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

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A1. Geological Setting

The NE-SW-trending Longmen Shan thrust belt, which is located at the boundary between the eastern margin of the Tibetan Plateau and the Sichuan Basin, is composed of three primary thrust faults: The Wenchuan-Maoxian, Yingxiu-Beichuan and Anxian-Guanxian faults, from NW to SE (Li et al., 2006). The 2008 Wenchuan earthquake caused two surface rupture zones along the Yingxiu-Beichuan and Anxian-Guanxian faults (Li et al., 2008). The Wenchuan Earthquake Fault Scientific Drilling (WFSD) was arranged to investigate the mechanism of the Wenchuan earthquake faulting and the physical properties of the large displacements along the ruptured faults (Xu et al., 2008). The second hole (WFSD-2) is located in Bajiaomiao Village, Hongkou County (Dujiangyan, Sichuan province), along the southern segment of the Yingxiu-Beichuan fault (Zhang et al., 2017). Pseudotachylyte veins were observed from 579.62 m depth to 599.31 m depth in the Pengguan complex (Zhang et al., 2017). The cataclasite zone consists of pseudotachylyte veins, cataclasite, and a few ultracataclasites.

Samples in this study were collected in the same location from the cataclasite (Figure DR1), which is the wall rock of the pseudotachylyte veins. Therefore, the microstructure, geochemistry and rock magnetism of all samples were homogeneous before heating experiments. Gray pseudotachylyte veins were injected into cataclasite as a flame (Figure DR1a). Fragments of the black vein were injected into the gray vein (Figure DR1a). The veins appear gray and black in macroscopic view (Figure DR1a), while they are evident as dark material under optical microscope (Figure DR1b). Different stages of veins are evident as different color tones under the optical microscope (Figure DR1c). New dark veins were injected into the old dark veins, and the contacts are sharp (Figure DR1c). A new dark vein can be seen cutting off one clast from another old dark vein (Figure DR1d). Figure DR1e shows the microstructural features of S1 (cataclasite) at room temperature. The sample contains 50-90% clasts by volume, these consist of feldspar, quartz, and calcite of various shapes, including rounded, embayed and other irregular forms (Figure DR1e).

A2. Heating experiment method

The heating experiments were completed at Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai, China.

To remove moisture and organic matter, 7 samples (S2-S8) were heated at 400 °C for 12 hours in a vacuum graphite tube furnace (Figure DR2a) under an argon atmosphere. The process is as follows. (1) Heating from room temperature to 100 °C in 47 minutes and then

hold for one hour. (2) Heating from 100 °C to 160 °C in one hour and then hold for one hour. (3) Heating from 160 °C to 270 °C in 110 minutes and then hold for one hour. (4) Heating from 270 °C to 320 °C in 100 minutes and then hold for one hour. (5) Heating from 320 °C to 400 °C in 80 minutes and then hold for one hour.

Six samples (S3-S8) were heated in a Thermo-Optical-Measurement system (TOM-AC) to temperatures of 700 °C, 900 °C, 1100 °C, 1300 °C, 1500 °C and 1750 °C, under an argon atmosphere. Firstly, the samples were placed in the charcoal stove (Fig. DR2b). Secondly, air was evacuated from the stove and replaced by argon. This flushing process was repeated three times to ensure the original gas content was less than 1%. Thirdly, the heating rate was set by the control panel before starting the test. The heating schedule is summarized below.

The heating rates of S3 (700 °C), S4 (900 °C) and S5 (1100 °C) were 30 °C/min. The heating rate of S6 (1300 °C) was 30 °C/min to 900 °C then 20 °C/min to 1300 °C. The heating rate of S7 (1500 °C) was 30 °C/min to 1200 °C then 20 °C/min to 1500 °C. The heating rate of S8 (1750 °C) was 30 °C/min to 1200 °C then 20 °C/min to 1750 °C.

Fourthly, the sample was held for 10 minutes in the charcoal stove and then cooled to about 60 °C in 3.5 hours. The cooling curves and average cooling rates of all samples are shown in Fig. DR3. The cooling rates of S3, S4, S5, S6, S7 and S8 were 3.04 °C/min, 4.00 °C/min, 4.95 °C/min, 5.90 °C/min, 6.86 °C/min and 8.05 °C/min.

Lastly, the sample was removed, and the apparatus prepared for the next heating experiment.

All heating experiments were completed under an argon atmosphere. This inert gas protects the samples from chemical reaction with the surrounding material, such as the carbon released by the vacuum furnace.

To preserve sample from avoiding oxidation, the heating and cooling process were completed under an argon atmosphere. When cooled to room temperature within Thermo-Optical-Measurement system (TOM-AC) after heating experiments, the samples were taken out and saved in vacuum plastic bags. Microstructural, geochemical and rock magnetic measurements of these samples were completed in two weeks after heating experiments.

A3. Measurement methods

Powder X-ray diffraction (XRD) analyses were carried out using a Dmax 12 kW powder diffractometer (CuK α) at 40 kV and 100 mA, with a scanning rate of 4° min-1 and a sampling width of 0.02°, and 0-70° (2 θ). XRD analyses were completed at the Micro Structure Analytical Laboratory in Peking University, Beijing, China.

Microstructural analyses were obtained using an optical microscope and Scanning Electron Microscope (SEM) at the Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China.

Magnetic susceptibility (MS) values were measured using an MLY-4S Kappabridge with a field strength of 300 A/m at room temperature. The measurement was completed at Key Laboratory of Paleomagnetism and Tectonic Reconstruction of Ministry of Land and Resources, Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing, China. Magnetic hysteresis loops were measured by a Princeton alternating gradient force

magnetometer (Model 3900 AGM), with 1 T maximum applied field. Saturation remanence (Mrs), saturation magnetization (Ms) and coercivity (Hc) were obtained after subtracting the paramagnetic contribution. Coercivity of remanence (Hcr) was obtained by backfield measurements after being magnetized at 1.0 T. Low-temperature isothermal remanence measurements were made using a Quantum Design Magnetic Property Measurement System (MPMS XP-5, sensitivity = 5.0×10^{-10} Am2). FORCs were measured using an averaging time of 0.5 s by a Model 3900 AGM and the data were processed using FORCinel software. Magnetic hysteresis loops, Low-temperature isothermal remanence measurements and FORCs were completed at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.

A4. Morphological characteristics

According to the real-time monitoring system, the shape of S8 remained almost unchanged below 1121 °C (Fig. 4a-e). The sample had then expanded in the horizontal direction and shortened in the vertical direction by 1302°C (Fig. 4f). Above 1421 °C, the cylindrical sample had become a bead (Fig. 4g). There was gas escape during the heating process from 1502 °C to 1743 °C (Fig. 4h-j). The bead shape was maintained at the end of the experiment.

Appendix Figures List

Figure DR1. Microstructural features of core around 580.65 m depth.

Figure DR2. (a) Vacuum graphite tube furnace. (b) Thermo-Optical-Measurement system (TOM-AC).

Figure DR3. The cooling curves of the samples at different temperatures.

- Figure DR4. The morphological characteristics of sample S8 at different temperatures.
- Figure DR5. Photomicrographs showing the microstructural features of samples at different temperatures.

Figure DR6. SEM images of representative samples.

- Figure DR7. Magnetic hysteresis loops for samples before para-/diamagnetic correction.
- Figure DR8. Figure DR8. (a) Plots of paramagnetic magnetic susceptibility (χ_{para}) versus low field magnetic susceptibility (χ_{lf}). (b) Day plot of the hysteresis ratios Mrs/Ms and Bcr/Bc.
- Figure DR9. FORC diagram for samples.

Appendix Tables List

Table DR1. XRD results for representative samples.

Table DR2. Magnetic parameters of samples from heating experiments.



Figure DR1. (a) Photograph of core from 580.62-580.97 m depth shows the location of samples. Yellow numbers 1-8 are the sample numbers (S1-S8). (b) Enlarged view of the square in Figure DR1a, showing the black pseudotachylyte and cataclasite. (c) Enlarged view of the square in Figure DR1b, showing different stages of dark veins. The boundaries between the dark veins are typically sharp but locally can be highly irregular. (d) Enlarged view of the square in Figure DR1c, illustrating clear flow structures and different layers of dark vein. (e) Microstructural features of cataclasite (S1).



Figure DR2. (a) vacuum graphite tube furnace. (b) Thermo-Optical-Measurement system (TOM-AC).



Figure DR3. The cooling curves of the samples at different temperatures



Figure DR4. The morphological characteristics of sample S8 at different temperatures. RT: room temperature.



Figure DR5. Photomicrographs showing the microstructural features of samples at different temperatures. (a) Cataclasite contains 50-90% clasts by volume, which are scatted in the fine-grained matrix. (b) Sample at 400 °C shows the blurred boundaries of clasts and consists of 50-90% clasts by volume. (c) Sample at 900°C, shows calcite veins along fractures. (d) Vesicles and flow structures are observed in the sample at 1500 °C.



Figure DR6. SEM images of representative samples. (a) Sample S5, irregular vesicles of $< 20 \ \mu m$ diameter are well developed. (b) Sample S6, note the penniform microlites and orbicular vesicles of $> 100 \ \mu m$ diameter. (c) Sample S6 shows acicular and lath-shaped microlites. (d) Sample S8, illustrating abundant orbicular vesicles with diameters changing from dozens to hundreds of μm . Mi: microlite; Ve:vesicle.



Figure DR7. Magnetic hysteresis loops for samples before para-/diamagnetic correction. (a) The magnetic hysteresis loop of cataclasite before para-diamagnetic correction is linear. (b)(c)(d) The results display wasp-waisted hysteresis loops. (e)(f)(g) The loops show a slight wasp-waisted shape.



Figure DR8. (a) Plots of paramagnetic magnetic susceptibility (χ_{para}) versus low field magnetic susceptibility (χ_{lf}). (b) Day plot of the hysteresis ratios Mrs/Ms and Bcr/Bc (plot of Day et al., 1977, as modified by Dunlop, 2002). Based on Roberts et al. (2017), we recommend abandonment of PSD in favor of "vortex state."



Figure DR9. FORC diagram for samples. (a) The result is noisy due to the small concentration of ferrimagnetic grains with respect to the paramagnetic contribution. (b) The FORC diagrams of S2 are consistent with a distribution of weakly interacting single domain (SD) particles (Pike et al., 2001; Rowan and Roberts, 2006). (c)(d)(e) The FORC diagrams of S3, S4 and S5 are consistent with the distribution of vortex state particles (Roberts et al., 2017). (f)(g)(h) The FORC diagrams of S6, S7 and S8 are consistent with the distribution of single domain (SD) grains.

Samples	Lithology	T (°C)	Quartz	Albite	Caltite	Muscovite	Cristobalite
S1	cataclasite	RT	47%	31%	9%	13%	-
S2	cataclasite	400	49%	34%	7%	10%	-
S3	cataclasite	700	36%	34%	15%	15%	-
S4	cataclasite	900	60%	25%	-	14%	-
S5	cataclasite	1100	71%	29%	-	-	-
S6	cataclasite	1300	58%	25%	-	-	17%
S7	cataclasite	1500	-	-	-	-	100%
S8	cataclasite	1750	80%	19%	-	-	1%

Table DR1. XRD results for representative samples

Table DR2. Magnetic parameters of samples from heating experiments

Samples	Lithology	Т	MS	χlf	χpara	χferri	Hc	Hcr	Ms	Mr
		(°C)	$(10^{-6}SI)$	$(10^{-8}m^3/kg)$	$(10^{-8}m^3/kg)$	$(10^{-8}m^3/kg)$	(mT)	(mT)	$(10^{-3} \text{Am}^2/\text{kg})$	$(10^{-3} \text{Am}^2/\text{kg})$
S1	cataclasite	RT	6	25	18	7	9.16	29.86	0.17	0.024
S2	cataclasite	400	17	46	9	37	18.70	34.13	0.79	0.20
S3	cataclasite	700	454	3246	46	3199	21.73	38.35	62.65	20.72
S4	cataclasite	900	42	220	13	206	23.71	57.31	59.00	14.50
S5	cataclasite	1100	108	539	28	511	7.83	41.13	27.49	1.06
S 6	cataclasite	1300	55	151	19	132	4.98	58.98	11.16	0.22
S 7	cataclasite	1500	195	428	26	402	6.23	77.48	36.22	0.56
S8	cataclasite	1750	651	2706	80	2627	3.27	78.32	122.80	1.01

Notes: ^aT: temperature; RT: room temperature; MS: magnetic susceptibility; χ_{lf} : low field magnetic susceptibility; χ_{para} : paramagnetic susceptibility verified by hysteresis measurements; χ_{ferri} : ferrimagnetic susceptibility calculated from the difference between χ_{lf} and χ_{para} ; Ms: saturation magnetization; Mrs: saturation remanence; Hc: coercivity; Hcr: coercivity of remanence.

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