Magnetic evidence revealing frictional heating from fault rocks in granites

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A B S T R A C T

Fault rocks share certain characteristics of melt-origin pseudotachylite due to elevated temperature caused by coseismic frictional heating. However, there is no broadly accepted quantitative evidence to identify signatures of coseismic frictional heating in fault rocks. We report systematic magnetic studies on a brown ultracataclasite layer in the rocks from Longmen Shan thrust belt, at the eastern margin of the Tibetan Plateau in Sichuan Province, China. The brown ultracataclasite has: (1) the highest magnetic susceptibility, (2) significant characteristics of magnetite neoformation and (3) similar demagnetization behavior of natural remanent magnetization and anhysteretic remanent magnetization. The principal mechanism responsible for the high magnetic susceptibility of the brown ultracataclasite is most likely caused by the production of new magnetites from iron-bearing paramagnetic minerals. These new magnetites can be formed by frictional heating on slip planes along a seismic fault. The study shows that magnetic analysis can help to recognize frictional heating events in specific fault rocks.

1. Introduction

The frictional heating within fault slip is now a widely reported phenomenon that occurs during large earthquakes (Ferré et al., 2012; Lin, 2008; Rowe et al., 2012; Sibson, 1975; Spray, 1987). Potentially the link between fault pseudotachylites and coseismic melting can be identified through paleomagnetic studies of the thermal remanent magnetization acquired during melt quenching (Ferré et al., 2012). In addition to pseudotachylites, other fault rocks, such as, fault gouge and some cataclastic rocks located within fault zones are usually thought to form by comminution at shallow depths (Janssen et al., 2010; Sibson, 1977). In fact, some fault gouges show characteristics of melt-origin pseudotachylite due to elevated temperature caused by coseismic frictional heating.

However, there is no broadly accepted quantitative evidence to identify signatures of coseismic frictional heating in fault rocks. Previous studies have used fission-track thermochronology to look for evidence of seismic frictional heat. The results provided no evidence to distinguish the effects of a localized thermal anomaly from transient frictional heating caused by individual earthquakes (d’Alessio et al., 2003). Ferromagnetic resonance signals produced by high-speed slip tests can be used to detect seismic frictional heating (Fukuchi et al., 2005). Recent magnetic studies from several drilling programs have shown that the neo-formed fault gouges formed during a large earthquake might have experienced frictional heating (Chou et al., 2012; Hirota et al., 2006; Mishima et al., 2006; Pei et al., 2014; Tanikawa et al., 2008).

Since magnetic properties of fault rocks have potential for tracing frictional heating during earthquakes, we report here results from a product of frictional melt in granite from the Longmen Shan.

2. Geologic setting

The Longmen Shan is the main mountain range and one of the steepest margins along the eastern edge of the Tibetan Plateau in Sichuan, China. The significant deformation in the Western Sichuan is governed by interactions among three crustal blocks (Songpan, Chuanudian, and South China) (Fig. 1). The Longmen Shan thrust belt consists of the Wenchuan–Maixian, Yingxiu–Beichuan (YBF) and Anxian–Guanxian faults (Fig. 1). The YBF, running over 300 km, striking NE, dipping at 60° to the NW, marks the contact between the Pengguan complex and the overlying Palaeozoic sediments. Recent studies suggest that most of the earthquake slip occurred in a relatively shallow crust at depths of ~20–30 km, where steeply dipping fault planes merge into a subhorizontal detachment fault (Wang et al., 2011; Xu...
et al., 2009; Zhang et al., 2010). The YBF and Anxian–Guanxian faults initiated the Thrust–Nappe Belt during the early episode of the Indosinian orogeny and thrusting during the Latest Triassic to Early Cretaceous in the Western Sichuan Foreland Basin (Chen and Wilson, 1995). Over the last 10–12 Ma, enhanced cooling/exhumation on the YBF has occurred by oblique slip (Tian et al., 2013; Wang et al., 2012). The occurrence of Wenchuan earthquake (Mw7.9, 12 May 2008) is generally considered to be the result of intense tectonic activity along the YBF by oblique convergence between the Songpan–Ganzi flysch belt and the Sichuan basin (Burchfiel et al., 2008; Jia et al., 2010; Liu-Zeng et al., 2009; Robert et al., 2010; Xu et al., 2009; Yin, 2010; Zhang et al., 2010). The right-lateral transpressional movement along the YBF is due to the counterclockwise motion of the Sichuan basin dragged by the left-lateral movement along the Xianshuihe fault (Wang et al., 2014).

The Pengguan complex is the hanging host of the YBF, which consists of biotite granite, plagiogranite, mylonite, granodiorite, tonalite, and some mafic–ultramafic intrusive rocks, with SHRIMP zircon U–Pb age of 850–750 Ma (Yan et al., 2004). The Triassic Xujiahe Formation, which consists of gray sandstone, siltstone, and dark gray mudstone with coal beds, is the foot host of the YBF. An ~240 m wide and complete outcrop of the YBF fault zone was investigated at the Bajiaomiao outcrop where multiple types of fault rocks occurred in the Pengguan complex (HBG section) (Fig. 2), including protocataclasite, cataclasite, ultracataclasite (Pei et al., 2010), and also pseudotachylyte (Wang et al., 2014).

A brown, hard, approximately 2 cm wide ultracataclastic belt is found in the HBG section. This belt occurs as a thin layer on, and sub-parallel to, the fault plane with the highest magnetic susceptibility (Pei et al., 2010) which we refer to as the “brown ultracataclasite layer”. Ultracataclastic veins, generated by crushing during the Wenchuan earthquake, with little or no melting, record seismic slip events in seismogenic fault zones (Lin, 2011). Based on our primary magnetic susceptibility studies, we believe that this brown ultracataclasite layer records a seismic slipsignature of ancient earthquakes.

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Fig. 1. Geological map of Longmen Shan and the western Sichuan basin area, showing the site of the Wenchuan Earthquake Fault Scientific Drilling, and two faults of the Longmen Shan thrust fault system (F1, Wenchuan–Maoxian Fault; F2, Yingxiu–Beichuan Fault; F3, Anxian–Guanxian Fault) (revised after Li et al., 2013). Cross sections across the central LMS modified after Robert et al. (2010), Tian et al. (2013) and Wang et al. (2014).
Fig. 2. (A) Overview photographs of the HBG section, (B) brown ultracataclasite and black ultracataclasite, (C) black ultracataclasite, (D) brown ultracataclasite and black ultracataclasite, (E) brown ultracataclasite and black ultracataclasite, and (F) high magnetic susceptibility brown ultracataclasite and black ultracataclasite.
To test for frictional heating during earthquakes, we report magnetic properties of multiple fault rock-types of the Pengguan complex. We identify, for the first time, a frictional heating related to a large magnitude earthquake from ultracataclasite in granites.

3. Methods and results

Earlier field measurements of magnetic susceptibility show that these fault rocks have a distinct peak relative to country rocks (Fig. 2F). We have systematically sampled rocks from a well-documented surface outcrop of the YBF in the Pengguan complex, crosscutting one of the fault slip planes. Sampled rocks were unaltered Precambrian granitoids and fault rocks and included protocataclasite, cataclasite and ultracataclasite. A total of twelve samples, including two HBG1-8 samples, were collected using a water-cooled portable drill (Table 1 and Fig. 3).

The surface magnetic susceptibility was measured on the HBG section surface at 1-cm intervals using a Bartington MS2E surface sensor. The active region of the MS2E sensor is at the end of a 25 mm diameter ceramic cylinder mounted in line with the electronics unit and comprises a 10.5 mm × 3.8 mm rectangular surface. The mass magnetic susceptibility (low frequency) of these twelve samples ranges from 3.56 × 10⁻⁹ to 17.24 × 10⁻⁹ m³/kg (Table 1). Sample HBG1-8 of brown ultracataclasite displays the highest magnetic susceptibility similar to the pattern obtained from surface measurements of the HBG section (Fig. 3B & D).

The k–T curves can help to identify magnetic mineral type (Deng et al., 2001; Dunlop and Özdemir, 1997) and were conducted in air in a steady field of 300 A/m. Samples were heated to 700 °C and then cooled to room temperature at a rate of 10 °C/min. Three-axis thermal demagnetization of IRMs (Lowrie, 1990) was conducted in the laboratory with fields of 2.4 T, 0.4 T and 0.12 T applied successively along Z, Y and X axes using a IM-10 impulse magnetizer. Subsequently, stepwise thermal demagnetization to 680 °C was performed and magnetizations were measured by a JR6 magnetometer. Experiments were performed at the Key Laboratory of Paleomagnetism and Tectonic Reconstruction of the Ministry of Land and Resources, China.

All curves are irreversible, with enhanced magnetic susceptibilities in cooling curves compared to the heating curves (Fig. 4). The heating curve of HBG1-10 shows asymptotic curves following the Curie Law until 680 °C (Fig. 4C & D), indicating that magnetism is dominated by paramagnetic phases. However, the heating curves of the HBG1-8 and HBG1-10 obey the Curie–Weiss law until 400 °C and 500 °C respectively.

The k–T curves of the HBG1-8 sample display a rapid increase in the slope after 420 °C, and a marked peak occurs at about 550 °C in the heating curves. The magnetic susceptibility decreases to near-zero at about 585 °C (Fig. 4E) with the cooling curve higher than the peak in the heating curves. The k–T curve of the HBG1-3 sample displays a relatively low increase in the slope after 510 °C and a marked peak at about 560 °C in heating curves. The magnetic susceptibility becomes effectively zero at about 600 °C (Fig. 4A & B). The cooling curves show a hump between 600 °C and 320 °C with a value obviously higher than the peak in the heating curves.

In addition, we note that the difference between the second cooling and heating cycle of HBG1-8 up to 700 °C after 400 °C is much higher than that of the 520 °C and 600 °C curves, until the k–T curve is almost reversible in the second heating/cooling cycle up to 700 °C after 680 °C (Fig. 4F–L). These observations indicate the production of more mineral with high magnetic susceptibility after heating to >400 °C.

All the cooling curves of HBG1-8 identify a Curie point corresponding to magnetite with a Hopkinson peak (Fig. 4F, H, J & L) indicating that is the final magnetic product of heating.

Thermal demagnetization of three-component IRMs show soft, medium and hard components unblocking at 580 °C supporting the presence of abundant magnetite (Fig. 5A & B). Hence magnetite is the main magnetic carrier both in the host rock and the black ultracataclasite. However, the curves of sample HBG1-8 are distinctly different from those of the HBG1-2 and HBG1-10 (Fig. 5C). The soft, medium and hard components are equal and show that the hard components unblock at 680 °C, indicating the presence of high unblocking temperature minerals. Another change in the slope of the medium component sample HBG1-8, at about 200 °C, suggests the unblocking of goethite.

Magnetic hysteresis loops were measured with an alternating gradient magnetometer (Princeton Micromag 2900) at the physics laboratory of Beijing University. The magnetic field was cycled between ±1.0 T. Saturation magnetization (Ms), saturation remanence (Mrs) and magnetic coercivity (Hc) was determined after correction for the paramagnetic contribution (χpara; the high-field slope). Coercivity of remanence (HcR) is the field required to erase remanent magnetization permanently; it was obtained by backfield measurements after being magnetized at 1.0 T.

Room temperature hysteresis analysis produces straight lines for samples HBG1-3 and HBG1-11 defining a dominant paramagnetism in these samples. HBG1-11 displays a significant drift after paramagnetic correction, indicating a very weak magnetic component. In contrast, ferrimagnetic susceptibility (χferri) is dominant in HBG1-8 sample (Table 1 and Fig. 6). Generally, both the Ms and Mrs of host rock are lower than ultracataclasite.

Day plots (Day et al., 1977; Dunlop, 2002) and Squareness–Coercivity (SC) plots (Tauxe et al., 2002) were constructed to estimate the grain-sizes of magnetic minerals (Fig. 7). Hysteresis parameters, Mr/Ms and Hc/HcR are plotted on a Day et al. (1977) plot with the

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology</th>
<th>χlt</th>
<th>χpara</th>
<th>χferri</th>
<th>Ms</th>
<th>Mrs</th>
<th>Hc</th>
<th>HcR</th>
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<td></td>
<td></td>
<td>10⁻⁸ m³/kg</td>
<td>10⁻⁸ m³/kg</td>
<td>10⁻⁸ m³/kg</td>
<td>10⁻⁸ Am²/kg</td>
<td>10⁻⁸ Am²/kg</td>
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<td>0.13</td>
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<tr>
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<td>0.29</td>
<td>14.0</td>
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<td>1.51</td>
<td>0.23</td>
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<td>0.11</td>
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<td>0.90</td>
<td>0.89</td>
<td>0.17</td>
<td>13.8</td>
<td>16.6</td>
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</table>

Notes: χlt—low field magnetic susceptibility; χpara—paramagnetic susceptibility verified by hysteresis measurements; χferri—ferrimagnetic susceptibility calculated from the difference between χlt and χpara; Ms—saturation magnetization; Mrs—saturation remanence; Hc—coercivity; HcR—coercivity of remanence.
Fig. 3. (A) Sketch map of the HBG section showing the sample location, (B) mass magnetic susceptibility of the HBG section, and (C) high magnetic susceptibility brown ultracataclasite and black ultracataclasite.
theoretical mixing curves (Dunlop, 2002). Most specimens display hysteretic parameters typical of the pseudo-single domain (PSD) field and the USD region on the SC plot. The plot of low-field magnetic susceptibility ($\chi_{lf}$) versus paramagnetic magnetic susceptibility ($\chi_{para}$) indicates that there is more magnetite in the brown ultracataclasite layer than in the host rock (Fig. 7).

Low temperature measurements of samples were performed with a quantum design magnetic property measurement system (MPMS XP-5, sensitivity = $5.0 \times 10^{-10}$ Am$^2$) at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, China. Zero-field-cooled (ZFC) and field-cooled (FC) curves were obtained by cooling samples from 300 to 20 K in zero field and in a 2.0 T field, respectively, followed by imparting a SIRM in a 2.0 T field and then measuring the remanence in zero field during warming to 300 K.

The AC susceptibilities were measured at 10 K intervals from 20 to 300 K with a Lakeshore AC susceptometer. Low temperature demagnetization curves of these samples show two distinctive behaviors (Fig. 8).

Fig. 4. Thermomagnetic susceptibility curves of selected samples.

Fig. 5. Three-axis thermal demagnetization IRMs of selected samples.
Fig. 6. Magnetic hysteresis loops before (left) and after (right) paramagnetic correction of selected samples.

**A**

**black ultracataclasite**

HBGI-3

\[ M_s = 1.28 \times 10^3 \text{Am}^2/\text{kg} \]
\[ M_r = 0.29 \times 10^3 \text{Am}^2/\text{kg} \]
\[ H_c = 14.0 \text{ mT} \]
\[ H_{cr} = 18.9 \text{ mT} \]

**B**

**brown ultracataclasite**

HBGI-8

\[ M_s = 1.51 \times 10^3 \text{Am}^2/\text{kg} \]
\[ M_r = 0.23 \times 10^3 \text{Am}^2/\text{kg} \]
\[ H_c = 13.4 \text{ mT} \]
\[ H_{cr} = 24.6 \text{ mT} \]

**C**

**granite**

HBGI-11

\[ M_s = 0.89 \times 10^3 \text{Am}^2/\text{kg} \]
\[ M_r = 0.17 \times 10^3 \text{Am}^2/\text{kg} \]
\[ H_c = 13.8 \text{ mT} \]
\[ H_{cr} = 16.6 \text{ mT} \]

Fig. 7. (A) Hysteresis parameters, Mr/Ms and Hc/Hc are plotted on a Day et al. (1977) plot with the theoretical mixing curves (Dunlop, 2002), (B) Mr/Ms and Hc are plotted on a Squareness-Coercivity (SC) plot (Tauxe et al., 2002), and (C) plots of paramagnetic magnetic susceptibility (\( \chi_{para} \)) versus low field magnetic susceptibility (\( \chi_{lf} \)).
No visible Verwey transition was found for the sample HBG1-10, implying either that magnetite particles are in the SP state or that the concentration of coarse-grained magnetite is undetectable (Dunlop and Özdemir, 1997). However, the Verwey transition was found in the sample HBG1-8 (Fig. 8), confirming the presence of magnetite (Verwey et al., 1947).

In contrast, the smeared feature of the Verwey transition found only in the ZFC and FC curves for sample HBG1-3 (Fig. 8), might result from gradual unblocking of the magnetic minerals during the warming process. In addition, sharp decreases at 35–40 K in ZFC and FC are consistent with the siderite Néel temperature of 38 K (Jacobs, 1963), showing the existence of siderite in the sample HBG1-3 and HBG1-8 (Frederichs et al., 2003; Housen et al., 1996).

4. Discussion and conclusions

Most previous studies have supported the assumption that the frictional heating was responsible for the high magnetic susceptibility of fault-related pseudotachylytes and gouges (Enomoto and Zheng, 1998; Ferré et al., 2005; Fukuchi et al., 2005; Hirono et al., 2006; Mishima et al., 2006, 2009; Nakamura and Nagahama, 2001). The high velocity frictional tests indicated that low heat generation could increase magnetic susceptibility of ultracataclasite by frictional heat (Tanikawa et al., 2007). Here we have applied rock magnetic methods to study natural ultracataclasite in the HBG section in order to reveal the frictional heating related to fault slipping in granite and to facilitate robust correlations between magnetic properties and fault rocks.

The mass magnetic susceptibility results confirm the high values of the brown ultracataclasite layer at the HBG section (Fig. 3B & D). The increased magnetic susceptibility of ultracataclasite might result from the decreased grain size of magnetic minerals caused by shearing (Dearing, 1999), as the formation of ultracataclasite is progressively comminuted by fracture and rotational attrition within crush zones (Sibson, 1977). However, when compared on a Day diagram (Day et al., 1977) and SC plot (Tauxe et al., 2002), all samples display values generally in the PSD area (Fig. 7).

The behavior of the heating curves above 400 °C or 500 °C of the ultracataclasite is probably associated with the neoformation of magnetic minerals from unstable iron-bearing minerals (Fig. 4). The Curie point near 580 °C indicates that nearly pure magnetite is the magnetic carrier (Figs. 4 and 5; Dunlop and Özdemir, 1997). The magnetic hysteresis experiments demonstrate the existence of paramagnetic minerals, however, paramagnetic susceptibility (χ<sub>para</sub>) forms a relatively smaller proportion in the brown ultracataclasite than the host rock (Table 1 and Fig. 6). Based on the above, the principal mechanism responsible for the frictional heating of the ultracataclasite is probably the neoformation of magnetite from unstable iron-bearing minerals (Fig. 4).
for the high magnetic susceptibility of the brown ultracataclasite is probably the production of new magnetite from unstable iron-bearing paramagnetic minerals.

A number of physical and chemical reactions, driven by frictional heating or hydrothermal activity, may account for the neoformation of high magnetic susceptibility minerals in fault rocks during fault slipping (Hirono et al., 2008; Yang et al., 2012). The production of magnetite from siderite during heating has been well documented in the laboratory (Pan et al., 2000, 2002) and in fault rocks (Han et al., 2007).

To investigate the existence of frictional heating due to alternate magnetic minerals during fault slipping processes, we performed alternating field (AF) demagnetization of the Natural Remanent Magnetization (NRM) acquisition and Anhysteretic Remanent Magnetization (ARM) on three selected samples (Fig. 9).

Zijderveld diagrams of NRM in situ show one component in HBG1-8. The HBG1-8 specimens are characterized by a gradual demagnetization of NRM and ARM. Both NRM and ARM display similar demagnetization behaviors. In contrast, the black ultracataclasite and the host rock specimens of granite display very different AF demagnetization behaviors for both NRM and ARM. These demagnetization experiments suggest that the brown ultracataclasite, in contrast to the black ultracataclasite and host rock, carry a thermal remanent magnetization (TRM) (Fig. 9). Therefore, the NRM, at least parts of the NRM of the brown

![Fig. 9. Alternating field demagnetization of NRM and ARM experiments of three selected samples normalized to initial magnetization. Zijderveld diagrams of NRM in situ showing one component in HBG1-8. Solid (open) circle symbols refer to the projection on the horizontal (vertical) plane.](image)
ultracataclasite, considered to be reset at the time of seismic slip. In contrast, the host rock and the black ultracataclasite generally display an erratic, often uninterpretable, demagnetization behavior, confirming the complicated component (Ferré et al., 2012).

From the above discussion, the high magnetic susceptibility of the brown ultracataclasite in granites can be explained by frictional heating on slip planes along a seismic fault. The NW–SE stress field generated the E–W component of the convergence and right-lateral shear along the YBF, which is responsible for the frictional heating. The scarcity of pseudotachylyte can be affected by many factors, for example the depth, dry conditions and host rocks (Silisbon, 1977). The formation of ultracataclasite and cataclasite is probably restricted within crush zones along slipping planes. As temperature increases to ~400 °C and less than the temperature of production pseudotachylyte, some unstable iron-bearing minerals can alter to magnetic minerals with high magnetic susceptibility (e.g., magnetite). Meanwhile, a TRM was acquired upon melt quenching through the blocking temperature interval of the remanence carrier (Ferré et al., 2012; Piper, 1981; Piper and Poppleton, 1988).

Using this approach, we have found convincing evidence that in the ultracataclasite or fault rocks, frictional heating temperatures have reached a point high enough to alter some iron-bearing minerals (e.g., biotite, siderite). This finding has implications towards revealing a frictional heating effect from ultracataclasite in granites, as well as other fault rocks, exposed in seismic fault zones.

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