Effect of Brine Composition and Concentration on Physical Properties of Clay and Shale

David Lockner[1], Sheng-Rong Song[2]
1 US Geological Survey, ms977, 345 Middlefield Rd, Menlo Park, Calif., USA; e-mail: dlockner@usgs.gov); 2 Dept. of Geosciences, NTU, Taipei, Taiwan.

Abstract

Water content has a dramatic effect on the shear strength of clays; especially expandable clays such as smectites. For example, the coefficient of friction, μ, of dry montmorillonite (a smectite clay) is approximately 0.7, but when fully saturated with distilled water and tested at the same effective normal stress (normal stress – pore pressure), μ is as low as 0.1. Apparently, structured water adsorbed on the surfaces of clay particles and penetrating between tetrahedral layers of adjacent clay platelets allows sliding at significantly reduced shear stress. While formation fluids contain dissolved ions that are known to have significant effects on clays and shales, systematic studies of the effects of brine on fault zone rheology are not common. We have conducted laboratory test of montmorillonite saturated with 1 molar brine solutions that show a systematic increase in μ of 0.05 relative to strength in distilled water. An additional increase in μ of 0.05 was observed for large-radius dissolved cations (i.e., K+, Cs+) relative to small-radius cations (Li+, Na+, Ca+2). In related studies, fault zone core samples retrieved from the Taiwan Chelungpu Drilling Program (TCDP) Borehole A around 1111 m depth also exhibit sensitivity to pore fluid composition. Permeability of a clay-rich siltstone sample was 60 times lower when tested with a 1 molar KCl brine solution than when tested with argon gas. The same sample tested with distilled water had 3 times lower permeability than when tested with the brine solution. Sample strength and elastic modulus were also found to be lower when tested with distilled water than with brine. These findings demonstrate the importance of conducting physical property measurements on clays and shales using appropriate pore fluids.

Dynamic mechanochemistry of seismic slip -nano spherules lubrication

Hidemi Tanaka[1], Wei-Min Chen[2], Yi-Ming Chen[3], Yen-Fang Song[3], Kuo-Fong Ma[2]
1Dept. of Earth and Planet Sci., Univ. Tokyo; 2 NCU, Taiwan; 3 NSRRC, Taiwan

Abstract

The Chelungpu fault, which was activated during 1999 Chi-Chi Earthquake, had been drilled to penetrate and recover the earthquake slip zone materials at deeper level (1100 m depth) in the crust, from year 2004 to 2005. Three holes are drilled (Hole A, B and C) and recovered the drilled core materials. Identification of slip layers of Chi-Chi Earthquake, thermal property measurements across the slip zones, estimates of frictional heat energy during earthquake, and quantifications of true fracture energy have been conducted using Hole A and C core (Tanaka et al 2006, GRL, Ma, Tanaka et al., 2006, Nature, Tanaka et al 2007, GRL). We present here the results of nano-scale observations for slip zone materials by using HR-TEM and TXM technique and fundamental process of generating nano-grains is discussed. Hole C core contained slip concentration zone, which is 12 cm in thickness, in which four independent layers composed of fine crushed materials were identified. The zone is directly juxtaposed with lower undamaged host mudstone by planner surface. Each of four layers shows about 3 cm in thickness, which contains crushed grains with maximum diameter of 0.1 mm. Further, each layer contains ultra-fine grained layer at the bottom, about 1 cm in thickness, which contains no visible grains. XRD analysis clarified that the materials in this layer are mostly composed of quartz. Grain size distribution is measured under OM, SEM, and HR-TEM, from 100 nm to 100 um in grain diameter. The distribution follows the fractal model (N(D) = 0.0045D2.3; N: numbers of grains, D: grain diameter). Under SEM (SEI) observation, many of fractured grains are enveloped by viscous thin film, which extends from one side of fractured grains. This texture is similar with that observed by Otsuki for his samples after slip deformation experiments. Minimum size of grains observed under HR-TEM is 3 nm. The grain size distribution for grains larger than 100 nm in diameter follows the fractal law and grain shape is highly irregular. Grains smaller than100 nm show some specific characteristics, that is, smaller the grains, more the spherical shapes and more equi-granular. Thus, the grains smaller than 100 nm are no longer described by fractal distribution model. We refer tentatively these grains as nano spherules. By SAD and EDX analysis under HR-TEM, the nano spherules are mainly composed of crystallized quartz associated with minor amounts of carbonates (siderite) and

amorphous materials. The result corresponds well with that of XRD analysis. These observations lead following three conclusions, (1) nano spherules are not generated just by fracturing, based on their shapes and grain size distributions. (2) Considering the results of SEM observations, nano spherules would compose viscous materials enveloping larger fractured grains. (3) Mica clay minerals and feldspars, which are common in host mudstone rocks, are disappeared in ultra-fine grained layer. This implies that chemical process of dissolution -elements dissipation -SiO2 precipitation occurred associated with mechanical fracturing. Therefore nano spherules would be generated through mechano-chemical process during co-seismic slip. Dynamic shear strength drop are recently observed by rapid slip experiments (DiToro et al., 2004, Nature). Some experiments reported that the products contain gelled materials. Large differences of ultra-fine products between previous reports and our observations are existence of nano spherules and their crystallinity. If the nano-spherules are generated during seismic slip, dynamic weakening would be expected because mode of friction turns into rolling friction, which is 10 to 20% of shear friction, by huge amounts of equigranular and spherical grains. This may be alternative explanations for dynamic weakening. Quantitative process of dynamic fracturing -dissolution and precipitation of nano grains will be discussed in our presentation.

Evaluation of the Pore Fluid Pressure at a Depth of 1111 Meters on the Chelungpu Fault During the 1999 Chi-Chi, Taiwan, Earthquake

Jeen-Hwa Wang
Institute of Earth Sciences, Academia Sinica , P.O. Box 1-55, Nangang, Taipei, 115 Taiwan (jhwang@earth.sinica.edu.tw)

Abstract

On September 20, 1999, the Ms7.6 Chi-Chi earthquake ruptured the Chelungpu fault in central Taiwan. Based on a 1-D conduction equation and 2-D faulting model, the heat strength and fluid pressure state on the fault plane at a depth of 1111 m are inferred from the temperature rises measured in a deep hole cutting the fault plane and the thermal constants measured from the core samples. Results show the heat strength is 2.93 oC-m and the pore-fluid factor is 0.86. The latter leads to a pore fluid pressure of 20.6 MPa. This indicates the existence of a suprahydrostatic state at this depth on the fault plane during the earthquake.

Subsurface Structure and Stress State in Scientific Drill Holes of Taiwan Chelungpu Fault Drilling Project (TCDP)

Jih-Hao Hung[1], Kuo-Fong Ma[1], Chien-Yin Wang[1], Weiren Lin[2], En-Chao Yeh[3]
1 Institute of Geophysics, National Central University, Jhongli, Taiwan; 2 Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, Japan; 3 Department of Geological Sciences, National Taiwan University, Taipei, Taiwan

Abstract

Subsurface structure in the TCDP drill site have been characterized through combined studies of cores and borehole images in two holes. The average dip of bedding above depth 1712 m, identified from both cores and FMI (or FMS) logs, is about 30 degrees towards SE with local increasing or decreasing bedding dips across fault zones. A drastic change of regional dip occurs across the Sanyi main thrust (FZ1712) from rather uniform to steep dip. A prominent increase of structural dip to 60^{o}-80^{o} below 1856 m could be associated with propagation of the Sanyi fault. The appearance of steep to overturned beds and thrust faults underlying the Sanyi thrust is contrary to the observation of normal faults in the structural position 15 km to the north of the drill site.

In-situ stresses at the drill site were inferred from, 1) leak-off tests, 2) borehole breakouts and drilling-induced tensile fractures from borehole FMS/FMI logs and 3) shear seismic wave anisotropy from DSI logs. The dominant fast shear wave polarization direction is in good agreement with regional maximum horizontal stress axis, particularly within the strongly anisotropic Kueichulin Formation. A drastic change in orientation of fast shear polarization across the Sanyi thrust fault at the depth of 1712 m reflects the change of stratigraphy, physical properties and structural geometry.

Introduction

In order to understand physical mechanisms involved in large displacements during the 1999 Chi-Chi earthquake, both cores and a suite of geophysical measurements were collected in both TCDP drill holes. An important question needs to be addressed is what physical properties or dynamic processes within the fault zone cause large coseismic displacements in the northern segment. Hypotheses have been proposed include: 1) change of the fault-plane geometry; 2) static (long-term) physical properties such as intrinsic low coefficient of friction, high pore-pressure and solution-transport chemical processes, and 3) dynamic change of physical properties during slip. To answer above questions two holes (hole-A and B) for TCDP were drilled during 2004-2005 at Dakeng, west-central Taiwan, where large surface slip was observed. Continuously coring and geophysical down-hole logging in two holes 40 meters apart were completed from a depth of 500 to 2003 m (hole-A) and 950 to 1350 m (Hole-B), respectively. In this paper we integrate results from cores and wire-line down-hole geophysical logs, including high-resolution micro-resistivity images (FMI and FMS, both marks of Schlumberger) of the borehole wall and shear-wave velocity anisotropy, to characterize subsurface structure and in-situ stress post-Chi-Chi earthquake around the drill site.

Subsurface Structure

Formations encountered in hole-A are mainly composed of clastic sedimentary rocks from Upper Miocene Kueichulin Formation to Pliocene Cholan Formation. Precise locations of formation boundaries were made by, 1) correlating wireline logs among hole-A and other nearby petroleum wells, and 2) comparing stratigraphic sequence between surface outcrops and cores.

. The geological displacement of the Sanyi fault in the profile across the drill is greater than 9 km (from eroded base of hanging-wall cutoff point “a” to footwall cutoff point “b” in Fig. 1). The coseismic displacement vectors obtained from GPS measurements are approximately parallel to the fault at depth except in the footwall of the rupture fault. The total displacement on the Chelungpu fault is estimated about 0.3 km determined from coseismic uplifted Hsinhse terraces immediately north of the drill site. Regional bed attitude above FZ1712, identified from both cores and FMI/FMS images in hole-A and correlation of fault zones between hole-A and hole-B, is striking N15^o-21^{o}E, dipping 20^o-40^o (30^o on average) toward SE. Nonetheless, intervals of increasing (from 30^o to 75^o) or decreasing (from 70^o to 20^o) dip as well as changes of dip azimuth appear across fault zones. A gradual increase of bedding dip with depth starts from FZ1712, and a drastic change of dip from 20^o-40^o to 60^o-80^o occurs across FZ1855 where steep to overturned beds extend to the bottom hole.

In-situ stress state

Hydraulic fracturing

To determine in-situ magnitudes of both maximum (S_{Hmax}) and minimum (S_{hmin}) horizontal stresses, a standard commercial procedure of open-hole, extended leak-off tests were conducted in hole-B at depths of 940 and 1350 m. Dual straddle packers connected by tubing pipes were used to isolate an interval of the wellbore, and fluid was pumped into the open-hole section between the upper and lower packers.

Successful leak-off tests have been done at 4 locations of hole-B: 1279.6, 1179.0, 1085.0 and 1019.5 m, with two above and two below the Chi-Chi rupture fault. At locations of 1019.5 m and 1085.0 m, clearly breakdown pressures, 6.5 MPa and 19.5 MPa, respective, are observed in the first cycle, and consistent P_s and P_r are recorded in subsequent repeated reopening test cycles. Calculated breakdown pressures at 1179.0 m and 1019.5 m are relatively low (16.8 and 16.3 MPa), and leakage occurs in the subsequent cycles at 1179.0 m. Estimated S_{Hmax} and S_{hmin} range between 32-35 MPa and 17-20 MPa, respectively, and do not vary much with depth except at 1085 m (Fig. 2).

Wellbore failure

Failure around the wall of a well could occur due to unequal horizontal stresses reaching the rock strength. There are two kinds of failure around the borehole wall: compressive shear failure (borehole breakouts) in the area of maximum compressive circumferential stress (at the azimuth of S_{hmin}) and tensile failure (DTF) in the area of the minimum compressive stress (at the azimuth of S_{Hmax}). Determining the orientation of these fracturing zones can be used to infer in-situ stress orientation. Orientations of the S_{Hmax} determined from breakouts and DTFs in the section of 700-1700 m compiled from hole-A and hole-B are shown in Fig. 3.

Shear seismic wave anisotropy

Shear waves propagating through microcracks or planar fabrics can develop polarized orthogonal components of fast wave in the stiff direction and slow wave in the compliant direction that separate in time. Data from Dipole-Shear Sonic Imaging (DSI) logs acquired over an interval of 508-1870 m in hole-A was used to assess shear wave velocity anisotropy. Except in a few depth zones, such as 500-650 m, 738-770 m, 785-815 m, 1517-1547 m, and 1650-1870 m, a prominent NW-SE fast shear polarizing direction was generally observed. Particularly, a very consistent mean direction with small dispersion of $115^o \pm 1^o \sim 2^o$ appears in the strongly anisotropic Kueichulin Formation at 1300-1650 m. Relatively consistent fast shear polarization directions appear across FZ1111 (average 165^o between 1105 and 1115 m) compared to the interval of 1078-1190 m with trending in a much broad range of 130^o-170^o (Fig. 4). Thus, to the first order, there is no observable systematic change of trend on fast shear fast shear polarization across the Chi-Chi slip zone. Besides the predominant fast shear azimuth of 115^o, other sub-directions occurred in $153^o \pm 5^o$ (500-650 m and 1078-1190 m) and $90^o \pm 5^o$ (500-650 m and 1190-1295 m), $75^o \pm 4^o$ (1650-1870 m) are also observed. The two subsets of orientation 153^o and 90^o are geometrically formed as conjugates with respect to the main orientation of 115^o. This mean direction of 115^o is in good agreement with direction of regional maximum horizontal principal stress deduced from earthquake focal mechanisms in western central Taiwan.

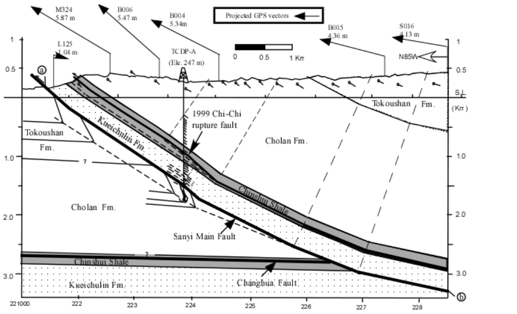

Fig.1 Interpreted structural profile across the Dakeng well (hole-A) based on the surface and subsurface drilled data. Measured depth intervals of formations in this borehole includes: Cholan, 0-1013 m; Chinshui, 1013-1300 m and Kueichulin, 1300-1712 m. Underlying the Sanyi fault is the repeated section of Cholan formation from 1712-2003 m. Locations of Chelungpu (Chi-Chi rupture), Sanyi and interpreted Changhua faults are shown by solid lines. Older faults formed prior to the Chi-Chi earthquake are shown by dashed lines.

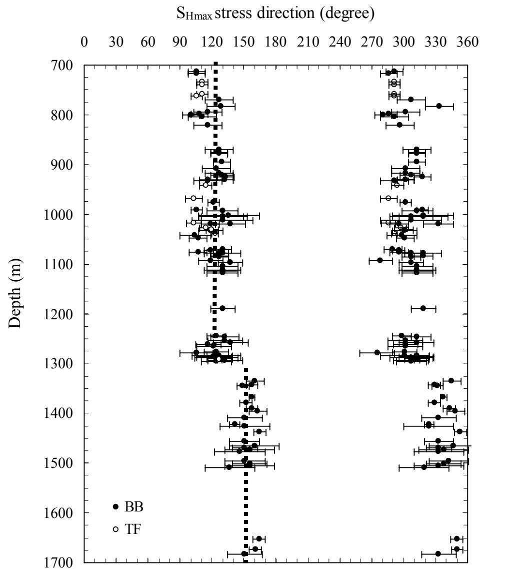

Fig. 3 The plot of azimuth of S_{Hmax} determined from breakouts (BO) and tensile fractures (TF) in the TCDP wells. Width of bar shows an opening angle of BO and TF with dark and open circles, respectively, as mid-point. Dotted lines are average of mid-points.

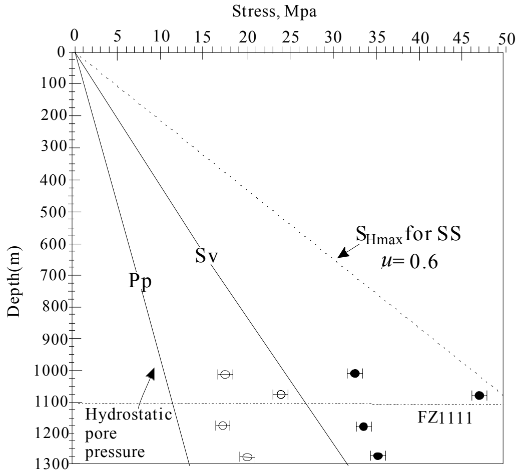

Fig. 2 Plot of overburden stress (S_v) from integration of density logs, hydrostatic pore pressure, and S_{Hmax} (filled symbol) and S_{hmin} values (open symbol) determined from leak-off tests at different depths. Dotted line shows the location of FZ1111. Heavy dashed line indicates the upper limit of the stress magnitude for a strike-slip fault stress regime with a coefficient of friction μ=0.6.

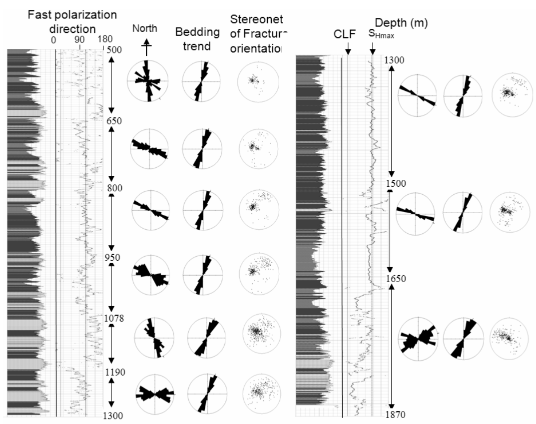

Fig. 4 Comparison of the fast-shear polarization direction with bedding trend determined from borehole images and fracture orientations measured from core images. Azimuths of the Chelungpu fault (CLF, 20^{o}) and maximum horizontal principal stress (S_{Hmax}, 115^{o}) determined from earthquake focal mechanisms in central western Foothills of Taiwan are shown for references.

Log Data and Borehole Image Analysis of Hole-B, Taiwan Chelungpu-fault Drilling Project

En-Chao Yeh[1, 2], Philippe Gaillot[3], Kyaw Thu Moe[3], Weiren Lin[1], Yun-Hao Wu[4], Hisao Ito[3], Tetsuro Hirono[1], Wonn Soh[1], Masa Kinoshita[5], Chien-Ying Wang[4], Sheng-Rong Song[2], Jih-Hao Hung[4] and Kuo-Fong Ma[4]

1 Kochi Institute of Core Sample Research, Japan Agency for Marine-Earth Science and Technology, Japan; 2 Department of Geosciences, National Taiwan University, Taiwan; 3 Center for Deep Earth Exploration, Japan Agency for Marine-Earth Science and Technology, Japan; 4 Institute of Geophysics, National Central University, Taiwan; 5 Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Japan

Abstract

Log data and digital borehole images collected from Hole-B of the Taiwan Chelungpu-fault Drilling Project are analyzed to establish the relationships between deformation structures and in-situ stress, and to identify the rupture zone of the 7.6Mw 1999 Chi-Chi earthquake. Based on standard scalar logs, three log units and five subunits are recognized and are consistent with lithologic units defined from visual core description. Fracture analysis based on the borehole images shows two pairs of conjugated conductive fractures in the strike of N030° and N110°. Three major fault zones, FZB1133, FZB1191, and FZB1240, are recognized from visual borehole image inspection at wireline logging depth of 1133, 1191, and 1240m, respectively. FZB1133 shows the lowest electrical resistivity and relatively lower sonic velocity within the black fault gouge as well as a clear asymmetric resistivity pattern, and thus it is believed to be the more recently activated rupture zone related to the Chi-Chi earthquake. The azimuth of the maximum horizontal stress (SHmax) inferred from drilling-induced fractures is regionally oriented in N130°, an orientation which is consistent with the direction of plate convergence. Local variations of SHmax correlate well with lithology changes. However, in a 20m depth interval around FZB1133, SHmax has an azimuth of N210° resulting from the stress perturbations of the Chi-Chi earthquake. The integration of in-situ stress, log data and deformation structures suggests that all fractures are conductive but might not have being activated by the Chi-Chi event.

Comparison of Textures in the two TCDP Gouges Zones FZA1111 and FZB1136

Anne-Marie Boullier[1], Sheng-Rong Song[2], Li-Wei Kuo[2], En-Chao Yeh[2]

1 Université Joseph Fourier & CNRS, Grenoble, France; 2 Geosciences Dept., National Taiwan University

Abstract

In TCDP boreholes A and B, the fault zones localized respectively at 1111m (FZA1111) and 1136m (FZB1136) depth are considered to correspond to the Chi-Chi earthquake slip plane. Textures related to deformation and fluid circulation have been studied on FZA1111 using a petrographical microscope and then compared to textures in FZB1136 using a SEM.

More than ten layers may be recognized in the 10 cm thick and dark FZA1111 gouge zone and show increasing deformation from bottom to top. The 2 cm thick bottom layer has been interpreted as the slip zone of the 1999 Chi-Chi earthquake because its depth is consistent with the outcrops of the Chelungpu fault and Chi-Chi surface rupture and it presents no recent deformation as opposed to the neighbouring gouge zones which exhibit numerous cracks and deformed calcite veins (Ma et al. 2006). This layer is mostly isotropic and contains rounded fragments of minerals or older gouges which are coated by clays suggesting that thermal pressurization may have been operative. Thin bands of oriented clays in this layer may also result from post-seismic creep. Above this 2cm thick layer, calcite is present either in thin veins indicative of hydraulic fracturing (inflation in all the directions) or as impregnation of sandy parts. All these elements are deformed by a schistosity which orientation is close to the fault plane and which intensity increases from bottom to top. We have also observed gouge injected within fractures into less deformed sediments above the 10 cm thick FZA1111 gouge zone.

Observations of FZB1136 using SEM allow to recognize similar textures (isotropic zones, clay-coated rounded fragments, fragments in fragments, thin shear zones, oriented clay minerals, deformed calcite veins, hydraulic fracturing, schistosity).

We will present the layered organization of the gouge zones, the textures observed in both of them, and suggest some interpretation in terms of seismic or aseismic deformation mechanisms and fluid circulation within the fault zone.

Analysis of clay mineralogy from the retrieved cores of Taiwan Chelungpu-fault Drilling Project, Hole-A

Li-Wei Kuo[1], Sheng-Rong Song[1], En-Chao Yeh[1], Huei-Fen Chen[2]

1 Department of Geosciences, National Taiwan University; 2 Institute of Applied Geosciences, National Taiwan Ocean University

Abstract

In order to understand the faulting mechanism for a particular fault, we can investigate physical and chemical properties of the fault zone by examining real materials of the fault zone. It is established way to evaluate the chemical reactions between fluid and rocks and the amount of heat occur in the fault zone via discussing the change of mineral assemblages within fault-related rocks. Clay minerals are well known as abundant contents in sedimentary rocks, and clayey transformation is also carefully and clearly examined in many previous studies to discuss the factors such as time, heat and ion exchange in clay interaction. Thus, analysis of clay mineralogy provides insights to obtain more precise information about the faulting mechanism and/or temperature, which is the most important parameter for calculating frictional energy.

Taiwan Chelungpu-fault Drilling Project (TCDP) was performed for many scientific purposes; one of them is to realize the faulting mechanism through analyzing the mineral assemblages within the fault zone. It is essential to know the origin of clay mineral assemblages existed in different formations as background data before comparing those of fault-related rocks with background level. In this study, we offer clay mineral relative contents within the Cholan Formation (500m-1027m), the Chinshui Shale (1027-1268m), the Kueichulin Formation (1268-1712m), and the Cholan Formation (1712-2003m), respectively in TCDP Hole-A. Besides, we analyzed fault zone samples with carefully sequential sampling and compared their clay minerals with those of host rocks.

Above the depth of 1300m, clay minerals within small faults do not show significant changes instead of within the fault zones located at the depth of 1111m and 1153m, which are considered as candidates of the slip zone of Chi-Chi earthquake. Below 1300m depth, relative clay mineral contents only change slightly between

fault-related rocks and host rocks, suggesting that clay minerals may not play a major role of controlling the faulting mechanism of the Sanyi fault system.

Anisotropy of acoustic, magnetic and electrical properties in TCDP core samples

Christian David[1], Fabien Humbert[1], Laurent Louis[1], Philippe Robion[1], Teng-fong Wong[2], and Sheng-Rong Song[3]

1 Université de Cergy-Pontoise, France; 2 State University of New York at Stony Brook, USA; 3 National Taiwan University, Taiwan

Abstract

The anisotropy of several physical properties like magnetic susceptibility (AMS), P-wave velocity (APV) and electrical conductivity was investigated in laboratory experiments on core samples retrieved from the TCDP holes A and B at depths ranging from 600 to 1400 meters. Two different facies were studied : sandstones and siltstones. Our data show that the AMS was similar for all the samples regardless of facies, with a magnetic fabric characteristic of weakly deformed sedimentary rocks that had undergone layer parallel shortening. This robust observation applies to both the siltstones and sandstones over the broad range of depths that was sampled. In contrast the P-wave velocity anisotropy in the TCDP samples reflect fundamental differences between the elastic fabrics of the two facies. Indeed APV of the sandstones seems to be controlled by microcrack porosity, with a preferred orientation correlated with the maximum principal direction of paleostress and tectonic deformation. This observation is confirmed by microstructure analyses on thin-sections, and by the anisotropy of electrical conductivity in the sandstone samples. Our study underscores the relatively strong anisotropy of several physical properties consistently for hole-A and hole-B samples, in relation with bedding foliation and tectonic loading. In addition our set of data on anisotropy provides a petrofabric framework for the characterization of hydromechanical anisotropy in the Chelungpu fault system.

Ongoing laboratory research is focusing on probing changes in physical properties as a function of the distance to the fault zones. Indeed the set of samples collected in hole B is representative of both wall rock and damage zones. Preliminary results tend to show that as far as AMS measurements are concerned magnetic fabrics remain similar in wall rock and damage zones, suggesting no further internal deformation in the damage zone (as opposed to deformation localized along fractures).

Further investigations are in progress like the study of P-wave of velocity anisotropy and anisotropy/density relationships in order to get more insight into a potential discrimination between wall rock and damage zone samples from the physical properties viewpoint.

References

Louis, L., Chen, T.M, David, C., Robion, P., Wong, T.-f., & Song, S.R., 2007: Anisotropy of magnetic susceptibility and P-wave velocity in core samples from the Taiwan Chelungpu-fault Drilling Project (TCDP), submitted to *Journal of Structural Geology*.

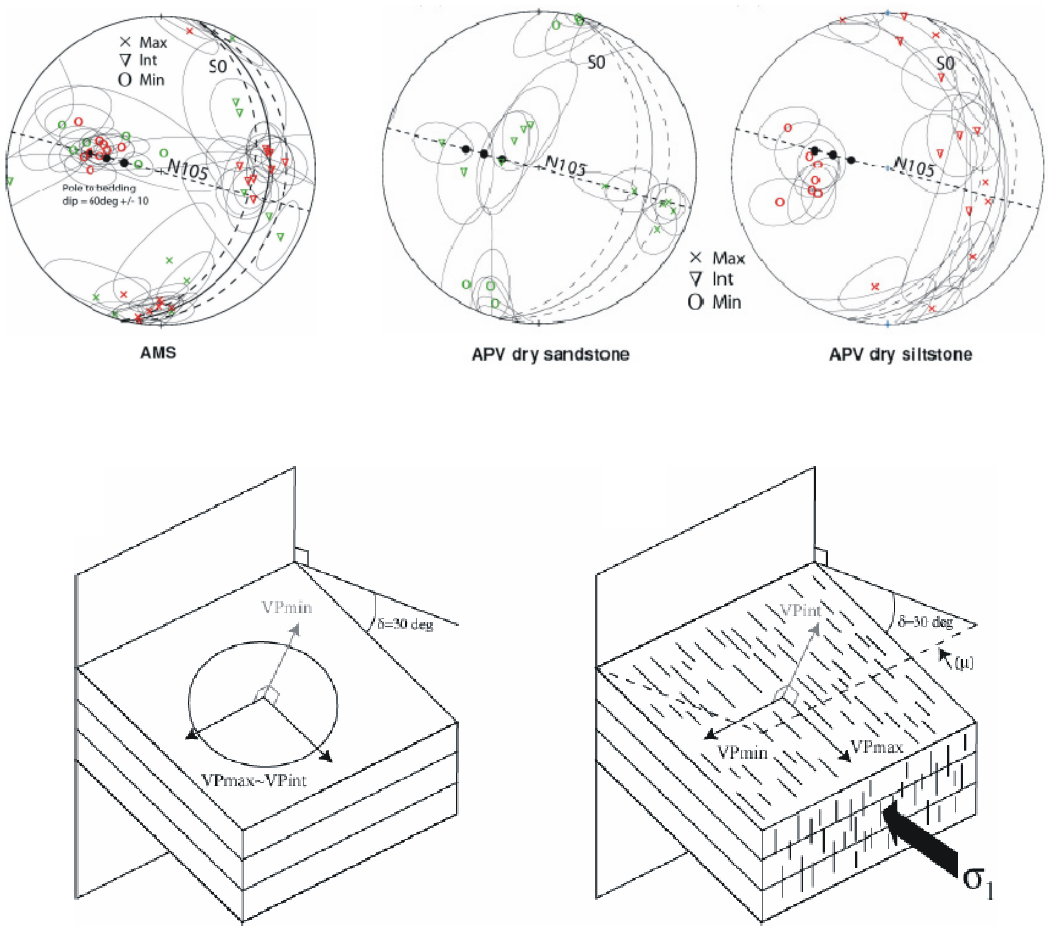

Figure 1: Top: equal area lower hemisphere projection of the principal axes for magnetic susceptibility and P-wave velocity for the hole A samples. Notice the difference in the elastic fabric (APV) between the siltstone and the sandstone samples. Bottom: the rotation of the principal axes for P-wave velocity in the sandstone samples is interpreted as resulting from the presence of microcracks which normal is parallel to the bedding strike.

Microcrack Fabric and Seismic Anisotropy of TCDP Sandstone Samples

Tzu-Mo Natalie Chen[1], Laurent Louis[2], Teng-fong Wong[1], Sheng-Rong Song[3]

1 Department of Geosciences, Stony Brook University, Stony Brook, NY 11794-2100, USA; 2 Département des Sciences de la Terre et de l'Environnement, Université de Cergy-Pontoise, CNRS UMR 7072, Bâtiment Neuville 3.1, Neuville-sur-Oise, F-95031 Cergy-Pontoise, France; 3 Department of Geosciences, National Taiwan University, P.O. Box 13-318, Taipei 106, Taiwan

Abstract

A recent study on cm-sized samples retrieved from TCDP Hole A showed that significant anisotropy of magnetic susceptibility and P-wave velocity likely related to regional tectonics could be observed in both sandstone and siltstone. In the sandstone samples, strong P-wave anisotropy was suggested to originate from the presence of a set of parallel cracks with a normal vector oriented along the bedding strike. Comparison between velocity measurements performed in dry and water saturated samples showed a maximum decrease in elastic compliance parallel to the bedding strike after saturation, and preliminary microscopic observation in a single-thin section indicates a very strong preferred orientation of intragranular cracks along the maximum velocity eigenvector, which may account for the observed seismic anisotropy. A thorough study of cracks length and orientation in 3D was performed to farther explore this microstructural interpretation. Sandstone samples collected from Hole A at depths 851 m, 1365 m and 1394 m were used for preparing 3 thin sections along mutually orthogonal planes at each location. On each thin section, intragranular cracks were characterized in length and orientation. Overall, more than ninety thousand observable microcracks data were collected and the resulting crack tensor was found to agree very well with the orientation of the principal velocity axes at these depths. We are in the process of analyzing the effects of crack density on velocity anisotropy and the relation between the microcrack failure and tectonic stresses.

Non-destructive Measurement Results of Water Content Distribution of Drilled Cores and Relative Physical Properties by Wireline Logging in Hole B, TCDP

Weiren Lin[1], En-Chao Yeh[2], Osamu Matsubayashi[3], Tetsuro Hirono[1,4], Wonn Soh[1], Masataka Kinoshita[1], Hisao Ito[1], Wataru Tanikawa[1], Kan Aoike[1], Hiroki Sone[5], Masafumi Murayama[6], Yoshitaka Hashimoto[6], Sheng-Rong Song[2], Chien-Ying Wang[7], Kuo-Feng Ma[7] and Jih-Hao Hung[7]

1 Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, Nankoku, Japan; 2 Department of Geosciences, National Taiwan University, Taipei, Taiwan; 3 National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan; 4 Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Japan; 5 Department of Geophysics, School of Earth Sciences, Stanford University, Stanford, California, USA 10 Institute for Geo-Resources and Environment, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan; 6 Center for Advanced Marine Core Research, Kochi University, Nankoku, Japan; 7 Dept. of Earth Sciences, National Central University, Chung-Li, Taiwan

Abstract

In the second drilling hole, Hole-B, of Taiwan Chelungpu-fault Drilling Project (TCDP), core samples were continuously retrieved in depth range of 950-1350 m including the Chelungpu fault slipped during 1999 Chi-Chi, Taiwan, earthquake. We did various non-destructive measurements including volumetric water content, density, thermal conductivities etc. on all the core samples of total length 400m. Especially, the water contents profiles in the three fault zones encountered at 1136m, 1194m and 1243m respectively, in the Hole-B, were successfully determined in a 10 cm interval which is enough thick to make comparing the profiles in the three fault zones. At the same time, we will report P-wave velocity, electrical resistivity obtained by wireline downhole logging.

As a result, the profile of volumetric water content revealed a peak in the center of all three fault zones, respectively. Importantly, the water content value in the 1136m fault zone was highest in the three fault zones. A possible explanation of the

measured results can be considered as that 1136 m fault zone is youngest due to the compaction effect depends on the elapsed time from seismic slipping.

S-C cataclastic rocks and their seismotectonic implications

Aiming Lin

Graduate School of Science and Technology, Shizuoka University, Shizuoka 422-8529, Japan

Abstract

Most large intraplate earthquakes are the result of slip on mature active faults, thus, investigations of the seismic faulting process require information about the nature of seismogenic fault zones. Fault rocks that occur within fault zones commonly provide primary evidence for the faulting history and deformation process of seismic slipping along all depths of seismogenic fault zone in the shallow depth near the surface to deep level of crust. They formed at deeper levels by ancient faulting even in the lower crust and have been uplifted by crustal movement and exhumed by erosion, and if fault movement continued throughout that process there will be exposed in the fault zone, a variety of fault rocks formed under different conditions from brittle regime in shallow depth near the Earth' surface to plastic flow regime in deep level of the crust within fault shear zones. It is, therefore, possible to gain an insight into the formation process operating throughout the faulting history by studying the structures, textures, physical properties, and chemical compositions of fault-related rocks exposed at the surface or from drill cores of deep fault zones.

It is well known that mature active fault zones generally comprise incohesive fault gouge and fault breccia formed at shallow depths of <4-5 km, and cataclastic rocks including S-C cataclasite that are well developed within seismogenic zones at 5-12 km, assuming an average geothermal gradient of 25°C/km for continental crust. Studies on the structural modes and physical properties of S-C cataclasite reveal that seismogenic fault zone strength and rheology property of the upper 5–12 km of crust is greatly influenced and controlled by the formation of S–C cataclasites. The universal presence of S-C cataclastic rocks with a lower friction coefficient in the nucleus depths of large earthquakes within seismiogenic fault zones may explain well why mature active faults where large earthquakes occurred repeatedly are weak.

In this study, we will introduce the structural modes and physical properties of S-C cataclastic rocks developed in well known active faults along which large earthquakes occurred recently such as the Rokko-Awaji Fault Zone, Japan that

triggered the 1995 Kobe M_w 7.2 earthquake and the Chelungpu Fault Zone, Taiwan that triggered the 1999 Chi-Chi M_w 7.6 earthquake and discuss their formation mechanisms and seismotectonic implications.

Microbial community structures associated with deep sedimentary rocks from an active tectonic region

Li-Hung Lin[1] and Pei-Ling Wang[2]

1 Department of Geosciences, National Taiwan University; 2 Institute of Oceanography, National Taiwan University

Abstract

The Taiwan Chelungpu Drilling Project (TCDP) has provided an unprecedented opportunity to probe terrestrial subsurface microbial ecosystem that may have experienced constant disturbance by the arc-continent collision since 5 Ma. The drilling penetrated through the Pleistocene-Pliocene sedimentary rocks to a depth of 2000m below land surface (mbls). Two major fracture zones with ~100 m thickness were encountered at depths of ~1100 and ~1750 mbls, respectively.

Among 40 samples retrieved from rock formations or within fracture zones, thirty were ground to powders, inoculated to media designed for fermenter, iron reducer, sulfate reducer and methanogen, and incubated at temperatures ranging from 30 to 70°C. Mesophilic and thermophilic fermenters and organotrophic sulfate reducers are ubiquitously present in most samples, whereas iron reducers and methanogens appear only in the samples retrieved from the upper (400-700 mbls) and lower depths (1800-1900 mbls).

Analyses of 16S rRNA genes for samples along the depth profile reveal that microbial communities were dominated by *Proteobacteria* at depths shallower than 1300m and by *Firmicutes* at great depths (>1900m). The diversity of community decreases as the depth increases. At great depths (1906m and 1979m), the communities of the consolidated siltstone were almost identical and primarily composed of sequences affiliated with a deep-branching environmental clone within *Clostridia* (92% similarity) by more than 50% of the clone libraries. The community of the fracture zone at 1810m, however, exhibited much greater diversity and primarily consists of *Proteobacteria*. Of the phylotypes identified from 1810m, one is similar with an iron reducing bacterium isolated from 545m and the other is similar with one known thermophilic heterotroph, suggesting that fluid carrying various nutrients may channel either upward or downward along the fracture zone and support diverse community structure. The pore throat of the consolidated siltstone is generally

less than 0.5 μm, inhibiting the migration of microbes across geological strata. The consistent dominance of *Firmicutes* clones suggests that microbes residing within the pore space at 1906m and 1979m are imposed by similar environmental stress.

Chemical and isotopic characteristics of Fluids from the Holes of Taiwan Chelungpu-fault Drilling Project (TCDP)

Sheng-Yuan Chen[1], Sheng-Rong Song[1], and Chung-Ho Wang[2]

1 Department of Geoscience, National Taiwan University; 2 Institute of Earth Science, Academia Sinica

Abstract

This study analyzed chemical composition and isotopic ratio of fluids from the Hole-A and Hole-B of Taiwan Chelungpu-fault Drilling Project (TCDP) to trace the source and find the possible causes of chemical variations along the depth. We collected 43 samples in Hole-A, 14 in Hole-B in 2006, each sample was separated into 4 sub-samples by adding 0、0.1、0.5、1.0 ml HNO_3 to evaluate the difference of chemical composition. For chemical composition, we measured cations such as Na^+、K^+、Ca^{2+}、Mg^{2+}、Al^{3+}、Fe^{3+}、Mn^{2+}、Si^{4+}; and anions such as F^-、Cl^-、Br^-、NO_3^-、PO_4^{3-}、SO_4^{2-}、HCO_3^-. We also used filtered fluids without adding HNO_3 for isotope analysis.

The results show that an abnormal change occurred between the depth of 600-700 m on the concentrations of Na^+、K^+、$Ca^{2+}$and Mg^{2+}. Besides, all ions show a slightly increase concentration at the depth of 1110 m. According to those variations with depth, we divided the fluids of Hole-A into four sections, named A, B, C, and D, respectively in the range of 0- 650 m, 650- 1080 m, 1080- 1140m, and 1140- 1290 m. The Na^+、K^+ and Ca^{2+} concentrations of fluid above or below 650 m depth (that is, section A and section B) is distinctly different so that the different sources of water could be suggested. The concentrations show slightly increasing on section C, including the main fault zone, where the casing was perforated, infer that fluid can actually flow into the well pipe via the punched holes to cause the chemical anomaly. Compositions between section B and D are different, especially on the Mg^{2+} ion. We, thus, separate them into two sections for further discussions and study. Based on casing and our data, the chemical difference between sections might caused by leakage from the location of casing shoes; where depth of 661 m and 1301 m could be the source of fluids. It is highly possible that the water leaked from 661 m depth to cause the obvious anomaly of 600- 700 m. Also, the high ionic concentration within

the section D could be respond to the leakage from below 1301 m in depth. Comparing to the compositions of Hole-A and Hole-B, it is clear that the fluid source of hole-A and hole-B core is different.

The preliminary results of thermal effects on clay mineralogy and comparing with fault-related rocks of TCDP

Lin Huang[1], Sheng-Rong Song[1], Huei-Fen Chen[2], Li-Wei Kuo[1], En-Chao Yeh[1]

1 Department of Geosciences, National Taiwan University; 2 Institute of Applied Geosciences, National Taiwan Ocean University

Abstract

To understand the frictional temperature and heat of earthquake, the mineralogical change of fault zone materials is the best candidate for it. The displacement of Chelungpu fault took place in the Chinshui Shale, which contains higher clay contents than neighbor formations. It, thus, might be suitable to discuss aforementioned questions via checking the reaction of clay minerals after heating. In this study we use materials from TCDP (1000m-1300m) which was identified as the Chinshui Shale and heat them with different temperatures in order to simulate the real product after high frictional heat by faulting. The aim is to realize the most important parameter of earthquake energies, temperature, via discussing the reaction of clay minerals after heating and comparing with fault zone materials from TCDP.

In this study we collected several samples between 1000m to 1300m to figure out the clay mineralogy of Chinshui Shale and heat host rocks with different temperatures: 600℃, 700℃, 800℃, 900℃, 1000℃, and 1100℃, respectively. The heating time was 5 minutes in high temperature furnace. We analyzed heated samples using X-ray Powder Diffraction (XRD) and Scanning Electron Microscopy (SEM) to realize mineral variations and phase changes. Meanwhile, we also heated pure illite by thermal gravimetric analyzer (TGA) with heating rate 200℃/minute. Based on the TGA data the melting temperature of pure illite was up to 900℃. Under SEM observations indicated that grains of minerals didn't change during the heating temperature from 600℃ to 900℃. When heating temperature was higher than 900℃, some melting phenomena have been detected from images of SEM, and many vesicles occurred by melting were observed over 1000℃. The results of XRD showed that clay minerals were thermal decomposed over 900℃ and started melting. Comparing with TGA we found melting point of TCDP core was a little lower than pure illite.

These preliminary results from heated materials of TCDP may provide us information for calculating the friction heat of the 1999 Chi-Chi Taiwan earthquake.

Preliminary Result of Clay Minerals Analysis of Chi-Chi Earthquake Fault Gouge, Wu-Feng, Central Taiwan

Yu-Min Chou[1], Tsung-Ming Tsao[2], Ming-Kuang Wang[2] and Sheng-Rong Song[1]

1 Department of Geology, National Taiwan University, Taipei, Taiwan; 2 Department of Agricultural Chemistry, National Taiwan University, Taipei, Taiwan

Abstract

We analyzed the clay mineral component of Chi-Chi earthquake fault gouge from Wu-Feng, Central Taiwan, with a goal of assaying the distribution of clay minerals in different particle size and investigating the faulting effect on fault gouges. The preliminary result exhibits that the major clay minerals are illte, smectite and mix-layer illte-smectite . The wall rock of the gouge is the Chinshui Shale which is predominantly composed of illite, kaolinite and chlorite in clay compositions but no smectite. There is no chlorite and kaolinite in fault gouge, indicates the temperature was higher than 800°C when the fault acting. The montmorillonite and mix-layer illte-montmorillonite, thus, were produced by weathering after fault gouge formation. In future work, we'll separate the clays in different particle size to determine their mineral species.

True Triaxial Strength and Deformability of the Siltstone Overlying the Chelungpu-fault (Chi-Chi earthquake); Taiwan

Haruyuki Oku[1], Bezalel Haimson[1], and Sheng-Rong Song[2]

1 Department of Materials Science & Engineering and Geological Engineering Program, University of Wisconsin, Madison, United States; 2 Department of Geoscience, National Taiwan University, Taiwan

Abstract

We have conducted true triaxial compression tests (in which σ_1 is monotonically raised to failure while holding σ_2 and σ_3 constant) to determine strength, deformability, and other mechanical properties of the fine-grained (70 μm), quartz- (70%) and clay-rich (20%), Pleistocene siltstone just above the Chelungpu fault, intercepted by the TCDP (Taiwan Chelungpu-fault Drilling Project) borehole at 1111 m depth. The fault zone is considered the host of the 1999 Chi-Chi earthquake. Specimens (19×19×38 mm^3 rectangular prisms) were instrumented with strain gages and a strain-gaged beam for recording strains in all three directions.. Five groups of tests were conducted, each for a constant σ_3 (10, 25, 40, 60, 100 MPa). Within each group σ_2 was varied from test to test between $\sigma_2 = \sigma_3$ and σ_2 approaching $\sigma_{1(at\ failure)}$. Contrary to the Mohr criterion assumption, for each σ_3 a consistent pattern was observed of gradually increasing strength with the rise of σ_2 until a peak was reached followed by a gradual decline, with $\sigma_{1(at\ failure)}$ always higher than the conventional-triaxial strength (at $\sigma_2 = \sigma_3$). Strength variation with σ_2 for a given σ_3 is best fitted by a second order polynomial. For example, for $\sigma_3 = 60$ MPa, the true triaxial strength is $\sigma_{1(at\ failure)}$ (MPa) = $237 + 1.65\sigma_2 - 0.004\sigma_2^2$ (r = 0.900). The maximum strength of 400 MPa is achieved at $\sigma_2 = 206$ MPa, which is 25% higher than the 320 MPa at $\sigma_2 = \sigma_3 = 60$ MPa. Integrating all the true triaxial strength data into a Mogi-modified Nadai strength criterion yields a monotonically increasing power function $\tau_{oct} = 2.32[(\sigma_2 + \sigma_3)/2]^{0.75}$ (r = 0.995), where τ_{oct} is the octahedral shear stress at failure. The modulus of elasticity, and the onset of dilatancy, exhibited a similar behavior to that of $\sigma_{1(at\ failure)}$ when subjected to a constant σ_3 (gradual increase followed by a decrease with rising σ_2). Upon failure the siltstone developed a shear through-going fracture dipping

steeply in the σ_3 direction. Moreover, the fracture dip angle steadily increased with rising σ_2 for unchanged σ_3, between 59° and 77°. The trend of the dependence of fracture dip on the deviatoric stress state is generally consistent with the prediction of rock failure based on localization of deformation (Rudnicki and Rice, 1975). SEM inspection of tested specimens revealed only sporadic microcrack localization adjacent to and predating the through-going shear fracture, unlike the pervasive microcrack accumulation within a shear band observed in crystalline rocks tested under similar conditions.

Effective Confining Pressure Dependency for Fluid Flow Properties of Young Sedimentary Rocks from TCDP

Jui-Yu Hsu[1], Jia-Jyun Dong[1], En-Chao Yeh[2], Yi-Nan Lyn[1]

1 Institute of Applied Geology, National Central University, Taiwan; 2 Department of Geosciences, National Taiwan University, Taiwan

Abstract

Accurate measurement of the stress-dependent fluid flow properties is essential to explore the process of fluid percolation in crust. This study utilized an integrated permeability/porosity measurement system to determine the confining pressure-dependent permeability/porosity of sedimentary rock cores from a 2 km borehole in Taiwan. The measured permeabilities of sandstone and siltstone/shale are 10^{-13}~10^{-14}m^2 and 10^{-16}~10^{-19}m^2 under confining pressure of 3~120 MPa. The Klinkenberg effect is considered to evaluate the difference between the gas- and water- derived permeability of core samples. The permeability of siltstone and shale is more sensitive to effective confining pressure than that of sandstone. Meanwhile, different rock types have almost identical pressure-sensitivity of porosity. The measured porosities of sandstone, siltstone and shale under confining pressure of 3~120 MPa are 15%~24%, 8%~11% and 13%~14%, respectively. Based on laboratory work, a power law describing the pressure-dependency of permeability/porosity appears superior to an exponential relation for fresh, young sedimentary rocks (Late Miocene to Pliocene) in the Western Foothills of Taiwan. Consequently, a power law describing the pressure-dependency of porosity is suggested to derive the specific storage of tested rocks. The calibrated porosity sensitivity exponent α ranges form 3.26 to 5.47 (loading) and ranges form 2.34 to 3.08 (unloading) for tested sandstones using a power law for describing the pressure-dependency of permeability/porosity. Specific storages of tested sandstone and siltstone/shale are 0.2~2.0×10^{-3} MPa-1 and 0.07~0.7×10^{-3} MPa^{-1}, respectively, under confining pressure of 3~120 MPa. With the adoption of a power law, a representative relation between specific storage and effective confining pressure was derived for tested rock samples. The suggested pressure-dependent specific storage and the pressure-dependent permeability/porosity were incorporated into one dimensional consolidation simulation to demonstrate the influence of pressure-dependency fluid flow properties on overpressure development.

High velocity frictional tests and an attempt to reproduce fault materials using TCDP Hole-B samples

Wataru Tanikawa[1], Toshiaki Mishima[2] , Toshihiko Shimamoto[3] , Won Soh[1]
1 Japan Agency for Marine-Earth Science and Technology; 2 Kochi University, Japan; 3 Kyoto University, Japan

Abstract

Taiwan Chelungpu-fault Drilling Project (TCDP) was started from 2002 to investigate the faulting mechanism of the 1999 Chi-Chi earthquake. Micro-textual observation, rock magnetic analyses, and mineralogical analysis for carbonate of fault zones in Hole-B implied the evidence of heat generation (Hirono et al.,2006), though the temperature did not reach the melting point. Mishima et al. (2006) carried out thermomagnetic analyses and also investigated frequency dependence of magnetic susceptibility. Their results indicate that high magnetic susceptibility at the center of fault zone can be explained by the decomposition of thermally unstable paramagnetic minerals into magnetite or maghemite at the time of slip event. However it is still uncertain that instantaneous heat generation during slip events can really produce such anomaly. Therefore we tried to reproduce the frictional products from the high velocity frictional tests, and various analyses are conducted to compare between original and frictional samples to investigate transformation of the fault rock due to frictional heating. We used crashed sedimentary rocks at the 3 m distance from the center of the fault zone in 1136m (Hole-B) for our tests. All high-velocity experiments were conducted by dry samples at a slip rate of 1.03 m/s and a normal stress of 0.5 MPa and 1.0 MPa. All tests showed similarity in frictional behaviors, and the friction continues to weaken from a peak frictional coefficient of 0.7 to 1.1 towards a steady state with a frictional coefficient of 0.1 to 0.3. After experiments, frictional samples are used for thermomagnetic, XRD, XRF and grain size analyses to compare the difference between original and frictional samples. In thermomagnetic analyses, original samples were characterized by “humps” above 400˚C which the induced magnetization on the heating branches began to increase at about 400˚C, reached a maximum at about 480˚C, and decreased from 480 to 600˚C. On the other hand “humps” were disappeared for frictional samples. The results suggest that

decomposed magnetized mineral was newly deformed by frictional heating. Frictional samples show slight peak reduction in calcite for XRD analysis, though no difference between original and frictional samples in most peaks. In grain size analyses, grain size is slightly decreased for frictional samples.

Geophysical Invesitigation from Taiwan Chelungpu-fault Drilling Project (TCDP): Stress field and Anisotropy

Hung Yu Wu and Kuo Fong Ma

Institute of Geophysics, National Central University, Taiwan (R.O.C.)

Abstract

TCDP drilled two boreholes penetrating the Chelungpu fault, where the large displacement was observed during the 1999 Chi-Chi, Taiwan, earthquake. A comprehensive geophysical log had been carried out through the hole to understand the geophysical status of the borehole. In borehole breakouts and drilling induced tensile fractures, the local variations in the direction of maximum horizontal stress (S_{HMax}) were observed at the depth of 1111 m, where the direction of N15°E was observed compared to the tectonic stress direction of N112°E. The simulation of reverse faulting stress regime reproduces the rotation phenomena as breakout directions varied with depth. The hydraulic fracturing experiments and density log help us to constrain the values of stress magnitude. Considering the influence of titling formations, Dipole Sonic Imager (DSI) shows that the fast polarization direction of shear wave is consistent with S_{HMAX} determined from borehole breakouts. Comparison on the seismic velocity anisotropy and borehole breakouts, the anomalies, which might be associated with the existence of slip zones, at the similar depth and stress direction were confirmed.

On the base of the geophysical information, the stress field before the Chi-Chi earthquake was estimated. Our results show that the magnitude of the maximum horizontal stress (S_{HMax}) changed from 45 MPa to 12 MPa, which is smaller than the value of S_{hmin} estimated from the logs near the fault. It suggests the exchanges in the maximum and minimum stress directions after the earthquake. Thus, the reverse regime before the earthquake had been changed to strike-slip regime. This result agrees with the most of the strike-slip focal mechanisms of the aftershocks in the northern portion of the fault after the earthquake. For the state-of-the-art TCDP borehole seismometers installed in the borehole after drilling, the anisotropy behavior of the micro-earthquakes will be also examined to observe the possible difference in polarization crossing the fault zones to the comparison of the DSI log.

Log Data and Borehole Image Analysis of Hole-B, Taiwan Chelungpu-fault Drilling Project

En-Chao Yeh[1, 2], Philippe Gaillot[3], Kyaw Thu Moe[3], Weiren Lin[1], Yun-Hao Wu[4], Hisao Ito[3], Tetsuro Hirono[1], Wonn Soh[1], Masa Kinoshita[5], Chien-Ying Wang[4], Sheng-Rong Song[2], Jih-Hao Hung[4] and Kuo-Fong Ma[4]

1 Kochi Institute of Core Sample Research, Japan Agency for Marine-Earth Science and Technology, Japan; 2 Department of Geosciences, National Taiwan University, Taiwan; 3 Center for Deep Earth Exploration, Japan Agency for Marine-Earth Science and Technology, Japan; 4 Institute of Geophysics, National Central University, Taiwan; 5 Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Japan

Abstract

Log data and digital borehole images collected from Hole-B of the Taiwan Chelungpu-fault Drilling Project are analyzed to establish the relationships between deformation structures and in-situ stress, and to identify the rupture zone of the 7.6Mw 1999 Chi-Chi earthquake. Based on standard scalar logs, three log units and five subunits are recognized and are consistent with lithologic units defined from visual core description. Fracture analysis based on the borehole images shows two pairs of conjugated conductive fractures in the strike of N030° and N110°. Three major fault zones, FZB1133, FZB1191, and FZB1240, are recognized from visual borehole image inspection at wireline logging depth of 1133, 1191, and 1240m, respectively. FZB1133 shows the lowest electrical resistivity and relatively lower sonic velocity within the black fault gouge as well as a clear asymmetric resistivity pattern, and thus it is believed to be the more recently activated rupture zone related to the Chi-Chi earthquake. The azimuth of the maximum horizontal stress (SHmax) inferred from drilling-induced fractures is regionally oriented in N130°, an orientation which is consistent with the direction of plate convergence. Local variations of SHmax correlate well with lithology changes. However, in a 20m depth interval around FZB1133, SHmax has an azimuth of N210° resulting from the stress perturbations of the Chi-Chi earthquake. The integration of in-situ stress, log data and deformation structures suggests that all fractures are conductive but might not have being activated by the Chi-Chi event.

Faulting Dynamics on Frictional Heat and Thermal Pressurization of the 1999 Chi-Chi, Taiwan, Earthquake

Hidemi Tanaka[1], Noriko Urata[2], Bunichio Shibazaki[3] and Kuo-Fong Ma[4]

1 University of Tokyo, Japan; 2 JMA, Japan; 3 BRI, Japan; 4 National Central University, Taiwan

Abstract

We calculated the dynamic friction of the 1999 Chi-Chi earthquake from the estimation of the frictional energy from temperature logs and the energy estimated from the calculation of thermal pressurization during faulting. The strength drop during faulting was estimated by thermal pressurization modeling of the slip zone materials recovered from deep borehole. Most of the parameters for thermal pressurization (TP) calculations are obtained directory from recovered core and geophysical logging of Taiwan Chelungpu-fault Drilling Program (TCDP). New approach on TP calculation was proposed by incorporating the inelastic dilatancy and slip zone architecture in the model as we named it Geological Thermal Pressurization (GTP). From GTP, it shows that the temperature rise and the strength drop are strongly related to the value of inelastic dilatancy during faulting. From the neutron log of the shallow hole, the inelastic dilatancy estimated in the slip zone is about 10%. This value will yield the temperature rise of up to 1000 degree under thermal pressurization, and a complete strength drop of to the value of 10.5 MPa, which is equivalent to the value of 11 MPa obtained from seismic waveforms. For the frictional heat from temperature logs, two data sets of temperature loggings both from shallow borehole in 2000 [Tanaka et al., 2002, 2006] and deep borehole in 2005 [Kano et al., 2006] penetrating Chelung-pu fault zone show positive thermal anomaly right on the slip zones. Considering the thermal conductivity directly measured from the retrieved core of the TCDP, we suggest that the temperature anomaly observed in the deeper hole might be resulted from the thermal conductivity fluctuation [Tanaka et al.,2006b]. Thus, only the temperature logs from shallow hole were used to estimate dynamic friction during faulting. The frictional energy from the temperature measurement is about 26 MJ/m2, which is approximately close to the value obtained from the TP of the value of 19 MJ/m2. It suggests that the frictional heat obtained from the temperature residual might be resulted from the temperature rise during TP.

The process of TP also yields the complete stress drop during faulting. The seismic break down work(Wb) estimated by dynamic wave inversion at large slip region (10 m) of northern part of the fault [Ma et al., 2006] has a large value around 40 MJ/m^2. The surface fracture energy (1-4 MJ/m^2) estimated from fault gouge was estimated to be only 2-6% from the seismic breakdown work. The energy of TP contributes about 50% to the breakdown work. The calculation of GTP suggests the necessary of incorporating the inelastic dilatancy and slip zone structure for understanding of dynamic faulting of earthquake rupture.

Fault Dynamics: Surface Fracture Energy and Possible Explosion during faulting

Kuo-Fong Ma[1] and Hidemi Tanaka[2]

1 Institute of Geophysics, National Central University, Taiwan; 2 Department of Earth and Planetary Sciences, University of Tokyo

Abstract

Some of the proposed physical explanations for non-double couple component for shallow earthquakes include source multiplicity, rupture on non-planar fault surfaces and tensile failure under high fluid pressure. The later explanation suggests that the existence of the non-double couple mechanism might be intrinsic to the source process. The Taiwan Chelungpu Fault Drilling Project (TCDP) drilled two vertical and one branch holes across the Chelungpu fault where slips for more than 10 m during the 1999 Chi-Chi (Mw7.6), Taiwan, earthquake. The retrieved cores from TCDP identified a slip zone associated with the Chi-Chi earthquake. The surface fracture energy estimated from the identified slip zone has about 2-6% to the seismic fracture energy. More than 90% of the seismic fracture energy might contribute to heat. The examination on the fault zone observed significant tensile cracks with arbitrary directions in the damage zone A gas monitoring carried out during coring observed a highly content of CH_4 at the depth corresponding to the identified fracture zone. The highly content of CH_4 along with a possible temperature rise of more than 200 degree by frictional heating could contribute to a source for explosion of the fault zone materials during faulting. We further examine the possible non-double components in focal mechanisms from close in strong motion waveforms, and the normal stress changes near the drill site to validate the observation of the explosion during faulting. The seismic data was used to invert the contribution of the possible non-double couple component during faulting. The normal stress changes were calculated from the temporal/spatial slip distribution over the fault. Thus, the evolution of the normal stress changes during faulting could be obtained. We will further compare these results for the region near the drill site to provide whether just the fluid pressure rise during faulting could provide reasonable explanations or explosion is more appropriate.

Particle size and fracture energy of gouge from the Taiwan Chelungpu-fault Drilling Project (TCDP) Hole-A

Ai-Chi Yu[1], Sheng-Ron Song[1], Yen-Fang Song[2], Li-Wei Kuo[1]

[1] Department of Geosciences, National Taiwan University, P.O. Box 13-318, Taipei 106, Taiwan; [2] National Synchrotron Radiation Research Center

Abstract

It is common to observe the grain-size reduction associated with the development of fault gouge within seismogenic faults. Also, the major displacement along mature faults usually occurred within the fault gouge. Thus, understanding the properties of fault gouge provides insights into the mechanism of earthquake rupture. Slip-weakening model can be used to explain the relationship between energy budget and physical processes of earthquake slip. Based on the model, the energy released during an earthquake is partitioned into the fracture energy (E_G), frictional heat (E_H), and radiation energy (E_R). Although radiation energy and fracture energy only occupy the small portion of total energy, their relative magnitude is the main factor to controlling earthquake rupture dynamics, expressed by radiation efficiency $\eta_R = E_R / (E_R + E_G)$. Fracture energy is defined as the energy at rupture tips that is required to form a rupture surface and produce a breakdown in strength. This study will report the fracture energy estimated from the grain-size distribution of fault gouge on the retrieved cores of Taiwan Chelungpu-fault Drilling Project (TCDP), Hole-A.

TCDP retrieved cores from two holes in the Dakeng area since 2004. Continuous cores of Hole-A between 430 and 2003m provide a good opportunity to obtain in-situ fault gouge samples. We collected images from thin sections of fault gouge samples under optical microscope and scanning electron microscope and further analyzed their grain-size distribution with image-process software. Based on the grain-size distribution of samples, we estimated fracture energy from the surface area of grains.

Microstructures of Major Fault Zones within Taiwan Chelungpu Fault System

Tetsuro Hirono[1,2], Masumi Sakaguchi[3], Kenshiro Otsuki[4], Wataru Tanikawa[2], Hiroki Sone[5], Tatsuro Fukuchi[6], Takuo Matsubara[6], Yoshitaka Hashimoto[7], Minoru Ikehara[8], Toshiaki Mishima[8], Masafumi Murayama[8], Miki Takahashi[9], Koji Masuda[9], Osamu Matsubayashi[10], Norihiro Nakamura[4], Kazuo Mizoguchi[11], Koichiro Fujimoto[12], Toshihiro Shimamoto[13], Masataka Kinoshita[14], Hisao Ito[15], Kan Aoike[15], Osamu Tadai[3], Weiren Lin[2], Masaharu Tanimizu[2], Tsuyoshi Ishikawa[2], Hiroyuki Kikuta[2], Wonn Soh[2], and Sheng-Rong Song[16]

1 Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Japan; 2 Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, Nankoku, Japan; 3 Marine Works Japan Ltd., Nankoku, Japan; 4 Department of Geoenvironmental Science, Graduate School of Science, Tohoku University, Sendai, Japan; 5 Department of Geophysics, School of Earth Sciences, Stanford University, Stanford, California, USA; 6 Department of Earth Sciences, Graduate School of Science & Engineering, Yamaguchi University, Yamaguchi, Japan; 7 Department of Natural Environmental Science, Kochi University, Kochi, Japan; 8 Center for Advanced Marine Core Research, Kochi University, Nankoku, Japan; 9 Institute of Geology and Geoinformation, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan; 10 Institute for Geo-Resources and Environment, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan; 11 Earthquake Research Department, National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan; 12 Faculty of Education, Tokyo Gakugei University, Koganei, Japan; 13 Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, Japan; 14 Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan; 15 Center for Deep Earth Exploration, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan; 16 Department of Geosciences, National Taiwan University, Taipei, Taiwan

Abstract

For the determination of the slip weakening mechanism during the 1999 Chi-Chi earthquake, we observed the three major fault zones in the Chelungpu fault system meso- and microscopically. We found two newly shear zones within the shallower fault zone as candidates of slip zones at the earthquake. The shear zone were composed of an abundant fine-grained matrix supporting rounded to subangular lithic fragments, and exhibited fragmentations of mineral particles and particle size reductions, characterized as cataclastic textures. Their particle size distributions were fractal, and the dimensions were both 3.07, which might result from small average particle sizes and high degrees of comminution. The probabilities of fragmented counterparts in the shear zones were nearly zero, indicating that the zones have been in a mechanically fluidized. Because of no evidence of pseudotachylyte and clay injection in and around the shear zones, frictional melting and elasto-hydrodynamic lubrication were not likely to have occurred at the earthquake. Instead, we proposed that comminution and particles fly have occurred simultaneously, corresponding to mechanical fluidization or thermal pressurization.

Characteristics of fault rock properties and structural distribution of the Chelungpu fault in Dakeng area

Yi-Kai Lin[1], En-Chao Yeh[1], Teh-Quei Lee[2] , Chia-Yu Lu[1]

1 Geosciences Department, National Taiwan University; 2 Institute of Earth Sciences, Academia Sinica

Abstract

On Sep 21 of 1999, a destructive earthquake took place in the Chi-Chi Town of central western Taiwan. The surface rupture during the Chi-Chi earthquake is along the N-trending Chelungpu fault at about 100km in length. The northern rupture reaches the largest displacement of ~8.5 m. Interesting on the propagation of northern rupture leads that Taiwan Chelungpu-fault Drilling Project (TCDP) aims to understand the seismic faulting by investigating lithology distribution and analyzing core samples. Due to information limitation from few drilling holes, it is complementary to evaluate the characteristics of fault rock and deformation distribution on the surface outcrop.

In this study, we mapped lithology and deformation structures and analyzed the fault gouge samples along the Dali riverbed closed to the TCDP drilling site in Dakeng area. Most of stratigraphy in the study area is the Chinshui Shale. By using core information from the Dakeng No.1 of the Central Geological Survey and the TCDP Hole-A, we can confirm the fault zone location from the field survey. Based on field mapping, most of strike-slip faults is sinistral fault, which crosscut dextral fault. The crosscutting relationship is distinct at the locations of 20 m, 100 m, and 160 m away from the surface rupture. At the same locations, bedding was bended and the direction of the maximum stress rotated to N030° from the regional direction of N110°.

Microstructural and magnetic analyses of fault rock samples with foliated gouge, which has the similar occurrence of the 1999 Chi-Chi slip zone located at 1111m depth of TCDP Hole-A, provided the crucial information on slip zone properties. The long-axis direction of clasts changed from N037° in the hanging wall to N053° in the foliated gouge and back to N025° in the footwall, suggesting that maximum stress within the foliated gouge rotated clockwisely. The aspect ratio of clasts reached the maximum in the lower black gouge (ultracataclasite?). Results of anisotropy of magnetic susceptibility also indicate that relative clockwise rotation of maximum

stress direction within foliated gouge, compared with the wall rock. The observations showed that the development of sinistral fault and foliated gouge might be related to clockwise block rotation due to the effect of Peikang basement.

Micro-earthquakes Observations in 7-level seismometers array in TCDP Borehole, Taiwan

Yen-Yu Lin, Hung-Yu Wu, Kuo-Fong Ma
Institute of Geophysics, Nation Central University, Taiwan

Abstract

Taiwan Chelungpu-fault drilling project (TCDP) drilled two holes to retrieve the fresh slip zone associated with the 1999 Chi-Chi earthquake. The TCDP hole-A is 2km deep, and a slip zone at depth of 1111m was identified. A 7-level borehole seismometer (TCDP borehole seismometers, TCDP BHS, Figure 1) was installed in hole-A in July, 2006 through the depth of 946m to 1274m with 50m to 60m interval in depth. For this layout, three seismometers were placed in the hanging wall and footwall, respectively. The forth one is located at the depth of 1110.28m, close to the slip zone. For the state-of-the-art TCDP BHS, several earthquakes with the possible magnitudes to -0.5 were recorded with nice waveforms. These waveforms were calibrated to confirm the orientation with near-by permanent short period station TCU from the Central Weather Bureau Seismic Network (CWBSN). Micro-earthquakes, which were not recorded in the catalog of CWBSN, were well recorded at TCDP BHS with small S-P travel time. The shortest S-P travel time observed so far is 0.9 second. A temporary seismic array with 10 short period seismometers around the TCDP drill site was installed to incorporate with the TCDP BHS for the locations of the micro-earthquakes. In collaboration with Fluid Injection Test (FIT) in last Nov., and Jan., 2007, we would like to observe the possible seismicity changes associated with FIT from TCDP BHS and temporary array, and the observation of the possible triggering events (Figure 2). In additions, the source parameters of the events will be examined to understand the scaling relationship of the small to large earthquakes in stress drop and the corner frequency.