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Magnetic remanence in the Murchison meteorite

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Abstract–The Murchison meteorite is a carbonaceous chondrite containing a small amount of chondrules, various inclusions, and matrix with occasional porphyroblasts of olivine and/or pyroxene. It also contains amino acids that may have served as the necessary components for the origin of life. Magnetic analyses of Murchison identify an ultrasoft magnetic component due to superparamagnetism as a significant part of the magnetic remanence. The rest of the remanence may be due to electric discharge in the form of lightning bolts that may have formed the amino acids. The level of magnetic remanence does not support this possibility and points to a minimum ambient field of the remanence acquisition. We support our observation by showing that normalized mineral magnetic acquisition properties establish a calibration curve suitable for rough paleofield determination. When using this approach, 1–2% of the natural remanence left in terrestrial rocks with TRM and/or CRM determines the geomagnetic field intensity irrespective of grain size or type of magnetic mineral (with the exception of hematite). The same method is applied to the Murchison meteorite where the measured meteorite remanence determines the paleofield minimum intensity of 200–2000 nT during and/or after the formation of the parent body.

INTRODUCTION

The amount of acquired magnetization in rocks can be characterized by ratio (REM) between the natural remanence (NRM) and saturated isothermal remanence (SIRM) (Cisowski et al. 1983; Cisowski and Fuller 1986; Wasilewski 1977). Most of the rocks on Earth acquire thermal remanence (TRM—the rocks' temperature is lowered through the blocking temperature) and chemical remanence (CRM—magnetic minerals chemically precipitated) in a geomagnetic field. Rocks can also acquire Detrital remanent magnetization (DRM) during the sedimentation processes. However, this DRM is often overprinted by later CRM acquired during the cementation processes. Methods used for paleofield determination (Fuller 1974; Stephens and Collinson 1974; Thellier and Thellier 1959) require an extensive sample heating. SD (single domain) grains (<40 nm in size) that carry the stable component of NRM have large surfaces and, therefore, a mild heating promotes chemical reactions destroying the original record. We offer an alternative approach accessing an approximate value of the primitive paleofield information without heating the sample.

NEW METHOD

By normalizing the experimental mineral TRM acquisitions for SD, PSD (pseudo single domain), and MD (multi domain) minerals (Dunlop and Waddington 1975; Kletetschka, Wasilewski, and Taylor 2000; Özdemir and O'Reilly 1982; Tucker and O'Reilly 1980; Wasilewski 1981) we obtain a uniform trend, indicating that magnetic grains of various mineral domain-states and/or mineral types saturate near 20 mT (see Fig. 1). The only exception from this trend is MD hematite, which saturates near 0.1 mT due to its low spontaneous magnetization and demagnetizing field, allowing domain walls to nearly saturate in magnetic fields of low intensity (Dunlop and Kletetschka 2001; Kletetschka, Wasilewski, and Taylor 2000). The normalized TRM acquisition trends allow quick and rough estimation of a paleofield in rocks that formed in an unknown magnetic environment. To test this approach, we used NRM and SIRM values from 85 terrestrial samples of various origin (Table 1) (Goddard database). Statistical means of NRM/SIRM ratios are 0.009 ± 0.002, 0.011 ± 0.004, and 0.017 ± 0.003 for metamorphic, sedimentary (with CRM), and igneous rock

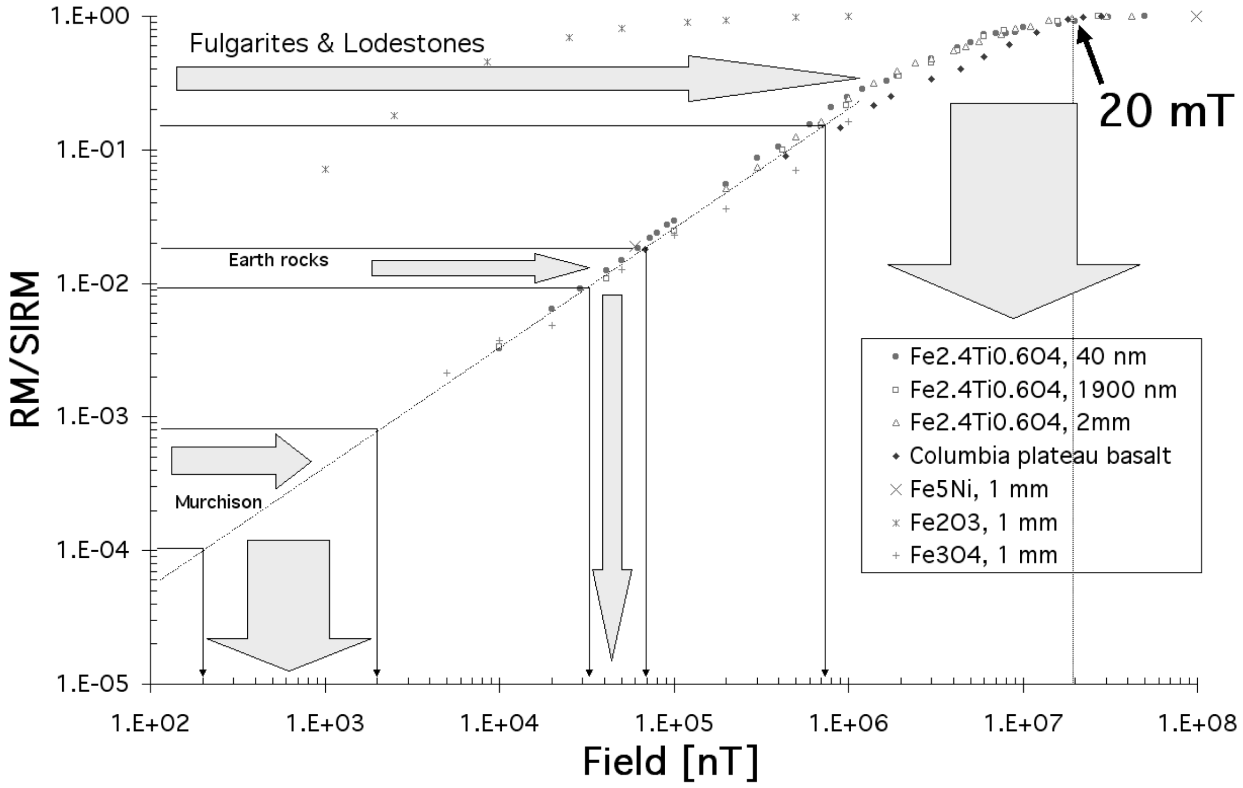

Fig. 1. RM/SIRM (RM is a remanent magnetization, e.g. CRM, TRM) is plotted against an acquisition magnetic field for various materials. This plot provides a basis for paleofield estimates. Data are calculated from TRM acquisitions on 40 nm titanomagnetite (Özdemir and O'Reilly 1982), 1900 nm and 2 mm titanomagnetite (Tucker and O'Reilly 1980), Columbia plateau basalt (Dunlop and Waddington 1975), iron-nickel spheres (Wasilewski 1981), and 1 mm hematite and magnetite (Kletetschka, Wasilewski, and Taylor 2000). The acquisition trend of all data except hematite is emphasized by the dashed line.

types, respectively. The statistical spread is caused by multiple remanent components in some of these rocks with contrasting direction recorded throughout the rocks' history. When we use these statistical means in Fig. 1, we obtain acquisition fields between 35,000 and 65,000 nT. This range of values falls within the actual values of geomagnetic fields. This 1% of TRM remanence left in various rock has been noted previously. Cisowski observed that a typical ratio in fine-grained magnetic material for TRM acquired in geomagnetic field will be of an order of 10^{-2} (Cisowski and Fuller 1986). Sedimentary samples where fine-grained secondary magnetite forms by chemical precipitation, giving rise to CRM, again gives magnetization about 1 part in 100 of SIRM (Hart and Fuller 1988). In light of these observations and the experimental data presented in Fig. 1, we apply an extension of the curve approximated by the data (Fig. 1) for estimation of pre-existing magnetic fields recorded in the Murchison meteorite.

MAGNETIC SIGNATURE OF MURCHISON

NRM measurements of the interior piece of Murchison revealed a peculiar magnetic instability. The natural remanent magnetization (NRM ~5 E-05 A m^2/kg, consistent with values observed previously [Banerjee and Hargraves 1972]) drifted as soon as the sample was shielded from the terrestrial field. This magnetic sensitivity, caused by fields as low as the geomagnetic field, has never been reported in the Murchison meteorite despite multiple magnetic analyses (Brecher and Arrhenius 1974; Banerjee and Hargraves 1972). Similar soft behavior has been observed in chondrules extracted from the Bjurbole meteorite (Kletetschka, Wasilewski, and Berdichevsky 2001). The effect of exposing and shielding meteorite fragments to and from the geomagnetic field, respectively, is illustrated in Fig. 2, where the acquired/relaxed component is shown to increase linearly with the logarithm of time. This property is independent of further demagnetization and/or acquisition and, thus, must be considered when deciphering the extraterrestrial magnetization signature.

The ultrasoft magnetic decay at 77 K is about 70% of room temperature decay. However, the NRM increased more than twice from 5 E-05 A m^2/kg at 300K to 13 E-05 A m^2/kg at 77 K. Contrary to intuition, the samples with low coercivity do not contain the ultrasoft component and have relatively high NRM. The SIRM/Js (Js = saturation magnetization) ratio (Table 2) of low coercivity samples suggests that magnetization carriers are multi-domain grains. This is also

Table 1. List of specific rock types used in the magnetic test study.

Ward sample (Ward's Natural Science)	Mass (g)	NRM (A m^2/kg)	SIRM (A m^2/kg)	Ward sample (Ward's Natural Science)	Mass (g)	NRM (A m^2/kg)	SIRM (A m^2/kg)
1 Biotite granite, Barre, Vermonth	7.05	0.00000285	1.11 E-04	48 Glauconitic sandstone, Hazlet, New Jersey	7.74	3.31 E-06	1.18 E-03
2 Muscovite granite, Concord, New Hampshire	9.85	7.00 E-08	9.21 E-06	49 Siltstone, Near Newhall, California	7.02	2.30 E-07	2.01 E-05
3 Biotite hornblende granite, St. Cloud, Minnesota	5.94	4.41 E-06	1.58 E-04	50 Arkose, Mt. Tom, Massachusetts	7.83	1.95 E-06	1.61 E-03
4 Alcalic granite, Quincy, Massachusetts	7.4	1.65 E-05	4.28 E-04	51 Graywacke, Grafton, New York	7.07	8.00 E-07	5.91 E-05
5 Aplite, Boulder County, Colorado	6.96	1.21 E-06	5.50 E-04	52 Argillaceous shale, Rochester, New York	10	2.00 E-08	6.45 E-06
6 Quartz monzonite porphyry, Garfield, Colorado	8.79	4.80 E-05	5.92 E-03	53 Aranaceous shale, Greene County, New York	6.3	1.98 E-06	4.48 E-04
7 Granodiorite, St. Cloud, Minnesota	7.76	5.97 E-04	1.38 E-02	54 Oil shale, Garfield County, Colorado	23.5	1.00 E-08	9.51 E-06
10 Rhyolite tuff, Frying Pan Basin, Montana	14	7.86 E-06	5.97 E-04	55 Bauxite, Bauxite, Arkansas	5.69	1.96 E-03	2.06 E-02
11 Rhyolite, Castle Rock, Colorado	7.3	5.34 E-05	1.69 E-03	57 Siliceous oolite, State College, Pennsylvania	28	1.40 E-07	5.13 E-05
12 Rhyolite porphyry, Chaffee County, Colorado	4.24	1.42 E-04	1.36 E-02	59 Encrinal limestone, Lockport, New York	32.1	6.00 E-08	1.84 E-05
13 Hornblende syenite, Cuttingsville, Vermont	9.84	8.67 E-06	5.88 E-03	60 Limestone, Fremont County, Colorado	28.9	5.20 E-07	1.58 E-03
14 Alcalic syenite, Cripple Creek, Colorado	7.09	2.65 E-04	6.21 E-02	61 Cherty limestone, LeRoy, New York	23.5	4.00 E-08	1.22 E-05
15 Trachyte porphyry (bostonite), Essex County, New York	8.52	3.77 E-06	2.06 E-03	62 Oolitic limestone, Tyrone, Pennsylvania	28.8	1.67 E-06	2.19 E-04
16 Trachyte porphyry, Cripple Creek, Colorado	7.25	7.30 E-07	3.91 E-03	63 Chalk, Oktibbeha Co., Mississippi	23.3	3.00 E-08	1.33 E-05
17 Nepheline syenite, Blue Mt., Methuen Twp, Ontario	8.76	3.24 E-06	2.84 E-04	64 Calcerous tufa, Mumford, New York	18.9	3.50 E-07	1.27 E-05
18 Nepheline-sodalite syenite, Red Hill, New Hampshire	8.1	3.54 E-05	5.41 E-02	65 Dolomitic limestone, Rochester, New York	25.2	3.50 E-07	4.28 E-05
19 Ijolite, McClure Mountain, Colorado	5.96	8.21 E-04	1.03 E-02	67 Hematite limestone, Wayne County, New York	7.4	2.14 E-05	4.18 E-02
20 Siderite carbonite, Iron Hill, Colorado	12.1	2.10 E-07	1.99 E-05	68 Siderite rock, Negaunee, Michigan	39.6	5.48 E-04	2.36 E-01
21 Phonolite, Cripple Creek, Colorado	4.1	7.58 E-05	1.38 E-02	72 Marble (pink), Tate, Georgia	31.1	6.00 E-08	8.99 E-06
22 Monzonite, Silvetron, Colorado	7.1	2.53 E-04	5.49 E-02	73 Dolomite marble, Thornwood, New York	29	3.00 E-08	1.07 E-05
23 Latite porphyry, Bear Paw Mountains, Montana	7.9	7.93 E-04	2.91 E-02	74 Verde antique (serpentine), Rochester, Vermont	27.4	5.27 E-04	8.26 E-02
24 Tonalite (quartz diorite), San Diego County, California	7.01	9.50 E-07	1.42 E-04	75 Garnet wollastonite skarn, Willsboro, New York	37	5.00 E-08	6.73 E-06
25 Diorite, Los Angeles County, California	9.41	1.71 E-06	1.42 E-03	77 Slate (gray), Bangor, Pennsylvania	30	5.00 E-08	8.95 E-06
26 Dacite, N. W. of Helena, Montana	5.73	5.99 E-05	7.53 E-03	78 Phyllite, Ely, Orange County, Vermont	2.45	1.95 E-05	1.02 E-03
27 Hornblende andesite, Mt. Shasta, California	6.97	1.52 E-03	4.78 E-02	79 Mica schist, Manhattan, New York	6.13	2.15 E-04	1.58 E-02
28 Hornblende gabbro, San Diego County, California	8.7	1.40 E-03	7.65 E-02	80 Chlorite shist, Chester, Vermont	8.92	1.66 E-04	4.45 E-02
29 Norite, Wollaston Twp., Ontario	10.2	4.90 E-03	8.90 E-02	81 Stilpnomeline schist, Mendocino County, California	36.7	7.00 E-08	2.51 E-05
30 Olivine gabbro, Wichita Mountain, Oklahoma	11.3	1.64 E-04	2.52 E-01	82 Talc-Tremolite schist, St. Lawrence County, New York	34.8	2.00 E-08	1.37 E-06
31 Hornblende gabbro, Salem, Massachusetts	9.02	4.11 E-04	3.37 E-02	83 Graphite schist, Warren County, New York	7.4	3.76 E-06	2.90 E-04
32 Anorthosite, Elizabethtown, New York	9.76	5.41 E-06	1.95 E-04	84 Andalusite (chiastolite) slate, Mariposa Co., California	7.68	5.60 E-07	2.28 E-04
33 Diabase, Jersey City, New Jersey	8.82	1.60 E-04	7.51 E-03	85 Staurolite quartzite, Petaca, New Mexico	34.6	2.75 E-03	2.57 E-01
34 Scoria, Klamath Falls, Oregon	3.46	7.99 E-03	2.01 E-01	86 Kyanite quartzite, Near Ogilby, California	14.6	1.65 E-07	4.49 E-05
35 Amygdaloidal basalt, Keweenaw County, Michigan	7.5	9.40 E-04	1.06 E-01	87 Sillimanite-garnet gneiss, Warren County, New York	8.03	8.00 E-07	2.11 E-05
36 Basalt, Chimney Rock, New Jersey	9.22	2.07 E-03	2.22 E-01	88 Cordierite anthophyllite skarn, Guffey, Colorado	13.1	1.18 E-06	1.11 E-04
37 Olivine basalt porphyry, Valmont, Colorado	10.1	1.32 E-03	7.35 E-02	89 Augen gneiss, St. Lawrence Co., New York	8.57	1.40 E-04	1.36 E+00
38 Diabase porphyry, Cape Ann, Massachusets	8.73	1.04 E-04	8.41 E-03	90 Granitoid gneiss, Salisbury, North Carolina	7.17	1.68 E-05	1.68 E-01
39 Lamprophyre, Spanish Peaks, Colorado	11.2	4.59 E-03	1.22 E-01	91 Biotite gneiss, Uxbridge, Massachusetts	7.64	4.66 E-07	7.11 E-03
40 Pyroxenite (harzburgite), Stillwater Complex, Montana	9.54	4.27 E-05	1.33 E-02	92 Eclogite, Sonoma County, California	16.8	4.50 E-06	1.09 E-04
41 Dunite (olivine peridotite), Balsam, North Carolina	8.7	2.12 E-06	8.82 E-04	93 Actinolite schist, Chester, Vermont	5.25	1.06 E-06	3.57 E-04
42 Kimberlite, Murfreesboro, Arkansas	15.7	1.22 E-06	8.89 E-05	94 Cummingtonite schist, Leeds, South Dakota	5.97	4.73 E-05	1.03 E-02
44 Quartz-pebble conglomerate, Nanticoke, Pennsylvania	8	3.00 E-07	3.95 E-05	95 Hornblende schist, Mitchell Co., North Carolina	10.5	4.29 E-07	3.40 E-05
45 Gray sandstone, Berea, Ohio	6.5	4.80 E-07	1.29 E-04	96 Glaucophane schist, Sonoma County, California	6.65	3.00 E-08	9.38 E-06
46 Red sandstone, Potsdam, New York	28.2	5.23 E-06	4.67 E-04	97 Hornblende gneiss, Clintonville, New York	10.4	6.00 E-07	9.42 E-05

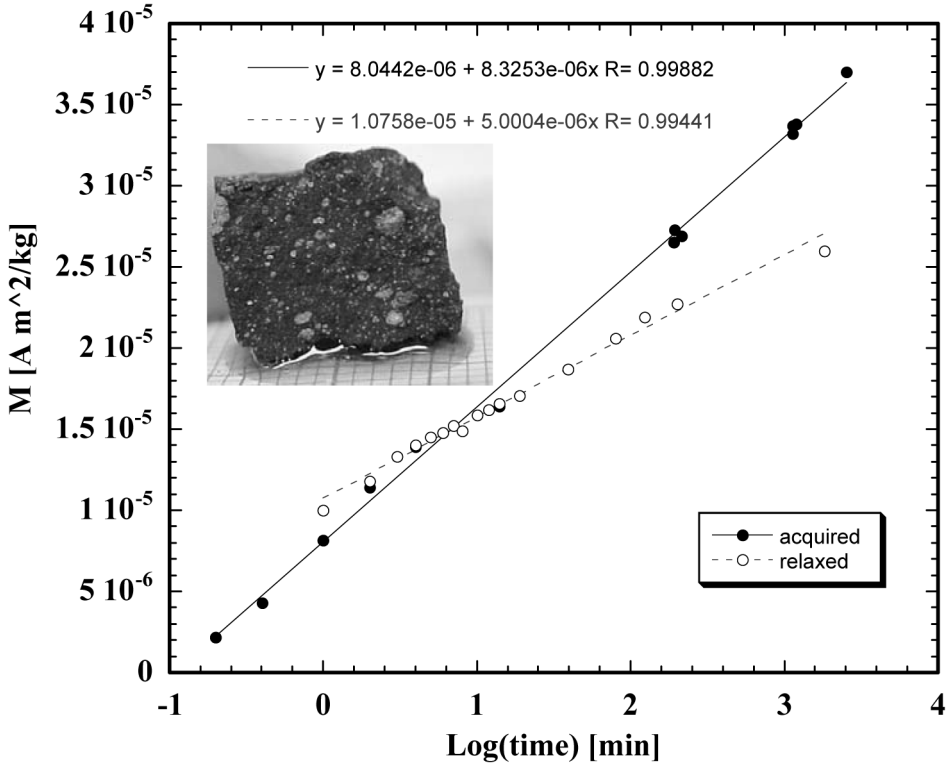

Fig. 2. Magnetic component gained and relaxed after exposing to and shielding from the geomagnetic field, respectively. This ultrasoft component modifies magnetization measurements (NRM ~5 E-05 A m^2/kg) during the examination and is always parallel to the external (geomagnetic) field. The inset picture shows the size of the actual fragment of the Murchison meteorite (Smithsonian Institution).

Table 2. Hysteresis parameters for representative samples at 300 K (suffix R) and 77 K (suffix N). Js (A m^2/kg) is saturation magnetization, SIRM (A m^2/kg) is saturation remanence, Hc (mT) is coercivity, and Fr (%) is remanence left after 5 minutes in magnetic vacuum.

Sample	Mass (g)	JsR	HcR	SIRMR/JsR	JsN	HcN	SIRMN/JsN	FrR(%)
1	0.0056	3.870	8.97	0.033	3.860	10.95	0.039	99
2	0.0097	2.210	13.72	0.070	2.110	30.76	0.134	93
3	0.0030	1.110	16.10	0.132	1.700	42.47	0.116	68
4	0.0059	0.768	19.30	0.114	0.931	52.80	0.175	86
5	0.0038	0.792	20.30	0.100	0.838	48.80	0.129	59
6	0.0346	0.857	21.50	0.105	0.938	42.06	0.157	60
7	0.0073	0.471	24.30	0.140	0.506	45.10	0.223	61
8	0.0509	0.532	25.80	0.140	0.668	51.30	0.181	70

consistent with high value of Js indicating a high concentration of iron (Table 2). The samples with the ultrasoft component have high coercivity and low remanence and point to a mixture of SD and super-paramagnetic grains finely dispersed throughout the sample. This is important because magnetic remanence carried by SD fraction of these grains is stable against artificial remanence acquisition and, thus, may preserve a record of pre-terrestrial magnetic events.

Magnetic results from Murchison fragments (Fig. 3) allow division of Murchison material into two distinct groups. Group A contains six fragments with REM just under 1 E-02. Five of these samples come from the part of the specimen (Czech Republic) that contained the fusion crust. Therefore, some part of each specimen was severely heated during the meteorite landing and acquired a terrestrial TRM component. One specimen within Group A clearly has a large level of magnetization (NRM/SIRM ~0.01 in Fig. 3) but is part of the Murchison interior with no evidence of fusion crust. This specimen also has the lowest Hc, indicating the magnetically softest material (See Table 2, Specimen 1 with mass 0.0056 g). Closer examination revealed a multi-domain metallic piece within this sample. Soft MD magnetic properties allow geomagnetic field contamination, characterized by a higher value of the measured natural magnetization. Soft magnetization in this sample also has low stability against the NRM demagnetization by alternating magnetic field (>90%

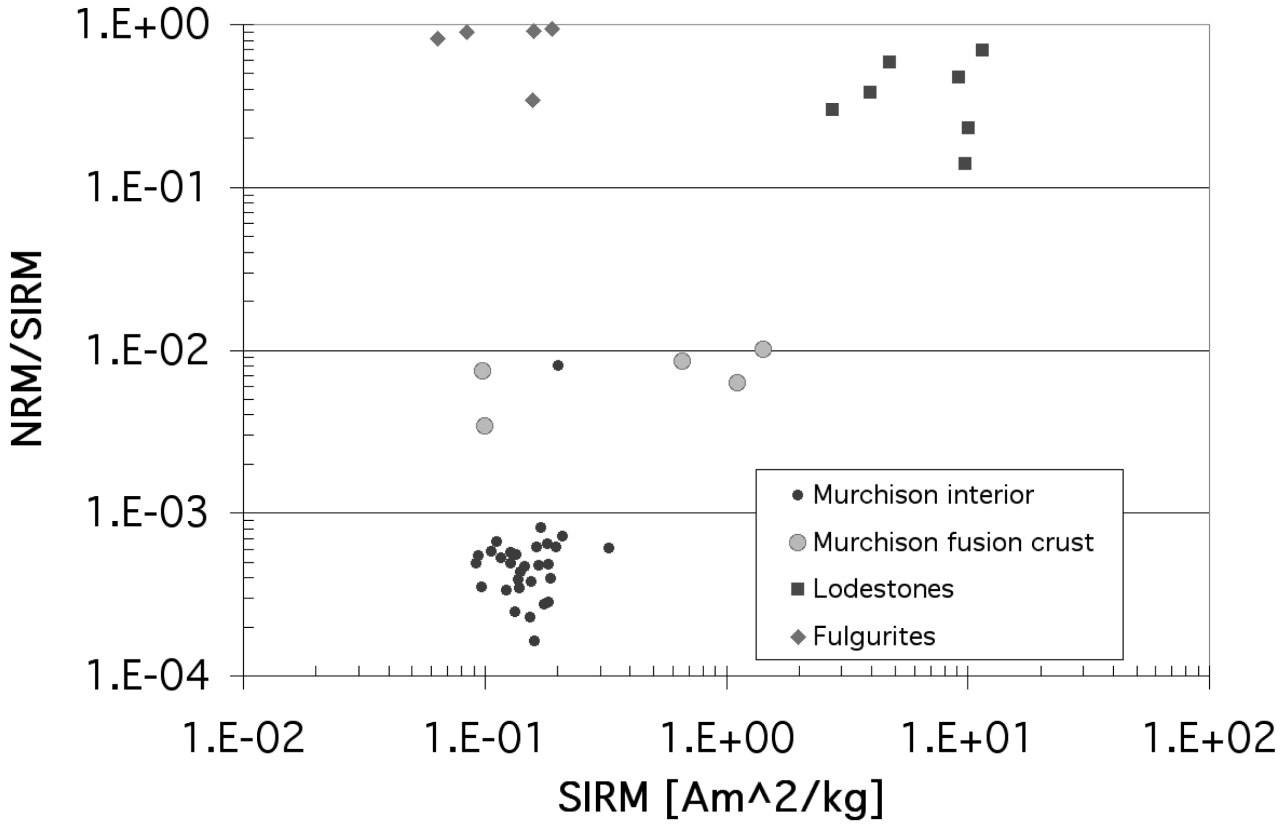

Fig. 3. Natural remanent magnetization versus saturation remanence for parts of Murchison is shown in comparison with terrestrial samples exposed to the lightning discharge (fulgurites and lodestones).

NRM loss in 20 mT). Group B contains only fragments from the Murchison's interior, and none of these fragments has a magnetization level over 0.001 (Fig 3). AF demagnetization of these samples revealed fairly stable NRM (<60% NRM loss in 60 mT).

In summary, Group A has samples with strong terrestrial magnetic components and Group B has a record of fairly weak, stable, and possibly extraterrestrial paleofield. Therefore, only Group B can be considered for paleofield estimation.

RM (Remanent magnetization) values of Group B samples are still subject to the ultrasoft component discussed earlier. According to Fig. 2, the Murchison meteorite is capable of acquiring almost 4 E-05 A m^2/kg in several days. To double this value, the sample would have to be exposed to the geomagnetic field for more than 2000 years, due to the logarithmic nature of remanence acquisition. Because the sample landed on Earth 32 years ago, the maximum extent of the ultrasoft component can not exceed 7 E-05 A m^2/kg according to the linear dependence in Fig. 2. During the course of measurement (1–5 minutes per sample), samples acquire an ultrasoft component of more than 1.5 E-05 A m^2/kg. This component can significantly contribute to the Murchison meteorite samples whose NRM range is 3–160 E-05 A m^2/kg. Ultrasoft acquisition will cause a slight overestimate of magnetization levels in Fig. 3. After subtracting this ultrasoft component (1.5 E-5 A m^2/kg) from each sample's NRMs, the range of magnetization levels from the Murchison interior is between 1 E-04 and 8 E-04. To use this range in the acquisition diagram (Fig. 1), we need to acknowledge the absence of mineral acquisition data for low field values. Assuming that the acquisition trend extends linearly into low fields, we obtain a paleofield of at least 200 and at most 2000 nT. This field was recorded by high coercivity fraction of magnetic carriers and, therefore, it is likely that the Murchison meteorite was exposed to this field during its formation.

MURCHISON METEORITE AND AMINOACIDS

The Murchison meteorite is well known for its content of amino acids (Engel and Macko 1997; Epstein et al. 1987; Kvenvolden, Lawless, and Ponnamperuna 1971; Oró 1990). The formation of organic compounds and their accumulation is considered a prerequisite to the appearance of life on primordial Earth (Oparin 1957). Various sources of energy, such as heat from volcanoes, heat and ultraviolet light from the sun, ionizing radiation from radionuclides, and electric discharges may be responsible for massive organo-synthesis from prebiotic compounds. Electric discharge events (Miller 1957) probably operated during the first stages of the solar

nebula development (Desch and Cuzzi 2000). This mechanism can be responsible for the major synthesis of amino acids in carbonaceous meteorites. This is supported by a similarity between the products and relative abundance of the amino acids produced by electric discharge and the amino acids present in the Murchison meteorite (Cronin and Moore 1971; Wolman, Haverland, and Miller 1972).

Models of early solar nebula evolution predict the presence of lightning discharges due to turbulent flows carrying dust particles rich in metal and silica (Desch and Cuzzi 2000). These authors speculate that discharge formed this way is comparable and/or several times more intense than terrestrial lightning and occupies larger volumes and distances during the stroke. The presence of lightning strokes in dust during the early solar nebula development may have been associated with magnetic field pulses stronger than magnetic fields generated by terrestrial lightnings. The magnetization acquired by primitive matter should closely approach saturation magnetization according to the principles reported for terrestrial lodestones and/or fulgurites (Wasilewski and Kletetschka 1999). Terrestrial rocks that experienced a lightning discharge are magnetized close to their saturation level (>10%) and are magnetically distinct from rocks which acquire remanence (1–2%) in the geomagnetic field on Earth's surface (Wasilewski and Kletetschka 1999). There is one exception, however: rocks with coarse-grained hematite as discussed above. In meteorites, however, the oxidized form of iron, hematite, is only rarely seen and is absent from the Murchison meteorite (Fuchs, Olsen, and Jensen 1973).

CONCLUSIONS

We offer a rough, non-distructive method for paleointensity estimation based on normalized magnetic mineral acquisition experimental data. We apply this method to various terrestrial rocks and obtain geomagnetic field intensities. When the Murchison meteorite is used, we estimate that Murchison was exposed to a paleofield of at least 200 nT before it entered the geomagnetic field environment.

It becomes clear, however, that the measured specimen from the parent body of the Murchison meteorite may not have been subject to lightning discharges during its residence in the interplanetary space. When the values for rocks affected by lightning are compared with those of the Murchison samples (Fig. 3), we see that the Murchison meteorite would require a past presence of magnetic fields exceeding 700,000 nT to allow amino acid formation by lightning discharges. If the amino acids in Murchison were, in fact, formed by the electric discharge, this would have to occur before the formation of the parent body of Murchison. Dust particles associated with amino acids formed by an electric discharge would acquire magnetization close to saturation. However, subsequent formation of the Murchison parent body would essentially randomize the strong magnetic moments, lowering the level of overall magnetization. This scenario is consistent with new isotopic and experimental evidence that suggest that the synthesis of amino acids (or their precursors) may have preceded the formation of the Murchison parent body (Caro et al. 2002).

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