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Stress orientations of Taiwan Chelungpu-Fault Drilling Project (TCDP) hole-A as observed from geophysical logs

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[1] The Taiwan Chelungpu-fault Drilling Project (TCDP) drilled a 2-km-deep research borehole to investigate the structure and mechanics of the Chelungpu Fault that ruptured in the 1999 M_w 7.6 Chi-Chi earthquake. Geophysical logs of the TCDP were carried out over depths of 500–1900 m, including Dipole Sonic Imager (DSI) logs and Formation Micro Imager (FMI) logs in order to identify bedding planes, fractures and shear zones. From the continuous core obtained from the borehole, a shear zone at a depth of 1110 meters is interpreted to be the Chelungpu fault, located within the Chinshui Shale, which extends from 1013 to 1300 meters depth. Stress-induced borehole breakouts were observed over nearly the entire length of the wellbore. These data show an overall stress direction (~N115°E) that is essentially parallel to the regional stress field and parallel to the convergence direction of the Philippine Sea plate with respect to the Eurasian plate. Variability in the average stress direction is seen at various depths. In particular there is a major stress orientation anomaly in the vicinity of the Chelungpu fault. Abrupt stress rotations at depths of 1000 m and 1310 m are close to the Chinshui Shale's upper and lower boundaries, suggesting the possibility that bedding plane slip occurred during the Chi-Chi earthquake. **Citation:** Wu, H.-Y., K.-F. Ma, M. Zoback, N. Boness, H. Ito, J.-H. Hung, and S. Hickman (2007), Stress orientations of Taiwan Chelungpu-Fault Drilling Project (TCDP) hole-A as observed from geophysical logs, *Geophys. Res. Lett.*, *34*, L01303, doi:10.1029/2006GL028050.

1. Introduction

[2] Taiwan Chelungpu drilling project (TCDP) drilled a 2-km-deep hole, 2.4 km to the east of the surface rupture of the 1999 Chi-Chi earthquake (Mw7.6), near the town of Dakeng (Figure 1a). The ~N-S trend of the Chelungpu-fault is a major 60-km structure that dips ~30° to the east (Figure 1b). Geological investigations showed that the 1999 Chi-Chi earthquake principally slipped within (Figure 1b), and parallel to the bedding of the Pliocene Chinshui Shale [*Lee et al.*, 2002]. The subsurface location of the Chinshui Shale was determined to be at a depth of approximately 1000 m depth based on high-resolution seismic reflection profiles [*Wang et al.*, 2002]. The TCDP carried out continuous coring from depths of 500–2000 m. Geophysical well logs were run to collect seismic velocities, densities, and anisotropy and borehole images. Based on the result of T. S. Lin et al. (Stratigraphy and geology of the Taiwan Chelungpu-fault Drilling Project-A borehole and its neighboring region, central Taiwan, submitted to *Terrestrial Atmospheric and Oceanic Sciences*, 2006), it suggested that the stratigraphy is as follows: Kueichulien formation of late Miocene to early Pliocene at depths of 1313–1707 m; Chinshui Shale of last Pliocene at depths of 1013–1313 m; and Cholan formation of late Miocene to early Pleistocene at depths of 0–1013 m and 1707–2003 m.

[3] The geophysical logging data provides the opportunity to measure the physical properties of the fault zones and surrounding formations. A Formation Micro Scanner (FMS) [*Ekstrom et al.*, 1987] and Formation Micro Imager (FMI) data are utilized to record high-resolution borehole electrical images to identify stress-induced borehole failures, bedding, fractures and fault zones. The FMS log was run in the upper section of the borehole (500–1300 m); resulting in coverage of borehole circumference of 60%. For the lower section (1280–1860 m), the FMI was run and obtained coverage of over 90% of the borehole wall.

2. Borehole Breakout and Fracture Orientation From Image Logs

[4] Borehole breakouts result from localized failure around a borehole in response to horizontal compression [*Bell and Gough*, 1979; *Zoback et al.*, 1985]. In a vertical borehole, the breakout directions are parallel to the minimum horizontal principal stress (S_{hmin}). Due to the symmetry of the stress concentration around the borehole, breakouts occur in pairs, offset by 180°. Figure 2 presents an example formation micro image from FMI for the depth of 1408.9–1411.3 m. The breakouts appear as dark zones of lower electrical conductivity 180° apart. Localized breakout rotations indicate stress perturbations associated with slip on active fault intersected by the borehole [*Barton and Zoback*, 1994]. Thus, by investigating localized changes in breakout direction, active fault zones can be identified. Figure 3a shows a profile of the orientation of the minimum horizontal principal stress (S_{hmin}) from 500–1860 m (solid cycles) based on wellbore breakout directions averaged over 2 m depth intervals. The borehole azimuth (open cycles) during drilling is shown for reference. As shown in Figure 3c, the borehole deviation from vertical is very small (<3°) except near bottom of the hole where it deviated slightly. Comparing the breakout direction and hole azimuth can help us to determine whether the failures results from changes in stress

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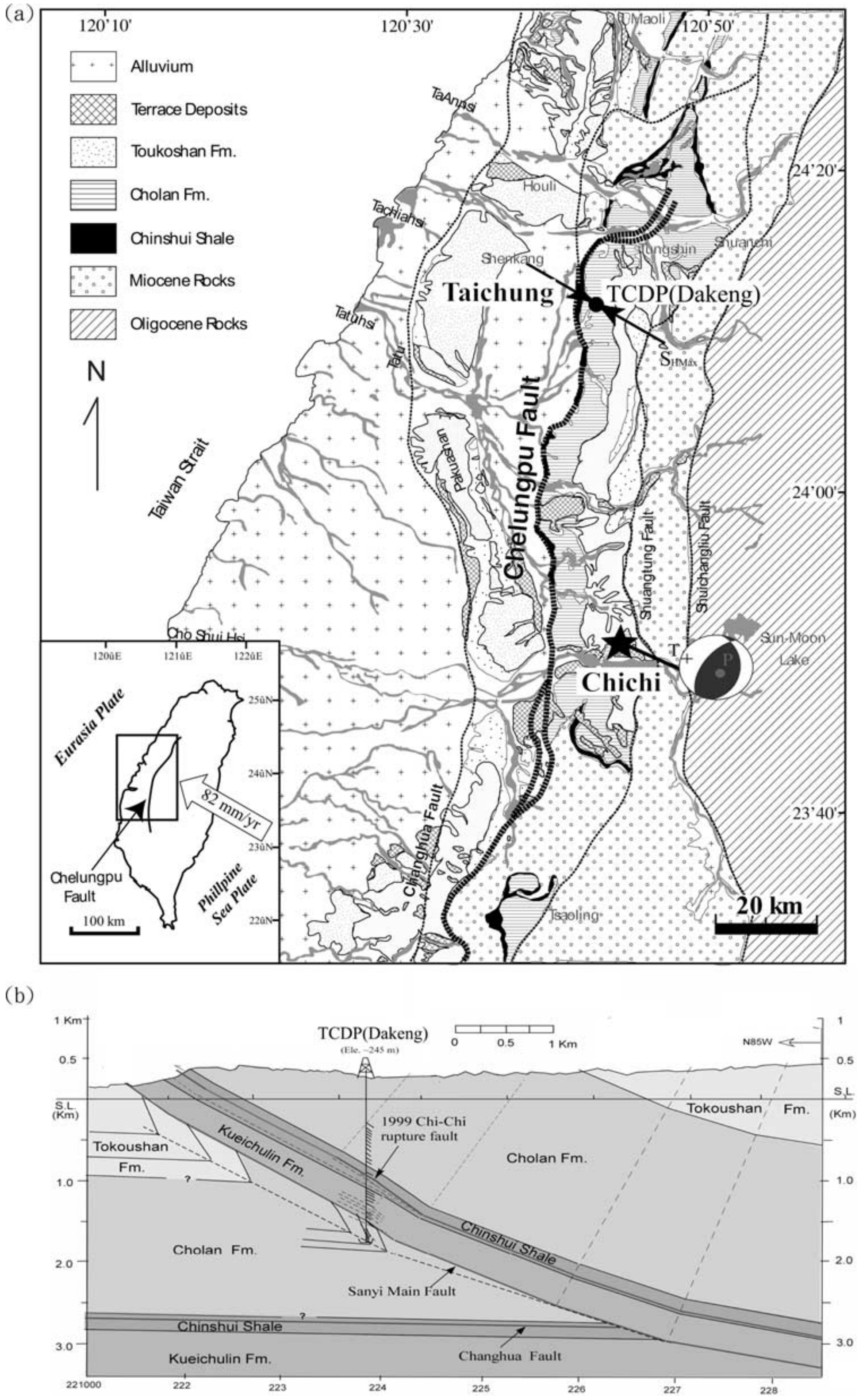
(a)
120°10'
120°30'
120°50'
24°20'
24°00'
23°40'
Alluvium
Terrace Deposits
Toukoshan Fm.
Cholan Fm.
Chinshui Shale
Miocene Rocks
Oligocene Rocks
N
Taiwan Strait
Maoli
TaAnhsi
Tachiahsi
Tatuhsi
Houli
Shenkang
Tungshin
Shuanchi
Taichung
TCDP(Dakeng)
S_{HMax}
Chelungpu Fault
Pakuashan
Shuangtung Fault
Shuichangliu Fault
Cho Shui Hsi
T
P
Sun-Moon Lake
Chichi
Changhua Fault
Tsaoling
20 km
120°E
121°E
122°E
25°N
24°N
23°N
22°N
Eurasia Plate
82 mm/yr
Chelungpu Fault
Phillpine Sea Plate
100 km
(b)
1 Km
0.5
S.L. (Km)
1.0
2.0
3.0
TCDP(Dakeng)
(Ele. ~245 m)
0
0.5
1 Km
N85W
1999 Chi-Chi rupture fault
Tokoushan Fm.
Kueichulin Fm.
Cholan Fm.
Chinshui Shale
Sanyi Main Fault
Chinshui Shale
Kueichulin Fm.
Changhua Fault
?
221000
222
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224
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228

Figure 1

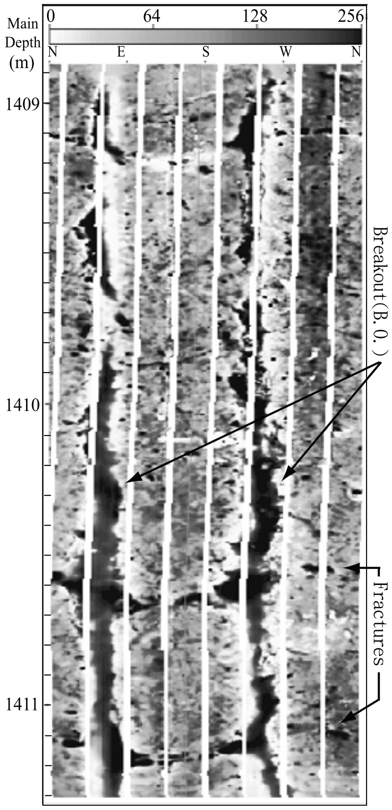

Figure 2. Sample of FMI image, the straight dark bands indicate stress-induced wellbore breakouts.

direction or from drilling-induced erosion of the wellbore wall [see *Plumb and Hickman*, 1985]. The borehole azimuth differs from the observed orientation of breakout pairs, suggesting that the breakout was resulted from stress rather than drilling. The borehole breakouts pairs obtained from the FMS data indicate an average orientation of N25°E over most of the 500–1800 m interval (Figure 3a). This orientation corresponds to a direction of S_{Hmax} of N115°E (Figure 3b) which is essentially parallel to the regional stress direction in the Taiwan region that results from the convergent Philippine Sea Plate to the Eurasian plate [*Kao and Angelier*, 2001] (see inset of Figure 1a). The deviation of TCDP-A was < 4° from the surface to a depth 1600 m, and only in the lower part of the hole (deeper than 1835 m) did the deviation of the borehole exceed > 12° where almost no breakouts were observed. Hence, the effect of borehole deviation was ignored in this study [*Peska and Zoback*, 1995].

[5] As shown in Figure 3b, minor fluctuations of the orientation of S_{Hmax} are seen at a variety of depths, with a major change of the S_{Hmax} direction seen between 950 m and 1310 m Below 1500 m, very few breakouts are observed and it is difficult to assess whether the variation of orientations observed are statistically significant.

[6] As mentioned above, the locations of abrupt breakout rotations indicate the presence of active shear zones. In total, five zones with significant rotation of the S_{Hmax} at the depths of 1000 m, 1110 m, 1230 m, 1310 m and 1460 m were identified within the depths of 600–1500 m. These zones are concentrated in the depth interval 980–1300 m, corresponding to the lithology in the Chinshui Shale 1500 m (Figure 3). The abrupt stress rotations at depths of 1000 m and 1310 m are close to the Chinshui Shale's upper and lower boundaries, suggesting the possibility that bedding plane slip occurred during the Chi-Chi earthquake. In addition to these rotations, the most significant changes in the S_{Hmax} direction occur near depths of 1110 m and 1230 m.

[7] Numerous fractures, faults and bedding-planes are obvious in the image logs. Figure 3c shows the distribution of number of visible fractures and faults in 10-m intervals. 63% of the fractures (4,473 of 7,093) are found between 500 and 1100 m with nearly 50% of the fractures concentrated between 900 and 1100 m. The number of fractures decreases gradually between 1100 and 1500 m and then more rapidly below 1500 m where they are nearly absent.

3. Physical Properties From Geophysical Logs

[8] Geophysical logs were run from 500 m to 1860 m to obtain the physical properties of fault zones and adjacent damage zones, including P & S wave velocities, density, resistivity, and gamma ray. The logs sample these properties every 15 cm. The velocity logs show a gradual increase in P and S wave velocity (Figures 4b and 4c) due to the increase in confining pressure with depth. The P wave (compressional) velocity ranges from 2.27 km/s at depth 551 m to 5.47 km/s at depth 1668 m. The S wave (shear) increases from 1.4 km/s at a depth of 597 m to 2.98 km/s at a depth of 1705 m. Overall average of P-wave velocity is 3.81 km/s and S-wave velocity value is 1.86 km/s. The overall resistivity of the formations encountered in TCDP is low from 20 ohm-m to 50 ohm-m between depths of 587 m to 1856 m (Figure 4d). Depths of abnormal geophysical properties can be identified at depths where the velocities and resistivities are lower than the average trend with depth. The gray bars in the lithologic column represent fault zones observed in the core (E.-C. Yeh, personal communication,

Figure 1. (a) Geology map of the region near the TCDP drill site (solid dot) (H. Tanaka, personal communication, 2006). Surface rocks near the drill site are identified as Cholan Formation and Chinshui Shale. The drill site is in the town of Dakeng, 2.5 kilometer east to the Chelungpu fault rupture (wide black dash line). The nearby faults from west to east are Changhua fault, Shuangtung fault and Shuichangliu fault (black dash lines). The regional tectonic stress of Taiwan is N126°E as shown in inset [*Kao and Angelier*, 2001]. The slip direction of the Philippine Sea Plate with respect to the Eurasian Plate is in this same direction. The convergence rate is 82 mm year^{-1}. The location of mainshock (asterisk) and its focal mechanism are also shown. (b) A geological cross-section near the drill site [*Yue et al.*, 2005]. The Chelungpu fault dips 30 degrees east. TCDP drilled a 1.8 km depth hole through from Cholan Formation to Chinshui Shale and Kueichuline Formation, then, to Cholan Formation. The Sanyi fault is interpreted to be at the base of the Kuichulin Formation with some uncertainties shown by dash line below it.

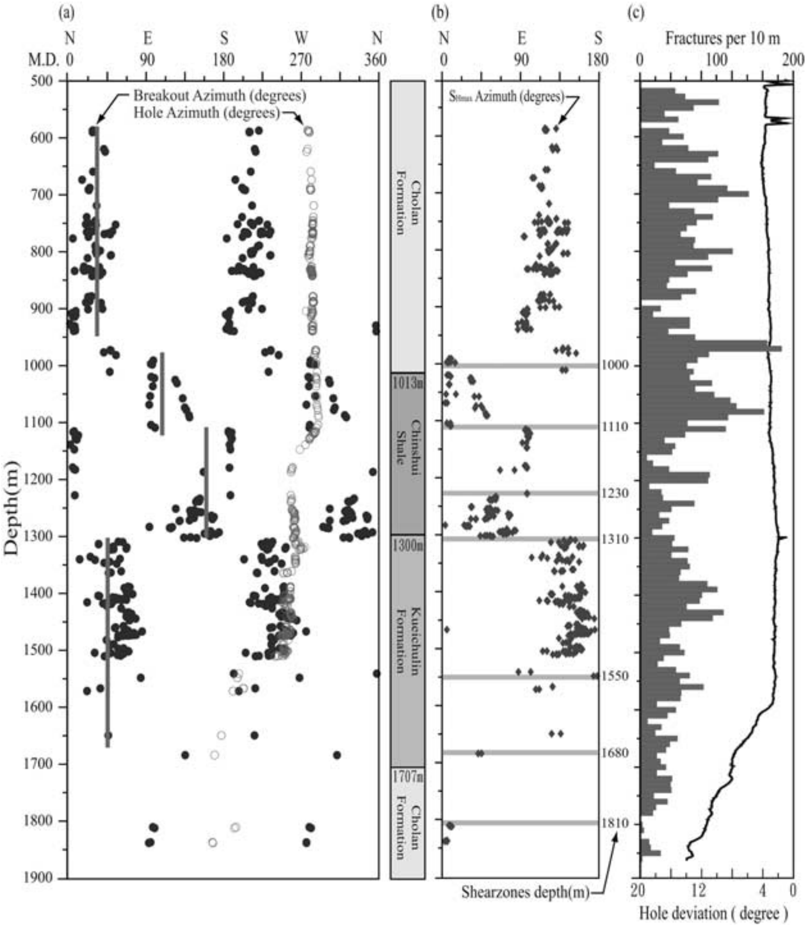

Figure 3. (a) The directions of breakouts (averaged over 2-meter intervals) are shown by filled dots and hole azimuth (represented by open dots) from depth of 500 m to 1900 m. The gray bars represent the average value in different depths. The lithology from T.-S. Lin (personal communication, 2006) is also shown for references. (b) The maximum horizontal principal stress (solid diamond) acquired from the breakout data. Gray bands denote the depths at which active shear zones were penetrated as indicated by the abrupt changes of stress direction with depth. (c) Fracture density (per 10 meter interval). The borehole deviation from vertical is shown by the solid curve.

2006). There is some degree of correlation between fault zones and anomalous geophysical properties as observed in other fault zone drilling project [e.g., *Boness and Zoback*, 2004]. However, this correlation is not compelling as a number of zone of anomalous geophysical properties do not correlate with identified shear zones and some of the shear zones identified in the core are not associated with anomalous properties.

[9] We can also compare the geophysical logs with the zones of localized S_{Hmax} perturbations seen in Figure 3b, which are shown by shaded in gray bands in Figures 4a–4f. The zone identified from the discontinuous rotation of S_{Hmax} at the depth of 1110 m corresponds to the most significant changes in Vp, Vs, and resistivity. It is also consistent with the fault zone identified from the core. Considering the observations from all of the various geophysical logs and the faults identified from cores, it suggests that the shear zone at the depth of about 1110 m is the most recent shear zone related to the 1999 Chi-Chi earthquake. Other zones of anomalous breakout rotations could be associated with co-seismic slip on secondary fault planes that moved during the Chi-Chi earthquake or slip that occurred during historical events. The geophysical logs close to the depth of 1680–1707 m show significant changes in Vp, and Vs, which have good correlation to the fracture zone observed from the core. This shear zone could be related to the SanYi fault beneath the Chelungpu fault as shown in Figure 1b. As mentioned above, the abrupt stress rotations at depths of 1000 m and 1310 m are close to the Chinshui Shale's upper and lower boundaries, suggesting the possibility that bedding plane slip occurred during the Chi-Chi earthquake.

4. Conclusions

[10] Continuous core, geophysical logs data and observations of stress-induced borehole breakouts were collected from the entire depth of TCDP hole-A. These data clearly to present the overall stress direction at the site, which is consistent with the regional stress field as well as anomalous stress rotations associated with the faults that cut through the hole. Active shear zones are identified at depths

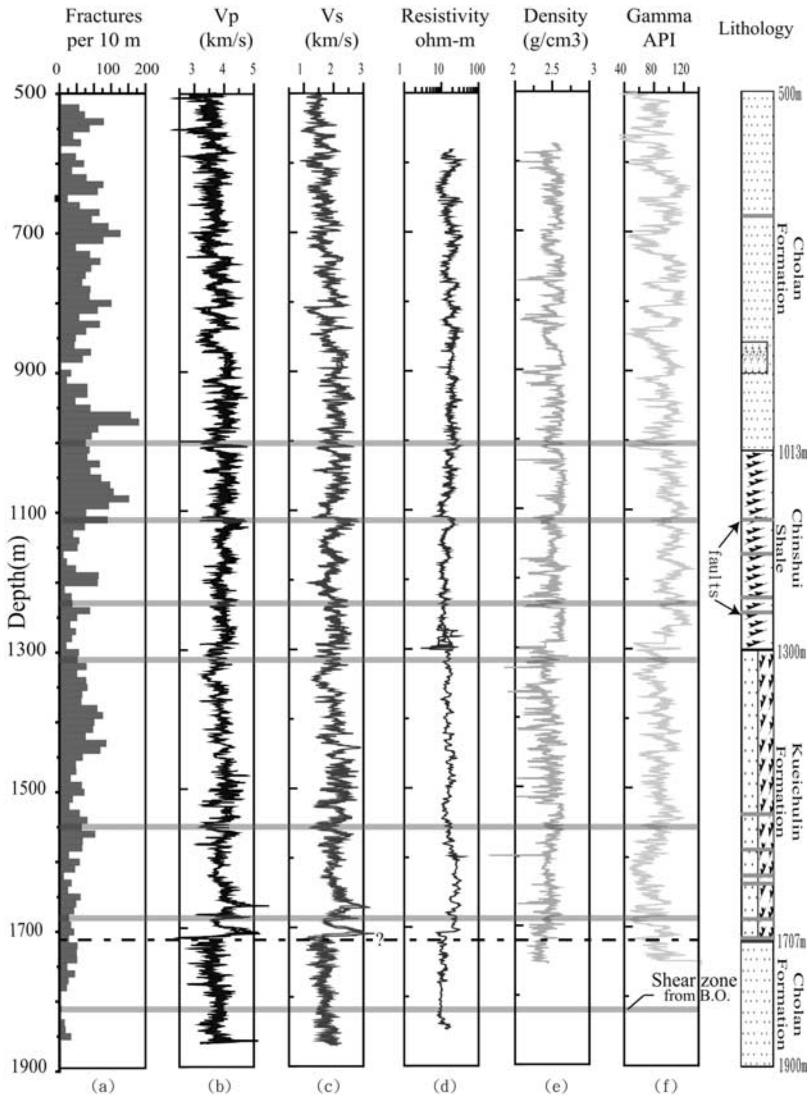

Figure 4. (a) Fractures density picked from FMS and FMI in 10 meter intervals. (b) P-wave velocity, (c) S-wave velocity, (d) Resistivity, (e) Density, and (f) Gammy ray and lithology from core descriptions. The zones with localized stress rotations are shown on geophysical logs with thick gray lines. The fault zones identified from the on-site core description (E.-C. Yeh, personal communication, 2006) are shown by gray bars in the lithology column.

of 1110 m and 1680–1707 m related to Chelungpu fault and SanYi fault, respectively. The shear zone at the depth 1110 m shows the most consistent features with fracture zones observed in core, the rotations of S_{Hmax} and anomalies in velocities and resistivity, suggest that this fault is most likely related to the 1999 Chi-Chi earthquake. Other observations were found for the rotation of the S_{Hmax} direction indicate other active faults as well as bedding plane slip at the boundaries of different formations.

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