WHEN THE MOON LACKED A PALEOMAGNETOSPHERE

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Introduction: A reconsideration of the rock and paleomagnetism of Apollo samples [1] challenges the longstanding idea of a lunar core dynamo [2] spanning billions of years [3], and instead offers a new paradigm whereby the Moon lacks a long-lived magnetic field of internal origin, or paleomagnetosphere that would have helped shelter Earth [4] during Eoarchean to Paleoarchean times when solar winds were extreme [5]. In fact, the posit of a lunar dynamo has long been a conundrum because (*i.*) core processes are inadequate to produce the proposed high sustained Earth-like surface magnetic field strengths proposed in some studies, (*ii.*) vast areas of crust lack magnetic anomalies that should have been imparted if a core dynamo and strong surface fields had been present, and (*iii.*) the lunar surface has been profoundly affected by impacts, and thus susceptible to magnetizations imparted by plasma fields [6]. Moreover, there are fundamental differences between lunar and terrestrial magnetic minerals that make paleointensity analyses challenging [7]. As a result, alternative methods have been employed, specifically the use of alternating fields rather than thermal treatments, to estimate past field strengths. But, the application of alternating fields does not duplicate the way lunar samples could have acquired magnetizations imparted by a dynamo, which instead would have been a thermoremanent or thermochemical remanent magnetization (TRM or TCRM, respectively) process, acquired during cooling. Hence, the accuracy of these alternating field techniques has not been universally accepted [7-8].

Yet another issue involves the size of the lunar magnetic recorders. Thermoremanent magnetization theory [7] requires small magnetic grains in the single domain state, but until recently nearly all paleointensity analyses on Apollo samples have been conducted on bulk samples containing larger magnetic grains in the multidomain state. These magnetic grains are problematic because they are prone to recording secondary viscous magnetizations (on the Moon, in spacecraft during recovery, and on Earth) and spurious magnetization during the application of laboratory alternating magnetic fields used in some paleointensity methods. Hypothetical TRM or TCRM acquired by many of these multidomain grains should have been lost by relaxation during the billions of years since their formation.

The silicate crystal paleointensity (SCP) technique provides a way to address the dominance of multidomain grains in bulk rocks [9]. Terrestrial silicate grains commonly contain single domain-like grains which are ideal magnetic recorders, meeting the demands of TRM theory, and able to preserve fields on timescales as old as the Moon. Thus, SCP methods may be ideally suited to address a fundamental recording flaw of most Apollo bulk samples.

Methods: Here we focus on Apollo 12 sample 12021,30, [10] a coarse-grained porphyritic pigeonite basalt with a Rb-Sr age of 3.3 Ga [11]. We separate pyroxene crystals using non-magnetic tools for SCP analyses. 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 [12] which afford heating times more than an order of magnitude shorter than standard paleomagnetic ovens. We use non-magnetic materials, documented in multiple laboratories [13], 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: We find that the natural remanent magnetization of the Apollo 12021 pyroxene crystals are incredibly weak, challenging even the ultra-sensitivity of the Rochester WSGI magnetometer, and consistent with formation in the absence of a magnetic field. We note that because of this null magnetization state, a standard Thellier approach is meaningless. Instead, what is needed is a new experiment to confirm that the pyroxenes are high fidelity field recorders. The approach developed [1] involves selecting a temperature where considerable magnetization should be blocked, but not so high such that alteration is likely, and inducing a partial thermoremanent magnetization (pTRM) by heating in an applied field. The next step involves reheating the sample to the same temperature in a zero field to confirm that the pTRM can be removed (the predicted behavior for high fidelity magnetic recorders). This is in turn followed by the application of a second pTRM in a field twice as strong as that used in the first experiment. This approach allows one to assess the recording efficiency of the crystals (Figure 1). We find that Apollo pyroxene crystals are capable of recording fields of 10s of microTesla (μT) with very high efficiency.

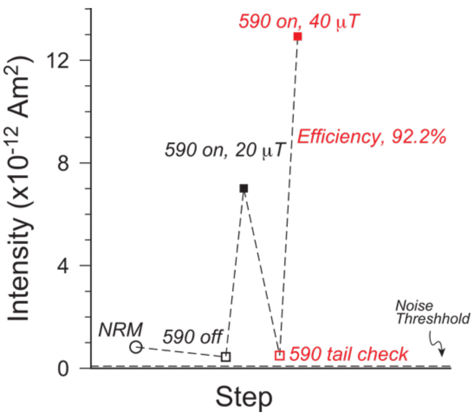

Figure 1. Magnetic intensity versus treatment step for a pyroxene crystal from Apollo 12021,30 (after ref [1]). NRM is natural remanent magnetization. "590 off" is heating to 590 °C in the absence of a field, after which the sample has unstable magnetic directions compatible with zero magnetization; "590 on, 20 μT", is heating to 590 °C in the presence of a 20 μT field after which a stable magnetization is recorded. "590 tail check" is a reheating to 590 °C in the absence of a field, after which the sample returns to its null magnetization state, demonstrating lack of alteration. "590 on, 40 μT", is a heating at 590 °C in a 40 μT field. The magnetizations (pTRMs) imparted at 20 and 40 μT allow a calculation of the magnetization efficiency.

As a further step, we use SEM analyses to examine the nature of the magnetic inclusions.

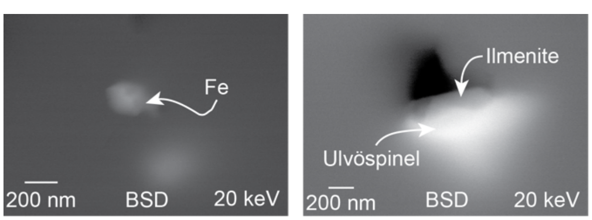

Figure 2. Backscatter detector (BSD) SEM images of pyroxene from 12021,30. Left: Small Fe particle within the SD/SV size range. Right: Ilmenite and ulvöspinel.

We find Fe inclusions compatible with single domain or single vortex state capable of retaining magnetic fields on billion-of-year time scales [5] (Figure 2). However, we also see evidence for ulvöspinel phases which may provide an answer why many thermal experiments using standard paleomagnetic ovens, irrespective of use of controlled atmospheres, often fail.

Discussion and Conclusions: Our SEM results indicate that for the first time in lunar basalts specimens have been isolated without the dominance of problematic multidomain grains that can mask the true magnetic recordings of lunar fields. The SCP approach, as in terrestrial samples, isolates grains of high fidelity recording as is documented by our pTRM experiments. However, the outstanding observation is that while these crystals are capable of recording strong fields comparable to those proposed for the erstwhile lunar dynamo, they do not. Instead, these high-fidelity recorders indicate null lunar fields. The results from Apollo 12021 (Figure 1) have been replicated as have data from crystals from other Apollo basalts spanning 3.9 to 3.2 Ga [1]. Together with results that illustrate how impacts can impart magnetizations to lunar surface rocks [1,6], these data indicate the lack of a long-lived lunar dynamo and paleomagnetosphere, resolving the varied geological and geophysical paradoxes.

The lack of a long-lived paleomagnetosphere that would otherwise shelter the Moon, indicates that buried lunar soils [14] could retain records of the early Solar System, including evolution of solar winds and Earth's earliest atmosphere. Targeting sites of such soils should be given high priority in future lunar exploration missions.

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