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Future Challenges in Continental Scientific Drilling

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Introduction

The Earth is a dynamic planet and shaping the Earths' surface and thus the environment we all live in and from is an ongoing process since billions of years. These continuous transient processes, however, remain largely unrecognized over most of the time. Exceptions are hazardous high-impact events such as earthquakes or volcanic eruptions, documenting the immense tectonic forces hidden below our feet. Besides mountain building in compressive regimes, associated non-hazardous slow but long-lasting deformation processes are basin formation and rifting resulting in sedimentation, thus storing and conserving key information on climate and environmental conditions at the time of deposit. To decipher the processes driving any long-term slow or immanent fast deformation of the Earth's crust or to directly access information on the geologic past is not straightforward. The only way to provide ground truth on our planet's interior is drilling. However, drilling is challenging, complex, and costly. It requires key expertise and a framework providing scientists with the necessary tools, know-how and logistics - this is where the International Continental Scientific Drilling Program ICDP comes in.

ICDP is a worldwide network of member countries and geoscientists to generate the most exact, fundamental and globally significant knowledge on the structure, composition and processes of the Earth's crust, through the unique capabilities of continental scientific drilling. The goal is to encourage Earth scientists to use the investigative tool of scientific drilling to test models derived from information gathered at the Earth's surface. Given the challenging logistics and typically high cost of drilling and of research in boreholes, any successful project ideas undergo a multi-stage evaluation process ensuring that the most ambitious scientific questions with a strong focus on societal needs are selected and addressed at world-class sites.

Key science themes for continental scientific drilling

The key questions in ICDP projects need to address fundamental science, but are, at the same time, also linked to wider societal challenges encompassed in the United Nations Sustainable Development Goals (SDGs). Relevant SDGs here are clean water and sanitation, affordable and clean energy, sustainable cities and communities, and climate action. The geoscience community clearly has the responsibility to contribute to a sustainable treatment of our habitat and one –if not the most pressing – focus of ICDP is to contribute to research on climate change and its mitigation. Likewise, the supply of mankind with clean energy and to better protect people from natural hazards are objectives where continental drilling can deliver contributions. Finally, the continents host information on more than 4 billion years of Earth evolution, and scientific continental drilling provides the only telescope into the past and thus to the origin of our world as we see it today.

ICDP concentrates its activity on four prime science themes. These are Geodynamic Processes, Geohazards, Georesources and Environmental Change (Figure 1). These themes are manifested in the new ICDP Science Plan 2020-2030 (Bohnhoff et al., 2020) and are briefly summarized in the following.

Geodynamic Processes: The debate continues around significant questions such as when plate tectonics began, and how the Earth's crust has grown and evolved. Current models for crust and mantle evolution through time involve the creation and subsequent recycling of continental crust versus continuous or episodic crustal growth over the past 4 billion years. Understanding the various feedback mechanisms controlling the relationships between plate tectonic processes, formation and emergence of large continental masses, and paleoclimate and environmental changes throughout critical periods of Earth history is important. Little is known about Earth's impact record during the first 2.5 billion years. However, evidence for impact events between about 3.4 and 2.5 billion years exists in the form of spherule layers, likely representing distal impact ejecta. These layers occur in South Africa and Australia, and provide the only traces of Earth's early (Archean) impact record.

Several ICDP projects have made substantial contributions to our understanding of crust-forming processes and mantle evolution. The Barberton Drilling Project in South Africa already provided important insights into the composition of Archean mantle. Drilling the Moodies Group in the Barberton Greenstone Belt (Barberton Archean Surface Environments – BASE project) will test the hypothesis of first oxygenation as early as 3.2 billion years ago. The Oman Ophiolite Drilling Project (Kelemen et al., 2020) evaluated Cretaceous juvenile crust formation and chemical mass transfer in the mantle, as well as between the mantle, crust and ocean via hydrothermal alteration. Drilling the Collisional Orogeny in the Scandinavian Caledonides in Sweden (Lorenz et al., 2015) has directly investigated tectonic processes operating at the depth of an ancient mountain chain. Studying how rift zone volcanic islands form and lithify today, the SUSTAIN project recently drilled on Surtsey Island, Iceland (Moore and Jackson, 2020).

Geohazards: Understanding the full chain from hazard to risk is a challenging –yet pressing- task. Our understanding of geohazards is constantly evolving through field observations, laboratory and theoretical studies, allowing to progress towards unraveling how earthquakes, landslides and volcanic eruptions initiate. Nonetheless, fundamental questions remain open. Geohazards pose an ever-increasing threat to humankind, driven in large part by dramatic global population growth in hazardous areas around the world. It is of utmost relevance to decipher their underlying causes and the physical processes that drive them, to understand the full chain from hazard to risk.

The San Andreas Fault Zone Observatory at Depth (SAFOD) in California is a prime example for drilling through a major transform fault at a key location a 3 km depth, providing novel and unprecedented insight in the processes governing earthquakes (Zoback et al., 2011). SAFOD followed the successful super-deep continental drilling project KTB in Germany along the multi-step approach of pre-site surveying, pilot hole, main hole, and observatory phase (Emmermann and Lauterjung, 1997).. Now, SAFOD's successor project is on Reservoir Triggered Earthquakes at Koyna in India, pushing the envelope by aiming to drill into the source zone of a reservoir-triggered magnitude M6.2 earthquake more than 6 km depth below the Koyna and Warna water dams (Gupta, 2018) (Figure 2). In line with previous ICDP lighthouse projects, this endeavor needs a long breath and benefits from India's long-lasting ICDP membership and strong engagement and interaction of Indian geoscientists with the international scientific drilling community. Currently, this led to the successfully drilled 3 km deep pilot borehole and further plans towards drilling the deeper main hole are underway.

Drilling in South African Goldmines has also been a centerpiece in fault drilling with the most recent project (DSEIS) that successfully penetrated into the aftershock plane of a M 5.5 earthquake (Ogasawara et al., 2019). Important progress has also been made through the Deep Fault Drilling Project (DFDP) on the Alpine Fault in New Zealand (Sutherland et al., 2017) and offshore drilling into the top of the rupture of the great Tohoku earthquake in Japan (JFAST project), supported by ICDP's offshore sibling, the International Ocean Discovery Program (IODP) (Chester et al., 2013).

Important volcanoes where eruptions threaten the population and infrastructure, are sites of previous ICDP projects. These include the Naples-Campi Flegrei region in Italy that sits on a supervolcano (De Natale et al., 2016), the Iceland hot spot with numerous active volcanoes drilled in the Iceland Deep Drilling Projects (IDDP) (Fridleifsson et al., 2018), or the Unzen volcano in Japan where the magma conduit was drilled by ICDP (Nakada et al., 2005). These, together with several other volcanoes, are dramatically important study objects, since a major eruption at any of these locations would have drastic consequences for humankind, both on a local and global level.

<u>Georesources:</u> We live in a rapidly changing environment, under pressure from population growth and climate change. As governments and industry commit to reducing greenhouse gas emissions in the frame of the Paris agreement, there will be a need to switch to low-carbon alternatives for energy and transport, which will require sustainable georesources. In addition, the Intergovernmental Panel on Climate Change, and United Nations projections indicate that CO_2 capture and storage will be essential to limit global warming to less than 2°C and it is thus expected to see a revival in both research and application. Also, the identification and exploration of rare materials supplying innovative critical new technology as part of the transformation towards a low-emission economy is a topic where ICDP can provide key input.

Geothermal energy has been an area of interest to ICDP since its start, with projects such as the Iceland Deep Drilling Projects (IDDP) (Fridleifsson et al., 2018) addressing the feasibility and economic potential of (supercritical) geothermal systems. The use of geothermal energy is still impeded by high financial risk, long development times, the high cost of drilling, and the inefficiency of converting conventional geothermal energy to electricity. Exploitation of super-hot geothermal fluid, known to be associated with magma, could solve many of these problems. Here, the Krafla Magma Testbed (KMT) drilling initiative (Eichelberger et al., 2020) is currently underway with ICDP support aiming at providing answers to many of the key questions related to heat provision, but also high-temperature drilling and borehole stability under extreme conditions. ICDP involvement in understanding of critical raw material resources will grow significantly with the ongoing Bushveld Complex Drilling Project (BCDP) in South Africa. There, the largest layered intrusion known on Earth, contains a substantial proportion of global platinum group elements, chromium and vanadium resources. The BCDP aims at creating a complete section through the Bushveld Complex to develop a more complete understanding of ore-forming processes.

The switch away from fossil fuels towards renewable and low-carbon energy sources brings with it a tremendous need for raw materials. Many of these are termed 'critical raw materials' because they are currently only produced in a small number of countries, and significant increases in demand are forecast. There is a pressing need for the scientific community to develop better geological models for deposits of critical raw materials. Many deposits are under cover, and so drilling is essential to understand their genesis.

<u>Environmental Change:</u> Records of the interactions between Earth's internal processes with the biosphere and with physico-chemical earth-surface processes throughout the entire earth history are

stored in sediments. They in fact hold the key to our understanding how past and future environmental change did and will continue to alter the Earth's surface and thus the backbone of our habitat. This topic is high on the agenda and further fueled by ever increasing global emissions of greenhouse gases. Key questions and challenges demanding our immediate attention include: What can we learn from past greenhouse conditions in Earth's climate to better anticipate future changes in the fundamentally important hydrological cycle? How was hominid dispersal pushed or pulled by environmental boundary conditions? Scientific investigations of high-resolution sediment records from lakes and continental basin systems are among the best approaches to determine the history of continental climate change at adequate spatial and temporal scales to be relevant to current and future societies. Humans are unquestionably playing a major role in shaping modern ecosystems and environments, but deeper time records are essential to understand the extent of human impacts and the role that environmental change has played in shaping human history. In particular, the scientific community still lacks long, continuous continental records of African paleo-environmental evolution spanning the full history of hominid evolution from late Miocene to present. Such records are essential to understand the relationship between environmental change and human evolution as they will allow tests of the linkages between climate trends and variability, terrestrial habitat expansion, contraction, fragmentation, and rift tectonic events against the numerous evolutionary transitions in the hominin fossil record.

Many ICDP projects have addressed a multitude of scientific objectives that rely on analysis of sedimentary drill cores. The strata addressed in these drilling projects range from sediments deposited deep in time all the way to modern lacustrine basins providing new insights into Plio-Quaternary environmental changes. To unravel more recent Earth history from lake basins, ICDP developed the GLAD lake drilling system, which was later followed by the Deep Lake Drilling System (DLDS). Their utilization has been enormously successful, as the scientific drilling community by now has been able to drill in around 20 lakes and paleo-lakes on 5 continents. As one lighthouse example of such a lake-drilling project, the Dead Sea Deep Drilling Project (DSDDP) in Israel successfully advanced knowledge in paleoclimate, tectonics and subsurface biosphere and combined these aspects in an interdisciplinary approach (Stein et al., 2011). At present, several lake and paleo-lake drilling projects are underway. These include drilling the Lake Tanganyika that is considered the crown jewel of the African lakes, and on the Ross Sea ice shelf in Antarctica for reconstructing a previous 2°C global warming phase in the frame of the SWAIS drilling project.

Land to Sea Drilling Transects: Crossing the shore

ICDP and its offshore sibling, the International Ocean Discovery Program (IODP), bring together more than 25 countries. Despite targeting two distinct geographical domains on Earth, scientific continental and ocean drilling are strongly aligned in their scientific objectives by having access to critical geological records attainable only by sustained and innovative drilling strategies. Clearly, geoscientific processes do not stop at the beach, and there are various challenges and research goals requiring drilling transects across the shoreline. Concerted efforts in land-to-sea (L2S) drilling recently led to a novel funding tool and the goal is to achieve major scientific breakthroughs in several challenges to humankind. L2S drilling will emphasize transects from the ocean basins onto the continents, in research areas near and along coastlines, enabling innovative collaborative amphibious drilling campaigns.

As an example, precise knowledge of active and passive plate margins, their structural transition from onshore to offshore, and associated magmatic and sedimentary budget will illuminate formational processes and timescales of these important, often nutrient-rich, environments. Also, global sea level changes not only directly impact coastal communities, they also affect the stability of methane hydrate reservoirs on continental shelves, with potentially devastating consequences for the ‘carbon cycle’ and Earth’s ‘climate factory’. These examples stress that L2S studies are crucial to tackle key challenges for humankind, considering that about 40% of the world population lives less than 100 km from the coastlines.

Future plans for both scientific ocean drilling and continental drilling emphasize the need to consider planet Earth as an interconnected and dynamic system, taking into account the coupling between deep Earth processes and their short timescale geological, environmental, economic, and societal effects. The new focus on L2S inter-connections requires reinforcing collaborations between ocean and continental drilling, and the development of integrated campaigns when the science requires crossing these boundaries.

How to realize an ICDP project?

ICDP organizes peer evaluation of project proposals and combines the annual financial contributions of its members to part-fund research projects. The benefits of being a member of the ICDP family are numerous. Scientists and engineers can apply for funding through proposals, they can lead projects seed-funded by ICDP, and they have priority access to data and sample repositories during the moratorium phase. Workshops, training and education are offered to member countries and the services of the ICDP Operational Support Group (OSG) and the ICDP Equipment Pool can be utilized. Furthermore, the member countries possess a seat and a vote in the decision-making ICDP panels and can determine the policy, the funding strategy and individual grant choices. ICDP funding typically covers 10-50% of the full cost of a drilling project, but more importantly provides leverage for project teams to generate other funding.

International groups of scientists with a project idea of far-reaching societal relevance that requires continental drilling can apply for funding through ICDP. This process typically starts with a so-called pre-proposal. If positively assessed by ICDP’s scientific review panel, the Science Advisory Group (SAG), proponents are invited to submit a workshop proposal. This will entail a further detailed scientific justification, basic site survey, draft plans for drilling location and depth, as well as a kernel of an international scientific team. An ICDP-funded workshop then serves to broaden the thematic spectrum and participation, and form an international team of leading experts. Finally, full proposals include detailed plans for drilling, science, costs, budget and management. For these demanding tasks the projects can rely on support from the OSG that is based at GFZ Potsdam, Germany. ICDP provides a regularly updated primer on key topics in planning and conducting scientific drilling projects (Harms et al., 2018). It serves as a best practice reference for those who tackle a continental scientific drilling project for the first time.

<u>Figure 1:</u> ICDPs key science themes for continental scientific drilling in the coming decade: Geodynamic Processes, Geohazards, Georesources, and Environmental Change.

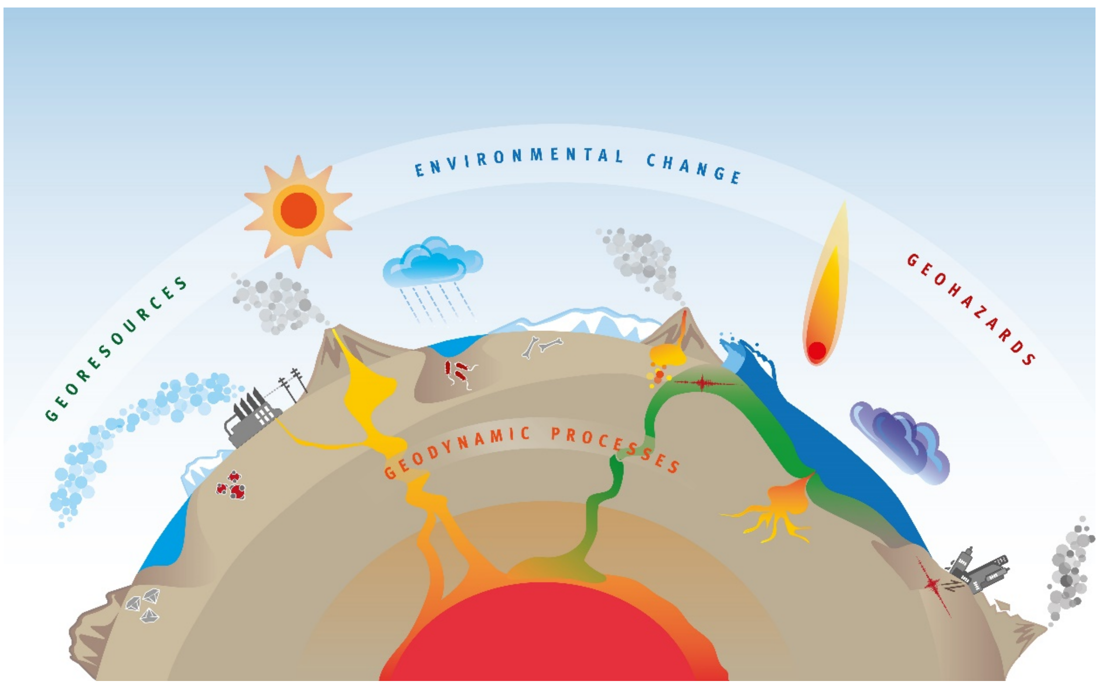

Figure 2: Drilling the 3 km deep Koyna/India pilot hole for near field studies of reservoir-triggered earthquakes.

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