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Subsurface structure, physical properties, fault-zone characteristics and stress state in scientific drill holes of Taiwan Chelungpu Fault Drilling Project

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Abstract

Continuous cores and a suit of geophysical measurements were collected in two scientific drill holes to understand physical mechanisms involved in the large displacements during the 1999 Chi-Chi earthquake. Physical properties obtained from wire-line logs including P- and S-wave sonic velocity, gamma ray, electrical resistivity, density and temperature, are primarily dependent on parameters such as lithology, depth and fault zones. The average dip of bedding, identified from both cores and FMI (or FMS) logs, is about 30° towards SE. Nevertheless, local azimuthal variations and increasing or decreasing bedding dips appear across fault zones. A prominent increase of structural dip to 60°–80° below 1856 m could be due to deformation associated with propagation of the Sanyi fault.

A total of 12 fault zones identified in hole-A are located in the Plio-Pleistocene Cholan Formation, Pliocene Chinshui Shale and Miocene Kueichulin Formation. The shallowest fault zone occurs at 1111 m depth (FZ1111). It is a 1 m gouge zone including 12 cm of thick indurate black material. We interpreted this zone as the slip zone during Chi-Chi earthquake. FZ1111 is characterized by: 1) bedding-parallel thrust fault with 30-degree dip; 2) the lowest resistivity; 3) low density, V_p and V_s, 4) high V_p/V_s ratio and Poisson's ratio; 5) low energy and velocity anisotropy, and low permeability within the homogeneous 1 m gouge zone; 6) increasing gas (CO_2 and CH_4) emissions, and 7) appearance of smectite within the primary slip zone.

In situ stresses at the drill site were inferred from leak-off tests, borehole breakouts and drilling-induced tensile fractures from borehole FMS/FMI logs, and 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 conjugate set of secondary directions are parallel to microcrack orientations. A drastic change of orientation of fast shear-wave polarization across the Sanyi thrust fault at the depth of 1712 m reflects the change of stratigraphy, physical properties and structural geometry.

Keywords: Chi-Chi earthquake; Taiwan Chelungpu Fault Drilling Project; Fault-zone properties; Borehole breakouts; S-wave anisotropy

1. Introduction

The 1999 Chi-Chi earthquake (M_w 7.6) produced over 90 km-long surface rupture zone along the north–south trending, west-vergent Chelungpu fault (MOEACGS, 2000; Fig. 1). The most striking feature of the coseismic displacement field in the hanging-wall is that areas of large surface displacement lie above the footwall ramp of the thrust and at the northern termination; by contrast, relatively smaller, but significant (1–3 m) displacements are recorded at the footwall detachment (Yu et al., 2001; Dominguez et al., 2003; Lee et al., 2003). Along strike, both horizontal and vertical components of surface displacements increase from south to north and reach up to 12 m at the northern end near the Shihgang area. Surface ruptures indicate that the Chelungpu thrust runs parallel in map-view to the hanging-wall of the Pliocene Chinshui Shale, which indicates that the fault plane is a detachment in the Chinshui Shale.

In map-view (CPC, 1982), south of Wufeng village, the Chelungpu fault merged with the Sanyi fault to the west into

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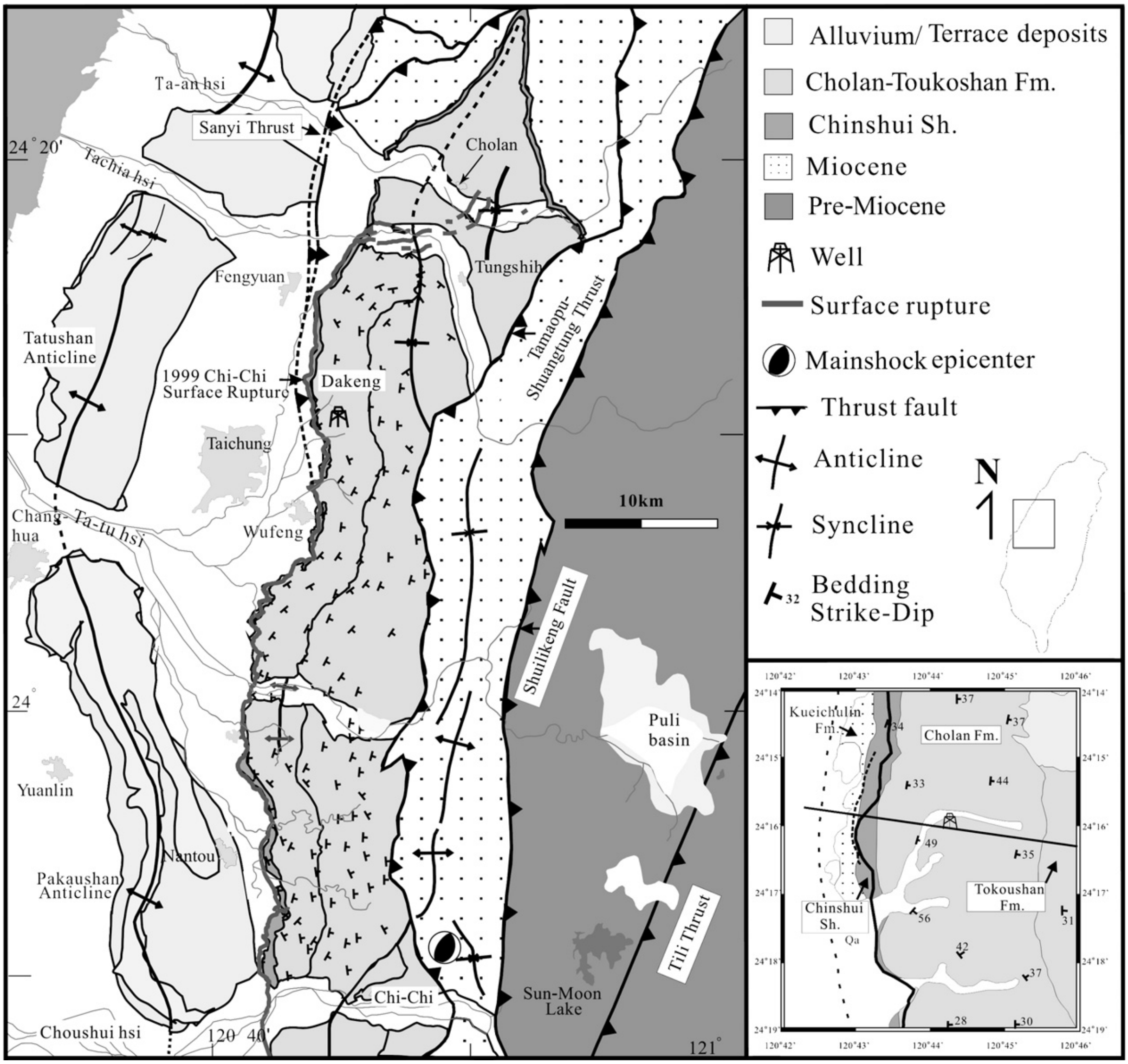

Fig. 1. Geologic map of the Chelungpu-fault area with location of the epicenter of the 1999 Chi-Chi main shock, surface ruptures (from MOEACGS, 2000) and the Dakeng drill site. Inset shows the stratigraphy near the drill site and location of structural section. Note that the rupture traces (thick lines) are confined within, but cut up and down within the Chinshui shale. Map modified from CPC (1982).

single fault (Chang, 1971; called Chelungpu-Sanyi fault hereafter) and emplaced the Pliocene Chinshui Shale on top of the Pleistocene Tokoushan Formation and Holocene deposits. The subsurface Chelungpu–Sanyi fault plane, imaged by both shallow and deep seismic profiling (Wang et al., 2002, 2004), shows a ramp-flat geometry from the base of the Chinshui Shale (Hung and Suppe, 2002; Yue et al., 2005).

Towards north, the Chelungpu–Sanyi fault branches into two segments (Fig. 1): a) the underlying fault, called Sanyi thrust, which steps up from a deeper Pliocene and late-Miocene detachment in the Kueichulin and Tungkeng Formations and is probably not active, and b) the North Chelungpu detachment (called Chelungpu fault hereafter) which is a relatively young, nearly bedding-parallel fault in the Chinshui Shale and is the focus of some largest displacements in the Chi-Chi earthquake. Subsurface investigations of northern fault segments through a number of shallow seismic (Wang et al., 2002), deep petroleum seismic profiles (Hung and Wiltschko, 1993) and shallow drilling (Tanaka et al., 2002; Huang et al., 2002) confirm that the near-surface segment of the Chelungpu thrust is parallel to both bedding and the underlying Sanyi fault to a depth of 3 km. The TCDP deep boreholes are drilled through this high-slip portion of the Chelungpu fault and through the Sanyi ramp in the footwall.

An important question that needs to be addressed is what physical properties or dynamic processes within the fault zone cause large coseismic displacement 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. A detailed three-dimensional