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HELIUM-3 FROM THE MOON – AN ALTERNATIVE SOURCE OF ENERGY

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ABSTRACT

Fusion of Helium-3 with deuterium offers an environmentally benign alternative to production of energy from fossil fuels and nuclear fission. Essentially unavailable from terrestrial sources, He-3 is potentially available from the Moon in very large amounts. This paper reports results of a study of the occurrence and distribution of helium on the Moon and lunar features that will govern helium mining and extraction.

He-3 has been implanted in the particles of lunar regoliths by the solar wind, along with He-4, hydrogen, nitrogen, methane, and carbon-oxygen compounds. Information on the occurrence, distribution, and content of helium in lunar regoliths is provided (1) directly by regolith samples from the Apollo and Luna missions and (2) indirectly by remote sensing of the lunar nearside by gamma-ray spectroscopy and spectral reflectance measurements. Regolith sample analyses show a strong correlation between the helium content and the titanium content of the regolith. Together with remote sensing, which shows the distribution of high-Ti regoliths, this information provides the basis for delineating lunar areas that should be high in helium content.

The most promising site for initial helium mining is Mare Tranquillitatis. Much of the mare is covered by high-titanium

regolith, inferred to contain 20 to 45 wppm total helium. Studies of very small craters on high-resolution photographs indicate an average regolith thickness in excess of 3 m. An area of 85,000 sq. km. in the northeastern part of the mare appears especially favorable to mining. The principal obstacles to mining are impact craters and their ejecta haloes. Plotting and measurements of craters on 27 high-resolution photographs that cover a total of 700 sq.km. of the Apollo 11 and Ranger VIII areas indicate that with appropriate mining equipment as much as 50 percent of the mare may be minable, with an estimated He-3 content of about 9,500 tons (equivalent to approximately 60 years of present world electrical production). Additional large areas of high-Ti regolith present in other maria will expand the usable He-3 resource base.

INTRODUCTION

The enormous increase in world consumption of energy during the 20th century has caused an increasing drain on conventional world energy resources and has brought in its wake the damage to the environment that is under discussion at this conference. The use of coal, the use of petroleum and natural gas, and the use of nuclear fission as sources of energy all create major environmental problems. For the 21st century there is an urgent need for an alternative source that would provide large amounts of energy in an environmentally benign manner. Using He-3 from the Moon to produce energy by fusion with deuterium now looms as such an alternative (Wittenberg et al., 1986; Kulcinski and Schmitt, 1987),

Nuclear fusion as a source of energy has been under study for over 30 years (Heppenheimer, 1984). The nuclear reaction between deuterium and tritium [Fig. 1(a)] is the major fusion fuel cycle pursued throughout the world. D-T fusion is environmentally more benign than nuclear fission, but there are problems associated

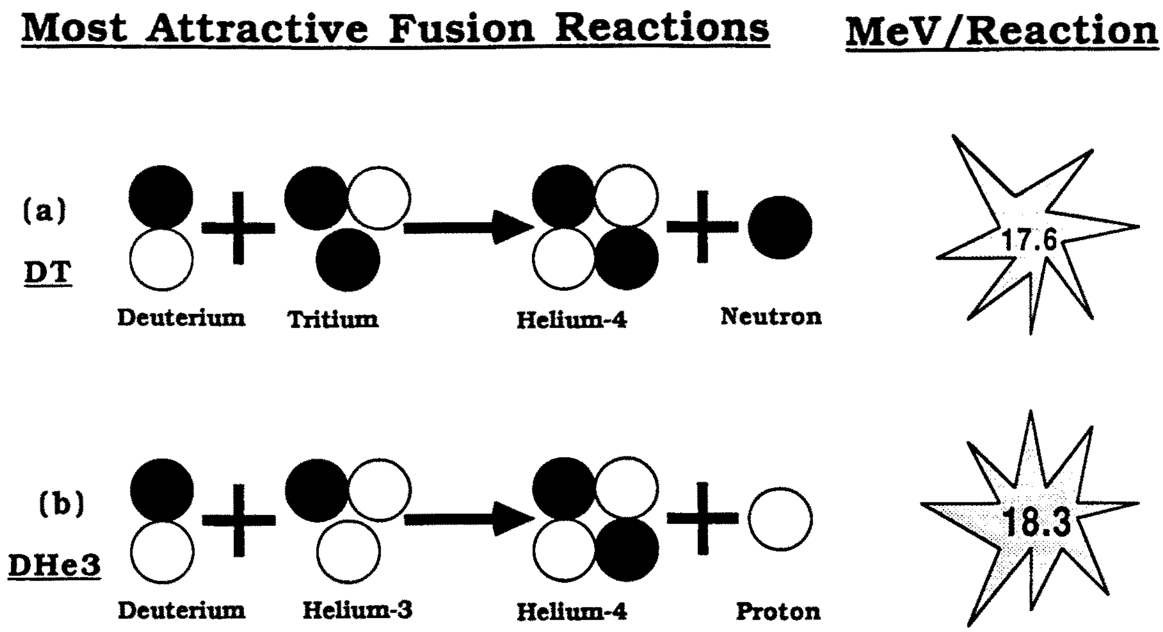


Fig. 1. The two most attractive fusion reactions and their energy outputs in million electron volts.

with its use. Eighty percent of the energy released by the reaction is in high energy neutrons that interact with the structural components of the reactor, induce long-lived radioactivity, and damage the metallic components. Furthermore, one of the fuels (tritium) is radioactive and must be carefully contained to avoid public exposure. Shutdowns for replacement of damaged components would be necessary every few years, exposing workers to ionizing radiation and generating large volumes of radioactive waste.

The D-T reaction, however, is not the only possible fusion cycle. It has been known since the mid 1950's (Post, 1956) that fusion of deuterium with the light isotope of helium, He-3, can produce large amounts of energy [Fig. 1(b)]. Use of this reaction would greatly reduce the problems involved in D-T fusion. The D-He3 reaction can be controlled so that only about 1 percent of the energy is released in neutrons (coming mainly from a side reaction between deuterium atoms). Most of the energy released (charged particles and synchrotron radiation) can be converted directly to electricity at efficiencies of over 80 percent. The low radioactivity of the reactor means that there can be no meltdown accidents, and the worst possible accident would cause no offsite injuries due to radiation release. Wastes are low-level wastes that are as easily and safely disposable as medical wastes from hospitals.

There are, however, two problems with the D-He3 reaction. One is that the reaction requires 2 to 3 times higher plasma temperatures than the D-T reaction and requires more demanding confinement conditions in the reactor. The second is that no major source of He3 has been identified on Earth. Owing to these problems, the D-He3 fuel cycle was ignored in favor of the D-T cycle for many years. However, recent progress in plasma physics has been such that it now appears that energy breakeven and ignition of the D-He3 cycle can be achieved in plasma physics devices by the year 2000. Objections to the cycle based on the stringent physics requirements therefore appear much less serious than in the past.

Until 1986 the problem of fuel supply seemed insurmountable. There is simply not enough He3 available on earth to provide a significant source of energy. However, in 1986 a group of scientists at the University of Wisconsin (Wittenberg et al., 1986) recognized that the regolith of the Moon might contain an enormous amount of He3 deposited from the solar wind over the 4.5 billion years since the Moon was formed. A review of analyses of regolith samples from the Apollo and Luna missions showed that this is indeed the case. Since 1986, therefore, an intensive study of information bearing on the occurrence of helium in lunar regoliths has been under way at Wisconsin. It is now clear that lunar regoliths have the potential for supplying sufficient He3 to satisfy Earth's requirements for electrical energy for hundreds of years.

THE LUNAR REGOLITH

The lunar regolith is the surficial layer of fragmental material, generally meters thick, that almost everywhere overlies the lunar bedrock. The regolith has been produced by the impacts of the innumerable bodies, very large to very small, that have bombarded the Moon throughout its history. There are two general types of regoliths. Highland regoliths cover the bright, mountainous areas of the Moon (Fig. 2), whereas mare regoliths cover the darker, more level areas that have long been called the maria.

Highland regoliths are derived mainly from plagioclase-rich rocks of the anorthosite-norite-troctolite suite, whereas mare regoliths are mainly derived from basaltic volcanics. Highland regoliths are rich in calcium, alumina, and silica but low in TiO_2. They could yield a variety of constructional materials, ranging from unprocessed regolith to cement, concrete, and ceramic materials such as fiberglass and rock wool. These materials will be needed both for construction of lunar facilities and for shielding occupied structures from solar flares and cosmic radiation. Highland regolith could also be used as a source of aluminum and calcium metal.

Compared to highland regoliths, mare regoliths are rich in iron, magnesium, and titanium and relatively low in calcium and aluminum. Mare regoliths are also potential sources of constructional materials as well as iron and titanium, but their great importance is as potential sources of a group of gases that have been implanted on the regolith particles by the solar wind - hydrogen, nitrogen, carbon-oxygen compounds, methane, and helium. The first four are essential for life support on the Moon (Bula et al., 1988). The helium, however, is important as a source of energy. More than that, it is the only potential product of the Moon that could provide an economic basis for future exploration of the Moon and planetary space.

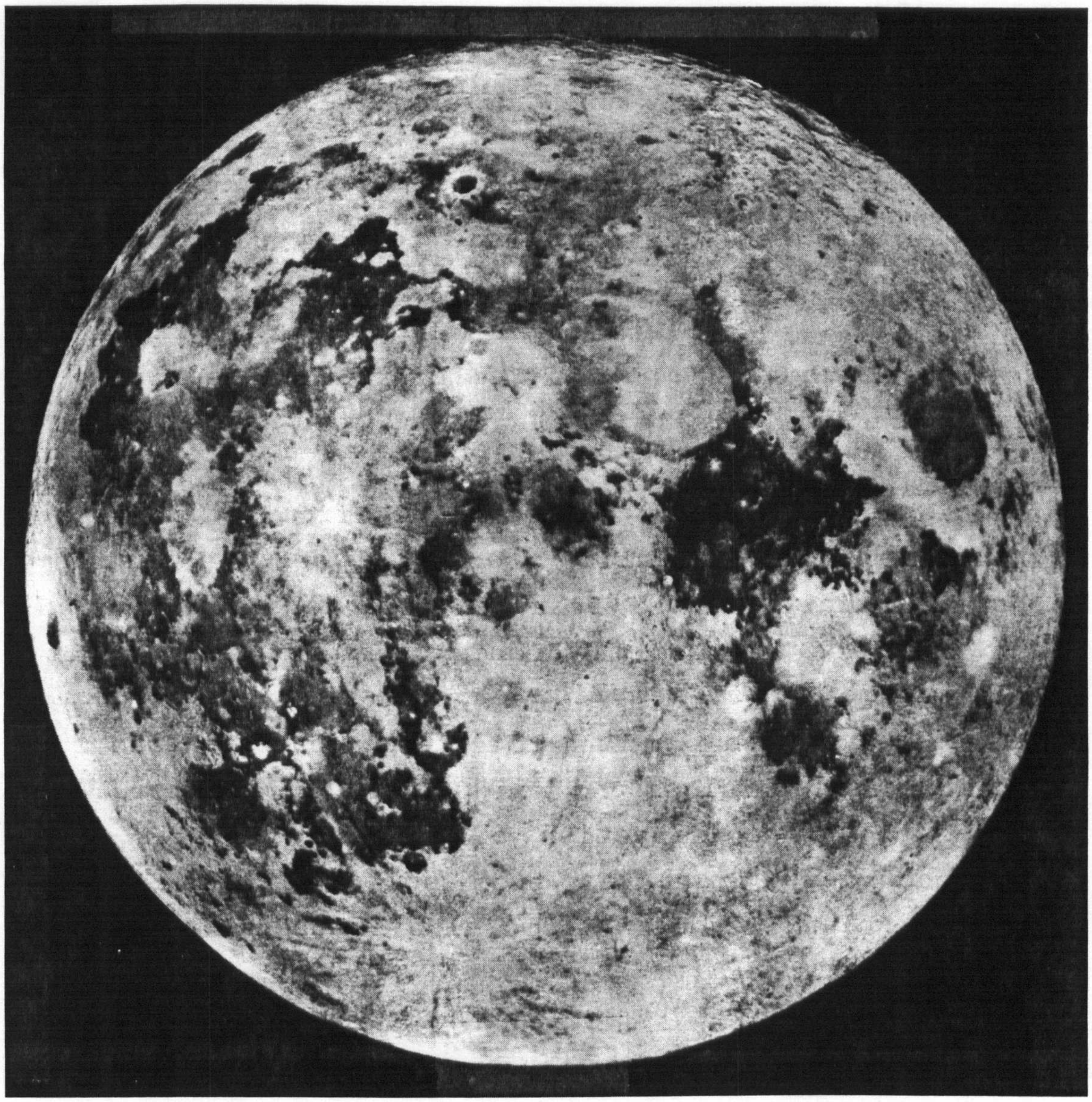


Fig. 2. Color difference photograph of the near side of the Moon, made by subtracting a photograph taken at 0.37 mm from one taken at 0.61 mm. From Whitaker (1965). Dark areas are maria covered by high-Ti regolith. The large, irregular dark area to right of center is Mare Tranquillitatis.

OCCURRENCE OF HELIUM IN LUNAR REGOLITHS

There is a substantial body of information on the occurrence and distribution of helium in lunar regoliths. Implantation of gases in particulate material is proportional to total particle surface area per unit of mass, hence helium is concentrated in the

-100 μm fraction (Fig. 3), which makes up about 60% of the regolith. When this fine fraction is heated to 700°C., essentially all the hydrogen and 90% of the helium-3 in the total regolith are released (Fig. 4) and can be collected in suitable apparatus.

As byproducts of the extraction of He3, various amounts of the other gases present in the regolith would be recovered (Fig. 5). The large amount of hydrogen is very important. Part

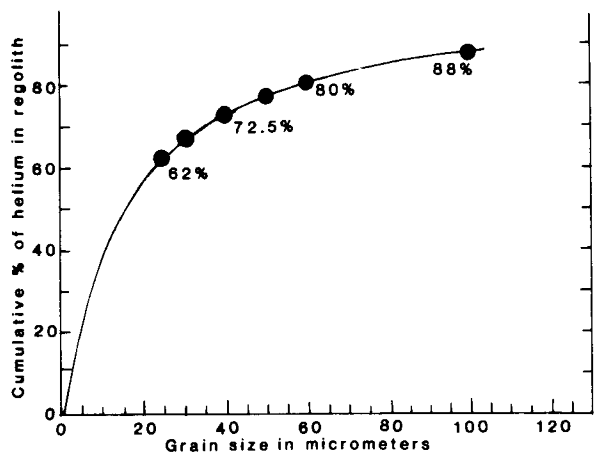


Fig. 3. Percentage of total helium in relation to grain size in Apollo II regolith sample 10084, based on data from Criswell and Waldron (1980) and Hintenberger et al. (1970).

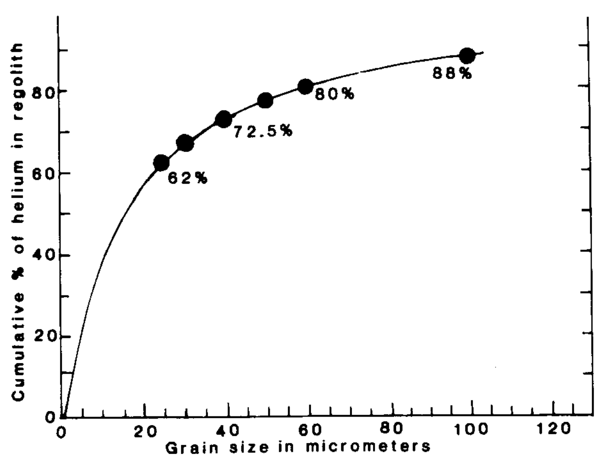


Fig. 4. Release of He3 from regolith on heating. Based on data of Pepin et al. (1970).

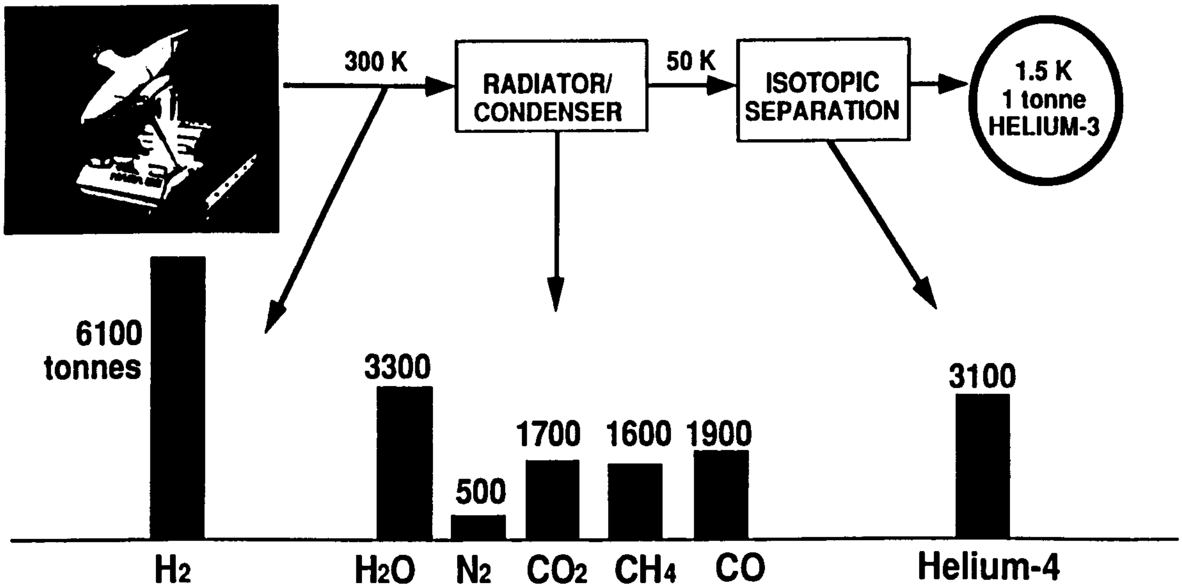


Fig. 5. Elements of the process for extracting He3 from regolith and amounts of various other gases released per tonne of He3.

of the gas could be used as a component of space fuel. The remainder could be used in the production of water and oxygen by any of several processes under investigation in various laboratories. Both oxygen and water are essential for life support, but oxygen is potentially important also as a component of space fuel.

Analysis of regolith samples from the Apollo and Luna missions has shown that there is a definite relationship between the titanium content of a regolith and its helium content (Fig. 6). As indicated below, this relationship is critical to the assessment of the helium potential of the Moon. Highland regoliths are low in TiO_2 and also low in helium. The same is true of some mare regoliths. Others, however, are relatively high in TiO_2, containing 8 to as much as 14%. Such high-Ti mare regoliths are enriched in helium, containing 30 or more wppm helium. The apparent reason for the He enrichment is that most of the Ti is contained in the mineral ilmenite ($FeTiO_3$). Kirsten and

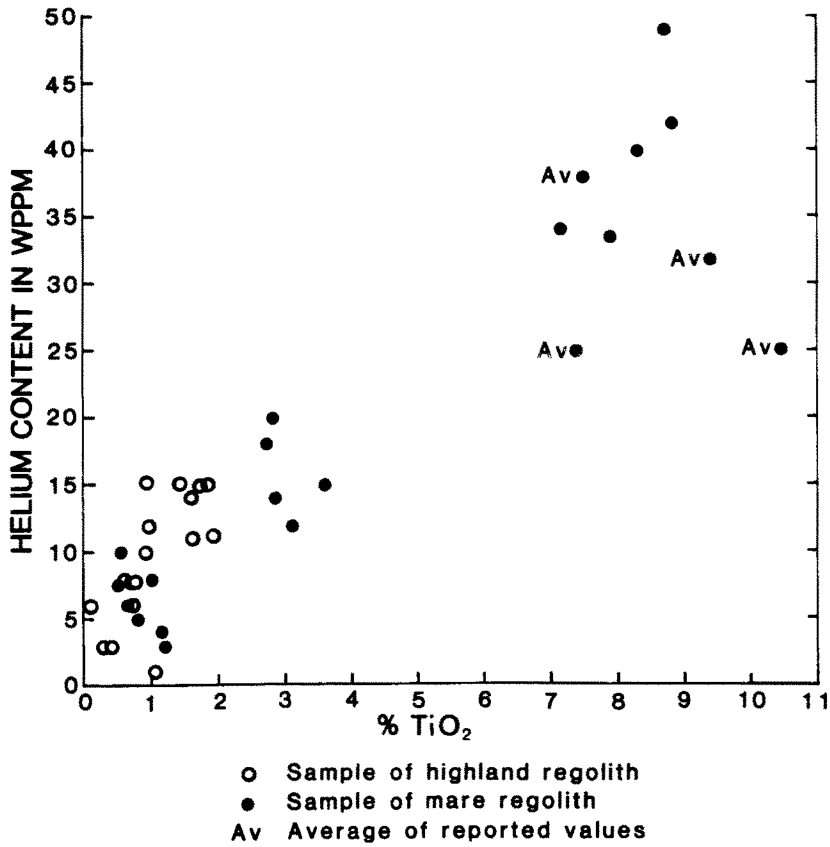


Fig. 6. Relation between He contents and TiO2 contents of lunar regolith samples. Data from Bogard and Hirsch (1978), Bogard and Nyquist (1972), Criswell and Waldron (1982), Cuttitta et al. (1971), Cuttitta et al. (1973), Eberhardt et al. (1970), Eberhardt et al. (1972), Eugster et al. (1975), Funkhauser et al. (1970), Heymann and Yaniv (1970), Heymann et al. (1972a, 1972b), Heymann et al. (1973), Heymann et al. (1978), Hintenberger et al. (1970), Hintenberger et al. (1971), Hintenberger et al. (1974), Hintenberger and Weber (1973), Hübner et al. (1973), Hubner et al. (1975), Kirsten et al. (1972), Laul et al. (1974), Laul and Papike (1980), 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), Wilhelms (1987), Willis et al. (1972). From Cameron (1988).

others (1970) have shown that ilmenite is a more efficient getter of helium than any other abundant mineral in lunar regoliths. Owing to the enrichment, high-Ti regoliths are of prime interest as potential sources of He3.

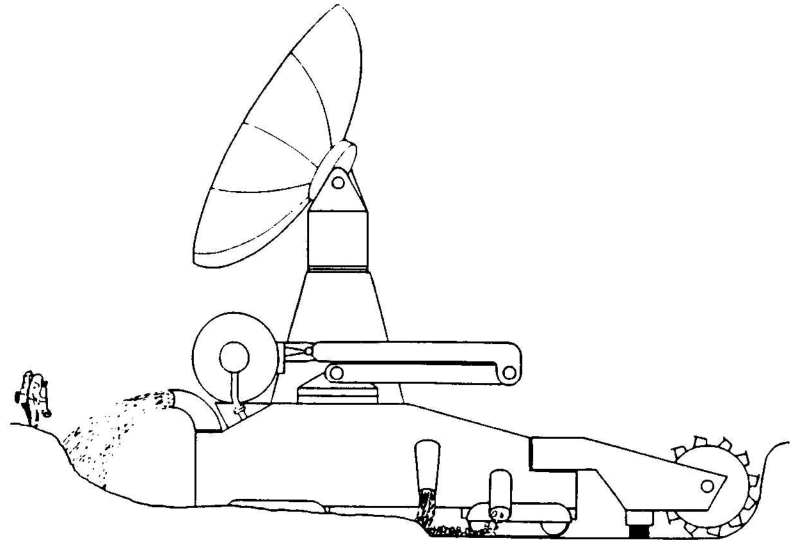
MINING AND PROCESSING OF REGOLITH

Figure 7 shows a machine for mining regolith for He, one of several models under consideration at Wisconsin. A bucket wheel excavator would feed regolith to a vibrating screen that would discard the coarse material. Material coarser than 100 µm would be removed electrostatically. The fine fraction would then be heated and the released gases collected, compressed into tanks, and transported to a gas processing plant. There the various gases would be separated, and He3 would be separated from He4. The basic elements of the processing are indicated in Fig. 5.

It has been calculated that 25 tonnes of He3 would supply U.S. energy needs for electricity for one year at the 1990 rate of consumption. The scenario under consideration for He3 fusion penetration of the U.S. electrical generating market (Thompson et al., 1990) calls for production of He3 at a rate rising from 10 kg. in 2015 to 52 tonnes in 2052. Assuming an average depth of regolith of 3 m, a conservative estimate, and an average total He content of 30 wppm, production of 52 tonnes per year would require mining about 8.5 billion tonnes of regolith. Production on that scale obviously is dependent on the availability of very large amounts of regolith with a helium content of 20 wppm or more. The distribution and extent of regoliths that are high in TiO_2 and thus should be high in helium content are therefore of prime importance.

DISTRIBUTION OF HIGH-TITANIUM REGOLITHS

Substantial information on the distribution of high-Ti regoliths is available from remote sensing (Basaltic Volcanism, 1981a, 1981b). Gamma-ray sensing has provided direct measurements of Ti content of regoliths in two belts of the equatorial region of the Moon. Measurements of spectral reflectance, calibrated against samples of lunar regoliths, have provided information for



SIDE VIEW OF LUNAR MINER MARK-II

TOP VIEW OF LUNAR MINER MARK-II

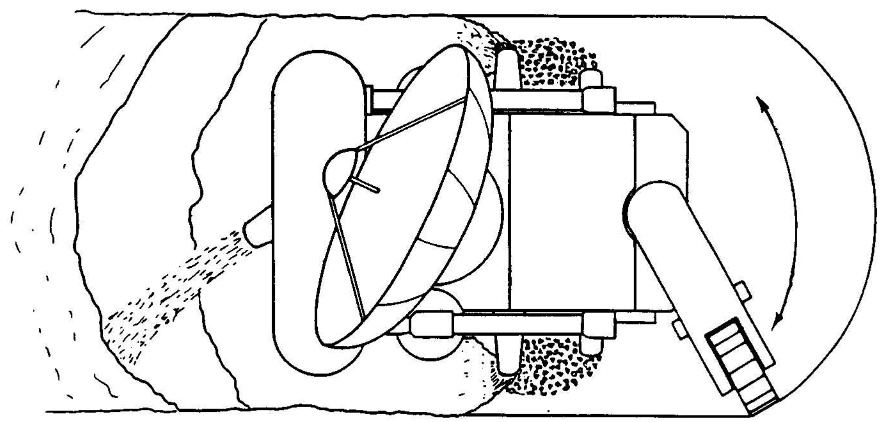


Fig. 7. Two views of Lunar Miner Mark II, from Sviatoslavsky and Jacobs (1988). The machine is powered by solar energy received by the collector at the top of the machine. The bucket wheel excavator swings from side to side as the machine advances. Rejected coarse material and spent heat-processed material are ejected from the rear and side of the machine.

the entire nearside of the Moon. Agreement of the two types of sensing is good. Figure 8 shows the results of gamma-ray spectroscopy of two equatorial belts, with high-Ti areas shown in black. The large area east of the 15°E meridian is Mare Tranquillitatis. Figure 9 summarizes what is known of the distribution of high-Ti regoliths on the near side of the Moon,

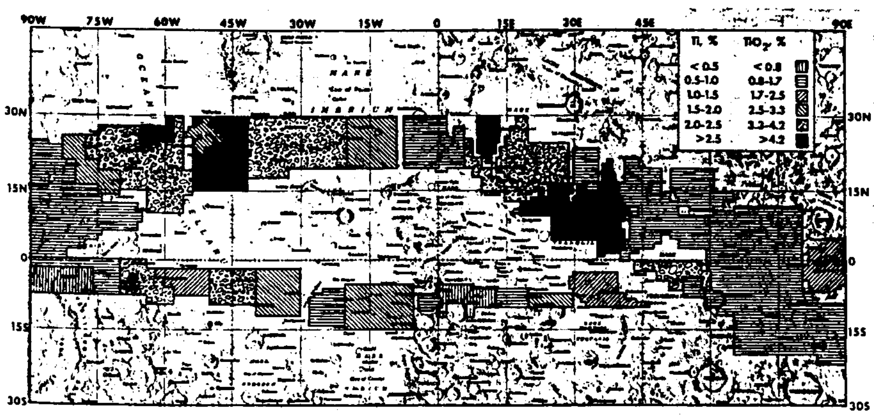


Fig. 8. Map of the titanium content of the lunar regolith covering nearside regions overflown by Apollo 15 and 16. From Metzger and Parker (1980), by permission.

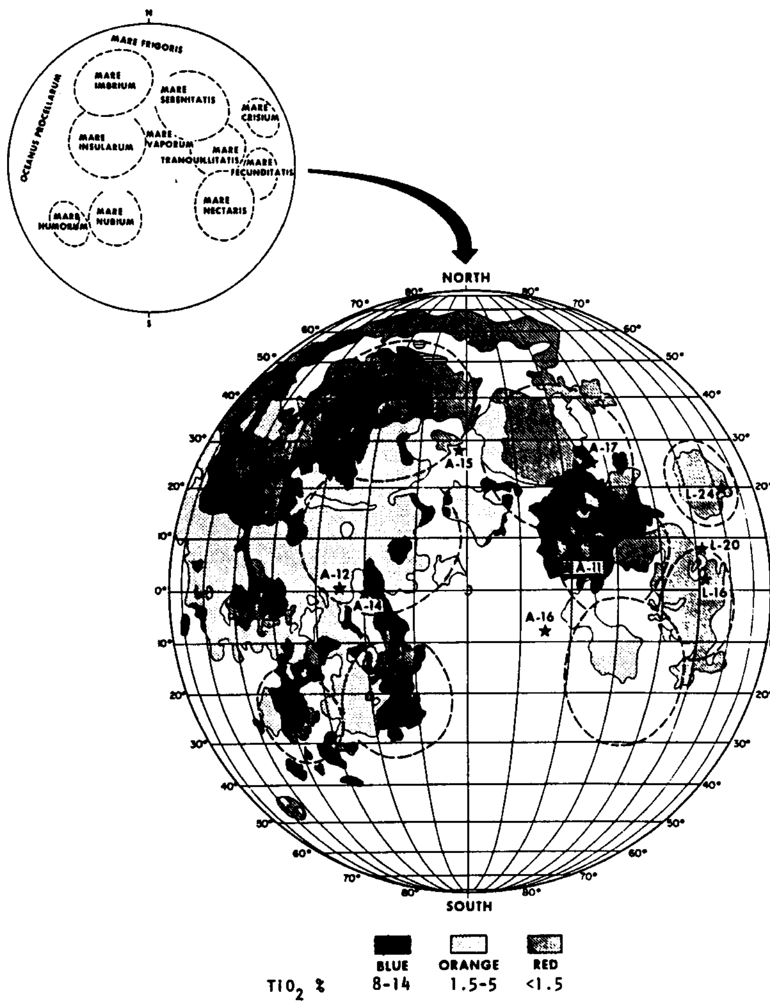


Fig. 9. Lunar sample localities and distribution of color groups of basaltic regoliths, with inferred TiO_2 contents. From Basaltic Volcanism (1981b).

from studies of spectral reflectance. Note that Mare Tranquillitatis appears as a high-Ti area, as it does in Figure 2.

In terms of present information, Mare Tranquillitatis is the most promising site for the first helium mining operation on the Moon. High-Ti regolith was first sampled at the Apollo 11 landing site in the southwestern part of the mare. Helium contents of various samples range from 34 to 44 wppm. Remote sensing indicates that high-Ti regolith occurs over about 93% of the roughly 300,000-sq. km. area of the mare. Comparison of color difference photographs made by Whitaker (Fig. 2) and by Johnson et al. (1977) indicates that about 28% of the area is occupied by regolith with 7.5% TiO_2 and about 65% by regolith containing 6.0 to 7.5% TiO_2 (Fig. 10). The inferred He contents of the two categories are respectively 30 to 44 wppm and 20 to 30 wppm.

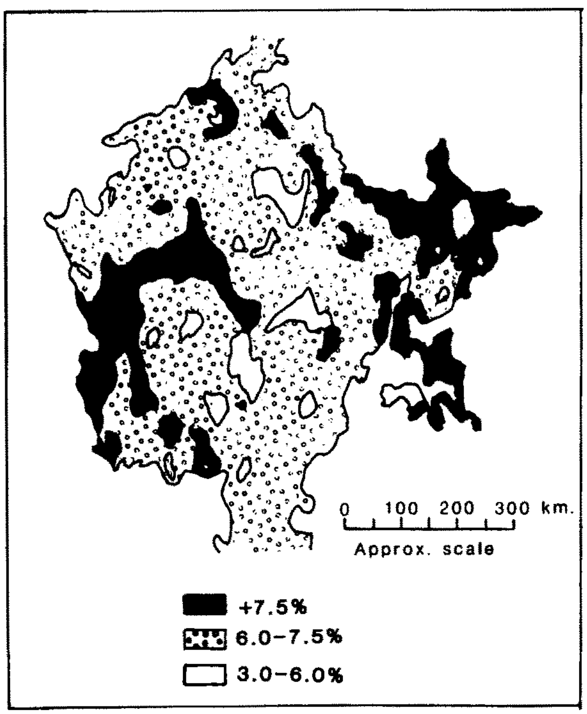


Fig. 10. Inferred variations in TiO_2 content of regolith of Mare Tranquillitatis, based on an enlargement of part of Fig. 2 and on the color difference photograph by Johnson et al. (1975).

MINABLE PERCENTAGE OF MARE TRANQUILLITATIS

The next question is: How much of the high-Ti regolith of Mare Tranquillitatis will be minable? Ideally, mining areas should be flat or gently undulating. The surface of Mare Tranquillitatis, however, is disturbed by various features. The larger features are ridges, rilles, domes, islands of basement rocks, major craters, and rays (Fig. 11). Areas occupied by the first five types of features will be mostly unminable; rays are likely to be minable. Measurements made on geologic maps of Mare Tranquillitatis indicate that the larger features occupy about 24% of the mare as a whole (Table 1). However, they occupy only about 12% of an area of 85,000 sq. km. in the northeastern part of the mare (Fig. 12). Figures 2 and 10 indicate that most of this area is covered by high-Ti regolith.

Table 1

Percentages of Mare Tranquillitatis Occupied by Major Features

	Whole Mare	Western Part	Northeast Part
Domes	0.8%	0.3%	1.0%
Ridges	4.1	5.6	3.4
Craters	7.0	10.9	2.0
Rilles	0.7	0.7	0.7
Basement rocks	5.0*	2.9	0.5
Rays	6.3	8.0	4.7
Totals	23.9%	28.4%	12.3%

*Includes patches of basement rocks on the Taruntius quadrangle outside the limit of the north-east area as shown on Figure 13.

Geologic maps give information only on the percentage of the mare that will be unminable owing to major features. In the intervening areas, minable percentages will depend on the number,

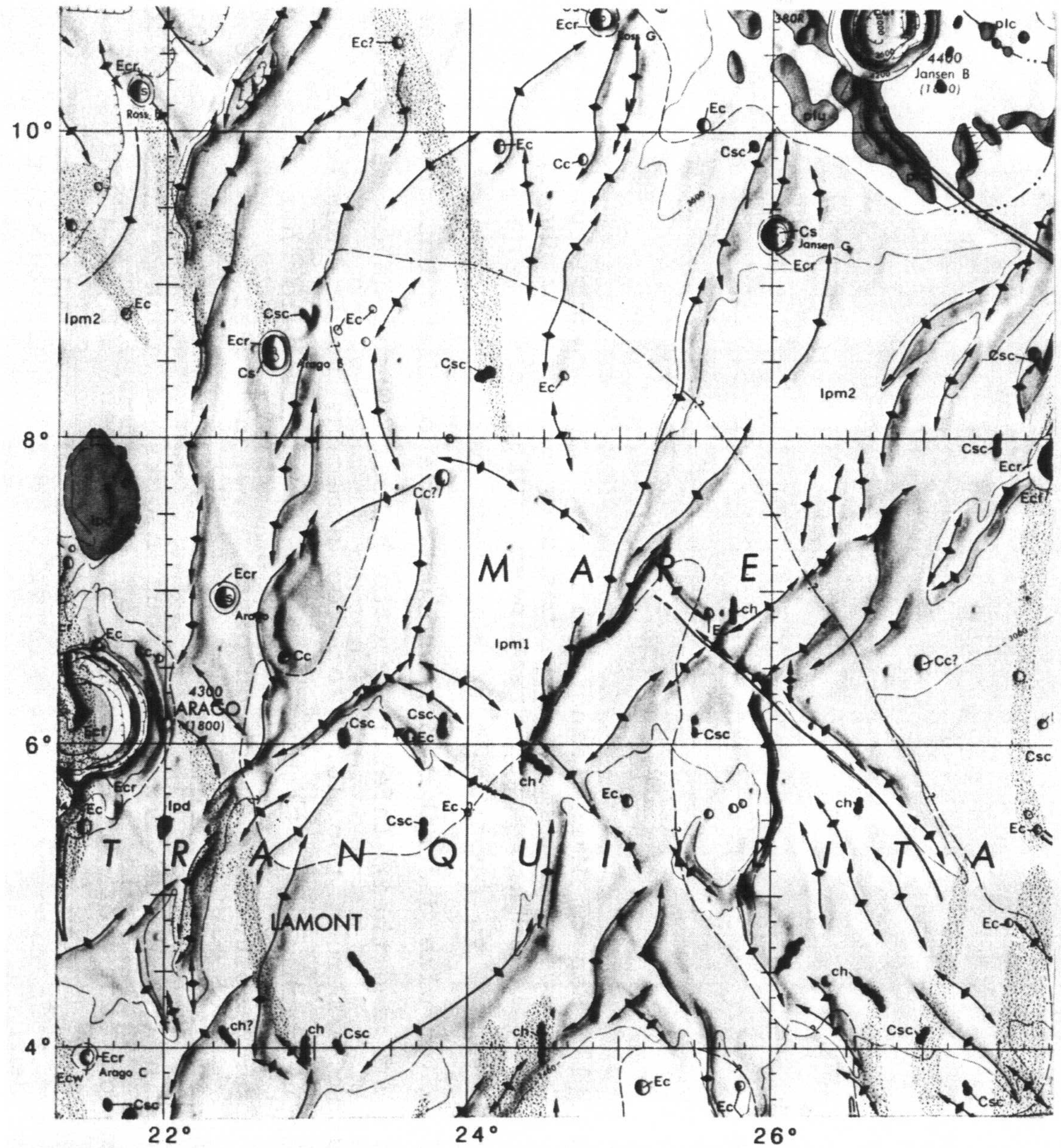


Fig. 11. Geologic map of part of Mare Tranquillitatis, from map of Julius Caesar quadrangle by Morris and Wilhelms (1967).

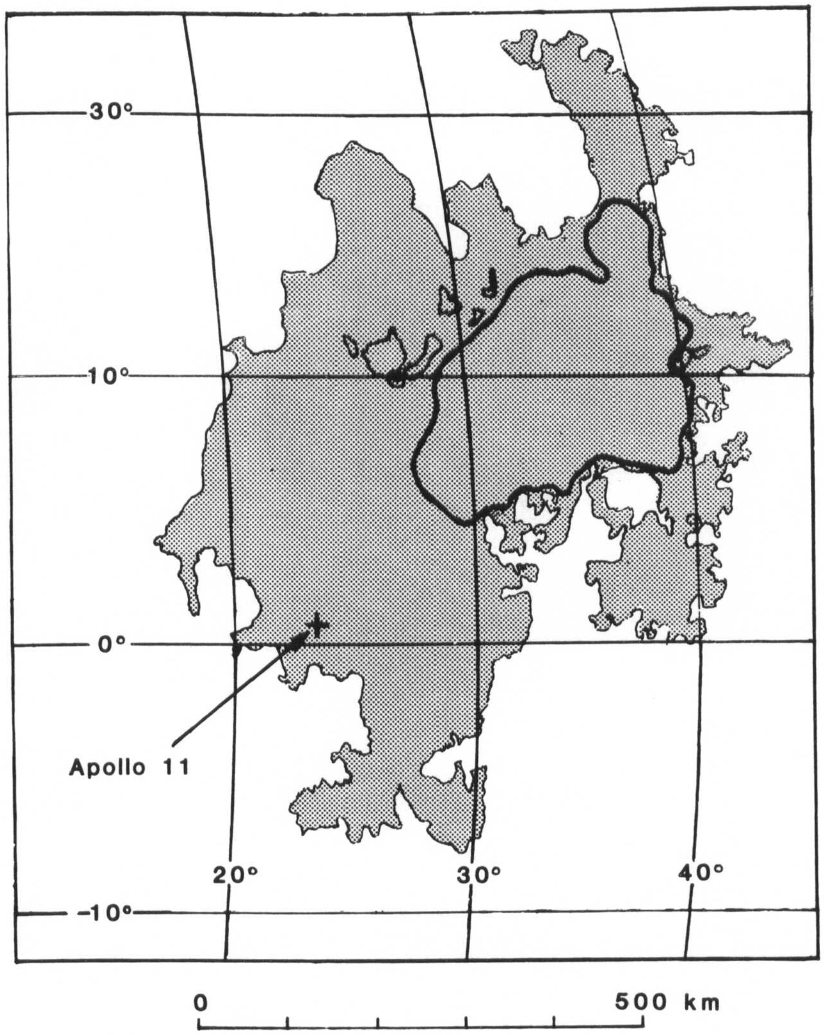


Fig. 12. Map of Mare Tranquillitatis. Major structural features are less numerous in the area bounded by the heavy black line than in the remainder of the mare.

size and size distribution, and patterns of distribution of lesser craters and their inferred ejecta halos. Those halos may contain blocks of rock too large or too numerous to be handled by the mining machinery. Figure 13 shows an ejecta halo that appears on a high-resolution photograph of an area just east of the Apollo 11 landing site. The limit of resolution is 2 m. Around the crater, within the white line, numerous blocks of rock ejected by the impact that formed the crater can be seen. Ejecta halos, like this one, that contain large blocks of rock must therefore be avoided.

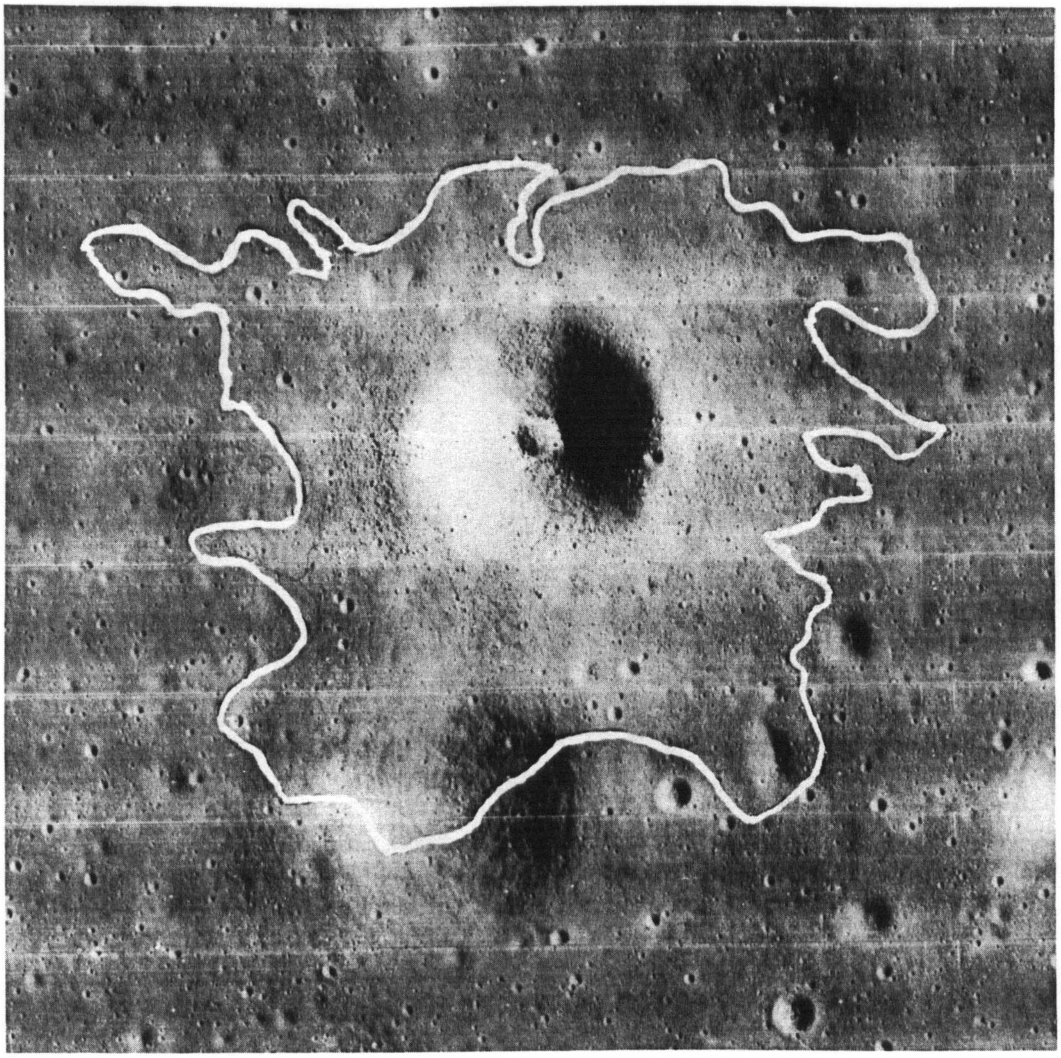


Fig. 13. Copernican crater, 440 m in diameter, on Lunar Orbiter photograph II 83-H_3. Ejecta blocks 2 m or more in diameter are shown over the area bounded by the white line.

Fortunately, only a small percentage of the craters can be expected to have blocky ejecta halos. Most of the craters that pockmark the mare surface are less than 12 m in diameter (Fig. 14). Measurements of fresh craters indicate that the average ratio of depth to diameter is close to 0.25 (Fig. 15), and a study of very small craters (Cameron, 1990) indicates that the average depth of regolith away from craters more than 12 m in diameter is in excess of 3 m. Craters with diameters less than

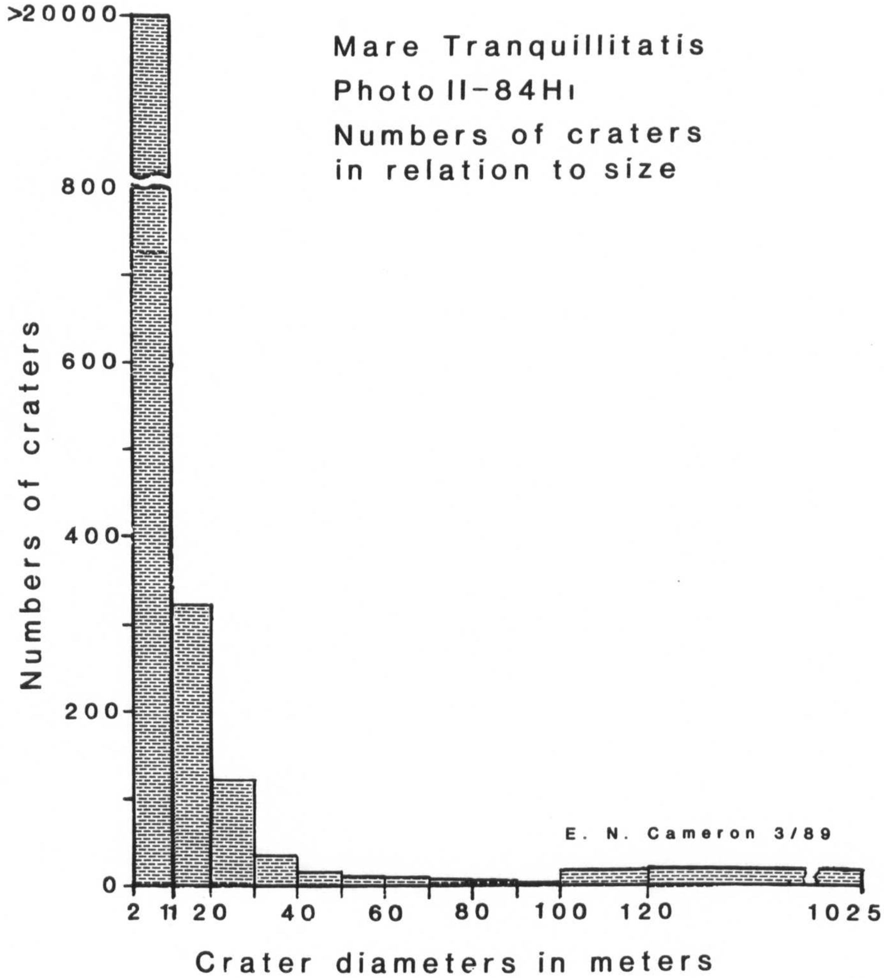


Fig. 14. Numbers of craters in relation to size. Mare Tranquillitatis, Lunar Orbiter photograph II 83-H_1.

12 m will certainly not have penetrated bedrock, from which blocky ejecta could be derived.

Measurements of craters 12 m or more in diameter on high-resolution photographs provide the basis for calculating the percentage of the area covered by each photograph that will be unminable owing to the craters and their inferred ejecta halos. However, there are three problems in measurement of craters and ejecta halos. The first is the range of craters, from fresh craters with steep walls to very old craters so indistinct as to be almost unrecognizable. Fresh craters are obviously unminable.

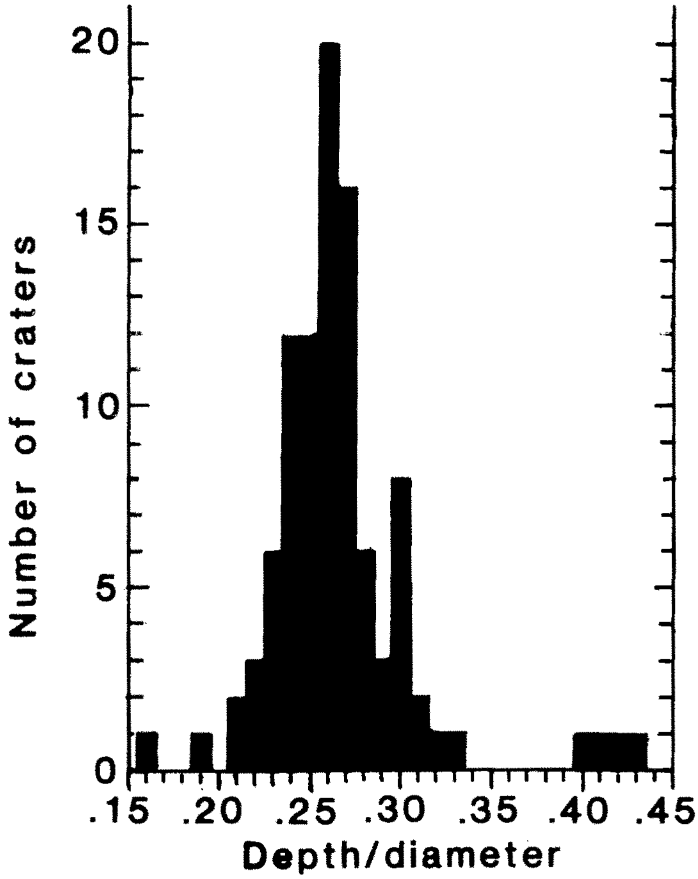


Fig. 15. Depth/diameter ratios of 98 young craters as determined from Lunar photograph II 84-H (prints H_1, H_2, H_3).

Very old craters cause only undulations of the surface. It seems likely that such craters (1) will pose no physical obstacles to mining and (2) will have regolith of sufficient depth and time of exposure to the solar wind to qualify as helium ore. However, in measuring craters, any attempt to draw a line between the two categories of craters quickly degenerates into a purely subjective exercise. All craters on a given photograph, from fresh and sharp to indistinct, have therefore been measured. The result is certainly a conservative approach to estimation of unminable ground.

The second problem is that only blocks 2 m or more in diameter can be seen on the photos. Ejecta blankets outlined from the distribution of visible blocks therefore understate the extent of blocky ground. There is no unequivocal solution of this problem. For purposes of the present study, with the advice of Harrison H. Schmitt, the following rules have been adopted:

(1) If no blocks are visible, either in or adjacent to a crater, the unminable area is taken as a circle centered on and having the diameter of the crater.

(2) If blocks are visible inside a crater, but not on the rim or outside it, the unminable area is taken as a circle centered on the crater and having a diameter twice that of the crater.

(3) If blocks are visible both on the rim and outside the rim, the unminable area is taken as a circle centered on the crater and having a diameter three times that of the crater.

The validity of these rules will be established only through future experience on the Moon, but my own studies of the high-resolution photographs persuade me that the rules will yield reasonable approximations of areas potentially unminable owing to the presence of abundant blocks of bedrock and that the overall result will be a reasonable and conservative estimate of the percentage of Tranquillitatis that will be minable.

The third problem lies in errors of measurement. I estimate that for sharp-rimmed craters, the error is ±0.2 mm for the crater diameter. As crater rims become less distinct, the accuracy of measurement undoubtedly falls off. More than this, for reasons noted above, it is not always possible to be sure what is or is not a crater, rather than an undulation of the mare surface or an artifact of the photography.

Replicate measurements of a few photographs indicate that two successive sets of measurements will not agree either in the numbers of craters measured or in the total areas calculated from the measurements. The error indicated is about 10% of the percentage given; i.e., if the percentage of the area of a photograph occupied by craters and associated blocky ground is given as 20%, the probable error is ±2.0%.

In accordance with the above rules, measurements of craters 12 meters or more in diameter and their inferred blocky ejecta halos as displayed on 15 high-resolution photographs of the Apollo 11 area and 12 photographs of the Ranger VIII area have been made, and areas occupied by craters and halos have been calculated. The total area covered by the photographs is about 700 sq. km. Percentages occupied by the craters and blocky halos range from 8.5% to 50.4%. The average for the Apollo 11 area is 12%, for the Ranger VIII area 22%. Prints 84-H_2 through 91-H_2 give an east-west transect across the area east of the Apollo 11 landing site covered by photographs 76-H through 91-H (Table 2). Prints 67-H_2 through 74-H_2 (Table 3) give an east-west transect across part of the Ranger VIII area.

The final factors that must be taken into account in calculating the minable percentage of the regolith are the capability of the mining system for handling material containing small blocks and the minimum size of a cost-efficient mining unit.

The total effect of all factors determining the minable percentage of the regolith of an area is illustrated by an analysis of high-resolution print II 84-H_3 (Fig. 16), which covers an area approximately 4.3 by 6.2 km. east of the Apollo 11 landing site. The print shows craters ranging from 450 m in diameter down to 2 m, the limit of resolution. We assume first that the mining system cannot handle blocky material. If the regolith depth is 3 m, all craters 12 m or more in diameter must be avoided, since in general these will have penetrated bedrock and will have blocky ejecta halos. On an overlay of Fig. 16 we plot all such craters

Table 2

Data from Prints 84-H_2 through 91-H_2

Print	Number of Craters Measured	Percentage of Area Unminable*
II 84-H_2	506	7.8
II 85-H_2	988	14.1
II 86-H_2	987	14.4
II 87-H_2	775	11.3
II 88-H_2	1129	12.3
II 89-H_2	872	13.3
II 90-H_2	1331	13.1
II 91-H_2	902	12.8
Average		12.5

*In this table and in Table 3, this figure indicates the percentage of the area occupied by craters 1 mm (11.7 m) or more in diameter plus associated blocky halos.

Table 3

Data from Prints II 67-H_2 through II 74-H_2

Print	Number of Craters Measured	Percentage of Area Unminable
II 67-H_2	664	23.2
II 68-H_2	806	15.0
II 69-H_2	847	12.1
II 70-H_2	930	11.1
II 71-H_2	520	50.4
II 72-H_2	740	16.4
II 73-H_2	619	39.0
II 74-H_2	883	15.8
Average		22.2

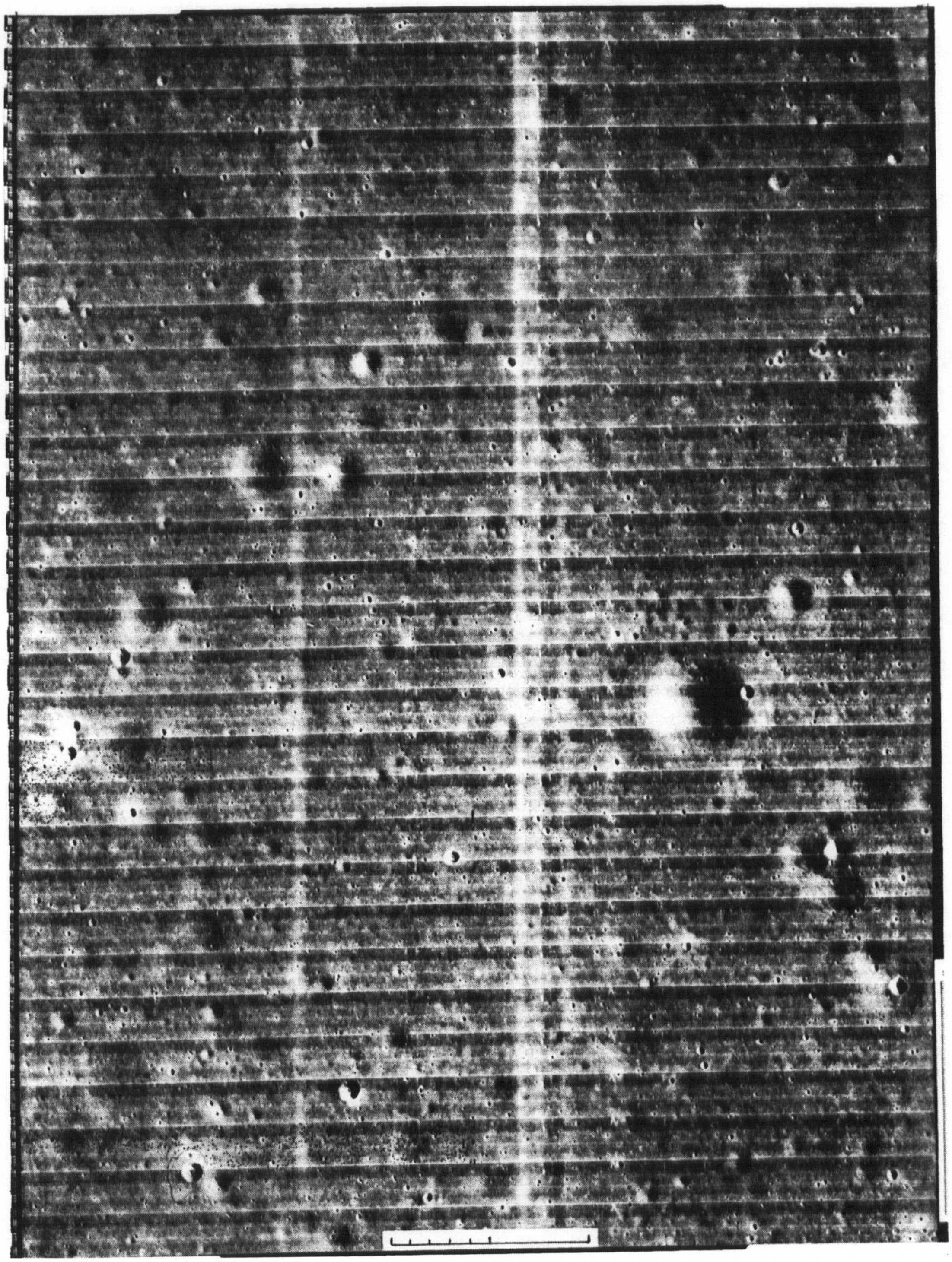


Fig. 16. Lunar Orbiter print II 84-H_3 reduced from original size of 39 × 53 cm. Note range in distinctness of craters. Scale is 1 km long.

(Fig. 17). Each crater is plotted as a circle with its center at the crater center and its diameter equal to the diameter of the crater plus its inferred ejecta halo. We assume next that the minimum feasible mining unit is 400 m square. We find that the area of minable regolith will not exceed 15% of the total area. Suppose, however, that the minimum feasible mining unit is only 300 m square (Fig. 18). About 22% of the area of the photograph is now minable.

If we assume that the mining system is capable of handling regolith with small blocks of rock, craters 12 to 24 m in diameter can be omitted from the overlay. With 400 m unit mining blocks plus possible extensions (Fig. 19) 22% of the area is minable, whereas with 300 m unit blocks (Fig. 20) 56% of the area is minable; minable regolith in the latter case (area in Fig. 20) is 95,200,000 tons.

Similar charts have been prepared for the areas of three additional high-resolution photographs. A plot of the data for all four areas (Fig. 21) shows very clearly the effect of unit block area on minable percentage. For each area, the minable percentage increases as the size of the unit block is decreased. The minable percentage reaches its maximum when the unit block size becomes zero. It is evident that for any given area of the mare, the design of the mining system, particularly its maneuverability and its capacity for handling small blocks of rock, will strongly affect the minable percentage.

The study suggests that for the Apollo 11 area minable percentages will range from 28 to 57% if the basic mining unit is 300 m square and small blocks of rock can be handled. With supplementary equipment to handle still smaller areas, it seems likely that an average of 50% can be achieved.

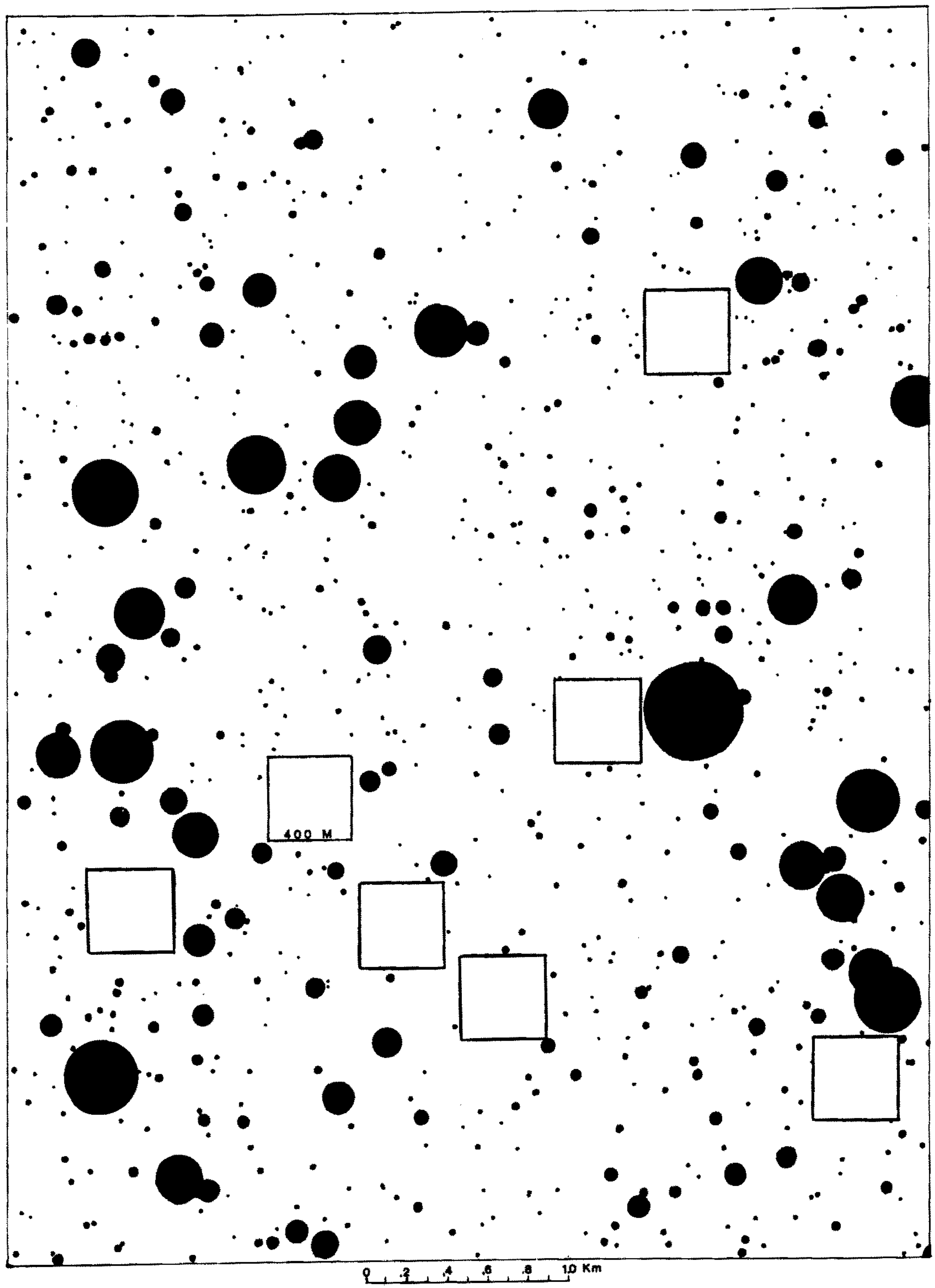


Fig. 17. Craters 12 m or more in diameter, plotted on an overlay of Fig. 17. Unit mining blocks are 400 m square.

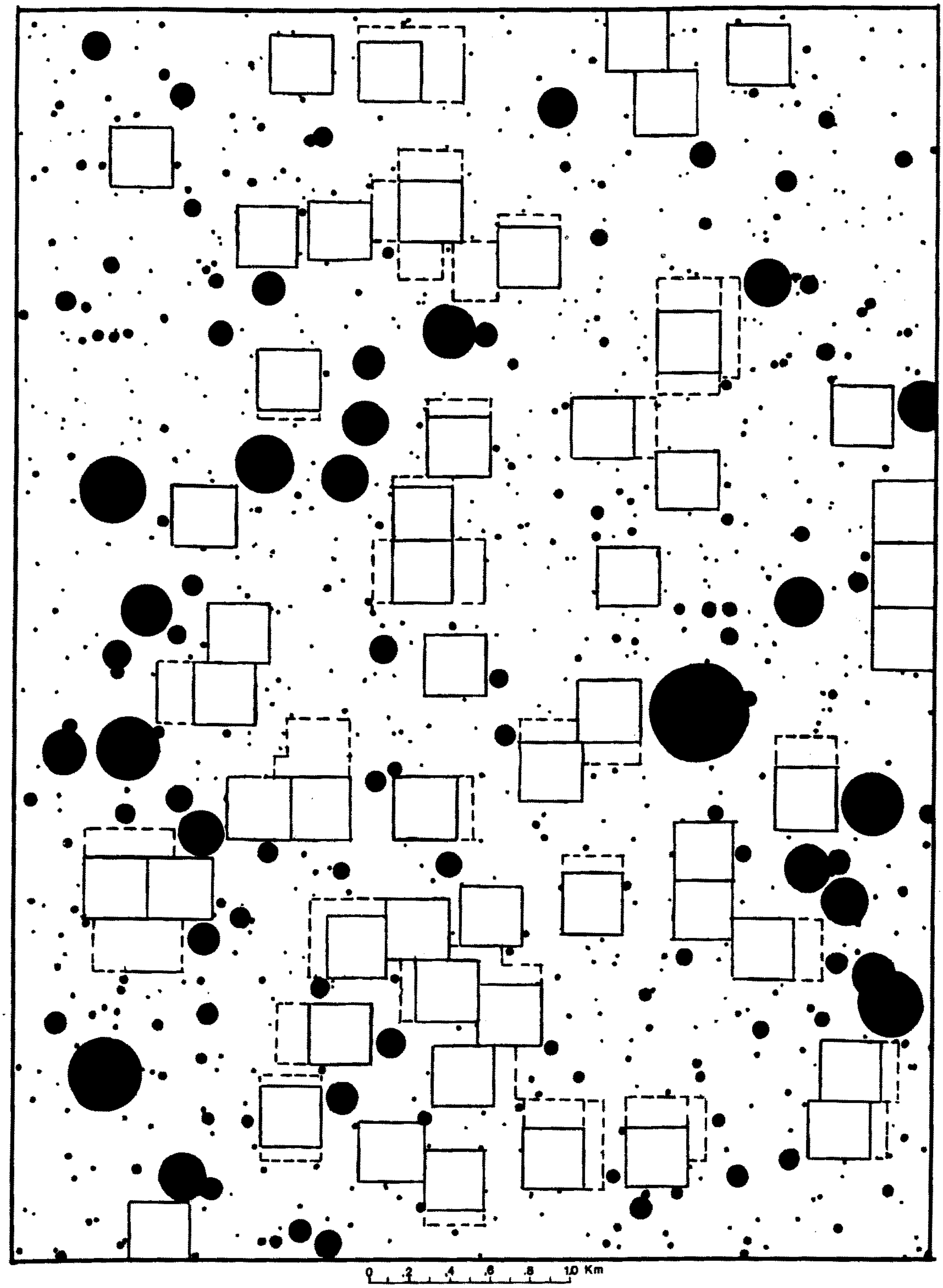


Fig. 18. Same as Fig. 18, but with 300 m unit mining blocks and possible extensions (bounded by dashed lines).

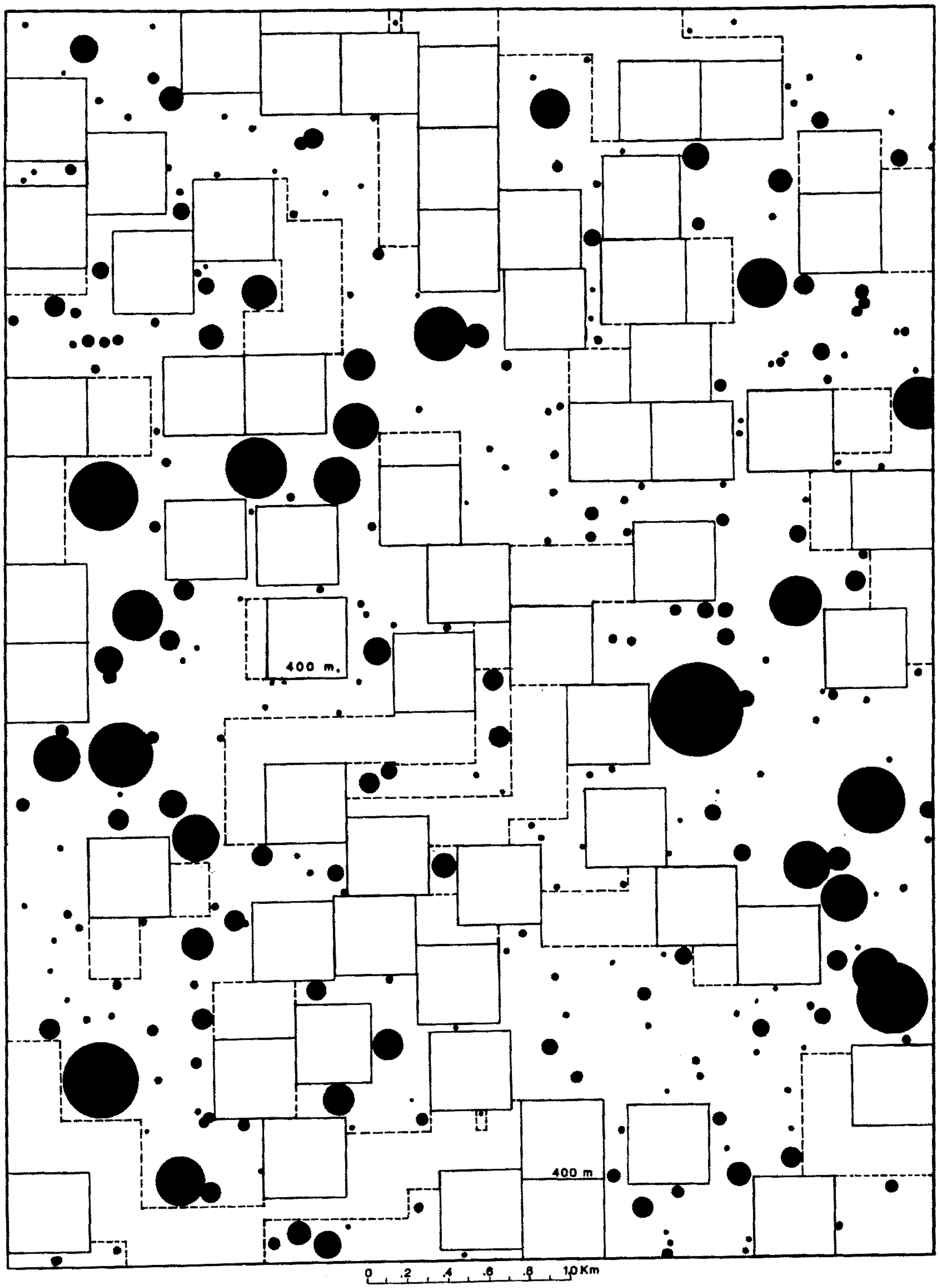


Fig. 19. Craters 24 m or more in diameter plotted on an overlay of Fig. 17. Unit mining blocks are 400 m square.

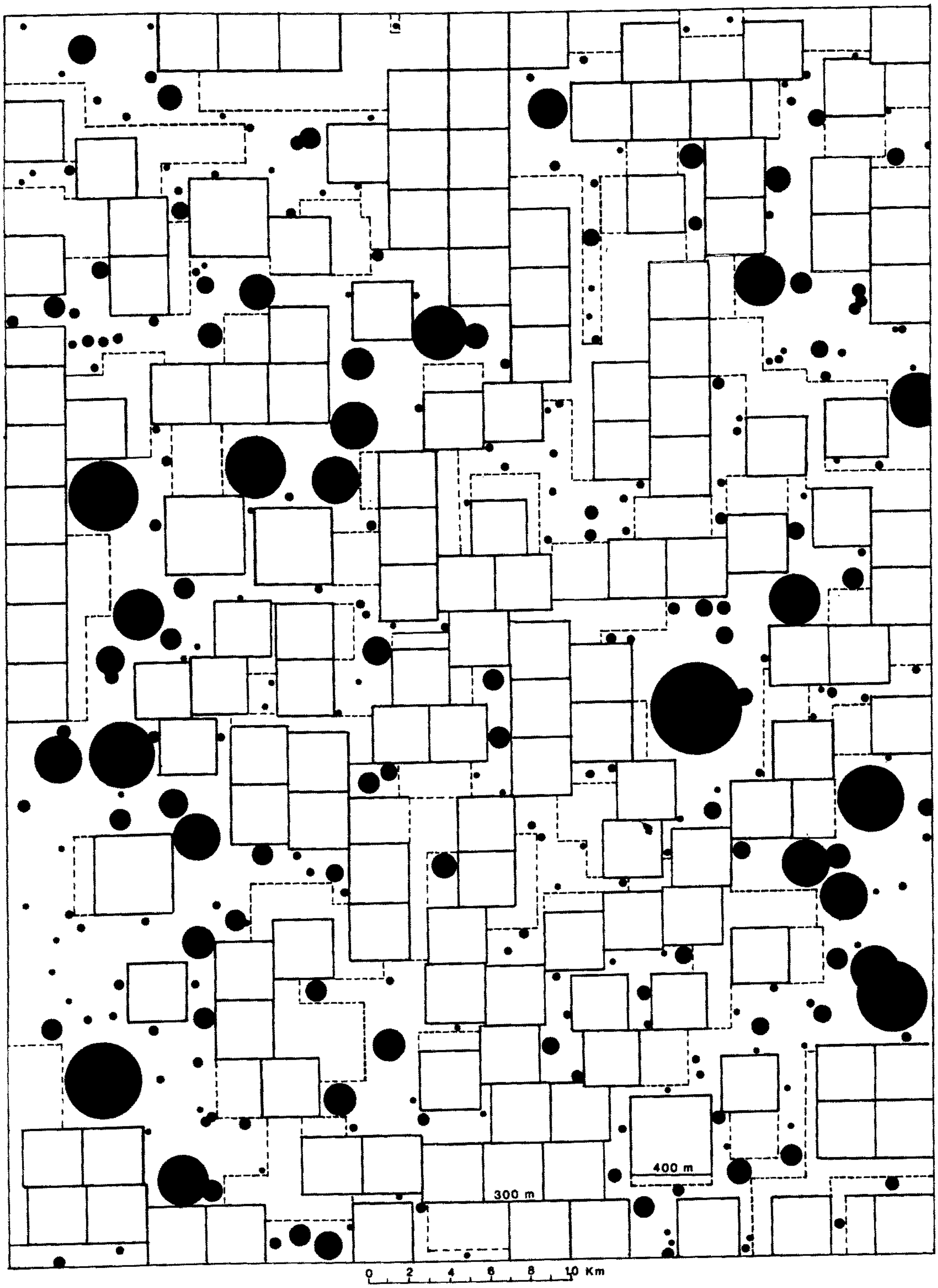


Fig. 20. Same as Fig. 20, but with 300 m unit mining blocks.

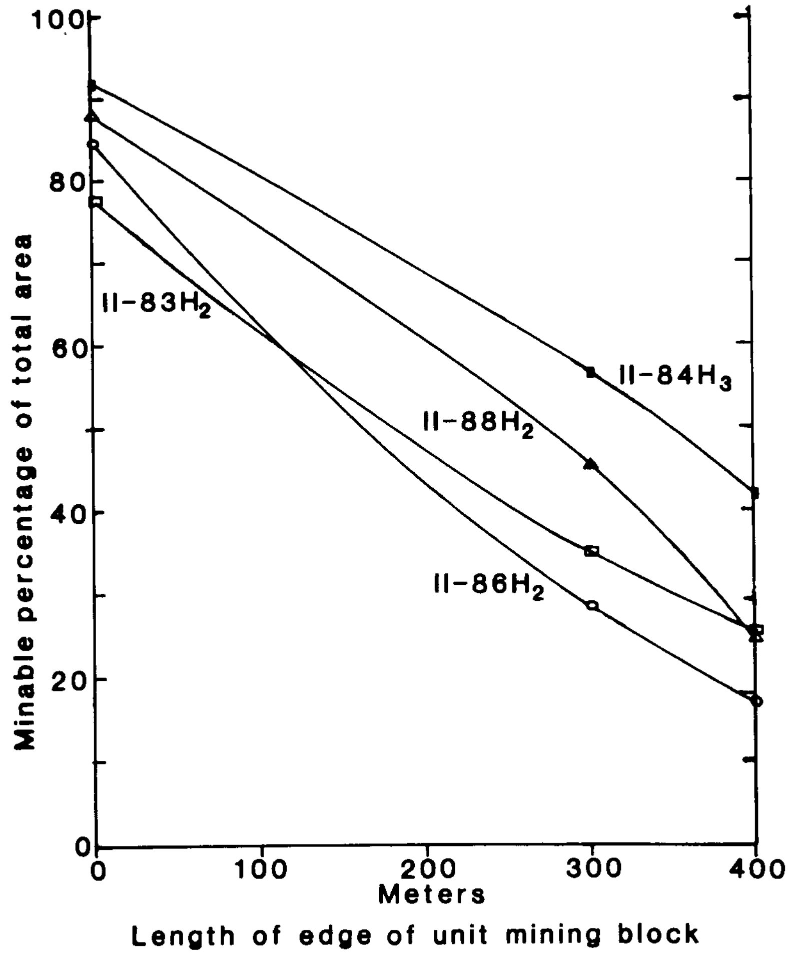


Fig. 21. Minable percentage of total area in relation to size of unit mining block, based on crater and crater-halo measurements for four high-resolution Lunar Orbiter photographs.

AMOUNT OF HELIUM IN MINABLE REGOLITH OF MARE TRANQUILLITATIS

The data discussed in preceding sections of this report provide the basis for an estimate of tonnage and grade of the regolith of Mare Tranquillitatis and an estimate of the amounts of He and He3 available in it. The area of the mare is estimated at roughly 300,000 sq. km., of which it is estimated that as much as 50 percent may be minable with a suitable mining system. The average thickness of regolith is taken as 3 m, although studies of small craters appear to indicate a greater thickness. As indicated earlier it is inferred that 28% of the total area in the mare is covered by regolith that contains 30 to 44 wppm total He, 65% by regolith that contains 20 to 30 wppm total He, and 7% by regolith that contains less than 20 wppm total He and is not of interest at the present time. Areas and minable tonnages of regolith, He, and He3 represented in the first two categories are given in Table 4.

Table 4

Minable Regolith and Helium Content of Mare Tranquillitatis

Regolith Category	Area in sq. km.	Average He Content, wppm	Regolith Minable tonnes	He tonnes	He3 tonnes
A	84,000	38	252×10^9	9.58×10^6	2,726
B	195,000	25	598×10^9	14.96×10^6	4,316
Totals	279,000		850×10^9	24.54×10^6	7,042

Note: He3 content based on He/He3 = 2600.

OTHER AREAS OF HIGH-TITANIUM REGOLITH

Remote sensing (Fig. 9) has indicated that other areas of high-Ti regolith occur on the nearside of the Moon. Large areas are indicated in Oceanus Procellarum, Mare Imbrium, Mare Humorum, and Mare Nubium, and smaller areas occur in Mare Insularum and southwest of Mare Serenitatis. The total of the areas is certainly several times that of Mare Tranquillitatis. No samples of regoliths of the areas are yet available, but the areas certainly deserve investigation as possible sources of He3. High-Ti regolith with He in excess of 30 wppm was found by Apollo 17 in the Taurus-Littrow area, along the southeast side of Mare Serenitatis; this appears to be an extension of the regolith of

Tranquillitatis. However, it is an area of complex geology that does not appear especially attractive for mining.

ENVIRONMENTAL CONSEQUENCES OF HELIUM MINING

The environmental consequences of helium mining are currently being studied by the University of Wisconsin Task Force on He3. According to the schedule of operations envisioned by the group, mining would begin in 2015 and proceed at a steadily increasing rate, reaching 8.5 billion tons of regolith in 2052. This is somewhat less than the tonnage of rock excavated annually by the coal mining industries of the world. Total area disturbed from 2015 to 2052 by mining and creation of access roads would be about 17,000 sq. km. After 2052 an additional 1420 sq. km. would be disturbed per year.

Regrading of excavated areas could proceed as mining progresses, and the surface could be restored to approximately its original contour. Craters less than about 24 m in diameter would be destroyed, along with some of the older, subdued larger craters. Major features - large deep craters, ridges, rilles, and volcanic domes - would be unminable and left untouched. Separating mined areas would be a large number of areas in which unminable craters and their ejecta halos are too closely spaced to permit mining. In those areas the full range of smaller features of the mare would be left in their pristine condition.

Surface installations at widely scattered mining bases would occupy only a minute fraction of the total area of the mare. As mining progressed across the mare, bases no longer useful could be successively abandoned and their installations torn down. Their materials could be buried in adjacent mined out areas.

None of the changes in the lunar surface would be visible from Earth, even with telescopes. During mining and processing of regolith gases would escape, but studies indicate that only in the immediate vicinity of installations would there be any deviation from the current 'hard' vacuum.

SUMMARY

The D-He3 fusion cycle is an environmentally attractive alternative to use of fossil fuels, nuclear fission, and D-T fusion as sources of energy. He3 is not available in sufficient quantity on earth, but the Moon is a potential source of very large amounts of He3. Mare Tranquillitatis has been identified as the potential source of enough He3 to provide the earth with electrical energy for more than 100 years, and other areas of the Moon could be major sources. The northeastern part of Tranquillitatis appears most attractive for an initial mining venture. The logical next step is verification of the He3 resource potential of the mare, by systematic surveying and sampling of the regolith to determine variations in thickness and He3 content, to delineate specific minable areas, and to provide the basis for more accurate estimates of tonnage and grade of minable regolith. This work should have high priority in future investigations of the Moon.

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