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Magnetic evidence revealing frictional heating from fault rocks in granites

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ABSTRACT

Fault rocks share certain characteristics of melt-origin pseudotachylyte 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 pseudotachylytes, 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 share characteristics of melt-origin pseudotachylyte 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; Hirono 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, Chuandian, and South China) (Fig. 1). The Longmen Shan thrust belt consists of the Wenchuan–Maoxian, 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

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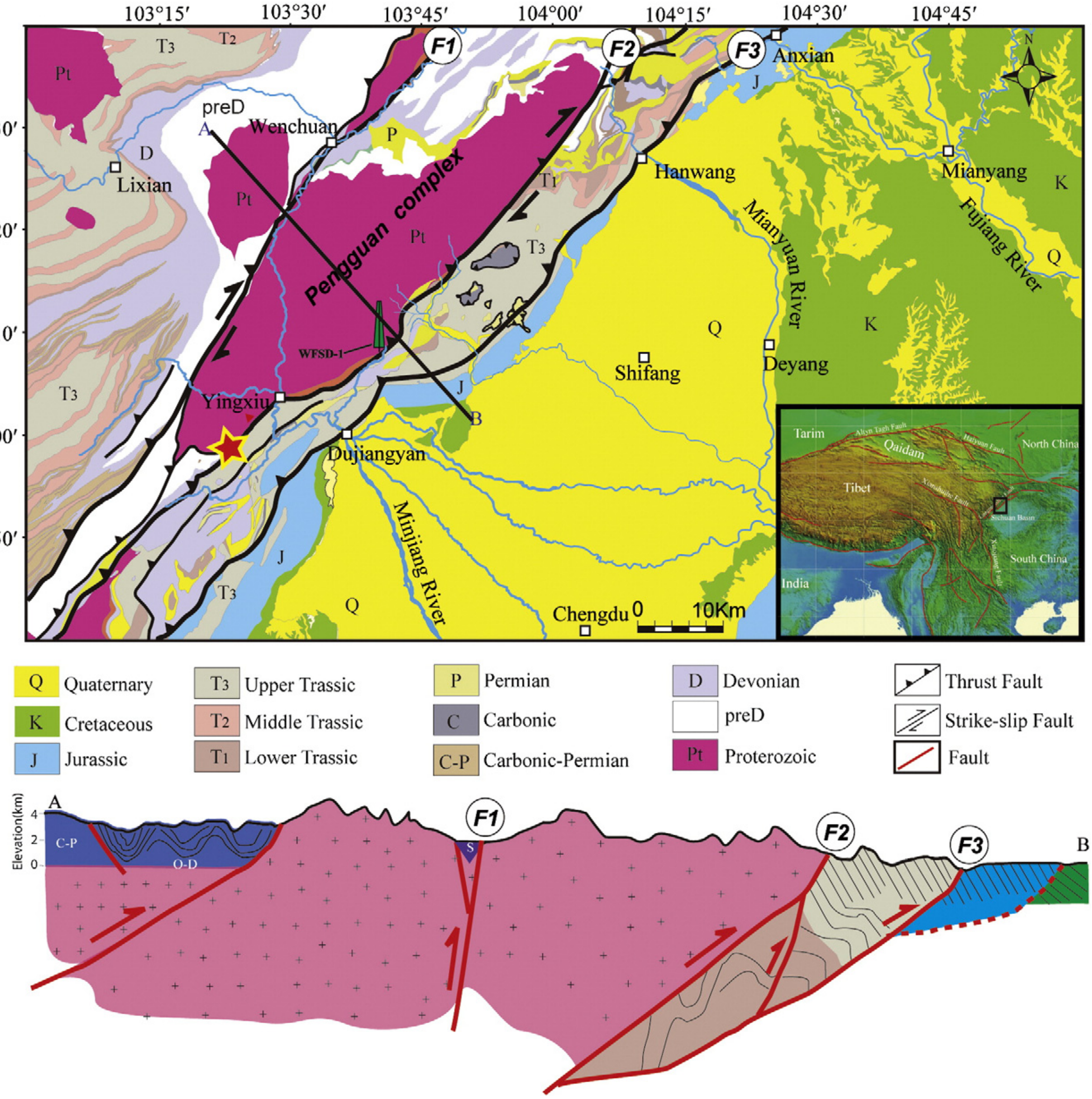

Fig. 1. Geological map of Longmen Shan and the western Sichuan basin area, showing the site of the Wenchuan Earthquake Fault Scientific Drilling, and two faults of the Longmen Shan thrust fault system (F1, Wenchuan–Maoxian Fault; F2, Yingxiu–Beichuan Fault; F3, Anxian–Guanxian Fault) (revised after Li et al., 2013). Cross sections across the central LMS modified after Robert et al. (2010), Tian et al. (2013) and Wang et al. (2014).

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.