PALEOMAGNETIC EVIDENCE FOR A LONG-LIVED REVERSING MARTIAN DYNAMO AT ~3.9 GA.

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Introduction: Mars' strong crustal magnetic fields indicate it once hosted a core dynamo, but this dynamo's strength, geometry, stability, and lifetime remain uncertain. Because a planet's magnetic field interacts with its atmosphere in complex ways, with atmospheric escape rates varying with the field's strength [1, 2] and structure [3], the cessation of Mars' dynamo may have triggered severe, planetary scale climate change.

The meteorite ALH 84001, which crystallized 4.091 ± 0.030 billion years ago (Ga) on Mars [4], may retain a paleomagnetic record of the martian dynamo. Two fusion crust baked contact tests have confirmed that the remanence hosted by ALH 84001 is of extraterrestrial origin [this work; 6]. Previous paleomagnetic studies of ALH 84001 carbonates and bulk samples have observed strong magnetizations that are heterogeneous at the millimeter scale [5–7], but interpretation of this unusual pattern has been complicated by the uncertain age and origin of the NRM of ALH 84001 carbonates.

One possibility is that ALH 84001 acquired this unusual magnetization via heterogeneous impact remagnetization. In this process, non-uniform post-impact temperature and pressure conditions may have remagnetized sub-volumes of the rock in the direction of the magnetic field during each impact, resulting in multiple magnetization directions [5, 8, 9].

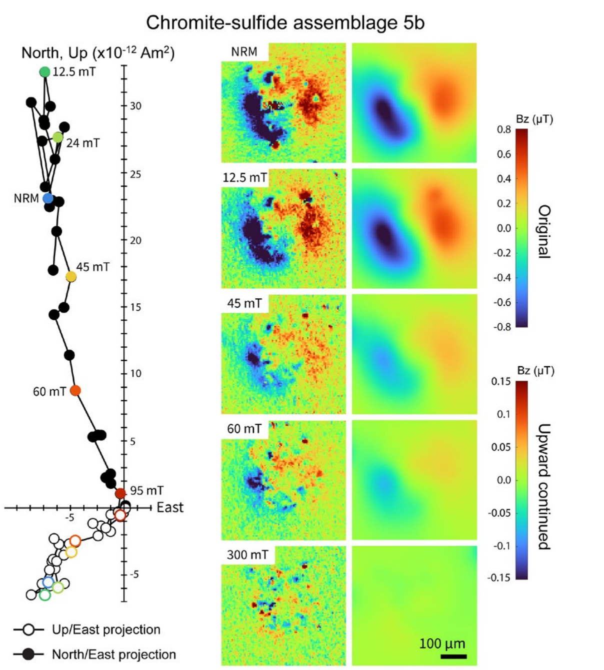

Figure 1: AF demagnetization of a chromite-sulfide assemblage in slice 462,5. The main component shown falls into Cluster A.

Chromite in ALH 84001 may provide insight into the rock's magnetic history. Many chromite grains host sulfides—identified as pyrrhotite—that carry strong room-temperature remanence. Since chromite-sulfide assemblages are primary igneous features, unlike carbonate, they may retain the oldest paleomagnetic records in the meteorite—potentially as old as 4.1 Ga—though subpopulations may have been remagnetized at ~3.9 Ga or 1.16 Ga during later impact events [10].

Unfortunately, the magnetic signals of chromite-sulfide assemblages have historically been difficult to spatially resolve. Here, we use the recently developed quantum diamond microscope (QDM)—a magnetic field imager with sufficient resolution to isolate the signals of single chromite inclusions—to study the NRM of chromite-sulfide assemblages in ALH 84001.

Paleomagnetic Analyses and Results: We characterized magnetizations of chromite-sulfide assemblages in three slices of the 0.64 g sample ALH 84001,462. Based on a baked contact test using segments of fusion crust, we restricted our focus to sources at least 1.5 mm away from that surface.

To isolate robust magnetization components, we subjected two slices (462,5 and 462,10) to alternating field (AF) demagnetization up to 300 mT (Figure 1) and one (462,9) to thermal demagnetization up to 340°C. This yielded 10 chromite-sulfide assemblages with strong magnetization components.

We computed anisotropy of magnetic remanence (AMR) tensors for sources in 462,5 and 462,10 from anhysteretic remanent magnetizations (ARM) imparted along six axes and for sources in 462,9 from thermoremanent magnetization (TRM) imparted along three axes. Correcting source components with their respective AMR tensors (or the average AMR tensor if one could not be computed) yielded two clusters with nearly antipodal centers at D=352.2, I=13.0 for Cluster A and D=162.9, I=34.0 for Cluster B, where D and I denote declination and inclination (Figure 2). We confirmed the statistical significance of these clusters by comparing their shape parameters to those of best-fit clusters from randomly generated 10-point datasets.

Finally, to estimate source paleointensities, we AF demagnetized a 200 μT ARM for slices 462,5 and 462,10 and performed stepwise pTRM acquisition in a

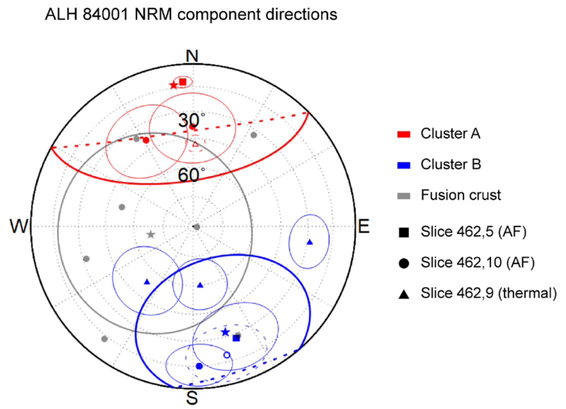

Figure 2: Component directions of ALH 84001 chromite-sulfide assemblages (red and blue) and fusion crust (gray).

200 μT field to 340°C for slice 462,9. Clusters A and B had average estimated paleointensities of 28.0 ± 20.3 μT and 71.3 ± 47.3 μT, respectively.

We also identified a population of sources that hosted no NRM components but could acquire strong ARM, consistent with cooling in a null field. We performed ARM recording limit tests on these sources to place upper limits on their paleointensities.

Discussion: Our identification of two directional clusters with source directions varying at the ~100 μm scale suggests that chromite-sulfide assemblages in ALH 84001 were not magnetized in a single event. As an alternative hypothesis, North et al. [9] performed mesoscale impact modeling of ALH 84001,462 to quantify the degree of heterogeneous heating associated with significant impacts. Their models demonstrated that non-uniform shear and mineralogy can induce sub-100 μm scale thermal heterogeneity, consistent with the magnetization pattern we observe. Critically, they also found consistently low post impact heating in chromite. While some chromites located near hot materials or shear zones experienced significant heating, others never exceeded the bulk post-equilibration temperature. Since equilibrium temperatures remained below 320 ˚C for shocks with average bulk pressures below 45 GPa, chromites located away from strong heat sources may have escaped remagnetization during late impacts.

Another prominent feature of this dataset is the large (>135°) angular separation of the clusters. Assuming ALH 84001 was initially uniformly magnetized, this pattern could result from heterogeneous remagnetization followed either a dynamo polarity reversal or a large clast rotation. Although a formal reversal test on our dataset yields an indeterminate result, the low likelihood of large clast rotations leads us to favor the former explanation. This interpretation is consistent with the tentative evidence for martian reversals from crustal sources [11–14].

We propose the following history to account for the magnetization pattern we observe in ALH 84001. Chromite-sulfide assemblages originally recorded the martian dynamo field during metamorphism at 4.1-4.0 Ga, resulting in a uniformly magnetized population. At least one other impact then remagnetized sub-volumes of the meteorite during a time of reversed dynamo polarity. A final impact after the dynamo's cessation may have demagnetized sub-volumes of the meteorite, producing the observed low-paleointensity sources. This is consistent with independent thermal histories of ALH 84001, which indicate that the rock experienced at least one major impact at ~3.9 Ga, a moderate impact at 1.16 Ga, and the ejection event [10].

Paired with this independent history, our results imply the martian dynamo was active at ~3.9 Ga. This may have important implications for the habitability of early Mars. The martian atmosphere must initially have been much denser than it is today, with a CO_2 partial pressure potentially as high as 1-2 bars. Much of the change in Mars' climate since valley network formation at 3.8-3.6 Ga can be attributed to the loss of a large fraction of this atmosphere to space [15]. Recent work suggests that a martian dynamo similar in strength to Earth's, as implied by our results, should reduce the rate of atmospheric escape [2] but weakening of the martian dynamo should accelerate mass loss [1]. A long-lived dynamo may therefore be more consistent with the persistence of martian surface water until 3.8-3.6 Ga.

Conclusions: We identified three populations of ALH 84001 chromite-sulfide assemblages: two strongly magnetized in near-antipodal directions, and one with null paleointensities. These results favor a martian dynamo that shut down after 3.9 Ga and potentially experienced polarity reversals, aligning with a growing body of literature that supports a post-3.8 Ga dynamo cessation [14, 16, 17]. If the cessation of Mars' dynamo triggered the change in the planet's climate, a long-lived martian dynamo may be better able to account for the long lifetime of water on Mars' surface.

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