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Integrating borehole-breakout dimensions, strength criteria, and leak-off test results, to constrain the state of stress across the Chelungpu Fault, Taiwan

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ABSTRACT

The paper describes the computation of the maximum horizontal stress (σ_H) magnitude in the vicinity of the Chelungpu Fault, Taiwan, host of the slip zone during the Chi-Chi earthquake (M_w 7.6; 1999). The scientific hole B intercepts the Chelungpu Fault at 1136 m. At the depths of logged breakouts (940–1310 m), the vertical stress (σ_v) as estimated from density logs increases linearly with depth from 22 to 31 MPa. A series of leak-off tests yielded two reliable shut-in pressures, 23.7 MPa at 1085 m and 29.8 MPa at 1279 m, which are lower than the estimated σ_v, albeit by only 2.1 and 0.6 MPa, respectively. In our analysis the shut-in pressures were considered to represent estimates of the least horizontal principal stresses (σ_h) at the respective depths, and consequently the test-induced fractures were assumed to have been vertical. Principal stress directions had been previously determined by others (105°–155° for the maximum horizontal stress, σ_H, except in the immediate vicinity of the Chelungpu Fault). The contribution of this paper is the estimation of the σ_H magnitude by considering that the state of stress at the points of intersection between breakout and borehole wall is in a state of limit equilibrium with the true triaxial strength criterion. The resulting σ_H in the range of logged breakouts increases with depth from 55 MPa at 940 m to 59 MPa at 1310 m. Thus, the estimated state of stress prevailing across the Chelungpu Fault is compatible with strike-slip, but marginally also with thrust faulting. However, the likelihood that the shut-in pressures actually represent σ_v magnitudes, and that the leak-off test-induced fractures were sub-horizontal, cannot be ignored. In that case the state of stress would clearly favor thrust faulting.

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1. Introduction

Borehole breakouts identified on geophysical logs have been widely used as an important indicator of in situ stress direction. They provide indispensable data for the construction of the World Stress Map (Heidbach et al., 2008). In addition, laboratory tests have shown that the angular span of breakouts in cross sections of vertical boreholes is directly related to the magnitudes of the far-field principal stresses (Song and Haimson, 1997). However, the explicit relationship requires knowledge of the rock strength criterion, because of the reasonable assumption that the points of intersection between breakout and borehole wall cross section represent the boundary between stable rock on the outside of the breakout and failed rock on the inside. Equating the correct strength criterion to the state of stress at the points of intersection, one obtains a relationship in terms of the three in situ principal stresses. The vertical in situ principal stress (σ_v) is typically determined from the gravitational gradient. The least horizontal principal in situ stress (σ_h) can only be ascertained through independent measurements, and practically the only reliable ones in deep holes are leak-off or hydraulic fracturing (hydrofracturing) tests. Thus the only remaining unknown is the maximum horizontal in situ stress (σ_H), which can be computed by solving the strength criterion-state of stress equation at the point of breakout-borehole wall intersection.

At the University of Wisconsin we designed and fabricated an apparatus for determining the true triaxial strength of rectangular prismatic specimens subjected to three unequal principal stresses (Haimson and Chang, 2000). The first opportunity to use it for constraining σ_H came in conjunction with the stress measurements in the KTB scientific ultra deep well, Germany (Brudy et al., 1997; Haimson and Chang, 2002). We experimentally obtained a true triaxial strength criterion for the amphibolite, the dominant rock between 3000 and 7000 m depth in the KTB hole. Applying the criterion to the state of stress at the points of borehole-breakout intersections yielded estimates of the magnitude of σ_H between 3200 and 6800 m depth, which reaffirmed the assertion that the state of stress there is compatible with strike-slip faulting (Haimson and Chang, 2002).

The scientific holes drilled through the Chelungpu Fault in Taiwan offered a new opportunity to integrate logged borehole-breakout spans,

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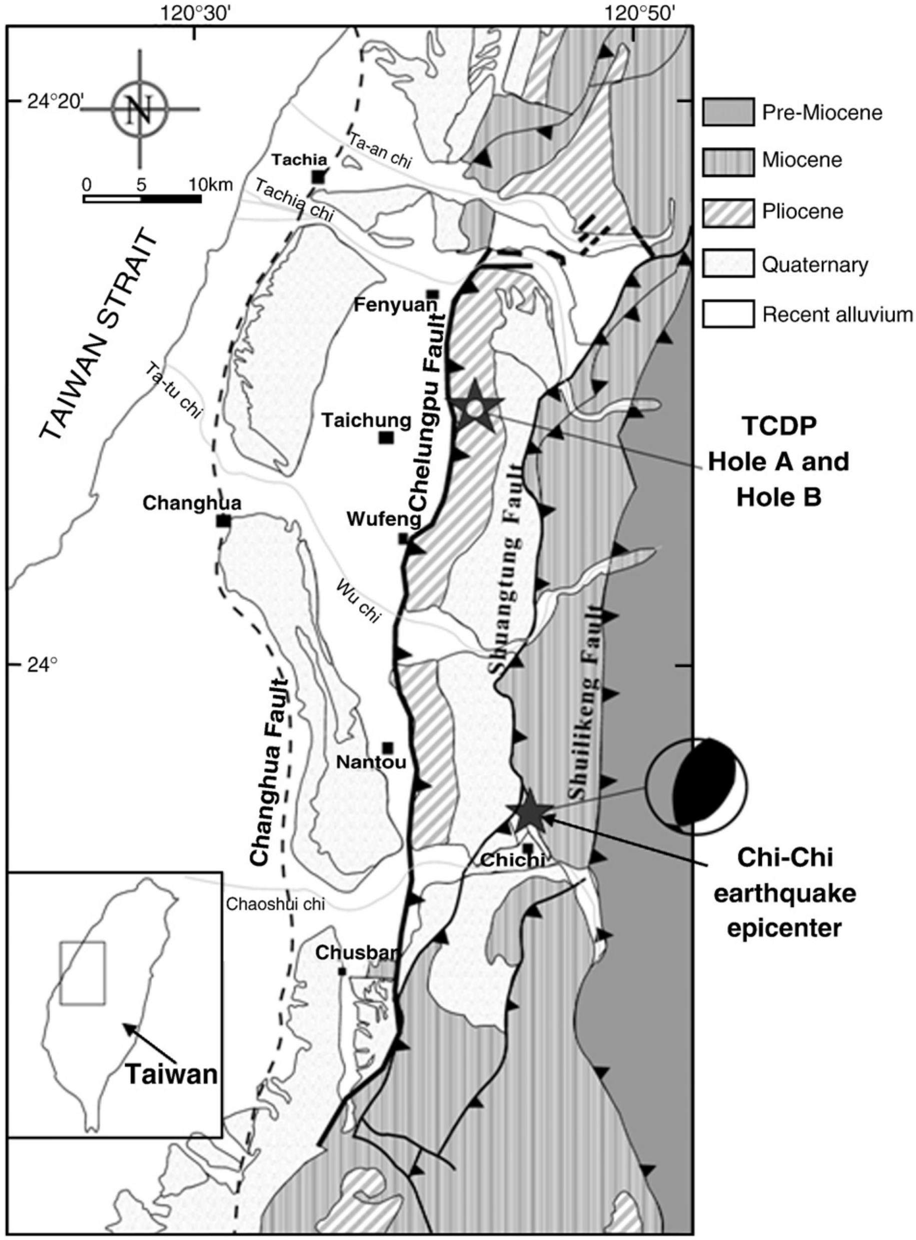

Fig. 1. Geological map of west-central Taiwan, showing the Chelungpu Fault, the epicenter of the Chi-Chi earthquake and its fault plane solution, and the TCDP drill site (modified after Song et al. (2007).

rock strength criteria, and hydraulic fracturing (leak-off test) results in order to constrain the complete state of in situ stress following the destructive Chi-Chi earthquake. This forms the topic of the present paper.

2. The Taiwan Chelungpu Fault Drilling Project (TCDP)

Chelungpu Fault, Taiwan, is a major north–south striking, 90-km long fault, dipping 30° to the east (Fig. 1). The fault slips parallel to the bedding of the Pliocene Chinshui Formation. In 1999 the Chi-Chi earthquake (M_w 7.6) created a multi-kilometer surface rupture along the fault. Extensive studies of the fault and the earthquake were undertaken by the Taiwan Chelungpu Fault Drilling Project (TCDP). Under this project two boreholes were drilled during 2004–2005 (holes A and B) in west-central Taiwan, north of the epicenter of the earthquake, and in an area where up to 10 m surface slip had occurred (Fig. 1). The two holes, 40 m apart and continuously cored, penetrated the fault at approximately 1111 m in hole A, and at 1136 m in hole B, and reached final depths of 2003 m and 1350 m, respectively. One of the objectives of the TCDP was to determine the state of stress across the fault.

3. Known stress data

It is rational to assume that the state of stress in the vicinity of the two scientific holes A and B is one in which the vertical stress is a principal component, rendering the other two principal stresses horizontal. This is because the topography is gentle and not a factor at the great depths of 940–1310 m, there are no known igneous intrusions or salt domes, and the sedimentary layers are sub-horizontal, and thus not affecting the general verticality of the gravitational force from which the vertical stress is derived.

In this paper we are concerned with the estimation of σ_H in the vicinity of the Chelungpu Fault. To accomplish this it is imperative to first have reliable estimates of the other two principal stress magnitudes. One of these, the vertical stress σ_v, is relatively simple to estimate from knowledge of the overburden density. In hole B, σ_v

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