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HELIUM MINING ON THE MOON: SITE SELECTION AND EVALUATION

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The feasibility of recovering helium (He) from the Moon as a source of fusion energy on Earth is currently being studied at the University of Wisconsin. Part of this study is selection and evaluation of potential sites for lunar He mining. Selection and evaluation of potential mining sites are based on four salient findings by various investigators of lunar samples: (1) Regoliths from areas underlain by highland materials contain less than 20 wppm He; (2) Certain maria regoliths contain less than 20 wppm He, but others contain 25 to 49 wppm; (3) The He content of a mare regolith is a function of its composition; regoliths rich in Ti are relatively rich in He; and (4) He is concentrated in the <100- μ m size fractions of regoliths. The first three findings suggest that maria are the most promising mining sites, specifically, those that have high-Ti regoliths. Information on the regional distribution and extent of high-Ti regoliths comes mainly from two sources: direct sampling by various Apollo and Luna missions, and remote sensing by gamma-ray spectroscopy and Earth-based measurements of lunar spectral reflectance. Sampling provides essential control on calibration and interpretation of data from remote sensing. These data indicate that Mare Tranquillitatis is the principal area of high-Ti regolith of the eastern nearside, but large areas of high-Ti regolith are indicated in the Imbrium and Procellarum regions. Recovery of significant amounts of He-3 will require mining billions of tonnes of regolith. Large individual areas suitable for mining must therefore be delineated. The concentration of He in the finer size fractions and considerations of ease of mining mean that mining areas must be as free as possible of sizable craters and blocks of rock. Pending additional lunar missions, information regarding these features must be obtained from lunar photographs, photogeologic maps, and radar surveys. The present study is decidedly preliminary; available information is much too limited to permit even a close approach to final evaluation. As a prelude to recovery of He from the Moon, systematic exploration and sampling of high-Ti maria regoliths should therefore have a high priority in future lunar missions.

INTRODUCTION

Part of the University of Wisconsin study of the feasibility of recovering He-3 from the Moon is the selection and evaluation of potential mining sites. First it is necessary to identify areas in which the regolith is enriched in He, preferably those containing 30 wppm or more. The occurrence of He in the regolith must then be examined, and consideration given to physical characteristics of terrain and regolith that could affect the feasibility of mining in the areas selected.

This paper summarizes the information pertinent to site selection and evaluation that is currently available from Apollo and Luna lunar samples and from remote sensing of the lunar surface. The use of this information in locating minable He-rich areas of the Moon is discussed, and preliminary conclusions as to favorable sites for mining are presented. Further work needed for site selection and evaluation is outlined.

BASIS OF SITE SELECTION

Of prime importance to site selection and evaluation are the following salient findings by the various investigators of lunar samples:

1. Regoliths from areas underlain by highland materials contain less than 20 wppm He, and many contain less than 10 wppm.
2. Regoliths of some maria or parts of maria contain less than 20 wppm He, but others have He contents ranging from 25 to nearly 50 wppm.

3. The He content of a mare regolith is a function of its composition. In particular, the He content appears to be a function of the Ti content of the regolith.

4. Helium is concentrated in the <100- μ m size fractions of regoliths.

These findings are used directly in site selection. Moreover, they serve for calibration of data from remote sensing and as controls on interpretation of such data.

TITANIUM AND HELIUM IN LUNAR REGOLITHS

The relationship between the He contents of regoliths and their Ti contents is shown in Fig. 1, in which He content is plotted against TiO₂ content for samples of highland and mare regoliths. Highland regoliths are all low in both He and Ti. Mare regoliths fall into two groups, one with high He and Ti contents, the other with low contents of the two elements. It is generally accepted that the compositions of mare regoliths are controlled by the nature of underlying basaltic rocks. More than a dozen different types of basalts have been described from various maria, being distinguished on the basis of mineral and chemical composition (*Basaltic Volcanism Study Project*, 1981a; *Wilhelms*, 1987). In terms of Ti content, however, these basalts are assigned to three principal groups: (1) very-high-Ti basalts (VHT) sampled by Apollo 11 and Apollo 17; TiO₂ content 8 to 14 wt%; (2) low-Ti basalts (LT) sampled by Apollo 12, Apollo 15, Apollo 17, Luna

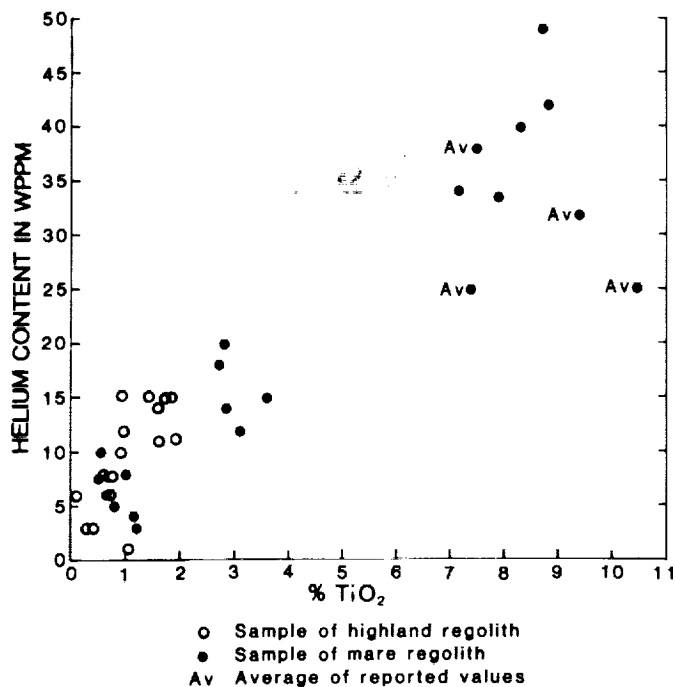


Fig. 1. Relation between He contents and TiO_2 contents of lunar regolith samples. Data from Bogard and Hirsch (1978a), Bogard and Nyquist (1972), Criswell and Waldron (1982), Cuttitta et al. (1971, 1973), Eberhardt et al. (1972), Eugster et al. (1985), Funkbauer et al. (1970), Haskin et al. (1973), Heymann et al. (1970, 1972a,b, 1973, 1978), Hintenberger et al. (1970, 1971, 1974, 1975), Hintenberger and Weber (1973), Hübner et al. (1973, 1975), Kirsten et al. (1972), Laul et al. (1974), Laul and Papike (1980a,b), Laul and Schmitt (1973), Ma et al. (1978), Marti et al. (1970), Nava (1974), Pepin et al. (1970), Pieters et al. (1980), Pieters and McCord (1976), Rose et al. (1974), Wakita and Schmitt (1971), Wänke et al. (1971), Wilhelms (1987), and Willis et al. (1972).

16, and Luna 24; TiO_2 content 1.5 to 5 wt%; and (3) very-low-Ti basalts (VLT) sampled by Apollo 17 and Luna 24; TiO_2 content less than 1.5 wt%.

In Fig. 1, the mare regolith samples fall into three distinct clusters corresponding rather closely to the above groupings of basalts on the basis of Ti content. The gap between VHT regoliths and LT regoliths is conspicuous. The diagram shows a broad correlation of He content with Ti content, but there is a considerable scatter, especially at the high TiO_2 end of the range. The samples highest in TiO_2 content are not all correspondingly high in He content. This is not unexpected. In lunar basalts, much of the Ti is in the form of ilmenite, and ilmenite fractions from Apollo 11 and Apollo 17 mare regoliths have been found to be enriched in He (Eberhardt et al., 1970, 1972; Hintenberger et al., 1974). However, ilmenite grains in high-Ti basalts range from a millimeter to less than a micrometer in size (see, for example, Cameron, 1970, Figs. 1 and 2), and variations in grain size are bound to affect the degree of exposure of ilmenite to the solar wind even in particles of the finer size fractions of regoliths. Moreover, TiO_2 can be dissolved in part in agglutinate glass or

in volcanic, pyroclastic Ti-rich glass particles. The latter particles in Apollo 11 regolith have been shown by Kirsten et al. (1970) to carry higher concentrations of He than associated particles of olivine, pyroxene, and plagioclase, but are less enriched than ilmenite grains. Finally, the He content of regolith is a function of the length of time of exposure to the solar wind, the ultimate source of lunar He.

Considering all the factors that have affected the absorption of He by regolith, a linear relation between TiO_2 content and He content is not to be expected. However, it seems clear that the Ti content of regolith can be used as a general guide in selection of areas where the regolith contains at least 20 wppm He and hopefully areas where the regolith contains at least 30 wppm. This is of critical importance in site selection. Only minute fractions of a few maria have yet been sampled. For information on the extent and distribution of the more He-rich maria and portions of maria, we must presently rely on information from remote sensing of the Ti contents of mare regoliths.

INFORMATION FROM REMOTE SENSING

Broad reviews of both methods and results of remote sensing have been given by Moore et al. (1980) and the *Basaltic Volcanism Study Project* (1981b). Two general types of remote sensing have furnished information on the Ti contents of lunar regoliths, namely, gamma-ray spectroscopy performed by Apollo 15 and Apollo 16 orbiters, and Earth-based telescopic measurement of lunar reflectance. The results of both types of measurements have been calibrated, as far as possible, against returned lunar samples of known Ti content, but Fig. 1 indicates that there can be no calibration for the intermediate range, i.e., for the gap between VHT and LT basalts. Whether this gap is real or is due to incomplete sampling of the maria is discussed in a subsequent section of this paper.

Gamma-ray spectroscopy makes use of radiation produced mainly by cosmic-ray bombardment of the lunar regolith. Its advantage is that it measures a property that is uniquely related to Ti content. However, there are serious deficiencies in gamma-ray data presently available. Resolution is very low, about 100×100 km. Coverage by the Apollo orbiters is limited to two bands lying between 30°N and 15°S . There are problems in interpreting the data, in part due to interference with Ti lines by Fe and O in the gamma-ray spectra. Nonetheless, the gamma-ray surveys are valuable because they indicate broad variations in Ti content of regolith over the equatorial region of the lunar nearside.

Figure 2 shows variations in the Ti content of lunar regolith as interpreted by Metzger and Parker (1980) from gamma-ray spectroscopy. Two principal areas of high-Ti regolith are indicated, one the area of Mare Tranquillitatis, with its extension northward into Mare Serenitatis (sampled at the Taurus-Littrow region of Apollo 17), the other a part of Oceanus Procellarum. Two smaller areas are also shown. Certain areas are shown as having intermediate Ti content (2.0-2.5% Ti), but none of these has been sampled by lunar missions, except possibly the one in Mare Fecunditatis. A soil sample recovered by Luna 16 contains 3.53% TiO_2 (Criswell and Waldron, 1982), but the He content of the bulk sample can only be approximated from data of Vinogradov and Zadorozhny (1972) for the $<83\text{-}\mu\text{m}$ fraction, and it may be as high as 30 wppm. In view of this uncertainty, the sample is not plotted in Fig. 1. Davis (1980) has used the orbital gamma-ray data to produce a map on which variations in Ti content are

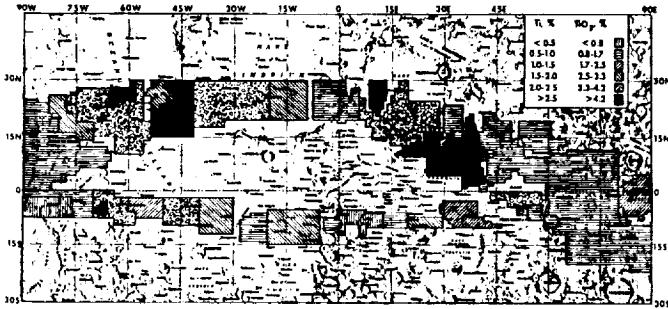


Fig. 2. Map of the Ti content of the lunar regolith covering nearside regions overflowed by Apollo 15 and 16. From Metzger and Parker (1980), by permission of the authors and Elsevier Publishing Company.

shown in image format. There are differences between his map and that of Fig. 2, but the broad picture of Ti variation is much the same.

There is a considerable variety of measurements of lunar reflectance. Figure 3 is a map of the entire lunar nearside prepared from superposed ultraviolet negatives and near-infrared positives. It shows the color groups of basaltic regoliths, with TiO₂ values thought to be indicated by the colors. Again, the only sizable area of high-Ti regolith shown in the eastern hemisphere is that of Mare Tranquillitatis, with its extension northward into the Apollo 17 area, but the map shows large areas of high-Ti regolith in the western hemisphere. Like Fig. 2, Fig. 3 shows large areas thought to be of intermediate Ti content.

Figure 3 is actually based on one form of spectral ratio mapping. Quantitative spectral ratio mapping is based on use of the 0.38 μm:0.56 μm ratio, the 0.38 μm:0.58 μm ratio, or the 0.38 μm:0.62 μm ratio, all of them UV:VIS ratios, or on the 0.38 μm:0.95 μm ratio (UV:IR). Compared to gamma-ray spectroscopy, spectral ratio mapping has the advantage of higher resolution (1 to 3 km) and broader coverage of the lunar surface. Johnson et al. (1977) prepared a map of a large part of the lunar nearside using the 0.38 μm:0.56 μm ratio. On it, Mare Tranquillitatis appears once again as a high-Ti area, but the higher resolution of this method shows that the mare is not uniform in Ti content. Spectral ratio mapping appears to be a good indicator in the high-Ti and low-Ti ranges, but it is ambiguous in the intermediate-Ti range, as indicated in Fig. 4. This is unfortunate, because it is in this range that sampling of the lunar surface is lacking.

Figure 3 is actually a version of a remarkable color difference photograph (Fig. 5) prepared by Whitaker (1965). High-Ti regoliths appear dark in this photograph, and it shows that high-Ti regolith in Mare Tranquillitatis is mainly in an irregular belt extending northward along the west side of the mare and thence eastward across it as shown in Fig. 6. The area south of the belt is a complex of high-Ti and lower-Ti regoliths, whereas the area north of the belt is apparently one of low-Ti regolith. Comparable variations in Mare Imbrium and Oceanus Procellarum are also suggested by the photograph.

Figure 7 shows the distribution of a number of petrographic types of basaltic regoliths as recognized by Pieters (1978) on the

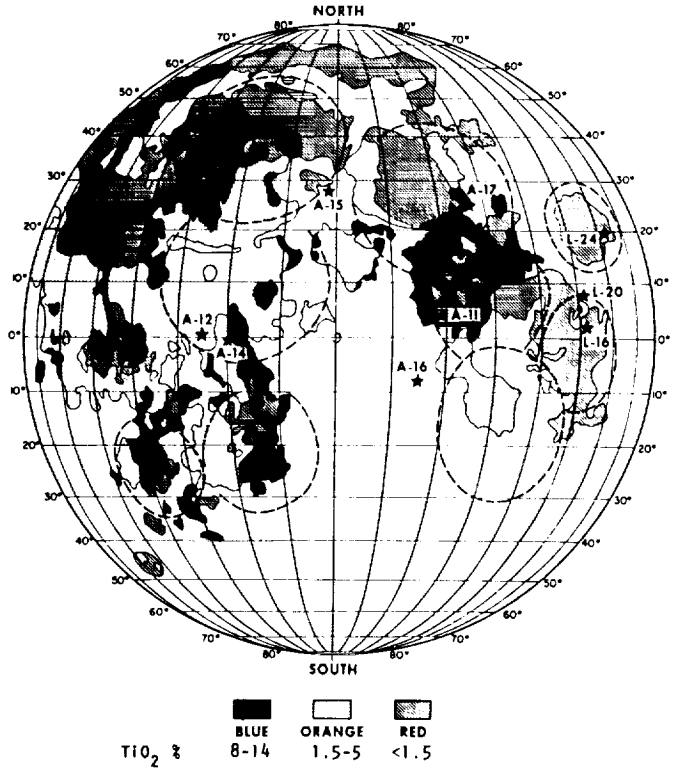


Fig. 3. Color groups of mare regoliths and TiO₂ values thought to be represented by the groups. From Basaltic Volcanism Study Project (1981a), by permission of the Lunar and Planetary Institute, Houston. Modified to show blue areas in solid black.

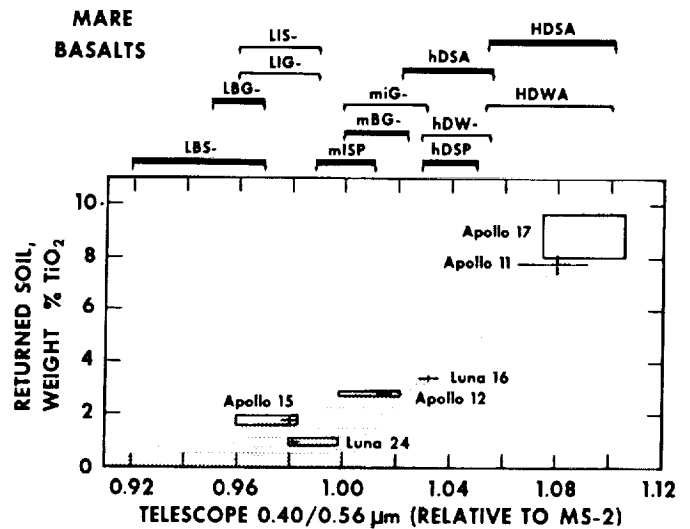


Fig. 4. Relationship between percent TiO₂ in lunar mare regoliths and the 0.40:0.56-μm reflectance ratio for telescopic spectra relative to MS2 (after Charette et al., 1974, and Pieters and McCord, 1976). The stippled area is the estimated range of TiO₂ that can be derived from a 0.40:0.56 μm ratio measurement of mature mare regions. Shown above the plot are the ranges of 0.46:0.56 μm ratio observed for each of the basalt types discussed by Pieters (1978). The heavy lines indicate unsampled basalt types. From Basaltic Volcanism Study Project (1981a), by permission of the Lunar and Planetary Institute, Houston.

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Fig. 5. Color difference photograph (from *Whitaker*, 1966), made by subtracting a photograph taken at $0.31 \mu\text{m}$ from one taken at $0.61 \mu\text{m}$. Courtesy of E. A. Whitaker.

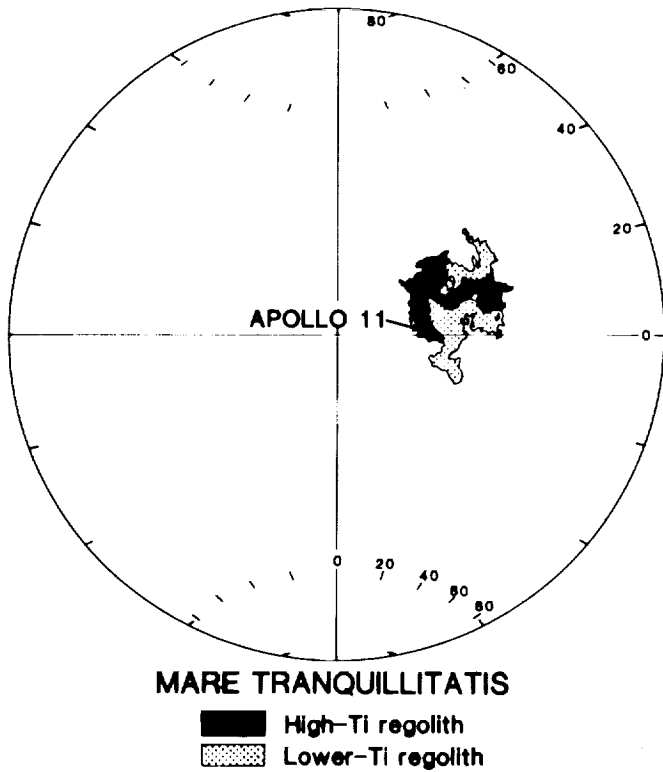


Fig. 6. Broad variations in TiO_2 content of regolith in Mare Tranquillitatis. Based on *Wilhelms* (1987, plate 4A).

basis of albedo, UV:VIS ratio, strength of the $1\text{-}\mu\text{m}$ band, and strength of the $2\text{-}\mu\text{m}$ band. Only Tranquillitatis and the Flamsteed area are regarded as occupied by high-Ti regolith.

There is considerable agreement among various maps that are based on reflectance measurements. There is agreement on certain high-Ti areas. There is also agreement that regoliths of intermediate or low-Ti content occupy considerably more area than those identified as high-Ti regoliths. However, there is disagreement on the location and extent of low-Ti and intermediate-Ti areas. *Metzger et al.* (1979) compared the results of gamma-ray spectroscopy with the work of Pieters expressed in Fig. 7. They found agreement for 10 of 14 map regions. However, this required a rather liberal interpretation of the data. In addition, they assume a uniformity of maria that probably does not exist and is, in fact, contradicted by the spectral ratio map of *Johnson et al.* (1977) and the photograph of Fig. 5. As noted above, there is a lack of intermediate-Ti samples that have been analyzed for both He and Ti. Given the poor resolution of most reflectance measurements, intermediate-Ti areas shown on maps may therefore be due to averaging high-Ti and low-Ti regoliths. The gap between the two suggested by Fig. 1 may therefore be a real one, not an apparent one that is due to incomplete sampling of the maria. Lack of samples from areas that are indicated as intermediate in Ti content is particularly unfortunate inasmuch as those areas occupy a substantial fraction of the total area of the maria.

It is important that there is substantial agreement among the maps on the locations of certain areas of high-Ti regolith, Mare Tranquillitatis in particular. Tranquillitatis has an area of at least 190,000 sq km and seems likely to contain substantial amounts of

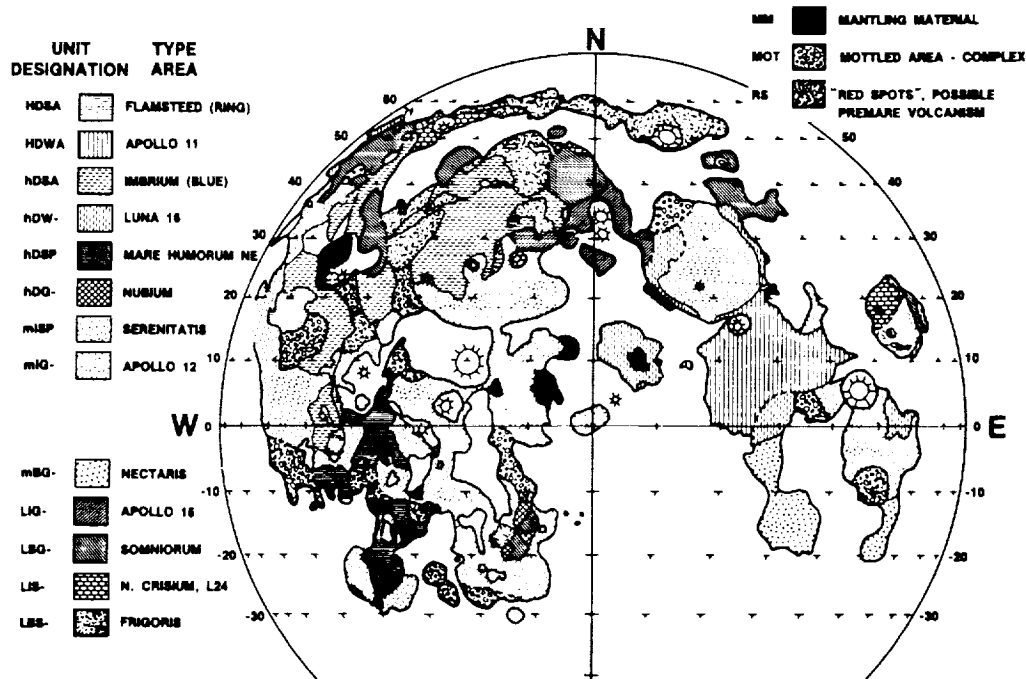


Fig. 7. Major basalt types for the front side of the Moon as derived from the current spectral reflectance data. The unit designations represent values for four measurable parameters (UV:VIS ratio, albedo, strength of the $1\text{-}\mu\text{m}$ band, and strength of the $2\text{-}\mu\text{m}$ band). By permission of the Lunar and Planetary Institute and Basaltic Volcanism Study Project.

regolith with 30 wppm or more He. If only 30% of the total area is minable at 30 wppm He, if mining is carried to an average depth of 3 m, and if recovery from mining and processing is 60%, roughly 1700 tonnes of He-3 could be recovered from this mare.

In summary, remote sensing has yielded a substantial amount of information on the location and broad distribution of high-Ti regoliths. The information serves as a general guide to the selection of potential mining areas. Beyond this, however, the use of remote sensing is limited by the low resolution of the methods.

REQUIREMENTS FOR MINING AREAS

The mining scenario envisioned by the University of Wisconsin group calls for the schedule of production shown in Table 1. In Fig. 8, line A shows the area in square kilometers having the amount of He-3 necessary to match the requirements for successive periods between 2015 and 2050, assuming a mining depth of 3 m, an average He content of 30 wppm, and 100% recovery of He. Line B shows square kilometers that must be mined to a depth of 3 m to meet the schedule if recovery from mining and processing is 80%. Line C shows square kilometers that must be mined to a depth of 3 m if recovery is 60%, probably a more realistic figure. At 10% recovery, the mined area would be 123 sq km by the year 2030, and 8110 sq km by the year 2050, when the full production rate of 20,000 kg He-3/yr would be achieved. Thenceforth, the mining area required per year would be 665 sq km. Thus, large mining areas must be delineated if the mining scenario is to be fulfilled.

The He content of regolith, recovery percentage, and depth of mining are not the only factors determining the areas over which mining operations will have to be extended. Knowledge of the maria, including Mare Tranquillitatis, is far from complete, but it is enough to indicate that there will be areas that cannot be mined, at acceptable costs, owing to the presence of large craters or abundant large blocks of rock. It is therefore to be expected that mining will have to extend over larger areas than indicated by Fig. 8, and that the pattern of mining will be complicated by the necessity of avoiding unminable areas.

Regolith high in Ti was found in the mare-filled valley of the Apollo 17 landing site. However, the site is one of complex geology and marked heterogeneity. It does not appear attractive as a potential mining site, but photogeologic maps (Scott et al., 1972) suggest that there may be minable areas in the Taurus-Littrow region west of the landing site.

DISTRIBUTION OF HELIUM IN MARE REGOLITHS

As indicated earlier, investigations of lunar samples have shown that He is concentrated in the <100- μ m size fractions of regoliths. This stems from the fact that absorption of He from the solar wind

TABLE 1. Schedule of He-3 production.

Period	Average annual production (mt)	Cumulative production (mt)
2015-2020	0.014	0.070
2020-2025	0.066	0.400
2025-2030	0.656	3.680
2030-2035	4.572	25.540
2035-2040	9.312	73.100
2040-2045	14.880	147.500
2045-2050	19.300	244.000

is proportional to particle surface area per unit of mass. The distribution of He in Apollo 11 regolith is indicated in Fig. 9, which is based on weight percentages of various size fractions given by Criswell and Waldron (1982) for sample 10084,853, and on He contents of a series of size fractions given by Hintenberger et al. (1970) for sample 10084,18. The latter authors did not give the weight percentages of the bulk soil represented by the various fractions, and the percentages had to be estimated from a size distribution curve plotted from the data of Criswell and Waldron. Calculations show that not all the He content of the bulk soil is accounted for in the size fractions, hence Fig. 9 should be taken as indicating only the pattern of He distribution in Apollo 11 regolith in relation to particle size.

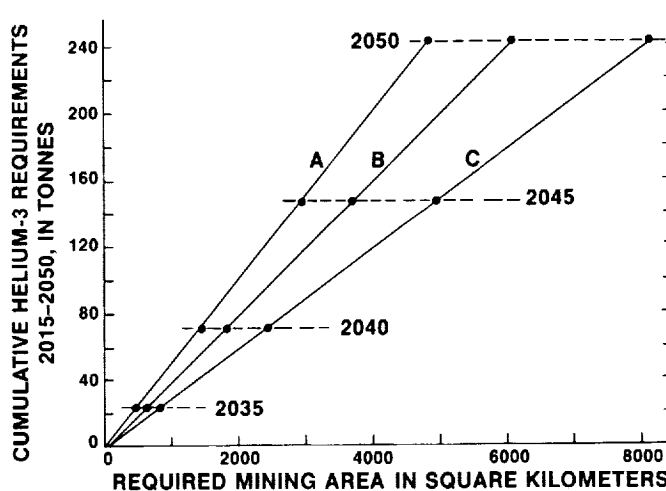


Fig. 8. Relation between required mining areas and cumulative requirements for He-3 for a mining depth of 3 m. See text for explanation.

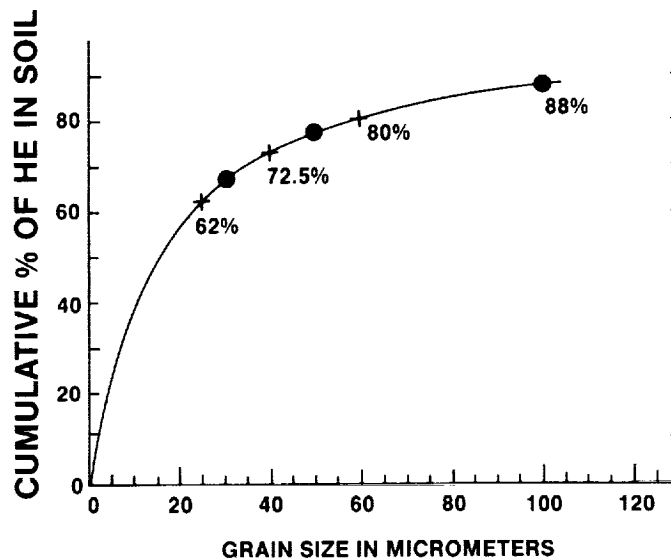


Fig. 9. Percentage of total He in Apollo 11 regolith in relation to grain size. Based on data of Criswell and Waldron (1982) and Hintenberger et al. (1970).

The significance of the above relations for site selection is that coarse material in the regolith is not important as a source of He. This and considerations of ease of mining and processing mean that mining areas should be as free as possible of blocks of rock and sizable craters. Information on these and other physical features of the regolith must be obtained from lunar photographs and photogeologic maps, and from radar surveys that indicate surface roughness at various scales (*Basaltic Volcanism Study Project*, 1981b; Moore *et al.*, 1980; Zisk *et al.*, 1974, 1987). Photogeologic maps should also aid in studying variations in the composition of lunar regoliths and in delineating suitable mining areas.

DARK-MANTLE MATERIALS AS AN ALTERNATIVE SOURCE OF HELIUM

Dark-mantle materials, distinguished on the basis of their radar and spectral reflectances, occupy certain areas of the lunar nearside. The largest such areas are along the southwest and south sides of Mare Serenitatis, including the Sulpicius Gallus and Taurus-Littrow regions, and in the Rima Bode region (Lucchitta, 1974; Head, 1974; Lucchitta and Schmitt, 1974; Wilhelm, 1987). Dark-mantle materials typically occur along the margins of maria, extending over parts of adjacent highlands. The deposits range up to tens of meters in thickness. Consisting of glass droplets with a mean size in the neighborhood of 40 μm , dark-mantle materials could be mined and processed for He much more easily than normal mare regolith.

From studies of spectral reflectance, Adams *et al.* (1974) concluded that droplets of black glass are the essential ingredient of dark-mantle material associated with Mare Serenitatis. The black glass has formed by devitrification of droplets of orange glass, now considered to be of pyroclastic origin. Haggerty (1974) and Heiken and McKay (1978) have shown that black ash droplets consist of ilmenite and olivine with varying amounts of residual glass.

Orange glass was sampled at the Apollo 17 site in the trench at Shorty Crater and in drive tubes put down beside the trench. Orange ash is reported to contain 8.09% to 8.9% TiO_2 (Wänke *et al.*, 1971; Nava, 1974). Its He content is reported as 2.6 wppm (Hintenberger *et al.*, 1974). The drive tubes show a progression downward from nearly pure orange glass at the top to material with 73.4% black glass at the bottom (Heiken and McKay, 1974).

In view of the ilmenite content of the black glass, it might be expected to show a higher He content than the orange glass, but Bogard and Hirsch (1978b) found He contents of 0.9 wppm or less in the black glass. However, petrographic studies of the drive tube section show that only the top 5.5 cm of the section has been gardened, and it has been exposed to the solar wind for only the past 10 to 30 m.y. We still do not know, therefore, the He potential of black glass in areas where it has been gardened and exposed to the solar wind over long periods of time. Such areas might prove to be important sources of helium. Sampling them should be a part of future missions to the Moon.

CONCLUDING COMMENTS

The study now in progress and reported here is preliminary. Study of photographs, photogeologic maps, and radar surveys of the lunar nearside should advance the process of site selection, but final selection of mining sites will not be possible with data presently available. Only very small fractions of a few of the maria have been sampled, and no area has been systematically sampled.

Information on thickness of regolith and on variation of He content with depth is limited. Remote-sensing maps, both those based on gamma-ray spectroscopy and on reflectance measurements, have insufficient resolution for purposes of site selection. All remote-sensing maps show large areas of intermediate-Ti regolith, but no such regolith has yet been sampled. The He potential of dark-mantle materials cannot currently be appraised. These significant deficiencies in present information must be remedied by systematic exploration and sampling of regolith, definition of minable portions of regolith, and estimation of tonnage and He content. Given the enormous potential of lunar He as a source of energy, such work should have a high priority in future lunar missions.

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