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EVALUATION OF THE REGOLITH OF MARE TRANQUILLITATIS AS A SOURCE OF VOLATILE ELEMENTS

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Technical Report

Wisconsin Center for
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Introduction

Lunar regoliths are recognized as potential sources of a group of volatile elements, of which the most important are H_2, N_2, CO, CO_2, He-4, He-3, and S. The first four are essential to life support on the Moon. H_2 has a double importance. It is necessary for the production of water, and it could also be used as a component of rocket fuel. He-3 is a potential source of energy to be produced on Earth by nuclear fusion. Sulfur is not currently of interest but might ultimately become useful if production of industrial chemicals on the Moon should become desirable. The volatiles listed are present in all regoliths sampled by the Apollo and Luna missions, both highland and mare regoliths, but study of volatiles in lunar regolith at the University of Wisconsin is currently focused on the regolith of Mare Tranquillitatis owing to its vast extent, its accessibility, topography more favorable to mining than that of highland areas, and the presence of large areas of high-TiO_2 regolith that should be enriched in He-3. However, the only direct information on the volatile contents of the regolith is that obtained from samples returned from the Apollo 11 mission, and there is an obvious need for systematic exploration of the mare to ascertain its true potential as a source of various volatile elements. A suggested program of exploration is the subject of this report. It is based on my studies of the geology and helium resources of Mare Tranquillitatis (Cameron, 1990, 1992).

Concentrations of Various Volatiles in Apollo 11 Regolith

Concentrations of important volatile elements in Apollo 11 regolith as indicated by analyses of various samples of regolith fines are given in Table 1. Hydrogen, helium, carbon, and nitrogen are derived mainly or entirely from the solar wind. Sulfur is derived at least mainly from sulfides in regolith particles. It is now established that concentrations of solar wind gases in regoliths are a function of maturity, which in turn is a function of length of exposure to the solar wind. It is also established that the helium content of

Table 1

Volatile Elements in Apollo 11 Regolith

(Lunar Sourcebook)

Element	Wt. ppm*
H	60
C	154
N	78
He	46
S	1240
*Average values	

regolith is a function of the ilmenite content, hence in general to the TiO_2 content. Bustin and Gibson (1992) conclude that the hydrogen content is also related to the TiO_2 content, but this is not clear from the data presented in their Table 1. Sample 75261, mature regolith from Apollo 17 containing 9-10% TiO_2, is reported to contain 60.2 wppm H. However, sample 15261, with only 1.50% TiO_2, is reported to contain 58.2 wppm H. The data of their table suggest that H content of regolith is far more a function of maturity than of TiO_2 content.

Release of various gases from Apollo 11 fines on heating has been studied by Gibson and Johnson (1971). Solar wind helium is almost entirely released between 300° and 700°C, along with most of the hydrogen. The ratio of H to He in regolith (7-7.5) is lower than the ratio in the solar wind (17), possibly due to diffusion of H_2 from the samples.

At temperatures below 500°C, CO_2 is the major C-containing gaseous phase. Its source is uncertain. CO_2 is further released at 675°C and 1125°C, and again above 1200°C. At temperatures above 700°C the principal gaseous phase released is mass 28, CO and/or N_2. The CO is believed derived by reaction of C-containing phases, such as cohenite [(Fe, Ni)3C], with silicates.

Sulfur is released as H_2S and SO_2. Evolution of the two gases begins above 900°C, which means that they will not be present during heating of the soil for release of hydrogen and helium. Most of the sulfur is evolved above 1,000°C.

As indicated in my previous report, various studies have shown that the solar wind gases are heavily concentrated in the finer size fractions of the regolith, since implantation of the gases is a surface phenomenon and is therefore proportional to particle surface area per unit of mass. This must be taken into account in devising and testing methods of processing the regolith on the Moon.

Objectives of an Exploration Program

Three categories of information must be sought by exploration of the regolith of Mare Tranquillitatis, as follows:

A. For delineation of physically minable areas:

(1) Detailed topographic information.

(2) The distribution of unminable craters and other unminable features.

(3) The distribution of ejecta containing blocks of rock too large to be handled by the mining system or systems selected.

B. For estimation of tonnage and grade of minable regolith:

(1) Thickness of regolith in minable areas.

(2) Contents of various gases.

C. For determining percentages of the gases recoverable:

(1) Applicability of particular mining systems.

(2) Applicability of systems of sizing and beneficiation.

(3) Results of heat processing of regolith: recovery percentages.

Methods of Exploration Available

Methods of exploration available are of two general kinds: (1) remote sensing and (2) methods requiring activities on the surface of the Moon. Remote sensing applicable to exploration for regolith gases includes high-resolution photography, gamma-ray spectroscopy, and reflectance ratio mapping from Earth or from lunar orbiters. Remote radar scanning may assist in delineating areas free of surface boulders. In general the function of remote sensing is to aid in selecting physically minable areas and areas of regolith that are high in TiO_2 and therefore likely to be enriched in helium. Remote sensing is invaluable in indicating surface characteristics of regoliths, but it will not yield information on the internal structure of regolith or on subsurface variations in contents of gases.

Surface exploration methods available are seismic surveying, ground radar surveying, detailed topographic mapping, trenching, core drilling, sample retrieval and analysis, and pilot testing of mining, beneficiation, and processing systems.

Plan of Exploration

Nature of the Exploration Problem

As a mineral deposit, the mare regolith has no counterpart in terrestrial mineral deposits, and any plan for exploring it must be adapted to its peculiar characteristics. The first of these is the structure of the regolith. The fundamental structural unit of regolith is the ejecta blanket, the material thrown out of a crater created by the impact of a body striking the surface of the Moon. In plan, each ejecta blanket was originally doughnut-shaped, the hole in the doughnut being occupied by the crater formed at the point of impact. In vertical section, each ejecta blanket had maximum thickness adjacent to the crater rim and was progressively thinner with distance from the rim. However, ejecta blankets range from very old to very young, and all older blankets have undoubtedly been disrupted, to varying degrees, by later impacts. Lateral continuity of blankets, except for the larger, youngest blankets, over substantial areas is hardly to be expected. Thus, although the regolith is layered, there will be only a very imperfect “stratigraphy” to use as a control on exploration.

The second characteristic that must be taken into account is the relation between contents of solar wind gases and length of exposure of the regolith to the solar wind as expressed in the “maturity” of the regolith. Exposure time may vary from layer to layer, hence surface scanning will not indicate gas contents in depth.

A final consideration in planning exploration is the possible scale of mining and processing operations. This will depend on what gases are sought. If only gases for life support and fuel are sought, the regolith mined annually is likely to be measured only in hundreds of thousands of tons per year. However, if mining for He-3 is undertaken, the scale of operations will be vastly enlarged. For example, if the scenario suggested by Sviatoslavsky and Jacobs (1988) is followed, mining would begin in 2015, and by 2050 production of He-3 would rise to 53.5 tonnes per year. The required rate of mining would then be about 7.6 billion tons of regolith per year, achieved by excavating regolith to a depth of 3 m over an area of about 1275 sq. km. Total area mined through 2050 would be about 14,000 sq. km. These figures are decidedly preliminary, but they indicate that establishing a reserve base for helium mining would require advance exploration on a scale not matched in any single mining enterprise on Earth.

Site Selection

On the assumption that mining for helium as well as other gases will eventually be undertaken, the first target of exploration should be an area in the western part of Tranquillitatis shown by reflectance ratio mapping to be covered by regolith with a high

TiO_2 content. An area 25 km square centered at 20° E. 9° N. looks attractive as an initial mining site. The spectral ratio map of Johnson and others (1991) shows this area as occupied by regolith containing 7% to 10% TiO_2, and the geologic map of the Julius Caesar quadrangle (Morris and Wilhelms, 1967) shows it to be free of major craters and other major obstacles to mining.

Delineation of Areas of Minable Regolith

The first step in exploration should be high-resolution photography of the target area, from a lunar orbiter. Study of high-resolution photographs of the Apollo 11 and Ranger VIII areas indicates that by far the most abundant and widely distributed obstacles to mining are craters and their ejecta halos, but that from place to place on the mare there is much variation in their number, distribution, distinctness, diameter, and depth. Figure 1 is a reduced photograph of a part of Mare Tranquillitatis that is typical of much of the area east and northeast of the Apollo 11 landing site. The largest crater is about 490 m in diameter. At least 50% of this area will be minable (see Cameron, 1992). In marked contrast is Fig. 2, which shows part of the heavily cratered belt that crosses the Ranger VIII landing area. Besides the largest craters completely shown, 600-1,000 m in diameter, there are numerous craters 100 to more than 300 m in diameter. Much of this area will be unminable by large excavating machines.

Despite the wide range in crater characteristics, such photographs can be used to classify various portions of the target areas roughly into the following types:

(1) Areas occupied by young craters large enough (hence deep enough) to have penetrated bedrock. Halos of ejecta containing blocks of rock 2 m or more in diameter accompany many of the larger craters of this group. These areas presumably will be unminable, at least in large part.

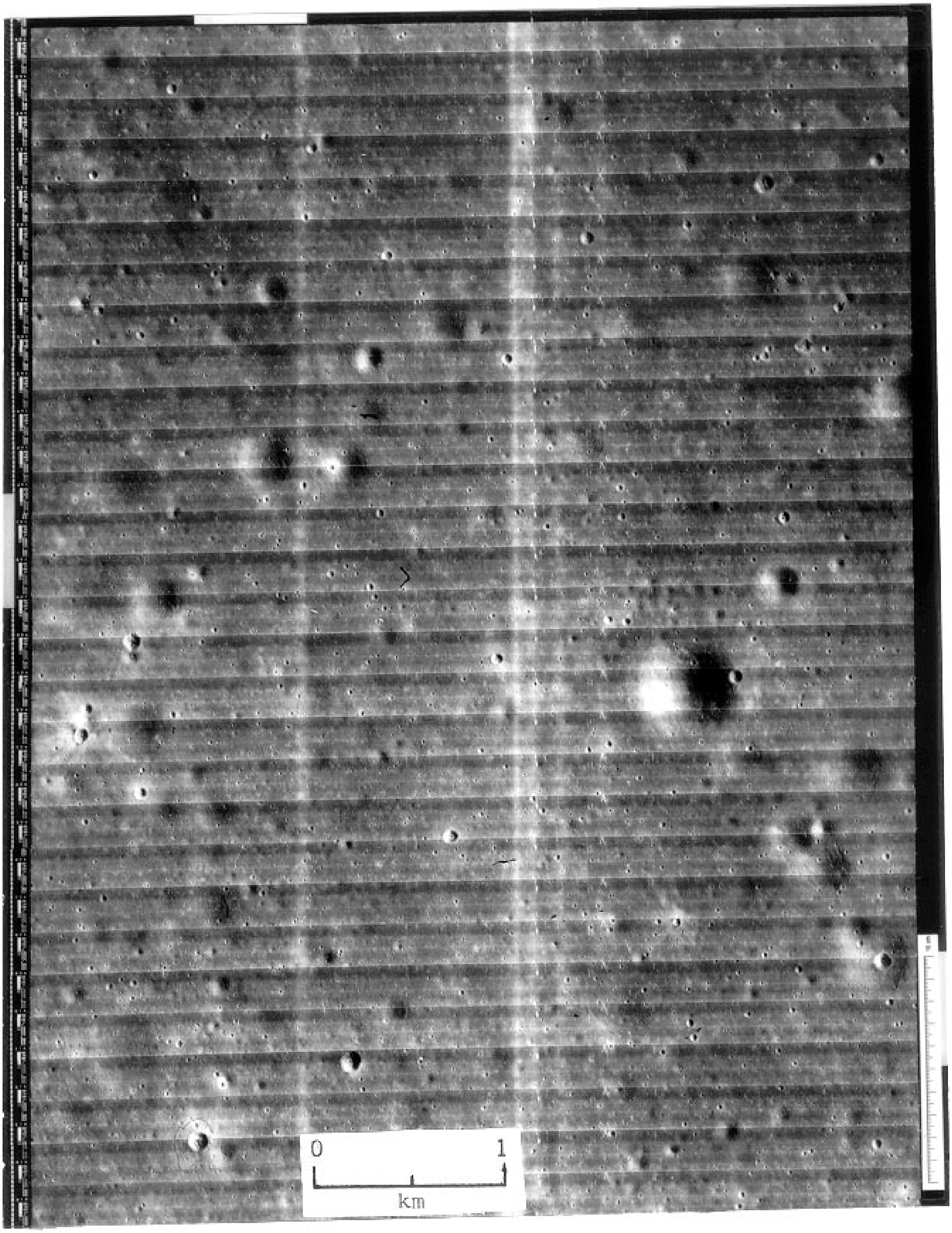

Figure 1. Lunar orbiter print II-84-H_3, reduced from original size of 39 × 53 cm.

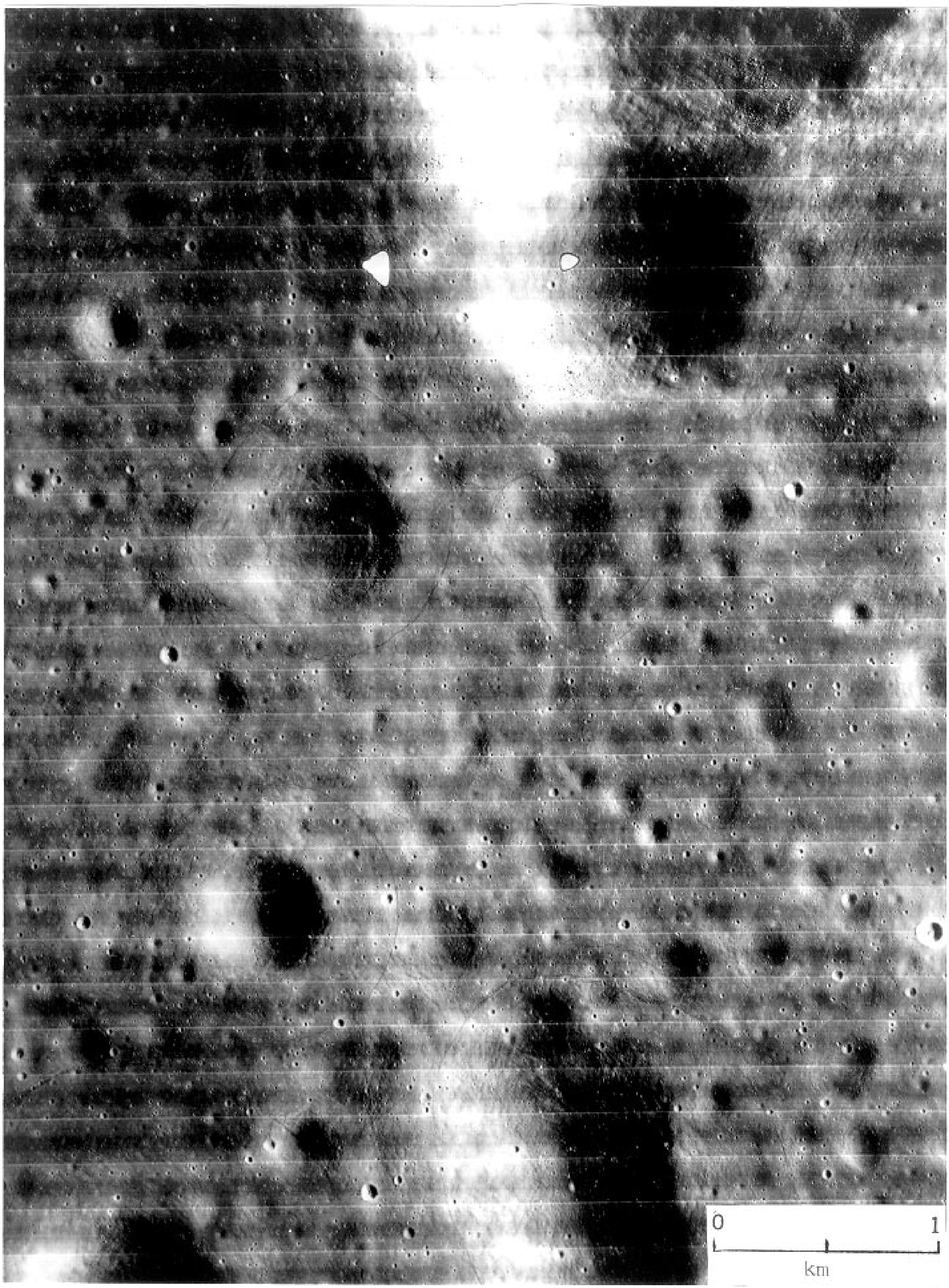

Figure 2. Lunar orbiter print II-71-H_2, reduced from original size of 39 × 53 cm.

(2) Areas occupied by very old craters large enough to have penetrated bedrock but now in advanced stages of obliteration by slumping and later impacts. These areas will have undulating topography that should present no obstacles to mining and should be covered by regolith in excess of 3 m in depth. No ejecta blocks with diameters in excess of 2 m in diameter (2 m is the limit of resolution of the photographs) are visible in or around them.

(3) Areas with craters of intermediate age that are large enough (18 m or more in diameter) to have penetrated bedrock but show no ejecta blocks. These craters are deeper (for a given diameter) and more distinct than craters in areas of type 2, but less so than craters in areas of type 1. However, they contain no ejecta blocks and have no ejecta blocks 2 m or more in diameter around their rims. The larger, deeper ones will probably prove to be unminable, but areas having only smaller craters may prove minable.

Areas of type 2 will obviously be most favorable to mining. However, in all such areas there are small younger craters superimposed on the older craters, and actual minable portions of areas of type 2 will depend on the size and distribution of the younger craters, especially those deep enough to have penetrated bedrock (see Cameron, 1992).

The 2 m resolution limit of the photographs of the Apollo 11 and Ranger VIII areas sets a limit on their usefulness in delineating minable areas. Higher-resolution photography would alleviate this problem. The other limitation of photographs, of course, is that they do not indicate the distribution of blocks in older, buried ejecta blankets, nor do they furnish positive information on variations in depth of regolith. Nonetheless, it seems clear that high-resolution photographs can serve an important function in exploration of the mare regolith, making it possible to eliminate much ground that is physically not amenable to mining. Their usefulness will increase as interpretation of their features is checked against ground truth.

Stage 2 - Exploration on Surface to Determine Tonnage and Grade

The first objective of on-surface exploration should be the more accurate delineation of minable regolith in terms of depth of regolith and freedom from blocks too large to be handled by the mining system selected. Drilling and trenching could do this but could involve a program of prohibitive magnitude and cost. Some method of rapid coverage of large areas of regolith is desirable. The only two methods of which I am aware are seismic surveying and radar scanning from a mobile vehicle.

Seismic methods were used by Nakamura and others (1975) to determine depth of regolith at the Apollo 11, 12, 14, 15, and 16 landing sites. They concluded that the lunar surface is covered by a low-velocity layer of material ranging from 3.2 to 12.2 m in depth. At the base of the regolith there was a sharp increase in P-wave velocity from 100 m/sec to 250-400 m/sec. Results of Cooper and others (1974) for the Apollo 14, 16, and 17 sites are similar. The seismic method would yield much information on depth of regolith but would not give continuous profiles necessary to detect blocks.

The second method is downward-looking radar scanning from a mobile vehicle. Use of radar would be favored by the sharp change in velocity at the base of bedrock (and presumably at the top of a block of rock) and by the dryness of the regolith. Radar scanning would give a continuous profile across an area along the line of traverse. Blocks of rock would give bumps on the profile. It would be far faster and far cheaper than seismic surveying and would give information of much better quality.

The work outlined above should provide the basis for firm estimates of tonnage of minable regolith in the portions of Mare Tranquillitatis investigated. However, grade in terms of contents of various gases can only be determined by sampling to whatever depth of mining is planned. Core drilling will be the preferred method of sampling. A choice will have to be made between onsite analysis of cores and transmittal of core to a base site for removal of cores and analysis. The latter would seem to offer advantages in uniform handling of core and recovery of gases. The pattern of drillholes will in general be that used in terrestrial mineral exploration of deposits that are so poorly exposed and internally unpredictable as to offer no guides to drill hole location. In such cases, drillholes on a grid pattern or equally spaced along equidistant parallel lines are generally used. Statistical methods are used in evaluating the results in terms of overall grade. Spacing of holes is ultimately dictated by the nature and scale of variation in grade as indicated in the earlier stages of exploration.

The depth of drillholes will be dictated by the depth of regolith and the depth to which regolith can be excavated with the mining system ultimately adopted. My estimate of helium resources in minable regolith in Mare Tranquillitatis is based on an average mining depth of 3 m, but this is probably a minimum. Drilling to depths of 4 m is probably a realistic goal for present planning.

Trenching is always an alternative to drilling as a means of exploring unconsolidated surficial materials. Trenching could yield either large bulk samples or channel samples from the walls of trenches. Either procedure, however, would be more cumbersome and more time-consuming than drilling.

Stage 3 – Determining Percentages of Gases Recoverable from Regolith

In most mining operations the amounts of valuable mineral or minerals actually recovered per unit of material mined and processed are less than the amounts originally present, and mining for the volatile elements on the Moon will certainly be no exception. There is some concern that portions of the volatile elements may be lost during excavation and other physical handling. There will be losses during heat treatment of the regolith to release the volatiles and in the processes for recovery of gases. No final evaluation of the potential of the regolith as a source of volatiles can be made until probable losses can be estimated with reasonable precision. Neither mining nor processing procedures can be satisfactorily evaluated on the basis of experiments on Earth. It will be necessary to establish pilot-scale operations on the Moon. Mining systems can then be tested against regolith material under the severe conditions of the lunar environment. Processing methods can then be tested with large bulk samples, again under actual lunar conditions.

Exploration Beyond Tranquillitatis

If lunar mining for helium is undertaken, the other maria and portions of maria indicated by reflectance mapping to be covered by regoliths relatively high in TiO_2 will ultimately command attention. The first step should be to calibrate reflectance ratio maps against the spectral ratios of actual samples taken from various regoliths.

Exploration Under the Space Exploration Initiative

The Space Exploration Initiative (SEI) of NASA has three phases related to the Moon: (1) the Lunar Orbiter Missions; (2) the Common Lunar Lander program (CCL), and the First Lunar Outpost program (FLO). The program of the SEI is outlined in the NASA publication entitled "3rd Technical Interchange Proceedings" (610 pp.), which covers the meeting of May 5 and 6, 1992. Except as noted below, all references below are to that volume. The "Proceedings" are actually the sets of viewgraphs presented by the various speakers on the program. As such they give illustrated outlines of the talks, not the full texts. Nor do they give any modifications of the program that may have resulted from discussions at or subsequent to the meeting.

The Lunar Orbiter Missions should yield further information on the distribution of high-TiO_2 regolith on the whole Moon, through gamma-ray spectroscopy. The value of the gamma-ray spectroscopy will depend on how much this technique has been improved in both resolution and accuracy over the original partial survey of the Moon [see Metzger and Parker (1980)]. Orbiter equipment will include soft x-ray, neutron, and imaging spectrometers. The purpose is stated to be to provide a detailed geochemical and mineralogical map of the Moon. Global stereoimaging to aid in site selection is also given as a function of the mission.

The CCL program will consist of a series of Apollo-type missions, mostly robotic. The mission of particular interest here is entitled "Outpost Site Survey and Resource Assessment" (pp. 53-58). This will involve the use of rovers. It will include preparation of large-scale topographic maps (high-resolution stereoimaging), rover traverses to map surface soil properties, block distribution and lateral variability, and study of hydrogen abundance.

The site selected is in Mare Tranquillitatis "near 15° N. 22° E." This point is on the boundary between mare material and the ejecta blanket of the huge (45 km diameter) crater Plinius, on the east margin of a 25-40 km-wide band of material separating the ejecta blanket from highlands to the west. This is not a good site for study of volatile elements in the mare. Reflectance ratio mapping by Johnson and others (1991) shows regolith of only 3-5% TiO_2, hence helium content should be low. As suggested above, a much better site would be an area at 9° N. 20° E. This area is indicated by Johnson and others (1991) to have regolith with 7-10+% TiO_2.

Vertical distribution of hydrogen is to be inferred by measuring its concentration in the ejecta of fresh, small craters (20-50 m in diameter). I do not understand this. It would seem to rest on the dubious assumption that H content of regolith is not affected by impacts. The full capabilities of the mission for sample recovery and analysis are not indicated in the publication. No mention is made of volatiles other than hydrogen, but it should be possible to include analyses for the other gases within the scope of the program.

The chief opportunities for systematic exploration of regolith as a source of volatiles would appear to be in the FLO missions, scheduled to begin in 1999. These missions would be fully equipped for photography and for soil sampling and analysis. The DEMO package (pp. 100,101) includes experimental units for oxygen extraction, for testing gas-solid transport, and for testing pneumatic size-sorting methods. Activities include regolith sampling and analysis. Radar scanning equipment is not mentioned, but presumably it could be added.

For establishment of the First Lunar Outpost (FLO) two possible sites are mentioned: (1) Mare Smythii, which has an equatorial position straddling the eastern terminator of the nearside of the Moon, and (2) the Aristarchus Plateau at 23° N. 48° W. The rationale for a FLO on Mare Smythii is given by Spudis and Hood (1992). Based on remote sensing by the Apollo 15 and 16 spacecraft, the mare regolith is taken to have 4 to 6% TiO_2. If this is correct, the He content could be in the 20-30 wppm He. This would not be as desirable a source of He as the regolith of Mare Tranquillitatis, but it could serve for purposes of testing methods of beneficiating and processing regolith for He and other gases. The regolith of the site on the Aristarchus Plateau is shown on the map by Johnson and others (1991) as having only 3-4% TiO_2, hence this site is ostensibly less desirable than the Mare Smythii site.

To sum up, the CCL and FLO programs do not have exploration of regoliths for volatile elements as a primary concern. However, the development of a systematic exploration program for volatiles appears well within the capabilities of the missions.

Acknowledgment

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