RECORDS OF AN ANCIENT MARTIAN MAGNETIC FIELD IN ALH84001. B. P. Weiss[1], H. Vali[2], F. J. Baudenbacher[3], S. T. Stewart[1], J. L. Kirschvink[1], [1]Division of Geological and Planetary Sciences, 170-25, California Institute of Technology, Pasadena, California 91125, USA, [2]McGill University, Montreal, Quebec, Canada, [3]Department of Physics and Astronomy, Vanderbilt University, 6301 Stevenson Center, Nashville, TN 37235, USA

Introduction: Eight martian meteorites exhibit stable magnetizations that originated sometime after the rocks crystallized at 1300-180 Ma. Martian meteorite ALH84001, an orthopyroxene cumulate which crystallized on Mars at 4.5 Ga [1], contains single domain and superparamagnetic monoclinic pyrrhotite (Fe_7S_8) and stoichiometric magnetite (Fe_3O_4) [2, 3]. The meteorite also possesses a stable magnetization that predates its ejection from Mars 15 million years ago (Ma) and could be much older [2, 3].

Magnetization in ALH84001: TEM imaging studies [4] and our rock magnetic analyses on three ALH84001 grains indicate that the magnetic material has blocking temperatures from ~575 °C to below room temperature. Using the Ultra High Resolution Scanning SQUID Microscope (UHRSSM), a magnetometer with a sensitivity of better than 0.1 nT that maps the out-of-the-page component of the magnetic field above samples with 100 µm spatial resolution, Weiss et al. [2] found that one carbonate bleb in ALH84001,232e was associated with an intense magnetization that persisted even after zero-field heating to 200 °C. UHRSSM images and backscattered SEM maps of several other 30-µm thin sections taken from ALH84001 show that many strongly magnetic features are associated with carbonate. These confirm that the carbonate blebs carry much of the magnetization in ALH84001.

We produced backscattered SEM maps and X-ray spot analyses from the phases in and around the carbonate identified by Weiss et al. [2] (Fig. 1A), as well as UHRSSM images of the sample after heating it to 360 °C in a zero magnetic field (Fig 1B). Like many other ALH84001 carbonate blebs, this carbonate is adjacent to anhedral feldspathic glass that, unlike its immediate surroundings, is essentially unfractured. Other carbonate blebs in the meteorite also appear to have been broken up and transported by the flow of feldspathic glass [5], which apparently has no short-range order [6]. These observations indicate that the feldspathic glass in Fig 1a and throughout the meteorite was mobilized at some point. The SEM data (Fig 1A) show how microfaults in the carbonate and fractures in the pyroxene do not extend into adjacent feldspathic glass, suggesting that the mobilization event occurred after the carbonate formed.

Because the glass was hot enough to flow during this event, it probably experienced a shock of 40-60 GPa [5, 7], with post-shock temperatures of 400-1000

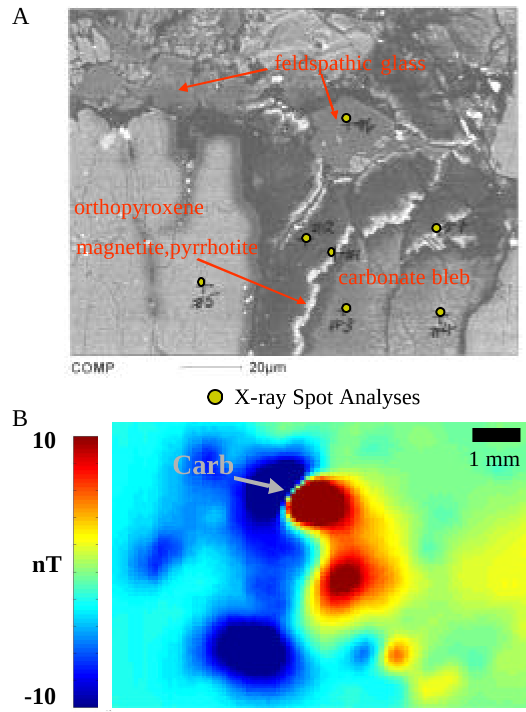

Figure 1 (A) Backscattered SEM image and x-ray spot analyses of carbonate identified in 1-mm thick slice ALH84001,232e [2]. (B) UHRSSM image of top half of ,232e after heating to 360 °C in zero field. This gives the intensity of the out-of-the page component of magnetization as observed ~0.1 mm above the slice. The image in (A) was taken at a location lableled "Carb". All of this magnetization must be from magnetite, which has only been identified in carbonate.

°C [8]. On the other hand, several studies of oxygen isotopic and cation gradients in ALH84001 indicate that other, unfractured carbonates have not been significantly heated since they formed [9, 10]. These studies need not contradict the textural evidence from the feldspathic glass that there was a high-temperature event following the formation of the carbonates. The studies were conducted on unfractured carbonates not visibly associated with flowed glass, and it is clear that shocks will heterogeneously heat rocks on small scales so that the carbonates in ALH84001 could have experienced a range of thermal histories. Furthermore, since the temperature of the glass mobilization event could be as low as 400 °C, sufficiently fast cooling times may not have even been hot enough to destroy these gradients. Nevertheless, for the purposes of dating the magnetism in the carbonates, we will consider both possibilities: that carbonates formed either before or after the feldspathic glass was mobilized.

Thermal Constraints on the Carbonates: $^{40}Ar/^{39}Ar$ dating of ALH84001 [11] shows that essentially all of the feldspathic glass in the meteorite last completely degassed Ar at 3.9-4.2 Ga. The $^{40}Ar/^{39}Ar$ plateau extended from ~450 °C to 1000 °C for 30 min. heating steps [11]. We used the temperature-dependence of the diffusion coefficient $D(T)$ of Ar through ALH84001 feldspathic glass as measured by [11] to calculate a time-temperature diagram for Ar loss (Fig. 2). This shows the time required for a given temperature to cause 10% Ar loss from those regions in the glass that degassed after heating at 450 °C for 30 min. Fig. 2 demonstrates that the feldspathic glass could have not been heated to 575 °C for even a minute or to 360 °C for ~2 hrs, since 3.9-4.3 Ga. Thus, the glass mobilization event occurred at or before 3.9-4.2 Ga. The diagram also demonstrates that ALH84001's exposure to space (15 My at 250-300 °C) accounts for most of the Ar lost by the glass, precisely confirming the observation [11] that glass with blocking temperatures of ~400-500 °C has already experienced Ar loss.

Because the feldspathic glass is rarely fractured, it has not been differentially stressed at pressures exceeding its tensile strength (~1 GPa) [12], and thus has experienced negligible shock heating [7] since it was mobilized. Thus, the only way that the glass could have been significantly heated since it was mobilized would be if it experienced a short thermal event that was not produced by a shock. However, any non-shock thermal event (which would have dissipated via heat diffusion) would probably last many orders of magnitude longer than that allowed by Fig 2. Thus, the feldspathic glass in the meteorite has experienced no major heating, from either transient shock events or non-shock events, since ~4 Ga.

Age of the Magnetization in the Carbonates: If the carbonate blebs formed before the glass was mobilized, then most of their magnetization originated during the mobilization event (constrained to 3.9-4.0 Ga), and may also include a primary remanence from the time the carbonates formed at 3.87-4.14 Ga. Othewise, if the carbonate blebs formed after the mobilization event, then nearly all of their magnetization dates to the formation of the carbonates at 3.87-4.14 Ga.

Thus, regardless of whether the carbonate blebs formed before or after the glass mobilization event, most of their magnetization was acquired 3.9-4.1 Gy ago on the Martian surface. This means that the magnetization in ALH84001 is the oldest ever identified in any planetary rock and the only well-dated remanence in a Martian sample. It is 500 million years older than the oldest magnetization identified in an earth rock. Given the intensity of the magnetic moment of individual carbonate blebs (~10^{-11} Am^2), ALH84001 was most likely magnetized by a Martian geodynamo or by nearby crustal remanent fields like those recently identified in the Martian southern hemisphere [13]. Since the latter crustal fields were themselves presumably magnetized by the field by a Martian geodynamo, our data demonstrate that Mars had a magnetic field generated by an active geodynamo by at least 4 Ga. This agrees with but is much more precise than the crater count ages (3.0-4.4 Ga, and most probably 3.8-4.2 Ga) inferred for the surfaces associated with the Martian crustal magnetizations. Our data do not support recent suggestions [14] that the Martian dynamo turned on substantially after the formation of the large impact basins. Instead these results are consistent with thermal evolution models of Mars that predict a convecting core and geodynamo extending from 4.6 Ga (or possibly delayed by several hundred My) to sometime after 4 Ga [15, 16].

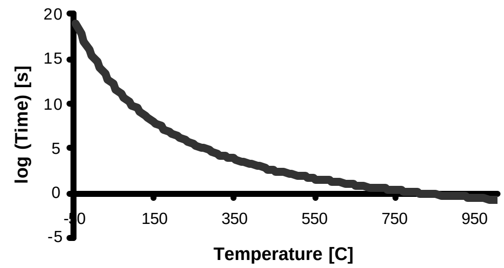

Figure 2 Time-temperature constraints for 10% Ar loss from plagioclase glass that degassed at ~450 °C during Turner et al.'s Ar/Ar experiments [11].

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