slip rate (e.g., Reinen et al., 1994; Reinen, 2000). This subduction zone is already instrumented by broadband seismometers and continuous GPS monitoring stations as part of the Geonet Network (http://info.geonet.org.nz/display/equip/Our+Equipment), so both seismic and aseismic slip distribution models can be constructed. However, densification of this network, which would allow significantly more precise analysis, should be undertaken. Also, there are a diverse range of ground-shaking proxies on land in the Fiordland area (e.g., landslide records), and the area is subject to a proposal to collect a large transect of geophysical data under the GeoPRISMS initiative. This site therefore represents a good future opportunity to investigate how serpentine in particular plays a role in slip style and rate along major faults.

4 Active magmatic systems

4.1 Scientific objectives

Active volcanic systems are important to science and society – hazards to human populations associated with volcanic eruptions are significant in many parts of the world and have resulted in tens to hundreds of thousands of deaths. Understanding the life cycle of typical volcanic systems is crucial to managing the risk associated with their eruptions (Eichelberger and Uto, 2007). Active magmatic systems also drive hydrothermal circulation, which has been linked to exhalative and epithermal mineral deposits, and to high-enthalpy geothermal energy resources (Elders and Sass, 1988; Fournier, 1999; Eichelberger and Uto, 2007). These linkages provide the opportunity for multi-disciplinary studies that combine hazards analysis with both green energy and mineral resource research. Such linkages are critical to obtaining funding from a range of sources, thereby spreading both the risk and cost associated with drilling across several agencies or interest groups.

Outstanding questions related to active magmatic systems revolve around the fundamental issues of understanding how volcanoes work and constraining what hazards they may pose in the future, and can be summarized in five main categories below:

1. Volcano eruption cycle. What is the spatial and temporal evolution of magma migration and storage? What is the temporal evolution of eruption style? What are the systematic and asystematic aspects of eruption cycles?

2. Sustainability, stress, and recovery. How do eruption cycles integrate with ecological and local societal systems?

3. Eruption hazards. How can we improve short- and long-term eruption prediction? To what extent can we forecast near-field (e.g., lava flows, pyroclastic flows) and regional to global hazards (e.g., ash plumes)?

4. Verification of geophysical models. How reliable are estimates and uncertainties for internal processes and structures of volcanoes, determined from surface observations?

5. Interactions with other Earth systems. What are the potential climate impacts of volcanic eruptions? To what extent can volcanic systems help us understand tectonic and geodynamic processes?

4.2 Recommended projects/sites: active magmatic systems

4.2.1 Okmok Volcano, Alaska, USA (white paper by Masterlink et al.)

Okmok Volcano has produced two caldera-forming eruptions in the last 10 000 years, along with frequent smaller eruptions. Okmok could serve as an interdisciplinary natural laboratory to address several relevant problems, which are transferrable to other volcanic systems. These include improving methods for identifying eruption history (timing, magnitude, and style) and constraining the rheological structure of shallow caldera regions and its influence on magma migration and storage. Key goals of the drilling project would include identifying eruptive materials comprising the shallow caldera, determining the rheologic structure of the shallow caldera, testing seismic tomography and magma migration models, quantifying related uncertainties, and characterizing, in space and time, stress and thermal regimes associated with the subsurface plumbing system.

4.2.2 Aso Caldera, Japan (white paper by Nakada)

Aso Caldera is a large caldera, which may be overdue for eruption. The scientific goals of drilling Aso Caldera include gaining a better understanding of the structural evolution of the last caldera eruption (controlled by a ring-fault zone on the caldera margin), temporal and spatial relationships of caldera collapse and climactic eruptions, precursory phenomena of climactic eruption events, environmental impact of eruptions on life and recovery, and determining the most effective monitoring and subsequent prediction techniques for associated hazardous volcanic events.

4.2.3 Newberry Volcanic Monument, Oregon, USA (white paper by Frone)

Newberry Volcano is one of the largest Quaternary volcanoes in the conterminous US; it covers 1600 km^2 and has a volume of 450 km^3 (MacLeod and Sherrod, 1988). It has experienced at least two caldera-forming eruptions (∼ 300 ka and 83 ± 5 ka), and has had several other recent eruptions, including the 7 ka (post-Mazama) sequence of dominantly basaltic andesite, and intra-caldera rhyolites, the youngest of which is 1.3 ka. Scientists are particularly interested in the depth, volume (estimated to be 1–8 km^3), composition, and melt fraction of the proposed magma chamber at 3–6 km depth. Significant geophysical data have been collected to support drilling efforts at Newberry, including lidar, gravity, magnetotellurics, aeromagnetics, and seismic tomography. In addition at least two holes have been drilled already (to 932 and 424 m depth), from which useful data may be extracted without additional drilling operations.

5 Geodynamic and geochemical evolution of Earth

The geodynamic and geochemical evolution of the Earth are intimately linked to two dominant processes of heat transfer: plate tectonics (driven by the sinking of cold lithospheric plates in subduction zones and the rise of hot asthenospheric mantle below midocean ridges to form oceanic crust) and the rise of thermally (and possibly compositionally) buoyant mantle to form hotspots with their associated ocean island basalts and flood basalts. Together these dominant processes are responsible for the Wilson cycle, during which continents continually grow by collision and amalgamation.

5.1 Science objectives – chemical geodynamics

Research into Earth's chemical geodynamics discussed at the workshop can be divided into three focus areas that can be addressed by continental scientific drilling:

1. Large igneous provinces exposed on land, which are largely continental flood basalts but also include the emergent portions of oceanic LIPs. The current paradigm suggests that LIPs represent catastrophic

melting of an engorged "plume head" at relatively shallow depths, whereas ocean island chains and continental hotspot tracks represent the plume "tails" (Hill, 1991, 1993);

2. Ocean island chains, which are thought to represent the active conduits of deep-seated mantle plumes erupted through oceanic lithosphere as it moves continuously over a relatively fixed thermal anomaly (hot spot);

3. Continental hotspot tracks, which are thought to represent the intracontinental equivalent of ocean island chains, and form as continental lithosphere moves continuously over the relatively fixed thermal anomaly.

Each of these focus areas engages a series of significant scientific questions that overlap in part, but also address some distinct issues. For example, continental flood basalts erupt over geologically short time spans and may have significant environmental impacts. But because they erupt through continental crust, their compositions are effected to various extents by interactions with subcontinental mantle lithosphere or continental crust. In contrast, ocean island chains erupt over prolonged time spans, but erupt through thin oceanic lithosphere, which has only minimal impact on their chemical and isotopic composition. Continental hotspot tracks erupt magmas that may be strongly affected by continental interaction, and their chemical and isotopic compositions may be decoupled (e.g., Hanano et al., 2008). Scientific issues addressed by CSD on LIPs, ocean island chains, and continental hotspots include the following:

- What are their modes of origin? How are they similar? How do they differ?
- What is the nature of the melting anomaly that produces LIPs and oceanic island chains? Is it heterogeneous spatially, or does it vary over time?
- What are the magma production and lava accumulation rates beneath each of these features? What is the duration of volcanism?
- What are the environmental impacts of LIP volcanism? Is LIP emplacement responsible for mass extinctions, oceanic anoxic events, etc.?
- How do the variations in magma chemistry, isotopic composition, and age of eruption constrain the dynamics of hotspot–continental lithosphere interaction?
- Can we establish geochemical and isotopic links between the plume head volcanic province and the plume tail province?

Workshop participants also endorsed the concept of integrated onshore–offshore studies that combine ICDP or other land-based projects on continental LIPs with IODP or special platform studies of ocean islands related to that LIP.

5.2 Recommended projects: continental hotspot track

Several high-priority projects were identified by the workshop participants, including projects that were recently drilled, or are currently being drilled, with non-NSF funding (ICDP, DOD, DOE, and international partners).

5.2.1 Deccan Traps, India: US participation in the Indian Koyna Drilling Project and joint ICDP–IODP drilling of the Deccan–Reunion hotspot track (white papers by Kale, Neal)

Onland drilling into the Deccan Traps flood basalt pile undertaken by the Koyna reservoir-induced seismicity project (Roy et al., 2013) can be expanded with further continental and ocean drilling. The Koyna project has drilled through the lava pile and into the underlying Precambrian gneiss, and there are plans to drill two more holes through the lava pile nearby. By combining additional continental drilling of the Deccan Traps in other locations with new drilling offshore along the hotspot trace, the plume hypothesis would be tested by evaluating the timing and extent of the change from plume head to plume tail magmatism, as well as investigating the heterogeneity of the two magma systems.

5.2.2 Snake River Plain continental plume track (white papers by Christiansen, Shervais, Hanan, Potter, Schmitt, and Lee)

The Snake River Plain (SRP) volcanic province represents *the* world-class example of time-transgressive intracontinental plume volcanism. The SRP is unique because it is young and relatively undisturbed tectonically, and because it contains a complete record of volcanic activity associated with passage of the hotspot, which can only be sampled by drilling. The central questions addressed by drilling the SRP are, (1) how do mantle hotspots interact with continental lithosphere, and (2) how does this interaction affect the geochemical evolution of mantle-derived magmas and continental lithosphere? At this time, three deep drill holes have been completed, with funding from ICDP, US DOE, and DOD. This project represents a prime example of the opportunities presented by intra-agency cooperation and joint support of projects by national and international funding sources (Shervais et al., 2013b).

5.2.3 Other potential LIP flood basalt targets

Participants identified additional potential targets for scientific drilling of LIPs and flood basalts, along with their related hotspot tracks. These include (1) the Etendeka–Walvis Ridge; this plume head–plume tail doublet in the South Atlantic Ocean formed coeval with the opening of the South Atlantic; (2) the Central Atlantic Magmatic Province (CAMP), which formed during the early opening of the central Atlantic Ocean, the first segment of the Atlantic Ocean to form, and a type locality for a "volcanic rifted margin" (this would require a joint onshore–offshore ICDP–IODP effort); and (3) the Ethiopian Traps, which represent the onset of LIP volcanism in a continental setting. They form our best modern example of LIP volcanism, and can be related to rift zone volcanism to the south, and ocean basin formation to the north.

5.3 Recommended projects: ocean islands – the oceanic record of plume tail volcanism

In order to evaluate geochemical and isotopic components of mantle geodynamics, it is necessary to obtain samples that have not been contaminated by continental crust, which has extreme chemical and isotopic compositions that can mask the more subtle mantle signatures. This is traditionally approached by sampling "plume tail" hotspot tracks that penetrate oceanic crust. Because the oceanic crust is thin and compositionally similar to plume-derived basalts, this minimizes contamination and allows detailed evaluation of the mantle component. Two projects are highlighted here – Mauna Loa and Mauna Kea – and two other locations were found promising: Reunion (with its tie-in to Deccan drilling) and Kerguelan, a major oceanic plateau in the southern Indian Ocean.

5.3.1 Mauna Kea Pöhakuloa Training Area (PTA) project (white paper by Garcia)

The Mauna Kea Pöhakuloa Training Area (PTA) project represents an unprecedented opportunity to gain a more detailed record of a Hawaiian volcano. Under this project, the US Army has funded (∼ $6 M) the drilling of two, ∼ 2000 m deep boreholes in search of water on the upper flank of Mauna Kea Volcano on the Island of Hawai'i. The first hole, located ∼ 10 km from the volcano's summit, was completed to a depth of ∼ 1760 m with a high rate of recovery (> 90 %). Drilling and coring of the second hole is scheduled to start before the end of 2013. Both holes will be cored continuously to total depth, and the core is being curated by the University of Hawai'i. These two holes provide a rare prospect for detailed examination of the volcanic history of a Hawaiian volcano and will allow many important issues to be examined, including the following. (1) What are the magma production and lava accumulation rates for Hawaiian volcanoes? (2) What is the scale of heterogeneity and variation in partial melting within the Hawaiian plume? (3) What is the nature of the transition from shield to post-shield volcanism? (4) How do Hawaiian and other volcanoes grow? (5) What is the heat flow within an oceanic volcano (e.g., conductive, or convective and controlled by ground water)? (6) What is the extent of explosive volcanism for Hawaiian volcanoes?

5.3.2 Mauna Loa Project (white paper by Rhodes)

The most important recent result of Hawaiian studies is resurrection of the concept of an asymmetrical mantle plume in which volcanoes along two en echelon trends, the Loa and Kea trends, exhibit distinct major element and isotopic compositions (Abouchami et al., 2005; Weis et al., 2011). This asymmetry in plume source components is attributed to asymmetry in the lowermost mantle preserved in the melting zone within the plume (Weis et al., 2011; Farnetani et al., 2012). Loa trend magmas are thought to contain a greater contribution of recycled crustal material than those of Kea trend volcanoes. An unresolved and contentious problem is whether Loa magmas result from melting discrete lithological domains (i.e., pyroxenite/eclogite) of this crustal material within the plume, or whether they reflect melting of peridotite fertilized by pyroxenite/eclogite melts (Jackson et al., 2012). To understand Hawaiian volcano growth, melt production, and the identity, composition, and lithology of plume components it is necessary to core a Loa trend volcano to obtain comparable information to that obtained by the Hawaiian Scientific Drilling Project for Mauna Kea, which is a Kea trend volcano (Stolper et al., 2009). Mauna Loa, the world's largest active volcano (∼ 100 000 km^3), is the obvious candidate because a great deal more is known of its recent sub-aerial history (< 120 ka) and also of its earlier (> 400 ka) submarine growth than other Loa trend volcanoes (Rhodes, 2014).

5.4 Science objectives – subduction systems

The large-scale evolution of subduction zones in relation to volcanic arcs is fundamental to understanding how continental crust forms. Some of the questions to be addressed by drilling within subduction systems include

- What magmatic processes create intermediate-composition magmas?
- What roles do lateral accretion and magmatic intrusion play in the growth of arc-related crust?
- Is the lower mafic crust of the arc recycled back into the mantle and, if it is, how is this accomplished?
- How much of the magma at a convergent margin is new juvenile addition to the crust and how much is recycled older crust?
- What causes the intrinsically high water and oxygen fugacities of arc magmas?

There are many questions about how arcs form and evolve that can only be addressed by drilling projects, especially those that look at the life cycle of magmatic arcs whose older roots are buried by younger activity.

Most drilling activity related to subduction systems will be carried out by IODP, because active subduction systems at depths that can be accessed by drilling are found primarily below the oceans. However, there are portions of some active systems, as well as many fossil systems, that are found on land. Some of these areas are the subject of the ExTerra initiative of the NSF GeoPRISMS program. The ExTerra initiative seeks to understand subduction dynamics by investigating exposed portions of active systems or a few well-preserved fossil systems. For example, drilling an exposed supra-subduction zone mantle wedge can provide continuous core through this system, which would be impossible to obtain from an active fore-arc. Further, drilling projects can be combined with surface mapping and geophysics to build a detailed 3-D model of mantle wedge architecture. Rock properties can be studied on recovered core and at the outcrop scale, and then scaled up using surface mapping, surface-based geophysical transects, vertical seismic profiles, or cross-hole experiments to provide more realistic constraints than possible using lab studies alone. Finally, if the core can be oriented relative to Earth's magnetic field, then intrinsic properties such as rock magnetism and lattice-preferred orientation fabrics can be measured and compared to experimental results on fabric development and seismic anisotropies observed in subduction systems.

5.5 Recommended projects – subduction systems

5.5.1 Josephine Ophiolite – direct observation of a subduction zone mantle wedge (Shervais and Dick white paper)

Characterization of geochemical flux in the mantle wedge during subduction is critical to our understanding of arc volcanism, and forms an important aspect of the global geochemical flux. Drilling is needed to provide unweathered samples of mantle wedge peridotites that represent vertical transects of the mantle. The Josephine Ophiolite, California, preserves the largest exposed tract of mantle peridotite in North America, and represents the fore-arc of a paleo-Cascadia subduction zone. Microstructures and macrostructures that document deformation processes in the mantle wedge are well preserved, along with alteration and mineralization that document low- to intermediate-temperature metamorphism within the mantle wedge. Major questions that can be addressed by drilling include the cumulative extent of melt extraction phases and the nature of the melt extracted, the nature and extent of mantle-melt interactions subsequent to melt extraction (e.g., addition of melt from deeper in the asthenosphere), and the nature, source, and extent of fluid flux to SSZ peridotites. The resulting drill holes can also be used to make in situ measurements of mantle wedge physical properties, e.g., using vertical seismic profiles or cross-hole seismic experiments.

5.5.2 The Puysegur Subduction Zone (white paper by Reinen and Toy)

The Puysegur Subduction Zone was discussed earlier under fault zone processes; it also represents an ideal location for the study of chemical geodynamics in the mantle wedge.

6 Technology issues

There are a number of technology issues that are critical for many of the drilling initiatives proposed here, and more generally for future scientific drilling projects worldwide. Some of these technological requirements are specific to certain environments (e.g., high temperatures in active magmatic systems), while others affect a range of drilling environments and project types. Areas in which technological advances are needed include the following:

- Downhole observatories. Permanent or semi-permanent downhole observatories to measure temperature, strain, fluid pressure or seismic activity are critical to the success of many drilling projects. For many of these observatories, drilling the hole is often the most expensive part of the operation, and installation of downhole observatories can be a cost-effective way to maximize scientific return. To be successful, it is necessary to develop robust sensors and deployment systems that can survive temperatures $> 120\,°C$ and under chemically hostile conditions.

- High-temperature downhole logging tools ($> 150\,°C$) for use in small-diameter holes (< 15 cm diameter). Although tools suitable for use in large-diameter holes are available that can operate at temperatures up to 300 °C, current slim-hole tools operate above 70 °C or 140 °C, which limits our ability to study active magmatic systems, active fault zones, geothermal settings, or other high-heat flow regimes using small-diameter (exploratory) drill holes.

- Improved gas and fluid sampling tools (downhole) for slim drill holes. Obtaining gas-saturated water samples from slim holes (< 15 cm diameter) is a delicate operation that takes considerable rig time (e.g., 12 h per run) and is often unsuccessful. Because water and gas chemistry is critical in many studies, more reliable and cost-effective tools for borehole liquid and gas sampling are critical.

- Drilling and completion technologies. Drilling/coring techniques, directional control, downhole measurements, and casing/cementation should be developed and modified to maximize success in highly deformed and unstable fault zone environments.

7 Summary and recommendations

Workshop participants discussed the significant science issues addressed by a targeted program of continental scientific drilling of faults, fault zones, volcanoes, and volcanic terranes, and specific targets that can best answer these questions. The scientific questions and targets discussed here align with the priorities specified in the recent National Research Council report "New Research Opportunities in the Earth Sciences" (NRC, 2012), as well as previous NRC reports (NRC, 2008, 2011).

Linkages between ICDP, IODP, and national science agencies are critical for a successful continental scientific drilling program because resources can be leveraged across programs and between countries to maximize return on investment for all participants. Recent examples of inter-agency and international efforts include the Chesapeake Bay Drilling Project (USGS, ICDP), the San Andreas Fault Observatory at Depth (NSF, USGS, ICDP, and various international funding agencies), the Snake River Drilling Project (DOE, ICDP, USAF), and the PTA drilling project on Mauna Kea (US Army, NSF). Additional linkages should be sought with industries that rely on drilling, as has been the case for numerous drilling projects carried out in the US and internationally that have addressed themes relevant to the petroleum and geothermal industries (e.g., the Iceland Deep Drilling Project).

Participants working on faults and fault zone processes highlighted two overarching topics: (1) understanding the seismic cycle and (2) long-term mechanical and structural evolution of fault zones. Five projects were recommended for consideration at this time: reoccupying and extending the SAFOD site; triggering earthquakes for science; mechanics of the Sevier detachment; tectonic evolution and mechanics of the Rio Grande rift; and fluid flow and supercritical fluid–rock interactions in the Little Grand Wash fault. Participants working on tectonics, magmatic activity, and active volcanism defined three dominant themes: volcanic and subvolcanic processes, hazards assessment, and resources. Four projects were recommended for consideration at this time. The recommended projects are Okmok Volcano, Alaska, USA; Aso Caldera, Japan; Mount St. Helens, Washington, USA; and Newberry Volcanic Monument, Oregon, USA. Participants working on chemical geodynamics highlighted five projects: Deccan Traps (potentially joint ICDP–IODP drilling of the Deccan–Reunion Hotspot track); Snake River Plain Continental Plume Track; Mauna Kea PTA project; Mauna Loa Project; and the Josephine Ophiolite – Direct Observation of a Subduction Zone Mantle Wedge.

Technology issues addressed include borehole observatories, new tools for oriented core, robust downhole tools for high-temperature or caustic environments, improved tools for liquid and gas sampling, and improved drilling and completion technologies.

Finally, participants emphasized the importance of cultivating early-career scientists and other young researchers, who will have to initiate and carry out many of the research programs defined at the workshop. Involvement of young scientists and, if possible, graduate students who are near completion of their PhD programs will have an enormous impact on their future research success, as well as on the continued success of continental scientific drilling. They will also bring new ideas to the table that will impact current projects, and those already in process. The preparation and education of the geoscience workforce has a high priority in industry and academia, and the implementation of strong scientific drilling projects will enhance these goals.

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Scientific Drilling
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Investigating ultra high-enthalpy geothermal systems: a collaborative initiative to promote scientific opportunities

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Abstract. Scientists, engineers, and policy makers gathered at a workshop in the San Bernardino Mountains of southern California in October 2013 to discuss the science and technology involved in developing high-enthalpy geothermal fields. A typical high-enthalpy geothermal well between 2000 and 3000 m deep produces a mixture of hot water and steam at 200–300 °C that can be used to generate about 5–10 MWe of electric power. The theme of the workshop was to explore the feasibility and economic potential of increasing the power output of geothermal wells by an order of magnitude by drilling deeper to reach much higher pressures and temperatures. Development of higher enthalpy geothermal systems for power production has obvious advantages; specifically higher temperatures yield higher power outputs per well so that fewer wells are needed, leading to smaller environmental footprints for a given size of power plant. Plans for resource assessment and drilling in such higher enthalpy areas are already underway in Iceland, New Zealand, and Japan. There is considerable potential for similar developments in other countries that already have a large production of electricity from geothermal steam, such as Mexico, the Philippines, Indonesia, Italy, and the USA.

However drilling deeper involves technical and economic challenges. One approach to mitigating the cost issue is to form a consortium of industry, government and academia to share the costs and broaden the scope of investigation. An excellent example of such collaboration is the Iceland Deep Drilling Project (IDDP), which is investigating the economic feasibility of producing electricity from supercritical geothermal reservoirs, and this approach could serve as model for future developments elsewhere. A planning committee was formed to explore creating a similar initiative in the USA.

1 Introduction

This workshop was under the aegis of DOSECC (Drilling, Observation and Sampling of the Earths Continental Crust), a consortium of United States universities with investigators that are interested in research involving subsurface sampling, measurement and observation. DOSECC is actively seeking to engage a wider earth science community by sponsoring five workshops on different topics where the science being investigated requires drilling (see www.dosecc.org). This initiative is designed to foster a more integrated continental scientific drilling program that will strengthen scientific drilling in the USA and interact in more fruitful ways with the International Continental Scientific Drilling Program (see http://www.icdp-online.org/home/).

The workshop had two objectives: firstly to discuss scientific studies of active very high enthalpy hydrothermal systems and, secondly, to stimulate collaboration between academic scientists, government agencies, and industry. Such collaboration is highly desirable because the scientific study of active hydrothermal systems requires drilling and sampling boreholes whose costs far exceed budgets normally available to academic scientists; it is industry that drills wells to access geothermal resources. Although drilling into these deep unconventional geothermal reservoirs is more expensive, the higher productivity per well should offset this by reducing the number of wells needed for a given power output (Friðleifsson and Elders, 2005). Developing these resources would make available new large and environmentally benign sources of alternative energy. In addition, such developments would make important scientific contributions. It would permit major advances in our understanding of active hydrothermal processes that are important on a global scale but are not otherwise available for direct investigation (Elders and Friðleifsson, 2010). These include the coupling of magmatic and hydrothermal systems and their mass and energy transfer, hydrothermal ore formation in magma-ambient conditions, the transition from low to higher grade metamorphism, and aspects of volcanic hazards.

The participant list and program of the workshop appear as appendices to this report, and the talks presented at the workshop are available on the workshop website: http://csdworkshops.geo.arizona.edu/Lake_Arrowhead_CA.html. Two scientists from New Zealand, two from Mexico, and one from each of Iceland, Italy, Philippines, and Russia participated in the workshop. This led to discussions of programs in various countries that are currently investigating, or planning to investigate, “ultra high-enthalpy” geothermal systems.

Plans for deep drilling to explore for deeper, much higher enthalpy, geothermal resources are already underway in Iceland (Iceland Deep Drilling Project), in the Taupo Volcanic Zone of New Zealand (Project HADES), and in northeast Japan the Beyond-Brittle Project (JBBP), which is an ambitious program attempting to create an enhanced geothermal system (EGS) reservoir in ∼ 500 °C rocks. Although there is a significant undeveloped potential for developing high-enthalpy geothermal systems in the western USA, Hawaii and Alaska, there is no comparable national program to develop such resources. The main difficulty in implementing such programs is the very high cost in drilling deep into hostile environments.

2 The Iceland Deep Drilling Project

One approach to mitigating the cost issue is to form a consortium of industry, government and academia to share the costs and broaden the scope of investigation. An excellent example of such collaboration is the Iceland Deep Drilling Project (IDDP). The aim of IDDP is to produce geothermal energy from magma-hydrothermal systems at *supercritical* conditions, similar to environments found at depth on mid-ocean ridges. It is funded by an industry–government consortium (Friðleifsson et al., 2014). The drilling and well completion was funded by an industry–government consortium and the science sampling program by the ICDP and the US National Science Foundation (Friðleifsson et al., 2014).

In 2009 this industry–government consortium drilled a well in the volcanic caldera of Krafla in NE Iceland (Fig. 1).

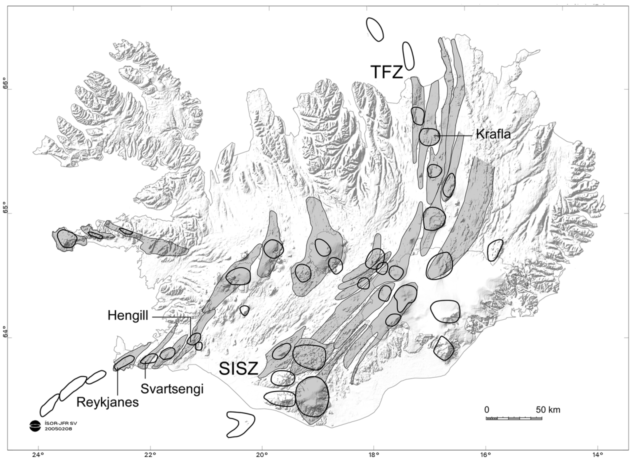

Figure 1. The location of rifting (shaded) in the neovolcanic zone of Iceland, an extension of the Mid-Atlantic Ridge. The map shows the location of the three high-enthalpy magma-hydrothermal systems – Krafla, Hengill, and Reykjanes – that are sites that were chosen for deep drilling by the Iceland Deep Drilling Project (IDDP). The irregular ellipses are active central volcanoes.

Continuing the search for supercritical geothermal resources in Iceland in 2014–2015, the IDDP will drill a new deep well on the Reykjanes Peninsula in SW Iceland that is the continuation of the Mid-Atlantic Ridge on land (Fig. 1; Friðleifsson et al., 2013). In the future, a third deep well will be drilled at Hengill, another high-temperature system.

The critical point for pure water occurs at 220 bar and 374 °C. Exceeding such pressure–temperature conditions, for likely pressure–temperature gradients, requires drilling to depths of 4 to 5 km (Fournier, 1999). Supercritical fluids have higher enthalpy and greatly enhanced rates of mass transfer relative to conventional lower-temperature geothermal resources (Dunn and Hardee, 1981; Hashida et al., 2001). Figure 2 shows that water at supercritical conditions with a temperature of 400 °C and a pressure of 250 bar has more than five times the power-producing potential than that of liquid water at 225 °C (Tester, 2006).

Geothermal wells in Iceland typically range up to 3.0 km in depth and produce a < 300 °C mixture of steam and water, at a rate sufficient to generate between 4 to 10 megawatts (MWe) of electricity. Modeling suggests that producing superheated steam from a supercritical reservoir could potentially increase the power output of geothermal wells by an order of magnitude relative to the output of lower enthalpy wells (Friðleifsson and Elders, 2005). A conventional dry-steam well with a downhole temperature of 235 °C and pressure of 30 bar with a volumetric flow rate of 0.67 $m^3\,s^{-1}$ can generate ∼ 5 MWe, whereas we estimate that a supercritical well at the same volumetric flow rate but with a downhole temperature of 430–550 °C and pressure of > 200 bar could generate ∼ 50 MWe. The IDDP aims to produce supercritical

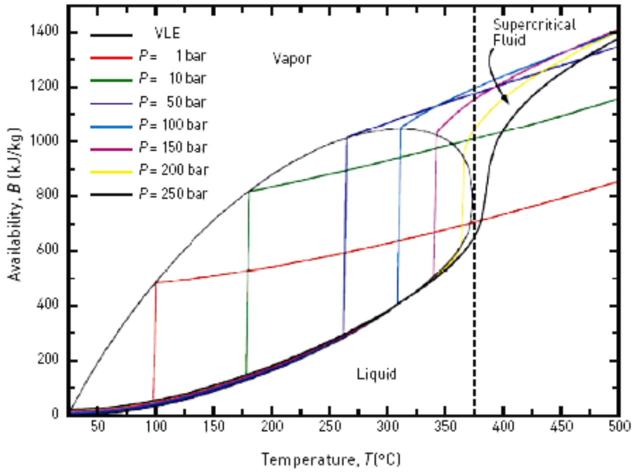

Figure 2. The availability diagram for pure water, i.e., its power-producing potential at specified specific-state conditions of temperature and pressure (Tester, 2006, Fig. 1.10).

Figure 3. The flow of the IDDP-01 into a rock muffler produced dry superheated steam with only 0.1–0.2 % of non-condensable gases. Initially corrosion products gave the steam a dark color, but after a few minutes it became clear and transparent. The condensate had a pH of 2.5–3 due to its HCL content. However, experiments on wet scrubbing to remove acid gases from the dry steam were very successful (Hauksson et al., 2014) (photograph courtesy of Kristján Einarsson).

fluid to the surface such that it transitions directly to superheated steam.

The IDDP-1 well

In 2009 the first IDDP well was drilled in the Krafla geothermal field within a volcanic caldera in the central active rift zone of NE Iceland (Fig. 1). At Krafla production wells drilled since 1971 supply steam to a 60 MWe geothermal power plant. During 1975–1984, a rifting episode occurred at the Krafla volcano, involving nine volcanic eruptions. A large magma chamber, believed to be the heat source of the active geothermal system, was detected by S wave attenuation at 3–7 km depth within the center of the caldera, and this was confirmed by a recent magnetotelluric survey. The well IDDP-1 was sited to reach 4.5 km depth close to the margin of this magma chamber (Friðleifsson et al., 2014). Difficulties were encountered during drilling this well due to caving that required cementing due to enlargement of the borehole, and getting stuck twice at 2100 m depth (Pálsson et al., 2014). The reason for these problems became clear when it became apparent that we were dealing with very high temperatures, as, at a depth of 2104 m, > 900 °C rhyolitic magma flowed into the drill hole and filled the bottom 9 m. Our studies indicate that this magma formed by partial melting of hydrothermally altered basalts within the Krafla caldera (Elders et al., 2011; Zierenberg et al., 2013). The decision was made to terminate drilling, cement production casing, allow the well to heat, and to flow test the well (Hauksson et al., 2014) (photograph courtesy of Kristján Einarsson).

The resultant well had very high enthalpy and produced superheated steam from the contact zone above the intrusion (Fig. 3). With a well-head temperature of ∼ 450 °C and a well-head pressure of up to 138 bar, it became the hottest producing geothermal well in the world, and, with a flow rate of 45 kg s^{-1} of dry superheated steam, it was estimated to be capable of generating > 35 MWe (Hauksson et al., 2014). In July 2012, after 10 months of full-scale flow, the well was shut down to recondition some of the surface equipment.

The future utilization of this magmatic resource at Krafla is still being discussed. It may be possible to recondition the IDDP-1, or several new wells could be drilled towards the contact zone of the magma. Ideally building completely new high-enthalpy turbines would be preferable, as the existing turbines at Krafla have an inlet pressure of only 7 bar. In the future it may even be possible to produce energy directly from the magma, either utilizing a downhole heat exchanger or by creating the world's first EGS production and injection wells in magma.

3 Wider applications

The IDDP-1 well engendered considerable international scientific and engineering interest. A special issue of the journal *Geothermics* was published in January 2014 reporting some of this work. In contrast to the freshwater system at Krafla, the Reykjanes geothermal system, which lies directly on the landward extension of the Mid-Atlantic Ridge, produces hydrothermally modified seawater. Processes at depth at Reykjanes should be quite similar to those responsible for black smokers on oceanic rift systems (Elders and Friðleifsson, 2010; Friðleifsson et al., 2013). If new IDDP wells at Reykjanes and Hengill prove successful, this could trigger similar activities elsewhere. In the future such very

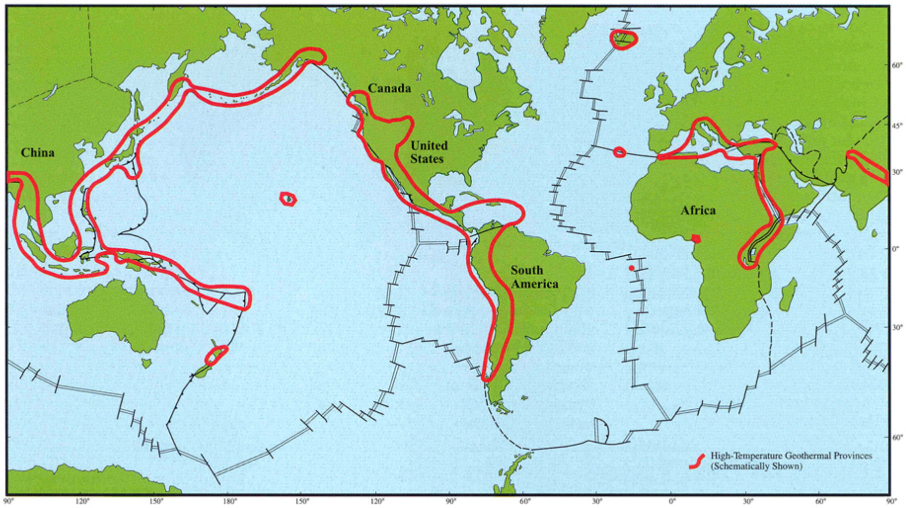

Figure 4. Outlined in red are the worldwide zones where very high enthalpy, possibly supercritical geothermal resources could exist at drillable depths.

high enthalpy geothermal systems could become significant resources worldwide, wherever suitable young volcanic geothermal systems occur (Fig. 4).

3.1 Developing "ultra" geothermal resources

Developing such ultra high-enthalpy supercritical geothermal resources at drillable depths is most credible

- at young volcanic rocks along plate boundaries and at hot spots
- near shallow, still hot (or partially molten) igneous intrusions
- at well-established high-enthalpy geothermal fields – for example in
  - Iceland – Reykjanes, Hengill, Krafla
  - Northeast Japan (JBBP)
  - New Zealand in the Taupo Volcanic Zone (HADES)
  - Philippines, Indonesia, Italy, Mexico (Cerro Prieto, Los Humeros)
  - USA – Hawaii, California, the Cascade Volcanic Chain, the Basin and Ranges, Alaska, etc.

In fact, projects comparable but differing in approach to the IDDP are already underway in both Japan and New Zealand. The plan in Japan is to drill beyond the brittle ductile transition in a 500 °C or hotter neo-granite and to thermally fracture the rocks to form permeability in the ductile zone and thus create a contained EGS system (Fig. 5) as is explained on the website (http://www.icdp-online.org/fileadmin/icdp/projects/doc/jbbp/JBBP_Concept_poster_En.pdf). The expectation is that a combination of government and industry funding will permit drilling to begin in 2 or 3 years.

A similarly ambitious project is underway in New Zealand, although possibly not so far advanced as the IDDP or the JBBP. Hotter and Deeper Exploration Science (HADES) is a long-term program of exploration and assessment in the Taupo Volcanic Zone in the North Island of New Zealand that aims to use geological, geochemical and geophysical data to assess the resource potential of deep geothermal systems in the Taupo Volcanic Zone (Fig. 6). Preliminary indications of this "Hotter and Deeper" project suggest that by 2025 New Zealand's deep geothermal resources (3–7 km) could supply at least 20 % of New Zealand's electricity requirement. Conservative estimates point to the total potential of accessible deep geothermal resource in the Taupo Volcanic Zone (TVZ) exceeding 10 000 MWe (see www.gns.cri.nz/Home/Our-Science/Energy-Resources/Geothermal-Energy/Research/Hotter-and-Deeper).

3.2 The potential for ultra geothermal resources in the USA

In contrast to the activities in Iceland, Japan, and New Zealand, there is no systematic activity in the USA directed towards developing ultra geothermal resources. This is not because valid targets for exploration for high-enthalpy geothermal resources are lacking. As shown in Fig. 7, an early estimate of the geothermal resource base of magma-ambient systems in the USA suggested that the potential of that resource was huge, exceeding even the estimate of enhanced geothermal systems ("hot dry rock resources" = EGS).

For more than a decade the US Department of Energy had a *magma energy program* aimed at extracting high-enthalpy energy directly from magma, using a downhole heat exchanger. A special issue of the *Bulletin of the Geothermal*

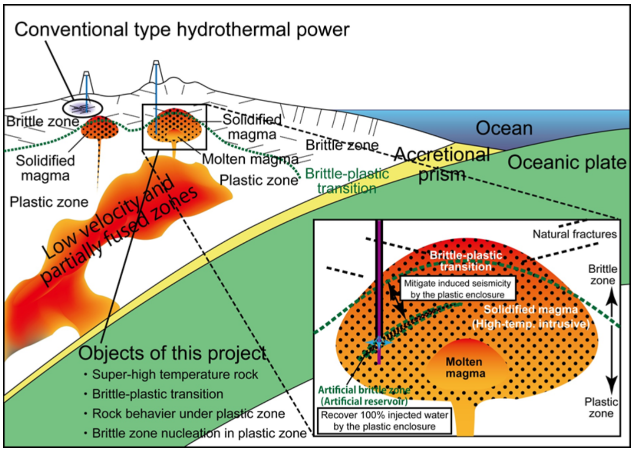

Figure 5. The principles behind the Japan Beyond the Brittle Project (JBBP). Figure courtesy of H. Asanuma (National Institute of Advanced Industrial Science and Technology, AIST), Japan.

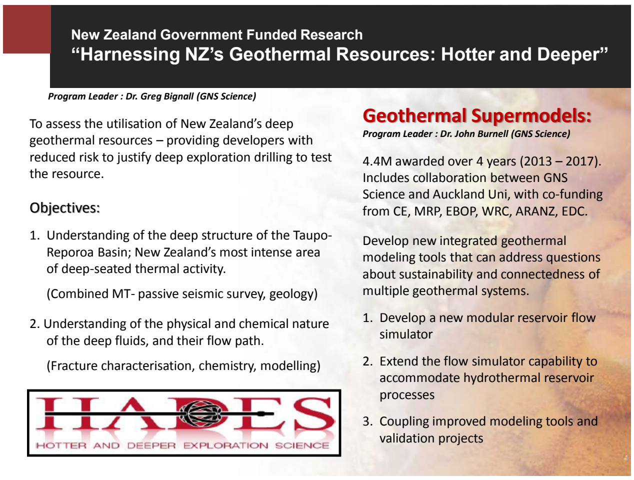

Figure 6. The aims of Project HADES in New Zealand. Figure courtesy of Ted Bertrand (GNS-Science, New Zealand).

Resources Council in 1990 was devoted to discussing that concept (Eichelberger and Dunn, 1990). After a nationwide study (Finger and Eichelberger, 1990), the Long Valley Caldera in California was chosen as the optimum site in the USA to drill into magma. A drilling rig began drilling a well designed to reach a depth of almost 7 km to reach a magma chamber believed to exist below the caldera. However, due to funding problems, it was abandoned far short of its target, at less than 3 km depth where the temperature was only 120 °C (Bender-Lamb, 1991). A more recent assessment of geothermal resource base to 10 km depth in the USA is shown in Table 1 for different categories of geological environment as reported in Tester (2006). The major thrust of that report was to assess the potential of enhanced (or engineered) geothermal systems (EGSs) in the USA, and it greatly increased the assessment of the EGS resource base of the USA in crystalline

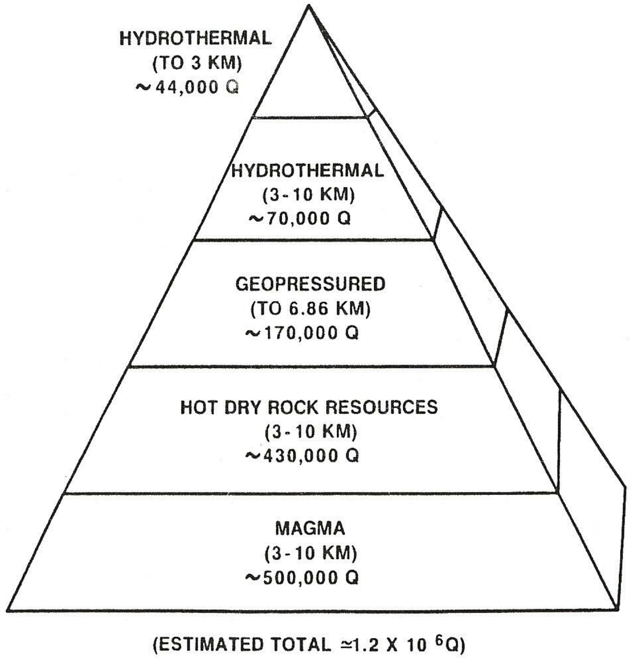

Figure 7. An early estimate of the resource base in various geothermal environments indicated that magma-ambient systems have a very large potential. Q = quad or 10^{15} BTU or about 1 exajoule = 10^{18} J (source: White and Williams, 1975, USGS Circular 726).

basement rocks over the estimate made in 1975. The overall conclusion of that comprehensive assessment was clearly that the largest part of the EGS geothermal resource base resides in the form of thermal energy contained in sedimentary and basement rocks that are heated by radiogenic heat sources and conductive heat transfer. The size of its resource base is orders of magnitude greater than the resource base of "conventional" geothermal systems in permeable rocks that are associated with volcanic-related hydrothermal temperature anomalies. However, as Table 1.1 from Tester (2006) shows, *supercritical volcanic* EGS also has a large potential in the USA.

Although field experiments to create EGS in crystalline rocks began in the USA in the 1970s, at present *all* of the 3400 MWe of geothermal power currently generated in the USA comes from conventional hydrothermal systems. Since the early experiments in the USA, development of EGS resources has been attempted in the UK, France, Japan, Australia, Sweden, Germany, and Switzerland. However today the total world installed generating capacity from EGS is less than about 10 MWe, and in each case its development has required large government subsidies. These EGS experiments have largely focused on systems with temperatures less than 300 °C (and in some cases only 200 °C as deep as 5 km). This slow development is a function of both some of the inherent technological difficulties and economic limitations of low to moderate enthalpy EGS.

Table 1. Estimated US geothermal resource base to 10 km depth by category.

Category of resource	Thermal energy in exajoules ($1\,EJ = 10^{18}\,J$)	Reference
Conduction-dominated EGS		
Sedimentary rock formations	100 000	Tester (2006)
Crystalline basement rock formations	13 300 000	Tester (2006)
Supercritical volcanic EGS[1]	74 100	Muffler et al. (1979)
Hydrothermal	2400–9600	Muffler et al.(1979)
Coproduced fluids	0.0944–0.4510	McKenna et al. (2005)
Geopressured systems[2]	71 000–170 000	White et al. (1975)

[1] Excludes Yellowstone Park and Hawaii
[2] Includes methane content
Source: Table 1.1, Tester (2006)

3.3 Developing a project to develop "ultra" geothermal system

One outcome of the workshop was the formation of a planning committee (consisting of the authors of this report) to develop a project similar to the IDDP in the USA. Implementation of such a plan will require formation of a consortium with participation from industry, government agencies, and universities. The planning committee is tasked with the creation and implementation an "ultra geothermal development project in the USA". Ultra geothermal resources are magma-ambient and/or supercritical geothermal systems that have much higher enthalpy and pressures than the geothermal systems that are currently utilized to generate electricity today.

Unlike the situation in the UK, France, Australia, Germany and Switzerland, as Table 1 shows, there is a large potential to develop supercritical volcanic EGSs in the USA. In addition supercritical hydrothermal geothermal systems not requiring EGS technology could be developed where convective heat transfer operates due to the existence of appropriate combinations of pressure, temperature and lithology. In basaltic terrains, such as in Iceland, the brittle ductile transition occurs at much higher temperatures than in the granitic terrains such as those being investigated by the JBBP. Today there is revived and growing interest in investigating high-enthalpy geothermal systems in the USA (Elders, 2013; Elders et al., 2014).

3.4 The aims of ultra geothermal development projects

- improve the economics and efficiency of base load electrical power production from sustainable geothermal resources without increasing their environmental footprint

- explore and demonstrate the feasibility of increasing geothermal electrical power production by approximately an order of magnitude through production of ultra high-enthalpy geothermal fluids

- create projects for developing ultra high-enthalpy resources that build upon those already underway in Iceland (IDDP), Japan (JBBP), and New Zealand (HADES)

- promote and enhance collaboration amongst governmental agencies, industry, and academia in the USA and internationally, to advance the capitalization, study, and development of ultra high-enthalpy as sustainable geothermal resources

- through such collaboration, to develop multidisciplinary approaches and best practices for site selection in the exploration for ultra high-enthalpy geothermal resources in the USA

- identify candidate sites where a drilling project targeting ultra high-enthalpy fluids has the greatest potential for transforming the ability of geothermal energy to contribute to sustainable, electrical power production

- explore the potential of using EGS technology to optimize electrical power production from ultra high-enthalpy geothermal resources

- develop the science and technology for ultra high-enthalpy exploration and development that is transferable to other earth and materials science applications

- enhance our understanding of fundamental problems in the earth sciences including ore genesis, very high-temperature fluid–rock interactions, and magmatic/hydrothermal transitions

- educate and train the future work force and create new employment opportunities in this field of green sustainable energy.

3.5 The criteria for site selection for the UGDP include

- The site must contain ultra high-enthalpy resources at depths attainable by current drilling technology on the basis of existing surface and subsurface data.
- The site must have substantial infrastructure, access, and permitting, as well as availability to power and testing facilities.
- The site must have an existing operator *willing* to be an *active partner* in this project.
- The site should maximize the scientific and technological benefits and transferability for a given capital investment.
- The initial site must be one in which this project could readily demonstrate the proof of concept that the development of ultra high-enthalpy resources is viable.

3.6 Some advantages and potential barriers to creating an UGDP

The principal barrier to creating programs to develop magma-ambient and supercritical geothermal resources is their high costs. The obvious solution therefore is to share the costs between industry and government, with involvement of national laboratories and university scientists and engineers participating and providing scientific and technical input.

Among the potential advantages of such collaboration with strong industrial involvement is that industry can furnish access to the following:

- “holes of opportunity”, i.e., deepening boreholes that are sited and drilled by industry in geothermal areas
- large and flexible funding sources
- industry databases relevant to site selection
- industry leasing and permitting
- industry technical expertise, equipment, and infrastructure.

Among the reasons why such collaborations have previously not been more common are the following:

- industry’s concern with protecting propriety data and leaseholds in competitive situations
- it is complicated and time-consuming
- the long lead time for return on investment for the industry partner
- it requires coordination of multiple funding sources and timetables.

To overcome these disadvantages requires good faith by all parties, patience, flexibility, mutual understanding, backup plans, and an optimism that continued progress will overcome obstacles with collaboration. This requires having clearly enunciated and understandable scientific and technical goals, seizing opportunities, building working relationships based on trust, stressing benefits to both parties, being flexible, and educating funding agencies about timetable constraints and drilling contingencies. This can be done, as was demonstrated by the IDDP.

4 Conclusions

Approaches to improving the economics of the geothermal industry development of ultra geothermal resources could reduce the number of wells needed and increase the power output of each well, by producing supercritical fluid and/or high-enthalpy dry superheated steam. The potential impact of utilizing geothermal resources at supercritical conditions could become quite significant. This would call for re-evaluation of the geothermal energy resource base not only on a local scale but also on a global scale. Accessing supercritical fluids within drillable depths could yield a significant enlargement of the accessible geothermal resource base.

The *practical significance* of attempting to implement an ultra geothermal development project in the USA, and elsewhere in the world, includes the following:

- Fewer wells are needed for a given power output.
- The power cycle has a higher thermodynamic efficiency.
- For a given power output, the “environmental footprint” is smaller.
- Already developed geothermal fields would have increased sustainability.

The *scientific significance* of investigating ultra geothermal systems is that it allows direct study of active

- supercritical phenomena
- coupling of hydrothermal and magmatic systems
- hydrothermal alteration and ore formation
- fluid circulation at continental rift systems analogous to that at mid-ocean ridges and black smokers
- related volcanic hazards.

Supercritical zones are most important for the practical goals of the ultra geothermal development project. It is predominantly there that mobile fluids are heated and interact chemically with their host rocks, where most of the geologically important heat flow, chemical alteration, and hydrothermal ore formation take place. Supercritical fluid–rock interactions are important in the overall heat and fluid budgets of mid-ocean ridges. Studying analogous systems on land is much more practical than drilling from a ship in 3 km of water. And finally supercritical fluid and/or superheated steam represent an attractive source of electric power generation.

The Supplement related to this article is available online at doi:10.5194/sd-18-35-2014-supplement.

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CSDCO/Continental Scientific Drilling Coordination Office Begins Operations

The US Continental Scientific Drilling Coordination Office (CSDCO) recently began operations at the University of Minnesota. This new National Science Foundation facility builds on the resources and experience of the personnel at the LacCore Facility.

The CSDCO provides leadership and support in geoscience research involving subsurface sampling and monitoring on Earth's continents, and in development of deeply embedded outreach, diversity, and education programs to maximize project profiles and community engagement. Together with the associated LacCore Facility for support of operations, core processing/analysis, and sample and data curation and dissemination, the CSDCO provides integrated project support for scientists using core samples and boreholes to address their research goals across the full range of geoscience domains.

The CSDCO supports scientists in project scoping: determining appropriate field techniques; budgeting, including soliciting and reviewing bids; addressing logistical requirements; planning for operational support and downstream analytical, curatorial, and data management considerations; coordinating community infrastructure development; developing and executing project-specific broader impacts activities; and funding strategies and proposals. The CSDCO is coordinating development of cyberinfrastructure to address longstanding needs in the CSD community, including a scientific drilling and coring data repository, and linkages to registration services, permanent data archives, visualization tools, and domain-specific resources.

The LacCore equipment pool provides quick access to rental equipment for soft-sediment coring, and to a small, portable Winkie Drill for shallow rock drilling. This system is particularly useful for drilling at remote sites with difficult access, and for low-cost drilling to generate preliminary samples for analyses and justification for deployment of larger drilling systems to reach deeper intervals. For deep drilling, the CSDCO coordinates drilling contractors to deploy the equipment and expertise required.

CSD projects offer an opportunity for local residents near field sites to partner with the project and take ownership in some of its goals. The CSDCO collaborates with project scientists to engage members of the public at the earliest stages of project planning, and to develop community-driven research in parallel with project scientific goals; and additionally coordinates student research, a summer institute for graduate students, and informal training programs for educators.

Contact Anders Noren (noren021@umn.edu), CSDCO Director, to utilize CSDCO resources to support research and educational goals.

Anders Noren, CSDCO Director

ICDP Training Course "Drilling in Active Fault Zones"

The annual ICDP Training Course took place at the Franz Josef Glacier resort in New Zealand from October 5 to 10 nearby the parallel running ICDP Alpine Fault drilling (DFDP). The training course touched upon relevant aspects of scientific drilling in active fault zones, including lecturers on drilling engineering, samples and sampling strategies, pre-site studies, downhole logging, permanent downhole monitoring, data management, and project planning and management.

Practical exercises and a one-day visit of the drill site helped deepen the acquired expertise.

33 Scientists from 13 countries involved in running or upcoming scientific drilling campaigns attend the training course, including New Zealand, USA, UK, Canada, Finland, India, China, Italy, Korea, the Netherlands, Swiss, Spain and Germany.

Thomas Wiersberg, ICDP

Joint Outreach at AGU Fall Meeting

ECORD and ICDP have organised a joint exhibition booth at AGU 2014. This was the first time that both programmes had been represented in San Francisco under the title "Scientific Drilling", building on the successful collaboration between the programmes at EGU.

A joint IODP-ICDP and ANDRILL Scientific Drilling Town Hall Meeting also took place at AGU on December 15. The event was very well attended with 350 participants. The meeting started with short presentations of the new ICDP Science Plan given by Carola Knebel, followed by Keir Becker, Chair of the IODP Forum, who introduced the new "Amphibious Project" concept and the Taira Prize for accomplishments in ocean drilling. Dr Becker also announced the call for nominations for the new IODP Forum Chair. Following the presentations, there was an opportunity for the participants to view 24 posters explaining the close links between the programmes and to discuss further opportunities for collaboration.

Patricia Maruéjol (ECORD),
Carola Knebel (ICDP),
Uli Harms (ICDP) and
Alan Stevenson (ESO)

Schedules

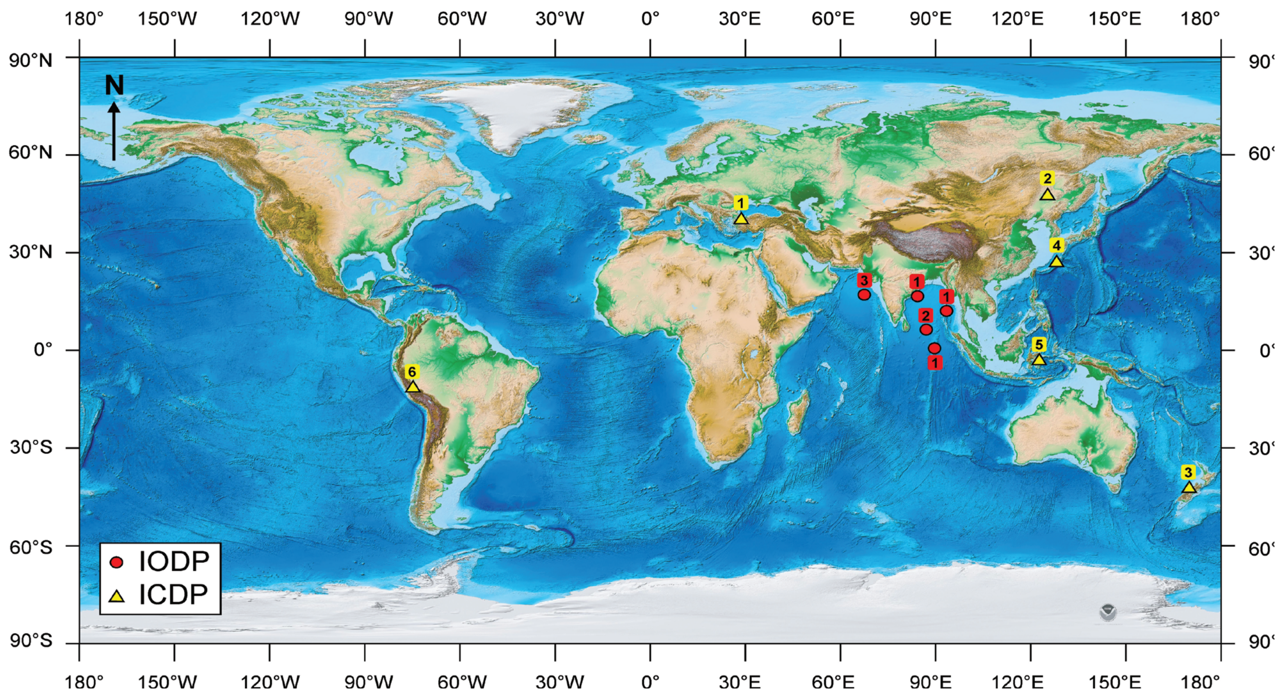
IODP – Expedition Schedule http://www.iodp.org/expeditions/

USIO Operations	Platform	Dates	Port of Origin
1 353 Indian Momsoon Rainfall	JOIDES Resolution	29 Nov 2014–29 Jan 2015	Singapore
2 354 Bengal Fan	JOIDES Resolution	29 Jan–31 Mar 2015	Singapore
3 355 Arabian Sea Monsoon	JOIDES Resolution	31 Mar–31 May 2015	Columbo, Sri Lanka

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

ICDP Project	Drilling Dates	Location
1 GONAF	since Sep 2012	Istanbul, Turkey
2 Songliao Basin	Apr 2014–Dec 2016	Songliao Basin, China
3 DFDP	Aug 2014–Jan 2015	Whataroa, New Zealand
4 COREF	Apr–May 2015	Ryukyu Islands, Japan
5 Lake Towuti	May 2015	South Sulavesi, Indonesia
6 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).