EVIDENCE FOR A LUNAR CORE DYNAMO AT 3.7 GA FROM MARE BASALT 10020?

E. K. Shea[1], B. P. Weiss[1], S. M. Tikoo[1], T. L. Grove[1], M. Fuller[2], [1] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA, 02139, nuptse@mit.edu, [2] Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, HI, 96822.

Introduction: The discovery of remanent magnetization in Apollo samples and in the lunar crust has long suggested that the Moon has a metallic core and once had a core-dynamo magnetic field [1]. However, the association of magnetization with the antipodes of impact basins and laboratory studies of transient magnetic fields generated by impact plasmas suggest that meteoroid impacts could also be the source of lunar magnetization (e.g., [2]). It has been difficult to distinguish between these two hypotheses because most lunar rocks are poor recorders of paleomagnetic fields [1]. In particular, because shock waves in the presence of ambient magnetic fields can magnetize the low-coercivity (<~30 mT) grains in lunar rocks [3], it is essential to study the magnetism of samples with high coercivity and that show no evidence of shock.

Recent paleomagnetic analyses of one such rock, lunar troctolite 76535, observed a stable natural remanent magnetization (NRM) blocked up to >200 mT [4]. The slow (millions of years) cooling timescale of this rock relative to the expected lifetime of impact-produced fields (< 1 day for even the largest impacts) suggests that the Moon had a core dynamo at 4.2 Ga.

Here we present a new paleomagnetic study of another extremely high coercivity, unshocked lunar rock, mare basalt 10020. This rock has the potential to contain records of lunar magnetism 500 Ma after the troctolite and apparently has a much simpler thermal history. Our initial results suggest it too has a stable NRM likely acquired over timescales that are long relative to impact-produced fields.

Lunar sample 10020: Sample 10020 is a fine-grained, vesicular, ilmenite basalt with a $^{40}Ar/^{39}Ar$ age of 3.72 ±0.04 Ga that is within error of Rb/Sr crystallization ages of similar composition Apollo 11 basalts [5, 6]. Collinson et al. [7] found that a single chip of 10020 has one of the most stable NRMs of any studied lunar sample (blocked up to >65 mT). These features make it an ideal candidate for testing the lunar dynamo hypothesis at 3.72 Ga.

The previous analyses [7], while pioneering, had three key limitations: (1) they did not fully demagnetize the rock (and so did not fully isolate the primary magnetization component) (2) they lacked measurements of mutually oriented subsamples [required to establish the unidirectionality of the magnetization, a key requirement for identifying a primary thermoremanence (TRM)] and (3) there was no attempt to characterize or reduce the introduction of spurious remanence during the alternating field (AF) demagnetization process. To address these issues, we analyzed two mutually-oriented subsamples of 10020: 234c (0.16 g) and 234d (0.12 g).

Natural remanent magnetization: Initial NRM measurements on subsamples 234c and 234d showed that their NRM directions diverged by 118º. Additionally, 234c preserved a 9× stronger NRM per unit mass than 234d. We conducted alternating field (AF) demagnetization up to 75 mT for 234c and 140 mT for 234d. For each field level, magnetization was measured after repeated application of the AF in each of the three orthogonal directions in order to reduce spurious remanence from anhysteretic remanence magnetization and gyroremanent magnetization (following [4]). The final NRM values were computed as the average of all measurements for each AF level (see [8]).

10020,234c: This sample had a strong overprint that was removed by AF 17 mT (Fig. 1a). Above this level, the moment remained in a high coercivity, origin-trending direction until at least 65 mT.

10020,234d: After demagnetization to 9.5 mT, 234d maintained a stable, origin-trending direction lasting until at least 80 mT (Fig. 1b).

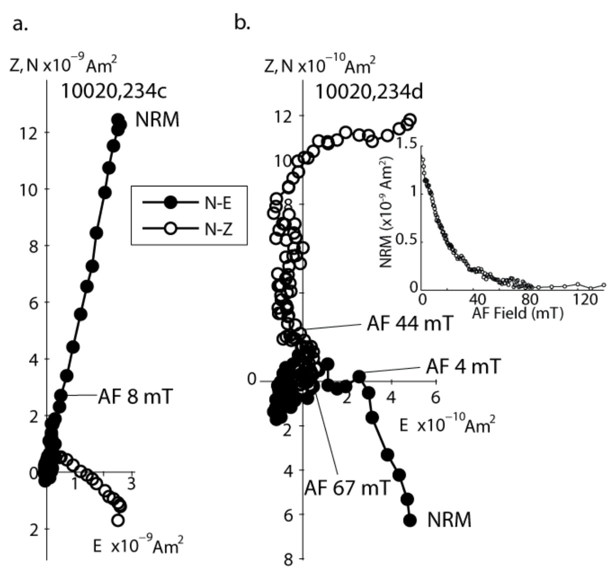

Fig. 1. Zijderveld diagram of samples (a)10020, 234c and (b) 10020, 234d. Inset shows decay of NRM intensity of 234d during AF demagnetization.

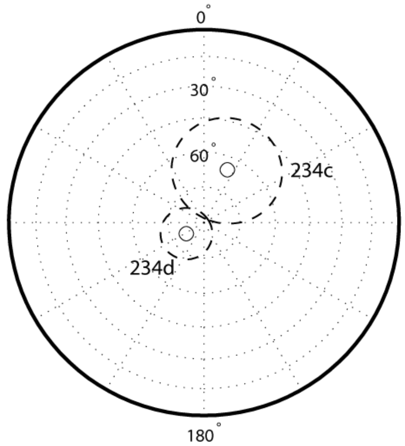

Fig. 2. Directions of characteristic components of 10020,234c and 10020,234d. Dashed circles are maximum angular deviation of the fit (~1σ dispersion on fit directions). These uncertainties do not account for mutual orientation errors (~5-10º).

Principal component analyses of the high coercivity components in the two subsamples demonstrate that they are unidirectional within error (Fig. 2).

Petrography: Our optical petrographic analyses of a thin section of 10020 reveal that the rock shows no evidence of shock: plagioclase shows no fracturing or alteration to maskelynite (Fig 3). Measurements of Al substitution in pyroxene and maximum plagioclase crystal widths give estimates of cooling rates of 30ºC/hr and 3ºC/hr, respectively [9]. Using these cooling rates, we estimate cooling times from the 780ºC Curie point of pure iron to ambient lunar surface temperatures of between ~30-300 hours.

Discussion: We have shown that two mutually oriented samples have a stable (>65-80 mT), origin-trending, unidirectional NRM component. Our petrographic analyses indicate that 10020 has never experienced peak shock pressures in excess of 5 GPa. Recent studies of laboratory-induced shock remanent magnetization (SRM) in lunar rocks found that shocks in this range magnetize grains up to ~30 mT [3], well below the maximum coercivity of grains carrying the NRM in 10020. This leaves a TRM, acquired during either primary cooling or burial metamorphism, as the most likely source of the NRM. If the NRM was acquired during primary cooling, then the cooling rates described above far exceed the ~1 day maximum lifetime expected from shock-induced magnetic fields [2]. In this case, the NRM would indicate a dynamo field, and therefore a convecting metallic core, at 3.7 Ga.

Conclusion: The existence of a lunar dynamo has been repeatedly questioned based on the lack of evidence for a fluid metallic core [10], the difficulty of sustaining a dynamo for ~800 Ma after accretion [11], the large paleointensities that are difficult to reconcile with theoretical predictions [10, 12], and the poor magnetic recording properties of lunar rocks [13]. However, recent work [14] has provided evidence that the Moon may even today contain a partially molten core. Finally, as described in an accompanying abstract [15], the lack of stable NRM in many lunar rocks is likely a reflection that they are simply incapable of retaining high-fidelity records of even substantial paleofields.

We have established that 10020 contains one of the most stable, unidirectional NRMs of any lunar rock. We are currently conducting additional magnetic and thermochronological studies on 10020 to establish the origin of this NRM (TRM or SRM), the time when it was acquired, and the timescale over which it was blocked. This will allow us to further test the hypothesis of a lunar core dynamo at 3.7 Ga.

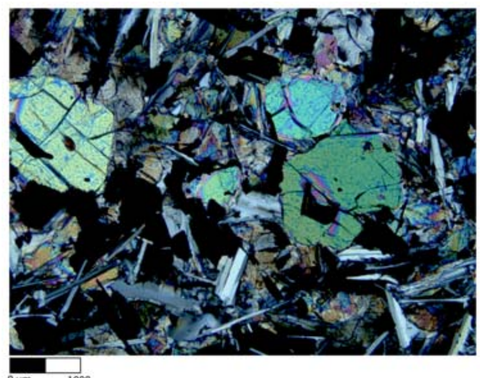

Fig. 3. Optical photograph (crossed polars) of a 30 µm thin section of sample 10020. Note the totally unfractured plagioclase crystals (white laths).

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