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

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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.

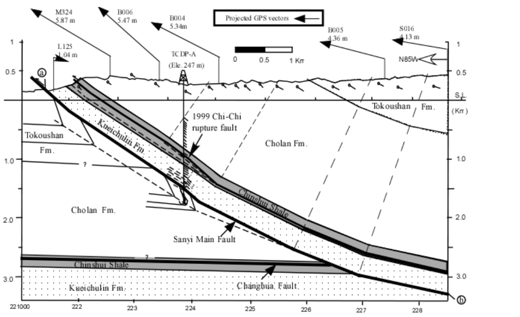

Fig.1 Interpreted structural profile across the Dakeng well (hole-A) based on the surface and subsurface drilled data. Measured depth intervals of formations in this borehole includes: Cholan, 0-1013 m; Chinshui, 1013-1300 m and Kueichulin, 1300-1712 m. Underlying the Sanyi fault is the repeated section 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.

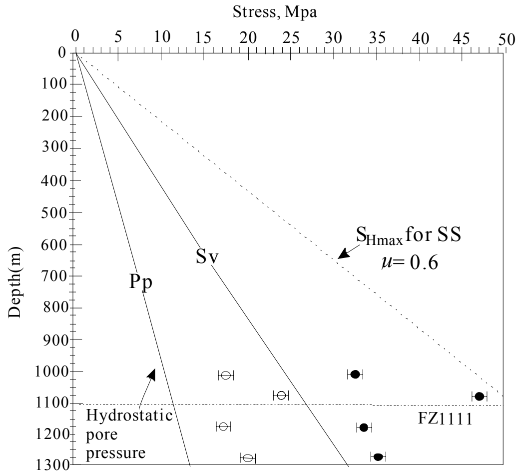

Fig. 2 Plot of overburden stress (S_v) from integration of density logs, hydrostatic pore pressure, and S_{Hmax} (filled symbol) and S_{hmin} values (open symbol) determined from leak-off tests at different depths. Dotted line shows the location of FZ1111. Heavy dashed line indicates the upper limit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

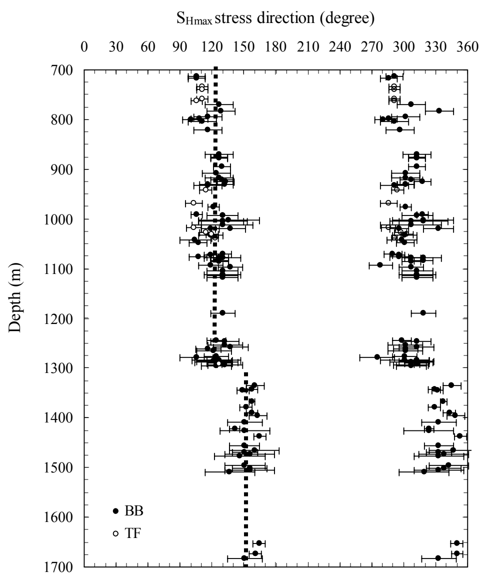

Fig. 3 The plot of azimuth of S_{Hmax} determined from breakouts (BO) and tensile fractures (TF) in the TCDP wells. Width of bar shows an opening angle of BO and TF with dark and open circles, respectively, as mid-point. Dotted lines are average of mid-points.

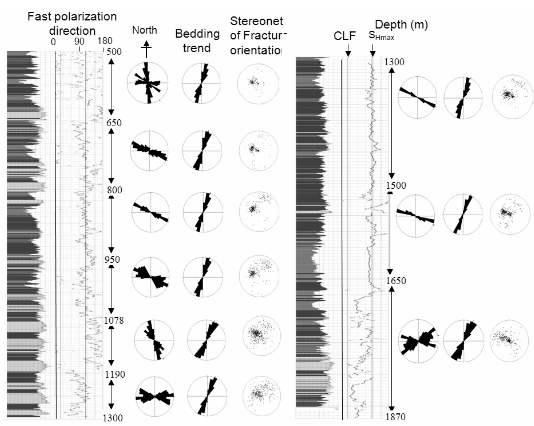

Fig. 4 Comparison of the fast-shear polarization direction with bedding trend determined from borehole images and fracture orientations measured from core images. Azimuths of the Chelungpu fault (CLF, 20^o) and maximum horizontal principal stress (S_{Hmax}, 115^o) determined from earthquake focal mechanisms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