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Laboratory verification of submicron magnetite production in pseudotachylytes: relevance for paleointensity studies

Norihiro Nakamura [a,*], Takehiro Hirose [b], Graham J. Borradaile [c]

[a] Research Center for Higher Education, Tohoku University, Sendai 981-8576, Japan
[b] Department of Geology and Mineralogy, Kyoto University, Kyoto 606-8502, Japan
[c] Geology Department, Lakehead University, Thunder Bay, ON, Canada P7B 5E1

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Abstract

Pseudotachylytes generally possess stable remanent magnetizations but the processes by which pseudotachylytes are magnetized remain poorly understood. Magnetic hysteresis and scanning electron microscope studies reveal that experimental frictional melting of granites produces dispersed submicron inclusions of weakly interacting pseudo-single-domain (PSD) magnetite, in artificial pseudotachylyte. The magnetite inclusions are absent in the undeformed granite protolith and result from oxidation of Fe in melt-susceptible mafic minerals during the melt-quenched event. The pseudotachylytes acquired a stable thermal remanence in fine-grained PSD magnetites during the rapid cooling of the melt, implying that fine-grained magnetite has the potential for paleointensity determinations of contemporaneous magnetic fields with co-seismic faulting in granitoids. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: pseudotachylite; thermoremanent magnetization; melting inclusions; pseudo-single-domains

1. Introduction

Frictional melting of rocks can generate pseudotachylytes due to quenching of melts during high-speed co-seismic faulting [1], during frictional heating along oblique impact surfaces inside meteorites [2,3], and due to impact cratering on the Earth [4,5]. In the case of frictional melting, comminution is an essential precursor [6]. Most natural pseudotachylytes appear to be more magnetic than their protoliths, due to the presence of fine-grained ferromagnetic minerals [7–9]. In the Nojima active fault, the natural remanent magnetization (NRM) of foliated fault gouges with black and blue-gray veins is 400 times more intense than in the adjacent ilmenite-series granites [10]. The difference between black and blue-gray veins is the existence of submicron-sized pseudo-single-domain (PSD) magnetite in the black veins [11]. Enomoto and Zheng [10] explained this intense magnetization as an isothermal remanent magnetization due to co-seismic electric currents ('earthquake-lightning'). This is supported by the observation that adjacent siltstones show a horizontal remanence orientation caused by a vertical electric

* Corresponding author. Tel.: +81-22-217-6613; Fax: +81-22-217-6634.
E-mail addresses: n-naka@mail.cc.tohoku.ac.jp (N. Nakamura), hirose@kueps.kyoto-u.ac.jp (T. Hirose), borradaile@lakeheadu.ca (G.J. Borradaile).

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current parallel to the fault plane of the Nojima fault during the 1995 Hyogo earthquake in Japan. Although recent frictional melting experiments in meteorites have reproduced submicron-sized Fe-metal inclusions [2,3], the effect of frictional melting on magnetic properties is still poorly constrained in meteorites and even in granitic crustal rocks. Here, we report the magnetic properties of an artificial pseudotachylyte produced by high-speed frictional melting experiments of ilmenite-series granite that permits an explanation of the intense and stable magnetization in pseudotachylytes.

2. Material and methodology

The friction experiment was performed on a pair of precision-machined hollow-cylindrical specimens of granite (length 25 mm with outer and inner diameters of 25 and 16 mm) at one atmosphere under dry conditions [12,13], in the presence of the Earth's magnetic field. The experimental apparatus consists of an air driven actuator to apply an axial force (9.8 kN) to the pair of cylindrical specimens and of a 7.5 kW AC servo-motor to rotate one of the specimens to 1500 r.p.m. (Fig. 1). The starting material is a medium-grained granite with the mineral assemblage of K-feldspar+plagioclase+quartz+hornblende+biotite, with accessory ilmenite, apatite and zircon. Sliding surfaces were prepared by lapping with a 100# SiC grinding wheel. The granite has a magnetic susceptibility of 163 μSI and NRM of 1.9×10^{-4} A m^{-1}, suggesting a negligible content of ferromagnetic minerals. In the first 5–6 s of the high-speed friction test, unmelted crushed rock chips were centrifugally ejected from the rotating interface. The pseudotachylyte was produced in 10 s at a velocity of 1.5 m/s under 1.5 MPa normal stress, after which the sliding surface glowed bright orange in color. Melt products sprayed out of the rotating surface and were quenched in air. The melt-origin dark, translucent and fibrous chips were recovered from unmelted crushed fragments of granite under a stereoscopic microscope.

Some chips were used for both magnetic hysteresis (MicroMag 2900 alternating field (AF) magnetometer) and scanning electron microscope (SEM) analysis. The remainder (0.34 g) of the chips were dispersed in non-magnetic epoxy resin in a plastic cube for plotting isothermal remanence (IRM) acquisition vs. AF demagnetization using a Sapphire Instruments SI-6 pulse magnetizer and SI-4 non-tumbling AF demagnetizer. These chips were first immersed in a sonic bath to remove extraneous crushed fragments and powdered residues.

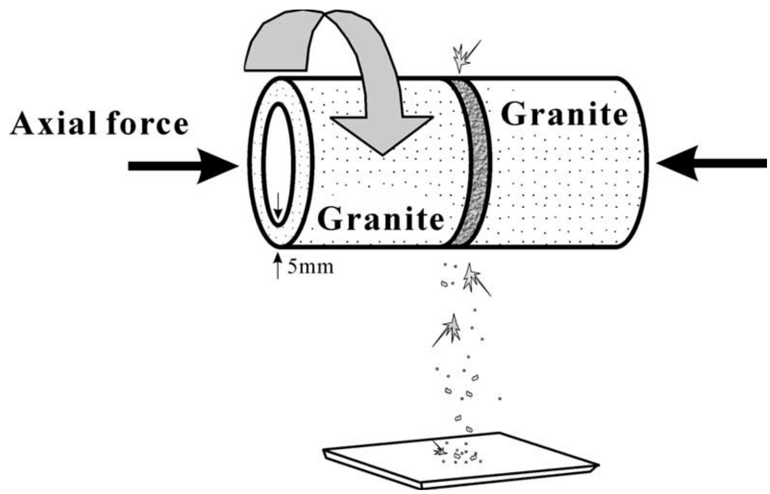

Fig. 1. Schematic diagram of high-speed, rotary-shear apparatus. The apparatus consists of a pair of hollow granite specimens. High-velocity slip is attained by rotating one of the specimens under an axial force of up to 9.8 kN, against the other specimen which is kept stationary.

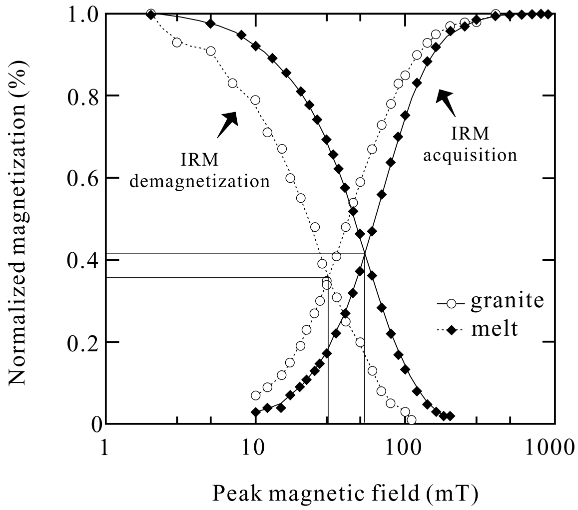

Fig. 2. Comparison of rock magnetic properties between the original granite and the frictional melt product. Both samples were progressively AF-demagnetized, followed by IRM acquisition up to a maximum magnetic field of 1 T. The IRM acquisition curve for the melt product saturates in fields greater than 300 mT, suggesting the presence of magnetite. The intersection of AF demagnetization vs. IRM acquisition curves shifts to higher remanence coercivity, from 32 to 53 mT, confirming the production of weakly interacting SD magnetite during frictional melting.

3. Hysteresis parameters and SEM analyses

The magnetic hysteresis of the chips exhibits SD or small PSD behavior, with ratios of maximum remanence at zero field (J_r) to saturation magnetization (J_s) ratios, such that $J_r/J_s \cong 0.5$. The mean J_s is 128 ± 51 mAm^2/kg which corresponds to representative magnetite. The mean coercivity (H_c) is 35 mT and mean remanent coercivity (H_{cr}) is 56 mT. The IRM acquisition of melt products saturates at nearly 300 mT, again suggesting the presence of magnetite (Fig. 2). Nearly symmetric, IRM acquisition vs. AF demagnetization curves indicate weakly interacting magnetic behavior with a remanent coercivity of 53 mT, whereas the curve for the original granite shows strongly interacting hysteretic behavior (Fig. 2) [14]. The hysteresis loops are obtained by measuring the induced magnetization of the chips during the application of large direct fields. The high-field linear portion of the loop exhibits the paramagnetic portion of the induced magnetization due to the saturation of the ferromagnetic component. The slope of the linear portion of the loop is proportional to the paramagnetic contribution to susceptibility, thereby estimating high-field paramagnetic susceptibility (k_p). Low-field ferromagnetic susceptibility (k_f) was calculated from the linear slope of hysteresis loops near the origin [15] to estimate the ferromagnetic contribution to susceptibility, after slope-cut for the paramagnetic component. These susceptibilities are

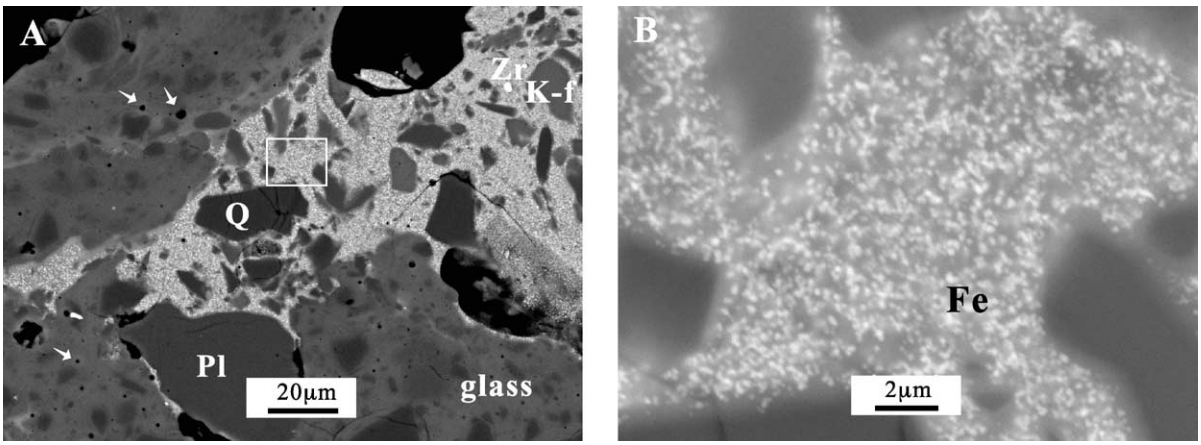

Fig. 3. Back-scattered scanning microscopy image of a frictional melt chip. (A) Dispersed inclusions of iron particles in silicate glass matrix with sub-angular to rounded quartz (Q), feldspar fragments and spherical vesicles (arrows). (B) Detail of inclusions of framed area in A, showing closely distributed, nearly equidimensional submicron iron crystals (100 ~ 500 nm). Pl: plagioclase, K-f: K-feldspar, glass: silicate glass matrix, Zr: zircon, and Fe: iron.

Table 1
Bulk magnetic and hysteresis properties among frictional melt products, original granite and natural fault gouges from the Nojima fault

Magnetic properties	Melt products	Original granite	Natural fault gouge	
			Black veins (bk)	Blue-gray veins (bl)
Bulkdata				
NRM (10^{-3} Am^{-1})	–	0.12	40	
SIRM (10^{-3} Am^{-1})	121 300	24	30 800	
k_m (μSI)	1 474	163	1 347	
Hysteresis data				
No. of samples	18	10	13	16
Mass (mg)	1.4–3.1	1.0–3.0	1.0–4.9	1.4–6.1
J_r (10^{-3} Am^2 kg^{-1})	21.6–108.8	0.3–13.8	19.7–100.9	0.5–10.5
J_s (10^{-3} Am^2 kg^{-1})	51.4–241.8	1.7–46.0	50.5–244.7	4.5–31.0
H_c (mT)	27.2–50.3	4.3–26.9	22.5–42.6	9.2–22.0
H_{cr} (mT)	45.4–68.7	–	39.6–80.5	23.4–46.0
k_f (10^{-9} m^3 kg^{-1})	938.4–3659.3	15.0–659.3	706.0–4 434.1	61.8–620.9
k_p (10^{-9} m^3 kg^{-1})	46.9–117.8	101.8–418.0	52.1–182.1	13.1–32.9
Mgt (%)	0.06–0.26	0.002–0.05	0.06–0.27	0.005–0.03

The volume percent (Mgt%) of magnetite is calculated by dividing J_s by the saturation magnetization of magnetite of 92 Am^2 kg^{-1} from Thompson and Oldfield [16]: magnetic content (%) = $(J_s \div 92) \times 100$. The magnetite contents are similar to an equivalent weight percent derived from the Js value of magnetite. Fault gouge is foliated with black-colored clay veins (bk) and blue-gray-colored ones (bl). Black veins may be pseudotachylyte veins. Some variables have no data from experiments, presented by '–' in the column.

derived from hysteresis loops where a chip of unknown orientation is measured in one direction. Since the preferred dimensional orientation of magnetite inclusions is anisotropic, it is conceivable and likely that the susceptibility derived in the one direction is not equal to the mean bulk susceptibility: k_m. Depending on which orientation of inclusions is most closely paralleled during hysteresis loop determination, k_f (10^{-9} m^3 kg^{-1}) will be greater or less than k_m (μSI).

Table 1 provides a summary of the magnetic properties: bulk magnetic properties and the hysteresis properties for melt products, original granite, and a natural fault gouge from the Nojima fault as a comparison. Frictional melt products have higher values of J_r, J_s, H_c and k_f than the original granite. These higher values are similar to the values for black veins in the natural fault gougen, but not for blue-gray veins. Moreover, high-field paramagnetic susceptibility of melt products shows a narrow range of 47–120 × 10^{-9} m^3 kg^{-1}. Such values are similar to weakly susceptible tektites from Australia, Europe, Indochina and Guatemala [17–19].

Back-scattered electron imagery by SEM shows that frictional melt products contain submicron-sized bright inclusions, surrounded by a silicate glass matrix with angular or sub-angular to rounded quartz-feldspar fragments and spherical

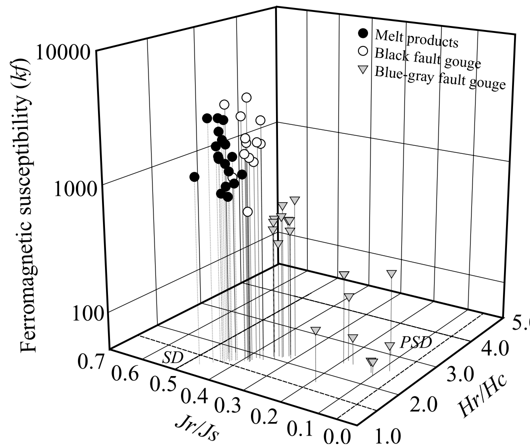

Fig. 4. A three-dimensional plot, combining the hysteresis plot of Day et al. [20] on the basal plane and low-field ferromagnetic susceptibility as the vertical axis. This discriminates magnetic properties for artificial pseudotachylytes and natural fault gouges with black veins, from those for blue-gray comminuted examples.

vesicles (Fig. 3A). These inclusions are 200–500 nm in size and are equidimensional in shape, scattered in the silicate glass matrix (Fig. 3B). An energy-dispersive X-ray spectrum shows that the inclusions are clearly enriched in Fe relative to the silicate glass matrix. Neither the inclusions nor the silicate glasses were observed in the natural, non-tectonized original granite samples. These magnetic, petrological and optical properties indicate that the iron-rich inclusions are fine-grained PSD magnetite, and that appreciable amounts of Fe were oxidized at the expense of melt-susceptible mafic minerals during the frictionally melt-quenched event.

4. Discussion and conclusion

Enomoto and Zheng [10] found intensely magnetized fault gouges (0.7 A m^{-1}) with black and blue-gray veins sandwiched between low susceptibility granite and siltstone in the outcrop. They suggested this remanent magnetization might have been caused by co-seismic electrical currents of $\sim$1000 A passed along the fault. If the intense magnetization is associated with a strong electrical current comparable to a lightning strike, the REM value (ratio of NRM to saturation IRM: SIRM) should exceed 0.1 (usually REM = 0.14–0.92 for fulgurites and Lodestones) [20]. However, intensely magnetized natural fault gouges with pseudotachylyte show REM = 0.0013, implying large electric currents were not involved. On the other hand, friction experiments reveal the production of fine-grained PSD magnetites due to oxidation of melt-susceptible mafic minerals, resulting in the SIRM being four orders of magnitude larger than that of the original granite. This result confirms that frictional melting can generate an intense and stable magnetization without large electric currents. Therefore, large electrical currents may not be necessary to explain the magnetization in pseudotachylyte, although the horizontal high-coercivity component in adjacent siltstone could have been caused by relatively weak electrical currents.

A previous study found that natural tektites from Australia, Indochina and Guatemala possess homogeneous high-field susceptibilities in a narrow range of $50–100 \times 10^{-9}$ m^3 kg^{-1} because the formation of iron oxides was suppressed during extremely rapid quenching [18]. Our frictional melting experiment also shows a similar narrow range of high-field susceptibilities. This confirms the view that the host silicate glass melted from low susceptibility granites. However, we find submicron magnetites embedded in the silicate glass. This argues for cooling rate as a crucial factor in the production of inclusions of magnetite in pseudotachylytes.

Magnetic hysteresis data may permit discrimination of pseudotachylytes from non-melted comminuted gouges in fault zones. However, its success may depend on the magnetic petrology of a wall rock. Fig. 4 illustrates this in a three-dimensional plot combining the hysteresis plot of Day et al. [21] on the base, and low-field ferromagnetic susceptibility as the vertical axis [22]. The data for black veins (i.e. pseudotachylyte) agree well with those of artificial pseudotachylytes, implying a melt-origin product. However, the comminuted-origin blue-gray veins have lower susceptibility and larger grain-size than melt-origin products, reflecting either an initial low content of magnetite in granite or different magnetic minerals (e.g. goethite). Therefore, magnetic hysteresis could be a useful microtechnique to detect melt-origin products from natural gouge samples in active faults.

The shock-induced melt pockets of the Tenham L6-chondrite showed that the FeO content of the melt is high compared to the FeO contents of the chondritic host (unmelted silicates) [23]. Although the protoliths are not granite, the effect of frictional heating is applicable to the interpretation of enigmatic magnetic properties in meteorites [24]. Therefore, it is apparent that more experimental work is needed on meteorites to characterize the effects of frictional heating on magnetic properties of mafic silicates. From the present pilot study, it would appear that the production of magnetic minerals by frictional heating should be considered in the interpretation of materials subjected to dynamic alteration, with localized acquisition of thermal remanence superimposed on the primary remanence on meteorites.

Our results also suggest that pseudotachylytes can be suitable for paleointensity studies, because they can contain submicron-sized PSD magnetites in a silicate glass, which are capable of carrying stable thermal remanence. Natural pseudotachylyte veins (i.e. black veins) in the Nojima active fault also contain PSD magnetites and show more intense remanent magnetization than their protoliths. Therefore, such frictionally melt-quenched material may be a promising source of information about ancient magnetic field intensities in the quest to determine whether a current-induced magnetic field is generated during seismic faulting or impact cratering events.

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