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MAGNETIC BENEFICIATION OF LUNAR SOILS

R.R. Oder
EXPORTech Company, Inc.

J. Graf
Department of Geology, Michigan Technological University

L.A. Taylor
Department of Geological Sciences, University of Tennessee

D.S. McKay
NASA Johnson Space Center

Abstract

We will present a review of recent laboratory results obtained in dry magnetic separation of one gram samples of the minus 1 mm size fraction of five lunar soils of widely differing maturities. Two highland soils were investigated as potential sources of low iron content feedstocks for space manufacture of metals, including aluminum, silicon and calcium. Pure anorthite was separated from the diamagnetic fraction of immature highland regolith. Three high titanium mare soils were investigated as potential sources of ilmenite for production of hydrogen and for recovery of ^3He. Ilmenite and pyroxene were separated from the paramagnetic fractions of the mare basalts. Agglutinates and other fused soil components containing metallic iron were separated from the strongly magnetic fractions of all soils.

We will present conceptual magnetic separation flow sheets developed from the laboratory data and designed for production of anorthite from highland soils and for production of ilmenite from mare soils. Using these flow sheets, we will discuss problems and opportunities associated with the magnetic separation of lunar soils. Separation of high-grade anorthite or other diamagnetic components at moderately high recovery can be achieved in processing immature highland soils. Similarly, small amounts of glassy components rich in metallic iron can be separated into the stll be discussed. Further, while magnet weight is always an issue in magnetic separation technology, recent developments in both low temperature and high temperature superconductivity present unusual opportunities for magnet design specific to the lunar environment.

MAGNETIC BENEFICIATION OF LUNAR SOILS

Lunar regolith contains lithic, mineral, and fused fractions which can serve as sources of important materials including oxygen, refractories, and metals for use in space. Realization of the economic advantages of using indigenous resources may involve the operations of minerals preparation and beneficiation. One objective of this paper is to focus attention on the emerging opportunities and challenges in beneficiation of extraterrestrial materials through a discussion of one technology, magnetic separation, which has been applied in the laboratory to specific applications in the beneficiation of lunar soils. Another objective of this paper is to review the status of recent work on magnetic beneficiation of lunar soils. That work has led to several general conclusions of a practical nature which are presented here.

Magnetic Beneficiation of Highland and Mare Soils: In earlier work (Oder and Jamison, 1989; Oder, Taylor, and Keller, 1989; Oder and Taylor, 1990; Taylor and Oder, 1990 a, b, c) we have shown that dry magnetic separation is a viable method for beneficiation of lunar soils because it is adaptable to dry processing of finely divided, weakly magnetic, granular material in the low-gravity, atmosphere-free environment of space. Diamagnetic anorthite, χ = -0.39 μcc/gm, paramagnetic ilmenite, $\chi \simeq 60$ μcc/gm, and ferromagnetic glass-encased metallic iron, apparent susceptibility χ_a > 130 μcc/gm, have been separated from the <1mm size fraction of the lunar soils. Conceptual designs based on these results indicate that a wide variety of modern methods for large scale separation of fine sized and weakly magnetic particles which combine advanced magnet design with proven commercial minerals processing technology are available for lunar application (Oder, 1992).

Contrary to the belief of some (Lewis, 1992), the limitation in magnetic separation of paramagnetic material such as ilmenite will not be imposed by the "weak magnetism" of the product but by the nature and physical state of the extraterrestrial material. Source materials which have been modified by natural or other processes to the point where their individual components (such as ilmenite, anorthite, etc.) have lost their identities will not be good candidates for beneficiation by any technology. The need now is to identify extraterrestrial materials which are good candidates for physicochemical separation and to proceed with testing specific beneficiation technologies such as magnetic separation. This paper presents a practical method of identifying lunar soils which are best suited for physical beneficiation by magnetic methods.

Effect of Soil Maturity on Magnetic Separation: The earlier work showed that the magnetic susceptibility at which separation is achieved is not affected by the maturity of the soil (Oder, 1991). It is a function of the magnetic susceptibility of the material to be separated. This is illustrated in the left portion of *Figure 1* for separation of **diamagnetic** anorthite from highland soils of widely differing maturities and in the left portion of *Figure 2* for separation of paramagnetic ilmenite from mare soils of differing maturities.

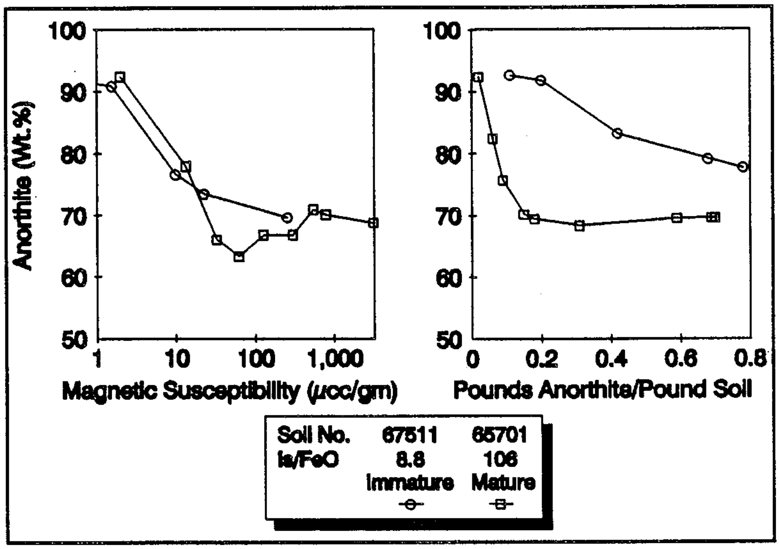

Fig. 1. Concentration of anthorite vs. magnetic susceptibility and recovery for two highland soils.

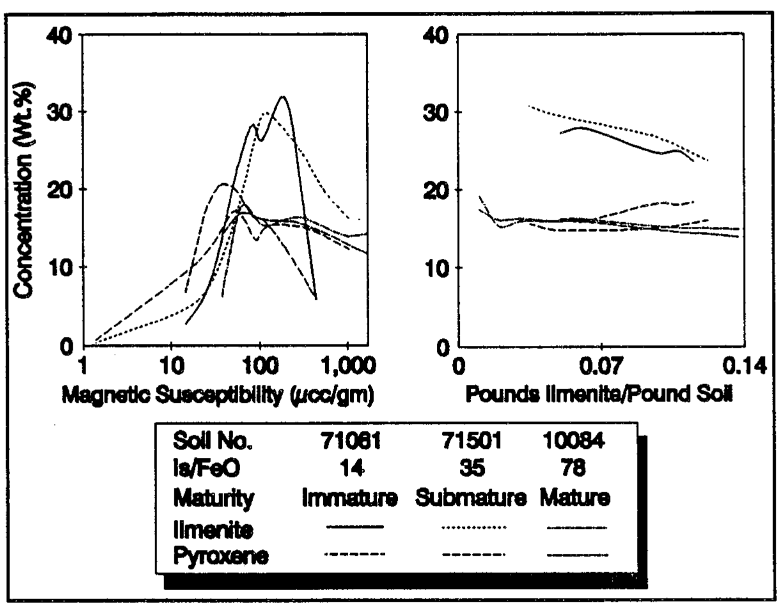

Fig. 2. Concentration of ilmenite and pyroxene vs. magnetic susceptibility and recovery for three mare soils.

The recovery of lunar soil components in magnetic processing is strongly affected by the maturity of the soil, however (Oder, 1991). Our work has shown that the distribution of lunar soil components in different magnetic susceptibility intervals changes significantly with soil maturity. This is illustrated in the MagnetoGraphs of Figure 3 for two highland soils of widely differing maturities.

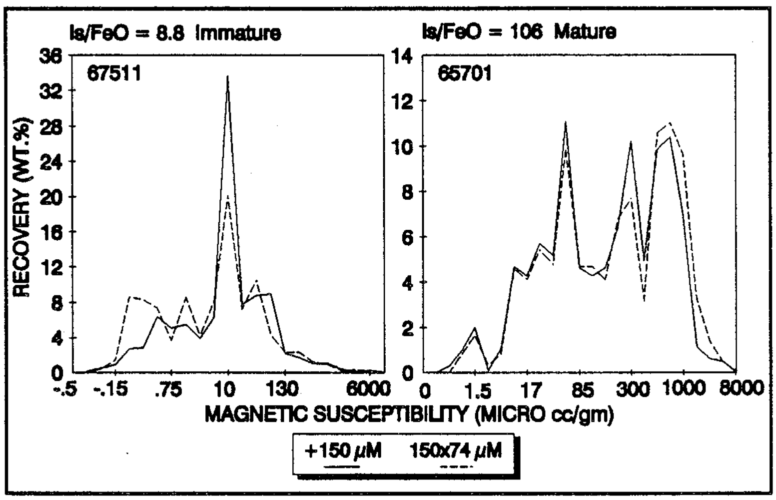

Fig. 3. MagnetoGraphs for two size fractions of anorthistic lunar highland soils 67511 and 65701.

In *Figure 3*, the distribution of sample weights vs. magnetic susceptibility is shown for two size fractions of immature soil 67511 and mature soil 65701. The maturity of a soil is represented by the intensity of single-domain iron (as determined by FMR) divided by the iron oxide composition -- I_s/FeO (Taylor, 1988). The higher the value, the greater the maturity. These soils have I_s/FeO values of 8.8 and 106 respectively (Morris, et al., 1983). Because the breadth of the distribution increases with maturity, the amount of material separated in the low susceptibility interval, nominally <130 μcc/gm, must decrease. As is apparent in the figure, this has an adverse effect on recoveries of paramagnetic and diamagnetic soil components. Conversely, the weight recovered in the +130 μcc/gm magnetic susceptibility interval indicates increased magnetism for the mature soil.

The effects of soil maturity on recovery of anorthite and ilmenite are illustrated in the right portions of Figures 1 and 2, respectively. **Soils of lowest maturity are the best candidates for magnetic separation for all materials ranging from diamagnetic alumino-silicates to paramagnetic iron oxides such as ilmenite or pyroxene** (Taylor and Oder, 1990).

Loss of efficiency in magnetic separation of mature lunar soils can occur in several ways.

♦ First, while physical separation may be aided by size reduction associated with micrometeorite impacts (liberation), it may also be hampered by destruction of rock components by fusion and other thermo-chemical reactions occurring as a consequence of the micrometeorite impacts. Fusion can also disseminate fine sized materials in a manner which makes mechanical separation impractical.

♦ Secondly, the apparent magnetism of subsidiary fused soil components produced by the impacts can range from diamagnetic to ferromagnetic. A very small amount of metallic iron in a glass matrix can overwhelm the magnetism of most lunar materials. As the metallic iron concentration increases with maturity, soils become more magnetic (see *Figure 3*). This has the effect of lowering the recovery in magnetic susceptibility intervals containing the diamagnetic and paramagnetic components.

Soil Magnetism and Metallic Iron Content: Lunar alumino-silicate rocks are diamagnetic in nature. Paramagnetism is generally associated with Fe^{2+} found in minerals such as ilmenite $FeTiO_3$ and pyroxene $(Ca,Mg,Fe)SiO_3$. The specific susceptibilities of these minerals generally range from 40 μcc/gm to 100 μcc/gm. Fe^{3+} is nonexistent in lunar materials so magnetite is not present. The lunar rocks we have investigated are generally less magnetic than are the soils sampled from the same area. The strong magnetism of lunar soils is associated with single- domain sized metallic iron (Fe^0, native iron) found in vesicular glassy agglutinates, splash glasses, melt rocks, and other fused soil products of the energetic micrometeorite impacts (Nagata et al., 1972). A large portion of the metallic iron in agglutinates is also sub-domain in size. This material is super-paramagnetic and is a major contributor to the magnetism of lunar soils. Agglutinates are unique to the surface of the Moon.

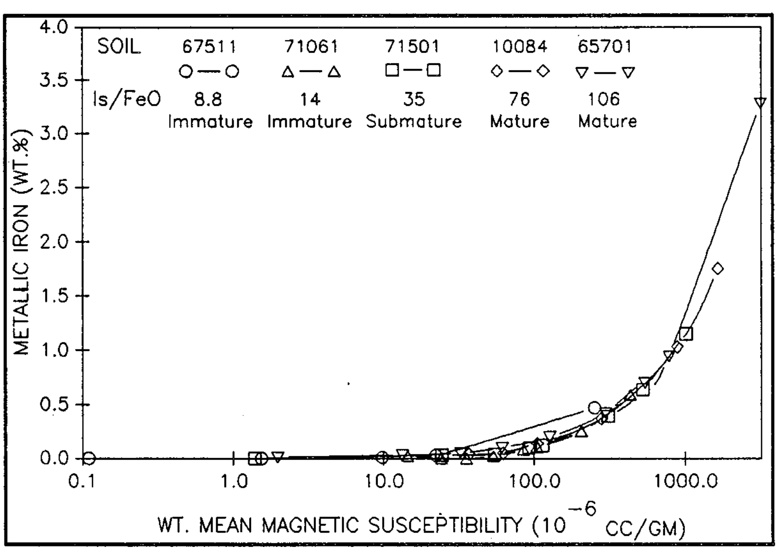

Fig. 4. Magnetic susceptibility dependencies of the concentration of metallic iron separated from five lunar soils.

The concentration of metallic iron determined from the magnetism and the chemistry of the highland and mare soils is shown in *Figure 4* vs. magnetic susceptibility. When the apparent magnetic susceptibility is greater than that of the most strongly paramagnetic minerals, nominally 100 μcc/gm, there is little else other than iron to account for the magnetism of the soils (Senftle et al., 1964). The extent to which the points extend upward along the curve depends only on the soil maturity; the more mature, the greater the metallic iron content and consequently, the greater the apparent magnetic susceptibility.

Rocks versus Soils

Measurements are now underway to test the effects of soil maturity on magnetic separation, suggested by our earlier work (Oder, 1991). Fresh samples of immature and mature mare soils and rock samples, taken from the same area, have been procured for testing in this new study, which is still at a preliminary stage. The rocks have been crushed and screened into size fractions similar to those of the soils. The rock and soil size fractions have been subjected to magnetic separation of ilmenite. The gross chemistry and modal analysis by electron microscopy of the magnetic isolates prepared by EXPORTech Company, Inc., are being carried out using the facilities of the Microprobe Laboratory at the Department of Geological Sciences at the University of Tennessee at Knoxville (Taylor, et al., 1992).

Figure 5 compares the MagnetoGraphs for the immature and the mature soils and their associated rocks. The comparison shows graphically that the mature soil is more magnetic than the immature soil; there is also a significant difference in the magnetism of the rocks and their associated soils. Separation of ilmenite from mature mare soil 10084 was not as good as that from the associated rock, 10058. Note that the peak in the MagnetoGraph corresponding to the interval from which ilmenite is to be separated is significantly higher for the rock than for the soil, indicating a larger weight recovery. The MagnetoGraphs for immature soil 71061 and its associated rock, 71055, are similar. The peak near susceptibility 300 μcc/gm represents the minus 20 micron fraction of the soil. This fraction contains the most native iron. The degree of separation of ilmenite is expected to be closer for the immature soil and its associated rock than for the case of the mature soil; here ilmenite separation from the rock is expected to be much better than from the soil. The manner in which the soil maturation process shifts the magnetism of the lunar material and destroys the tendency toward separation of paramagnetic and diamagnetic components is apparent in the figure.

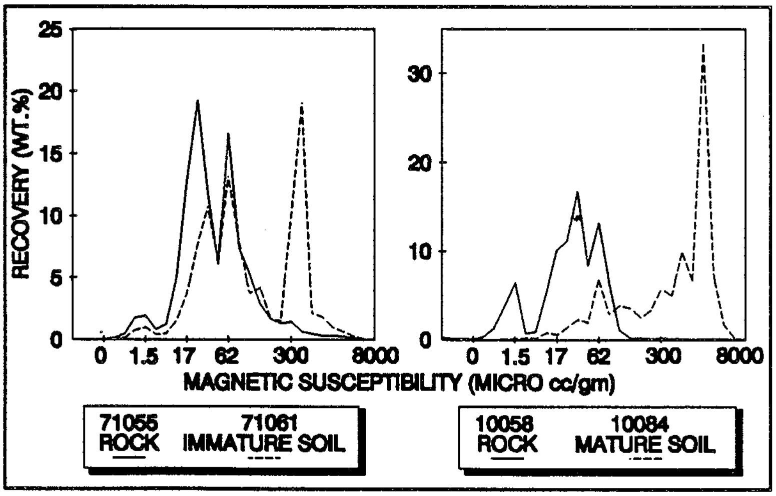

Fig. 5. Comparison of MagnetoGraphs for mare rocks and associated soils.

Magnetic Susceptibility and Soil Maturity: Soil maturity and magnetism are synonymous. The more mature soils are more magnetic. Magnetic susceptibility is a convenient measure of the maturity of the soil (Oder, 1991). The data of Table I summarize our measurements of the magnetic and chemical characteristics of the soils investigated. The values for the maturity parameters, I_s/FeO, have been taken from the Handbook of Lunar Soils (Morris, et al., 1983).

Table I
Magnetic and chemical parameters
for minus 1 mm fraction of lunar soils (Oder, 1991)

Soil	χ (μcc/gm)	Iron Oxide (Wt.%)	Fe^0 (Wt.%)	I_s/FeO
67511	147.5	14.16	0.08	8.8
71061	196	13.84	0.24	14
71501	434	16.54	0.49	35
10084	786	14.15	0.87	78
65701	433	4.9	1.55	106

The ratio of apparent magnetic susceptibility to iron oxide content is plotted against the maturity parameter in *Figure 6*. Magnetic susceptibility and FeO are each directly measured. No chemical, image analysis, or magnetic interpretations are employed. The excellent correlation between the susceptibility and conventional maturity parameters suggests that the magnetic susceptibility is a good indicator of soil maturity.

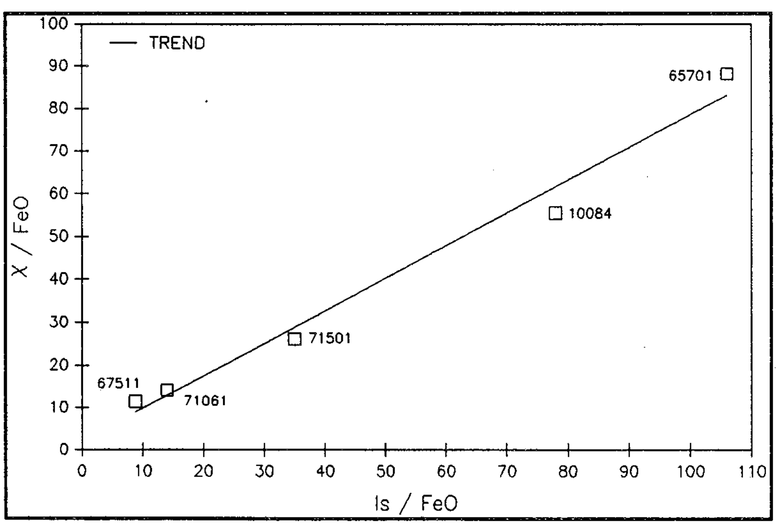

Fig. 6. Comparison of soil maturities inferred by magnetic susceptibility and by magnetic resonance.

SUMMARY

- We have separated feebly magnetic material from the highland soils. This material can serve as a source of anorthite for manufacture of cement and recovery of metals and oxygen by electrolysis.

- We have separated intermediate magnetic susceptibility material from hi-titanium mare basalts; this material can serve as a source of ilmenite for oxygen production by chemical reduction. We have also separated intermediate magnetic susceptibility material from the associated mare soils but achieved a lesser grade and yield.

- We have separated metallic iron from all soils.

- The lowest maturity soils are the best candidates for beneficiation by magnetic separation.

- The magnetism of lunar soils increases with maturity because of the inclusion of disseminated metallic iron which is concentrated in the finest size and highest susceptibility fractions.

- Magnetic susceptibility is a convenient measure of soil maturity and should be incorporated into the instrumentation package carried by lunar rovers to identify candidate soils for resource utilization. Generally speaking, instrumentation to measure magnetic susceptibility is less expensive and more widely available than that used to measure magnetic resonance.

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