

Metallic iron formed by melting: A new mechanism for magnetic highs in pseudotachylyte

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ABSTRACT

Previous studies of rock magnetism in fault rocks imply frictional heating temperatures from ~300 °C to ~700 °C, which are far below the temperatures needed to form pseudotachylyte. Here, heating experiments were performed at elevated temperatures (as high as 1750 °C) on cataclasites from the Wenchuan Earthquake Fault Scientific Drilling borehole 2 (WFSD-2) cores, Longmen Shan thrust belt, China. Based on microstructural, geochemical, and rock magnetic analyses, the main conclusions are as follows. The melting occurred at 1100 °C. The newly formed magnetite generated by the thermal decomposition of paramagnetic minerals contributed to the high magnetic susceptibility values of samples below 1100 °C. Above 1300 °C, many circular metallic iron spherulites were formed by the reducing action of Fe-bearing minerals at elevated temperatures. As the temperature increased, metallic iron content and magnetic susceptibility increased, indicating that the newly formed metallic iron was responsible for the high magnetic susceptibility values. Therefore, in addition to the newly formed magnetite, the metallic iron is another factor contributing to the magnetic highs of pseudotachylytes. The frictional melting temperature reached 1300 °C during ancient earthquakes in the Longmen Shan thrust belt, indicating that metallic iron might be responsible for the strong magnetic highs in pseudotachylyte.

INTRODUCTION

Previous rock magnetic studies have revealed magnetic highs (high magnetic susceptibility or remanence) in pseudotachylyte and fault gouge; these might be indicative of earthquakes (Fukuchi et al., 2005; Chou et al., 2012). Newly formed ferromagnetic minerals caused by frictional heating, or the refining of ferromagnetic grain sizes by shearing, are thought to be responsible for these magnetic highs (Hirono et al., 2006; Ferré et al., 2012). Existing rock magnetic properties of fault rocks represent temperature rises from ~300 °C to ~700 °C (Yang et al., 2016), and it is unknown whether newly formed ferromagnetic minerals (such as magnetite) still respond to magnetic highs at temperatures above 700 °C. Pseudotachylytes are generated by melting during the high temperatures (1000–1730 °C) caused by coseismic frictional heating (Lin, 1994; Di Toro and Pennacchioni, 2004). The monitoring temperatures of magnetic remanence or susceptibility have only reached 700 °C (Geshev et al., 1990; Goguitchaichvili et al., 2001). Previous isothermal heat experiments on fault gouge at effective confining pressure conditions have usually been carried out at temperatures below 1000 °C (Giger et al., 2008; Hamada et al., 2009).

However, monitoring and experimental temperatures are far below those of the frictional melting needed to form pseudotachylyte. Therefore, heating experiments above 1000 °C conducted under reducing conditions are vital for revealing the magnetic response to high temperatures.

The 2008 Wenchuan (China) earthquake occurred in the Longmen Shan thrust belt, the boundary between the eastern margin of the Tibetan Plateau and the Sichuan basin (Fig. 1A) (Zhang et al., 2010). The Wenchuan Earthquake Fault Scientific Drilling borehole 2 (WFSD-2) is located in Bajiaomiao Village, Hongkou County, China, on the southern segment of the Yingxiu-Beichuan fault (Fig. 1B) (Li et al., 2014). More than 20 layers of pseudotachylyte, with thicknesses varying from 1 mm to 5 cm, have been found in the ~20-m-thick cataclasite zone (579.62–599.31 m depth) within the WFSD-2 cores, indicating that ancient large earthquakes have occurred repeatedly in the Yingxiu-Beichuan fault (Zhang et al., 2017). In our study, we conducted heating experiments under atmospheric pressure on cataclasite (the wall rock of pseudotachylytes) obtained from the WFSD-2 cores. Based on the results of microstructure, geochemistry, and rock magnetic analyses of samples subjected to different temperatures (room temperature and 400, 700, 900, 1100, 1300, 1500 and 1750 °C), the

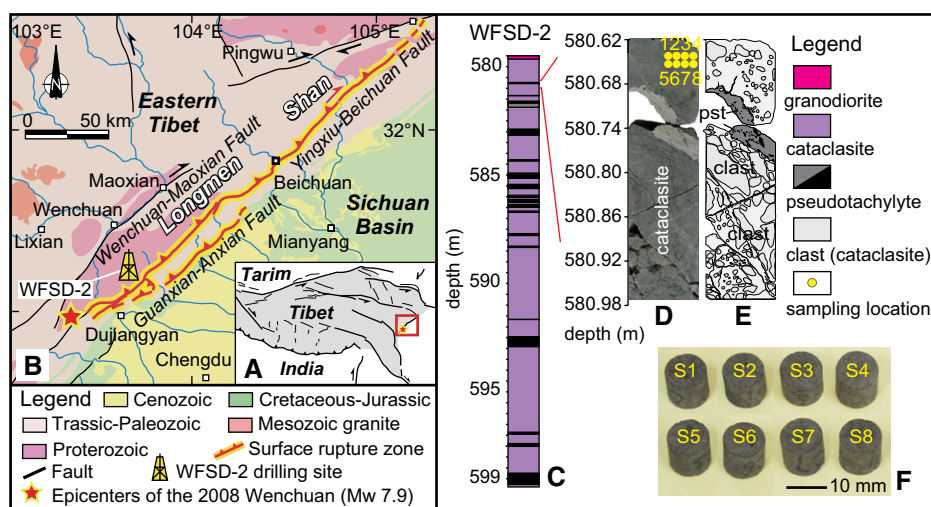


Figure 1. A: Tectonic sketch map of the Tibetan Plateau. B: Geological map of Longmen Shan, China (modified from Li et al., 2014). C: Lithology chart from 579.50 m to 599.31 m depth. D: Photograph of the core from 580.62 to 580.97 m depth. Yellow numbers 1–8 correspond to the samples S1–S8 in F. E: Core sketch from 580.62 to 580.97 m depth. F: Photographs of samples. WFSD—Wenchuan Earthquake Fault Scientific Drilling; pst—pseudotachylyte.

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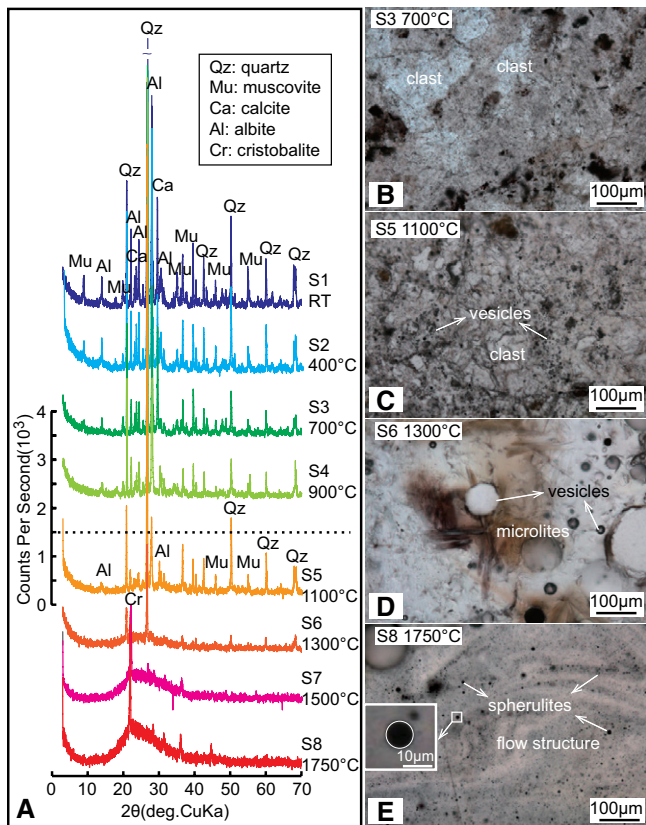


Figure 2. A: Powder X-ray diffraction profiles. B: Microstructural features of sample S3 (from Wenchuan Earthquake Fault Scientific Drilling WFSD-2 cores, Longmen Shan thrust belt, China), showing the amount of dark minerals. C: Microstructural features of sample S5, where vesicles are visible. D: Microstructural features of sample S6, showing vesicles and stellate aggregate microlites. E: Microstructural features of sample S8, showing vesicles, spherulites, and flow structures.

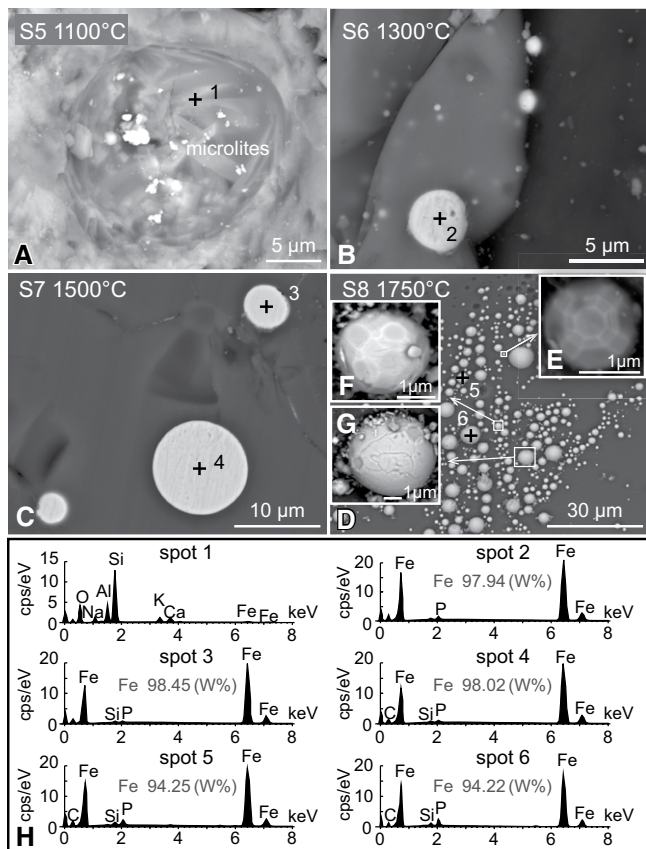


Figure 3. Scanning electron microscopy (SEM) results of the samples from Wenchuan Earthquake Fault Scientific Drilling WFSD-2 cores (Longmen Shan thrust belt, China). A: Image of sample S5 shows a floriform microlite. B: Sample S6 shows three spherulites. C: Sample S7 shows three spherulites. D: Sample S8 shows some spherulites. E: Small, regular polygonal spherulites. F: Medium-sized polygonal spherulites with blurred sides. G: Large spherulites without a regular polygonal shape, and neighboring clasts. H: SEM-EDX results for the spots in A, B, C, and D (indicated by black crosses).

melting characteristics and magnetic response to the high temperatures are discussed.

SAMPLING AND METHODS

Eight cataclasite samples (S1–S8) chosen for heating experiments were collected from ~580.65 m depth in the WFSD-2 cores (Figs. 1D and 1F). Samples were 10 mm in diameter and 10 mm in length. The microstructural characteristics of cores at ~580.65 m depth are described in the GSA Data Repository¹ (Fig. DR1). Samples S2–S8 were heated to 400 °C in a vacuum graphite tube furnace (Fig. DR2a) under an argon atmosphere. Then, samples S3–S8 were heated to temperatures of 700 (S3), 900 (S4), 1100 (S5), 1300 (S6), 1500 (S7), and 1750 °C (S8) and immediately cooled to room temperature in a Thermo-Optical-Measurement system (Fig. DR2b) under an argon atmosphere. Following the heating experiments, microstructural, geochemical, and rock magnetic measurements were conducted on these samples. The experimental and measurement methods are described in the Data Repository.

RESULTS

Powder X-ray diffraction (XRD) profiles yielded mineral compositions of quartz, muscovite, calcite, albite, and cristobalite (Table DR1). The XRD patterns of samples S1, S2, S3, and S4 showed no obvious broad band in the range of low 2θ values (Fig. 2A). The spectra for samples S5, S6, S7, and S8 comprised broad bands of 2θ values of 12–42° (Fig. 2A).

Cataclasite usually contains 50%–90% clasts by volume, which are scattered in a fine-grained matrix (Figs. DR1b–DR1e and Fig. DR5a). The microscopic structure of samples at 400 °C and 700 °C (Fig. 2B; Fig. DR5b) did not reveal any significant alteration to the cataclasite. Small fractures formed in sample S4 (Fig. DR5c). Sample S5 displayed an embayed clast and irregular vesicles (Fig. 2C; Fig. DR6a). When heated to 1300 °C, many orbicular vesicles with diameters on the order tens of microns, and stellate aggregate microlites were observed (Fig. 2D; Figs. DR6b and DR6c). Orbicular vesicles, flow structures, and black spherulites were well-developed in samples S7 and S8 (Fig. 2E; Fig. DR6d).

Scanning electron microscopy (SEM) images revealed feldspar microlites in samples S5 and S6 (Fig. 3A; Figs. DR6b and DR6c). No microlites were observed in samples S7 and S8. Circular spherulites <15 μm in diameter were well-developed in samples S6, S7, and S8 (Figs. 3B–3D). The spherulites were distributed only along the edge of the sample at 1300 °C, before

¹GSA Data Repository item 2018286, geological setting, heating experiment method, measurement methods, morphological characteristics, Figures DR1–DR9, and Tables DR1–DR2, is available online at <http://www.geosociety.org/datarepository/2018/> or on request from editing@geosociety.org.

extending through the whole samples at 1500 °C and 1750 °C. The small spherulites were regular polygonal in shape (Fig. 3E); the medium spherulite also comprised polygonal spherules but with blurred sides (Fig. 3F). In contrast, the large spherulites formed balls without any regular polygon shape (Fig. 3G). The spherulites were largely composed of elemental iron (Fig. 3H).

Magnetic susceptibility (MS) values increased from S1 to S4 and from S6 to S8 (Fig. 4A; Table DR2). Under an applied field of up to 1 T, the magnetic hysteresis loop of unheated cataclasite before para-diamagnetic correction was linear, indicating that paramagnetic components were dominant (Fig. DR7a). After para-diamagnetic correction, wasp-waisted hysteresis loops were observed in all samples (Fig. 4B), indicative of a mixture of coercivities in the ferromagnetic grain-size distribution. The loops of samples that were heated below 900 °C show that these samples were saturated below 0.4 T (Fig. 4B), indicating that magnetite is the main ferromagnetic mineral. The loops of samples heated above 1100 °C were saturated above 0.6 T (Fig. 4B), showing a slight goose-neck shape (Figs. DR7e–DR7h). The values of χ_{hf} (high field magnetic susceptibility) / χ_{lf} (low field magnetic susceptibility) decreased with increasing temperature (Fig. DR8a; Table DR2). Samples S3 and S8 had higher MS values and χ_{ferri} than those of other samples (Fig. 4A).

Samples below 900 °C plot in the vortex state, while the sample at 1100 °C plots in the multidomain (MD) region (Fig. DR8b). First-order reversal curves (FORCs) show that samples above 1300 °C plot in the single-domain (SD) region (Figs. DR9f–DR9h). The observation of Verwey transition at ~120 K (Özdemir and Dunlop, 2010) in all samples indicates magnetite (Figs. 4C–4F).

DISCUSSION

Determining the melt texture is key to understanding melting temperature and its implications for earthquakes. Irregular vesicles were formed at 1100 °C, and as the temperature increased from 1100 °C to 1750 °C, small irregular vesicles developed into large, orbicular vesicles because of the low viscosity coefficient. Glass/amorphous material was present in the samples above 1100 °C (Fig. 2A). The amount of glass/amorphous material increased with temperature (Fig. 2A). Both the microstructural analyses and the presence of amorphous material indicate that the sample was melting at 1100 °C. The decreasing intensities of some of the quartz peaks at ~1300 °C imply that quartz was partially molten at 1300 °C (Fig. 2A). Previous studies have found partially melted quartz in the WFSD-2 cores and surface outcrops along the Yingxiu-Beichuan fault (Wang et al., 2015; Zhang et al., 2017), suggesting that earthquakes with frictional heating temperatures

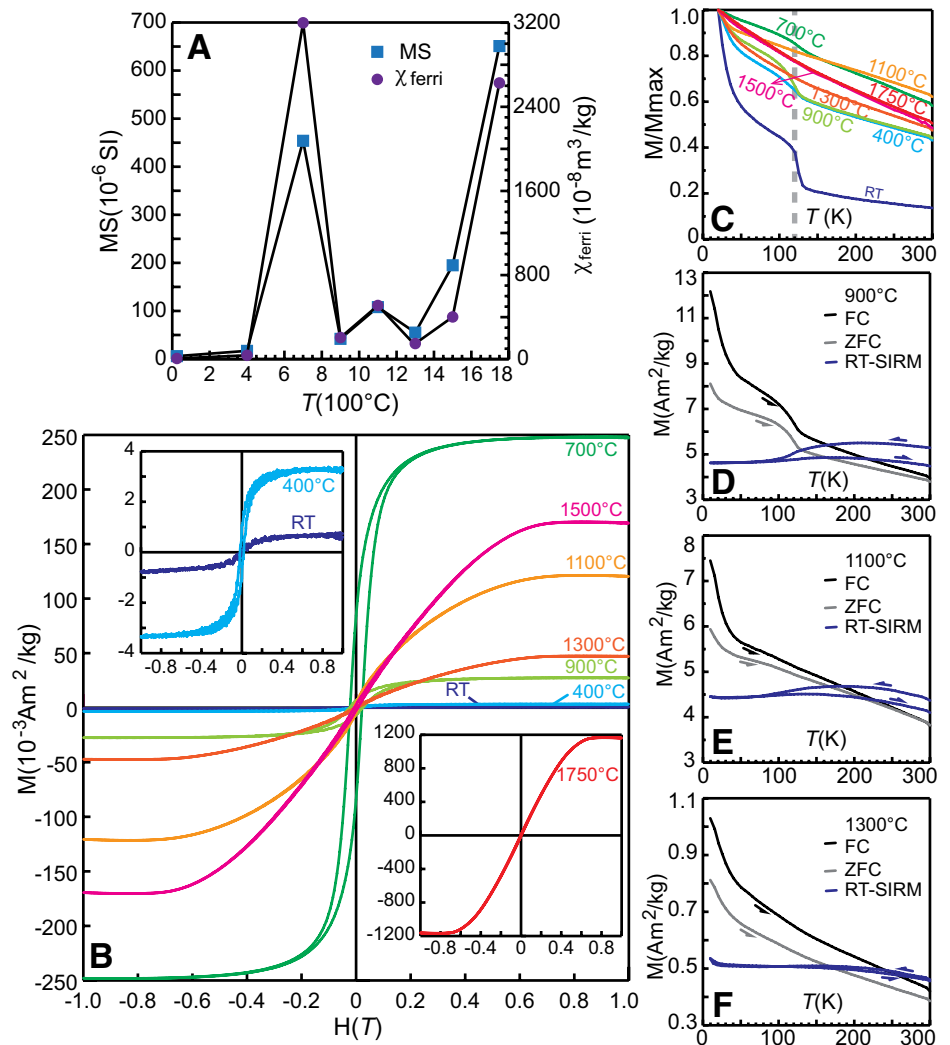


Figure 4. Rock magnetic properties of samples at different temperatures. A: Plots of mass magnetic susceptibility (MS) and ferromagnetic magnetic susceptibility (χ_{ferri}) versus temperature. **B:** Magnetic hysteresis loops for all samples after para-/diamagnetic correction. **C:** Low-temperature magnetic properties of all samples. **D:** Low-temperature magnetic curves of sample S4 from Wenchuan Earthquake Fault Scientific Drilling WFSD-2 cores (Longmen Shan thrust belt, China). **E:** Low-temperature magnetic curves of sample S5. **F:** Low-temperature magnetic curves of sample S6. RT—room temperature; FC—field-cooled magnetization; ZFC—zero field-cooled magnetization; RT-SIRM—room-temperature saturation isothermal remanent magnetization.

above 1300 °C have occurred in the Longmen Shan thrust belt. The appearance of microlites at 1100 °C and 1300 °C shows that high temperatures are needed for the formation of microlites. Furthermore, microlites disappeared above 1500 °C, when the cooling rate reached 6.86 °C/min (Fig. DR3). Both the absence of crystallization nuclei for microlites at high temperatures, and the high freezing rate, may hinder the formation of microlites. Therefore, microlites may be absent in pseudotachylite formed at high temperatures if it was then rapidly quenched.

Abundant spherulites of several microns in diameter formed in samples above 1300 °C (Figs. 3B–3G). The mass percentage of iron exceeded 80% in most spherulites, with some spherulites containing 94.22%–98.45% elemental iron

(Fig. 3H). The high iron content and low oxygen content imply that spherulites are pure iron; therefore, pure iron was formed by melting above 1300 °C. Many experiments and production processes have demonstrated the reduction of iron oxides by carbon (Man et al., 2014). Graphite was found in the experimental products and in the natural principal slip zone of the 2008 Wenchuan rupture (Kuo et al., 2014); therefore, carbon could be the reductant in the thermal reduction of ferric oxides. Previous studies of native iron in basalt show that, if iron formed by a carbon-reduction mechanism, the basalt should have experienced high temperatures and should contain abundant carbon (Bird and Weathers, 1977).

The cataclasites have the same MS values as those of the host rock (granodiorite) (Zhang et al.,

2017), but achieved higher MS values after the heating experiments than those of the unheated cataclasite (Fig. 4A; Table DR2). Rock magnetic analysis revealed the dominant paramagnetic components, and low concentrations of magnetite, in the cataclasite (Figs. 4B and 4C; Fig. DR7a) and showed that magnetite was the main ferromagnetic mineral in the samples heated to 400, 700, 900, and 1100 °C (Figs. 4C–4E). The high χ_{ferri} values of samples (Fig. 4A; Table DR2) indicate that magnetite was newly formed during the heating experiment. Therefore, the magnetite generated by the decomposition of Fe-bearing paramagnetic minerals in samples heated to 400, 700, 900, and 1100 °C contributed to the high MS values.

The magnetic hysteresis results indicated high concentrations of ferromagnetic minerals in the samples above 1300 °C. No obvious transitions for pyrrhotite, hematite, or goethite (Figs. 4B–4F) were observed, but there was slight fining (SD in the FORC diagrams; Figs. DR9f–DR9h) of magnetite in samples S6, S7, and S8. MS values decreased from 700 °C to 1300 °C, and then increased from 1300 °C to 1750 °C. The MS value of sample S8 (heated to as high as 1750 °C) was ~100× and ~1.43× those of cataclasite and sample S3 (heated to 700 °C), respectively. Therefore, the magnetite grains were too scarce to induce the high MS values of samples heated above 1300 °C. It is worth mentioning that many metallic iron spherulites were observed in the samples above 1300 °C. Therefore, metallic iron is the main reason for the high MS values of samples heated above 1300 °C.

At least two reasons for the magnetic highs in fault rocks can be inferred. First is the formation of magnetite by the thermal decomposition of paramagnetic minerals in the fault rocks (heating temperatures from 400 °C to 1100 °C). Second is metallic iron formed by melting at high temperatures (above 1300 °C). Therefore, the formation of metallic iron during melting is another reason for the magnetic highs of pseudotachylyte. The Longmen Shan thrust belt has experienced earthquakes with high frictional melting temperatures (above 1300 °C) (Wang et al., 2015; Zhang et al., 2017); therefore, the metallic iron might be responsible for the magnetic highs of pseudotachylyte.

CONCLUSIONS

(1) Granodiorite-derived cataclasite samples start to melt at 1100 °C and quartz is partially molten at 1300 °C. A high freezing rate and high temperatures (above 1500 °C) may impede the formation of microlites during large earthquakes.

(2) Magnetite is the main ferromagnetic mineral in cataclasite. In the samples from heating experiments below 1100 °C, newly formed magnetite contributes to the high MS values of samples heated to 400, 700, 900, and 1100 °C.

(3) Many circular spherulites were well-developed in the samples heated above 1300 °C. The spherulites are composed of metallic iron, formed by the reducing action of Fe-bearing minerals at high temperature in a reducing environment (above 1300 °C). We conclude that the metallic iron might be the main contributor to the higher MS values of fault rocks above 1300 °C.

(4) The Longmen Shan thrust belt has experienced large earthquakes with high frictional melting temperatures (above 1300 °C); therefore, the metallic iron formed by the melting might be responsible for the magnetic highs of pseudotachylyte.

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REFERENCES CITED

- Bird, J., and Weathers, M., 1977, Native iron occurrences of Disko Island, Greenland: *The Journal of Geology*, v. 85, p. 359–371, <https://doi.org/10.1086/628305>.
- Chou, Y.M., Song, S.R., Aubourg, C., Lee, T.Q., Boullier, A.M., Song, Y.F., Yeh, E.C., Kuo, L.W., and Wang, C.Y., 2012, An earthquake slip zone is a magnetic recorder: *Geology*, v. 40, p. 551–554, <https://doi.org/10.1130/G32864.1>.
- Di Toro, G., and Pennacchioni, G., 2004, Superheated friction-induced melts in zoned pseudotachylites within the Adamello tonalites (Italian Southern Alps): *Journal of Structural Geology*, v. 26, p. 1783–1801, <https://doi.org/10.1016/j.jsg.2004.03.001>.
- Ferré, E.C., Geissman, J.W., and Zechmeister, M.S., 2012, Magnetic properties of fault pseudotachylites in granites: *Journal of Geophysical Research: Solid Earth*, v. 117, B01106, <https://doi.org/10.1029/2011JB008762>.
- Fukuchi, T., Mizoguchi, K., and Shimamoto, T., 2005, Ferrimagnetic resonance signal produced by frictional heating: A new indicator of paleoseismicity: *Journal of Geophysical Research: Solid Earth*, v. 110, B12404, <https://doi.org/10.1029/2004JB003485>.
- Geshev, J., Popov, O., Masheva, V., and Mikhov, M., 1990, Thermomagnetic curves for a disordered system of single-domain ferromagnetic particles with cubic anisotropy: *Journal of Magnetism and Magnetic Materials*, v. 92, p. 185–190, [https://doi.org/10.1016/0304-8853\(90\)90630-9](https://doi.org/10.1016/0304-8853(90)90630-9).
- Giger, S.B., Cox, S.F., and Tenthorey, E., 2008, Slip localization and fault weakening as a consequence of fault gouge strengthening—Insights from laboratory experiments: *Earth and Planetary Science Letters*, v. 276, p. 73–84, <https://doi.org/10.1016/j.epsl.2008.09.004>.
- Goguitchaichvili, A., Morales, J., Urrutia-Fucugauchi, J., and Soler, A.M., 2001, On the use of continuous thermomagnetic curves in paleomagnetism: A cautionary note: *Comptes Rendus de l'Académie des Sciences: Series IIA, Earth and Planetary Sciences*, v. 333, p. 699–704.

- Hamada, Y., Hirono, T., Ikehara, M., and Song, S.R., 2009, Estimated dynamic shear stress and frictional heat during the 1999 Taiwan Chi-Chi earthquake: A chemical kinetics approach with isothermal heating experiments: *Tectonophysics*, v. 469, p. 73–84, <https://doi.org/10.1016/j.tecto.2009.01.036>.
- Hirono, T., et al., 2006, High magnetic susceptibility of fault gouge within Taiwan Chelungpu fault: Nondestructive continuous measurements of physical and chemical properties in fault rocks recovered from Hole B, TCDP: *Geophysical Research Letters*, v. 33, L15303, <https://doi.org/10.1029/2006GL026133>.
- Kuo, L.W., Li, H., Smith, S.A.F., Di Toro, G., Suppe, J., Song, S.-R., Nielsen, S., Sheu, H.-S., and Si, J., 2014, Gouge graphitization and dynamic fault weakening during the 2008 M_w 7.9 Wenchuan earthquake: *Geology*, v. 42, p. 47–50, <https://doi.org/10.1130/G34862.1>.
- Li, H.B., et al., 2014, Structural and physical property characterization in the Wenchuan earthquake Fault Scientific Drilling project—Hole 1 (WFSD-1): *Tectonophysics*, v. 619, p. 86–100, <https://doi.org/10.1016/j.tecto.2013.08.022>.
- Lin, A.M., 1994, Glassy pseudotachylyte veins from the Fuyun Fault zone, Northwest China: *Journal of Structural Geology*, v. 16, p. 71–83, [https://doi.org/10.1016/0191-8141\(94\)90019-1](https://doi.org/10.1016/0191-8141(94)90019-1).
- Man, Y., Feng, J.X., Li, F.J., Ge, Q., Chen, Y.M., and Zhou, J.Z., 2014, Influence of temperature and time on reduction behavior in iron ore-coal composite pellets: *Powder Technology*, v. 256, p. 361–366, <https://doi.org/10.1016/j.powtec.2014.02.039>.
- Özdemir, O., and Dunlop, D.J., 2010, Hallmarks of maghemitization in low-temperature remanence cycling of partially oxidized magnetite nanoparticles: *Journal of Geophysical Research: Solid Earth*, v. 115, B02101, <https://doi.org/10.1029/2009JB006756>.
- Wang, H., Li, H.B., Janssen, C., Sun, Z.M., and Si, J.L., 2015, Multiple generations of pseudotachylyte in the Wenchuan fault zone and their implications for coseismic weakening: *Journal of Structural Geology*, v. 74, p. 159–171, <https://doi.org/10.1016/j.jsg.2015.03.007>.
- Yang, T., Dekkers, M.J., and Zhang, B., 2016, Seismic heating signatures in the Japan Trench subduction plate-boundary fault zone: evidence from a preliminary rock magnetic ‘geothermometer’: *Geophysical Journal International*, v. 205, p. 319–331, <https://doi.org/10.1093/gji/ggw013>.
- Zhang, L., Sun, Z.M., Li, H.B., Zhao, L.S., Song, S.R., Chou, Y.M., Cao, Y., Ye, X.Z., Wang, H., and He, X.L., 2017, Rock record and magnetic response to large earthquakes within Wenchuan Earthquake Fault Scientific Drilling cores: *Geochemistry Geophysics Geosystems*, v. 18, p. 1889–1906, <https://doi.org/10.1002/2017GC006822>.
- Zhang, P.Z., Wen, X.Z., Shen, Z.K., and Chen, J.H., 2010, Oblique high-angle listric-reverse faulting and associated straining processes: the Wenchuan earthquake of 12 May 2008, Sichuan, China: *Annual Review of Earth and Planetary Sciences*, v. 38, p. 353–382, <https://doi.org/10.1146/annurev-earth-040809-152602>.

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