FEB 1986
RECEIVED
NASA STI FACILITY
ACCESS DEPT.

# FINAL TECHNICAL REPORT

| | |
|---|---|
| PRINCIPAL INVESTIGATOR: | Stanley M. Cisowski<br>Department of Geological Sciences<br>University of California<br>Santa Barbara, California 93106 |
| GRANT TITLE: | Magnetism of Nakhlites and Chassignites |
| GRANT NUMBER: | NASA NAG 9-72 |
| PERIOD: | 3/1/84-2/28/85 |

(NASA-CR-176518) MAGNETISM OF NAKHLITES AND CHASSIGNITES Final Technical Report, 1 Mar. 1984 - 28 Feb. 1985 (California Univ.) 27 p
HC A03/MF A01
CSCL 03B
N86-20277
Unclas
G3/90 05442

Through the support of this grant, complete magnetic analyses have been completed for the shergottite meteorites Shergotty, Zagami, EETA 79001, and ALHA 77005, and for nakhlite meteorites Nakhla and Governador Valadares. The studied samples of Shergotty meteorite included the subsamples of the Shergotty Consortium, which were made available for interdisciplinary studies by the Geological Survey of India. Magnetic measurements included high field hysteresis loops to determine the size of the magnetic grains, thermomagnetic curves to determine the composition of these grains, and remanence measurements to determine the nature of the magnetization that these various samples carry. A detailed paleointensity experiment was conducted on a subsample of Shergotty meteorite to determine the strength of the magnetic field in which the meteorite was magnetized.

The results of these analyses are that the magnetic carriers for the shergotite and nakhlite meteorites are generally fine grained titanomagnetites similar in composition to the titanomagnetites in oceanic basalts. Although the Shergotty and Zagami meteorites display large variations in remanence intensity, it is believed that the strong magnetizations result from post-sampling contamination in stray magnetic fields. The detailed paleointensity experiment on the Shergotty Consortium subsample revealed a high temperature remanence acquired in a field of less than 1,000 gammas, which would be consistent with a Martian origin for the parent meteorite.

BIBLIOGRAPHY:

Magnetic Studies on Shergotty and other SNC Meteorites, Geochimica et Commochimica Acta (Shergotty Consortium Issue), in press.

# MAGNETIC STUDIES ON SHERGOTTY AND OTHER SNC METEORITES

S. M. Cisowski
Department of Geological Sciences
University of California
Santa Barbara, California 93106

## ABSTRACT:

Hysteresis measurements on three shergottite and two nakhlite meteorites indicate single domain grain size behavior for the highly shocked Shergotty, Zagami, and EETA 79001 meteorites, with more multidomain-like behavior for the unshocked Nakhla and Governador Valadares meteorites. High viscosity and initial susceptibility for Antarctic shergottite ALHA 77005 indicate the presence of superparamagnetic grains in this specimen. Thermomagnetic curves likewise reveal a range of oxidation states for the high ulvospinel titanomagnetite grains which dominate the magnetic properties of these first five meteorites. Thermomagnetic analysis indicate Shergotty and Zagami as the least initially oxidized, while EETA 79001 appears to be the most oxidized. Cooling of the meteorite samples from high temperature in air results in a substantial increase in magnetizaion due to the production of magnetite through oxidation exsolution of titanomagnetite. However, vacuum heating substantially suppresses this process, and in the case of EETA 79001 and Nakhla, results in a rehomogenization of the titanomagnetite grains.

Remanence measurements on several subsamples of Shergotty and Zagami meteorites reveal a large variation in intensity that does not seem related to the abundance of remanence carriers. The other meteorites carry only weak remanence, suggesting weak magnetizing fields as the source of their magnetic signal. A paleointensity experiment on a weakly magnetized subsample of Shergotty reveals a low temperature component of magnetization acquired in a field of 2,000 gammas. Also present was a high temperature component reflecting a paleo-field strength of between 250 and 1,000 gammas, depending on the nature and degree of alteration that the sample may have undergone with heating. This is consistent with an earlier paleointensity estimate of 1,000

gammas for ALHA 77005. The weak field environment that these meteorites seem to reflect is consistent with either a Martian or asteroidal body origin, but inconsistent with a terrestrial origin.

## INTRODUCTION:

The SNC meteorites (Shergottites, Nakhlites, Chassignites) are especially interesting from a magnetic viewpoint, first, because of their relatively young crystallization ages, and second, because the oxidation conditions under which they formed resulted in magnetic minerals more commonly associated with terrestrial rocks than with other extraterrestrial materials. Instead of containing metallic iron as do lunar rocks and other types of meteorites, the SNC meteorites are unique amongst known extraterrestrial materials in containing titanomagnetite, the most common magnetic mineral in terrestrial basalts.

This study involves both a description of the basic magnetic properties of various meteorites within the SNC group, and an attempt to estimate the strength of the magnetic field which produced the remanent magnetization of Shergotty meteorite. This latter effort has the potential to constrain the choices for the parent body of these objects, or at least to describe the magnetic environment in which they evolved.

## ROCK MAGNETIC PROPERTIES:

Table 1 lists the intrinsic magnetic properties of the six SNC meteorites measured to date, including the four known shergottites (Shergotty, Zagami, and Antarctic meteorites ALHA 77005 and EETA 79001) and two Nakhlites (Nakhla and Governador Valadares). Shergotty, Zagami, and EETA 79001 exhibit single domain hysteresis properties, with IRMs (saturation isothermal remanence) to Js (saturation magnetization) ratios at or near to 0.5, and minimum coercive force (Hc) and remanent coercive force (Hrc) values of 470 and 700 oersteds respectively. Nearly symmetric IRM acquisition and demagnetization curves for Shergotty and Zagami also indicate non-interacting single domain behavior

(Cisowski, 1981).

Curie temperature experiments on the shergottite specimens reveal a high temperature phase of 550° to 590°C, corresponding to magnetite or low Ti-content titanomagnetite, and a low temperature phase of 150° to 325°C, corresponding to titanomagnetite with ulvospinel content of 65 to 45% (Nagata, p. 89, 1961). The high temperature Curie point is well defined for EETA 79001, but only poorly defined for Shergotty and Zagami (Fig. 1a,b,c). The titanomagnetite ulvospinel content as measured magnetically for Shergotty (~60%) agrees with the microprobe analysis estimate (63% - Stolper and McSween). The low titanium titanomagnetite phases in all three meteorites may result from partial oxidation exsolution of an originally homogeneous titanomagnetite, as ilmenite lamellae, indicative of high temperature oxidation, are observed in polished section.

Thermomagnetic cooling curves for Shergotty and Zagami were initially reversible in the high temperature region when done in a vacuum of <150 mtorr. Heating and cooling curves in air, however, resulted in a four fold increase in magnetization, beginning at 590°C (Fig. 1a,b). This indicates production of magnetite through oxidation exsolution of titanomagnetite. Below 200°C however, the vacuum cooling curves also began to show an increase in magnetization as compared to the initial heating curves, eventually producing a doubling of magnetization at room temperature (Fig. 1a). The subsequent reheating curve indicated that this increase in magnetization persisted, although in a somewhat diminished manner, up to temperatures of 590°C. At 550°C the observed magnetization due to magnetite was about 67% greater than the magnetization recorded at this temperature on the initial heating and cooling curves. Thus vacuum conditions suppress oxidation exsolution of titanomagnetite in the shergottites, although some alteration of the initial magnetic phases seems inevitable.

The higher Curie temperature for the titanomagnetite component of EETA 79001 (325°C) and the better defined magnetite Curie point (Fig. 1c) suggests that this sample represents a higher oxidation state than either Shergotty or Zagami. Upon cooling in a vacuum, only a gradual rise in magnetization with temperature is seen, suggesting varying stages of homogenization of the titanomagnetite (Vincent et al., 1957). Both measured subsamples of this heterogeneous meteorite came from the dominant finer grained lithology A (McSween and Jarosewich, 1982).

On comparison to data for synthetic titanomagnetite grains of similar composition, the hysteresis properties of Shergotty and Zagami suggest that the dominant grain size for their magnetic component is about 2 microns (Day et al., 1977). However, titanomagnetite grains >100 microns are observed in polished section for both meteorites, although thin ilmenite exsolution lamellae subdivide these grains into smaller units (Stolper and McSween, 1979). Dislocations and strain effects resulting from the ~300 kbar shock event which both meteorites suffered may also have increased the magnetic hardness of these specimens.

The fourth shergottite, ALHA 77005, exhibited a significantly lower remanent coercive force (210 oersteds) than the other three (Table 1). During IRM acquisition experiments, a pronounced viscous decay of IRM was noted as the sample was being measured. This is similar to the behavior of lunar regolith materials which contain abundant superparamagnetic grains. The higher initial susceptibility ($\chi_0$) of this sample (Table 1) might reflect a similar abundance of superparamagnetic grains in this sample. Nagata (1980a) also noted the propensity of ALHA 77005 to acquire a viscous component of remanence. Unlike the other shergottites, chromite, rather than titanomagnetite, is the dominant Fe oxide phase in this meteorite (McSween et al., 1979).

The intrinsic magnetic properties of Nakhla and Governador Valadares meteorites were nearly identical, with hysteresis properties less single domain-like than the shergottites (Table 1). Possibly related to this magnetic result is that shock effects appear to be absent in the nakhlites (Wood and Ashwal, 1981). The dual Curie point determinations of 150° and 490°C for Nakhla correspond to ulvospinel contents of 65 to 18% ulvospinel (Nagata, 1961). Polished sections of the nakhlites have revealed large titaniferous magnetite grains subdivided by broad ilmenite exsolution lamellae, with average ulvospinel contents of 44% (Bunch and Reid, 1975), about halfway between the two compositions determined magnetically. The thermomagnetic curve for Nakhla, done in a vacuum of 200 mtorr, was non-reversible, with a dramatic suppression of both Curie points on cooling, similar to the behavior of EETA 79001 (Fig. 1c,d). Subsequent reheating and cooling curves in vacuum were of the same character and reversible. Again this behavior can be interpreted in terms of homogenization of two originally discrete titanomagnetite phases.

In summary, the thermomagnetic curves for Shergotty and Zagami suggest that they are the least initially oxidized of the titanomagnetite-bearing SNC meteorites, while the most oxidized (based on its well developed magnetite Curie point) is EETA 79001, with Nakhla being intermediate. Shergotty, Zagami, and EETA 79001 are single domain-like in their hysteresis properties, while Nakhla and Governador Valadares are more multidomain in character.

ALHA 77005 appears to contain a significant fraction of superparamagnetic grains.

REMANENCE PROPERTIES:

Table 2 summarizes the magnetic remanence properties of the measured shergottite and nakhlite meteorites. Both Shergotty and Zagami show large variations in natural remanence (NRM) intensities between subsamples. Similar saturation remanence (IRMs) values for the Shergotty subsamples suggest that this variation is not caused by different abundances of magnetic carriers. For Zagami, the sample with the greatest intensity (fc) contains fusion crust as a significant portion of the sample. Nagata (1979) has shown that the outer 0.5 mm of an achondrite's skin is contaminated due to cooling in the Earth's field. However for Shergotty, only subsample B, which has the weakest NRM intensity per unit mass, contains fusion crust, although its large size (10.7 gm) as compared to the Zagami subsample (0.42 gm) would make the magnetic effect of the fusion crust much less important.

Figure 2 shows the alternating field (AF) demagnetization response of NRM and IRMs for several subsamples of Shergotty, and the NRM intensities of the other measured subsamples. A1, A2, B, B' and C refer to the Shergotty Consortium subsamples, while the other symbols refer to specimens obtained from the Smithsonian Institute. Subsample A and C were initially adjacent to each other in the parent meteorite, while B came from another part to the specimen. Because of uncertainties about the original orientations of the subsamples, the vector directions in Figure 2 do not have any inter-sample significance. However comparison of the shapes of the subsamples from photographs taken at the time of cutting and removal suggests that the vector direction of A1 and C varied by 90°.

Consortium subsample A2 is not only weaker but also considerably less resistant to demagnetization above fields of 200 oersteds. The directional stability for all demagnetized subsamples is very high (Figure 1, insert). Thermal demagnetization of one of the three strongly magnetized samples ($\chi$) revealed that about 90% of its NRM was blocked below 100°C. This observation, along with the large gradient in NRM intensity observed across the 12 cm diameter meteorite, suggests that the strong NRM intensities observed in three of the subsamples represent terrestrial contamination, rather than the record of an extraterrestrial field or magnetizing event. However the strong magnetization's resistance to AF demagnetization makes it unlikely that it represents a simple isothermal remanence acquired through exposure to a hand magnet or other magnetized metal object.

The other two Antarctic shergottites and the two nakhlites exhibit similar weak NRM intensities, but with variable resistance to alternating field demagnetization. ALHA 77005 loses ~80% of its NRM intensity by 200 oersteds, accompanied by considerable rotation of its magnetic vector. Governador Valadares over this same demagnetization range loses only about 25% of its intensity with only a moderate rotation of its vector, while Nakhla and EETA 79001 show respectively no change and a slight increase in intensity, with only a slight directional change to 300 oersteds AF.

The saturation remanence intensity values for the SNC meteorites, although considerably stronger than metallic iron-bearing extraterrestrial igneous rocks such as achondrites (IRMs 0.044 - 0.750 x 10E-02 emu/gm, Nagata, 1979) and mare basalts (IRMs 0.02 - 0.22 x 10E-02 emu/gm), fall at the lower end of the terrestrial mafic igneous rock IRMs intensity range. Exceptions are the Nakhlites, whose IRMs intensities compare favorably to terrestrial basalts. Because magnetite and titanomagnetite are less magnetic than most naturally occurring iron alloys, the iron-titanium oxide abundances in the SNC meteorites are obviously much greater than the free metal abundances in achondrites and lunar basalts.

The stability of saturation remanence to AF demagnetization for the SNC samples is reflective of the dominant magnetic grain size as indicated by the hysteresis properties in Table 1. Thus the single domain-like Shergotty, Zagami, and EETA 79001 meteorites are more resistant to IRMs demagnetization, while the less single domain-like ALHA 77005 and the nakhlites are less resistant (Table 2).

In Table 2, R(200) represents the ratio of NRM to IRMs intensity after demagnetization to 200 oersteds. This ratio is useful in estimating the relative intensity of the paleofield in which rocks acquired their remanence, providing that the samples have not been remagnetized or demagnetized since. For terrestrial igneous rocks heated and cooled through their Curie temperatures in the Earth's field this ratio is between 0.7 to 7.0 x 10E-02 (Cisowski and Fuller, 1985). Aside from Shergotty subsample Sb, which may carry a terrestrial magnetization, the other measured subsamples all display ratios below the range generally encountered for terrestrial rocks thermally magnetized in the Earth's field, but similar to normalized ratio values found in achondrites (Nagata, 1979). The nakhlites and EETA 79001 have particularly low ratios, perhaps reflecting the least contaminated, most pristine paleomagnetic record amongst the SNC meteorites.

## PALEOINTENSITY EXPERIMENT ON SHERGOTTY:

A 0.3 gm, fusion crust-free fragment of Consortium sample B (B' on Fig. 2), the least magnetic and hence potentially the most magnetically pristine subsample, has been subjected to a modified KTT experiment (Koenigsberger, 1938; Thellier and Thellier, 1959) to determine the strength of the magnetic field in which it evolved. The procedure used was to first heat and cool the sample in a null (<10 gamma) field, measure and compute the loss of remanence, and then reheat and cool the sample to the same temperature in a field of 2,000 gammas, and measure and compute the partial thermal remanence (PTRM) gained. To minimize the increase in magnetization with heating seen to accompany the thermomagnetic curves, the 2,000 gamma applied field was left on only during cooling to the previous heating's temperature, for heating steps greater than 338°C. Since vacuum conditions suppressed generation of additional magnetic signal in the Curie point experiments, each KTT heating was done in a vacuum of <100 mtorr pressure. In addition, above 400°C a titanium getter was added to the vacuum tube, and the tube was repeatedly flushed with helium gas and repumped to eliminate as many oxygen molecules as possible. The experiment was carried out using a three stage μ-metal shield inside a large three stage shielded room at the UCSB magnetics laboratory. A 2G Enterprises 760-R cryogenic rock magnetometer was used for sample measurements.

Figure 3 shows the results of the KTT experiment. The blocking temperature distribution for this sample is biomodal, with about 80% of the NRM blocked below 134°C. This result is similar to an earlier KTT experiment attempted on a fragment of Zagami meteorite. However because that experiment used the Earth's field rather than a weaker applied field, only an approximate maximum value of 5,000 gammas could be assigned to the Zagami paleofield estimate. For the Shergotty sample, the slope of the low temperature portion of the experiment corresponds to a paleofield of slightly less than 2,000 gammas. The simultaneous loss of both NRM and PTRM (partial thermoremanent magnetization) between 134°C and 338°C may indicate the destruction of a small amount of the magnetic carriers with both higher and lower blocking temperatures, although part of the loss of NRM might result from unblocking.

In order to verify that the decrease in PTRM acquired within this temperature range was not due to interactions between two magnetic phases, an additional heating experiment was done on a small (0.060 gm) fragment of Shergotty obtained from the Smithsonian Institute. This sample was first heated in vacuum to 338°C and allowed to cool in an applied field of 1.0 oersteds. After measurement the sample was again heated to 338°C, but cooled in a zero field to 134°C, at which point the 1.0 oersted field was applied only during cooling to room temperature. A third heating and cooling to 134°C was done in the 1.0 oersted applied field. In both the second and third cases, the resultant PTRM measured at room temperature was about 4% less ~~than~~ the PTRM acquired upon cooling from 338°C in the 1.0 oersted field. This experiment rules out the possibility that any significant negative interaction takes place between two magnetic phases within the 134°-338°C temperature range, as such an interaction would result in a reduced PTRM at room temperature following the first heating. Instead progressive destruction of fine grained carriers during the six heatings originally done in this temperature range is the most likely cause for the observed decrease in PTRM between 134° and 338°C in Figure 3. The high temperature portion of the KTT curve could thus indicate a paleofield of from 250 to 600 gammas, depending on whether the loss of NRM between 134°C and 338°C is due to unblocking or also to destruction of magnetic carriers during heating.

There are at least three possible interpretations for the results of

Figure 3. The first is that only the low temperature (<134°C) portion of the experiment is valid for estimating paleointensity. This would be the case if the increase in acquired PTRM above 338°C results solely from the production of new, high blocking temperature magnetic phases within the temperature range for which the applied field was turned on. Although the thermomagnetic reheating curves in vacuum did indicate that additional high blocking temperature phases are produced during the first cooling, these components comprised only about 67% of the pre-cooling magnetic signal for magnetite. While the conditions employed to minimize oxidation were considerably better for the KTT experiment than for the thermomagnetic experiment, a correction of KTT slope for the measured 67% increase in induced magnetization at high temperature still leaves the field estimate at a relatively low 410 to 1000 gammas.

The second interpretation is that the only substantial magnetization carried by the Shergotty meteorite is of a non-thermal origin, and inhabits only the lower blocking temperature portion of the thermal spectrum. The third interpretation is that two sequentially milder thermal events, the second in a higher field environment, affected the meteorite. Both of these scenarios imply that the oldest magnetic environment (recorded by the high blocking temperature component) was of a weak field ($\leqslant$1,000 gammas) nature.

The paleointensity result reported here is in substantial agreement with an earlier published result of 1,000 gammas for ALHA 77005 (Nagata, 1980a). However the technique used in this earlier experiment did not involve heating the sample, but instead employed a less conventional method of comparing the AF demagnetization of NRM to ARM (anhysteretic remanence) to estimate the strength of the paleofield. This method obviously does not allow for separate determinations over different blocking temperature ranges, as does the KTT experiment.

A similar KTT experiment was attempted on a fragment of Nakhla meteorite. However the experiment was unsuccessful due to anomalous and irregular acquisition of PTRM, which may be related to the homogenization effects seen with heating during the thermomagnetic experiment on Nakhla (Fig. 1d).

## IMPLICATIONS FOR THE SOURCE OF THE SHERGOTTY METEORITE:

Table 3 summarizes the history and probable magnetic consequences for the Shergotty meteorite. Some uncertainty still exists over whether the intense shock event dates to 180 or 2.5 m.y. The other shergottites, particularly Zagami and ALHA 77005, are believed to have similar histories, but with older crystallization and somewhat different cosmic ray exposure ages. It is unlikely that any of the primordial thermal remanence that these meteorites may have acquired during crystallization on their parent body would survive the intense shock they all suffered. Instead even the high temperature component of magnetization probably was acquired during the 300 kbar event. If this episode occurred on the parent body, then the weak (<1,000 gamma) result derived from the high temperature portion the KTT curve would relate to the strength of the surface field of this body. The low temperature, 2,000 gamma KTT result might relate to the magnetic environment during cooling of the ejecta blanket in which the specimens may have been deposited. The higher field value for the low temperature range then might reflect the greater efficiency associated with the acquisition of thermal remanence as compared to shock remanence. However at 300 kbar, it is possible that the instantaneous temperature pulse reached during the passage of the shock wave would nearly equal or surpass the Curie point of magnetite, thus resulting in a thermal-like, rather than an isothermal shock remanence being acquired. A similar shock event which also resulted in significant argon outgassing is thought to have thermally reset the magnetization of nickel iron in the Farmington chondritic meteorite at 0.7 AE during its parent body break-up (Rowe, 1975). A more probable explanation for the low temperature remanence is that it is of terrestrial origin, particularly since the bulk of it (>60%) does not survive heating to 78°C. Thus it could represent a viscous remanence acquired since falling to Earth, or a much-reduced analogue to the suspected contamination found in the other more intensely magnetized Shergotty subsamples.

Although no direct measurement of the surface field of Mars has been made, estimates of the dipole field from Russian flyby spacecraft result in a calculated surface field of less than 100 gammas (Strangway, 1977). Because of the uncertainties about the degree of alteration with heating and about the history of the meteorite discussed above, such a precise estimate of the Shergotty parent body field strength cannot be made, although the high temperature portion of the experiment, taken at face value, is indicative of a similar low field (<1,000 gamma) environment. However it must be stated that nearly all potential sources of the SNC meteorites (e.g., an asteroidal body), with the exception of the Earth itself or possibly the moons of the giant planets, would represent a low field environment origin over the past 1,300 m.y. And so this low field paleointensity result cannot be considered as restricting the SNC meteorites' origin to Mars. The paleointensity determinations on Shergotty and ALHA 79001 do, however, strongly contrast with the 10,000 gamma paleofield intensities found associated with more typical achondrites (Nagata, 1979).

# ACKNOWLEDGEMENTS:

The author would like to thank John Annexstad of the Meteorite Working Group, Kurt Fredriksson of the Smithsonian Institute, J. C. Laul of Battelle, Larry Nyquist of NASA Johnson Space Center, and the Geological Survey of India, Calcutta, for assistance in obtaining the meteorite samples described in this manuscript. Thanks are also offered to M. Fuller for useful discussions pertaining to this work, to D. Crouch for drafting the figures, and to J. R. Dunn for assistance in the performance of the experimental work. This work was performed under NASA Grant No. NAG 9-72.

REFERENCES:

Bunch, T.E. and Reid, A.M. (1975) The nakhlites, Part 1: Petrography and mineral chemistry; Part 2: Where, when, and how. Meteoritics 10, 303-324.

Cisowski, S. (1981) Interacting vs. non-interacting single domain behavior in natural and synthetic samples. Phys. Earth Planet. Int. 26, 56-62.

Cisowski, S.M. and Fuller, M. (1985) Lunar paleointensities via the IRMs normalization method and the early magnetic history of the Moon, Origin of the Moon, Lunar and Planetary Institute, Houston, in press.

Day, R., Fuller, M. and Schmidt, V.A. (1977) Hysteresis properties of titanomagnetites: grain-size and compositional dependence. Phys. Earth Planet. Int. 13, 260-267.

Jagoutz, E. and Wanke, H. (1985) Sr and Nd isotopic systematics of Shergotty meteorite. This volume.

Koenigsberger, J.G. (1938) Natural residual magnetism of eruptive rocks. Terr. Mag. Atmos. Phys. 43, 119-127.

McSween, H.Y. and Jarosewich, E. (1982) Petrogenesis of the Elephant Moraine A79001 achondrite. Lunar and Planet. Sci. 13, 503-504 (abstract).

McSween, H.Y., Taylor, L.A. and Stolper, E.M. (1979) Allan Hills 77005: A new meteorite type found in Antarctica. Science 204, 1201-1203.

Nagata, T. (1961) Rock Magnetism, Maruzen Ltd., 350 p.

Nagata, T. (1979) Meteorite magnetism and the early solar system magnetic field. Phys. Earth Planet. Int. 20, 324-341.

Nagata, T. (1980a) Paleomagnetism of Antarctic achondrites. Mem. Natl. Inst. Polar Res., Spec. Iss. 17, 233-242.

Nagata, T. (1980b) Magnetic classification of Antarctic meteorites. Proc.

Lunar Planet. Sci. Conf. 11, 1789-1799.

Rowe, M.W. (1975) Duration of magnetic field(s) acting on meteorite parent body(s). in Proc. Takesi Nagata Conf., Univ. of Pittsburgh, ed. Fisher, R.M., Fuller, M., Schmidt, V.A., and Wasilewski, P.J.

Shih, C.-Y., Nyquist, L.E., Bogard, D.D., McKay, G.A., Wooden, J.L., Bansal, B.M., and Wiesman, H. (1982) Chronology and petrogenesis of young achondrites, Shergotty, Zagami, and ALHA 77005: Late magmatism on a geologically active planet. Geochim. Cosmochim. Acta 46, 2323-2344.

Stolper, E. and McSween, H.Y. Jr. (1979) Petrology and origin of shergottite meteorites. Geochim. Cosmochim. Acta 43, 1475-1498.

Strangway, D.W. (1977) The magnetic fields of terrestrial planets. Phys. Earth Planet. Int. 15, 121-130.

Thellier, E. and Thellier, O. (1959) Sur l'intensite du champ magnetique terrestre dans le passe historique et geologique. Ann. Geophys. 15, 285-376.

Vincent, E.A. and Wright, B. (1957) Heating experiments on some natural titaniferous magnetites. Min. Mag. 31, 624-655.

Wood, C.A. and Ashwal, L.D. (1981) SNC meteorites: Igneous rocks from Mars? Proc. Lunar Planet. Sci. 12B, 1359-1375.

FIGURE CAPTIONS:

Figure 1. Thermomagnetic curves for a) Shergotty b) Zagami c) EETA 79001 d) Nakhla. (1) initial heating in vacuum (2) initial cooling in vacuum (3) reheating in vacuum (4) cooling in air.

Figure 2. Response of IRMs (~10E-02 emu/gm) and NRM (10E-04 to 10E-05 emu/gm) to alternating field demagnetization for Shergotty subsamples. A1, A2, B, B' and C refer to Consortium subsamples, other symbols refer to subsamples obtained from the Smithsonian Institute. Insert shows NRM directional behavior for the three demagnetized subsamples. These subsamples were not oriented relative to one another.

Figure 3. Results of modified KTT paleointensity experiment on Shergotty Consortium subsample B', showing NRM remaining and PTRM acquired after heating to various temperatures in a field of 2,000 gammas.

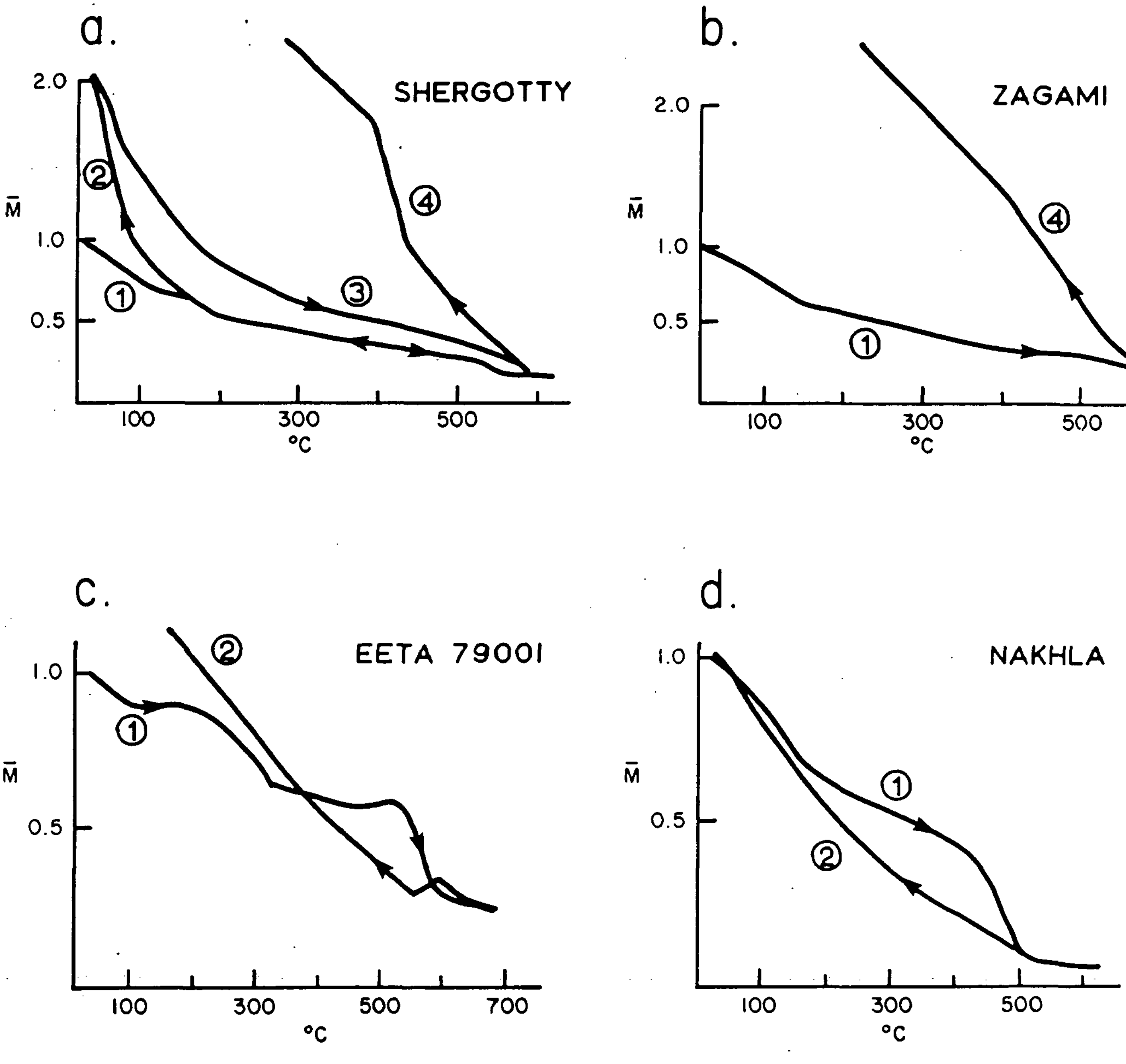
a.
SHERGOTTY
2.0
1.0
0.5
M̄
①
②
③
④
100
300
500
°C
b.
ZAGAMI
2.0
1.0
0.5
M̄
①
④
100
300
500
°C
c.
EETA 79001
1.0
0.5
M̄
①
②
100
300
500
700
°C
d.
NAKHLA
1.0
0.5
M̄
①
②
100
300
500
°C

Figure 1.

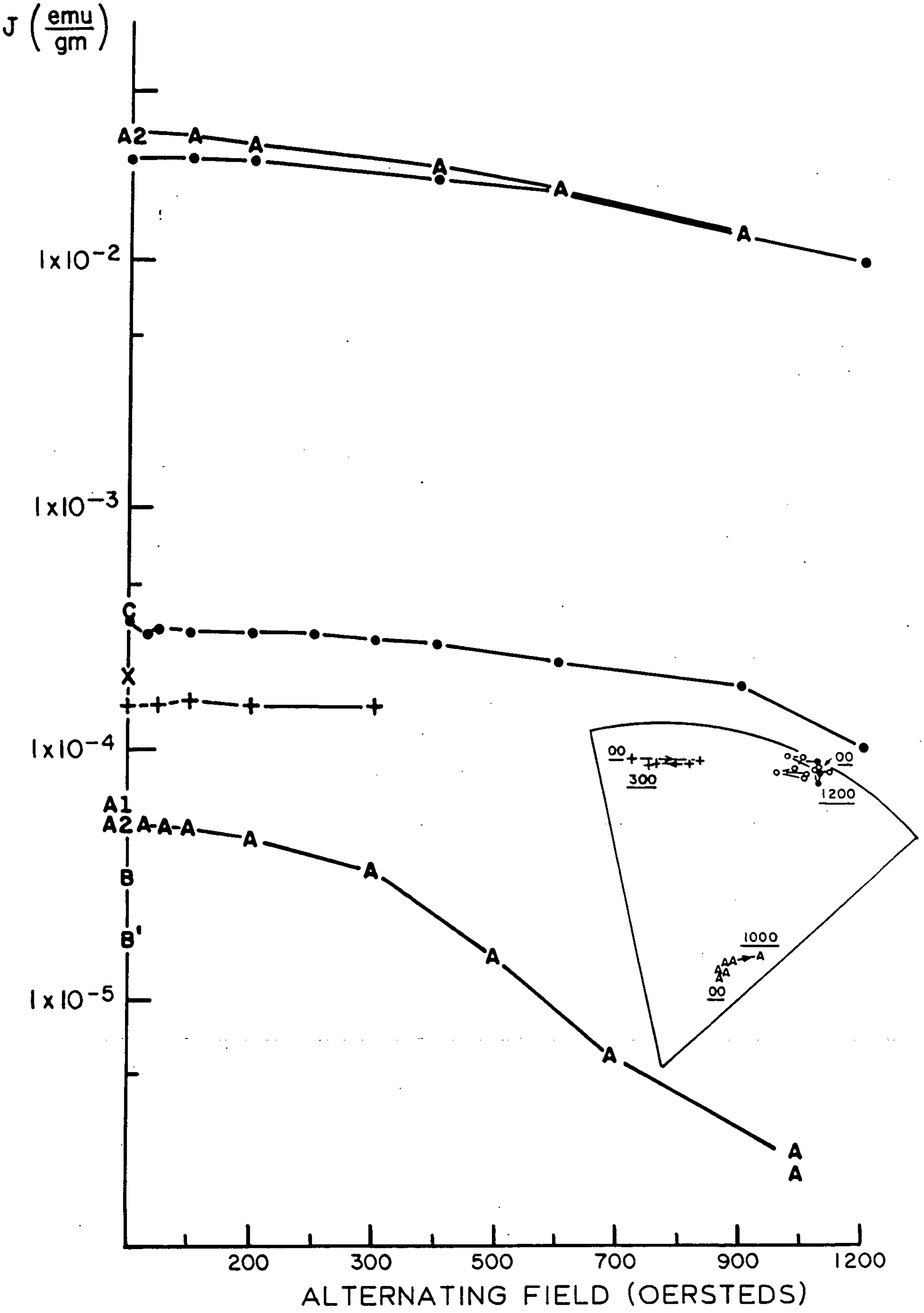
J (emu/gm)
1x10^-2
1x10^-3
1x10^-4
1x10^-5
A2
A
C
X
A1
A2
B
B'
200
300
500
700
900
1200
ALTERNATING FIELD (OERSTEDS)
00
300
00
1200
1000
00

Figure 2.

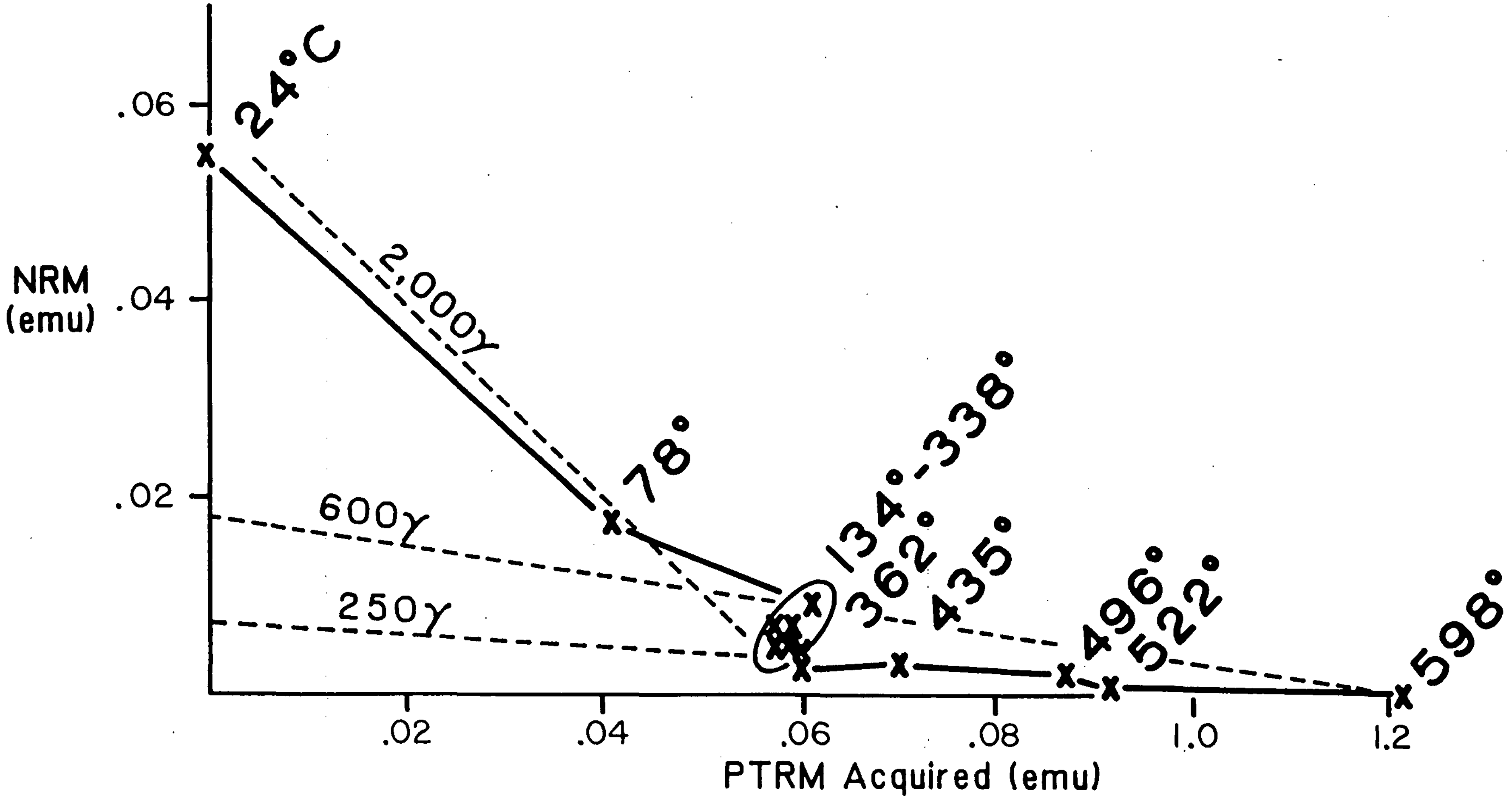
NRM
(emu)
.06
.04
.02
24°C
2,000γ
600γ
250γ
78°
134°-338°
362°
435°
496°
522°
598°
.02
.04
.06
.08
1.0
1.2
PTRM Acquired (emu)

Figure 3.

Table 1. Intrinsic magnetic properties of shergottites and nakhlites

| I.D. | | IRMs/Js | Hc (oe) | Hrc (oe) | $\chi_o$ (G) (10E-02) | Tc |
|---|---|---|---|---|---|---|
| Shergotty | A2 | 0.5 | 1032 | 1300 | 1.06 | |
| | B | | | | 0.95 | |
| | C | | | | 1.12 | |
| | Sa | 0.4 | 700 | | | 200° + 550°C |
| | Sb | | | 1000 | | |
| Zagami | S1 | | 700 | | | 150° + 550°C |
| | fc | | | | 0.8 | |
| | 1b | 0.46 | 470 | | | |
| EETA 79001 | | 0.47 | 775 | 800 | 0.7 | 325° + 590°C |
| ALHA 77005 | .77 | (0.18)* | - | 210 | 5.12 | |
| Nakhla | | 0.2 | 400 | 625 | 1.45 | 150° + 490°C |
| Gov. Valadares | | 0.26 | 425 | 575 | 1.33 | |

| | |
|---|---|
| IRMs | Saturation Isothermal Remanent Magnetization |
| Js | Saturation Magnetization |
| Hc | Coercive Force |
| Hrc | Remanent Coercive Force |
| $\chi_o$ | Initial Susceptibility |
| Tc | Curie Temperature |

* Js measurement from Nagata (1980b)

Table 2. Magnetic remanence properties of shergottites and nakhlites

| I.D. | | NRM | (200) | (300) | IRMs | (200) | (300) | R(200) |
|---|---|---|---|---|---|---|---|---|
| | | (x10E-05 emu/gm) | | | (x10E-02 emu/gm) | | | (x10E-02) |
| Shergotty | A1 | 5.89 | | | | | | |
| | A2 | 5.36 | 4.99 | 3.50 | 3.44 | 3.09 | 2.07 | 0.16 |
| | B | 3.27 | | | | | | |
| | B | 1.8 | | | | | | |
| | C | 36.1 | | | | | | |
| | Sa | 20.5 | | | 1.98 | 1.83 | 1.78 | |
| | Sb | 34.5 | 31.8 | 31.0 | 2.62 | 2.59 | 2.50 | 1.23 |
| | Sc | 15.0 | 15.6 | 15.2 | | | | |
| Zagami | S1 | 11.8 | 2.1 | 0.5 | 1.08 | 0.85 | 0.73 | 0.25 |
| | fc | 26.0 | 12.4 | 7.7 | | | | |
| | S2 | 3.75 | | | | | | |
| ALHA 77005 | .77 | 3.24 | 0.52 | 0.13 | 1.5 | 1.1 | 0.8 | 0.04 |
| (Nagata, 1980) | | 3.61 | 0.72 | 0.42 | | | | |
| EETA 79001 | A | 1.72 | 1.93 | 1.92 | 1.95 | 1.75 | 1.44 | 0.11 |
| | B | 3.29 | | | | | | |
| Nakhla | | 1.3 | 1.3 | 1.3 | 9.2 | 6.7 | 5.3 | 0.02 |
| Gov. Valadares | | 5.1 | 3.6 | 3.2 | 9.8 | 6.9 | 5.4 | 0.05 |

| | |
|---|---|
| NRM | Natural Remanent Magnetization |
| IRMs | Saturation Isothermal Remanent Magnetization |
| (200) | Magnetization remaining after alternating field demagnetization to 200 oersteds. |
| (300) | Magnetization remaining after alternating field demagnetization to 300 oersteds. |
| R(200) | Ratio of NRM (200) to IRMs (200). |

Table 3. Postulated history of the Shergotty meteorite (derived from Shih *et al.*, 1982 and Jagoutz & Wanke, 1985)

| Time | Event | Magnetic consequence |
|---|---|---|
| 343 m.y. | Crystallization | Acquisition of TRM in parent body field |
| 180 m.y. | Intense (?) shock event (300 kbar), inclusion in hot ejecta blanket (200°C - 400°C) | Shock demagnetization of primary TRM, acquisition of SRM and/or PTRM |
| 2.5 m.y. | Low energy(?) shock event initiating cosmic ray exposure | Slight shock demagnetization of SRM and PTRM |

| | |
|---|---|
| TRM | Thermo-remanent magnetization |
| PTRM | Partial thermo-remanent magnetization |
| SRM | Shock remanent magnetization |