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# The Lunar Core Dynamo

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## Abstract

By the end of the Apollo era, paleomagnetic studies had established that lunar rocks carry a remanent magnetization that was acquired on the Moon. However, it was unclear whether this magnetization was produced by a core dynamo field or by plasmas generated by meteoroid impacts. We have been reexamining the paleomagnetism of lunar rocks with the goal of establishing the origin of the magnetizing field and its temporal history. Our recent analyses of troctolite 76535 and mare basalts 10020, 10017, and 10049 have now confirmed that a lunar core dynamo existed with a surface intensity of ~60-70 μT from at least 4.2 to 3.6 billion years (Ga) ago. Furthermore, our analyses of mare basalts 12022 and 15597 have identified no stable magnetization, indicating that the dynamo field had declined to weak (<7 μT) or null intensities by 3.3 Ga. The protracted lifetime of the lunar dynamo may require an unusual power source like mechanical stirring. Furthermore, the strong inferred intensities present a challenge to current dynamo theory.

## 1. Introduction

A variety of geophysical and geochemical data indicate that the Moon is fully differentiated and contains a ~350 km radius partially molten metallic core [1]. Our recent paleomagnetic studies focusing on slowly cooled, unshocked samples with high magnetic recording fidelity demonstrated that the Moon had a core dynamo at 4.2 Ga (as recorded by troctolite 76535 [2]) and 3.7 Ga (as recorded by mare basalt 10020 [3]) with intensities of several tens of μT (i.e., Earth-strength). However, the subsequent history of the lunar dynamo is uncertain. By the end of the Apollo era, there were two main competing models. The first proposed that the lunar dynamo shut off before the eruption of high-K basalts (i.e., before 3.6 Ga) [4] while the second proposed that the dynamo slowly decayed but persisted until at least ~3.2 Ga [5]. Two resolve this issue, we have been conducting paleomagnetic studies of several samples with excellent magnetic recording properties: the 3.6 Ga high-K basalts 10017 and 10049 and the 3.3-3.2 Ga olivine-normative and pigeonite basalts 15597 and 12002. All of these rocks contain kamacite (*α*-FeNi) as their main ferromagnetic phase, exhibit no petrographic evidence for shock, and cooled from the kamacite Curie point to ambient surface temperatures over a period longer than the lifetime of putative impact-generated fields. Therefore, these samples should have recorded any dynamo field that was present at the time of their formation.

## 2. Methods

We analysed the natural remanent magnetization (NRM) of mutually oriented subsamples from each of these basalts with alternating field (AF) and thermal demagnetization. To determine the origin of the NRM, we compared its demagnetization behaviour with that of various laboratory-induced magnetizations: anhysteretic remanent magnetization (ARM) as an analog of thermoremanent magnetization (TRM), pressure remanent magnetization (PRM) as an analog of shock remanent magnetization, and isothermal remanent magnetization (IRM) as an analog of stray fields during sample handling. We also conducted viscous remanent magnetization (VRM) experiments estimate the effect of the residence in the Earth field since the samples were collected. Finally, we conducted IRM and ARM paleointensity experiments.

## 3. Results

### 3.1 High-K basalts 10017 and 10049

Both of these samples had two components of magnetization: a nonunidirectional low coercivity

(LC) component erased by fields of 9-20 mT and a unidirectional high coercivity (HC) component stable up to 85-290 mT. Similarly oriented components were isolated by thermal demagnetization. These results suggest that the LC component is an overprint acquired in an artificial field during transportation or preparation of the sample. The HC component demagnetizes like an ARM and differently than a PRM and IRM. Our VRM experiments show that the HC magnetization cannot be explained by residence in the Earth's field. Therefore, the HC component is likely a TRM acquired by cooling in a stable field on the Moon at 3.6 Ga. Moreover, these samples formed after the youngest known basin (the >3.72 Ga crater Orientale), providing further strong evidence in favour of a core dynamo over impact-generated fields. Our paleointensity experiments indicate that this field had an intensity of 60-80 μT.

### 3.2 Olivine-normative basalt 12022 and pigeonite basalt 15597

We found that nearly all subsamples of 12022 and 15597 lack stable magnetization at AF levels above 25 mT and temperatures >300°C. Furthermore, the highest coercivity magnetization in each rock is nonunidirectionally oriented. Our AF demagnetization of VRM, IRM, PRM, and ARM experiments suggest that the NRM is a combination of terrestrial VRM and magnetization acquired during sample handling at Johnson Space Center. Furthermore, the ARM experiments indicate that there are numerous grains in these rocks with coercivities and blocking temperatures greater than those carrying the NRM. Therefore, the high coercivity grains in these samples are not carrying a TRM. This is consistent with our paleointensity experiments on this coercivity range, which find that the paleofield intensity is indistinguishable from zero (and certainly <7 μT).

## 3. Implications

Our results suggest that the lunar dynamo was active from at least 4.2 to 3.6 Ga and generated surface fields of tens of μT. However, by 3.3 Ga, the dynamo had ceased or at least weakened considerably (intensity <7 μT). Furthermore, although Apollo-era paleointensity compilations have identified lunar paleofields ranging from 0.1-10 μT at times ranging from 3.3 Ga to <200 Ma, we have found that many or all of these values are also likely just upper limits due to the poor magnetic recording properties of the majority of lunar rocks [6].

It is becoming increasingly clear that the lifetime of the lunar field may be inconsistent with a thermal convection driven dynamo, as the minimum heat flux required to sustain thermal convection is estimated to have lasted until no later than 4.1 Ga [7]. These results support the idea of an unconventional power source for the lunar dynamo such as a mechanical stirring due to precession [8] or basin-forming impacts [9]. Given that there were almost certainly no basin-forming events within several thousand years of the formation of 10002, 10017, and 10049, a precession-dynamo is the more likely source for their magnetization. However, because mechanical dynamos are expected to produce surface fields ranging from ~0.2-15 μT [8, 9], the high paleointensities of these samples are a challenge to dynamo theory.

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