Hand magnets and the destruction of ancient meteorite magnetism

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Key Points:

- The magnetic records of meteorites provide information about planetary formation and evolution, yet they are routinely destroyed by magnets.
- Magnets are not useful for distinguishing Martian and lunar meteorites from Earth rocks because of their low Fe metal contents.
- We recommend the use of susceptibility meters for meteorite identification as a non-destructive and more accurate identification technique.

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Abstract

The paleomagnetic record of meteorites provides invaluable information about planetary formation and evolution. Yet, the potential of these magnetic records in advancing the field of planetary science is severely hindered by a widely used identification technique: application of hand magnets. Here we showcase the destructive effects of touching meteorites with magnets as exemplified by the oldest known Martian meteorite, the Northwest Africa (NWA) 7034 pairing group. We recommend that magnets not be applied to meteorites during collection and curation. Instead, a low-field susceptibility meter is a far more sensitive and completely nondestructive tool for meteorite classification.

Plain Language Summary

Meteorites are rocks that originate from a planetary body other than Earth. They were ejected from their parent bodies by a meteoroid impact and landed on Earth. The permanent magnetism of meteorites provides invaluable information about how planets formed and evolved. Unfortunately these ancient magnetic records are commonly destroyed soon after they are discovered due to a widely-used identification technique: touching them with strong magnets. Here, we discuss the example of the oldest Martian meteorite currently available on Earth, Northwest Africa (NWA) 7034. NWA 7034 has crystals that are older than 4.4 billion years old and date from the time that Mars had an internally generated magnetic field. As such, the study of NWA 7034's magnetic record has the potential to provide valuable insights about the Martian magnetic field, and consequently about the geological and climatological evolution of Mars. However, we show that its magnetic record has been destroyed by hand magnets. We suggest that susceptometers (which apply only weak magnetic fields) be used instead of hand magnets because they are non-destructive and a more accurate identification technique.

1 Hand magnets on meteorites

The tens of thousands of known meteorites are thought to be samples of more than 100 parent bodies including asteroids, the moon and Mars (Weisberg et al., 2006). They provide unique records of planet formation and evolution, including evolution of the protoplanetary disk, planetary accretion, and planetary thermal evolution and differentiation.

The study of the more than 200 known Martian meteorites has significantly advanced our understanding about the geochemical and geophysical evolution of planet Mars, especially given that they are our only geological samples from the red planet (Udry et al., 2020). Yet, one aspect of their precious record remains relatively unexploited: their natural remanent magnetization (NRM), the semi-permanent alignment of electron spins that provides a record of exposure to past magnetic fields.

Mars currently does not possess a global, internally-generated, magnetic field but regions of its crust are strongly magnetized (Morschhauser et al., 2018). This indicates that Mars once had a global dynamo field powered by its convecting metallic core, which may have ceased about 4 billion years (Ga) ago (Mittelholz et al., 2020). All but two of the Martian meteorites postdate by billion of years the likely shutdown of the Martian dynamo and therefore can only retain records of crustal remanent magnetic fields. The only exceptions are Allan Hills 84001, an orthopyroxenite with a crystallization age of approximately 4.1 Ga (Weiss et al., 2008), and the Northwest Africa (NWA) 7034 pairing group (hereafter, NWA 7034), a polymict breccia with zircon and baddeleyite crystals with U-Pb crystallization ages older than 4.4 billion years old (Bouvier et al., 2018; Cassata et al., 2018; McCubbin et al., 2016). As such, NWA 7034 is the only known meteorite to be sufficiently old to likely have acquired a direct record of the Martian core field. Access to this record could provide unique constraints on the strength, timing and

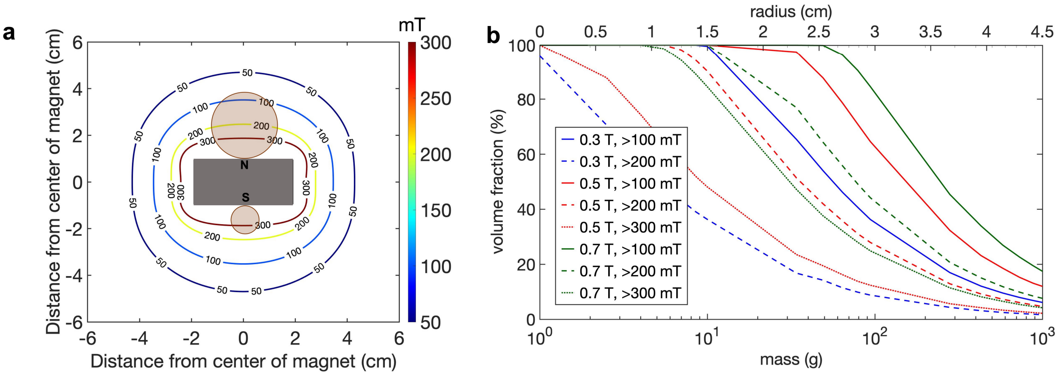

Figure 1. The magnetic field of a neodymium bar magnet and its effect on rock samples. (a) The intensity of the magnetic field surrounding a bar magnet (grey) with a 0.5 T surface field. The brown circles at the north and south poles of the bar magnet represent the cross-sectional areas of rocks with masses of 80 g and 6 g, respectively. (b) The volume fraction of a rock that experiences >100, >200 and >300 mT fields (solid, dashed, and dotted line respectively) when placed at the pole of the bar magnet with the same dimensions as in (a), assuming 0.3 T, 0.5 T and 0.7 T polar surface fields (blue, red and green lines, respectively). Results shown as a function of the rock's mass (lower abscissa) and radius (upper abscissa), assuming a spherical shape and density of 3 g cm^{-3} density.

evolution of the Martian dynamo, and by implication on the composition and thermal state of Mars' deep interior. In particular, measurements of the field's paleointensity could test the hypothesis that Mars' thick ancient atmosphere was once protected from loss by a strong ($>\sim$ 50 μT) dynamo field. Two other exceptional aspects of this meteorite are that it is just one of 4 known Martian meteorites with sufficient concentrations of magnetic minerals to account for the strong crustal magnetic fields (Gattacceca et al., 2014), and the only meteorite whose composition matches the estimated composition of the average Martian crust (Agee et al., 2013).

However, no study has been able to study its ancient magnetic record. Gattacceca et al. (2014) found that the NRMs of NWA 7034 and one of its paired stones, NWA 7533, have been completely overprinted by magnets. The use of magnets as an identification technique is widespread among meteorite hunters, collectors and curators particularly when dealing with meteorites found in hot deserts (Weiss et al., 2010; Gattacceca & Rochette, 2004). Magnets can help identify chondrites (meteorites that are agglomerations of unmelted materials from the solar nebula) by their property of being rich in iron-nickel, which makes them more strongly attracted by magnets relative to most Earth crustal rocks. However, some of the most rare and valuable meteorites, including most Martian meteorites, are poor in magnetic minerals and so cannot be easily distinguished from terrestrial rocks with a magnet.

Magnets commonly used for meteorite identification are rare-earth magnets (i.e., composed of neodymium or samarium-cobalt), with typical surface magnetic fields between 0.3 T and 0.7 T and typical sizes of a few centimeters. Unfortunately, exposing most rocks to such a strong magnetic field results in the erasure of their magnetic record within nanoseconds. According to Figure 1 [calculated following Cébron (2021) and Camacho and Sosa (2013); see Supplementary Information for details], even bringing a rock to within 3 magnet radii of such a magnet will remagnetize a substantial fraction of its NRM. As a result, the vast majority of hot desert meteorites that have been studied paleomagnet-

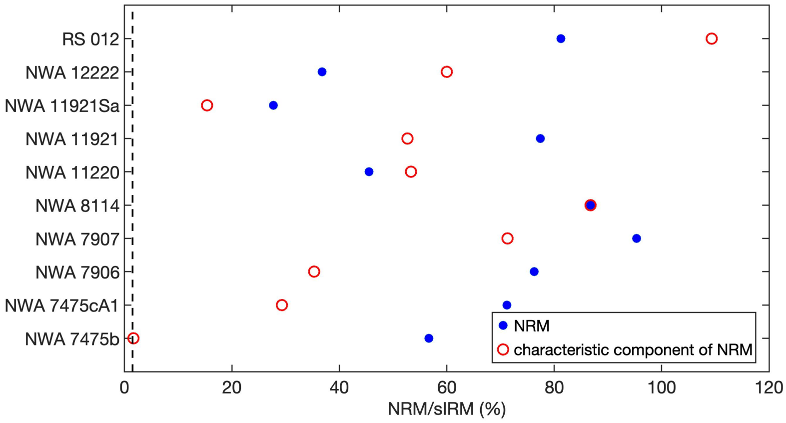

Figure 2. The ratio of NRM to sIRM of ten specimens from eight NWA 7034 paired stones. Blue dots correspond to $(\text{NRM/sIRM})_t$ and red open circles correspond to $(\text{NRM/sIRM})_c$. The vertical dashed line marks the value 1.5%.

ically have been found to be heavily or completely remagnetized by magnets (Weiss et al., 2010; Gattacceca & Rochette, 2004).

Meteorites that break up in the atmosphere can form strewn fields composed of multiple scattered fragments in a small region. In such cases, meteorite hunters sometimes use magnets only to identify the first few fragments until they become confident at identifying them visually (Weiss et al., 2017). Because NWA 7034 is a pairing group, it apparently formed a strewn field somewhere in northern Africa. With this in mind, we conducted an extensive search for samples of all paired stones of NWA 7034 in an effort to find any whose Martian magnetism has fortuitously survived arrival on Earth.

2 The case of Martian meteorite NWA 7034

We analyzed the NRM of 10 specimens taken from 8 different paired stones (NWA 12222, NWA 7906, NWA 7907, RS 012, NWA 8114, NWA 11921, NWA 11220, and NWA 7475) using a 2G Enterprises Superconducting Rock Magnetometer (SRM) in the Massachusetts Institute of Technology (MIT) Paleomagnetism Laboratory. Our goal was to assess whether the stones have been touched by magnets. For this, we characterized their NRMs by using progressive alternating field (AF) demagnetization (i.e., exposure to an AC field with decreasing amplitude) with peak fields up to 420 mT. This value exceeds the peak coercivity of grains in the meteorite (300 mT; Gattacceca et al. (2014)). This allowed us to identify the characteristic components of the NRM for each specimen (i.e., the most stable part of the NRM). Such components can be identified based on the fact that they trend linearly toward the origin during AF demagnetization. We then compared the NRM of each specimen to a saturation isothermal magnetization (sIRM) (i.e., a magnetization produced in the laboratory after exposure to a strong field at room temperature). We did this both for the entire NRM and sIRM (Figure 2, blue dots) and for the NRM and sIRM of the characteristic component (Figure 2, red open circles). The ratio of NRM to sIRM is a proxy for the paleointensity of the magnetic field that gave rise to the magnetization (Gattacceca & Rochette, 2004). For an NRM acquired during cooling in the presence of a Martian magnetic field with an intensity like that of Earth, this ratio is about 1.5% (Figure 2, black dashed line). An NRM-to-sIRM ratio that is an order of magnitude or more stronger would signify that the magnetization source is not of planetary origin and instead likely a hand magnet.

We found that the total NRM/sIRM, $(\text{NRM/sIRM})_t$, for the 10 specimens ranges between 28% and 95% (Figure 2, blue dots). This indicates that these rocks have been remagnetized since their arrival on Earth by strong hand magnets. Nine of them have apparently not retained any record of the magnetic field on Mars [e.g., NWA 8114, whose NRM demagnetization is shown in Figure 3a)]. In particular, the NRM of NWA 8114 is characterized by a single, origin-trending component. For all specimens but one, the NRM/sIRM of the characteristic component, $(\text{NRM/sIRM})_c$, is still an order of magnitude larger than 1.5% and ranges from 15% to 109%. For one specimen of the 80-g stone NWA 7475 (specimen b), we find $(\text{NRM/sIRM})_c = 1.67\%$, which indicates that its magnetization may have not been completely overprinted. According to Figure 1, this specimen could have originated from the core of the NWA 7475 stone, where the maximum field of a typical $2 \times 4 \times 4$ cm hand magnet with a 0.5 T surface field would have not exceeded 200 mT. The 1.67% ratio corresponds to a magnetization acquired during cooling on Mars in a field with paleointensity ≈ 50 μT. In contrast to NWA 8114, the origin-trending component of NWA 7475b, shown in the inset of Figure 3b, is much flatter and noisier than the initial part of the demagnetization curve. However, the remanence of the characteristic component is only 0.02% of the initial NRM and so likely provides an upper limit on the intensity of the Martian field (Figure 3b). The second smallest $(\text{NRM/sIRM})_c$ is 15%, which we measured for NWA 11921Sa, a specimen obtained from the core of a 5.95 g NWA 11921 stone, while specimen NWA 11921, which was obtained from the surface of the same rock, gives $(\text{NRM/sIRM})_c = 53\%$. According to Figure 1, the near-total remagnetization of the center of NWA 11921 can be also explained by the use of a $2\times 4\times 4$ cm hand magnet with a 0.5 T surface field, which would have produced fields up to 300 mT peak coercivity at this location.

3 Perspectives

Meteorites carry unique information concerning the geological history of other planetary bodies. While touching a meteorite with a hand magnet is inconsequential for many kinds of analytical studies (e.g., of petrography and elemental and isotopic composition), it is enormously detrimental to the paleomagnetic record of the meteorite. We therefore recommend that meteorites never be touched with magnets. A better alternative identification technique is to use magnetic susceptibility meters because they are non-destructive due to their weak fields (< 0.5 mT), quantitative, and can more sensitively distinguish between meteorite groups including identifying rare meteorites like those from Mars and the Moon that are poor in iron (Folco et al., 2006).

We remain hopeful that more paired stones of NWA 7034 and new Martian meteorite finds will become available in the near future that are free of the effects of magnet remagnetization. Otherwise, we anticipate future magnetic studies of rock samples from Mars using the cores currently being collected at Jezero crater by the Perseverance rover (Mittelholz et al., 2018; Mangold et al., 2021), expected to get delivered to Earth in the early 2030s. The Perseverance rover and downstream Mars sample return missions are expected to not expose these samples to fields larger than 0.5 mT during the entire process from sampling to return to Earth (Beaty et al., 2019).

Acknowledgments

We wish to thank Prof. Addi Bischoff, Institut für Planetologie, Münster, Germany for a loan of NWA 12222, Prof. Dr. Beda Hofmann, Natural History Museum Bern, Switzerland, for a loan of NWA 7906 and NWA 7907, Dr. Alan Rubin, UCLA, USA, for a loan of RS012, Prof. John Bridges, University of Leicester, UK for a loan of NWA 8114, and Mr. Said Yousfi for kindly offering to cut a rock of NWA 11921 in slices and let us choose the innermost piece of the middle slice for our measurements. One specimen of NWA 11220 was purchased by Mr. Martin Goff, two specimens of NWA 7475 were purchased by Mr. Luc Labenne, and two specimens of NWA 11921 were purchased by Mr. Said Yousfi,

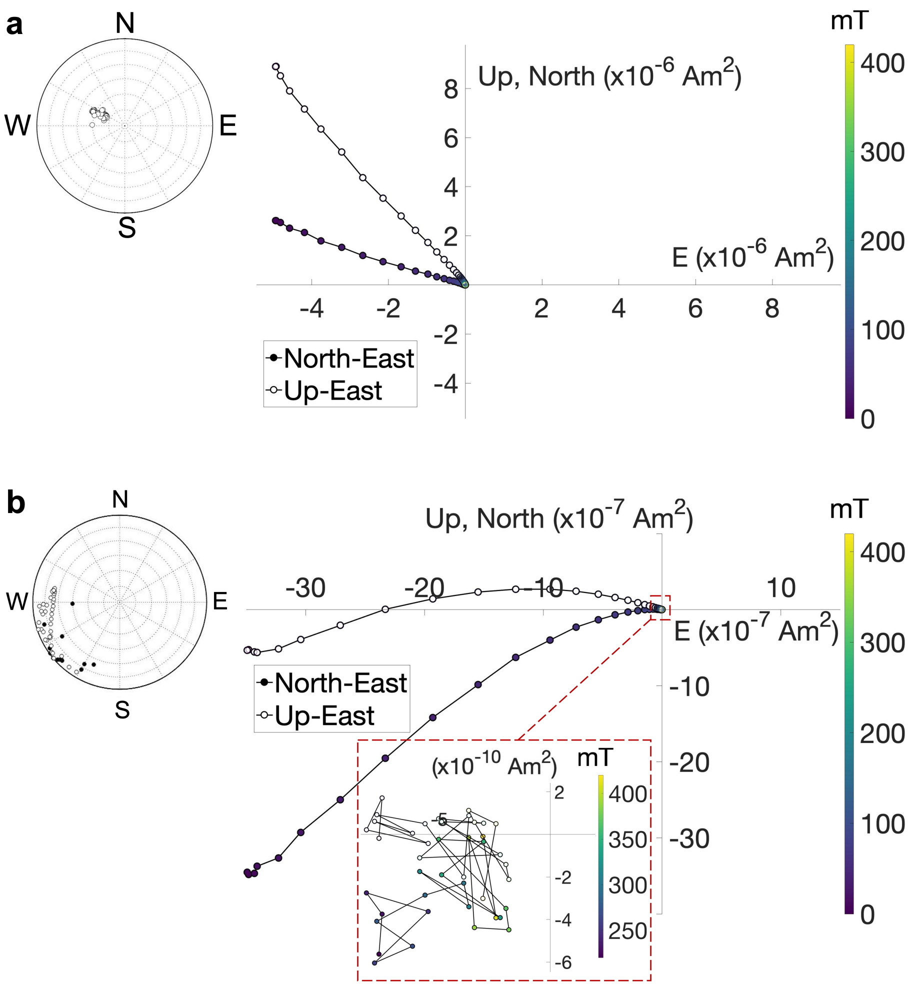

Figure 3. NRM demagnetization of two paired stones of the ancient Martian meteorite NWA 7034. Shown are endpoints of the NRM vectors during progressive alternating field (AF) demagnetization. Closed (open) symbols on the stereoplot correspond to endpoints on the lower (upper) hemisphere. Closed and open symbols correspond to projections of the NRM vectors onto the horizontal (N-E) and vertical (U-E) planes, respectively. The coordinate system relates to the specimens' orientation and not to actual Martian geographic coordinates. (a) Specimen NWA 8114, which has been remagnetized up to 420 mT by a hand magnet. (b) Specimen NWA 7475b, which has been remagnetized up to 220 mT by a hand magnet. Inset: AF demagnetization steps from 220 to 420 mT.

with funds from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 844252. F.V. and B.P.W. acknowledge the latter programme and the NASA Mars 2020 Returned Sample Scientist Participating Scientist grant 80NSSC20K0238 for funding.

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