Reports

The Remanent Magnetization of Lunar Soils

Abstract. *The magnetic material in the lunar soils makes them potentially strong carriers of remanence and magnetically viscous. The soils therefore block remanence in the temperature range of the lunar diurnal cycle. This remanence is stable against alternating-field demagnetization. A mechanism whereby such hard natural remanent magnetization may be acquired by material buried in the regolith is proposed.*

Some of the most surprising and enigmatic results of the Apollo program have concerned lunar magnetism. The returned samples exhibit natural remanent magnetization (NRM) (*1*), and remanent magnetic fields have been detected both on the lunar surface (*2*) and in the immediate vicinity of the moon (*3*). Nevertheless, we know that at present the moon has no internally generated field like the geomagnetic field (*4*). It is important to understand this lunar magnetism and the fields which gave rise to it, because of the implications these fields have for the early history of the moon. In attempting to understand lunar magnetism, one should pay some attention to the possible magnetic effects of such essentially lunar processes as thermal cycling, solar-wind and cosmic-ray exposure, and impact shocking. So little is known about these processes that we cannot be sure that they do not contribute to NRM, even though it seems unlikely that they alone account for it. In this report I consider the effects of thermal cycling and point out that the grain-size distribution of the iron in the soil and in the most lightly metamorphosed breccias or fragmental rocks makes their remanent magnetization particularly sensitive to the lunar diurnal temperature cycle.

The lunar crystalline rocks, such as the mare basalts, carry a small stable or hard component of NRM of the order of 10^{-6} gauss cm^3 g^{-1}, which is virtually unaffected by alternating-field (AF) demagnetization in fields of up to several hundred oersteds. This hard moment is in general accompanied by a larger soft moment, which is demagnetized in fields of tens of oersteds and is likely to have been generated, at least in part, by magnetic fields in the spacecraft (*5*). The NRM of the breccias or fragmental rocks correlates in a rough manner with the degree of metamorphism to which they have been exposed (*6*). Thus, the Apollo 14 low metamorphic grade rocks tend to have an NRM that is larger and more stable to AF demagnetization than that of the more highly metamorphosed material. A decrease in magnetic viscosity also accompanies increasing metamorphic grade. The lunar soils contain between 0.2 and 1 percent metallic iron. This is more metallic iron than is found in the igneous rocks but it is comparable with that in some of the lightly metamorphosed breccias. This iron is mostly fine grained, and the soils are highly viscous (*7, 8*). Thus, the magnetic material in the soil and in the lightly metamorphosed breccias makes them potentially strong carriers of remanence and magnetically viscous.

Magnetic viscosity arises in fine particles when the relaxation times of the magnetization of the particles are comparable with experimental observation times (*7–9*). Such particles are close to their blocking temperatures (T_b). Above this temperature, in the superparamagnetic state, their magnetization is in thermal equilibrium with ambient fields, but below T_b, in the stable single-domain state, the particles can carry thermally stable remanence. Lunar samples 10021, 10048, 14047, and 14301 are fragmental rocks, all of which are of relatively low metamorphic grade and exhibit strong viscosity [type II in Nagata's classification (*7*)]. However, samples 14303 and 14311 are of high metamorphic grade and are type I low-viscosity rocks. The origin of the difference in viscosity becomes apparent if we consider the ratio of the saturation isothermal remanent magnetization (IRM_s) at room temperature to that at 5°K (*7*). The IRM_s at the low temperature is, in general, larger than that at room temperature. This is because of the presence of particles that are superparamagnetic at room temperature and are thus unable to contribute to room-temperature remanence but are in the stable single-domain state at 5°K and do contribute to the low-temperature remanence. For samples 10048 and 14047, and the soil 14259-69, the ratios are 1 : 4, 1 : 5, and 1 : 7, respectively, showing the presence of plentiful iron which blocks remanence between room temperature and 5°K. In contrast, the ratio for sample 14303 is only 1 : 1.6. It is therefore clear that the viscosity of the soils and of the lightly metamorphosed breccias is due to the presence of superparamagnetic and near superparamagnetic iron, and that, moreover, in the higher metamorphic grades such iron is not so plentiful.

Most of the measurements described below were carried out on a soil sample from the Apollo 11 collection (soil 10084-89). [The properties of this and the other soil samples are given in Table 1 (*7*).] Initially the sample exhibited remanence of 10^{-5} gauss cm^3 g^{-1}, after stirring and redeposition in null-field conditions (< 10 gamma). These moments were reduced by about an order of magnitude by the removal of particles larger than 150 μm. Although the demonstration of such random moments is of interest, for the purposes of the work discussed here they were minimized by the sieving and in some cases by thermal demagnetization.

The first experiment consisted of a determination of the range of blocking temperatures in the soil, at temperatures comparable with those of the lunar day. This was achieved by thermal demagnetization of the room-temperature IRM_s. Demagnetization was carried out by step heatings followed by field-free cooling. Heatings to 353°, 393°, and 413°K gave a progressive decrease in remanence to 75 percent of its initial value at a temperature of 413°K, which

Table 1. Magnetic properties of soil samples: initial susceptibility, χ_0; saturation magnetization, I_s; saturation remanence, IRM_s; coercive force, H_c; remanent coercivity, H_{rc}.

Soil sample	χ_0 (× 10^{-3} gauss cm^3 g^{-1} $oersted^{-1}$)	I_s (gauss cm^3 g^{-1})	IRM_s (gauss cm^3 g^{-1})	IRM_s/I_s	H_c (oersteds)	H_{rc} (oersteds)	H_{rc}/H_c
10084-89 at 300°K	8.3	1.17	0.08	0.07	36	460	12.8
12070-102 at 300°K	7.2	1.28	0.06	0.05	22	450	20.5
14259-79 at 300°K	10.0	1.50	0.06	0.04	19	300	15.8
14259-79 at 5°K		2.6	0.44	0.17	140	350	2.5

corresponds approximately to the maximum lunar surface temperature. In a similar experiment designed to investigate the distribution of blocking temperatures in the temperature range of the lunar night, the sample was given saturation remanence at 77°K, and allowed to warm to room temperature in field-free space, during which time the remanence was continuously monitored. The remanence decreased from 0.21 gauss cm^3 g^{-1} at liquid-nitrogen temperature to 0.11 at room temperature. These experiments demonstrate that more than half of the magnetic carriers that are blocked at 77°K are unblocked on heating to 413°K. Although this temperature range is somewhat larger than that of the lunar diurnal cycle, it is clear that there is considerable overlap between the distribution of blocking temperatures of the magnetic material in the soil and the lunar diurnal temperature cycle.

Remanence blocked as partial thermoremanent magnetization (pTRM) was investigated next. This form of remanence is acquired when magnetic materials are field cooled through part of the temperature range between their Curie point and the observation temperature. The pTRM was generated by field cooling from 373°K and 423°K to room temperature in a variety of weak fields. Alternating-field demagnetization of the pTRM revealed considerable stability (Fig. 1). For example, the pTRM was much more stable than a 20-oersted isothermal remanence (IRM). Similar results were obtained with a number of soil samples and with certain lightly metamorphosed breccias. It is interesting to note that the AF demagnetization characteristics of these partial thermoremanent magnetizations are very similar to those of the NRM of the breccias.

The comparatively hard nature of the pTRM is not inconsistent with the low blocking temperature of the remanence. The relaxation times of magnetization which determine the blocking temperature are strongly dependent upon particle size: in Néel's model (*9*) they depend primarily upon exp $(K_u v/kT)$, where K_u is the uniaxial anisotropy of the particle, v is its volume, k is Boltzmann's constant, and T is the temperature. On the other hand, the critical field or the coercivity of the particle, which determines its ability to resist AF demagnetization, is given by $2K_u/J_s$, where J_s is the saturation magnetization of the particle. Hence, remanence may have a low blocking temperature as a result of the small size of the particles carrying it, but yet be hard or able to resist AF demagnetization owing to the high anisotropy of the particles.

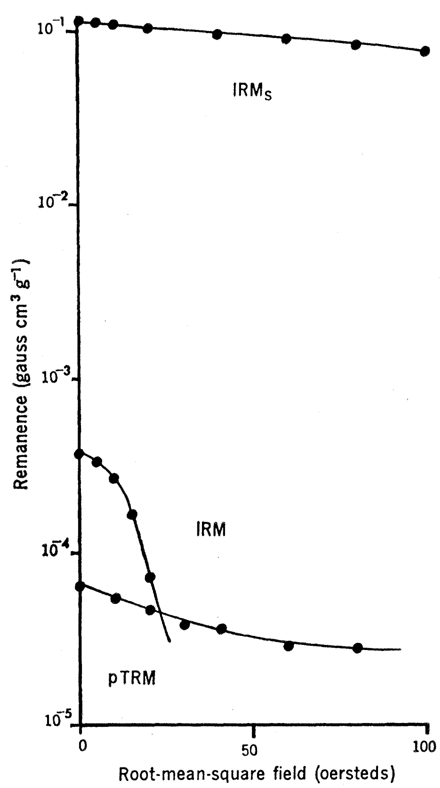

Fig. 1. Alternating-field demagnetization characteristics of soil sample 10084-89-3: IRM_s, IRM (20 oersteds), and pTRM from 373° to 300°K (5000 gammas).

It appears from the pTRM experiments that lunar material, such as the soils and breccias of low metamorphic grade, containing plentiful amounts of very fine iron with a distribution of blocking temperatures which overlaps the lunar diurnal temperature cycle, will, when at temperatures within the cycle, carry a pTRM type of remanence. This remanence will record the fields in which the material cooled from the maximum temperature to which it was exposed. When such material is buried in the regolith, its temperature at a depth of about a meter is steady at 250°K (*10*). It should then carry a pTRM type of NRM, recording the ambient field experienced during the drop in peak temperature from approximately 400° to 250°K. It is not clear as yet what the effect of soil dynamics will be on such a mechanism. Nevertheless, the work described in this report implies that the burial of soil in fields comparable with those observed at the Descartes site could give rise to NRM of a magnitude similar to that of the crystalline rocks. If a rock becomes buried in the regolith, it will also acquire pTRM although, apart from the most lightly metamorphosed breccias, it will contain so little very fine-grain iron that the effect is not likely to be important.

In this report emphasis has been placed upon the acquisition of remanence by weak-field cooling. A complementary effect which has been considered elsewhere is the demagnetization brought about by thermal cycling in field-free space (*11*). As a consequence of these effects of thermal cycling upon NRM, it is important to subject lightly metamorphosed breccias to thermal demagnetization to distinguish NRM, which, although stable against AF demagnetization, is thermally unstable. Natural remanent magnetization blocked below the collection temperature would be indicative of contamination acquired since the sample was picked up from the lunar surface and blocked during subsequent field cooling, wherever that may have taken place. The possibility that the soil carries NRM may be of interest in stratigraphic studies aimed at understanding soil dynamics. It also provides a mechanism for the generation of NRM on the moon, other than at the times of formation of the crystalline rocks and breccias. This magnetization may contribute to the surface fields observed by the astronauts using the surface magnetometers. It is hoped that measurements of the NRM of the soil may eventually be made on returned core tube material, so that we may see if it is greater than can be accounted for by random moments.

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12. I thank W. A. Cassidy and A. A. de Gasparis of the Department of Earth and Planetary Sciences, University of Pittsburgh, for helpful discussions on the magnetization of regolith material and D. W. Strangway and G. W. Pearce of the Manned Spacecraft Center, Houston, Texas, for their help in trying to arrange a measurement of the NRM of a returned core tube sample. I am also grateful to J. R. Dunn for help with the experimental work and to T. Nagata and F. C. Schwerer, who established the basic magnetic characteristics of the soil samples.

2 June 1972; revised 24 July 1972

North Atlantic Ocean: Preliminary Description of Normal Modes

Abstract. *The three lowest gravitational modes of free oscillation of the North Atlantic Ocean are estimated by numerical integration of Laplace's tidal equations. These modes have periods of approximately 21, 14, and 11 hours, and structures, respectively, of one, two, and three positive amphidromic systems. The phase distribution of the first mode resembles cotidal charts of the diurnal tide, and the period of the second mode is consistent with that inferred by Wunsch from tidal data in Bermuda and the Azores.*

By a method described previously (*1*) it is now feasible to calculate two-dimensional normal modes of the major ocean basins. Preliminary results for the North Atlantic are shown in Fig. 1. They are based on a numerical integration in which the lateral boundary and bathymetry are resolved on a grid of 4° squares on a Mercator projection. The boundary is assumed to be totally reflecting. In particular, on the boundary between the North and South Atlantic oceans a zero elevation of sea level is prescribed; on all other boundaries there is zero volume transport. The Caribbean Sea and Gulf of Mexico are excluded, as are the Norwegian Sea and Baffin Bay. The model thus defined is designated "model 401."

Figure 1d shows the bathymetry (*2*) of model 401, the most conspicuous features of which are the two major deep-sea basins and the intervening ridge system. The broad-scale shelving northward of 50°N accounts for most of the generally larger amplitudes of all modes in that region.

The lowest gravitational mode in this

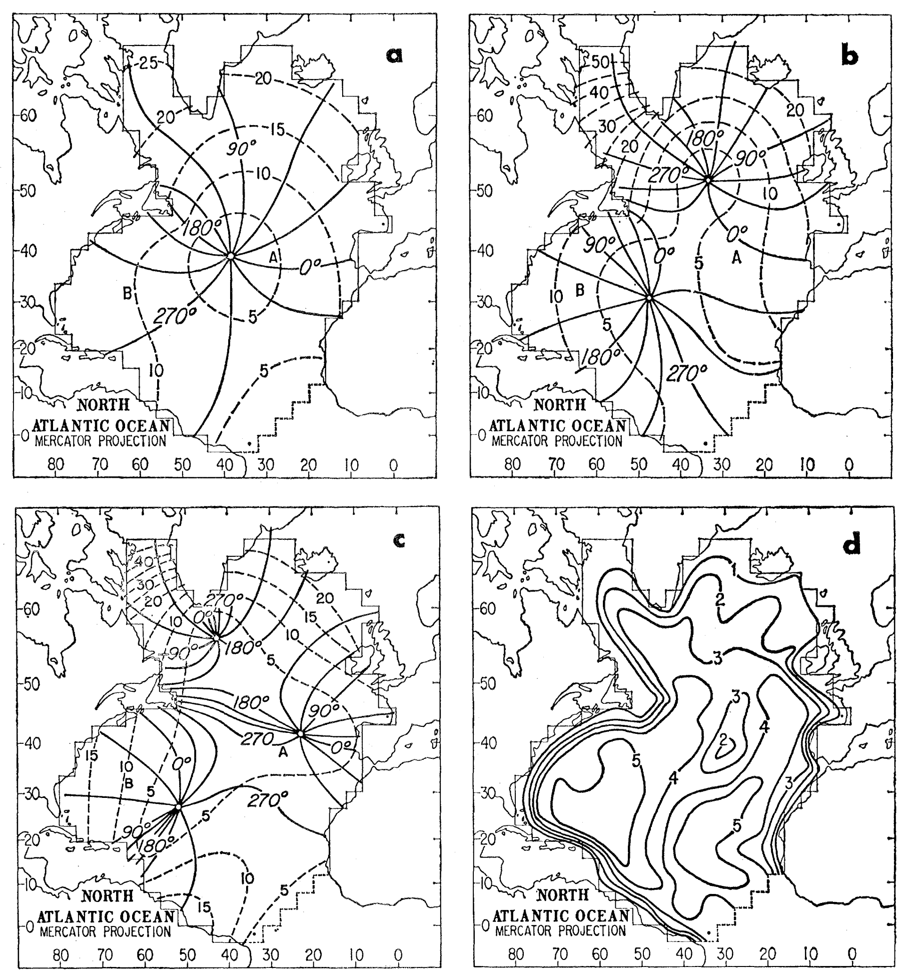

Fig. 1. (a to c) First, second, and third modes of free oscillation of the North Atlantic Ocean. The solid lines show the phase of maximum sea level in degrees (interval: 30°) referred to 0° at Lisbon; the broken lines show the amplitude of sea level normalized to root-mean-square 10 arbitrary units (interval: 5). (d) Bathymetry in kilometers.