A LUNAR CORE DYNAMO LIMITED TO THE MOON'S FIRST 200 MILLION YEARS

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Introduction: Interpretations calling for a past long-lived lunar dynamo, producing a surface field at times as strong or stronger than Earth's field [1] and spanning some 2 billion years [2], are based on magnetic studies of Apollo samples. These interpretations are paradoxical because of the lack of sufficient energy to produce such a sustained field [3], and because of a lack of time-correlative strong, long wavelength lunar magnetic crustal anomalies [4]. Single crystal paleointensity studies of Apollo samples provide evidence for the lack of a lunar dynamo at and after 3.9 Ga, whereas studies of young lunar glass provide evidence that impacts can impart magnetizations [5]. Together, these data provide the basis for a new paradigm whereby the Moon lacks a long-lived magnetic field of internal origin. The corresponding absence of a long-lived lunar paleomagnetosphere heightens the potential for Earth's early atmosphere to be recorded by buried lunar soils [5-6], especially given the intensity of early solar winds [7-8].

However, several key unknowns remain. First, the exact origin of high field values reported from some Apollo rocks, recently used to support a model of a transient dynamo [9], remains uncertain. Second, a thermally driven dynamo is feasible for the first several hundred million years of lunar history, and this could play a role in forming weak magnetic anomalies that are particularly well-documented at the south polar region of the Moon [10], and possibly representative of large areas of the deep lunar crust [4]. But the age of such a potential dynamo is unknown. We address the first issue through a study of paired single crystal paleointensity (SCP) and whole rock paleointensity studies of ~3.8 Ga Apollo mare basalts, and the second question through SCP analyses of a 4.3 Ga Apollo anorthosite. Specifically, we investigate Apollo 17 70035, a high-Ti mare basalt with a mean age derived from multiple $^{40}Ar/^{39}Ar$ and Rb-Sr geochronological analyses [11] and updated decay constants of ~3.8 Ga, and Apollo 16 60025, a ferroan anorthosite with an age of 4360 ± 3 Ma based on ^{207}Pb–^{206}Pb, ^{147}Sm–^{143}Nd and ^{146}Sm–^{142}Nd isotopic systems [12].

Methods: We separate single silicate crystals (feldspar) using non-magnetic tools for SCP analyses [13]. Silicate crystals analyzed in this investigation are approximately 0.5 mm in size. Bulk rock samples analyzed from Apollo 70035 are approximate 3 mm in size. We use the ultra-sensitive WSGI 3-component DC SQUID magnetometer in the University of Rochester's magnetically shielded room (ambient field < 200 nT) and CO_2 laser heating techniques [14] which afford heating times more than an order of magnitude shorter than standard paleomagnetic ovens. Samples are heated and cooled rapidly in air; a controlled (reducing) atmosphere is not used because this can promote further reduction and the formation of new magnetic particles [5, 15]. We use non-magnetic materials, documented in multiple laboratories [16], to mount crystals. We investigate magnetic mineralogy using a Zeiss Auriga scanning electron microscope (SEM) with an energy dispersive x-ray analysis (EDAX) at the University of Rochester Integrated Nanosystems Center.

Findings: *High-Ti Basalt 70035*: We find that the natural remanent magnetization (NRM) of 70035 feldspar crystals are extremely weak, suggesting that their magnetic minerals cooled in the absence of a magnetic field. Moreover, we find a magnetization indistinguishable from zero after heating to 590 ºC, a temperature where considerable magnetization of lunar magnetic carriers should be unblocked. Given this null magnetization state, the standard Thellier paleointensity approach is meaningless. Instead, we assess whether the crystals can record a magnetic field in accordance with magnetization theory [17] by the following procedure [5]. First, we impart a partial thermoremanent magnetization (pTRM) at 590 ºC in the presence of a 20 µT field. The sample is then demagnetized by heating to 590 ºC, and the magnetization assessed to determine whether it returned to the null magnetization state. Next, a pTRM is imparted in a 40 µT field. The magnetizations of the two field strength pTRMs allow a determination of the recording efficiency [5]. We find the 70035 feldspars have high efficiencies and can record dynamo fields, but instead they record zero magnetization levels. As a final check of the magnetization recording, we conduct SEM and EDS analyses on the exact crystals used for

SCP measurements. These analyses confirm that the crystals contain Fe-Ti magnetic carriers with single domain-like (SD) characteristics. Next, we analyze a bulk sample by nonthermal methods to compare with prior data. Our sample shows an irregular demagnetization pattern, but with a distinct component isolated up to ~50 mT. We use the REM' nonthermal method, applying and subsequently demagnetizing a saturation remanent magnetization, to estimate the paleofield strength. These experiments yield nominal paleointensity values between 10 and 20 µT.

Ferroan Anorthosite 60025: We find that the NRM of feldspars from Apollo 60025 are extremely weak, consistent with null magnetizations. We check the recording fidelity by applying pTRMs at 20 and 40 µT; these yield magnetizations indicating that the crystals could record ambient magnetic fields had they been present, but they do not. SEM and EDS analyses demonstrate Fe-Ti magnetic particles having sizes and shapes indicating SD magnetic recording properties.

Discussion and Conclusions: Our new results from ~3.8 Ga high-Ti basalt 70035 shed light on both the origin of Earth-like fields recorded by Apollo samples [1] and a potential transient dynamo [9]. The single crystals have magnetic particles with ideal magnetic properties and recording efficiencies and record null ambient fields, whereas the bulk rocks, known to contain nonideal magnetic particles, yield relatively strong fields using nonthermal techniques (Figure 1). These data are consistent with there being no field during the cooling of high-Ti basalt 70035 at ~3.8 Ga, but that sometime later the bulk sample was affected by a shock remanent magnetization (SRM) with the ambient field supplied by an impact plasma [5]. A similar finding results from a comparison of SCP results for the 3.95 Ga Apollo 14 low-Ti/high-Al basalt 14053 [18], which yielded a null magnetization [5], and bulk samples which yield 20 µT using the nonthermal REM' method [19] (Figure 1). We note that if the shock remanent magnetization is less efficient than a thermal remanent magnetization, the field values estimated using the REM' method could be underestimated by as much as a factor of 3 [20]. However, this is still well within the range of fields produced by impact charge-separation [21-23]. Such an underestimate must be weighed against the potential for false high paleointensity readings with nonthermal techniques. Notwithstanding the uncertainties inherent to nonthermal methods, shock magnetizations with ambient fields supplied by impact plasmas can explain the enigmatic nominal high paleointensities [1] derived from other Apollo samples. Because an episodic dynamo relies on these values [1], we conclude there is no reliable evidence from Apollo samples supporting its existence. Our high-Ti basalt 70035 and ferroan anorthosite 60025 data further extend back in time the period of lunar history lacking a strong sustained dynamo to 4.3 Ga (Figure 1). Hence, our new data are compatible with the potential presence of a core dynamo in the Moon only during its first 200 million years.

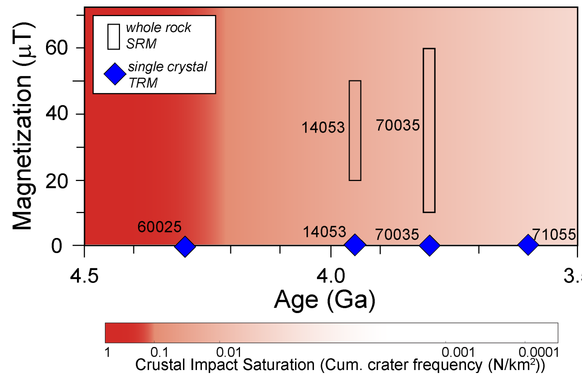

Figure 1. Magnetic field strength recorded by select Apollo single crystals paleointensity (SCP, diamonds) and whole rocks (WR, rectangles): 71055 and 14053 SCP data from [5]; 14503 WR data from [19]; 70035 SCP and WR data, and 60025 SCP data from this work. Crustal impact saturation density from [24].

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