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Preface

Drilling into fault zones

Scientific drilling research is becoming increasingly common in a number of diverse fields. Certainly one of the reasons is that drilling is the only way to observe directly the deep interior of the earth, and it can provide a means to monitor the earth system. Another reason is great advances in technology, including remote observation, such as seismic, GPS, and electro-magnetic methods, to precisely and reasonably site the location for fruitful drilling, as well as significant advances in drilling technology that allows probing more extreme environments. Among many drilling targets, active fault zones offer great potential to answer key questions of earthquake physics and chemistry, through in situ observations, down hole experiments, laboratory analysis of materials recovered from fault zones, and long-term monitoring.

Scientific drilling to penetrate a fault zone shortly after an earthquake began with drilling the Nojima fault after the 1995 Kobe earthquake, Japan (Oshiman et al., 2001; Shimamoto et al., 2001), which was followed by drilling the Chelungpu fault after the 1999 Chi-Chi earthquake, Taiwan. Analyses of core samples of the Nojima fault have provided a nearly complete characterization of the architecture of a seismic fault, and geochemical and other analyses are continuing. In addition, water injection hydrologic tests were conducted using the Nojima boreholes in 1997, 2000 and 2003 to understand evolution of hydraulic properties of the fault zone after a large earthquake, and future monitoring of the Nojima boreholes will continue to provide new information. After the 1999 Chi-Chi, Taiwan earthquake, two shallow boreholes were drilled to investigate causes of the distinct differences in rupture characteristics between the northern and southern parts of the fault zone. Given the status of these two drilling programs, it is appropriate to provide a collection of many of the most recent results from seismic fault zone drilling to as a means to facilitate addressing questions of earthquake physics.

An important and outstanding problem of seismic faulting is the extent of frictional heating during coseismic slip; three papers report on analyses of core materials recovered from Nojima drilling to estimate transient thermal anomalies in slip zones. Fukuchi et al. analyzed several slip zones in the Hirabayashi NIED core of the Nojima fault by Electron Spin Resonance method and concluded that the slip zone materials had never experienced frictional heating to temperatures over 350 °C. Tagami and Murakami applied Fission track thermo-chronological method to the fault zone rocks obtained from Hirabayashi GSJ core (center of the trace of the fault 630 m depth) and Toshima DPRI core (edge of the trace of the fault 400 m depth) and revealed the heterogeneity in time and space of thermal disturbances resulting from localized fluid flow along the fault. Yamada et al. applied also the fission track method to the Hirabayashi NIED core (1140 m depth) to both zircon and apatite obtained from fault zone materials, and found that the zone 2 m from the fault surface show clear disconcordant ages between zircon and apatite, also suggesting thermal disturbance resulting from fluid flow. The results are in good agreement with that from Tagami and Murakami.

Fault zone materials also are used to better define the architecture of faults, particularly as it pertains to fluid flow and the mechanical involvement of fluids in faulting. Several papers in the volume address these topics. Lin et al. describes the characteristics of the damage zone observed in the deep Toshima DPRI core (1800 m); it is reported that the thickness of damage zone is around 50 m and the fault-fracture networks in the damage zone likely are generated by co-seismic fluid infiltration by carbonate-bearing subsurface water. Fujimoto et al. analyzed water samples directly obtained from 624 m depth fault zone in Hirabayashi GSJ borehole in 2000 and 2004 and suggested the depth and temperature of the fluid reservoir source is

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approximately 4 km, and 90 °C, respectively. They also suggested that the Nojima fault has not been healed from a hydrological point of view even 5 years even after the Kobe earthquake. This result is in some contrast to hydrological properties estimated using geophysical methods.

Kitagawa et al. examined the temporal change in permeability of the damage zone of the Nojima fault at Toshima using repeated water injection experiments in 1997, 2000, and 2003. They monitored water discharge rate and change in water pressure of in an 800-m-deep well during water injection into a neighboring deep borehole, and concluded that the permeability is reduced to 40% after 6 years. Mukai and Fujimoto examined the change in strain during water injection experiments using a precise strain meter in a borehole, and estimated the change in hydraulic conductivity with time. They found an approximate 50% reduction of hydraulic conductivity in 2003 compared to that obtained in the 1997 and 2000 experiments. Murakami et al. examined electro-kinetic and hydraulic properties of the fault zone during injection tests by measurement of self-potential variation, and examined the change in hydraulic properties with time. They concluded that hydraulic conductivity decreased approximately 40% during the 8 years after the Kobe earthquake. The results of several experiments presented in these papers agree that hydraulic conductivity was reduced over the 8 years after earthquake, although the estimates of magnitude vary from 40% to 70%.

The final paper concerning the Nojima fault addresses the initiation of the earthquake instability, and represents some of the unique types of geophysical research possible with down-hole instrumentation. Hiramatsu and Furumoto investigate the initial rupture process of micro-earthquakes using borehole seismometer installed at deep Toshima DPRI borehole. They analyzed the slow initial phase of P waves from 31 earthquake events by applying two models of circular crack nucleation region models, and conclude that the ultimate size of earthquakes is controlled by the size of the nucleation region.

Five papers in the special issue are related to drilling into the Chelungpu fault zone activated in the 1999 Chi-Chi, Taiwan earthquake. Sakaguchi et al. used vitrinite reflectance as a paleo-thermal index, and analyzed both exhumed parts of the fault zone and the core samples of the fault zone acquired through drilling. The total displacement of the exhumed fault was determined based on the difference in maximum temperature between the hanging wall and footwall. From the slip zone activated by the 1999 Chi-Chi earthquake, sample analysis suggests that a maximum temperature of 580 °C was achieved by frictional heating above the background temperature of 130 °C. Hashimoto et al. analyzed clay mineralogy of Chengpu fault zone rocks using XRD to show that the common clay minerals are illite, smectite and chlorite in both the host and fault zone. They found reduction of smectite in some slip zones, and suggest this could be reaction from a frictional temperature rise. Chlorite chemical composition between north and south of the Chelungpu fault may reflect varying fluid conditions. Chen et al. analyzed the core from southern Nanto borehole in order to understand fluid behavior during co-seismic and interseismic periods. Mineralogical and chemical data from the core provide evidence for volume loss by coseismic frictional wear and by infiltration of acidic fluids during interseismic periods.

Geophysical investigations of Chelungpu fault zone include ultra-shallow P-wave seismic reflection across the Chelungpu surface rupture by Jeng et al. The fault zone structure in the near-surface could be resolved to resolution similar to that of Ground Penetration Radar methods. Lin showed a clear tomographic image across the Chelungpu fault by using more than 2000 aftershocks of Chi-Chi earthquake, and depicted 7 to 9 km vertical offset of velocity structure along the Chelungpu fault. They also found that most aftershocks are concentrated within the 5 to 6 km/s velocity layer and concluded that seismogenesis in western Taiwan is more correlative with seismic velocity than absolute depth. Chen et al. investigate electric structure across the Chelungpu fault and found a low resistivity zone at the focal area of Chichi earthquake. They suggest that the low resistivity zone reflects deep crustal fluids, which may have participated in the rupture process of the Chi-Chi earthquake. They also hypothesize that aftershocks beneath the Chelungpu fault might be caused by a post-seismic adjustment of pore pressure based on the spatial correlation between aftershock clusters and the low resistivity zone.

We sincerely hope that this special issue contributes to the further communication between geologists and geophysicists that is necessary to understand fault zone dynamics, and illustrates the unique scientific opportunities provided through scientific drilling through seismic zones. We thank Dr. K. Nishigami, DPRI, Kyoto University, and the reviewers for their valuable comments on the articles in the special issue. Finally, we would like to offer our sincere gratitude to Prof. M. Ando, Nagoya University, who played a significant role in initiating timely scientific drilling into fault zones after large earthquake slip.

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