fact being smelted in the early third millennium B.C., as suggested by the radiocarbon date for mining activity. This would have direct bearing on the view held by many scholars that the smelting of sulfide ore did not become important before the end of the second millennium B.C. Spectrographic studies of the matte and of pieces of Kozlu ore may shed some light on the issue.

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7. We stress that we are professional geologists and that the finer points of archeological interpretation (for example, interpretation of Pre-Hittite Pontic pottery) are outside our expertise. Our intent has been to present an interdisciplinary research report emphasizing a significant geologic discovery that contains important archeological evidence. We hope that our archeologist colleagues overlook what may appear to be errors of omission or incomplete research on our part, and that the report stimulates in-depth archeological studies of Kozlu on their part. We thank the United Nations Development Program and the Turkish government for permission to publish.

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Lunar Magnetic Field: Permanent and Induced Dipole Moments

Abstract. *Apollo 15 subsatellite magnetic field observations have been used to measure both the permanent and the induced lunar dipole moments. Although only an upper limit of 1.3 × 10¹⁸ gauss-cubic centimeters has been determined for the permanent dipole moment in the orbital plane, there is a significant induced dipole moment which opposes the applied field, indicating the existence of a weak lunar ionosphere.*

The lunar magnetic field has been studied indirectly via the natural remanent magnetization of the returned lunar samples, and directly with magnetometers carried to the surface and placed in orbit at low altitude above the surface on the Apollo 15 and Apollo 16 subsatellites (*1*). These measurements reveal widespread lunar magnetism with scale sizes ranging up to many tens of kilometers. The origin of these fields remains a puzzle. According to one model, there existed an ancient lunar dipole field either generated by an internal dynamo, induced by a strong external field, or acquired during accretion (*2*). If this were true, then some trace of this ancient global field might still be present, and it is of some interest to attempt to detect this field. It has also been reported that, when the moon is in the geomagnetic tail, it possesses a substantial induced dipole moment (*3*), which could interfere with the measurement of the permanent moment. Fortunately, it is possible to separate the permanent from the induced moment in the orbital measurements. In this report, we reevaluate earlier orbital measurements of the permanent moment which did not take this into account (*4*) and examine the induced moment observed in the orbital data.

Measurements of the lunar magnetic field are usually made during the 4- to 5-day period each month when the moon is shielded from the solar wind plasma by the geomagnetic tail. The tail consists of two bundles of oppositely directed magnetic flux, the north and south lobes, separated by a plasma sheet. In the north lobe the magnetic field induced in a ferromagnetic moon would be in the solar direction and in the south lobe the induced magnetic field would be in the antisolar direction, whereas a permanent field would be fixed in selenographic coordinates. Thus, we can separate permanent from induced effects by giving measurements from each lobe equal weight, even though there may be more data obtained from one of the lobes than the other. A total of 25 lunar orbits were used in the analysis reported here: 17 from the north lobe and 8 from the south lobe.

To measure the permanent dipole field, one separates the average field in inertial coordinates from the data and then rotates the residual fields into a coordinate system that has directions radially outward, parallel to the orbit plane (eastward) and perpendicular to the orbit plane (northward). Data from each lobe are averaged separately by azimuthal angle around the orbital plane from the 0° selenographic meridian and are Fourier-analyzed at the orbital period. This provides four estimates of the dipole moment: one from each of the radial and tangential components in each of the lobes. Table 1 lists the radial and tangential estimates of the moment after the data from both lobes have been averaged, as well as the resultant average moment and the two error estimates, that is, the difference vector and the equivalent moment from the perpendicular component. The magnitude of the expected error vector, 1.33×10^{18} gauss-cm^3, is comparable to the magnitude of the measured dipole moment. Thus, we have measured only an upper limit for the permanent dipole moment. Although the upper limit applies only to the components of the moments in the orbital plane, it is unlikely that the moon is principally magnetized along the orbital normal (116°E, 62°N).

To measure the induced field, we proceed as above except that we measure the azimuthal angle eastward from the direction of the orbital average field projected into the orbital plane. The orbital average magnetic field is taken to be the external field, and, since this analysis is insensitive to induced moments perpendicular to the orbital plane, we use the magnitude of the field projected on the orbital plane to normalize the induced field. Table 2 shows the radial and tangential measures of the induced dipole after the north and south lobe data have been averaged, as well as the average moment, the difference between the average and the radial estimates, and the equivalent moment deduced from the perpendicular component. The induced moment is $(6.3 \pm 2.4) \times 10^{22}$ gauss-cm^3 per gauss of applied field, and is opposite to the applied field.

If an ancient lunar dipole field were responsible for the magnetization of

Table 1. Apollo 15 subsatellite measurement of the permanent lunar magnetic dipole moment.

Measurement	x-Component ($\times 10^{18}$ gauss-cm^3) (0°E)	y-Component ($\times 10^{18}$ gauss-cm^3) (90°E)
Radial	2.58	1.04
Tangential	−0.20	0.05
Average	1.19	0.54
Difference vector	1.39	0.50
Perpendicular	−2.81	1.44

Table 2. Apollo 15 subsatellite measurement of the induced lunar magnetic dipole moment.

Measurement	Parallel to the external field ($\times 10^{22}$ gauss-cm^3/gauss)	Perpendicular to the external field ($\times 10^{22}$ gauss-cm^3/gauss)
Radial	−6.83	6.46
Tangential	−5.67	−1.66
Average	−6.25	2.40
Difference vector	0.58	4.06
Perpendicular	0.68	0.41

the returned lunar samples, it must have had a moment of at least 1.5×10^{23} gauss-cm^3 (*5*). The value presented here is less than 2×10^{-5} of this value. If the ancient lunar field were due to an internal dynamo, this dynamo has effectively stopped. If the moon obtained such a moment through accretion, as Runcorn and Urey have proposed (*2*), this magnetization has been rather efficiently removed. Given an initially uniform magnetization of magnitude sufficient to cause the postulated ancient magnetic moment, erased from the inside outwards as material was heated above the Curie point, our data constrain such material to a layer less than 11 m in present thickness. If, instead of this hypothesized value, we take a common value of natural remanent magnetization (10^{-4} gauss-cm^3 g^{-1}), reported for the most magnetic lunar samples (*6*), there may be a layer up to 300 m thick. We believe that it is unlikely that all traces of the ancient field could have vanished so completely, and therefore it is highly improbable that the moon ever had a large permanent dipole moment.

In view of the magnetic permeability ratio of 1.03 reported previously from surface measurements (*4*) and our expectations about the behavior of lunar material, the negative induced dipole moment is surprising. However, the orbital and surface measurements are in accord if a substantial diamagnetic layer exists between the subsatellite altitude of 100 km and the lunar surface, that is, a lunar ionosphere. Permeabilities for the ionosphere (μ_1) and the moon (μ_2) consistent with the orbital and surface measurements (*7*) range from a strongly diamagnetic ionosphere, $\mu_1 = 0.63$, and a moderately ferromagnetic moon, $\mu_2 = 1.03$, to that of a much weaker ionosphere, $\mu_1 = 0.85$, and a slightly ferromagnetic moon, $\mu_2 = 1.008$. The ionospheric permeability requires an average energy density of approximately 100 ev cm^{-3} in the region between the subsatellite and the moon. This could be provided if 0.2 to 5 percent of the lunar atmosphere were to be ionized (*8*). The observed photoelectron layer would make only a minor contribution to the energy density of the plasma in this region (*9*).

The permeability of the moon is determined mainly by its metallic free iron content in regions below the Curie temperature of iron, and permeability measurements have been used to place constraints on both the iron content and the thermal properties of the moon (*3*). To correct for the effect of the lunar ionosphere on the apparent lunar permeability, the calculated models would have to be revised to include even more cold iron either by a reduction in the internal lunar temperature or by an increase in the specific free iron content or both. However, the lunar metallic iron content estimated from this technique is already much higher than that observed in the samples returned from the lunar surface (*6, 10*). Furthermore, the observed correlation between magnetic, petrologic, and chemical properties (*11*) suggests that the observed iron content of the surface material is indeed representative of the upper lunar crust. One resolution of this apparent contradiction is that the lunar permeability is measured relative to the diamagnetic tail lobes. An energy density of 10 ev cm^{-3}, which may be beyond the level of detection of present plasma instrumentation, would lead to an apparent permeability of 1.02 if the true lunar permeability were that of free space. In view of these uncertainties, we should treat present estimates of lunar permeability with caution.

In summary, there is no present-day evidence for the existence of an ancient lunar dipole field in the data of the Apollo subsatellites. Although there are substantial magnetic fields at many of the lunar landing sites and although extensive magnetic anomalies, or magcons, have been observed from lunar orbit, there is little overall order to the field. Finally, the negative induced moment implies the existence of a substantial lunar ionosphere when the moon is in the lobes of the geomagnetic tail. Thus, both orbital and surface measurements are required to deduce the ratio of the lunar permeability to that of its plasma environment.

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