An impulsive magnetic field from shock-induced polarization in lunar rocks as a possible cause of field anomalies associated with craters

B. A. Ivanov, B. A. Okulesskii, and A. T. Bazilevskii

O. Yu. Shmidt Institute of Earth Physics, USSR Academy of Sciences, Moscow, P. P. Shirshov Institute of Oceanography, USSR Academy of Sciences, Moscow, and V. I. Vernadskii Institute of Geochemistry and Analytical Chemistry, USSR Academy of Sciences, Moscow

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Magnetic profiling by Lunokhod 2 in the Le Monnier area has revealed quasisinusoidal field anomalies associated with impact craters 50–400 m in diameter. These anomalies might have been produced at the time of crater formation, when shock-induced electric polarization in the rocks could have resulted in an impulsive magnetic field.

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In the magnetometric profile obtained by Lunokhod 2 in the area of the crater Le Monnier following its deployment in January 1973, local variations in the direction and intensity of the magnetic field have been identified.[1] Sometimes these variations can be correlated to definite geological structures, particularly craters. Such anomalies were recorded when Lunokhod 2 crossed eight craters 50–400 m in diameter. These craters characteristically have a depth greater than the thickness of the regolith layer and a floor penetrating deep into the basalt base. No anomalies were observed when smaller pits (no larger than the regolith thickness) were crossed.

Crater-associated anomalies are manifested by distinctive quasisinusoidal variations in the vertical and horizontal field components relative to the mean background level of the magnetic field (20–30 γ in the region investigated) when craters are crossed (Fig. 1).

Crater formation by meteoritic impact is accompanied by a strong shock wave. As the wave passes through the rock, electric-charge separation or polarization can develop at the shock front. The principle underlying our hypothesis is that the polarization electric current can induce a significant impulsive magnetic field in the surrounding space and, in particular, ferromagnetic rock constituents can become magnetized. For lunar rock metallic Fe amounting[2] to $\approx 0.1\%$ represents the main ferromagnet capable of producing local magnetic fields of the intensity observed on the moon.[3]

Lunar rocks consist of plagioclase, pyroxene, and olivine with an admixture of other minerals including those of the silica group. Plagioclase, pyroxene, and olivine are dielectrics, while silica-group minerals are piezoelectrics. Upon passage of a shock wave polarization will develop both in piezoelectrics[4] and in some dielectrics.[5–7] Theoretical and experimental work in this field of research has been surveyed by Ivanov et al.[7]

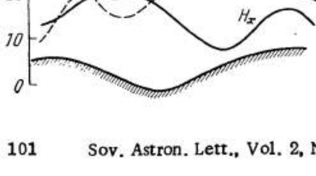

Fig. 1. Typical behavior of magnetic-field anomalies beneath a crater. Measurements by Lunokhod 2 in the Le Monnier area, March 16, 1973. H_x, H_z are the horizontal and vertical field components.

Let us estimate the intensity and some geometrical parameters of the magnetic field arising from the propagation of a hemispherical shock wave into the interior of a half-space filled with a dielectric polarizable in a shock wave. To simplify the discussion we shall assume that polarization of magnitude P arises at the shock front and that its relaxation time is infinitely long (we neglect the depolarization current). We can then obtain for the horizontal field component an expression of the form

$$H_x = H_0 I, \tag{1}$$

where I is a dimensionless quantity depending only on the relative position of the shock front and the point of measurement, while

$$H_0 = D \cdot P, \tag{2}$$

with D the velocity of the shock front. For the typical values D = 8 km/sec and P = 10^{-9} coulomb/cm^2 we have

$$H_0 = 10^{-3}\,\text{gauss} = 100\gamma. \tag{3}$$

Figure 2b illustrates the geometry of such an impulsive field beneath a crater 200 m in radius and 50 m deep. The field is calculated for the time when the shock wave has a radius of 30 m, and is expressed in units of H_0. If we assume that the ferromagnetic constituents of rocks lying beneath the floor of the newly formed crater become magnetized in this field, and that after the field decays a certain amount of residual magnetism remains, proportional to the strength of the operative field, then the variations in the horizontal field component as the crater is crossed will take a form like that shown in Fig. 2a.

There is a definite resemblance between the geometry of the hypothetical shock-induced magnetic field calculated from our proposed model and the actual pattern of vari-

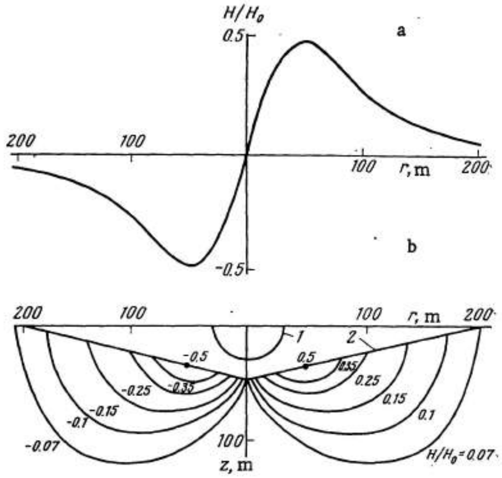

Fig. 2. Computed magnetic-field configuration. a) Theoretical variation of the field across the floor of a future crater at the time when the radius of the shock front is 30 m (pressure at shock front, ≈ 200 kbar). b) Geometry of curves of equal field strength beneath the crater at that same time: 1) position of shock front; 2) floor of future crater (the minus sign indicates that the field is directed away from the observer).

ation in the horizontal field component measured above the crater (Fig. 1). The absence of anomalies above craters small enough to remain within the regolith layer may come about because the passage of the shock wave does not result in shock-induced polarization of friable material.

If the proposed magnetizing mechanism does operate on the moon, then its contribution should have been quite large during the era of intensive meteoritic bombardment of the lunar surface. It is interesting to note that the largest values of residual magnetism are in fact found in lunar rocks that were formed at this time of intensive impacting.[2]

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Tidal deformations in the moon

B. Bodri

Budapest University

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Several dimensionless functions serving as coefficients in the spherical-harmonics expansion of tidal deformations (radial and tangential displacements and stresses) are calculated.

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A tidal disturbing potential can be expressed as a sum of spherical harmonics. As shown by Love,[1] all deformations induced within a planet by such a potential may be represented as a sum of the same harmonics, multiplied by a certain function corresponding to the given deformation, depending only on the model of the planet. Thus if W_n is the n-th order harmonic of the tide-raising potential W, then the additional potential U resulting from the deformation of the planet by the potential W will have the form

$$U = \sum_{n=2}^{\infty} K_n(\tau) W_n. \tag{1}$$

The total potential

$$V = V_0 + W + U = V_0 + \sum_{n=2}^{\infty} R_n(r) W_n, \tag{2}$$

where $R_n(r) = 1 + K_n(r)$ and V_0 is the gravitational potential of the planet.

Tidal deformations of a planet are described by the six functions H, T, N, M, R, L, where H and T describe the radial and tangential displacements, respectively; N and M, the radial and tangential stresses; and R and L, the potential and its gradient. In this notation the components of the displacement vector **u**, for example, become

$$\begin{aligned} u_r &= \frac{1}{g} \sum_{n=2}^{\infty} H_n(r) W_n, \\ u_\vartheta &= \frac{1}{g} \sum_{n=2}^{\infty} T_n(r) \frac{1}{r} \frac{\partial W_n}{\partial \vartheta}, \\ u_\varphi &= \frac{1}{g} \sum_{n=2}^{\infty} T_n(r) \frac{1}{r \sin\vartheta} \frac{\partial W_n}{\partial \varphi}, \end{aligned} \tag{3}$$

where r, ϑ, φ denote the radius, polar angle, and longitude in a coordinate system coupled to the planet, and g is the gravitational acceleration. The values of the functions H, T, N, M, R, L on the surface of the planet are called the Love numbers.