Scientific Drilling of Active Faults: Past and Future

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Abstract

Drilling into active faults has become a major scientific endeavor during the last decade and it appears as a most promising approach to resolve long-standing questions in earthquake and faulting processes. The first boreholes were drilled into the Nojima Fault following the 1995 Kobe earthquake. Since then, drilling into active faults has begun or been planned in a wide range of tectonic settings, such as a strike-slip plate boundary (San Andreas Fault, California), a thrust zone in an active orogenic belt (Chelungpu Fault, Taiwan), a normal fault in an active rift zone (Aigion Fault, Greece), a reactivated Archean fault (Pretorius Fault, South Africa), and a major subduction thrust (Nankai Thrust, Japan).

These projects have already revealed many details on in-situ stresses, fault-zone structure, fault-rock composition, mechanical properties, heat flow, and near-field seismicity. Furthermore, most of these projects will continue to serve as observatories for monitoring fault deformation, fluid pressure and near-field earthquake source processes for a decade or two. Future drilling projects will focus on near-field observations and long-term monitoring of time-dependent processes and in-situ experimentation in active fault zones. Collaboration with industry and government will address practical issues pertaining to petroleum and geothermal energy, radioactive waste disposal, and urban seismic hazards. The outcome of these international efforts in drilling active faults will revolutionize our understanding of the processes controlling faulting and earthquakes and lead to a stronger scientific basis for earthquake hazard mitigation.

Keywords: faulting, earthquakes, drilling, active faults, natural hazards

1. Introduction

Most earthquake investigations are based on data collected at or near the earth surface and on the analysis of earthquake rupture zones observed in soils or soft sediments. This situation leads to incomplete sampling of high-frequency seismic data due to wave attenuation in the crust and to lack of representative observations on the earthquake rupture processes in the focal depth. Further, the surface observations provide no option for direct measurements of pore pressure, in-situ stresses, or heat generation that are associated with earthquakes and faulting (Zoback and Emmermann, 1994) . These inherited conditions of surface observations could limit the needed progress in earthquake science. For example, the National Academics (2002) identified specific long-term research goals in earthquake science: (1) Fault recognition: location, slip rate, and earthquake history; (2) Earthquake forecasting as function of location, time, and magnitude; (3) Fault-system dynamics: The kinematics and dynamics of interacting; (4) Fault-Zone characterization: three-dimensional structure and material properties of fault-zones; (5) Earthquake source: nucleation, propagation, and arrest in realistic fault systems; (6) Ground-motion and nonlinear response of surface layers; (7) Seismic hazard analysis; (8) Develop reliable information systems for rapid alert; and (9) Partnerships between earthquake scientists and other communities. Seismic observations at the earth surface are restricted in addressing goals 2 to 7 above due to the lack of direct and near-field data. On the other hand, studying earthquakes by drilling active faults or by using the infrastructure of deep mines could remove some of these restrictions.

This central advantage of drilling was the main drive for the initiative of Zoback and Emmermann (1994 p. 47-69), in which they projected that drilling active faults will provide better answers to the fundamental questions of earthquake science. These questions are being investigated in scientific drilling projects, such as the Nojima fault drillings, San Andreas Fault Observatory at Depth (SAFOD), Drilling Active Faults in South African Mines (DAFSAM), Corinth Rift Laboratory (CRL), and Taiwan Chelungpu-fault Drilling Project (TCDP). This paper outlines questions and answers addressed in these projects.

2. Past and present scientific drilling into active faults

2.1. A LARGE STRIKE SLIP FAULT IN AN ISLAND ARC SETTING: NOJIMA FAULT

Immediately after the 1995 Kobe earthquake (M=6.9), the Geological Survey of Japan (GSJ), the National Research Institute of Earthquake Science and Disaster Prevention (NIED), and the University group drilled boreholes along segments the Nojima fault that exhibited surface rupture during the earthquake. The boreholes depth ranged from 747 m to 1800 m. The three groups made extensive logging, detailed core analysis, and stress measurements, as well as temperature logging (NIED, University Group), repeated hydrological tests (GSJ), and repeated injection tests (University Group). The preliminary results were published in the special volume of the Island Arc (Oshiman et al., 2001). Integrated borehole systems (3-component strain meter, 3-component seismometer, and water-level sensors) were installed at the center part of the Nojima fault (by GSJ), and its southern end (by the University group).

The GSJ and NIED boreholes at Hirabayashi, where the maximum slip of 2 m was observed, penetrated the core of the Nojima fault, which allowed to study seismic and aseismic slip deformation features, and to measure the physical properties of the fault zone (Tanaka et al., 2001; Ohtani et al., 2001; Fujimoto et al., 2001; Boullier et al., 2001). The major findings of the fault structure indicate that the Nojima fault zone is characterized by a narrow fault core with three types of fault gouge, the hanging wall of the fault displays many minor shear zones; also observed an increase toward the fault core of brown feldspar and decrease of mafic minerals (Fig. 1). The footwall of the fault is significantly less deformed and less altered with respect to the hanging wall.

Tadokoro and Ando (2002) analyzed the shear wave polarization associated with aftershocks of the 1995 Kobe earthquake. They showed that while the fast shear direction was parallel to the Nojima fault strike until 12 months after the Kobe earthquake, it changed into E-W direction (parallel to regional stress orientation) in the period of 33-45 months after the earthquake. They interpreted this observation as indicating fracture healing: immediately after the large earthquake, fractures of shear fault origin are created subparallel to the active fault, then their density decrease with time as they heal.

2.2. A MAJOR TRANSFORM PLATE BOUNDARY: SAN ANDREAS FAULT

The San Andreas Fault Observatory at Depth (SAFOD) is located in Parkfield, California, 1.8 km southwest of the surface trace of the San Andreas Fault (Fig. 2) (http://www.icdp-online.de/contenido/icdp/front_content.php?idcat=712). Because of its propensity for regular earthquake activity, a wide range of geophysical and geological investigations were carried out the Parkfield region since 1985 as part of the earthquake prediction experiment of the US Geological Survey (Roeloffs, 2000), and in preparation for SAFOD drilling (Hickman et al, 2004). The SAFOD Pilot Hole was drilled in 2002 to lay the scientific and technical groundwork for the Main Hole. The Pilot Hole has been used for collecting seismic data and monitoring deformation and fluid pressure (Hickman et al., 2004). The SAFOD Main Hole was drilled in two phases (2004 and 2005), as part of the EarthScope program funded by the National Science Foundation.

The Main Hole was drilled vertically to 1.5 km and then steered northeast to a vertical depth of 3.1 km, taking it through the San Andreas Fault. In the third phase (2007), four multilateral core holes will be drilled off the Main Hole, each extending approximately 250 m into regions with repeating microearthquakes in the San Andreas Fault Zone (Fig. 2). The Main Hole is being outfitted as a long-term fault observatory that will collect data for at least the next 20 years. Observatory-mode monitoring will include near-field, wide-dynamic-range seismological observations of earthquake nucleation and rupture as well as continuous monitoring of pore pressure, temperature and strain during the earthquake cycle. The major data products from the SAFOD project include physical samples (e.g., core, cuttings, and fluids) from the fault zone and surrounding crust, geophysical measurements (e.g., well logs, hydraulic fracture tests), and monitoring data (e.g., seismic, temperature).

The drilling and logging in SAFOD Main Hole revealed a broad, ~250 m, fault-zone of the San Andreas Fault, characterized by intensely damages rocks (low wave velocities). A few narrow zones of localized active slip were recognized inside the broad damage zone, and the slip magnitude and slip nature (creep or seismic), along these narrow zones were determined by repeated surveys of the borehole casing and recording of microearthquakes (Zoback et al., 2006). It was found that the fault-zone separates two hydrologic regimes with higher pore pressure and distinct geochemistry in the NE block of the San Andreas. However, no evidence of elevated pore pressure is found within the fault-zone of the San Andreas. The measurements of in-situ stresses (Hickman and Zoback, 2004) and heat flow in the SAFOD boreholes are in agreement with the longstanding analyses, which indicated that the San Andreas Fault is weak relatively to the stronger crust on both its sides.

2.3. A MAJOR THRUST IN AN ACTIVE OROGENIC BELT: CHELUNGPU FAULT

The 1999 M 7.7 Chi-Chi earthquake in Taiwan produced large zones of surface rupture, with a maximum displacement of 8 m on the Chelungpu Fault. The north portion of the fault is characterized by low damage, large slip and slip velocity, and relatively low acceleration, suggesting that this portion of the fault slipped "smoothly." The Taiwan Chelungpu-fault Drilling Project (TCDP) framework defined the main scientific objectives and rationale for the drilling as follows (Tanaka et al., 2002; Ma et al. 2005) (http://www.icdp-online.org/): (1) The dense seismic instrumentation in Taiwan allows accurate modeling of the slip and slip velocity distribution of the Chi-Chi earthquake, and the identification of an asperity with displacements of 10-15 m at shallow depths. This is an ideal site to drill to an asperity for testing various mechanisms of nucleation and rupture of large earthquakes. (2) The drilling could provide answers to fundamental questions on the relations between the Chelungpu thrust and regional tectonics. For example, does the main fault zone remain sub-horizontal, causing "thin skin" deformation across central Taiwan, or does the fault zone steepen into the mantle, producing "thick skin" deformations?

TCDP drilling was started in 2004 and two boreholes were completed in 2005, including successful continuous coring, logging and borehole monitoring. In Hole-A, ten fault-zones were identified in the Pliocene Chinshui Shale and Miocene Kueichulin Formation. The shallowest one at depth 1111 m is considered as the fault zone that ruptured during the Chi-Chi earthquake (Fig. 3). This fault is associated with bedding-parallel thrusting with a gentle dip of about 20° and is characterized by over 1 m of gouge (fault core) and gradational breccia to protolith zonation (damage zone) in both the upper and lower blocks (Fig. 3). The observed inclination of the active fault-zone implies that the Chelungpu Fault may cut up-section from depth to the shallow horizon of the Chinshui shale.

2.4. A NORMAL FAULT IN AN ACTIVE RIFT ZONE: AIGION FAULT

The Corinth Rift Laboratory (CRL) project drilled into the Aigion fault, Gulf of Corinth, Greece, which is one of the most seismic regions in Europe. This site offers excellent conditions for in-situ investigation of earthquake sources, for developing seismic hazard reduction procedures, for better understanding of the rifting processes, and for monitoring fluid-fault interactions (Cornet et al., 2004; Forster et al., 2005; http://consortium.ifp.fr/corinth/sommaire.html). This rift zone is also a currently active analogue of the North Sea region that was active some 20 million years ago, and thus, CRL can provide better understanding of the largest hydrocarbon resources in Western Europe.

The AIG10 borehole was drilled in 2002 to 1000 m depth and it intersected the Aigion Fault at 760 m (Fig. 4). The laboratory operations focus on analysis of faulting processes from both quasi-static and dynamic points of view, through direct in-situ observations and experimentation. A key goal of the Laboratory is to understand the relationships between outcrops of steeply dipping fault-zones and the deeper seismogenic sources. Special attention is directed to the interactions between circulating fluids and fault mechanics, including hydro-thermo-mechanical coupling and the role of healing and alteration. Similarly to the San Andreas Fault (see above), the Aigion fault-zone forms a hydraulic barrier that sustains a 0.5 MPa differential pressure; the highly karstic limestone in the footwall is continuous down to 1000 m, with 0.9 MPa overpressure and isothermal temperatures. Geochemical data indicate a shallow continental origin of this water, and the absence of deep fluid input from the mantle. The present monitoring of downhole pressure yields data on tidal variations, as well as pressure variations induced by teleseisms. The preliminary ^{14}C dating results suggest that the fault is about 50 ky old with mean slip rate of about 3.5 mm/y.

The CRL team proposes to drill a 4.5 km deep borehole that would allow monitoring transients in pore pressure within the seismogenic zone and providing clues to the origin of deep fluids. It would also provide rock samples for determination of the rheological properties of fault rocks to constrain proposed models for the temporal and spatial variations in the slip surfaces (Forster et al., 2005).

2.5. REACTIVATED FAULTS IN DEEP GOLD MINES

The deep gold mines of South Africa offer unique environments to study earthquakes by providing access to the focal area (McGarr et al., 1979). The mining operations generate thousands of earthquakes per day, and some of these events approach M 5. Two research groups used this setting.

In 1992, a group in Japan initiated a research program on semi-controlled earthquake generation experiment in the deep gold mines of South Africa (Ogasawara et al., 2002). The main initial objectives were to monitor temporal variations in strain and seismicity in close proximity to hypocenters activated by mining operations. The operations included installations of the Isii strain meters and broadband seismic systems in several mines, and continuous monitoring of normal and shear strains in the proximity of faults that generate earthquakes at depths down to 3 km (Ogasawara et al., 2002). Recently, this group started an experiment in Mponeng mine at 2,900 m depth to measure the heat production during earthquakes (Nakatani, et al., 2004). They drilled seven short holes across a single weak fault surface within the Pretorius Fault Zone, and installed a network of thermistors. Continuous monitoring of temperature in proximity to this fault will allow to determine the heat production (and hence the frictional resistance) during the anticipated earthquake. These studies revealed that the source parameters for mine earthquakes in the range of M=0.8～1.4 are essentially the same as for larger natural earthquakes (Yamada et al., 2005). The proximity to the fault allows high strain resolution, yet Ogasawara et al. (2005) reported that no acceleration in the deformation was detected prior to the monitored events.

The Natural Earthquake Laboratory in South African Mines (NELSAM) is another project that utilizes the advantages deep mines for earthquake research (Reches et al., 2006) (earthquakes.ou.edu). The central part of this project is dense instrumentation and detailed characterization of a large fault-zone in TauTona mine, which is the deepest mine on earth located within the Western Deep Levels of the Witwatersrand basin, South Africa. The laboratory is built around the Pretorius fault that it is at least 10 km long with 30-200 m of displacement, and which has been inactive for the last 2.5 Ga. The mining plan for the next few years is likely to induce earthquakes of significant magnitude ($m > 2$) along this fault (Fig. 5). The operation at the site started in 2005 with site characterization, including mapping of 3D structure and composition of the Pretorius fault-zones with emphasis on segments that were reactivated during recent earthquakes, in-situ stress analysis, and drilling of five boreholes, 20-60 m in length, across the 30 m wide Pretorius fault-zone. Once completed, the earthquake laboratory will include a dense array (250 m footprint) of accelerometers (3D broadband, up to 15 earth acceleration), seismometers, strain-meters, temperature sensors, creep-meters, electromagnetic radiation system, and acoustic emissions. Fault-zone fluid chemistry will be monitored with on-site mass-spectrometer.

The preliminary results show that an M 2.2 earthquake of December 12, 2004, which occurred in the center of the planned earthquake laboratory, reactivated 2-4 segments of the Pretorius fault (Heesakkers et al., 2005). The 3D mapping of the rupture zone of this earthquake revealed quasi-planar, crosscutting reactivated segments with inclinations ranging 21°□to 90°. The rupturing formed fresh fine-grained white rock powder almost exclusively along the contacts of the ancient, sintered cataclasite and the quartzitic host rock.

3. Challenges for future drilling projects

3.1. OVERVIEW

The concepts and objectives for future drilling are guided by contributions from three main sources. The first is the cumulative experience of scientific drilling in general, and drilling into active faults in particular. These projects reveal the capabilities and limitations of direct probing of faulting and earthquakes processes at depth, and should guide selection of realistic options for the future. Second, current geodynamic investigations, like EarthScope (earthscope.org), which generate new ideas and avenues for linking drilling projects to complementary field research at a larger scale. Third, it is anticipated that collaboration with industry and government agencies will increase in the near future to the benefit of all sides. These future collaborations could follow the examples of Mallik Gas Hydrate wells, or the involvement of industry technology experts in downhole measurements and monitoring in SAFOD.

The approaches and emphases for future drilling will probably differ from the operations of the first decade of International Continental Scientific Drilling. It is anticipated that future expansion will focus on (1) Near-field monitoring of time-dependent processes; (2) In-situ experimentation; (3) Collaboration between scientific and economic projects; and (4) Technological developments.

3.2. NEAR-FIELD MONITORING

3.2.1 Near-field observations

One of the main obstacles in earthquake investigations is the lack of direct, near-field observations, and the answers to some key questions can be resolved only by direct observations close to the earthquake source. One such question is whether the final size of an earthquake can be determined during the nucleation stage (Ellsworth and Beroza, 1995). As the nucleation region of an earthquake is small, and as its characterization requires high frequency data, this question can be investigated only in the near field, and avoiding inelastic wave attenuation between the hypocenter and surface stations. Source parameter analysis is also affected by this attenuation, and significant progress has already been made with near-source recordings in boreholes (Abercrombie, 1995; Prejean and Ellsworth, 2001; Stork and Ito, 2004). Drilling into active faults significantly reduces this limitation by investigating seismogenic processes at focal depths.

3.2.2. Time-dependent processes

Many scientific drillings are devoted to the characterization of composition, structure, and properties of their target at crustal depth. This is a “static” characterization because the observations do not vary during the lifetime of the project. For example, no temporal changes in properties or conditions are expected to occur during the drilling and maintenance of impact craters targets or Quaternary lake deposits. Drilling active faults is a different story and the timing is critical. The relative time with regard to nearby episodic earthquakes is crucial for interpreting the results of downhole measurements, sampling and monitoring; for this reason, several of the current projects are defined as natural laboratories or observatories. One can distinguish between two types of time observations: high-speed phenomena associated with the seismic event, and slow phenomena related to the build up to those events as outlined below.

High-speed dynamic activity. The main task for the next phase of SAFOD (2007) is to drill four sub-horizontal offshoots from the main borehole (Fig. 1). One of these offshoots will be targeted to hit a site of repeated earthquakes of M~ 2.0, which ruptured the same “patch” on the fault at recurrence intervals of about 2-3 years (Nadeau et al., 2004). Tomographic analysis of the recorded seismic events indicates that the absolute location errors of the potential earthquakes are about 50 m horizontally and vertically, and the average of the location calculations places the target event epicenter within about 100 m of the surface trace of the San Andreas Fault (Thurber et al., 2004). Hitting this ‘patch” presents the opportunity to monitor an earthquake on a major fault from inside the rupture zone (or very close to it). The instruments in this offshoot borehole will monitor high-frequency data related to earthquake nucleation and rupture processes (e.g., seismicity, deformation, fluid pressure, and temperature) through multiple earthquake cycles.

Similarly, the TCDP project of in Taiwan focuses on measuring a wide range of parameters (imaging, pore pressure, permeability, stratigraphy, static stress levels, and residual temperatures) from the Chi-Chi earthquake, as well as continuous seismic, thermal, and pore pressure monitoring within the active Chelungpu Fault Zone (http://www.icdp-online.de/contenido/icdp/front_content.php?idcat=662; Tanaka et al., 2002).

Slow phenomena of the earthquake cycle. Boreholes across and near active faults allow to monitor, in the near field, the slow processes that prepare the fault zone for an earthquake, and the processes that are associated with the post-earthquake relaxation. These slow phenomena include temporal variations of strain/stress, creep, heat flow, and pore pressure, as well as electromagnetic phenomena.

After the 1995 Kobe earthquake, several boreholes were drilled along the Nojima fault that ruptured during the earthquake. Rapid changes were observed in aftershock focal mechanism (Yamada et al., 2001) and S wave splitting (Tadokoro and Ando, 2002). Yamashita et al., (2004) estimated the stress field before and after the 1995 Kobe earthquake, and found that the fault-zone was completely coupled before the earthquake.

It is anticipated that during its 20-year lifetime, the SAFOD project will monitor multiple cycles of M ~ 2 earthquakes at distances from less than a few tens of meters to about 1.5 km (Hickman et al., 2004). The primary fault-zone monitoring plan consists of a removable array with multiple levels of 3-components seismometers and accelerometers, tiltmeters and thermistors; formation pore pressure will be monitored in one of the multilateral core holes where it crosses the fault patch that ruptures in these recurring earthquakes. This cross-fault monitoring array is being augmented by repeat gyroscopic directional surveys and casing deformation logs in the Main Hole (to identify zones of casing shear accompanying creep and/or earthquakes), a high-resolution (1 nanostrain) fiber optic strainmeter cemented behind casing in the Main Hole at 1.5 km, and a removable seismometer, accelerometer and tiltmeter sonde deployed in the Pilot Hole at 1 km.

3.3. INTERACTIVE EXPERIMENTATION

3.3.1. Fluid Injection

Scientific drilling in tectonically active regions, and particularly into active faults, offers unique experimental opportunities. Erzinger et al. (2005) reported a long-term experiment of production and injection in the pilot hole of the KTB project. The first part of the experiment included a one-year (2002-03) production of 22,300 m^3 of saline crustal fluids pumped from a fault-zone at 4.0 km depth. The water level and seismicity were monitored continuously in both the KTB main and pilot hole. After one year of recovery, a second, one-year fluid injection test started in June 2004. No significant seismic activity was observed in the first four months of injection, induced seismicity started to be recorded in October 2004 and continued to increase slowly with time. The subsurface data were supported by surface measurements of electromagnetic field, nano-radian tilt monitoring, and high-resolution seismic surveys in an attempt to image the hydraulic expansion of the fault-zone. Similar hydraulic testing is planned for the 7.2 km deep fault system in the main KTB hole (Erzinger et al., 2005).

Induced seismicity by fluid injection has been studied in uncontrolled cases (Raleigh et al., 1976), and in an attempt to reduce earthquake hazards in deep mines in South Africa (Lightfoot and Goldbach, 1995). Several water injection experiments into the deep borehole (1800 m) across the Nojima fault-zone were carried out in 1997 and 2000. During the 1997 experiment, the seismicity increased in the region 1-2 kilometers away to the injection borehole about 4-5 days after the beginning of the injection (Tadokoro et al., 2000). These earthquakes of magnitudes -2 to +1 were attributed to the injection. The permeability estimated from the time lag is $10^{-14}–10^{-15}m^2$, and the friction coefficient estimated for the induced earthquakes was < 0.3. The repeated injection tests revealed permeability change with time. It was also shown that the fault-zone has high hydraulic diffusivity and acts as a conductive body, in agreement with borehole logging results (Kiguchi et al., 2001). It appears that the fault-zone could slip with small increase of pore fluid pressure or shear stress.

It is likely that similar, and more advanced, experiments of fluid injection into or near active fault-zones will be conducted in the future. This experimentation and the analysis of the induced seismicity are likely to become an integral part of the collaborative studies with the energy industry and government agencies.

3.3.2. Rapid Response Drilling

The timing of drilling may be critical for capturing the fundamental features of an earthquake. Several drilling projects were conducted after a major earthquake, e.g., the TCDP and the Nojima Fault drillings; it would have been an outstanding experiment if these boreholes had been drilled before the earthquake. Although the primary purpose of SAFOD monitoring was to capture transient processes associated with recurring small-magnitude earthquakes on the San Andreas Fault, it was also hoped to capture the long-delayed Parkfield M 6 earthquake that repeatedly ruptures the San Andreas Fault south of SAFOD. This M 6 event occurred on September 28, 2004, after the completion of SAFOD Phase 2 drilling, but too early for the full deployment of the SAFOD observatory.

Another example of the significance of the timing of drilling is related to the frictional heat generated by earthquakes, which is a central puzzling problem of earthquake mechanics (Lachenbruch and Sass, 1980). While the largest component in the earthquake energy budget is frictional heat, there are no direct measurements of this parameter for large earthquakes. Such measurements would contribute substantially to understanding rupture dynamic, weakening mechanisms, thermal pressurization, and resolution of the heat flow paradox. The difficulty of conducting such measurements was demonstrated for the M7.9 Denali earthquake of 2002 (D. Lockner, written communication, 2005). With surface rupture length > 300 km and slip magnitude of > 5 m, this earthquake could be an ideal site for drilling at moderate cost (~$200,000 U.S. for a 750-m-deep borehole). However, the time needed to raise the necessary funds was probably too long to detect a sufficiently strong thermal signal. To facilitate measuring frictional heating generated by a similar-sized earthquake, which will certainly occur somewhere in the world during the next few years, drilling plans and funds should be ready long before the event. We believe that a concerted international effort to plan and obtain funding for such an event in advance would be a very fruitful endeavor.

3.4. COLLABORATION WITH ECONOMIC AND SOCIETAL PROJECTS

3.4.1. Seismic hazard challenges

The evaluation of maximum expected ground motion is a critical component for the design and approval of major facilities; the nuclear waste repository at Yucca Mountain, Nevada, is an outstanding example of this need. The regulations for the Yucca Mountain site require design for very rare earthquakes (probability $< 10^{-4}$) during very long periods ($> 10^4$ years). Extensive geological, geophysical and engineering studies were conducted at this site to determine likely earthquake ground motion for such periods (http://www.ocrwm.doe.gov/ymp/). A few modeling procedures yielded high values of peak ground acceleration and velocity (e.g., $V_{peak} \sim 13$ m/s), with large uncertainties for the largest (and rarest) events (Hanks et al., 2004). These uncertainties stem, in part, from limited information on the effects of variations in seismic velocities, densities, and nonlinear dynamic properties on seismic radiation, wave propagation effects and site response. Andrews (2005) calculated the effect of nonlinear properties of the Solitario Canyon fault-zone for estimated values of the rheological properties and structure at depth and the rock mass below the Yucca Mountain repository. He showed that the internal structure of the fault-zone and its properties have a profound impact on the expected ground motion about 1 km away. These properties, which are currently only estimated, could be determined by dedicated drilling to suitable targets.

The need for safe design of public facilities in major cities that are close to active faults requires detailed knowledge of the anticipated ground motion, and the near-field radiation from the large faults. The simulations of the ground motion depend on knowledge of the real 3D structure of the fault-zones and their associated damage zones at seismogenic depth (Andrews, 2005). This need for better, more relevant information on active fault-zones in metropolitan regions will drive future collaboration between scientists and government agencies. Such projects could also be linked to research in development of more reliable early warning systems in urban areas (Wu and Kanamori, 2005). These systems are based on fast collection and processing of seismic data starting at the early stages of a significant seismic event, and allow for early deployment of emergency response personnel and quick action to preserve critical gas and electricity supply distribution system. Drilling into active faults will provide the data on structure and physical properties that is needed to for realistic models of strong ground motion. Further, installation of seismic systems at depth could significantly augment surface-based early warning systems in urban areas.

3.4.2. Energy related research

Many existing geothermal energy projects take advantage of heat and fluid transport along active faults that require understanding of the relationships between faulting, natural and induced fractures, in-situ stress, and fluid/heat transport (Pine and Batchelor, 1984; Willis-Richards et al., 1996; Hickman et al., 1999; Tezuka and Niitsuma, 2000). There have been several scientific-industry-government collaborations; for examples, the Dixie Valley (Nevada) and Coso (California) projects were funded by U.S. government agencies with significant cost sharing from the industry partner who runs the field. Similar projects with intense component of induced seismicity are underway or completed elsewhere in Japan, Europe, and Australia.

The basic research approach in geothermal projects is to compare fracture orientations (from core and borehole images) and measured in-situ stresses, with focal mechanisms associated with injection induced events and flow paths. Hickman et al., (1999) analyzed the fracture systems in producing and the non-producing wells in the Stillwater fault zone of Dixie Valley geothermal project. They found that producing fractures are optimally oriented for shear failure with respect to the active stress field, and are subparallel to the Stillwater fault. Tezuka and Niitsuma (2000) showed, for Hijiori hot dry rock project, Japan, that the growth direction of the geothermal reservoir is strongly controlled by the distribution of favorably oriented pre-existing fractures and their interaction of the stress field. One project in progress is the geothermal project in Basel, Switzerland, in the Rhine graben, and about 150 km south of the Soultz geothermal field (Fig. 6). The injection of cold water to 5 km depth and the production of hot water and steam are likely to trigger earthquakes close to a large city; this hazard led to science/industry collaboration in installation and continuous monitoring of natural and production-induced seismicity (Deichmann et al., 2005).

It is not surprising that the oil and gas industry faces similar questions on the relationships between faults, natural and induced fractures, in-situ stress, and fluid flow (Finkbeiner et al., 2001). However, it seems inappropriate to use the limited budget of scientific drilling for research in the multibillion hydrocarbon industry. Potential links between active faults research and the hydrocarbon industry are issues related to fault-sealing (what controls the seal and non-seal modes of active faults) (Jones and Hillis, 2003), induced mircoseismicity and fault reactivation (Segall et al, 1994; Wiprut and Zoback, 2000). Many of these same questions are relevant to commercial and potential geothermal systems, where faults can act as either barriers or conduits to the flow of high-temperature fluids.

3.5. NEEDED DEVELOPMENTS

3.5.1. Technology Development

Although instrumental observations have been conducted in deep boreholes and deep mines [United States (SAFOD), Japan (Nojima fault, western Nagano region), Europe and South Africa], new methods are needed for long-term monitoring of deformation, seismicity, and pore pressure in the near-field of earthquakes. For example, this requires the ability to measure strain changes in the range of 10^{-12} to 10^{-2}, as accumulated and released during the earthquake cycle, and the need for seismic sensors that cover frequencies from 0.01 Hz to several kilohertz with wide dynamic ranges.

Equipment and techniques for deploying removable instrumentation and multiple sensors systems that can operate at high temperature must be developed. Developments in drilling, coring and core handling technologies are also necessary, especially for recovering fragile fault zone samples. New developments in Logging While Drilling and logging while coring technologies are also needed to adequately characterize and sample the near-fault environment. Real-time mud gas logging is useful in characterizing major influx zones during drilling, supplemented by improved methods for down-hole fluid sampling using wireline and drill-pipe-deployed techniques.

3.5.2. Link between ICDP and IODP

More than 90% of the global seismic energy is released in subduction zone earthquakes, and thus drilling seismogenic subduction zones is a central theme in the Integrated Ocean Drilling Program (IODP; www.iodp.org). The Nankai Trough subduction zone, Japan, (Fig. 7) is a promising site for fault-zone drilling, with the main objectives of characterizing in-situ properties of the megathrust, monitoring long-term fault conditions, investigating the shallow aseismic to seismic transition, and studying earthquake processes and tsunami generation mechanisms. These targets are in accord with the objectives of ICDP for scientific drilling into fault zones on land. Thus, a strong collaboration should form between ICDP and IODP to study active fault zones at both convergent and transform plate boundaries. This collaboration would also require construction of an integrated land-ocean monitoring network.

3.6. CONCLUDING REMARK: TARGETS FOR FUTURE DRILLING

We outlined above possible topics and approaches for future drilling into active faults as guided by experience and estimated need. Actual sites for future drilling projects are not proposed here, as we believe that future targets will be developed by interested and motivated groups according to opportunities that change with time, place and scientific interest. As an illustration for this process, one may use the 1994 meeting on scientific drilling in which Zoback and Emmermann (1994) listed five to seven attractive sites for drilling into active faults. Only one site (SAFOD that was already in preparation in 1994) on this list has materialized to become a drilling project.

We hope that the second decade of drilling into active faults will use the experience, knowledge and enthusiasm in the scientific community to surpass the exciting achievements of the first decade.

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Figure captions

Fig. 1. Fault rocks in the fault-zone of the Nojima Fault, Japan, as observed in the borehole of the Geological Survey of Japan; see text (after Ando, 2001)

Fig. 2. Long-term and near-field monitoring in SAFOD Observatory. Stage 1 (Pilot hole): seismometers and tiltmeters; Stage 2 (Main Hole): Laser strainmeter, seismometers and accelerometers; Stage 3 (Off-shoot holes and Main hole): seismometers, accelerometers, tiltmeters, pore pressure and temperature gages (after http://www.icdp-online.de/contenido/icdp/front_content.php?idcat=889).

Fig. 3. Core of the fault-zone at depth 1111 m in hole–A of TCDP. This fault-zone is the most likely fault that slipped during the Chi-Chi earthquake. Note the meso-structures and thick shale zones (after icdp.gfz-potsdam.de/sites/chelungpu/news/TCDP_NEWSLETTER0820.pdf).

Fig. 4. A hydrological model of the Aigion area, Corinth, Greece (after Forster et al., 2005)

Fig. 5. Site design of the DAFSAM-NELSAM project in Tautona gold mine, South Africa. The figure is a map at levels 118-120 (depth range of 3597 m to 3657 m). Red lines: five boreholes with creepmeters and thermister arrays; blue lines: tunnels; brown lines: faults; red (small) solid circles: sites of 3D broad band accelerometers and seismometers (20 systems) and SP; colored circles: hypocenters of earthquakes $2.0 < M < 3.4$ since February 2000.

Fig. 6. Monitoring wells OT2 and injection well BS1 in The Basel Deep Heat Mining Project, Switzerland (after Deichmann et al., 2005).

Fig. 7. Cross section of the planned drilling in to the Nankai meagthrust by the NanTroSEIZE project. The profile shows the Kii/Kumano plate interface, accretionary prism, Kumano basin, prominent splay fault system, the 1944 Tonankai estimated coseismic slip (red line), and the décollement stepdown to the top of the oceanic basement (orange dotted circle. Proposed drill sites are in some cases projected to this line (after http://ees.nmt.edu/NanTroSEIZE/).

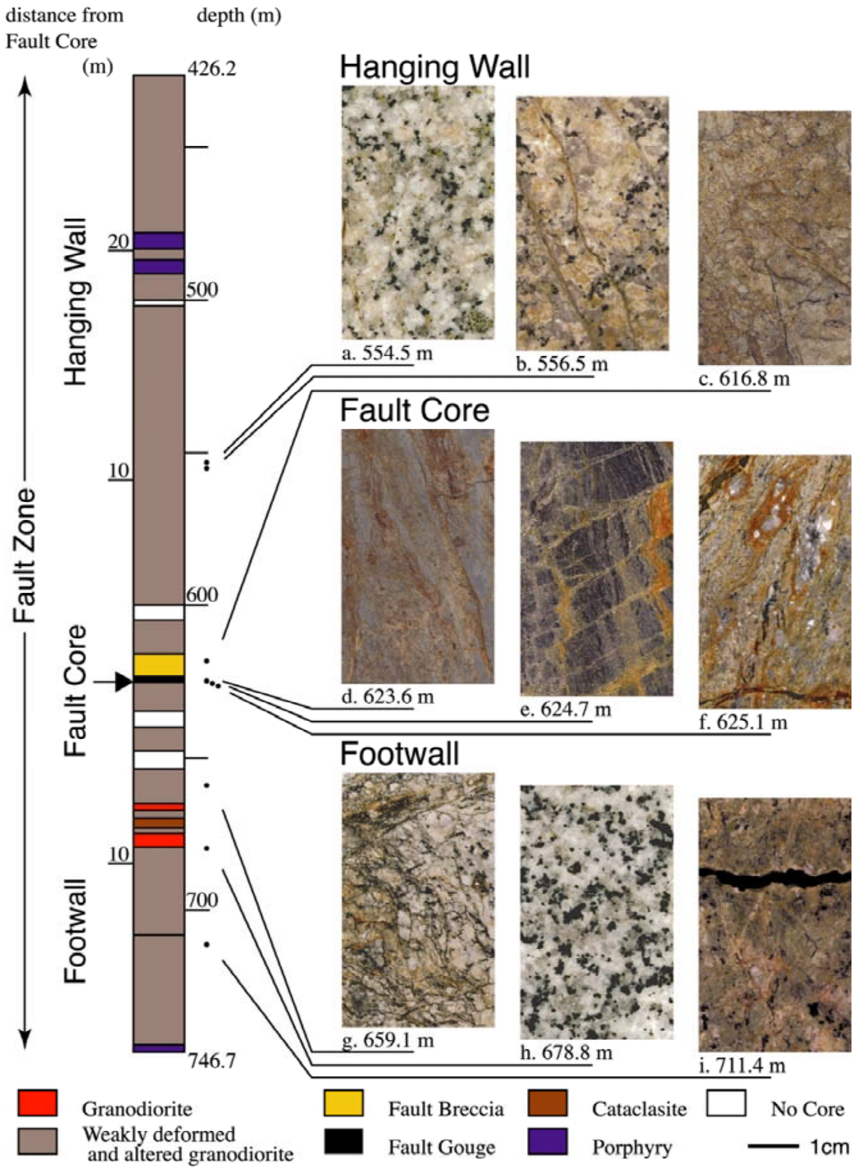
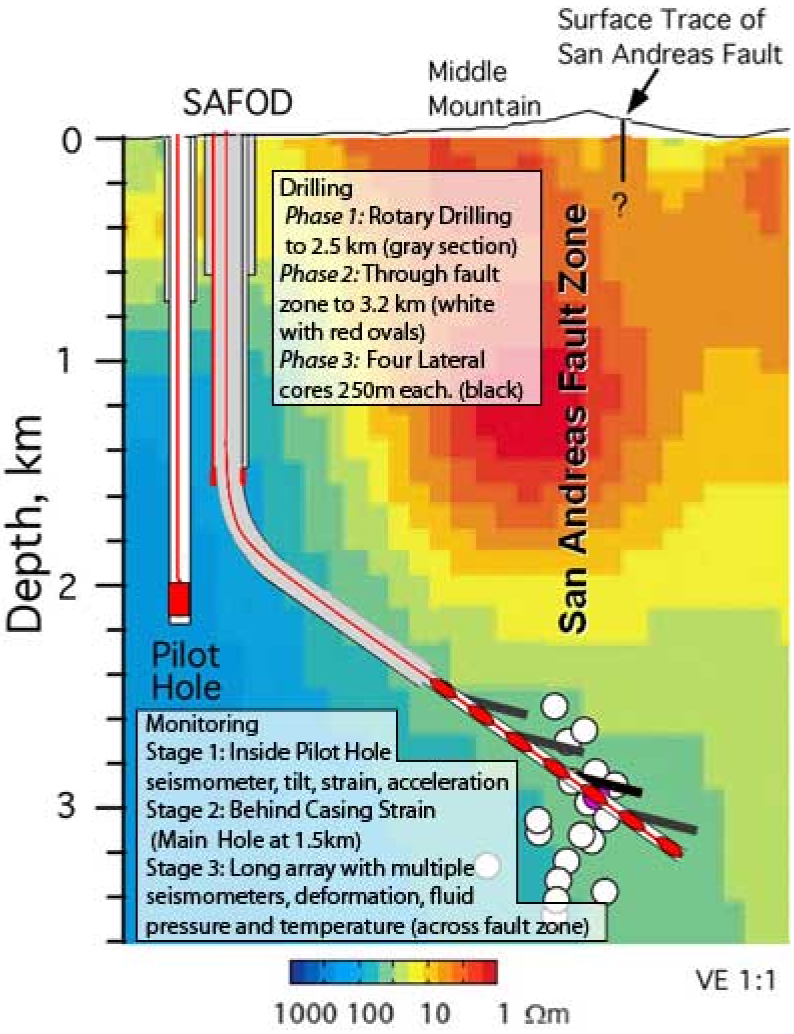

distance from
Fault Core
(m)
depth (m)
426.2
20
500
10
600
10
700
746.7
Fault Zone
Hanging Wall
Fault Core
Footwall
Hanging Wall
a. 554.5 m
b. 556.5 m
c. 616.8 m
Fault Core
d. 623.6 m
e. 624.7 m
f. 625.1 m
Footwall
g. 659.1 m
h. 678.8 m
i. 711.4 m
Granodiorite
Weakly deformed and altered granodiorite
Fault Breccia
Fault Gouge
Cataclasite
Porphyry
No Core
1cm

FIG1



Drilling
Phase 1: Rotary Drilling to 2.5 km (gray section)
Phase 2: Through fault zone to 3.2 km (white with red ovals)
Phase 3: Four Lateral cores 250m each. (black)

Monitoring
Stage 1: Inside Pilot Hole seismometer, tilt, strain, acceleration
Stage 2: Behind Casing Strain (Main Hole at 1.5km)
Stage 3: Long array with multiple seismometers, deformation, fluid pressure and temperature (across fault zone)

FIG2

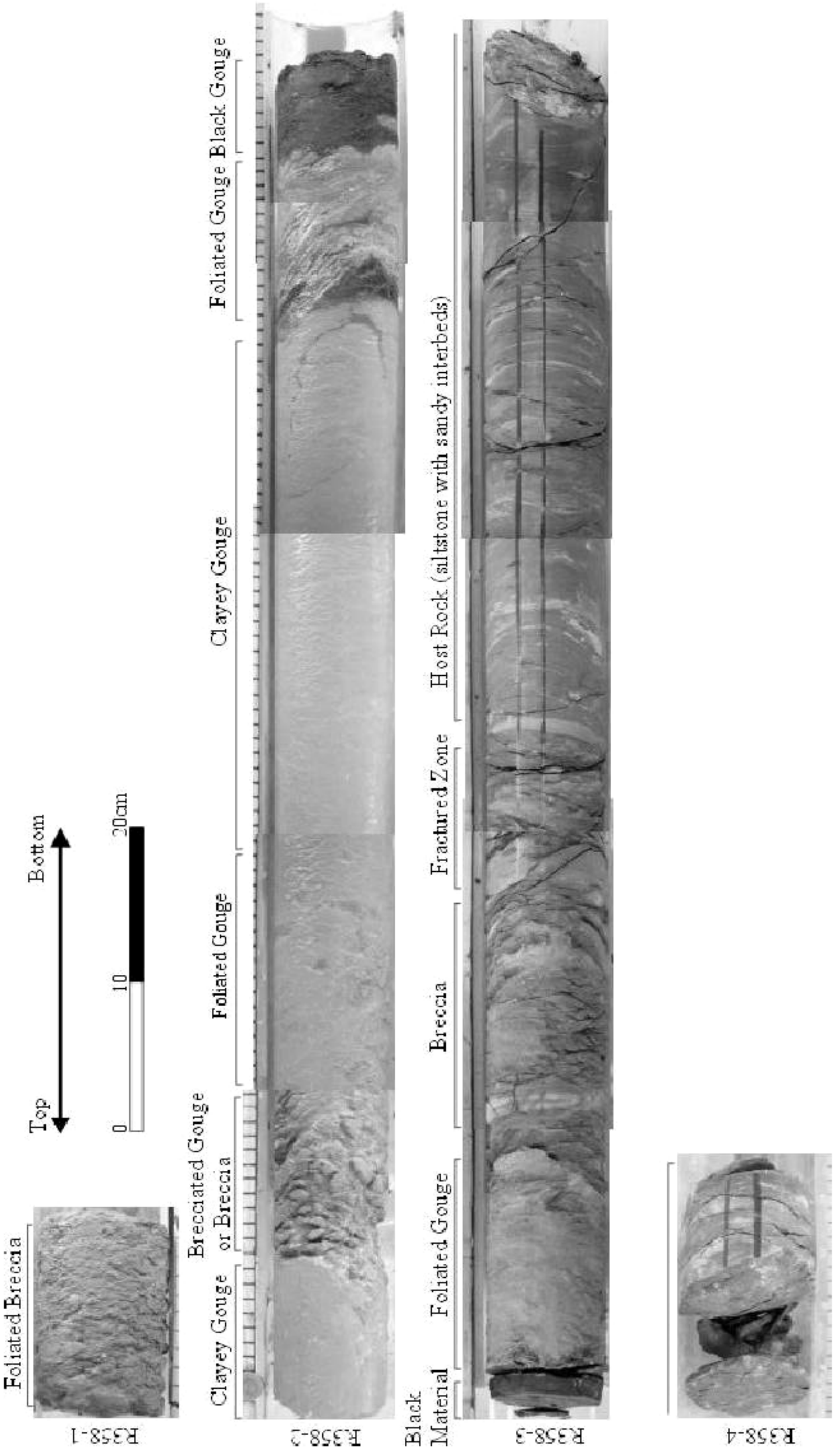

Top
Bottom
0
10
20cm
Foliated Breccia
R358-1
Clayey Gouge
Brecciated Gouge or Breccia
Foliated Gouge
Clayey Gouge
Foliated Gouge
Black Gouge
R358-2
Black Material
Foliated Gouge
Breccia
Fractured Zone
Host Rock (siltstone with sandy interbeds)
R358-3
R358-4

FIG3

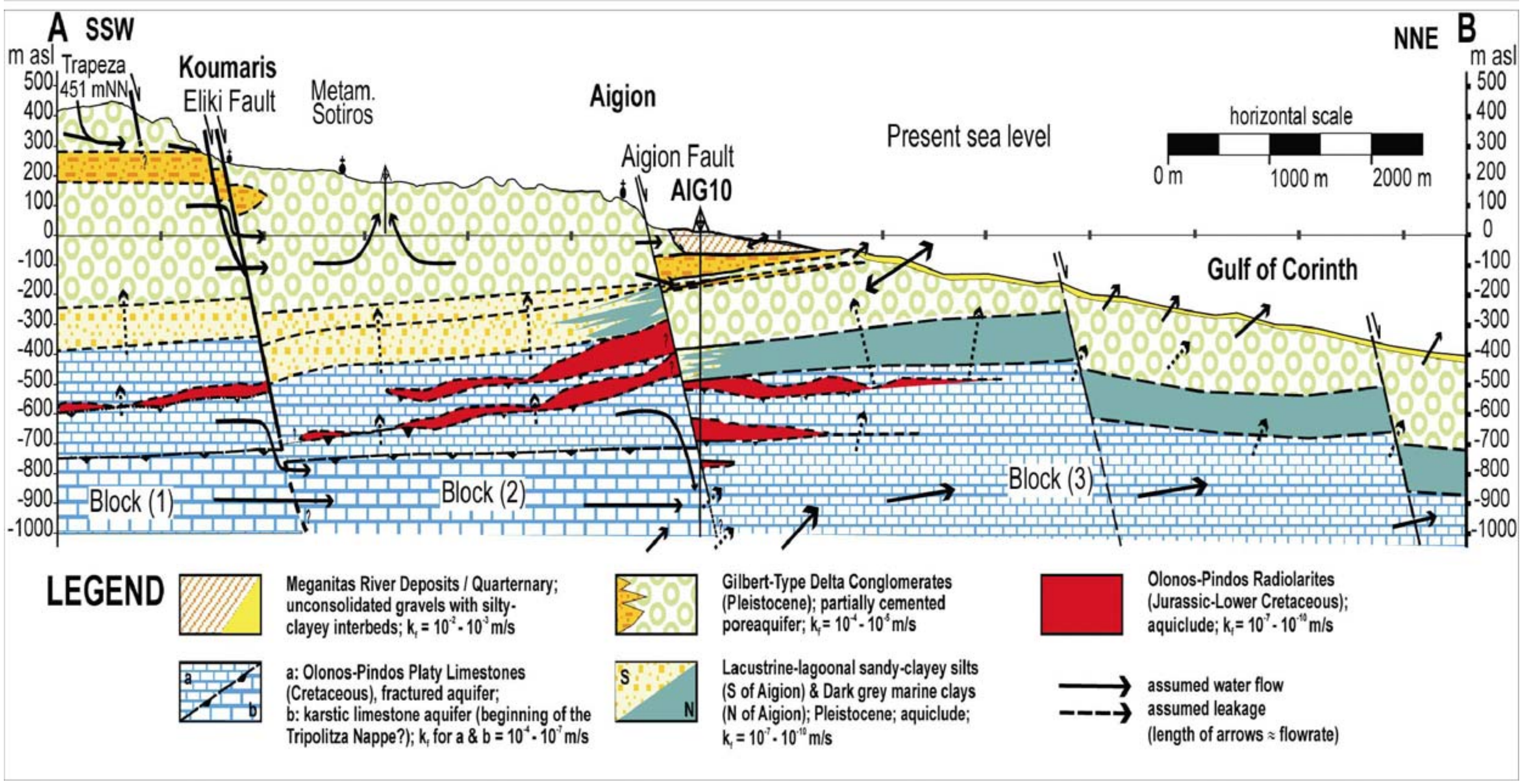

A SSW
NNE B
m asl
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
Trapeza 451 mNN
Koumaris
Eliki Fault
Metam. Sotiros
Aigion
Aigion Fault
AIG10
Present sea level
horizontal scale
0 m
1000 m
2000 m
Gulf of Corinth
Block (1)
Block (2)
Block (3)
LEGEND
Meganitas River Deposits / Quarternary; unconsolidated gravels with silty-clayey interbeds; $k_f = 10^{-2} - 10^{-3}$ m/s
Gilbert-Type Delta Conglomerates (Pleistocene); partially cemented poreaquifer; $k_f = 10^{-4} - 10^{-5}$ m/s
Olonos-Pindos Radiolarites (Jurassic-Lower Cretaceous); aquiclude; $k_f = 10^{-7} - 10^{-10}$ m/s
a
b
a: Olonos-Pindos Platy Limestones (Cretaceous), fractured aquifer;
b: karstic limestone aquifer (beginning of the Tripolitza Nappe?); k_f for a & b = $10^{-4} - 10^{-7}$ m/s
S
N
Lacustrine-lagoonal sandy-clayey silts (S of Aigion) & Dark grey marine clays (N of Aigion); Pleistocene; aquiclude; $k_f = 10^{-7} - 10^{-10}$ m/s
assumed water flow
assumed leakage
(length of arrows ≈ flowrate)

FIG4

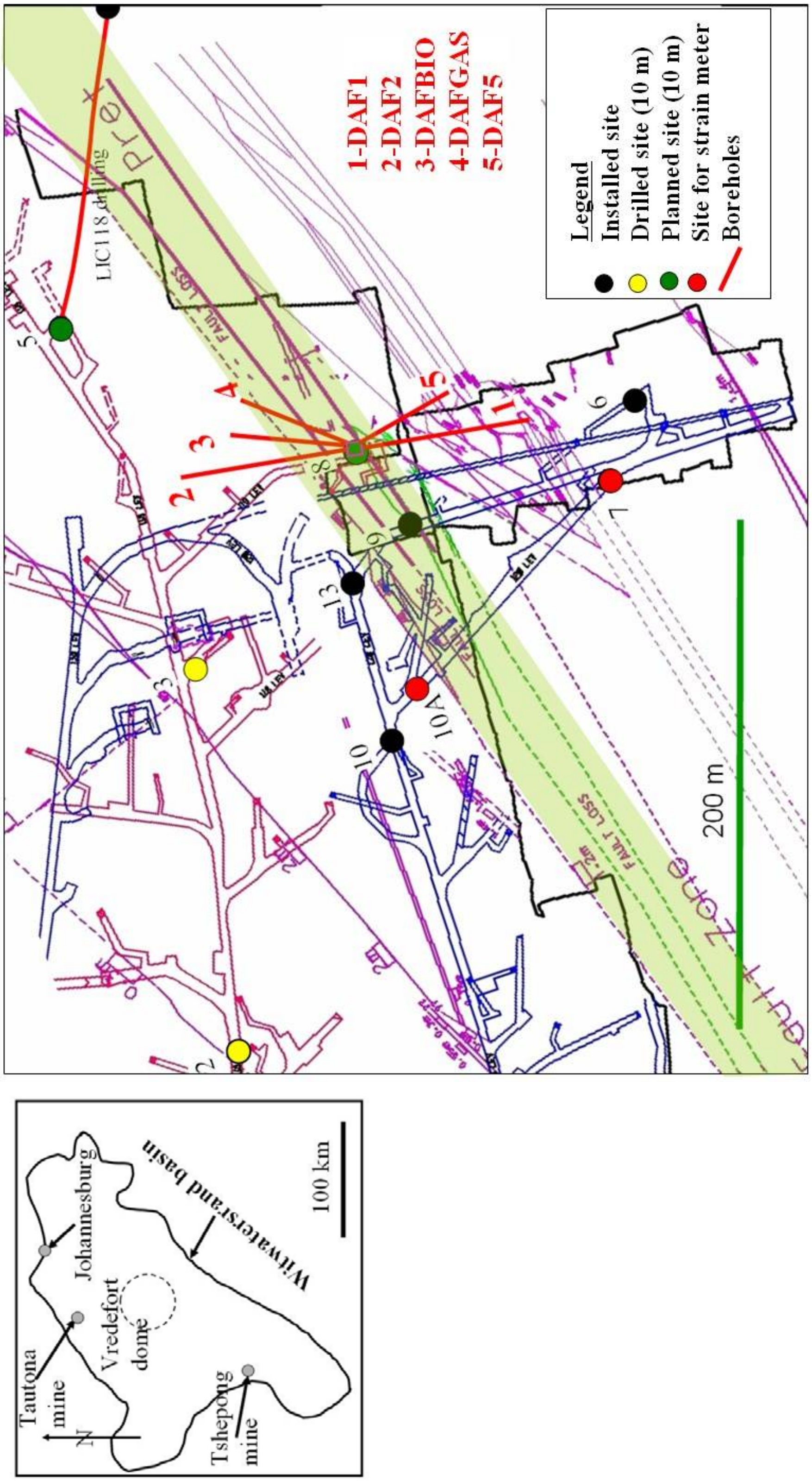

1-DAF1
2-DAF2
3-DAFBIO
4-DAFGAS
5-DAF5
Legend
● Installed site
● Drilled site (10 m)
● Planned site (10 m)
● Site for strain meter
/ Boreholes
LIC118 drilling
Pret
Fault Zone
FAULT LOSS
1
2
3
4
5
5
6
7
8
9
10
10A
13
3
2
200 m
Tautona mine
Johannesburg
Vredefort dome
Witwatersrand basin
Tshepong mine
100 km
N

FIG5

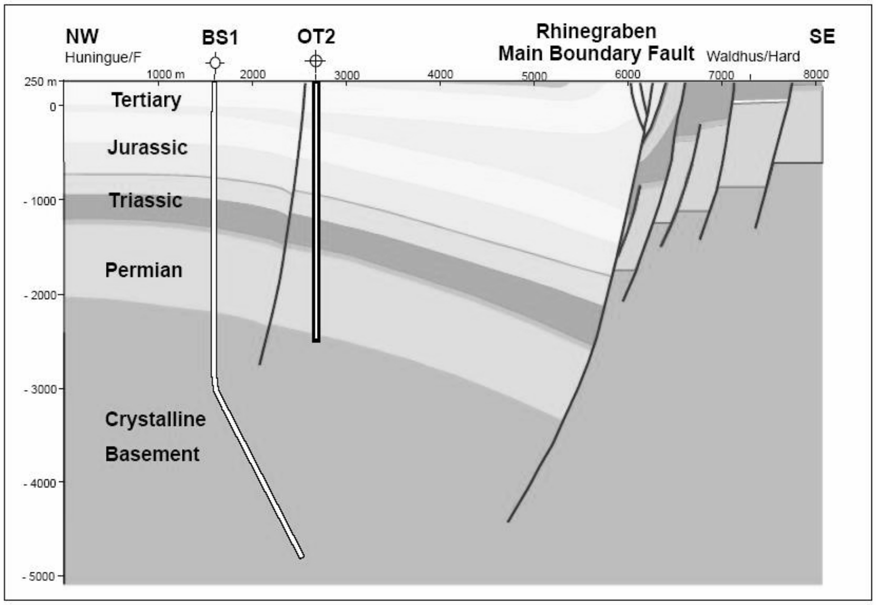

NW
Huningue/F
BS1
OT2
Rhinegraben
Main Boundary Fault
Waldhus/Hard
SE
1000 m
2000
3000
4000
5000
6000
7000
8000
250 m
0
- 1000
- 2000
- 3000
- 4000
- 5000
Tertiary
Jurassic
Triassic
Permian
Crystalline
Basement

FIG6

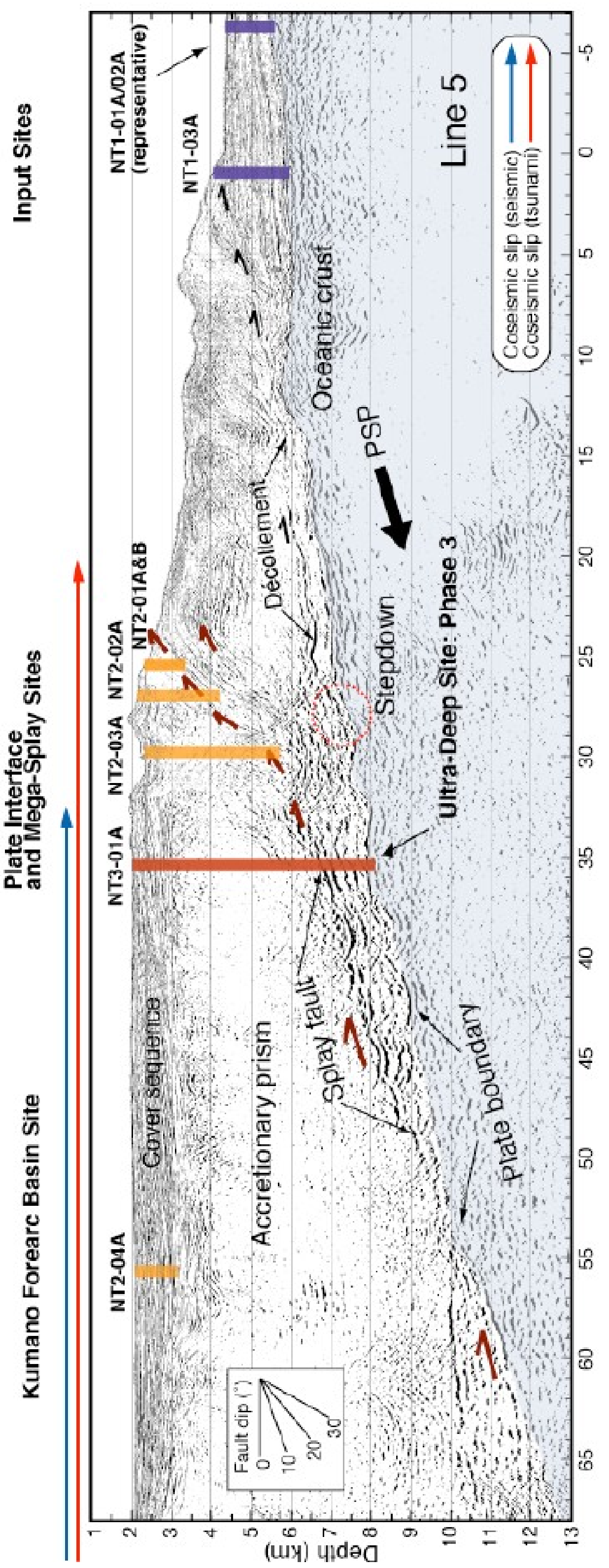

Input Sites
Plate Interface and Mega-Splay Sites
Kumano Forearc Basin Site
NT1-01A/02A (representative)
NT1-03A
NT2-01A&B
NT2-02A
NT2-03A
NT3-01A
NT2-04A
Oceanic crust
PSP
Décollement
Stepdown
Ultra-Deep Site: Phase 3
Cover sequence
Accretionary prism
Splay fault
Plate boundary
Line 5
Coseismic slip (seismic)
Coseismic slip (tsunami)
Fault dip (°)
0
10
20
30
Depth (km)
1
2
3
4
5
6
7
8
9
10
11
12
13
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65

FIG7