Deliverable D5.6 Deep Scientific Drilling

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This deliverable is reporting the activities performed in Task 5.4 dealing with the *Long-term vision of global Deep Scientific Drilling*. This topic is of relevance both for European initiatives, such as **EPOS** (European Plate Observing System), and US initiatives like **Earthscope**. Scientific deep drilling is a unique approach to obtain data for understanding structures and processes in the Earth. Therefore, deep scientific drilling is relevant for environmental sciences, including global changes and geo-resources. For these reasons, ICDP (International Continental Scientific Drilling Program) has been involved in the discussions for elaborating a position paper concerning the long-term vision of global deep scientific drilling. Scientists involved in EPOS and Earthscope are also involved with ICDP initiatives and projects and they actively participated to the discussions in recent meetings and international conferences.

Deep scientific drilling is a fundamental approach for unravelling the physical processes generating earthquakes. Underground observations provide unprecedented access to the anatomy of active fault zones and earthquake cycles and is therefore a key topic in drilling research. ICDP is the international program coordinating deep scientific drilling worldwide. SAFOD (San Andreas Fault Observatory at Depth) has been one of the most ambitious projects to drill an active fault zone, and the National Science Foundation (NSF) has funded it through the Earthscope program jointly with ICDP. Other initiatives are presently under implementation or discussion globally.

The objective of task 5.4 in COOPEUS was aimed at joining efforts for organizing an international workshop to discuss the achievements, the progress, the bottlenecks, the actual technological difficulties for establishing long-term deep observatories as well as the optimal strategies for fund raising and governance of these ambitious and costly initiatives. The idea was to organize a joint meeting sponsored by EarthScope, ICDP and EPOS in order to trigger the implementation of the global coordination of these projects. This plan to organize an international workshop for discussing the long-term vision for deep scientific drilling as well as the present state of the art for establishing Earth observatories at depth coincided with the ICDP initiative to organize a Conference in Potsdam in November 2013 to launch the elaboration of the ICDP Science Plan[1].

The conference was held in Potsdam from November 11th to 14th 2013 and it was attended by EPOS and Earthscope researchers as well as by numerous outstanding scientists. The whole ICDP Science Plan includes the expected outcomes of this task and provides a global perspective for the entire community

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[1] http://www.icdp-online.org/fileadmin/icdp/media/Science_Conference/ICDP_SciencePlan2014.pdf

concerning deep scientific drilling. In this deliverable, we focus on the impact of scientific drilling for active faulting and earthquake processes because it matches the interest of SAFOD and EPOS. In EPOS Near Fault Observatories are engaged in a Working Group and they have a specific task for implementing services in the Implementation Phase project (EPOS IP). Deep scientific drilling is also of relevance in EPOS the monitoring of geo-thermal and volcanic areas.

For the reasons described above, we include in this deliverable a document elaborated by Jim Mori (of the Disaster Prevention Research Institute, Kyoto University, Japan) and William Ellsworth (US Geological Survey, Menlo Park, California USA) for contributing to the ICDP Science Plan.

The ICDP Science Plan document[1] includes guidelines and perspectives for deep scientific drilling that have been considered also in COOPEUS for illustrating the EPOS and Earthscope visions.

Past Accomplishments

During the last two decades, deep borehole drilling into fault zones has opened new fields of research for better understanding of earthquake processes. Land based drilling projects on the Nojma Fault Japan, (Ando et al., 2001), San Andreas Fault,USA (Zoback et al., 2011), Chelungpu Fault, Taiwan, (Ma et al., 2006), Wenchuan Earthquake Fault, China, Li et al., 2012), Gulf of Corinth, Greece (Cornet et al., 2004), and Alpine Fault,New Zealand, (Toy et al., 2013a) along with ocean drilling in subduction zones of the Nankai Trough (Tobin et al., 2009), Japan Trench (Chester et al., 2013), and Costa Rica (Vannucchi et al., 2013), have obtained valuable samples from active fault zones from depths reaching several kilometers. We have obtained a much better knowledge of the physical properties of active fault zones that produce large damaging earthquakes. An important result is recognition of the immense complexity observed in the fault zone rocks, including their varied structural and chemical characteristics, along with the associated fluid properties (Figure 1).

We have begun to answer some of the key questions raised 20 years ago when the first boreholes into fault zones were being planned, and significant progress has been made in answering these questions.

- Why are major plate-boundary faults like the San Andreas weak?
- How do stress orientations and magnitudes vary across the fault zone?
- What are the width and structure (geologic and thermal) of the principal slip surface(s) at depth?
- What are the mineralogies, deformation mechanisms and frictional properties of the fault rocks?
- How is energy partitioned within the fault zone between seismic radiation, frictional heating, comminution and other processes?

In the next decade, future fault zone projects will continue to improve our understanding of the structure and processes of active faults which result in large earthquakes, by focusing on issues such as:

- How do earthquakes nucleate?

- How do they propagate?
- Why do they stop?
- What controls the levels of ground motion during earthquakes?
- What controls the frequency & size of earthquakes
- How does fault permeability & fluid pressure vary during earthquakes?
- How does stress magnitude and orientation vary during the earthquake cycle?

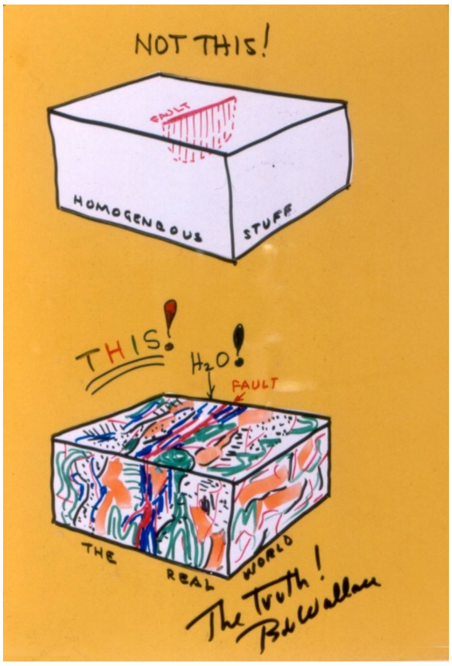

Figure 1. Complexity of real fault zones, from Bob Wallace.

Future Scientific Targets

From discussion at the 2013 ICDP Science Meeting, we have identified several research areas that can be advanced through drilling projects and have the potential for producing critical new results for understanding earthquakes.

Induced Earthquakes

It has been recently recognized that an increasing number of earthquakes are associated with human activities such as, reservoir filling, mining, waste water injections, and CO_2 sequestration. Induced earthquakes of small to moderate size have caused damage throughout the world (e.g. 1967 Koyna, India, 2011 Oklahoma, 2006 Basel, Switzerland). In many of the documented cases in the literature variations in pore fluid pressure are implicated as the primary physical mechanism that triggers earthquakes (e.g. Gupta, 2002, , Deichmann and Giardini, 2009, Ellsworth, 2013), . Major questions remain about how fluid pressure migrates through the Earth, and how ancient faults can be reactivated by this mechanism. Resolution of these and other questions requires in-situ observations in boreholes in the source regions of these earthquakes. ICDP can play an important role in investigating the physical and chemical processes and evaluating hazard implications of such human-induced seismic events.

Role of Fluids

The importance of the effects of water for both natural and induced earthquakes has long been appreciated; however there is currently only limited information about the permeability structure of fault zones, flow paths of fluids and the role chemical reactions of introduced waters in modifying the permeability structure. Permeabilities can vary by orders of magnitude across varying geological structures and have a strong effect on the frictional properties of the fault during large earthquakes (e.g. Tanikawa et al., 2013). Borehole studies of the fluid flow and pressure transmission regimes thus may produce important results.

Borehole Observatories

The last decade has seen a rapid increase in the development and installation of borehole instrumentation on the San Andreas Fault (Zoback et al., 2011) , Chelungpu Fault (Ma et al., 2012), North Anatolian Fault (Bohnhoff, 2013), and at various other locations around the world. (Figure 2), These instruments record a variety of types of data such as, seismic waves, deformation and tilt, temperature, and fluid pressure. Boreholes provide unique access into the nearfield region of the earthquake source and provide extremely low noise conditions for observing the system, which is not attainable at the Earth's surface. ICDP can play an important role in coordination of instrument development among different groups and support for deployment at important sites on active seismic regions.

For example, little is known about the source mechanisms of low-frequency earthquakes that may occur in more ductile regions of the crust. Borehole observations of these and other types of seismic and deformation events can lead to a better understanding of the wide range of mechanisms for strain accumulation and release in the crust.

Experiments on core material and modeling

Laboratory analysis of rock, fluid and gas samples from active faults obtained from depth provide important information on the physical and chemical properties of fault deformation mechanisms. These mechanisms span the range from continuous creep to sudden slip in earthquakes (e.g. Ikari, 2013). The rate-dependence of friction and temporal evolution of fault-zone permeability are just two of the important parameters that can only be obtained from direct sampling of faults in-situ. Understanding of the physical and chemical processes that lead to the development of the fault core where the great majority of the sliding occurs and surrounding damage zone requires the retrieval of a broad suite of samples of fault rocks and fluids. Such physical data is especially needed to constrain dynamic modeling of earthquake ruptures (Avouac et al., 2013)

In situ experiments

In order to bridge the gap between simulated earthquakes in the laboratory (millimeter to meter scale) and the kilometer dimensions of natural earthquakes more needs to be known about the behavior of Earth materials under in situ conditions. Experiments performed at depth in fault zones can study the conditions for producing earthquakes using small displacements of the actual rock masses of the fault zone under natural stress and temperature conditions (e.g. Henry et al., 2013).

Deep mines also provide a natural laboratory for studying failure mechanisms in the near field. They provide straightforward access to the locus of deformation induced by mining that can be extensively instrumented with seismic and deformation instrumentation in the extreme near-field of the process, such as in the South African goldmines (e.g. Ogasawara et al., 2013) .

Another potential experiment uses injection of water into a fault zone to produce small earthquakes. An experiment of this type was done at Rangely, Colorado, USA more than 40 years ago when an array of boreholes into a fault zone were used to modulate the rate of earthquakes (Raleigh et al., 1976) . This experiment verified the effective stress mechanism for triggering earthquakes by modulating the pore fluid pressure inside the fault. Today, critical questions remain about the feedback between fault movement and the enhancement of permeability within a fault as it moves in a series of small earthquakes, or the controls on the magnitude of earthquakes induced by this mechanism.

Geological Records of Tsunamis and Earthquakes

Geologists are always seeking new methods for extending the record of past earthquakes and other large catastrophic events beyond the written historical record. Coastal deposits from large tsunamis (produced by earthquakes, volcanic events, meteorite impacts), as identified in borehole cores, can be used to gain a better knowledge of such events. Giant M9 earthquakes, such as the recent 2004 Sumatra, Indonesia and 2011 Tohoku, Japan earthquakes, produced global scale tsunamis which can be studied using coastal boreholes (e.g. Fujiwara, 2013). Also records from regions that have very high sedimentation rates, such as glacial and lake deposits, can provide new opportunities for extending earthquake histories (Toy et al., 2013b).

Deep processes and Tectonics

In addition to providing detailed fault zone characterizations, observations made in boreholes provide the only direct means for measuring the state of stress in the Earth. Knowledge of the orientation and magnitude of the stress field and its spatial variability may hold the key to understanding the variability in earthquake rupture and seismic wave radiation, as well as providing important constraints on regional tectonic processes and deeper mantle processes.

Capture the complete earthquake cycle

Past drilling projects have investigated fault zones soon after the occurrence of a large earthquake (Chelungpu and Wenchuan), while others have studied physical characteristics of faults in various stages of the earthquake cycle. In the future, we envision a large-scale project to make detailed subsurface observations before, during and after a large earthquake. For such studies, it is essential to measure the physical state of the fault before the event and have in place a borehole that can rapidly be reoccupied to observe the rapid temporal evolution of the fault immediately after a large slip event. Clarifying time dependent changes in the physical and chemical properties should lead to important new insights for understanding the whole process of earthquake occurrence.

Figure 2. Locations of continental fault zone drilling projects, borehole observatories and in situ experiments discussed in the Active Faults and Earthquake Processes session

Drilling Technologies

Reaching the depths of the seismogenic zone where earthquakes nucleate has always been a challenge for fault zone drilling projects. The maximum depth reached so far in a fault zone drilling project was 3.0 km at SAFOD, athough exploratory oil wells have been drilled to over three times this depth. For core sampling, there is always the desire to reach greater depths and pressures which may be more representative of the overall fault conditions of a large earthquake. Obtaining fault zone cores from depths of 5 to 10 km will need new cost effective techniques for deep drilling. This includes advanced techniques for better recovery of the fragile fault zone sections of the core.

For borehole observatories, such as the GONAF array along the North Anatolian Fault in Turkey (Bohnhoff et al., 2013), more numerous sites with relatively shallow boreholes are needed to emplace seismometers, strainmeters and other instruments in competent rock at a depth of a few hundred meters.. ICDP could lead efforts to develop efficient drilling and deployment strategies for such borehole installations.

Also, improved logging tools and new techniques for analyzing cuttings are needed to optimize the information gained during the drilling.

Recommendations

1. Studying earthquakes using drilling provides unique opportunities for high profile, high scientific return investigations that hold the potential to revolutionize our understanding of active faulting and earthquake processes.

2. These questions are of high interest to the public and appropriate education and outreach efforts should be considered from the planning stages. Furthermore, serious consideration should be given to the practical applications of the scientific results to seismic hazard evaluations and mitigation.

3. ICDP workshop should be convened to discuss broader issues other than just the development of specific drilling proposals. Possible topics that would be of interest to the scientific community could include technologies in borehole observatories, applications for seismic hazard assessment, roadmap for a coordinated global fault zone drilling program.

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