**ANCIENT LIFE ON MARS: APPLICATION OF NEW PALEOMAGNETIC AND ROCK MAGNETISM TECHNIQUES TO TEST THE ORIGIN OF MAGNETITES IN ALH84001 CARBONATES.**
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**Introduction:** Some of the fine-grained magnetite crystals embedded in carbonate blebs of ALH84001, a ~4 Ga Martian meteorite are strikingly similar to those made by magnetotactic bacteria on Earth, and a biogenic origin for them was proposed by McKay et al. [1]. High resolution TEM analyses have demonstrated that ~10-20% of these magnetite particles are indistinguishable from bacterial magnetosomes [2]. Great debate has raged concerning the origin of the putative biological magnetites trapped in the carbonate blebs along fracture surfaces in this meteorite. `

Two leading hypotheses exist to explain the magnetite crystals associated with the carbonate blebs: high-temperature shock deformation leading to the decomposition of iron-bearing carbonate minerals to form magnetite [3], and the sedimentary deposition of previously-formed, mature magnetite in an aqueous micro-environment as would be the case for a biogenic origin [2]. The two hypotheses can be tested through laboratory measurements of the ALH84001 carbonates because they each lead to dramatically different magnetization efficiency. It has previously been established that Mars had a magnetic field of ~50 µT when the carbonates formed at ~4 Ga, capable of imparting a remanent magnetization. If the magnetite crystals grew in size via a solid-state process inside the carbonate blebs in a field of this strength, they would be unable to physically rotate as they become stably magnetized. Most magnetic moments would align in the direction of the local field, and the assemblage would be efficiently magnetized. In contrast, mature particles that are suspended in an aqueous solution are subject to Brownian motion that acts to disrupt their alignment, allowing their magnetic moments to clump [4]. This will reduce the net magnetization 2 to 3 orders of magnitude less than those that are magnetized in place. A simple yet robust analysis based on these magnetization efficiency differences which distinguishes between chemical and depositional magnetization is the Fuller et al. [5] test of natural remanent magnetization.

An additional test of the two hypotheses will be utilization of the susceptibility of Anhysteretic Remanent Magnetization (ARM susceptibility), which is the inverse slope of the initial acquisition of ARM magnetization in an alternating field in the presence of progressively stronger static (DC) biasing fields. This parameter probes the effective r.m.s. field strength between magnetic particles [6]. Magnetites formed by the method of Treiman & Essene [3] should have high ARM acquisition slopes, whereas those formed from the process of sedimentological partical aggregration would have low slopes.

Thus far, the small size and associated magnetization of the carbonate blebs have precluded any paleomagnetic studies on the carbonates themselves; however, the new ultra-high resolution scanning superconducting magnetic microscopes have increased our measurement sensitivity 4 orders of magnitude over conventional superconducting magnetometers. With this instrument, we have demonstrated recently the ability to measure quantitatively the magnetic moments associated with 50-µm sized ALH84001 carbonate fragments.

**Methods:** *Scanning SQUID Microscopy.* Thick sections of fracture surfaces on the ALH84001 meteorite which contain carbonate blebs like that in Figure 1 were studied first. By scanning the surface of these thick sections with the SQUID microscope we can observe the interior magnetization of the meteorite. By overlaying scans of the magnetic field above the samples with images of the samples we can correlate individual dipoles to specific grains in the rock.

*Demagnetization* Using extreme caution, we removed carbonate blebs, which subsequently broke into pieces or fragments, from chips of ALH84001 (Figure 2). These fragments were then glued onto clean, demagnetized glass microscope slides. We then measured the samples using our scanning SQUID microscope, at an offset distance of ~ 450 um. The strength and direction of the dipoles present in our scan were estimated using the dipole-fitting routing created by Lima and Weiss [7], and subjected to a rock-magnetic demagnetization and remagnetization series needed for the two tests. After each step we rescanned the entire slide and again determined the strength and direction of the magnetization of each carbonate.

**Results:** We have been able to resolve individual dipoles present in the ALH84001 thick sections. Although we cannot uniquely identify dipoles to carbonate blebs, the dipoles align along fracture surfaces in the thick section, as do the carbonates (Fig. 1). The strength and direction of the individual dipoles vary throughout a sample, indicating heterogenous magnetization. Determination of the magnetization direction of the measured dipoles has indicated some clustering of dipoles.

We have successfully resolved the magnetization in individual flakes of carbonate removed from

ALH84001 (Fig. 3). Thus far in demagnetization, alternating fields as weak as 6 mT have resulted in a decrease in the magnetization of the measured dipoles. AF fields as weak as 8 mT have resulted in significant direction changes in the magnetization, implying the NRM is multicomponent.

**Conclusions:** Heterogenous magnetization in the interior of the meteorite indicates that the meteorite was not heated to temperatures capable of demagnetizing the carbonates. This result is consistent with work done by Weiss et al. [8]. Clustering of dipoles could indicate that multiple deposition or alteration events occurred or that portions of the meteorite have been fractured after emplacement of the magnetite crystals.

Although the rather laborious measurements are still in progress we have demonstrated that our technique for measuring the moment of carbonate fragments does indeed work. The new high-precision superconducting microscopes have measurement capabilities adequate for giving a definitive answer to the test between the magnetite formation hypotheses.

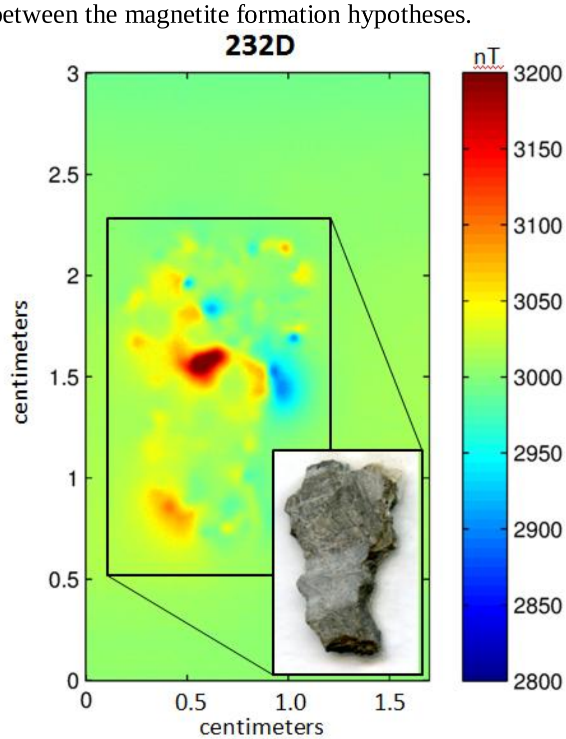


Figure 1. Magnetization in sample ALH84001, 232D. The interior of the meteorite is heterogeneously magnetized. A row of dipoles align along a fracture in the thick section. Individual dipoles can be distinguished in the meteorite interior.

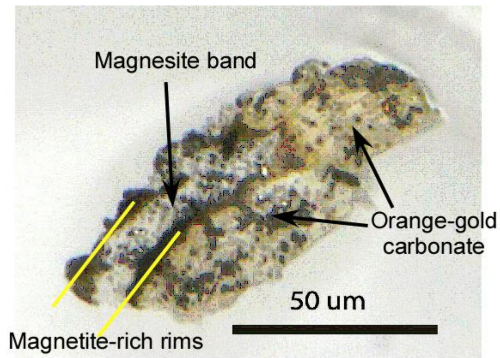


Figure 2. Flake of carbonate removed from ALH84001. The carbonate blebs have characteristic magnetite rich rims which are clearly demonstrated here and highlighted in yellow. The carbonate is distinct from the orthopyroxene in the meteorite.

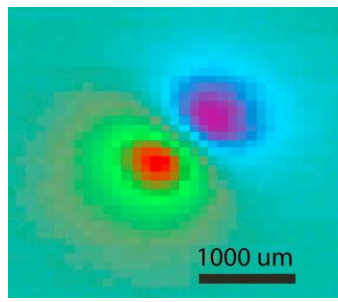


Figure 3. This magnetic field map corresponds to a flake of carbonate of the approximate size of the one shown in Fig. 2.

**Future Work:** We will also measure hysteresis curves on the samples in order to determine the saturation magnetization and coervitiy of the magnetites. Pairing these results with observations from fractional saturization IRM experiments we will be able to place the ALH84001 magnetites on the Dunlop Day plot for comparison with biogenic magnetite and magnetite formed through alteration of siderite.

**References:** [1] D. S. McKay *et al.* (August 16, 1996, 1996), *Science* **273**, 924-930. [2] K. L. Thomas-Keprta *et al.* (2009), *Geochimica et Cosmochimica Acta* **73**, 6631-6677. [3] A. H. Treiman and E. J. Essene (2011), *Geochimica et Cosmochimica Acta* **75**, 5324-5335. [4] A. Kobayashi *et al.* (2006), *Earth and Planetary Science Letters* **245**, 538-550. [5] M. Fuller *et al.* (1988), *Geophysical Research Letters* **15**, 518-521. [6] S. Cisowski (1981), *Physics of the Earth and Planetary Interiors* **26**, 56-62. [7] E. A. Lima and B. P. Weiss (2009), *Journal of Geophysical Research: Solid Earth (1978–2012)* **114**. [8] B. P. Weiss *et al.* (2000), *Science* **290**, 791-795.