SHOCK DEMAGNETIZATION DOES NOT FULLY EXPLAIN VARIATIONS IN THE LUNAR PALEOINTENSITY RECORD. J. Jung[1] (jiinjung@stanford.edu), S. M. Tikoo[1,2], J. Gattacceca[3], and C. Lepaulard[3], [1]Department of Geophysics, Stanford University, Stanford, CA 94305; [2]Department of Geological Sciences, Stanford University, Stanford, CA 94305; [3]Aix-Marseille Université, CNRS, IRD, INRAE, CEREGE UM34, Aix-en-Provence, France.

Introduction: Paleomagnetic studies of lunar rocks and spacecraft measurements of remanent crustal fields indicate that the Moon generated a dynamo from ~ 4.25 Ga to at least 1.9 Ga [1-4]. Apollo-era paleointensity datasets [5,6] considered in combination with those from more recent studies [7-10] show that the lunar dynamo produced field intensities comparable to modern Earth between ~3.85 and 3.56 Ga with a large dispersion even for sets Apollo samples with similar ages (**Fig. 1**). It is possible that dynamo behavior such as non-dipolar field geometries, secular variation, and reversals could have caused short-term, large field intensity fluctuations on the Moon [11,12]. Alternatively, inconsistent paleointensity values within a sample could be produced due to differences in paleointensity techniques, experimental settings, and acceptability criteria [6,13].

It is also possible that samples have assigned geochronologic ages not correspond to their magnetization ages due to remagnetization by impact-related heating or shock [7,14]. Samples lacking petrographic evidence of shock could still have experienced shock pressures up to 5 GPa [15]. Studies of magnetite-bearing samples suggest paleointensity determinations from shocked samples could be underestimated by up to 20% per GPa if thermal paleointensity methods (e.g., Thellier-Thellier) are used [16]. However, the main magnetic carriers within lunar rocks are FeNi alloys and may have different sensitivities to pressure-induced demagnetization than magnetite. Furthermore, most lunar paleointensity determinations have been obtained using non-heating paleointensity methods that often exclude contributions of magnetization from the lowest coercivity grains (<20 mT) within rocks [4-11], which are the grains most likely to be demagnetized via pressure [e.g., 17]. Here, we quantified the amount of hydrostatic pressure demagnetization within Apollo samples up to 1.80 GPa and the effects of pressure on paleointensities obtained from room-temperature methods.

Samples: We analyzed 60-280 mg chips obtained from 7 Apollo samples with no petrographic evidence of shock: 3 ilmenite basalts (10020, 12008, and 12022), 2 olivine basalts (12015 and 15529), 1 pigeonite basalt (15597) and 1 impact melt breccia (65055). Hysteresis properties indicate multidomain FeNi grains are the dominant magnetic recorders within these samples [10,18].

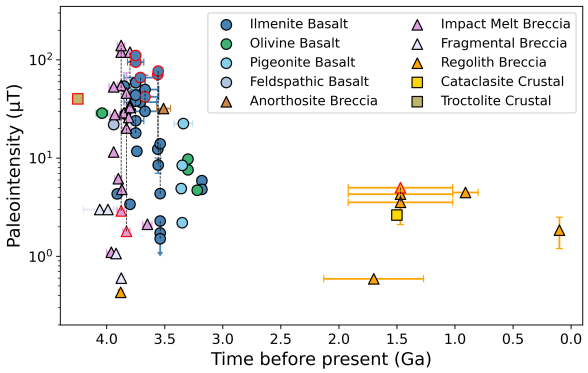

Fig. 1. Apollo-era (black outlined symbols) and recent (red outlined symbols) paleointensity determinations versus radiometric age. Vertical dashed lines connect measurements obtained from the same samples by different studies.

Methods: A series of pressure demagnetization experiments were conducted at CEREGE following the method of [17]. First, to characterize a baseline magnetization intensity and alternating field (AF) demagnetization behavior for our samples, each chip was initially imparted with an anhysteretic remanent magnetization (ARM) (i.e., a 200 μT dc field superimposed upon a 170 mT ac field) and then stepwise AF demagnetized. Second, each chip was re-imparted with an equivalent ARM and then individually placed in a nonmagnetic hydrostatic pressure cell with an ambient field < 5 μT and pressurized to a given level. Third, each chip was removed from the cell and stepwise AF demagnetized. This cycle of pressure demagnetization was repeated for pressures of 0.36, 0.72, 1.26, and 1.80 GPa. After each pressurization step, we measured the residual magnetization intensity. We also determined paleointensities for the remaining magnetization within each chip using the room-temperature ARM method [19]. As many lunar rocks contain low coercivity viscous or isothermal contamination [6], we excluded demagnetization data < 20 mT from our paleointensity determinations.

Results: The amount of pressure demagnetization increased roughly logarithmically with higher pressures (**Fig. 2A**). After pressurization to 1.8 GPa, the samples lost 3-18% of their initial ARM. Based on logarithmic extrapolations, by peak pressures of 5 GPa samples are expected to lose ~5-45% of their initial magnetization. Most samples' ARM paleointensities were not reduced by >20%, irrespective of pressure (**Fig. 2B**). There was

also no obvious correlation between the amount of applied pressure and normalized paleointensity value.

Samples that were resistant to pressure demagnetization yielded more accurate paleointensities. With the exception of 15529 at 0.36 GPa, samples which lost <10% of their initial ARM at all pressure steps (i.e., 10020, 12015, 12022, and 15529) have normalized paleointensities within ±10% of the expected value. In contrast, samples which lost >10% of their ARM at even 0.36 GPa (i.e., 12008, 15597, and 65055) have larger variations in normalized paleointensity values (e.g., up to 20% for the 15597 and 65055, and 39% for 12008).

Discussion: Most basalts subjected to recent paleomagnetic studies lack petrographic evidence of shock and do not show evidence of exposure to temperatures approaching the 780°C Curie temperature of iron in $^{40}Ar/^{39}Ar$ thermochronology data [8-10, 18]. Although apparently unshocked Apollo samples may have experienced pressures up to 5 GPa, our results suggest that shock is unlikely to yield paleointensities underestimated by >~20% in most cases. Furthermore, assuming our repeated loading of samples is an analog for multiple impacts [17], samples would still yield mostly accurate paleointensity values even if they have been shocked multiple times. As such, shock demagnetization alone cannot explain the high paleointensity dispersion between ~3.85 and 3.56 Ga, especially observed in ilmenite and pigeonite basalts (Fig 1). This suggests the high dispersion during this period is likely due to the true lunar magnetic field behavior.

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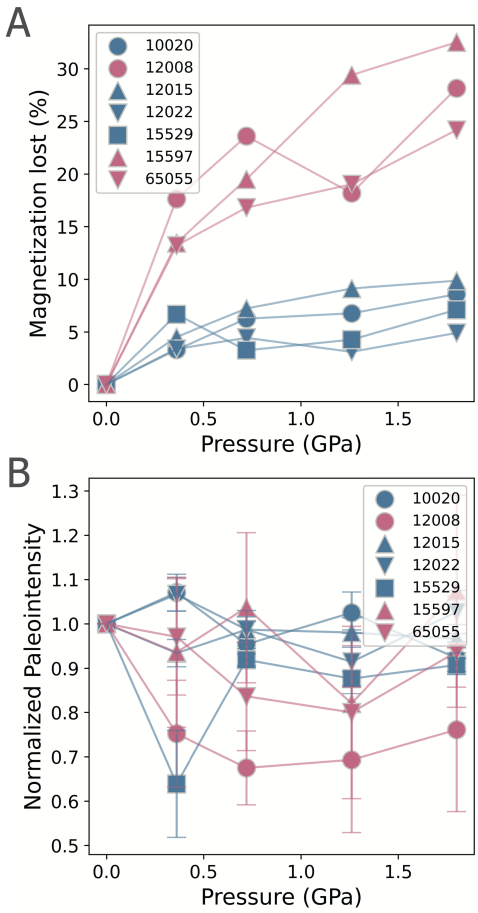

Fig. 2. Effects of pressurization on magnetization intensity and ARM paleointensity. (A) Percentage of initial laboratory ARM lost. (B) Pressurized paleointensity normalized by unpressurized paleointensity as a function of applied pressure.