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Clay mineral anomalies in the fault zone of the Chelungpu Fault, Taiwan, and their implications

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[1] The Taiwan Chelungpu-fault Drilling Project (TCDP) Hole-A recovered continuous core samples across the rupture zone of the 1999 Chi-Chi earthquake (Mw7.6). Studying in-situ chemical properties sequentially from fresh-fault-zone materials of the Chelungpu fault provides insight into possible faulting mechanisms. Distinct anomalies of mineral assemblages at the 1111-m fault zone of TCDP Hole-A are found to be: (1) A decrease in clay content within the primary slip zone (PSZ); and (2) A significant decline of illite, disappearance of chlorite and kaolinite, and spike in smectite within the PSZ. Meanwhile, features relating to melting or amorphous material in the PSZ have been observed by SEM and TEM. The results suggest that the PSZ might have experienced generation of glassy materials such as pseudotachylyte by the expense of clay minerals due to strong shear heating, then prompt alteration of pseudotachylyte into smectite. Characteristics of clay minerals and images obtained from electronic microscopes in the PSZ thus imply that pseudotachylyte possibly developed during the 1999 Chi-Chi earthquake, but quickly altered into smectite. This particular phenomenon may explain why pseudotachylyte is rarely found in exhumed hydrated fault zones. **Citation:** Kuo, L.-W., S.-R. Song, E.-C. Yeh, and H.-F. Chen (2009), Clay mineral anomalies in the fault zone of the Chelungpu Fault, Taiwan, and their implications, *Geophys. Res. Lett.*, *36*, L18306, doi:10.1029/2009GL039269.

1. Introduction

[2] The Chi-Chi earthquake (Mw 7.6) struck central Taiwan in 1999, producing large slip (~8m) in its northern segment [*Lee et al.*, 2002]. In 2004, TCDP Hole-A retrieved continuous cores from 500 to 2003 m in depth. These cores penetrated the Chelungpu fault at around 1111 m revealing that slip had occurred within and parallel to the Pliocene Chinshui Shale during the Chi-Chi earthquake (Figures 1a and 1b) [*Lee et al.*, 2001; *Yue et al.*, 2005]. In the Chinshui Shale, clay content is relatively high compared to the surrounding formations. This relative abundance of clay minerals in the Chinshui Shale makes the site suitable for a study of transformation of clay minerals in a context of a fault zone within sediments. The 1111-m fault zone can be divided into the wall rock, damage zone, and fault core (Figure 1c) [*Yeh et al.*, 2007] based on *Chester and Logan*'s [1986] definition of fault structures. The fault core is a part of the fault zone, where most of the slip and high shear stress accumulates. Fault cores are typically characterized by comminuted rocks and chemical alteration such as clayey gouge [*Caine et al.*, 1996], and sometimes pseudotachylyte [e.g, *McKenzie and Brune*, 1972]. Clay mineral is the most common constituent of clayey fault gouge, and clay alteration, such as illite-smectite transformation, in the fault core may be the result of fluid flow and/or co-seismic frictional heating host rocks [*Solum et al.*, 2005; *Vrolijk and van der Pluijm*, 1999]. The discovery of altered smectite from glassy material such as pseudotachylyte [e.g., *Bauluz et al.*, 2004] has not as yet been reported in fault cores.

[3] Pseudotachylyte is generally known as a product of shearing, comminution, and friction-induced melting during coseismic slip along a fault [*McKenzie and Brune*, 1972; *O'Hara*, 2001; *Di Toro and Pennacchioni*, 2004]. Also, melting could be one of the earthquake faulting mechanisms for rupture propagation [*Di Toro and Pennacchioni*, 2004], like the huge slip that occurred in the northern segment of the Chelungpu fault during the Chi-Chi earthquake. Furthermore, the existence of pseudotachylyte in the slip zone of seismic faults is often considered reasonable; however, it is relatively rare to identify pseudotachylyte in exhumed hydrated fault zones [*Sibson*, 2003].

[4] The fresh fault zone materials of TCDP Hole-A thus provide us a unique opportunity to study in-situ clay minerals and further to evaluate the possible faulting mechanism(s) and the achieved temperature for the Chi-Chi earthquake. Moreover, in this study we focus on the fault zone at 1111 m within the Chinshui Shale because of its special clayey characteristics, and on the black gouge (Figure 1c), which is considered to be the PSZ of the Chi-Chi Taiwan earthquake [*Ma et al.*, 2006; *Song et al.*, 2007; *Boullier et al.*, 2009]. Last but not least, the particular phenomenon of glass-smectite transformation in the PSZ may explain why pseudotachylyte was rarely identified in exhumed fault zones, certainly not in proportion to the expected dominance of seismic slip [*Sibson*, 2003].

2. Experimental Methods and Results

2.1. XRD Analysis

[5] To understand the background of mineral assemblages and the average clay contents of sedimentary formations, twenty-eight powdered samples, extracted at equal intervals, were examined from the TCDP Hole-A core by XRD analysis (Figure 2a). In addition, twenty-six samples were sequentially analyzed across the Chelungpu fault zone

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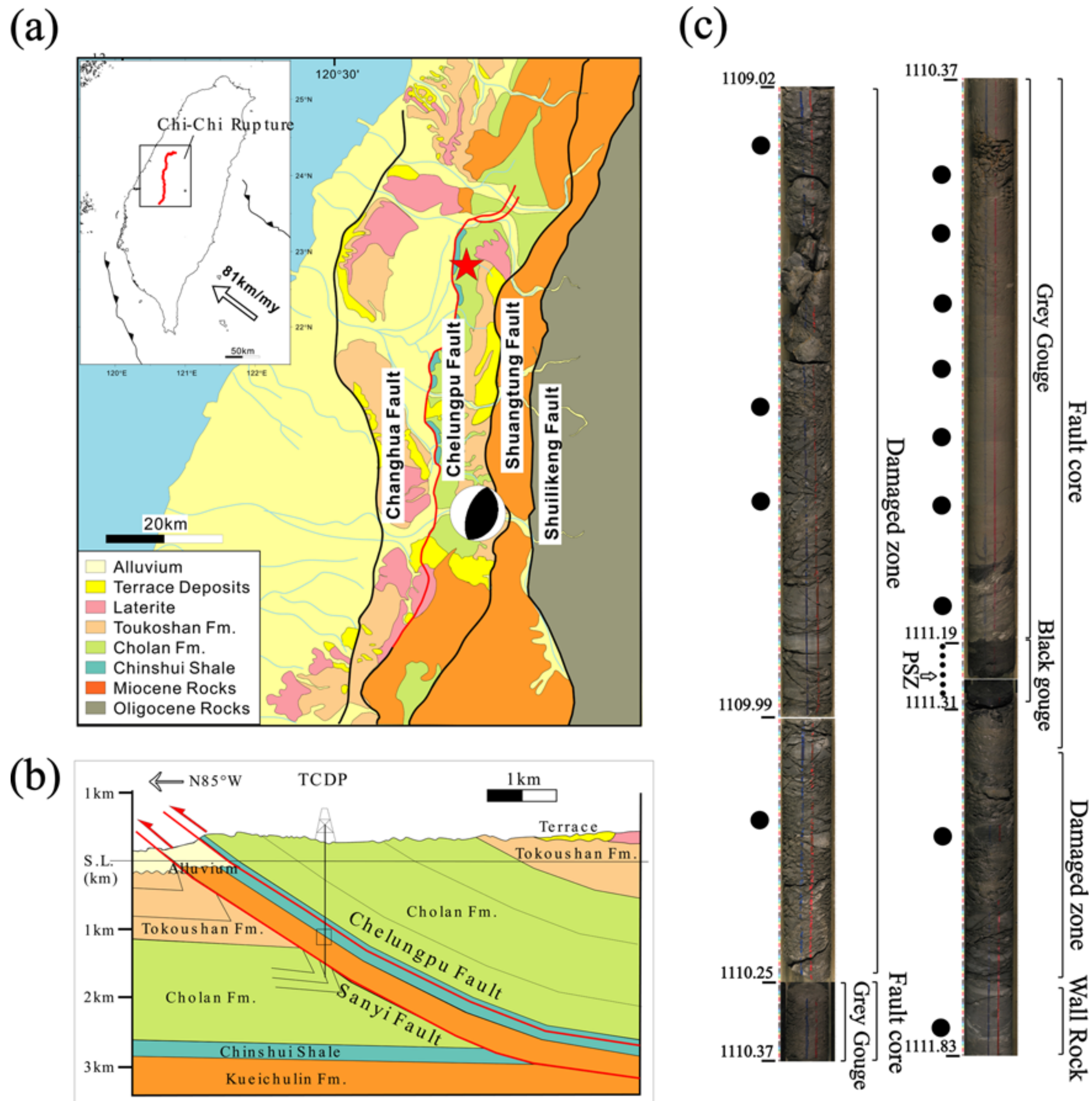

Figure 1. (a) Geological map of the central part of western Taiwan showing the distribution of formations and major fault zones. The TCDP site is indicated by a red star. The focal mechanism of the Chi-Chi main shock is located at the hypocenter of the Chi-Chi earthquake [*Kao and Chen*, 2000]. The insert box is the tectonic setting of Taiwan. (b) Cross section displaying the relation between formations and fault zones (as per *Hung et al.* [2007]). The rectangle is the Chelungpu fault zone and enlarged in Figure 1c. (c) The image exhibiting major portions of the Chelungpu fault zone. Big and small black spots are our sampling locations.

(Figure 1c), including eight samples of the 1m-thick gray gouge (~1 m), seven samples of the 12 cm-thick black gouge (12 cm), and another eleven samples from the damage zone and wall rocks. For identifying and quantifying clay minerals of the clay-size fraction, glass slides of oriented samples are made. All samples are disaggregated in distilled water using ultrasonic bath. After centrifugation, draft suspensions of <2 μm were deposited on glass slides. Further, ethylene glycol was used to hydrate the clay samples so as to recognize swelling clays (smectite and Illite/Smectite mineral). A Science MXP 3X X-ray diffractometer was used under the conditions of filtered CuKα (1.540 Å) radiation, 35 KV and 15 mA of X-ray generator, 1.0° min^{-1} scanning speed, and 3° ~ 40° of 2θ coverage.

[6] The major mineral assemblages via bulk XRD experiments are identified as quartz, feldspar, and phyllosilicate minerals such as muscovite/illite, smectite, kaolinite and chlorite (Figure 2). On the basis of the semi-quantitative XRD method [*Biscaye*, 1965], the relative clay percentage of sedimentary formations is found in the constant range of 20–40% but drastically increases to >40% in the gray gouge zone and black gouge zone, except in the PSZ (10 ~ 20%) (Figure 2b).

[7] Clay minerals of <2 μm from our samples are recognized as illite, smecctite, chlorite, and kaolinite, and are estimated by semi-quantitative XRD method [*Biscaye*, 1965]. The relative percentage of illite varies between 50% and 80% for all samples except at the PSZ where dramat-

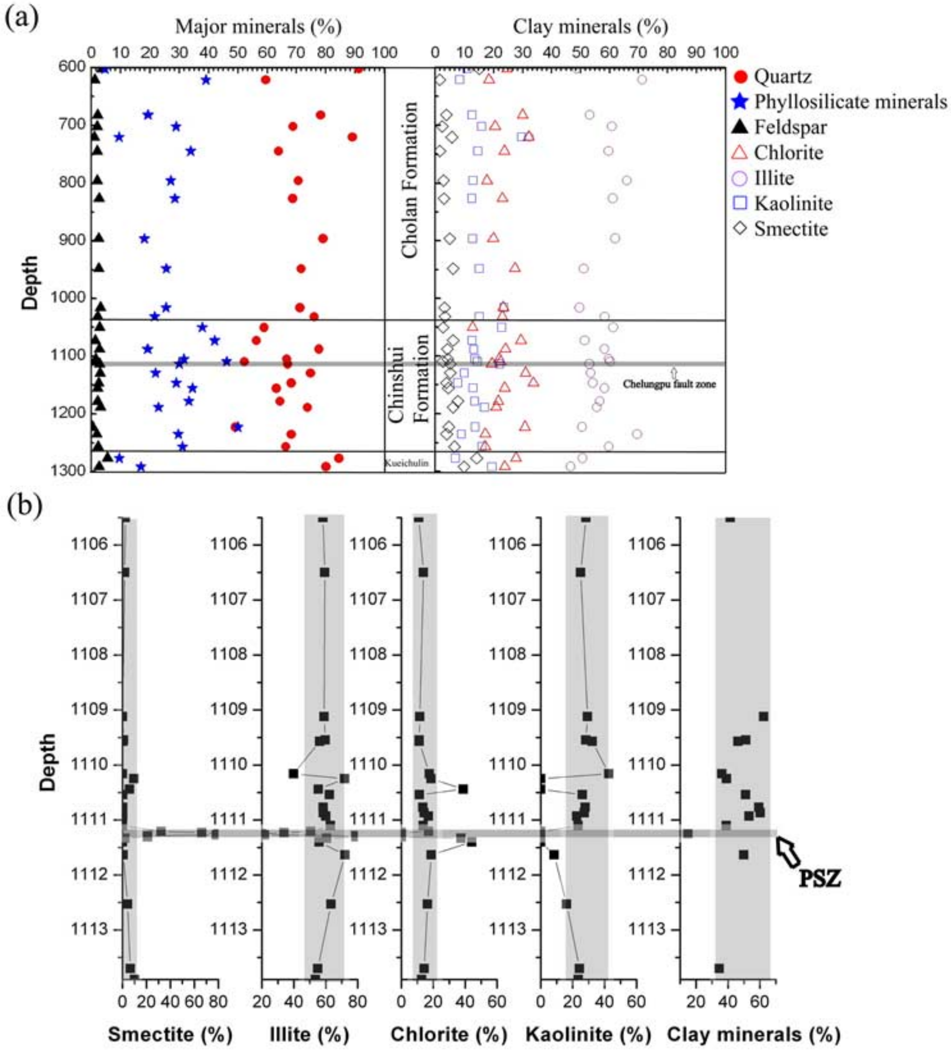

Figure 2. (a) Results of relative percentage of major minerals and clay minerals from TCDP cores from 600 to 1300 m in depth. (left) Plot of relative major mineral content from bulk XRD analysis. (right) Result of relative clay mineral percentage by clay mineral XRD analysis. (b) Relative clay mineral percentage and clay mineral abundance across the Chelungpu fault zone. Gray area is noted as the representative of clay content.

ically decreases to 20% (Figure 2). The relative percentage of chlorite and kaolinite for all interval are around 10 ~ 20% and 15 ~ 35% respectively, but they diminish to zero in the PSZ (Figure 2). On the other hand, smectite is rare or absent in all portions of the fault zone and the Chinshui Shale but becomes abundant (up to ~80%) in the PSZ (Figure 2). This suggests that the PSZ can be identified by examining smectite distribution (Figure 3a).

[8] The XRD patterns of ethylene-glycol samples indicate only smectite but no Illite/Smectite mineral in the PSZ (Figure 3b). This result is different from the finding of surface outcrops [*Liao*, 2003; *Issacs et al.*, 2007] contaminated by surface weathering processes. The evidence of low smectite content in all our samples except the PSZ and no Illite/Smectite minerals in the PSZ supports that we should be able to obtain useful information about the faulting mechanism and/or frictional heat via interpreting the characteristics of in-situ clay mineralogy.

2.2. Evidence of Pseudotachylyte at the 1111-m Zone

[9] SEM images from the PSZ in our study show the melting-origin textures (Figures 4a and 4b). These are similar to the occurrence of pseudotachylyte in TCDP Hole-B [*Otsuki et al.*, 2009], although the micro-scale observations from TCDP Hole-A display no typical structure of pseudotachylyte [*Boullier et al.*, 2009]. Many vesicles of about 1- to 40-μm diameter within the PSZ are found (as the vesicule in Figure 4a), indicating that this sample indeed melted. Also, thin strings connecting grains are expected to be stretched melted or amorphous (Figure 4b). Besides which, TEM images of the PSZ show no crystal lattice phenomena (Figures 4c and 4d). These observations suggest that melting certainly occurred. The finding of no clear bump in the XRD patterns of PSZ (Figure 3c) indicates that glass content is less than 25% [*Lin*, 1994]. Consequently, we conclude that melting occurred in the PSZ of the black gouge but may have been at a

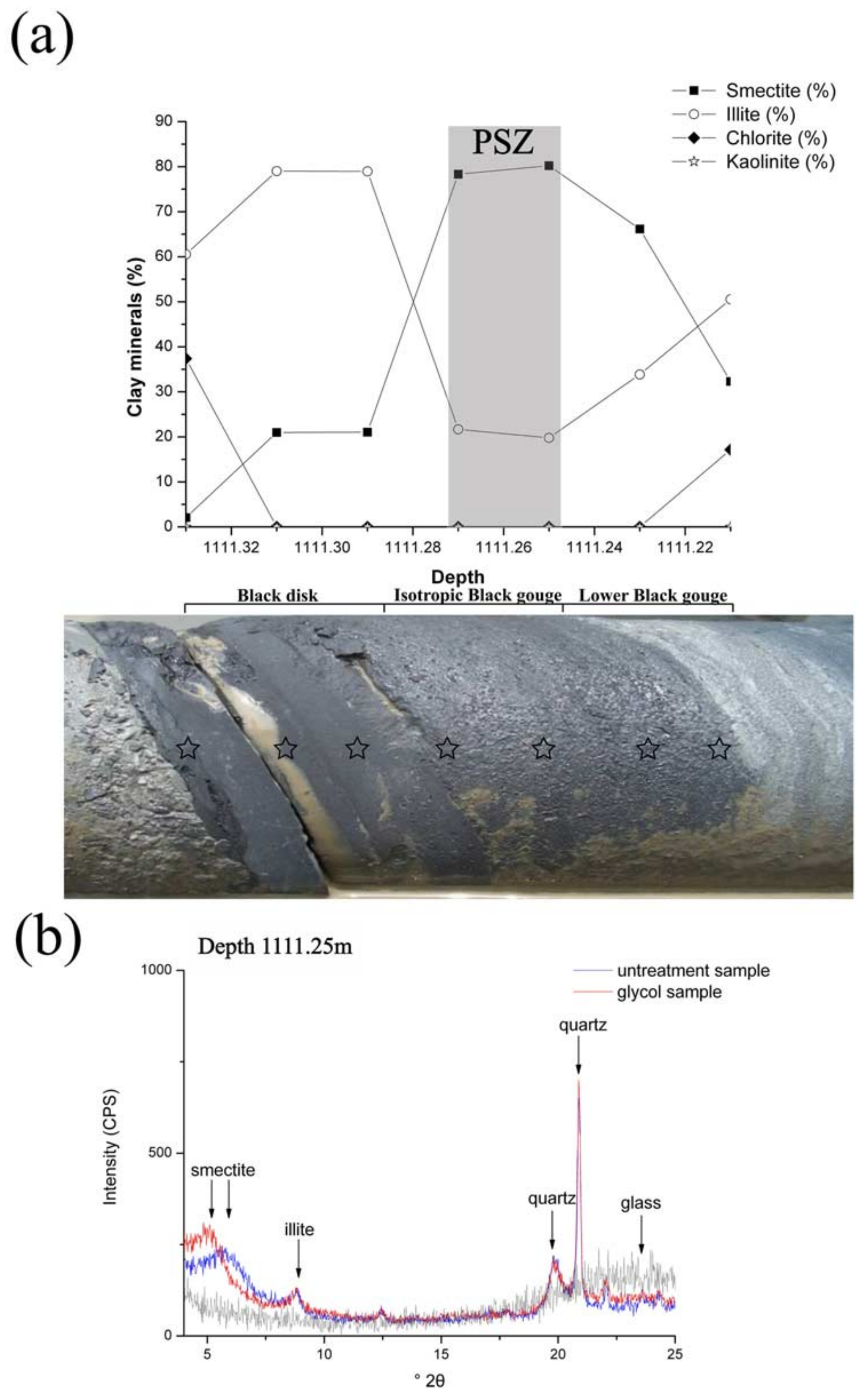

Figure 3. (a) Detailed distribution of clay mineral relative percentage across the black gouge zone which are described as lower black gouge, isotropic black gouge and black disk by *Boullier et al.* [2009]. Stars are the location of collected samples for XRD. Distinct anomaly of clay minerals is observed within the PSZ. The gray zone indicates the PSZ. (b) X-ray diffraction patterns of the PSZ for identifying the I/S mix-layer. Blue and red lines are the results from untreated and glycolated samples, respectively. Light gray lines are shown as glass peaks (the glass is the melt of Chinshui Shale) if pseudotachylyte existed in the sample.

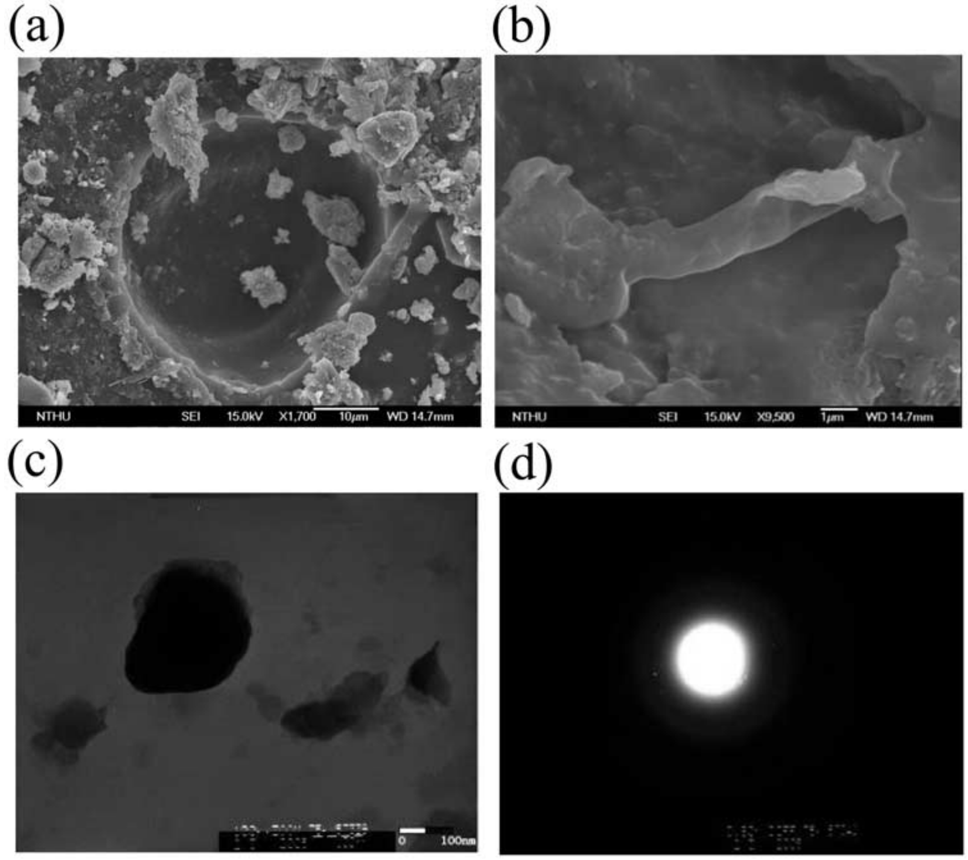

Figure 4. (a) SEM image of the typical surface texture of the pseudotachylyte sample in the PSZ. The image shows several vesicles or bubbles on the surface in the PSZ. (b) SEM image of pseudotachylyte displays string that is melted material drawn out when cracks opened. (c) TEM image of the grains collected from the PSZ, and (d) no light spots are evident indicating no crystal lattice in this grain. These images indeed provide evidence of melting and suggest pseudotachylyte indeed existed.

level where it was too little or not preserved sufficiently to be observed by eye or with microscopes.

3. Discussion and Conclusion

[10] Semi-quantitative results of bulk and clay minerals from X-ray diffraction analysis show extreme anomalies in the PSZ. A drastic decrease in clay percentage for the black-gouge zone of the PSZ could possibly be explained by two different processes: 1) sedimentation; and 2) tectonic deformation. However, the first possibility can be ruled out for the following two reasons. First, the Chinshui Shale is almost homogeneous and its clay percentage is relatively high according to our data (Figure 2) and the literature [*Liao*, 2003; *Issacs et al.*, 2007]. So, the probability of a lower clay content caused by any special sedimentation event within the several-centimeter horizon of the short sampling interval would be very low. Second, the clay assemblage in the PSZ is completely different from other portions of the fault zone and wall rocks. If this difference between clay assemblages resulted from sedimentation processes, it should show a transition zone with gradual changes in clay minerals. However, no such transition zone has been observed but only a clear-cut boundary has been revealed under a dense sampling (Figure 3a). Thus, the most obvious possibility is that tectonic processes have been responsible for the decrease in clay percentage in the PSZ. Furthermore, the high clay content of surrounding gray gouge is consistent with the prediction of fault core characteristics [*Caine et al.*, 1996].

[11] The smectite in TCDP is rare to nonexistent in all parts of the 1111-m fault zone but significantly increases in the PSZ. Since sedimentary origin is not favored as previously discussed and no Illite/Smectite mineral is observed, the alteration of smectite in the PSZ from glass (pseudotachylyte) may be the most possible scenario. Although we do not directly observe the occurrence of glass-smectite reaction under the microscope, such a reaction is well documented in many natural environments and experimental tests [*Bauluz et al.*, 2004]. Generally, the advance of glass-smectite reaction only takes 3 days at 90°C with 1–10M NaOH solution [*Tomita et al.*, 1993]. Provided that the achieved temperature of the Chi-Chi slip zone was at least over 400°C [*Mishima et al.*, 2009] and fluid was sealed in the fault, it is a very reasonable conclusion that the transformation of smectite from glass occurred in less than a few days to years after the Chi-Chi earthquake, even though the kinetics of this reaction is not probed in this study because of a lack of chemical composition of glass, and fluid in this stage. The smectite abundance distribution (Figure 3a) thus implies that the most possible PSZ of the 1999 Chi-Chi earthquake is located in the black gouge, and

this is consistent with previous suggestions [*Ma et al.*, 2006; *Boullier et al.*, 2009].

[12] Average-clay-content anomalies and relative individual clay percentages across the 1111-m fault zone can be explained by tectonic process involving melting caused by friction. Due to comminution and chemical alteration, clay mineral content within the fault core has increased, compared with wall rocks. However, within the PSZ, frictional heat may have caused mineral melting or thermal decomposition depending on temperatures achieved and reaction temperatures for clay mineral formation. The occurrence of pseudotachylyte is imaged as extremely fine droplets widely spread throughout the matrix of the PSZ instead of from old clasts, as described by *Boullier et al.* [2009] via counting the relative percentage of smectite and old clasts. The frictional temperature of the Chi-Chi earthquake must have been at least 800°C because of the melting or thermal decomposition of chlorite [*Brindley and Ali*, 1950]. It is expected that heat and fluid exist for glass-smectite reaction which are necessary factors for the model of thermal pressurization as well. Thus, we are providing the possible scenario for the PSZ of Chi-Chi earthquake that frictional heat melted most of the clay except for illite, then thermal pressurization proceeded and altered tiny glass to smectite. This particular description of a transfer process for pseudotachylyte could explain why it is rarely identified in exhumed clay-rich hydrated fault zones, certainly not in proportion to the expected dominance of seismic slip.

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