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Characteristics of chlorites in seismogenic fault zones: the Taiwan Chelungpu Fault Drilling Project (TCDP) core sample

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Abstract

The iron content and the asymmetry of iron and magnesium ions in chlorites are examined for the Chelungpu Fault in Taiwan, which is a seismogenic fault. The samples are collected from the cores drilled for the Taiwan Chelungpu Fault Drilling Project (TCDP). Three fault zones are recognized as candidates for the source of seismogenic materials. The fault zones are composed of fractured-damaged rocks, breccia, gray gouge, black gouge, and black material. Chlorite from each type of rock was analyzed by using X-ray diffraction (XRD). The iron content and asymmetry of the iron and magnesium ions in the chlorites were estimated from the XRD peak ratios. The hydroxide and silicate layers in the black gouge and black material have low iron contents. Many studies have suggested that a temperature rise occurred at the fault zones. In addition, the temperature rise can result in the production of iron oxides such as magnetite or maghemite, as reported by other studies. However, the temperature rise cannot explain the low value of iron content in the chlorites. Another reason for the low value of iron content is the variation in the pH of the fluid, which can be controlled by radical reactions. Therefore, the reactions at the seismogenic fault are due to not only the thermal decomposition resulting from the temperature rise and but also rock-fluid interactions based on the chlorite characteristics.

1 Introduction

The formation of clay minerals within gouges is strongly related to fault activities because gouges are common products of shallow faulting (e.g., Sibson, 1977) and clay minerals are dominant in gouges. Because the clay-rich gouges are often observed in natural fault zones, clay minerals are important to understand fault processes. However, the mechanism or reaction resulting in the formation of clay minerals along fault zones is poorly understood because of the complexity of the interaction between clay formation and faulting (Vrolijk and van der Pluijm, 1999).

In this study, we focused on the characteristics of clay minerals in seismogenic fault rocks. In particular, the characteristics of chlorite were analyzed because chlorite can be classified on the basis of the detailed composition of iron and magnesium from X-ray diffraction analysis (Moore and Reynolds, 1989). The iron and magnesium composition in chlorite can be related to the thermal condition (Ohta and Yamaji, 1988), rock-fluid interaction (e.g., Ross, 1969; Malmstrom et al., 1996) or chemical variation in source materials.

The analyzed samples are from the Chelungpu Fault in Taiwan. The fault is located at the western side of Taiwan forming a fold and thurst belt with other thrust faults such as Changhua Fault or Shuagtung Fault (Fig. 1). The Chelungpu fault was activated during the Chi-Chi earthquake (Mw=7.6) on 21 September 1999 (e.g., Ma et al., 2000). On the basis of a high-resolution map of the displacement on the fault surface, an area with a large displacement (asperity) is located in the shallows in the northern part of the fault (e.g., Ma et al., 2000). The Taiwan Chelungpu Fault Drilling Project (TCDP) was conducted to investigate the fault zone to a depth of approximately 1 km at the northern site of the Chelungpu fault (Fig. 1). In this study, the Hole B core samples recovered from the depth range of 948.42 m to 1352.60 m are analyzed.

In the northern part of the Chelungpu fault, the absence of high-frequency radiations has been reported. The mechanism for the generation of low-frequency radiations is suggested to be hydrodynamic lubrication (e.g., Ma et al., 2000; Kano, 2006). On the other hands, the frictional heating at the time of seismisity is also suggested by former studies of the same fault (Kano et al., 2006; Hirono et al., 2006b; Mishima et al., 2006). Therefore, both fluid-rock interaction and frictional heating are expected to control the clay composition along the fault. We use chlorite to examine the mechanisms of clay mineral formation along seismogenic fault.

2 Occurrences of fault rocks

From the drilled core, we identified three fault zones with thick gouges as the candidates for the source of the seismogenic material; these fault zones are located at 1136 m, 1194 m, and 1243 m in depth (Hirono et al., 2006a) and are named FZB 1136, FZB 1194, and FZB 1243, respectively. All the fault zones are located in the Chinsui shale (Fig. 1), which is mainly composed of black shale with minor sandstones. Schematic images of the fault zones are presented in Fig. 2. The rock types are divided into two-host rocks and fault rocks. The fault rocks are classified into five types: Fractured-damaged rock, breccia, gray gouge, black gouge, and black material (Fig. 2). The black material is an ultra-fine-grained material with small fragments (less than 100 μm) as reported by Hirono et al. (2006a). Clay minerals are formed in the gouges representing strong preferred orientation texture parallel to the fault planes in microscopic scale, which indicates that the clay mineral formation might be related to faulting. In the host rock, such kind of preferred oriented clay minerals are not observed. The distributions of the fault rocks in each fault zone can be summarized as follows:

FZB 1136: Approximately 1.23 m of thick breccia zone is located above the gouges. The gouges are composed of gray and black gouges. There is no black material within the gouge zone in this fault zone. A relatively thin (approximately 30 cm) breccia zone is located below the gouge zone. The fractured-damaged zone (up to 1.2 m) is located outside the breccia zone (Fig. 2).

FZB 1194: There is no breccia zone above the gouge zone. Instead, a 2-cm layer of black material exists at the top of the fault gouge zone. Below the black material, black gouge and gray gouge are present. A relatively thin breccia zone is identified below the gouge zone. The fractured-damaged zone is also located outside the fault core.

FZB 1243: There is no breccia zone both above and below the gouge zone. The fractured-damaged zones are located outside the gouge zone. Gray gouge zones are situated in the upper and lower parts of the gouge zone. Black material exists below

the upper gray gouge. Below the black material, there is a black gouge zone about 10 cm in thickness (Fig. 2).

3 XRD analysis

We analyzed the clay minerals using an X-ray diffractometer (XRD) (PANalytical X'Pert PRO MPD). The oriented samples were prepared using 1.4 μm grains. The XRD analysis was conducted under the following conditions: 45 kV, 40 mA of Cu kα radiation, step size of 0.01°, and the range of 2θ was from 3° to 40°.

The result of the XRD analysis reveals that most of the samples contain smectite, illite, kaolinite, and chlorite. Figure 3 depicts examples of the intensity profile of the XRD analysis in this study. Note that the intensities of chlorite peaks, denoted by the ratios 002, 003, 004, and 005, are different in host rocks and black materials (Fig. 3). The numbers of samples analyzed are 36, 35, and 24 for FZB 1136, FZB 1194, and FZB 1243, respectively.

4 The characteristics of chlorite

Chlorite is identified in all the analyzed samples. The chlorite in the study is Fe-Mg chlorite (Clinochlore-1MIIb, ferroan) in both the host rock and fault rocks (Fig. 3). Chlorite is composed of a silicate layer and hydroxide layer with three sites for positive ions in both the layers. Although the oriented samples are analyzed in this study, we used the configuration to estimate the iron and magnesium contents in chlorite from XRD chart is given in the method proposed by Moore and Reynolds (1989), which was meant for randomly oriented samples. According to Moore and Reynolds (1989), the total number of iron ions is related to the intensity ratio I(003)/I(005), and the asymmetry of the ions is related to [I(002)+I(004)]/I(003)′. Here, I(003)′ is corrected by using

the following equation (Moore and Reynolds, 1989):

$$I(003)' = \frac{I(003)(114)^2}{(114-12.1D)^2} \quad (1)$$

The NEWMOD calculation of chlorite provides the reference frame in the configuration described above for iron and magnesium from 0 to 3 at intervals of 0.5 in the silicate and hydroxide layers (the total number of patterns is 49), respectively. The results of the NEWMOD calculations are shown in Fig. 4 in the I(003)/I(005) vs. [I(002)+I(004)]/I(003)′ space as dotted lines.

The peak intensities are obtained using MacDiff 4.2.5. Kaolinite is also identified in almost all the samples in this study. Therefore, I(002) and I(004) for chlorite are carefully obtained using the fitting operation of MacDiff 4.2.5.

Figure 2 represents the distribution of the parameters with the depth. Figure 4 shows the differences in the iron content and asymmetry of ions between the rock types in each fault zone using the NEWMOD reference frame indicating the amount of iron in each layer.

In a broad sense, the iron content in host rocks, fractured-damaged rocks, breccia, and most of the gray gouge is constant. There is approximately 2.5–3 of iron in the hydroxide layer and 2–2.5 of iron in the silicate layer (Fig. 4), which is very high iron content. For black gouge and some gray gouge, a relatively low iron content is found (Fig. 4). In particular, the trend is very clear in FZB 1136. In FZB 1194, the change in iron content between black gouge and host rocks is smaller than that in FZB 1136. The differences in iron contents between black gouge and host rocks in FZB 1243 is not clear because of the small number of samples. Although the number of samples is limited, the black materials have a fairly low iron content when compared to that of the other types of rocks both in FZB 1194 and FZB 1243 (Fig. 4). The distribution of the parameters also represents lower values of the parameters at the fault core (Fig. 2), which means that lower values of the iron contents are observed at the faults.

5 Discussion and conclusion

The iron content in chlorite is controlled by the temperature of the source fluid (Ohta and Yajima, 1988) or the pH of the fluid (e.g., Ross, 1969; Malmstrom et al., 1996). It is also possible that the source material can be control the iron content in chlorite. In this study, however, the source materials of Chinsui shale is enough homogeneous and could not control the low value of iron content. This might be supported by that the iron and magnesium contents in host rocks are enough constant as represented in Fig. 4.

Thermal anomalies have been reported at the fault zones on the basis of borehole logging in TCDP. Kano et al. (2006) assumed that the thermal anomaly is caused by frictional heating. They estimated a low frictional coefficient on the basis of the thermal conductivity and diffusivity around the fault zone. They discussed that the low frictional coefficient can be a cause for the absence of high-frequency radiations in the northern part of the Chelungpu Fault.

High magnetic susceptibility has been observed in the black gouge and black material (Hirono et al., 2006b). Mishima et al. (2006) conducted magnetic analysis on the ferrimagnetic minerals in more detail and concluded that the formation of magnetite or maghemite can be the cause of the high magnetic susceptibility in the fault core. They discussed that the ferrimagnetic minerals are formed by the thermal decomposition of inferrimagnetic minerals, such as siderites (Pan et al., 2000), lepidocrosite (Özdemir and Dunlop, 1993), or ferromagnetic iron sulfide (Snowball and Torii, 1999). They estimated the temperature to be at least 400°C on the basis of the thermomagnetic analysis.

On the other hand, Ohta and Yajima (1988) reported that the iron-rich chlorite is deposited at a high temperature (approximately 200°C–450°C). In this study, the iron content in the chlorite is low in the fault core where a temperature rise is expected. Therefore, the temperature rise cannot explain the low value of the iron content in the chlorite.

Another factor that may control the iron content in the chlorite is a variation in the pH of fluid. The pH of fluid can be changed by a radical reaction, which is an interaction between a surface that has been newly formed by fracturing and water (Kameda, et al., 2003; Saruwatari et al., 2004), although it is difficult to apply the result to a natural example quantitatively because of the complexity of the mineral composition (Saruwatari et al., 2004).

The low values of iron contents in the chlorites are observed within the black gouge and black material at the center of the fault zone where magnetite or maghemite is formed. The formation of iron oxide can be related to the low value of iron content in the chlorite at the fault core because the iron might be consumed by the formation of ferrimagnetic minerals. However, the temporal relationship between the formation of iron oxide and the low value of iron content in the chlorite is not clear so far.

In conclusion, the complex reactions are controlled not only by thermal decomposition but also by rock-fluid interaction. This is because the low value of the iron content in the chlorite is likely to be affected by the pH of fluid rather than the temperature raise at the seismogenic fault zones.

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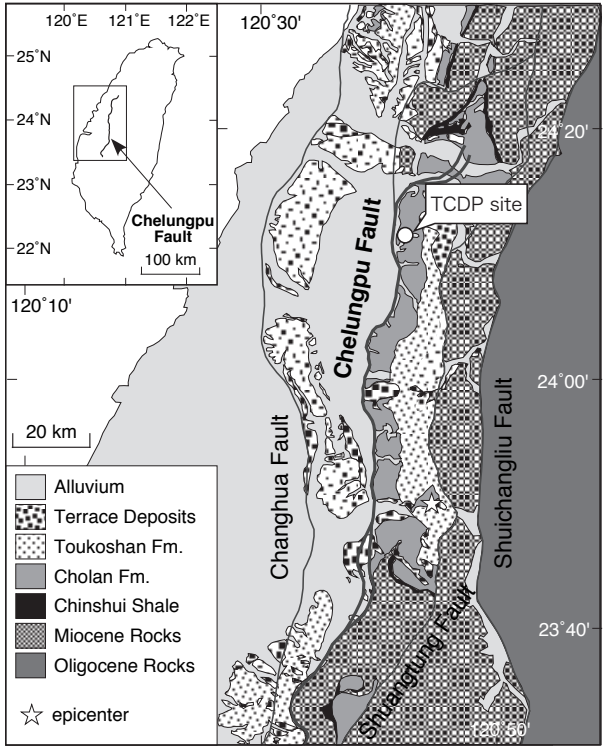

Fig. 1. A geological map of central Taiwan. Location of the TCDP site is shown.

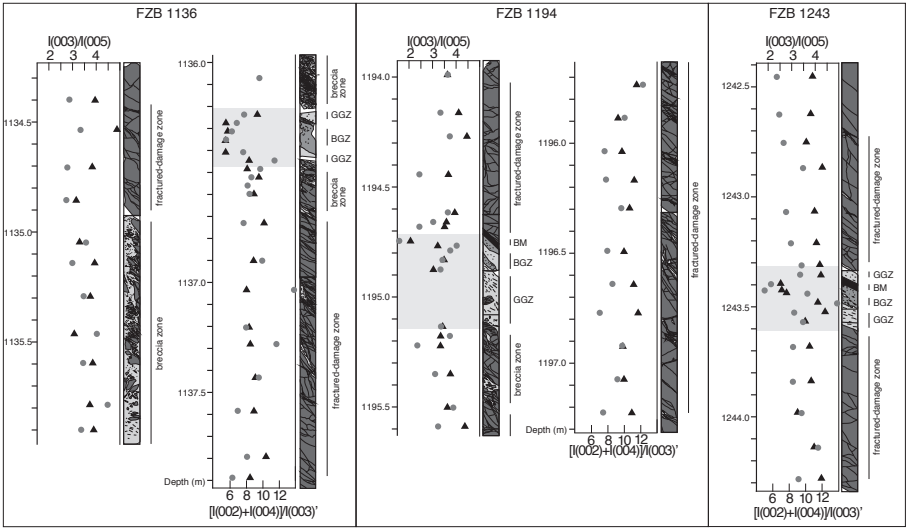

Fig. 2. Schematic images of the fault zones and distributions of I(003)/I(005) (gray circle) and [I(002)+I(004)]/I(003)′ (black triangle). Shaded areas indicate the gouge zone in each fault zone.

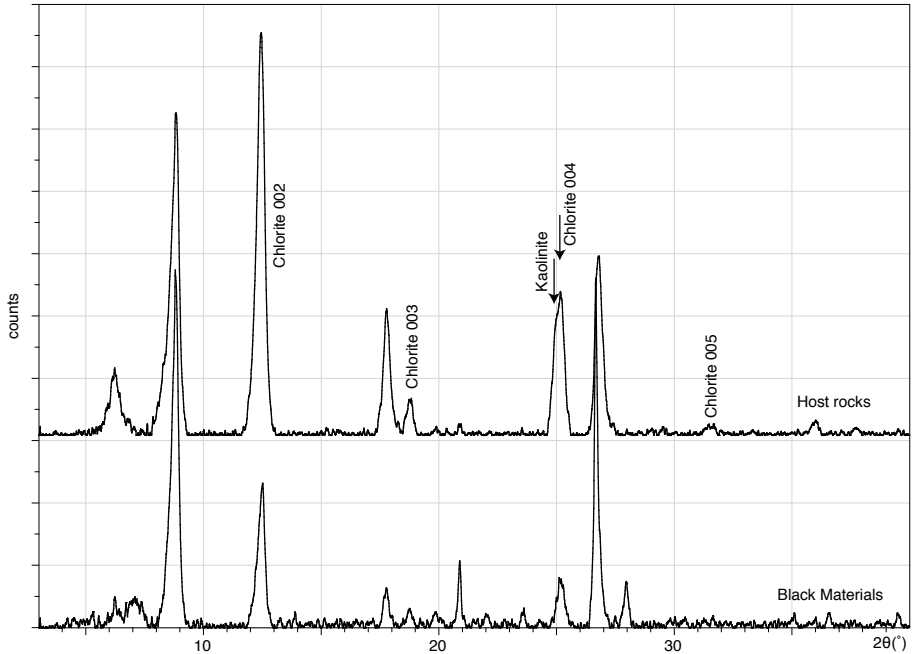

Fig. 3. Examples of the intensity profiles of XRD charts for host rock and black material. Chlorite peaks are indicated.

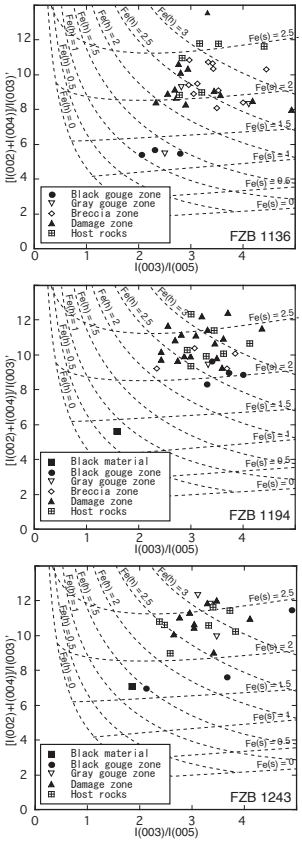

Fig. 4. Characteristics of chlorite in each fault rock expressed in I(003)/I(005) vs. [I(002)+I(004)]/I(003)′ space. Dotted lines indicate the reference frame calculated from NEWMOD. The amount of iron in the hydroxide layers is denoted by Fe(h) and in the silicate layers by Fe(s).