Drilling of the Chelungpu Fault after the 1999 Chi-Chi, Taiwan Earthquake (Mw7.6): Understanding Physics of Faulting
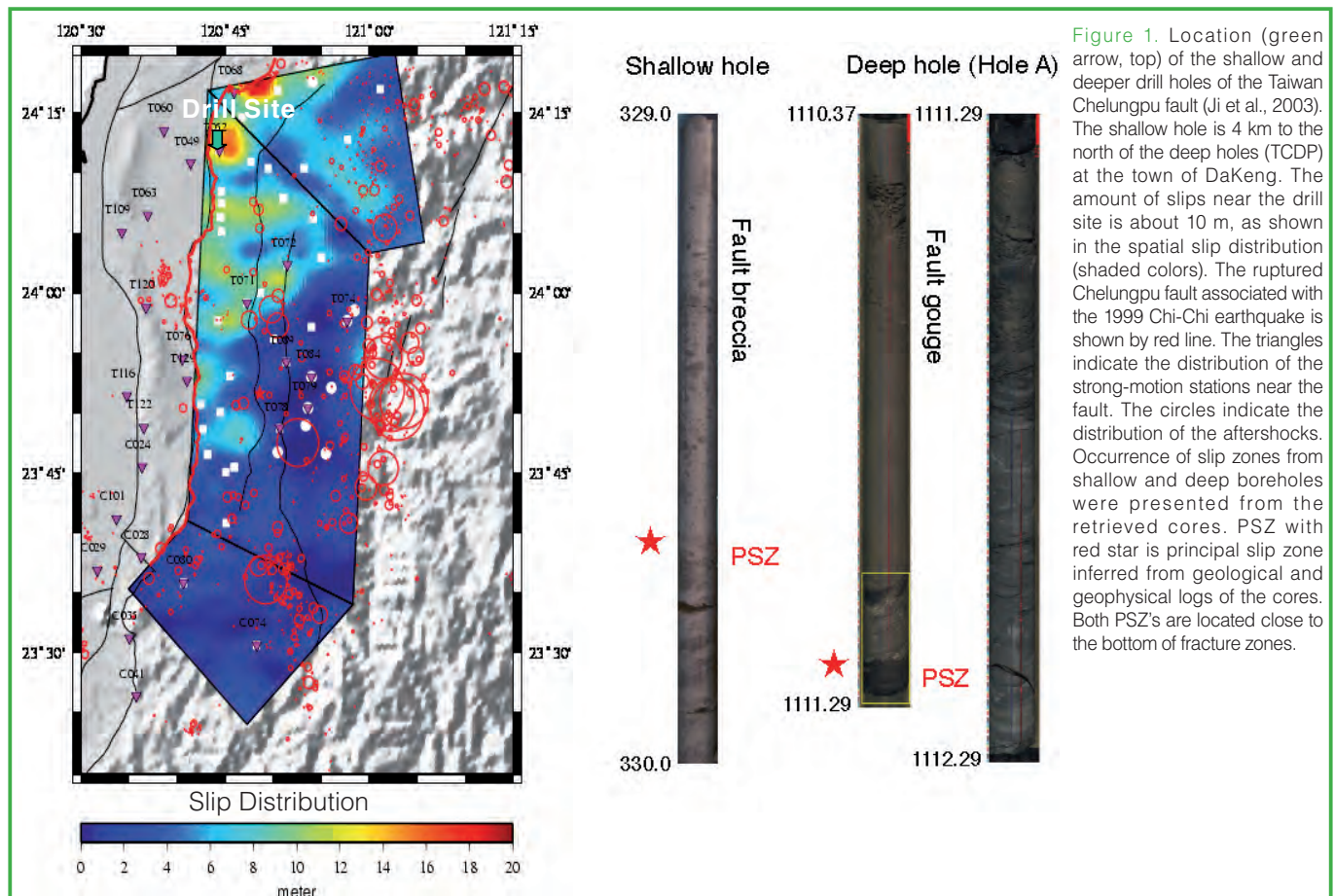
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The 21 September 1999 Chi-Chi, Taiwan earthquake (Mw 7.6) ruptured the N-S trending Chelungpu fault with a major 90-km structure that dips shallowly (30°) to the east, and principally slips within and parallel to bedding of the Pliocene Chinshui shale. A shallow borehole was drilled into the northern portion of the fault in the year 2000 (Fig. 1) in order to sample the slip zones that had large slip (>10 m) during the earthquake. The borehole was drilled at an angle of about 50° to the west, penetrating the fault at a drilling depth of around 300 m in January, 2001 (Tanaka et al., 2002). The success of the shallow hole drilling led to the deeper holes drilling named TCDP (Taiwan Chelungpu-fault Drilling Project; Ma et al., 2006), which drilled two vertical holes 40 m apart (Hole A to a depth of 2 km, and Hole B to a depth of 1.3 km) and a side-track from Hole B (Hole C, depth 0.95–1.2 km) about 2 km east of the surface rupture and 3 km to the south of the shallow hole, near the town of DaKeng (Fig. 1). TCDP carried out continuous coring for depths of 500 m to 2000 m, 950 m to 1300 m, and 950 m to 1200 m for

Hole A, Hole B, and Hole C, respectively. Geophysical well logs were carried out in Hole A to collect seismic velocities, densities, and digital images.

For the shallow hole, the distributed fracture zone ranges from 285 m to 330 m depth, which contained nine slip zones. The neutron geophysical logs show that the porosity abruptly increases in the drilling interval between 285 m and 330 m, suggesting that this zone would be the newest, being fractured during co-seismic slip by the Chi-Chi earthquake. Slip zones are basically composed of fault gouge and fault breccia. The fault gouge is brighter gray than host rocks. The boundary between fault gouge and host rock is gradual and is associated with a thin transition zone (<2 mm) from host rock to fault gouge. The mineral grains are more disaggregated nearer to the slip zone. Grains in fault gouge are of extremely fine cryptocrystalline materials (<2 μm diameter), and the maximum size is about 25 μm in diameter. Microscopic textures were not indicative of frictional melting, such as

Figure 1. Location (green arrow, top) of the shallow and deeper drill holes of the Taiwan Chelungpu fault (Ji et al., 2003). The shallow hole is 4 km to the north of the deep holes (TCDP) at the town of DaKeng. The amount of slips near the drill site is about 10 m, as shown in the spatial slip distribution (shaded colors). The ruptured Chelungpu fault associated with the 1999 Chi-Chi earthquake is shown by red line. The triangles indicate the distribution of the strong-motion stations near the fault. The circles indicate the distribution of the aftershocks. Occurrence of slip zones from shallow and deep boreholes were presented from the retrieved cores. PSZ with red star is principal slip zone inferred from geological and geophysical logs of the cores. Both PSZ's are located close to the bottom of fracture zones.

spherulitic or dendritic crystal morphology, microlites or grassy matrix in the slip zones. In the deep holes, the Chelungpu fault zone from the Hole A core is observed within the Chinsui shale at depths from 1105 m to 1115 m, and consists of fractured rocks, fault breccia, and thin fault gouge layers. The degree of fracturing increases from the top to the bottom of the zone. Near the bottom of the broad zone of deformation, a 12-cm-thick primary slip zone (PSZ) can be identified based on the presence of ultra-fine grained fault gouge and increased fracture density at depths of 1111.23 m to 1111.35 m. A corresponding feature was also found in Hole B core at the depths of 1136.50 m to 1136.62 m, confirming the fault dip of 30°E. The geophysical logging measurements of low seismic velocities and low electrical resistivity around 1111 m depth also confirm that this is the main fault zone (Wu et al., 2007). The PSZ observed in the core from Hole C after splitting and polishing shows several layers of slip zones associated with several repeating earthquakes. The individual slip zone has a thickness of about 2–3 cm with a 5-mm ultra-fine grain zone at the bottom. Among the slip zones, the bottom zone in the PSZ, 2-cm in thickness, suffered the least disturbance from later events, suggesting that this narrow band might be the major slip zone (MSZ) that corresponds to the Chi-Chi earthquake. Other estimates of the thickness for the slip zone from nearby sites are 50–300 µm observed at the surface near the DaKeng drill site, and 1 cm from a fault core at a depth of 330 m in shallow drilling. These determinations of slip zone thicknesses are all from layers located near the bottom of the fracture zone. The variation of thickness of the slip zone at different depths might correspond to differences in normal stress as observed in Nojima fault core and other exhumed faults (Gratier et al., 2003; Tanaka et al., 2007).

The grain size distribution of the major slip zone was observed to estimate the surface fracture energy to compare with the seismic fracture energy to understand the energy partition of the earthquake. Direct measurements of the heat generated by this large earthquake were made for the shallow and deep holes. The local increases in the temperature profile across the fault observed both in shallow and deep holes were interpreted to be the residual heat generated during the earthquake. The frictional heat was calculated from temperature anomaly data observed at the depth associated with the identified slip zones of the Chi-Chi earthquake. Using the thermal parameters measured on-site with non-destructive methods as constraints, the analyses of the temperature anomalies lead to low estimates of the dynamic shear stress and to small values of the frictional coefficient. These results suggest the involvement of dynamic weakening mechanisms of faulting, such as thermal pressurization, during the large earthquake.

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