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THE REGOLITH AS A SOURCE OF MATERIALS. G. Heiken, Los Alamos Scientific Laboratory, Los Alamos, NM, 87545 and D. S. McKay, TN6, NASA Johnson Space Center, Houston, TX, 77058.

It has been proposed that the lunar regolith be used as a source of raw materials for lunar colonies and space colonization (1,2,3). With this in mind, a brief review of some basic facts concerning the properties of lunar soils was prepared for this meeting. The O'Neill concept (1,2) places quarrying operations on the lunar farside; with this in mind, we will cover the general characteristics of nearside highlands and mare regoliths and compare them with what we may find on the farside.

Regolith is the layer of unconsolidated debris, overlying bedrock, which covers most of the Moon's surface (4). Nearly all lunar investigators have concluded that this debris was formed mainly by impact-cratering processes (5,6). The presence of shock-metamorphosed rocks and minerals, micro-craters on particle surfaces and impact-generated melt within the soil supports this interpretation.

Turkevich (7) has determined "average" soil compositions of mare and highlands regoliths, based on analytical data from Apollo, Surveyor, and Luna landing sites and orbital measurements (Table 1). These compositions are greatly simplified, but representative of the two settings. Soils of the highland regions have been derived mainly from anorthositic rocks and the complex breccias and impact melt rocks developed during the early, large-scale cratering events. In bulk, the soils are rich in Ca and Al relative to the regoliths developed on mare surfaces. Soils from mare regoliths consist of mostly lithic, mineral and glass fragments formed by the comminution of Fe- and Ti-rich basaltic lava flows. Regolith soils are composed mostly of locally-derived particles, with only minor contributions from craters in distant provinces and meteorites.

The most ubiquitous component of all lunar soils which have been characterized is the agglutinate, which consists of lithic, mineral and glass fragments bonded by glass droplets. The irregular dark brown to black particles are heterogeneous and are crossed by bands of iron droplets 20 Å to 10 µm in diameter. The amount of Fe° in agglutinates ranges from 0.1 to 1.7 wt.% (8). Due to the presence of Fe°, agglutinates are easily separated from the bulk soils magnetically. Most of the total Fe, however, is present as FeO in the glass and not as the iron droplets. Agglutinitic glass is generally vesicular, with vesicles ranging from less than 1 µm to several cm in diameter. Agglutinates generally make up 10 to 60%, by volume, of lunar soil samples. The proportion of agglutinates increases with the length of time a soil was exposed at the lunar surface (9,10,11), as indicated by particle tracks, solar wind components, etc. Most investigators agree that agglutinates are formed by the mixing of melt from micrometeorite impacts and soil particles (reviewed in Ref. 5). The increase of agglutinates in a regolith effectively lowers the albedo, a characteristic which may be useful in the search for regolith quarry sites by remote sensing of the lunar surface (13). Rhodes et al. (12) determined that agglutinates are enriched in iron and titanium relative to the bulk soils (Table 2). This enrichment may be due to the selective melting of mafic soil components.

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When treating the regolith as a source of materials, remember that it is already partly processed; the crushing and sorting is well along, thanks to the millions or billions of years of pounding and turnover by meteorite impact. Most lunar soils are fine grained; the samples collected on Apollo and Luna missions have mean grain sizes of around 100 to 200 µm (Table 3). The description, in terrestrial terms, which best fits an "average" lunar soil, in both mare and highlands areas, is that of a "cobble-bearing silty sand."

Based on studies of core samples and theoretical models of regolith formation, there is considerable variation of grain size with depth in a regolith. This variation is random, but generally coarser with increasing depth. If fine grain sizes are most desirable in a lunar quarry, then fresh craters, characterized by coarse grained soils, should be avoided.

Finer grained soils are best to process for many reasons: 1) they are easy to quarry, 2) minimal energy is spent for crushing, 3) they are richer in agglutinates and therefore richer in Fe°, FeO and TiO_2, 4) there is more surface area and therefore more solar-wind derived hydrogen, and 5) they are more easily sintered to form compressed soil blocks for construction or transport.

The process of concentrating fine-grained, agglutinate-rich soils as an ore has been studied by one of the authors (DSM) and is outlined in Fig. 1. The purpose is to make a concentrate which would have economic potential for oxygen and hydrogen extraction and for the extraction of metallic Fe, Ti, Al, S, Co, Cr and Ni. It involves a closed-system water slurry and size and magnetic separations.

Regolith thicknesses have been estimated by such techniques as measuring minimum depths of blocky craters, seismic data from Apollo sites and observation of rille and crater walls. The thicknesses range from 3 to 5 m for mare regoliths at the Apollo 11, 12 and 15 sites to 12 m of regolith at the Apollo 16 site in the lunar highlands. Observation of trenches and cores from the regolith indicate that at least the upper 3 m consists of soil layers which vary from a few mm to several tens of cm thick. There are changes in grain size, composition and soil fabric from layer to layer within individual sections, reflecting complex histories of impact comminution and mixing.

Quarry sites should not be located near large craters. For example, the cluster of craters in the northeast corner of the Valley of Taurus-Littrow had ejecta blankets which were sintered to form vitric breccia units. Such breccias may be difficult to quarry and will require energy for crushing. Large bodies of impact melt should be avoided for the same reasons.

If lunar soil is used as raw material for factories in space according to the concepts of O'Neill (1,2), the quarries and soil transporters must be on the lunar farside in areas with low topographic relief for a distance of 200 km. These restrict the location of the quarries to large farside basins such as Mare Moscoviense, Mendeleev, Korolev and Jules Verne.

Old plains areas such as the floor of Mendeleev Crater have high Al/Si ratios and are similar in appearance to plains areas of the lunar nearside. The abundance of smooth-rimmed craters is one indicator of a thick regolith characteristic of highlands regions. Basins with low albedos, such as Tsiolkovsky, Mare Moscoviense and Jules Verne have lower Al/Si ratios and, by analogy with nearside maria, more Fe°, FeO, and TiO_2 in their regoliths than those of the adjacent highlands. The relatively featureless crater floors satisfy the terrain limitations on sites.

If a site is chosen, for example, in Mendeleev, only small areas will be affected by the quarrying. Assuming a bulk density of 1.7 gm/cm^3 and mining the regolith to a depth of 8 m, a 1 km^2 quarry will supply 13.5x10^6 mtons. According to O'Neill (2), a soil transporter, with maximum use, could launch 940x10^3 tons per year. At this rate, the 1 km^2 quarry would last nearly 15 years.

For this brief review, we have used only what is known from nearside landing sites and orbital γ-ray and XRF data from narrow bands around the Moon. It is probable that, by analogy with what is known about samples from the nearside and from the farside orbital data, we may reasonably assess the physical properties and composition of quarry sites on the lunar farside. For a more detailed exploration program we need the following:

- Better studies of available orbital photography to assess regolith thicknesses.
- More orbital geochemical data.
- Topographic profiles of regions where quarries may be established.
- Radar and infrared data to interpret surface roughness and limits on grain size of the regoliths.
- Lunar orbiter multispectral measurements of soil maturity (grain size, agglutinate contents) similar to those made of the nearside by Earth-based observations (14).

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FIGURE 1.

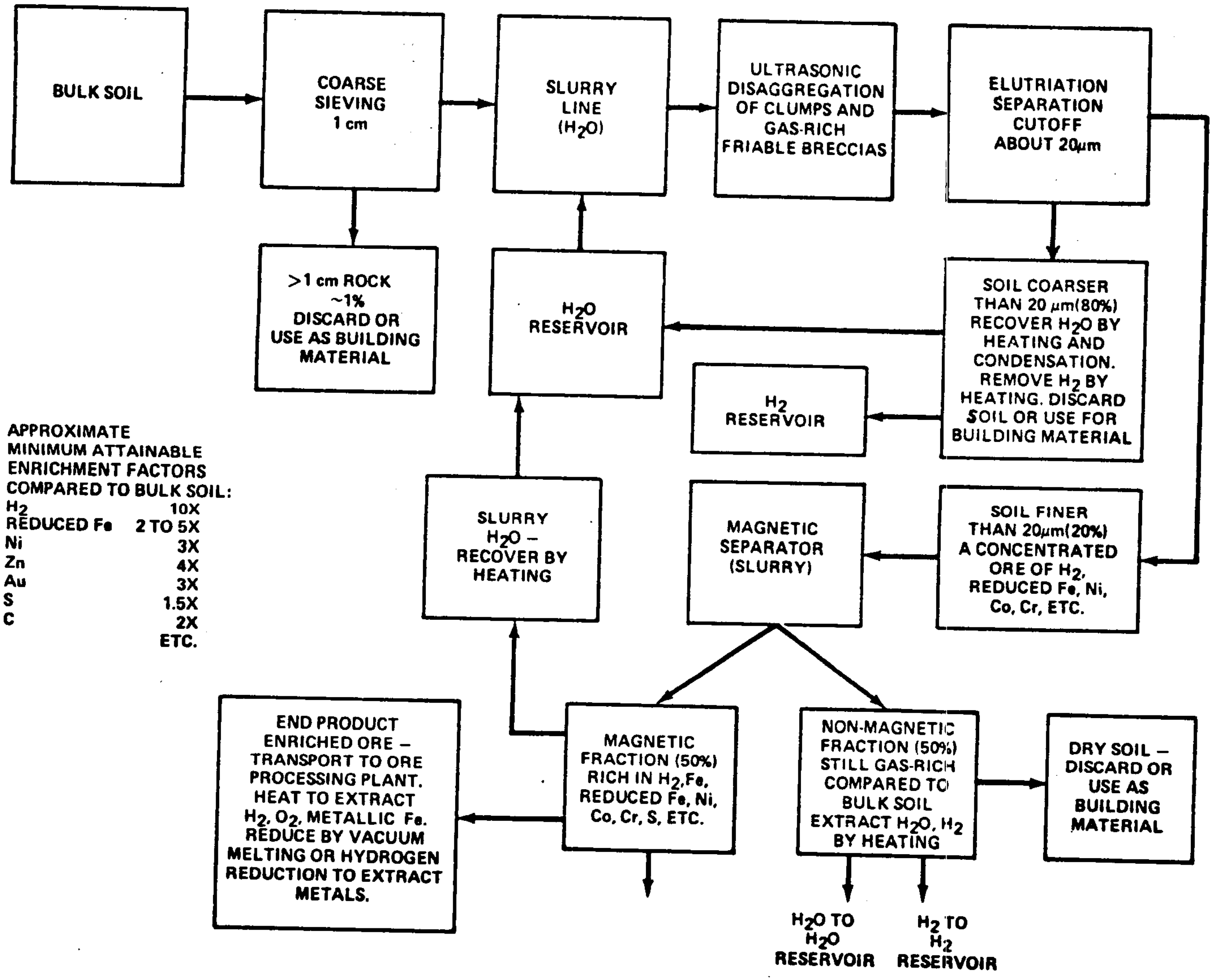
BULK SOIL
COARSE SIEVING 1 cm
>1 cm ROCK ~1% DISCARD OR USE AS BUILDING MATERIAL
SLURRY LINE (H_2O)
ULTRASONIC DISAGGREGATION OF CLUMPS AND GAS-RICH FRIABLE BRECCIAS
ELUTRIATION SEPARATION CUTOFF ABOUT 20μm
SOIL COARSER THAN 20 μm(80%) RECOVER H_2O BY HEATING AND CONDENSATION. REMOVE H_2 BY HEATING. DISCARD SOIL OR USE FOR BUILDING MATERIAL
H_2O RESERVOIR
H_2 RESERVOIR
SOIL FINER THAN 20μm(20%) A CONCENTRATED ORE OF H_2, REDUCED Fe, Ni, Co, Cr, ETC.
MAGNETIC SEPARATOR (SLURRY)
SLURRY H_2O – RECOVER BY HEATING
MAGNETIC FRACTION (50%) RICH IN H_2,Fe, REDUCED Fe, Ni, Co, Cr, S, ETC.
NON-MAGNETIC FRACTION (50%) STILL GAS-RICH COMPARED TO BULK SOIL EXTRACT H_2O, H_2 BY HEATING
DRY SOIL – DISCARD OR USE AS BUILDING MATERIAL
H_2O TO H_2O RESERVOIR
H_2 TO H_2 RESERVOIR
END PRODUCT ENRICHED ORE – TRANSPORT TO ORE PROCESSING PLANT. HEAT TO EXTRACT H_2, O_2, METALLIC Fe. REDUCE BY VACUUM MELTING OR HYDROGEN REDUCTION TO EXTRACT METALS.
APPROXIMATE MINIMUM ATTAINABLE ENRICHMENT FACTORS COMPARED TO BULK SOIL:
H_2 10X
REDUCED Fe 2 TO 5X
Ni 3X
Zn 4X
Au 3X
S 1.5X
C 2X
ETC.

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Table 1
"Average" Chemical Composition of Highlands and Mare Regoliths (Ref. 7).

	Maria (wt.%)	Highlands (wt.%)
SiO_2	45.4	45.5
TiO_2	3.9	0.6
Al_2O_3	14.9	24.0
FeO	14.1	5.9
MgO	9.2	7.5
CaO	11.8	15.9
Na_2O	0.6	0.6
	Atomic %	
O	60.3	61.1
Si	16.9	16.3
Ti	1.1	0.15
Al	6.5	10.1
Fe	4.4	1.8
Mg	5.1	4.0
Ca	4.7	6.1
Na	0.4	0.4

Table 2
Concentration of Elements in Bulk Soils and Agglutinate Fractions (12)

Major Elements (Wt.%)	Highlands (64421)		Mare (71501)	
	Bulk	Aggl.	Bulk	Aggl.
SiO_2	44.97	44.85	39.82	38.96
TiO_2	0.53	0.68	9.52	9.98
Al_2O_3	27.82	26.32	11.13	10.87
FeO	4.71	6.07	17.41	18.16

Table 3
Grain Size Characteristics

	Apollo 16 (Highlands)	Apollo 17 (Mare only)
Mean Grain Size:	101 to 268 µm	67 to 169 µm
Sorting:	2.3 to 3.45ϕ (poorly to very poorly sorted)	2.03 to 3.33ϕ (poorly to very poorly sorted)

DISCUSSION (Heiken and McKay Paper)

SPEAKER 1: I don't want to beat this point to death, but I still don't understand why the farside is the location of the first lunar colony.

HEIKEN: Ask someone in the O'Neill group, if they are here. I believe it's because you can't get things to L-5 from the lunar nearside.

McKAY: Yes, just one additional comment: I think that there was maybe one more slide in Grant Heiken's group. Could we have the last slide please? (See flow chart in abstract) Grant alluded to the idea of processing and concentrating on lunar soils in the regoliths. And if we think of lunar regoliths as ores, then we have to think in terms of concentrating them. And this is a simple scheme, I'm sure there are many and better schemes of concentrating the fine-grained fraction, the sub-20 micron in this case. This scheme uses a combination of elutriation or sedimentation combined with magnetic separation to concentrate the fine-grained fraction. Now, why do we want to do this? Well, it turns out the fine-grained fraction is highly enriched in some elements; for example hydrogen might be enriched by a factor of 10 over the bulk soli. Reduced iron is enriched. Nickel is enriched, zinc, gold, sulfur, carbon; other elements are all enriched in this fine-grained fraction which we can concentrate by elutriation and by magnetic spearation. We have to start now to think in terms of concentrating this portion of the soil, I think. This happens to be a closed-water-slurry system. I'm sure there are other systems that will do the same thing.

SPEAKER 2: What are the minimum concentrations of iron and titatniun that are needed in the soil so that the mining process will be practicable? How well does the geochemistry of the soil have to be known to actually instigate a mining process? The aluminum-silica ratio - the only aluminum-silicon ratio of the back-side basins that are known - is the aluminum-silicon ratio of Tsiolkovsky.

HEIKEN: There is also an aluminum-silicon ratio for Mendeleev. Am I correct? I'm pretty sure there is. We quoted one recently, we looked it up. As far as the processing goes, you've got me, I look at what's there and put it out and say, okay, here are the elements, and I think there are going to be several other talks on the processing, later in this session. That's the reason they're here.

SPEAKER 3: You must also depend on the - how much the energy costs. You're willing to say, "I've got lots of solar energy, and it doesn't cost you anything." That's one boundary condition. Not a very realistic one.

DISCUSSION (Heiken and McKay Paper)

SPEAKER 4: One comment on the siting requirement. That siting requirement on the backside of the Moon was for direct launch either to L-4 or L-5. If you change it so that you can launch to the unstable Lagrangian points in front and back of the Moon, then you can do your siting anywhere.

HEIKEN: We're just going on the assumption that L-5 or L-4 was most desirable.