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Ultrafine spherical quartz formation during seismic fault slip: Natural and experimental evidence and its implications

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ABSTRACT

In recent works on the determination of pseudotachylyte within the principal slip zone (PSZ) of the Chelungpu fault (Taiwan), we demonstrated that frictional melting occurred at shallow depths during the 1999 Mw 7.6 Chi-Chi earthquake. Thus, the characteristics of melts are of paramount importance to investigate processes controlling dynamic fault mechanics during seismic slips. We conducted rock friction experiments on siltstone recovered from the Taiwan Chelungpu fault Drilling Project (TCDP) at a slip rate of 1.3 m/s and a normal stress of 1 MPa. Here we not only target to characterize experimental pseudotachylyte and evaluate the associated frictional behavior, but also compare it with natural frictional melts of TCDP. Our results show that (1) initial shear stress drop was related to the generation of low viscosity melt patches, (2) the evolution of shear stress in the postmelting regime was congruent with frictional melt rheology, and (3) the slip strengthening presumably resulted from the extremely low content of water of the frictional melt. In particular, the state-of-art of in situ synchrotron analyses (X-ray diffraction and Transmission X-ray Microscope) determine the presence of ultrafine spherical quartz (USQ) grains (~10 nm to 50 nm) in the glassy matrices presumably produced at high temperature. Our observations confirm that the USQ grains formed in rock friction experiments do occur in natural faults. We surmise the USQ is the result of frictional melting on siltstone and represents the latest slip zones of the Chelungpu fault, and further infer that the viscous melts may terminate seismic slips at shallow crustal conditions.

1. Introduction

Determination of the physical and chemical processes having occurred during fast fault slips and associated products remains highly challenging due to heterogeneous fault zone properties and geometry. Integration of field geology, rock friction experiments, and theoretical simulation is a way to better address earthquake mechanics (Di Toro et al., 2012; Niemeijer et al., 2012). In particular, with the efforts of rock friction experiments in the last two decades several physical and chemical processes have been suggested to result in coseismic fault lubrication (Tsutsumi and Shimamoto, 1997; Rice, 2006; Di Toro et al., 2004, 2006; Han et al., 2007, 2010; Brantut et al., 2008; Goldsby and Tullis, 2011), but with the exception of frictional melting (pseudotachylyte) evidence for these processes in natural fault zones is scarce (Di Toro et al., 2006). Pseudotachylyte determined both in nature (Sibson, 1975) and rock friction experiments (Spray, 1987; Tsutsumi and Shimamoto, 1997) has been used to infer the seismically natural fault zones, and is allowed to obtain key parameters of the earthquake source (Di Toro et al., 2009). Therefore, the fault mechanics of active faults can be revealed with the presence of the robust seismic indicators such as pseudotachylyte.

The Chelungpu thrust fault was northward ruptured ~90 km as a result of the Mw 7.6 Chi-Chi earthquake which struck central Taiwan on 21st September 1999 (Fig. 1a) (Lee et al., 2001; Ma et al., 2000). After the 1999 Chi-Chi earthquake, the urgent need for investigating the catastrophically active fault drove the initiation of Taiwan Chelungpu fault Drilling Project (TCDP). TCDP was conducted in 2005 and drilled two holes to a depth of 2003 m for Hole-A (Fig. 1b) and 1353 m for Hole-B. Currently, on the basis of continuous coring (Sone et al., 2007; Song et al., 2007a; Yeh et al., 2007), a suite of geophysical measurements (Hirono et al., 2008a; Hung et al., 2007; Wu et al., 2007, 2008), microstructural observation (Boullier et al., 2009; Ma et al., 2006), mineral anomalies (Chou et al., 2012a,b; Hirono et al., 2008b; Kuo et al., 2009, 2011), chemical composition and physical parameters (Hirono et al., 2006a,b; Ishikawa et al., 2008; Kano et al., 2006; Mishima et al., 2006, 2009; Mizoguchi et al., 2008), the active fault zone of the

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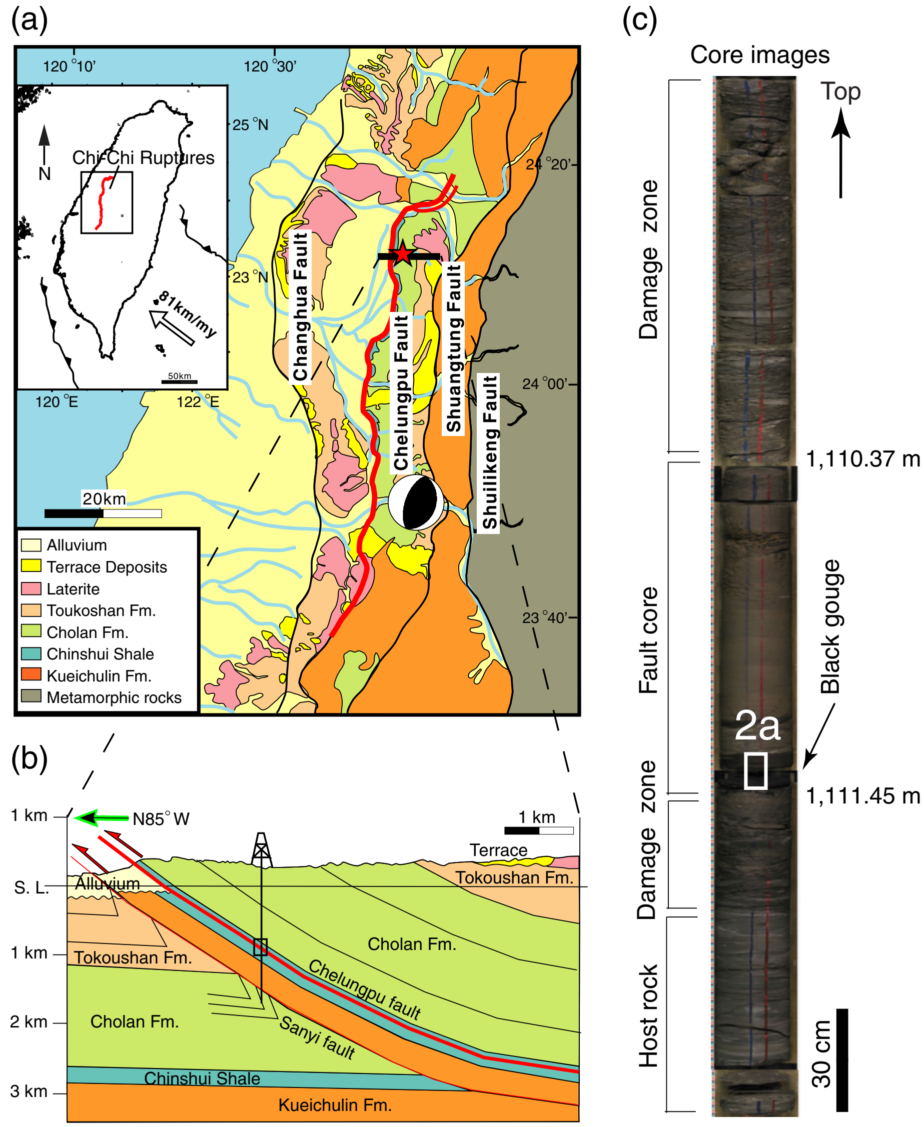

Fig. 1. Geological setting of the 1999 Mw 7.6 Chi-Chi earthquake and location of the TCDP-A drilling site. (a) Location of the TCDP-A drilling site and the 90-km-long surface ruptures associated with the Mw 7.6 earthquake at the central part of western Taiwan. The TCDP site is indicated by a red star. The focal mechanism of the Chi-Chi main shock is located at the hypocenter of the Chi-Chi earthquake. The insert box is the tectonic setting of Taiwan. (b) An E–W cross section of the TCDP-A showing the Chelungpu fault zone and surrounding formations encountered in the borehole (after Hung et al., 2007). The rectangle displaying the principal slip zone active during the 1999 mainshock was identified in the borehole at 1111.29 m depth and the images of fault core samples of the TCDP-A were enlarged in the right panel as (c). (C) The image exhibiting major portions of the Chelungpu-fault along the borehole of TCDP.

Chelungpu fault corresponding to the 1999 at the depth of 1111 m (described as FZ1111 hereafter) in Hole-A (Fig. 1c) and 1137 m in Hole-B.

Boullier et al. (2009) determined the Chi-Chi principal slip zone (PSZ) as a ca 2 cm thick isotropic layer in which the pseudotachylyte-bearing layer is included. Kuo et al. (2009) presented the evidence of frictional melting within the PSZ of FZ1111: (1) lower clay content than surrounding rocks; (2) thermal decomposition of illite, chlorite and kaolinite, and enrichment of smectite; and (3) amorphous materials resulting from transient frictional heating, and suggested that pseudotachylyte was generated and transferred to smectite with hot fluid during the 1999 Chi-Chi earthquake. In addition, on the basis of the determination of pseudotachylyte within the PSZ of the Chelungpu fault, the key parameters related to the earthquake source were obtained such as (1) the temperature (900 °C to 1100 °C) generated during fast fault slips (Kuo et al., 2011), and (2) the localized interval of pseudotachylyte (1 mm) and associated surface fracture energy (Fig. 2a in Kuo et al., 2014a). Recently, rock friction experiments show that frictional melting does occur in clayey gouge during seismic fault slips (Han et al., 2014). Microstructures of the PSZ of TCDP show the transformation from pseudotachylyte to smectite (Janssen et al., 2014). Integrated with natural observation of TCDP and laboratory rock experiments mentioned above, we surmise that pseudotachylyte was generated at shallow depths and promptly altered to smectite in the Chelungpu fault.

In particular, ultrafine spherical quartz (USQ) grains ranging from 50 nm to sub-microns in sizes and pyrite aggregates were obtained from pseudotachylyte within the PSZ of TCDP Hole-A (Fig. 2b and c, and also see Fig. 2b in Ma et al., 2006; see Supporting information Audio S1 for the 3D tomography of Chi-Chi PSZ constructed by TXM). Results of high-velocity friction experiments on clayey gouge show that clay minerals were melted by flash heating at asperities, but USQ was not observed (Han et al., 2014). Results of milling experiments on siltstone of TCDP display that ultrafine particles covered by amorphous surface layers can be generated by comminution (up to 6 h) and fit the mineral anomalies of the PSZ obtained in Hole-B (Hirono et al., 2014). However, the combination of pseudotachylyte with clay anomalies, clay-clast aggregates (CCAs), vesicles, and USQ observed within the Chi-Chi PSZ (Boullier et al., 2009; Kuo et al., 2009, 2011; Ma et al.,