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Evidence of frictional melting from disk-shaped black material, discovered within the Taiwan Chelungpu fault system

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[1] The Taiwan Chelungpu-fault Drilling Project penetrated three fault zones as the Chelungpu fault system, which slipped during the 1999 Chi-Chi earthquake, discovering disk-shaped black material (BM disk) within the middle and lower fault zones in Hole B. The microscopic features of the BM disks indicated that they were pseudotachylytes, and they showed high magnetic susceptibility, possibly the result of intense shearing or high temperature conditions. Inorganic carbon content of the BM disks was low, possibly because of thermal decomposition of carbonate minerals. The high temperatures might be related to frictional heating during the earthquake, implying that the BM disks were produced under intense shearing with frictional heating that reached melting temperature. Because the disks, which provide the only evidence of melting, pre-date the 1999 earthquake, we concluded that frictional melting did not occur during the earthquake. **Citation:** Hirono, T., et al. (2006), Evidence of frictional melting from disk-shaped black material, discovered within the Taiwan Chelungpu fault system, *Geophys. Res. Lett.*, *33*, L19311, doi:10.1029/2006GL027329.

1. Introduction

[2] The 2002 Taiwan Chelungpu-fault Drilling Project (TCDP) was undertaken to investigate the faulting mechanism of the 1999 Chi-Chi earthquake, which occurred at lat 23.853, and long 120.816, with a focal depth of 8 km [*Ma et al.*, 1999] (Figure 1). A relatively high slip velocity and large displacement (4.5 m/s and 12 m, respectively) and low level of high-frequency radiation were recorded in the northern part of the Chelungpu fault, where the earthquake rupture occurred [*Ma et al.*, 2000]. *Andrews* [2005] proposed that the high slip velocity and large displacement resulted from thermal pressurization, through which fluid pressure generated by shear-related heating reduces the fault strength during seismic slip [e.g., *Fialko and Khazan*, 2005]. Frictional melting, which can lower friction on the fault plane [e.g., *Hirose and Shimamoto*, 2005], is another mechanism that might explain the high slip velocity and large displacement. The main aim of TCDP was to assess these hypotheses through observation and analyses of rock samples. TCDP penetrated the Chelungpu fault (Figure 1) and recovered core samples from two holes, Hole A (total depth, 2003.00 m) and Hole B (total depth, 1352.60 m). In Hole B, drilled cores were recovered only from depths between 948.42 and 1352.60 m, and three fault zones, 1136mFZ (1134–1137 m), 1194mFZ (1194–1197 m), and 1243mFZ (1242–1244 m), were recognized in the core samples as a series within the Chelungpu fault [*Hirono et al.*, 2006]. The architecture of each fault zone consisted of fracture-damaged zones, breccia zones and gouge zones, and in each gouge zone, black and gray gouges were observed. In particular, disk-shaped black materials, called BM disks [*Hirono et al.*, 2006], were developed only in 1194mFZ and 1243mFZ. BM disk appeared to be pseudotachylyte and it might be the only evidence of frictional melting because no other candidates for this mechanism were observed. Therefore, its identification was regarded as important for elucidating the faulting mechanism of the 1999 Chi-Chi earthquake. We examined the BM disk mesoscopically and microscopically using optical and scanning electron microscopes, measured its magnetic susceptibility, and analyzed its carbon content with the aim of determining the slip mechanism that characterized the 1999 Chi-Chi earthquake.

2. Meso- and Microstructure of the BM Disk

[3] BM disks were developed only within 1194mFZ and 1243mFZ in Hole B [*Hirono et al.*, 2006]. In 1194mFZ, the BM disk was 2 cm thick, and stiffer and more cohesive than the gouge (Figure 2). The upper surrounding rock was slightly deformed sandstone with minor included shear bands. The boundary between the sandstone and the BM disk was extremely sharp, and minor cracks crossed the boundary. The lower surrounding rock was black gouge, which was composed of fine-grained materials with weak foliation and/or random fabric texture. Although the boundary between the lower gouge and the BM disk was relatively sharp, there was some fragmentation at the boundary, and there were some fragments of BM disk within the gouge. Similarly, in 1243mFZ (Figure 3), an extremely sharp boundary separated the BM disk from the gray gouge above. Below the BM disk was black gouge, and, as in 1194mFZ, fragmentation of the BM disk at the boundary was observed.

[4] Petrographic observations showed that the BM disk in 1194mFZ was composed of an abundant fine-grained

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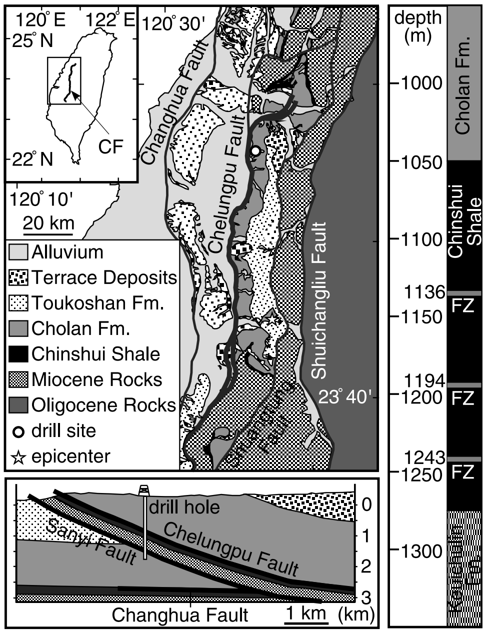

Figure 1. Geological map of central Taiwan, showing the site of the Taiwan Chelungpu-fault Drilling Project, an E-W cross section through the site location, and the lithological column of core samples recovered from Hole B [from *Hirono et al.*, 2006]. CF, Chelungpu Fault; FZ, fault zone.

matrix supporting well-rounded lithic fragments, which were composed mainly of quartz, plagioclase, and potassium feldspar (Figure 4a). Foliations, indicated by the preferred orientations of fine platy minerals, were observed parallel to the boundaries with the upper and lower surrounding rocks.

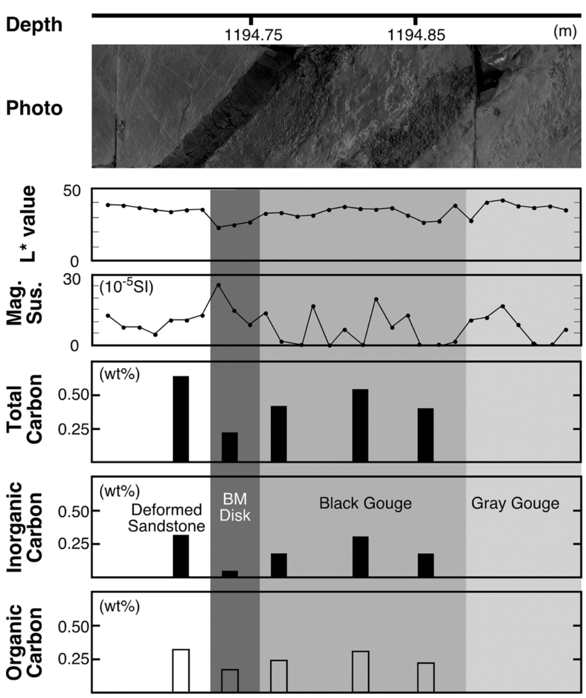

Figure 2. Photograph of the 1194mFZ core section showing BM disk and corresponding L* values, magnetic susceptibilities, and total, inorganic, and organic carbon contents.

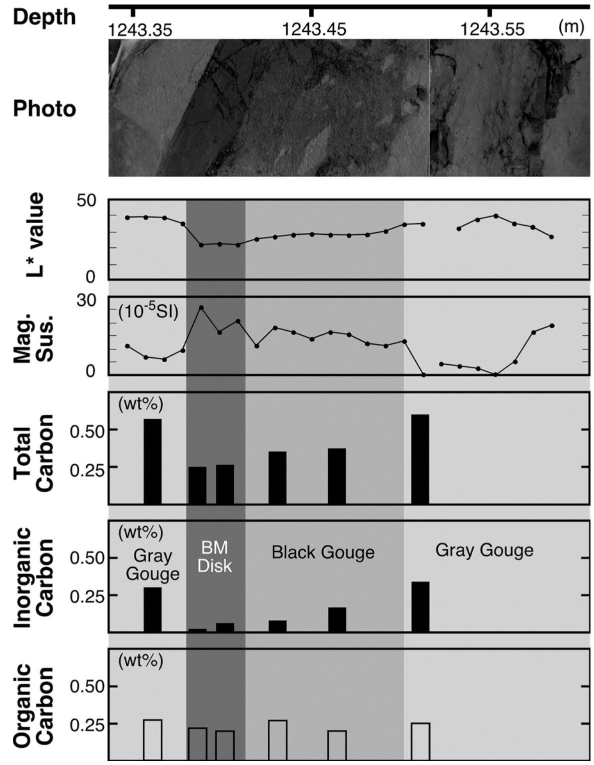

Figure 3. Photograph of the 1243mFZ core section showing BM disk and corresponding L* values, magnetic susceptibilities, and total, inorganic, and organic carbon contents.

Scanning electron microscopy (SEM) showed subangular to well-rounded micrometer-sized grains within a poorly sorted abundant matrix (Figure 4b). At higher magnification, SEM showed hourglass structures around the edges of

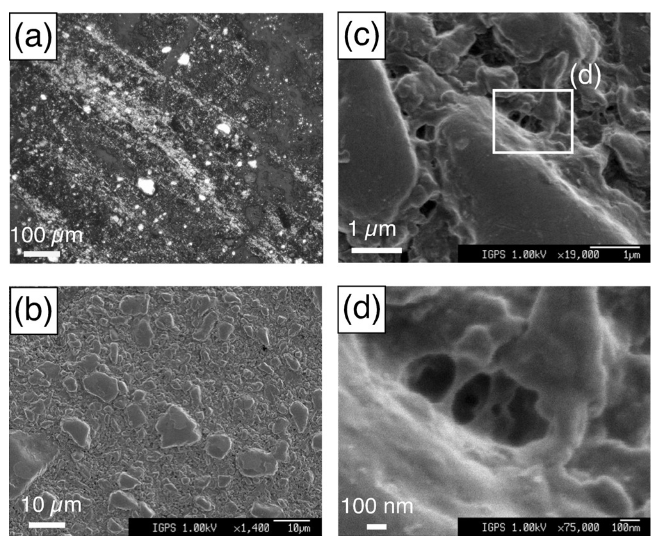

Figure 4. Microstructural observations of the BM disk in 1194mFZ. (a) Optical microscope image. (b) Scanning electron microscope image. (c) High magnification scanning electron microscope image. Hourglass structure can be seen on the edge of the large grain in the center of the image. (d) High magnification scanning electron microscope image. Hourglass and bubble structures can be seen in the center of the image.

individual grains (Figures 4c and 4d), which might be evidence of quenching immediately after melting. On the basis of these features, the BM disk was identified as pseudotachylyte. Based on the criteria of degree of melting determined by the volume fraction of unmelted grains [*Otsuki et al.*, 2005], it appears that only a low degree of melting occurred (MD0 or MD1 of *Otsuki et al.* [2005]). The microstructure of the BM disk in 1243mFZ had similar features to that in 1194mFZ, and it was also identified as pseudotachylyte with ultracataclastic texture and a low degree of melting.

3. Carbon Content and Magnetic Susceptibility Measurements

3.1. Methods

[5] Although we concluded from the microscopic observation that the BM disk could be identified as pseudotachylyte, we measured its total and inorganic carbon content to determine whether coal was present. We also measured the brightness (L* value) and magnetic susceptibility of the BM disk.

3.1.1. Total Carbon Analysis

[6] Concentrations of total carbon (TC) within and around the BM disk were determined using an elemental analyzer (Thermo Finnigan FlashEA 1112). Powdered samples (1–10 mg) were wrapped with tin foil and combusted at 1000°C in a quartz column. Released CO_2 gases were measured by the analyzer. Relative standard deviations from the means of multiple determinations of a standard material were within less than 1%.

3.1.2. Inorganic Carbon Analysis

[7] Concentrations of inorganic carbon within and around the BM disk were measured by coulometric titration using a CM5012 CO_2 coulometer (UIC Inc. Coulometrics). Powdered samples (10 mg) were reacted with 20% phosphoric acid for 1 h, and released CO_2 gases were analyzed with the coulometer. Relative standard deviations from the means of multiple determinations of $CaCO_3$ were within less than 1%.

3.1.3. Magnetic Susceptibility Measurement

[8] Magnetic susceptibility is the degree to which a material can be magnetized in an external magnetic field. *Hirono et al.* [2006] reported high values of magnetic susceptibility within the black gouge zone of all three fault zones, as measured by a Bartington loop sensor (MS2C). However, the spatial resolution of the loop sensor, 20–30 cm, was not high enough to distinguish values within the BM disk. Therefore, the magnetic susceptibility was measured again on the longitudinally split surface of the core using a Bartington MS2E surface sensor. The operating frequency used was 2 kHz, and the sensitive area of the sensor probe was 3.8 × 10.5 mm. Measurements were made at 1.0-cm intervals, with a sensitivity of 10^{-6} SI unit.

3.1.4. L* Value Measurement

[9] A Minolta CM-2002 color spectrophotometer was used to quantitatively evaluate the blackness of the BM disk and gouge zones. The spectrophotometer used a xenon arc light source, and collected light in 10-nm increments from 360 to 740 nm. The measurement area of the instrument was 8 mm in diameter, and measurements were made at 1.0-cm. intervals. Measured data were expressed as brightness and chromaticity in terms of L*, a*, and b*, which correspond to brightness, red-green, and blue-yellow, respectively. Only L* values, with lower values corresponding to darker, are shown in Figures 2 and 3.

3.2. Results

[10] In 1194 mFZ, both the total and inorganic carbon contents were significantly lower within the BM disk than in the surrounding rocks (Figure 2). The organic carbon content, calculated by subtracting the inorganic carbon content from the total carbon content, was slightly lower within the BM disk. In addition, magnetic susceptibility of the BM disk was notably higher, and it had a relatively lower L* value. In the black gouge zone, magnetic susceptibility fluctuated and in several positions had a zero value. The carbon contents did not differ, however, between the relatively intact sandstone and the gouge zones.

[11] In 1243 mFZ, the BM disk showed similar properties to those in 1194mFZ, characterized by lower total and inorganic carbon contents, higher magnetic susceptibility, and lower L* values (Figure 3). These carbon contents were lower within the black gouge zone than within the gray gouge.

4. Discussion

[12] Although *Hirono et al.* [2006] reported that magnetic susceptibility was high within the black gouge zones, which included the BM disk, they were unable to correlate the position of the highest value with that of the BM disk, owing to the low spatial resolution of the sensor. By using a higher resolution sensor than that used by *Hirono et al.* [2006], we were able to show that the highest value of magnetic susceptibility was associated with the BM disk. Magnetic susceptibility is strongly influenced by the concentration of ferrimagnetic minerals such as magnetite and hematite, and also by the grain size of those ferrimagnetic minerals [e.g., *Dearing*, 1999]. There are two possible explanations for the high magnetic susceptibility of the BM disk: (1) ferrimagnetic grains were newly formed by thermal decomposition of paramagnetic phases; or (2) ferrimagnetic grains were crushed into submicrometer size by shearing, although the total concentration of the magnetic minerals did not change. Based on the microscopic observations of the BM disks, the first possibility is more likely because the BM disks have experienced frictional heating at temperatures beyond melting point. However, the second possibility may also be valid because the BM disks displayed ultracataclastic texture. Cataclasis accompanies grain-size reduction by intense shearing. Therefore, both mechanisms are likely to have occurred when the BM disks were formed.

[13] On the other hand, lower concentrations of total and inorganic carbons within the BM disks compared with the surrounding rocks are especially notable. Inorganic carbon generally occurs as carbonate minerals such as calcite and siderite. Thus, lower concentrations of inorganic carbon may imply that carbonate minerals are missing, owing either to their dissolution into pore water, or to thermal decomposition. *Golden et al.* [2004] demonstrated that thermal decomposition of siderite ($FeCO_3$), accompanied by magnetite formation and the release of CO_2 and CO gases,

occurs upon heating to 550°C. Newly produced magnetite might have caused the higher magnetic susceptibility within the BM disk. The lower organic carbon contents within the BM disks might have resulted from pyrolyzation of organic matter at high temperature accompanied by the release of carbon gas. For example, *Sackett* [1995] demonstrated the thermal decomposition of methane at temperatures of 700–1000°C. As the BM disk has been identified as pseudotachylyte, it is likely to have experienced frictional heating at temperatures beyond melting point; thus, the hypothesis of reduction of carbon content by thermal decomposition of carbonate minerals and organic matter may be valid.

5. Conclusions

[14] Based on microscopic examination, we concluded that the BM disks within both 1194 mFZ and 1243 mFZ were pseudotachylytes. The cause of the lower inorganic carbon contents within the BM disk is most likely the result of thermal decomposition of carbonate minerals by frictional heating. The stiffer and more cohesive nature of the disks compared with the gouges may be the result of sintering. The higher magnetic susceptibility may be the result of newly formed ferrimagnetic grains and/or grain-size reduction of pre-existing ferrimagnetic grains by intense shearing. Consequently, we conclude that the BM disks were produced under intense shearing with frictional heating reaching melting temperature.

[15] However, an unresolved question is whether the BM disks formed during the 1999 Chi-Chi earthquake or not. Which fault zones, shear zone, or plane slipped during the earthquake is unknown. The BM disks in both 1194 mFZ and 1243 mFZ were overprinted by small cracks extending from the upper rocks, and there were fragments of BM disk within the lower gouges. These observations indicate that the BM disks might have formed before the 1999 earthquake.

[16] Low friction along the fault zone during the 1999 earthquake can be explained by the generation of melt, which might reduce frictional resistance. However, friction experiments by *Tsutsumi and Shimamoto* [1997] indicate that resistance increases instantaneously at the onset of melting and decreases thereafter. This implies that the frictional melting does not necessarily follow low friction. Moreover, the BM disks showed a low degree of melting, which would be unlikely to provide efficient melt lubrication.

[17] Within the sections of the Chelungpu fault system that we investigated (1136 mFZ, 1194 mFZ, and 1243 mFZ in Hole B), there was no evidence of frictional melting other than that provided by the BM disks. Thus, we concluded that frictional melting did not occur during the 1999 earthquake because the disks, which provide the only evidence of melting, pre-date the earthquake. An alternative hypothesis is that thermal pressurization and/or hydrodynamic lubrication might have been responsible for decreasing friction along the fault plane. Further investigations are needed of other aspects of the fault system, such as the fault gouge, to identify the slip plane or slip zone responsible for the most recent earthquake activity, and to better understand the faulting mechanism of the 1999 Chi-Chi earthquake.

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