THE ROLE OF SHOCK IN LUNAR PALEOMAGNETISM. M. D. Fuller[1] and J. S. Halekas[2], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa (mfuller@soest.hawaii.edu), [2]Space Sciences Laboratory, U.C. Berkeley (jazzman@ssl.berkeley.edu).

Introduction: Lunar magnetism remains an enigma, but new techniques and interpretations are modifying earlier pictures. In particular, recent work has suggested that the effect of impact related shock on the lunar paleomagnetic record may have been even greater than considered earlier. Virtually all the lunar samples, which we study, have suffered some degree of impact related shock. Therefore, if we wish to understand the lunar paleomagnetic record, the effects of this shock on magnetization must be identified and understood. The following relevant phenomena will be discussed: (1) impact crater morphology with terrestrial craters providing ground truth, (2) shock effects on magnetization (3) the generation of fields in impacts and (4) the manifestation of shock effects in lunar magnetism.

Effects of impact related shock on magnetization: The magnetization of terrestrial craters can in principle provide ground-truth for interpretations of lunar craters and their shock related magnetic effects. It is evident that melt rocks and breccias, which contain glass, and other molten material carry a NRM recording the ambient geomagnetic field. The magnetization of weakly shocked material is less clear. The paleomagnetism of the Vredefort crater has demonstrated that strongly shocked basement rocks have randomly oriented but strong magnetization [1]. The most common magnetic anomaly over terrestrial craters is a magnetic low, with a local high over central peaks, if they are present.

Experimental work has outlined the principal features of shock remanent magnetization (SRM). For shock pressures of 10^2 bars with waveforms of approximately 0.5 msec, SRM was found to be dependent upon the peak pressure and was large compared with IRM in the same field [2]. Air gun experiments with peak pressures of 10 and 20 kbars) demonstrated that the SRM acquired was very soft [3]. Samples from close to the impact point of shaped charges traveling at 17 Km/s in fields of 1mT field acquired shock magnetization which was stable against AF demagnetization and had similar AF demagnetization characteristics to IRMs [4].

Plasma was generated in the shaped charge experiments. Such fields have also been demonstrated with experiments at the NASA Ames Vertical Gun Range and shown to have geometries and durations dependent upon impact angle, velocity and target material [5]. A second mechanism has been proposed by Freund et al., [6], who demonstrated that with the application of stress, currents flowed from rock samples. Given the necessary return paths, such currents could generate fields. In summary there is little reason to doubt that major impact events can generate magnetic fields.

Paleomagnetism of melt rock and mare basalts: Turning to the lunar paleomagnetic record, the Apollo 16 melt rock 62235 a key sample. It has yielded some of the highest paleointensity estimates of ancient lunar fields. Yet, from the earliest analyses [7] to the most recent [8], results have been puzzling. AF demagnetization shows the magnetization to be largely lost by 30 mT. Thermal demagnetization yields blocking from room temperature to more than 700°C. The NRM can be divided into lower and higher temperature blocked parts, with the lower giving the high estimate of paleointensity. The intensity and demagnetization characteristics of NRM are inconsistent with a single component NRM of thermal origin acquired at the time of formation of the rock. They are consistent with a small high temperature TRM accompanied by a strong SRM acquired in a later event. This reexamination of 62235 suggests that it is time for further reanalysis of other samples. For example, samples 68415 and 68416 come from the same Apollo16 boulder and yet have dissimilar NRM that cannot be a simple TRM.

The lunar mare basalts should also have acquired a TRM at the time of origin. Some of the older Apollo11 and 17 basalts including the orange soil give high NRM:IRMs suggesting acquisition of remanence in relatively strong fields. The efficiency of 10058 that gives the strongest relative paleointensity is consistent throughout AF demagnetization [9]. This is consistent with either a TRM in multidomain material, or an SRM. Other basalts of the same age have far weaker magnetization and yield lower paleointensity estimates. The younger Apollo 11 mare basalts, the Apollo 12 and 15 have consistently weak NRM and yield low paleointensity estimates.

The Lunar Surface Magnetic Fields: Results from the surface magnetometers [10], from the subsatellite magnetometers [11] and the electron reflectance experiments [12] revealed stronger fields over the highlands than over the Mare, with the highest concentrations of strong fields found antipodal to young large impact basins. The electron reflectance experiments, with higher sensitivity to weaker fields, also reveal that impact basins and craters tend to be demagnetized with respect to their surroundings, suggesting shock demagnetization of pre-existing remanent magnetization [13].

Some lunar basins, similar to the terrestrial case, also have localized central anomalies [14]. Basins with this secondary signature tend to be from the early Nectarian period. These central basin anomalies, first seen in the ER data, have now been confirmed by two independent investigations of the magnetometer data [15]. This suggests that some impact basins may record a primary TRM in the basin melt rocks; alternatively, this signature may represent SRM in the shocked materials of the central uplift [14]. Interestingly, the youngest large impact basins (Imbrium and Orientale) do not show any sign of this central basin magnetization.

Forward modeling of the expected magnetic signatures of impact basins, given reasonable assumptions for the impact demagnetization, the remanent magnetization acquired via SRM and TRM, and its dependence on the strength of the ambient field may help determine which of these explanations is more likely, and provide constraints on the strength of any magnetizing field.

Discussion: Models of lunar magnetism should explain at least three remarkable aspects of lunar paleomagnetism, (1) that the Natural Remanent Magnetization (NRM) in the returned samples includes samples that suggest a relatively strong field era in lunar history from about 3.95 to 3.7 Ga, (2) that magnetic anomalies are found antipodal to the largest young (Late Nectarian and Imbrian)basins of a similar but possibly slightly older age , (3) the absence of strong magnetic anomalies over the major basins and the presence of moderate central peak anomalies found only in the Nectarian basins.

With respect to observation (1), there is little doubt that the paleomagnetic record of key lunar rocks magnetized during the possible high field era is too complicated to be primarily NRM of thermal origin acquired at the time of initial cooling in a lunar dynamo field. Moreover, it appears that shock is playing a major role, even in samples that do not show strong petrological shock effects. However, if the remanence is caused by impact related shock, the concentration of the ages of strongly magnetized rocks in a remarkably short time scale, (3.95 to 3.7 Ga.) is puzzling: shock remanence should be acquired throughout lunar history. This suggests that there was something particular about the magnetic environment of the moon during the late heavy bombardment.

Observation (2) is explained by some variant of the model of Hood [16] invoking compression and transport of the magnetic field at the impact point to give a stronger field at the antipode and magnetization in that enhanced field. This mechanism is easier if there is a lunar dynamo field, but does not require such a field.

Observation (3) may be nothing more than a manifestation of the analogous lows over terrestrial craters which were magnetized in the geomagnetic field, or a particular pattern of thermal demagnetization caused by the influx of later mare basalts (though thermal calculations show that it is difficult to demagnetize a significant thickness of magnetized crust via the direct effect of individual flows).

Conclusion: Lunar magnetism has set us a fascinating problem. However, the paleomagnetism of the samples is so strongly affected by shock that it is not clear that their magnetization requires a lunar dynamo. The strong anomalies on the far side antipodal to the major young basins appear to be explained by Hood's model [16]. The absence of strong anomalies over the major basins and the presence of central peak anomalies over older basins remain puzzling, but the former may be due to particular patterns of thermal demagnetization and the latter to shock magnetized and uplifted basement.

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