The Paleomagnetic Record of the Apollo Samples. Mike Fuller[1], and Benjamin P. Weiss[2], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, HI, 96822 (mfuller@soest.hawaii.edu), [2] Dept. Earth, Atmospheric and Planetary Sciences,Massachusetts Institute of Technology, 77 Massachsetts Avenue, Cambridge, MA. 02139

Introduction: The burst of early work on the magnetism of the Apollo samples was followed by a quiescent period until recently. It had been thought that the strong magnetization in samples, whose ages ranged from approximately 3.65 to 3.9 Ga, was evidence of a lunar dynamo at that time. New results have yielded evidence for a possible early dynamo at ~4.2 Ga giving surface fields of the order of μT's [1], a better understanding of Shock Remanent Magnetization [2] and new paleointensity determinations [3]. As recognized [3], to address the question of a lunar dynamo, it is essential to separate more convicingly effects of impact related shock magnetization and other contamination from any possible primary NRM recording a lunar dynamo field. The key to this work will be (1) the determination of the origin of the Natural Remanent Magnetization (NRM) by comparison of its demagnetization characteristics with those of the various possible origins of the magnetization and (2) classical paleointensity methods to obtain estimates of the ancient lunar surface fields.

Demagnetization characteristics and the origin of NRM: As an example of the value of demagnetization characteristics in the interpretation of NRM consider Mare basalt 14053. Figure 1 shows the AF

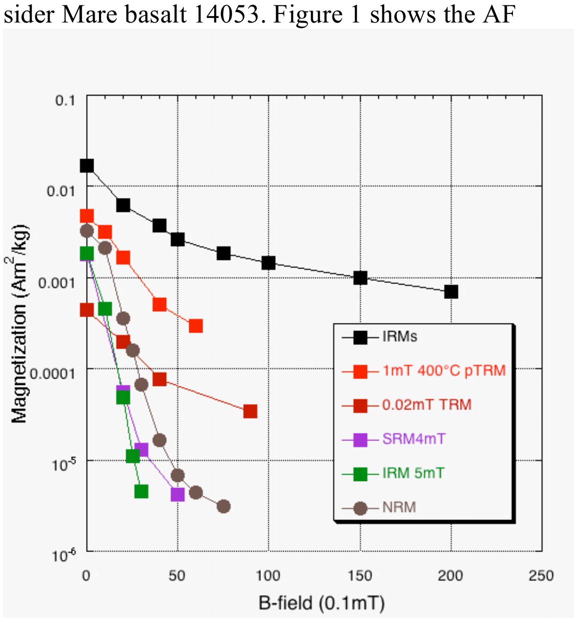

Fig.1. AF demagnetization characteristics of 14053: NRM, TRM, pTRM, SRM and Weak field IRM.

demagnetization characteristics of NRM, Thermal Remanent Magnetization (TRM), partial TRM from 400°C in a 1 mT field, Isothermal Remanent Magnetization (IRM) in a 4 mT field, weak Shock Remanent Magnetization (SRM) of < 0.1GPa in a 4mT field and saturation IRM. It is immediately obvious that the AF demagnetization characteristics of NRM are unlike those of TRM. This sample should therefore not be used for paleointensity estimates. Thermal demagnetization of NRM, TRM and mixed weak field TRM and IRM is also available and again demonstrate that the NRM cannot be a simple TRM. Moreover, given an IRM combined with a weak field TRM, the IRM may contaminate the thermal demagnetization spectra to high temperature. Similar analyses were carried out with 10048, a regoltih breccia which showed TRM like characteristics [4], but only rarely is such a complete set of demagnetization characteristics available for the Apollo samples.

Paleomagnetism of mare basalts:. The lunar mare basalts acquired a primary remanent magnetization in the ambient field as they initially cooled. However, what happened to their NRM subsequently is unclear.

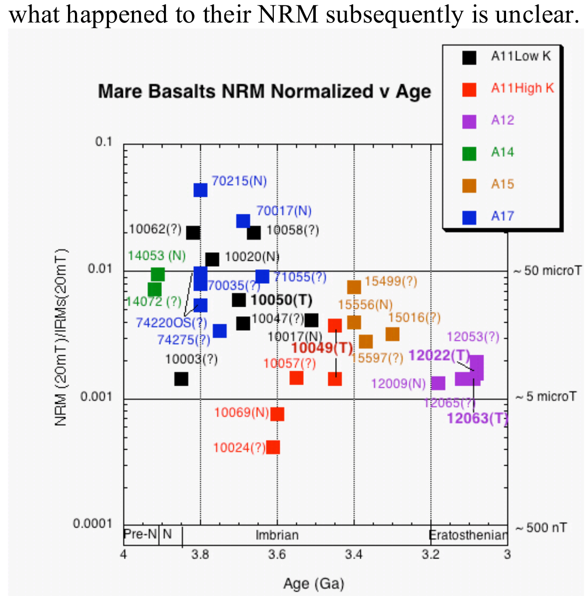

Fig. 2 NRM/IRMs at 20mT Alternating field demagnetization for the Mare Basalts.

To aid interpretation of the NRM, the samples have been divided according to the following criteria. If the NRM has AF or thermal demagnetization like TRM in the same sample and exhibits directional stability, the NRM is considered to satisfy the necessary conditions for an origin during cooling on the lunar surface, and it is shown with a T appended. If these criteria are not met by the analysis, an N is appended. When the critical AF data are not available the sample is marked with a "?". Clearly the majority of the samples have insufficient data to make a determinaton. However 4 do appear to have TRM like characteristics and 8 do not. 70215 and 70017, whose ages are between 3.9 and 3.6 Ga and have high NRM/IRMs ratio do not carrying a primary NRM of thermal origin. Nearly all samples have NRM/IRMs ratios more than an order of magnitude larger than the strongest surface fields observed on the moon. If the criteria are relaxed to directional stability and NRM demagnetization similar to TRM characteristics, then five more samples are accepted including the orange soil, and the trend with age is preserved. In summary, there is a major contribution of secondary magnetization in the NRM of Mare Basalts, probably impact related shock magnetization, but there may be a record of a waning dynamo field giving fields of the order of μT's at the lunar surface [5].

Paleomagnetism of breccias: The paleomagnetism of the breccias studied divides them into three groups: (1) regolith breccias, (2) melt rock and melt

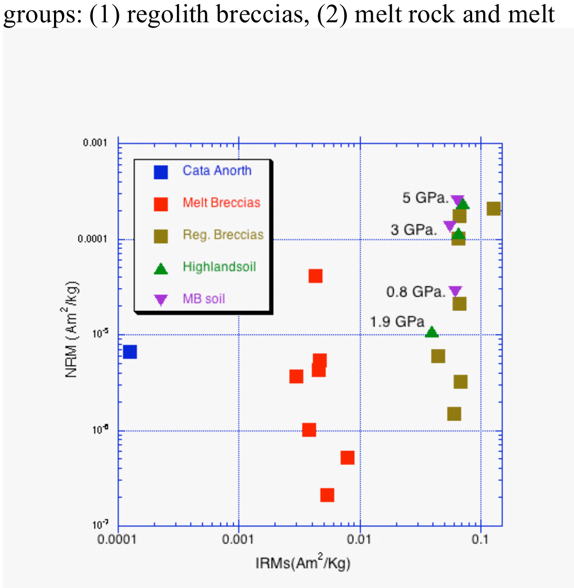

Fig. 3 The Natural Remanent Magnetization (NRM) plotted against saturation Isothermal Remanent Magnetization (IRMs) for breccias and synthetic regolith breccias formed by shocking soil.

breccias and (3) cataclastic anorthosites. Little has been done paleomagnetically with group 3, whose NRM is likely to be particularly problematic. The paleomagnetic record of group 2 provided examples of the largest NRM/IRMs ratios, although at least some of them do not carry primary TRM like NRM. The regolith breccias are some of the most strongly magnetized lunar samples and are a likely source of the magnetism of such strongly magnetized formations as the Cayley. Some have demagnetization characteristics of NRM like TRM, or pTRM. Synthetic regolith breccias were made in the geomangetic field with shocks in the range of tenths to a few GPa, and have rock magnetic properties very similar to the natural regolith breccias and including new glass [5]. Shocks of a few GPa may therefore have been experienced by many lunar samples. The young glass on 70019 (7) exhibits primary NRM characteristics similar to TRM and recorded surface magnetic fields of μT's, but its behavior during KTT is reminiscent of that of samples not carrying primary NRM (3). The age of the young glass studied is far too young to be a record of an ancient dynamo and must either record an ambient surface field, or a field related to the shock event that formed it.

Discussion: Even after restricting the Mare Basalt data set to those passing the initial criteria, or the reduced criteria, discussed above for primaryNRM, the normalized remanence still decreases with age from a maximum between ~3.9 - 3.6 Ga to 3.0 Ga. However, the origin of the NRM of the young glass and of the regolith breccias of unknown age remains unclear. The glasss is far too young to record a dynamo field, so that there is some strong NRM that cannot be recording a dynamo field. The NRM of some Mare Basalts may record a dynamo giving fields of the order of μT's at the lunar surface, but it is very hard to distinguish from impact related magnetization of the same order of magnitude. Since the normalized NRM of the Mare Basalts decreases from a maximum at the time of the Late Heavy Bombardment, the LHB may be involved in the explanation of the lunar paleomagnetic results. This suggests that if there was a dynamo, its efficency was related to the effects of the LHB on a lunar core. Alternatively, NRM related to shock in impact events of the LHB may explain the maximum the NRM/IRMs ratios at this time. Determination of the AF and thermal, demagnetization characteristics of TRM and SRM of individual Mare Basalts should reveal those samples with a primary NRM, for which paleointensity experiments are likely to be successful.

References: [1] Garrick-Bethell and Weiss (2007), LPSC, 38, 2405. [2] Gattacceca et al., (2008) PEPI, 166, 1-10. [3] Lawrence et al., (2008) PEPI, 168, 71-87. [4] Dunn and Fuller, (1972) LSC3ed, 2363-2386.[5] Collinson et al., (1972) LSC3ed, 2343-2361. [6] Cisowski et al., (1975) LSC6th, 3123-3141. [7] Sugiura et al., (1979) LSC10, 2189-2197.