Magnetism of Lunar Soils

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I. Introduction

The lunar regolith contains lithic, mineral, and fused soil fractions which can serve as sources of important materials including gases, refractories, and metals for use in space. Gaseous hydrogen and oxygen are first on the list of priority materials. Lunar hydrogen will be used for manufacture of water and as a local reconnaissance fuel. Lunar oxygen will be used for breathing and eventually as a fuel for long range space travel. One day, metals and refractories will be used for space construction and manufacture. Realization of the advantages of using indigenous resources will require mining, minerals preparation and beneficiation, and physicochemical processing to extract the important components such as gases from lunar materials. Dry magnetic separation is a viable method for extracting feedstocks from 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.

II. Sources of Oxygen and Hydrogen in Lunar Soils

Oxygen is part of the elemental structure of minerals such as anorthite, $CaAl_2Si_2O_8$, and ilmenite, $FeTio_3$, found in lunar rocks. These minerals can also be found to some degree in the lunar soil which was made from the rocks by impacts of meteorites occurring over geological time spans. In addition to pulverizing the rocks, the micrometeorite impacts release heat which melts the rock fragments and welds them together again in complex glassy fused soil components which are also rich in oxygen. Oxygen is a major constituent of all lunar soils.

Hydrogen is continually being implanted in the lunar soil by influx of light gases contained in the solar wind streaming from the sun. These gases tend to adsorb preferentially on the surfaces of ilmenite which was liberated in the process of soil generation. The gas can

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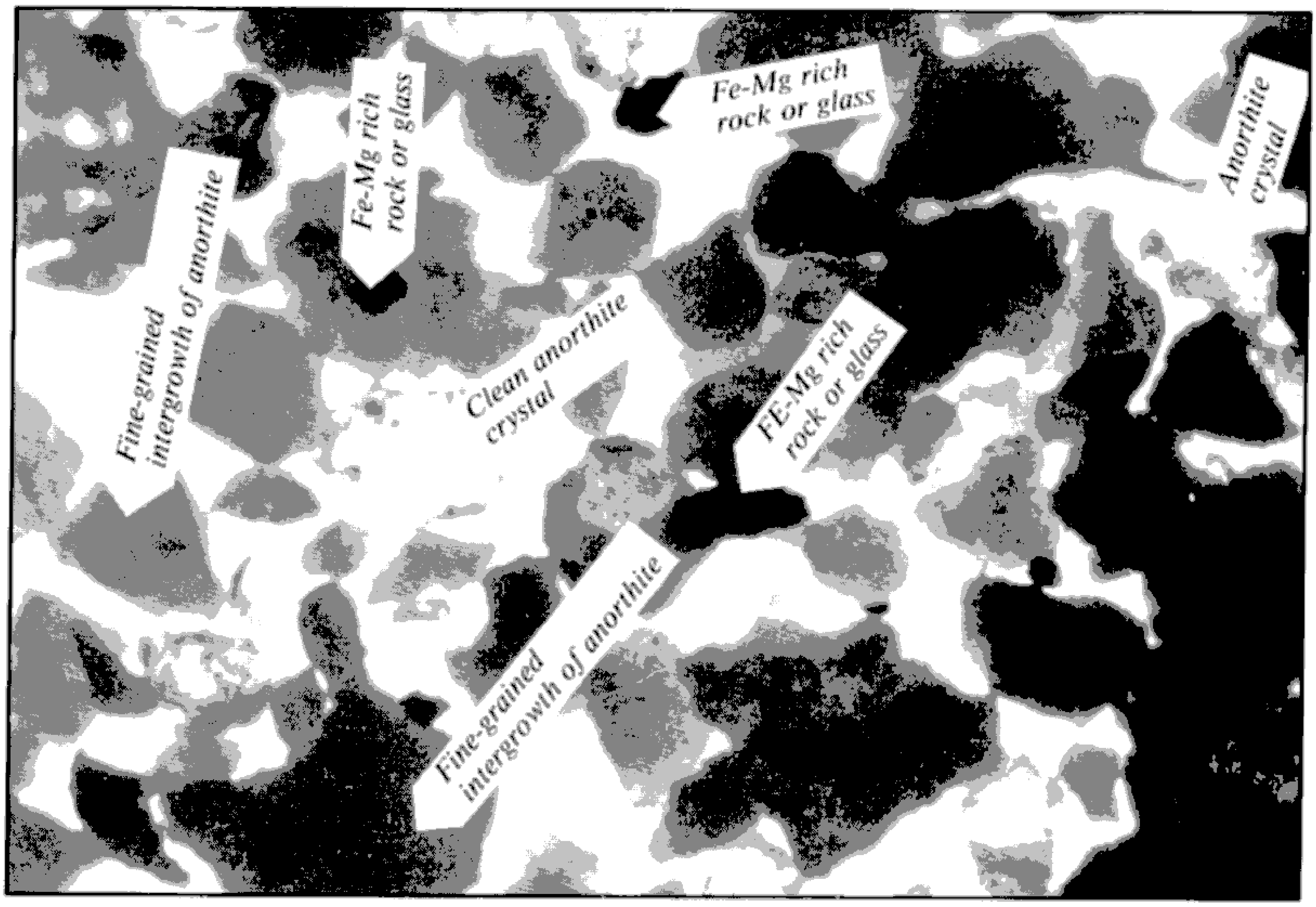

Photograph of 75 x 150 µm fraction of Lunar Soil Sample 64421.31, a very mature highland anorthositic soil, showing rocks and glasses.

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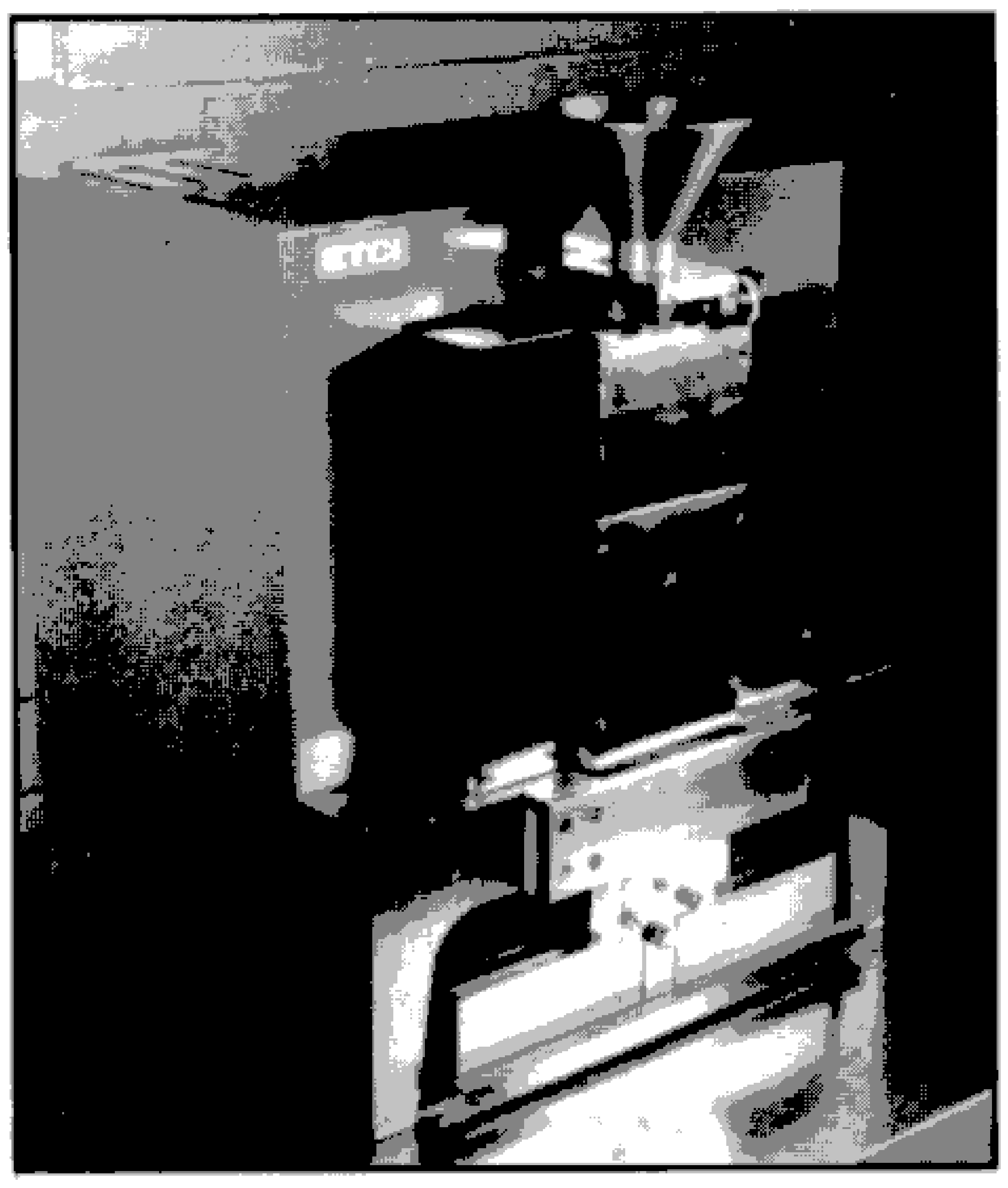
be released by heating. Indeed, the adsorbed hydrogen has played a role in creation of metallic "native" iron also found in the lunar soil. Driven by the heat of impact, the hydrogen reduces meteoric iron oxides to produce microcrystalline iron, Fe°, which is found in strongly magnetic vesicular glass components called agglutinates. They are unique to the surface of the Moon. Hydrogen is a minor constituent of lunar soils.

Long periods of exposure to the solar wind and to impacts by micrometeorites create mature soils which are fine in size and which concentrate gases such as hydrogen. At this time it is believed that extraction of hydrogen and oxygen from the soil rather than from rocks will prove to be more practical because heavy machinery for crushing and grinding operations will not be required to liberate the rock components.



ETCi ParaTrap Magnetic Separator (U.S. Patents 5,017,283 and 5,127,586)

III. Magnetic Separation of Lunar Soil Samples

Most lunar 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 up to 100 μcc/gm. Fe^{3+} is nonexistent on the moon 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°, native iron) found in the vesicular glassy agglutinates, splash glasses, melt rocks, and other fused soil product of the energetic micrometeorite impacts.

In recent laboratory work, diamagnetic anorthite, χ = -0.39 μcc/gm, paramagnetic ilmenite, $\chi \cong 60$ μcc/gm, and ferromagnetic glass-encased metallic iron, apparent susceptibility $\chi_a > 130$ μcc/gm, have been separated from the <1mm size fraction of eight different lunar soils and associated rocks taken from crater rims and mare basins. The samples were furnished by the Lunar and Planetary Sample Team (LAPST). Support for the work was furnished in part by NASA through its Small Business Innovation Research (SBIR) program. Conceptual designs for magnetic separators based on these results indicate that application of magnetic separation technology to processing of lunar soils is feasible.

This work, however, has shown that processing lunar soils will not be without its own problems. While exposure to the solar wind implants hydrogen in the soil, simultaneously, this exposure also brings micrometeorite impacts which destroy the identity and separability of individual soil components such as ilmenite. Soil components which have lost their identities will not be good candidates for separation by any method. A compromise will be required between choosing mature soils for production of hydrogen on the one hand and choosing less mature soils for production of oxygen on the other. Assessments of both chemistry and soil maturity will be vitally important in the first robotic missions to prospect the lunar surface.

IV. Effects of Lunar Soil Maturity

Magnetic separation of lunar soil is strongly affected by the maturity of the soil. Our work has shown that the distribution by weight of the lunar soil recovered in different magnetic susceptibility intervals is significantly affected by soil maturity. This is illustrated in the MagnetoGraphs of Figure 1 for two size fractions of anorthositic highland soils of widely differing maturities. The maturity of a soil is measured scientifically by the ratio of single-domain iron concentration, I$_s$ (as determined by Ferromagnetic Resonance (FMR) divided by the ferrous iron oxide composition, FeO,—I$_s$/FeO. The higher the value of the ratio, the greater the maturity. The highland soils have I$_s$/FeO values of 8.8 and 106 respectively. The MagnetoGraphs show the percentage of the total sample weight which is recovered in the magnetic susceptibility intervals in which the separations were made.

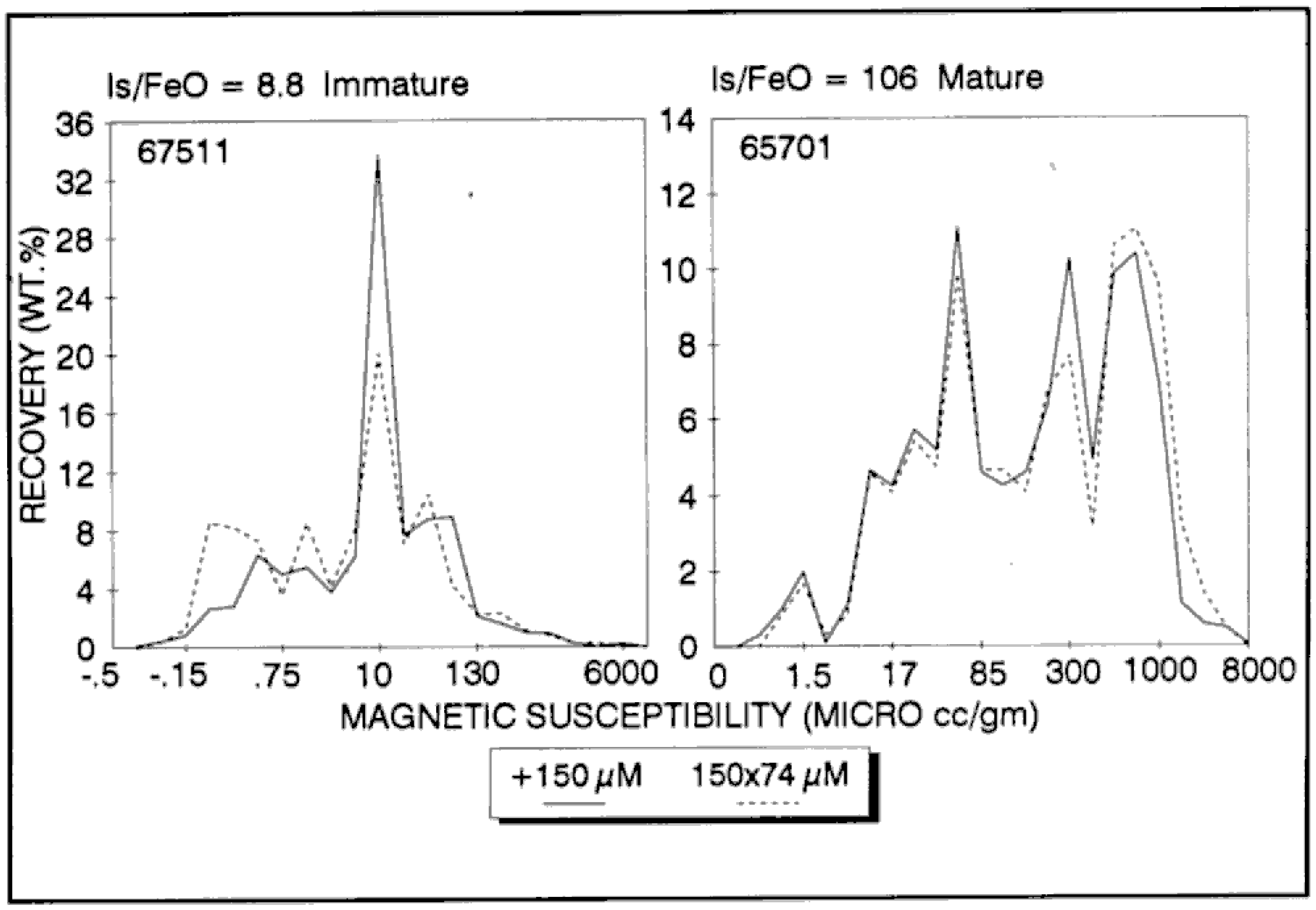


Fig. 1. MagnetoGraphs for two size fractions of anorthositic lunar highland soils 67511 and 65701.

Because the breadth of the distribution shown in Figure 1 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. Soil maturity and soil magnetism are synonymous.

As a general rule, soils of lowest maturity are the best candidates for magnetic separation for lithic and mineral soil fractions ranging from diamagnetic alumino-silicates to paramagnetic iron oxides such as ilmenite or pyroxene. Soils of high maturity, however, are the best candidates for separation of strongly magnetic fused soil components which are the best sources for production of hydrogen and metallic iron.

V. Magnetic Susceptibility and Soil Maturity

Soil maturity and magnetism are synonymous. The more mature soils are more magnetic and magnetic susceptibility is a convenient measure of the maturity of the soil. Our measurement of soil maturity, as given by the ratio of magnetic susceptibility to ferrous iron content, is plotted vs. the maturity parameter in Figure 2. The values for the maturity parameter, I$_s$/FeO, have been taken from the *Handbook of Lunar Soils* (Morris, et al., 1983). Magnetic susceptibility and FeO are each directly measured. No chemical, image analysis, or magnetic interpretations are employed. The excellent correlation between

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the susceptibility and conventional maturity parameters confirms that the magnetic susceptibility is a good indicator of soil maturity. The significance of this observation lies in the simplicity and effectiveness of measurement of the magnetic susceptibility compared to measurements of FMR.

CONCLUSIONS

NASA's newly re-established Office of Exploration is planning several small, robotic missions to the Moon within the next three years to begin the Space Exploration Initiative, the nation's program to return to the Moon and journey to Mars. Some of these missions will be directed at acquiring knowledge about the distribution of lunar resources and the detailed characteristics of the surface at proposed human outpost sites. These goals move resource assessment to the forefront. As part of this strategy, NASA's Artemis program to design a common lunar lander offers an opportunity for deployment of innovative, simple, and feasible instrumentation packages for assessing the potential for processing lunar soils.

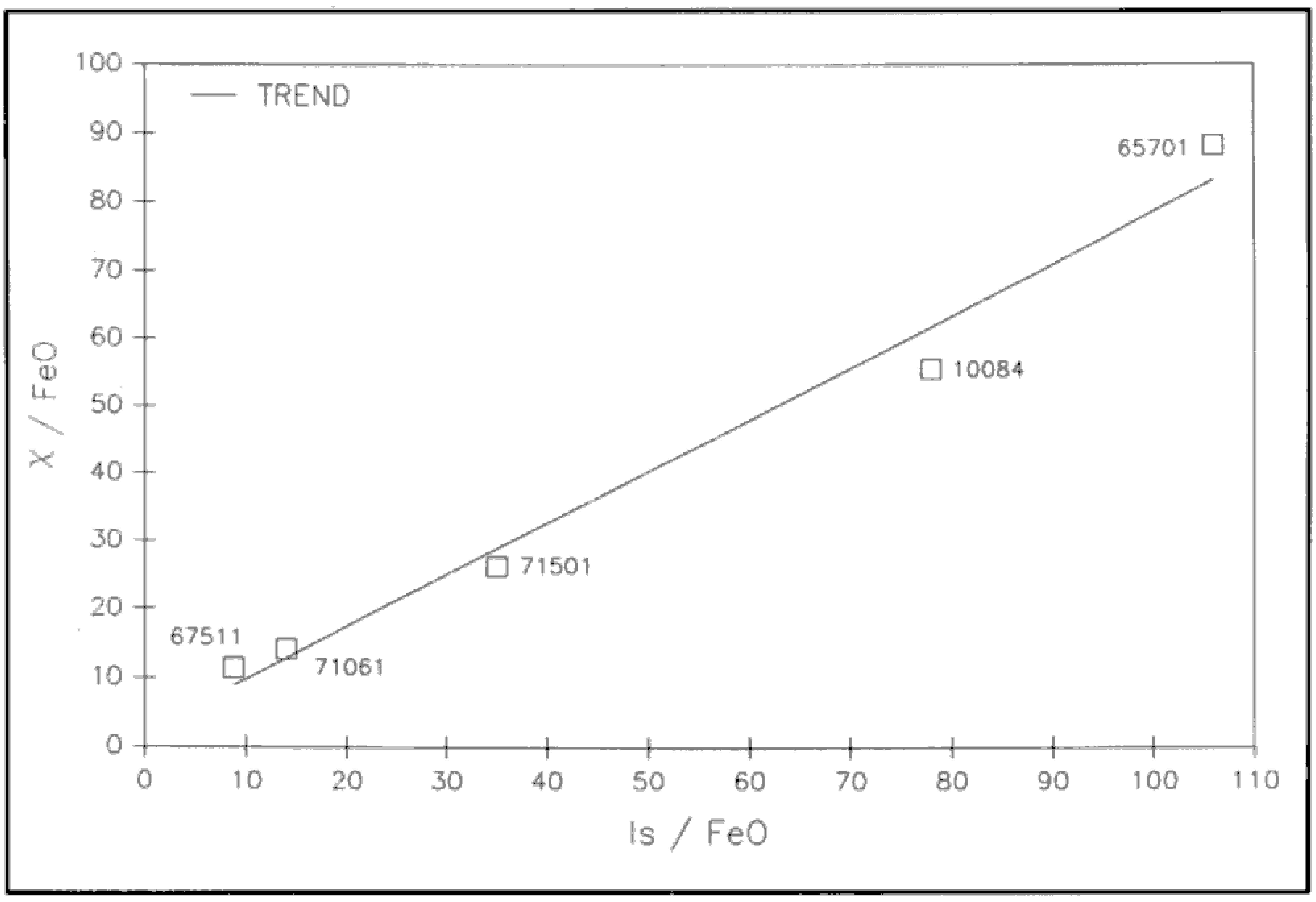

Fig. 2. Comparison of soil maturities inferred by magnetic susceptibility and by ferromagnetic resonance.

Before the surveillance missions begin, there is a need to test the response of lunar soils to a variety of beneficiation techniques, such as has been done with magnetic separation. NASA's existing library of lunar samples brought back during the earlier Apollo missions and administered by LAPST should be opened and used for this test work. This will give us a base of knowledge with which to judge the viability of proposed future human outpost sites on the moon. We must also begin to develop practical instrumentation for use in the robotic prospecting missions of the next few years. NASA's planning calls for a series of missions of both orbital and landed payloads. The surface rover missions will be designed for surveying the lunar surface for identification of sites for future outposts and for testing of innovative process packages which meet the criteria for simplicity and feasibility.

We believe that magnetic susceptibility should be incorporated into the first rover instrumentation packages to identify candidate soils for resource utilization. Techniques such as Mossbauer spectroscopy have been proposed because the method is sensitive to iron oxidation states. Ultimately this information will be very important, but the cost of obtaining it now at this early stage of exploration may be prohibitive. For the first attempt, the goals of simplicity and feasibility suggest that magnetic susceptibility is a better choice. In addition, the rate at which information on the magnetism, and hence the maturity, of lunar soils can be returned to Earth is more than two orders of magnitude greater for susceptibility measurements than for gamma-ray spectrometric methods. That could prove to be vitally important for these first exploratory missions!

SUGGESTED READING

R.R. Oder and L.A. Taylor, "Magnetic Beneficiation of Highland and HI-Ti Mare Soils: Magnet Requirements," *Engineering, Construction and Operations in Space II, Proceedings of Space 90,* Albuquerque (April, 1990), Edited by S.W. Johnson and J.P. Wetzel (American Society of Civil Engineers, New York, 1990) pp. 133-142.

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R.R. Oder, "Beneficiation of Lunar Soils: Case Studies in Magnetics," Preprint 91-137, AIME-SME Annual Meeting, Denver, CO (February 25-28, 1991); to be published in *Journal of Minerals and Metallurgical Processing* (August, 1992). ■