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Lunar Resource Evaluation and Mine Site Selection

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I have considered two scenarios in this evaluation of lunar mineral resources and the selection of possible mining and processing sites. The first scenario assumes that no new surface or near-surface data will be available before site selection (presumably one of the Apollo sites). The second scenario assumes that additional surface geology data will have been obtained by a lunar orbiter mission, an unmanned sample return mission (or missions), and followup manned missions.

Regardless of the scenario, once a potentially favorable mine site has been identified, a minimum amount of fundamental data is needed to assess the resources at that site and to evaluate its suitability for mining and downstream processing. Since much of the required data depends on the target mineral(s), information on the resource, its beneficiation, and the refining, smelting, and fabricating processes must be factored into the evaluation. The annual capacity and producing lifetime of the mine and its associated processing plant must be estimated before the resource reserves can be assessed. The available market for the product largely determines the capacity and lifetime of the mine.

While realistic market determination is several years away, this study starts by assuming a 40 000-metric-ton-per-year lunar mining

operation with a minimum lifetime of 10 years. This size would be sufficient to supply 100 metric tons of liquid oxygen (LOX) per year to low Earth orbit (LEO), assuming a 100-percent extraction efficiency and using an additional 300 metric tons of lunar oxygen to deliver the usable lunar oxygen to LEO and to bring tankers and hydrogen back to the Moon.

A 10-year operation requires processing of nearly 500 000 metric tons of ore. In the cases of iron-titanium mare basalts and of aluminous material from the lunar highlands, this amount of ore is insignificant compared to the potential reserves. And there should be no problem defining adequate reserves of oxygen, iron, titanium, silica, and bulk materials at any otherwise acceptable site.

How does one go about evaluating an ore body on the Moon? On Earth it is fairly straightforward. Data on ore grade, grade continuity, geometry and size of the ore body, grain size and grain size distribution, state of aggregation, accessibility, local relief, availability of power and water, and environmental issues must be collected, analyzed, and evaluated for economic impact. In the terrestrial case, the underlying constraint is profitability. In the lunar case, the only constraint is that the cost of placing the final product in LEO be less than the cost of bringing it from Earth.

Physical and chemical characterization of a potential ore body (prospect) on Earth is accomplished by a detailed sampling program that includes extensive core drilling. Terrestrial remote sensing rarely locates actual ore bodies, only prospects which are then explored in more detail on the ground. It is unlikely that such a sampling program would be carried out at a new landing site. Most of the exploration for lunar mining prospects would probably be done

by remote sensing. The proposed resolution of the lunar resource mapper will not yield as much site information as is already known about the Apollo sites. For this reason an Apollo site, if it contains the appropriate materials, would be the most suitable site for a regolith mining operation. Since water has not yet been discovered on the Moon, it is not considered here. However, if water (ice) were discovered in the polar regions, its availability alone could strongly influence site selection.

William Snow, another participant in the summer study and the author of a paper in volume 2 entitled "Electromagnetic Launch of Lunar Material," has this to say about siting the lunar mine and oxygen production plant:

To obtain lunar oxygen at the earliest possible date, the electromagnetic launcher and liquid oxygen production plant should be deployed at one of the Apollo landing sites. Doing so would eliminate the need for a geochemical orbiter to survey the entire Moon first. To send a geochemical orbiter is good science, but it is not required for siting a lunar oxygen plant. Requiring a preliminary survey would be like having Sutter discover gold in California and then requiring a complete survey of the state before gold mining could begin. We know the mineralogy and chemistry sufficiently well at six locations on the Moon and could begin today designing and constructing a lunar oxygen processing plant on the basis of the samples brought back by the Apollo missions.



California "Forty-Niners"

Soon after the news leaked out that gold had been discovered at Sutter's mill on January 24, 1848, the California gold rush began. No one waited for a government study to determine the most likely mine locations. Instead, in the following year, tens of thousands of prospectors—the "forty-niners"—streamed to California and began to look for a share of the 550 million dollars' worth of gold that was mined there in the next 10 years.

Return to an Apollo Site

Even with our current knowledge of the Apollo sites, we need additional information to assess their suitability for mining. For example, even at the best characterized site, Apollo 17 (fig. 13), small- to medium-scale (in meters) variability in composition and particle size is not sufficiently well known. Because such characteristics profoundly affect the success of a mining and ore processing venture,

many more regolith cores would need to be collected before a mine was specifically located within the area where Apollo 17 landed. The coring locations would be chosen so as to define a grid over each prospect. Each block in the grid would be on the order of several meters square by 2 meters deep. Variations in grain size and mineralogy across the grid would be used to assess the suitability of a specific prospect.

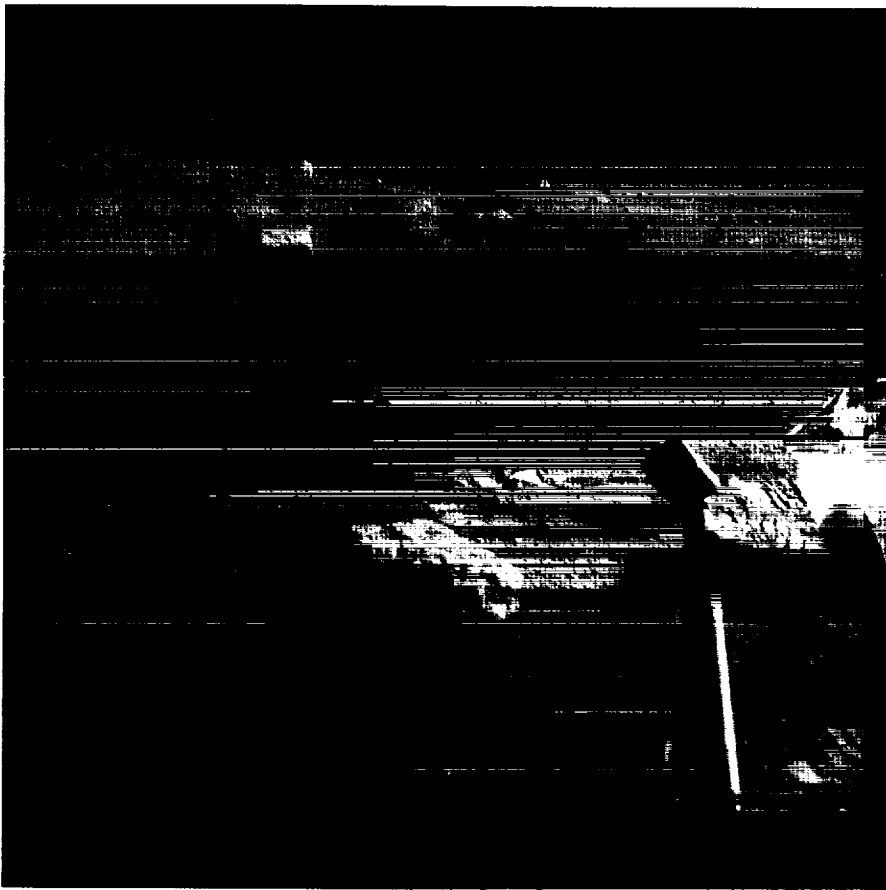


Figure 13

Typical Lunar Surface View at Apollo 17

The crater in the photograph (Ballet Crater) is about 30 meters in diameter. The rock in the foreground is about 40 centimeters across. We have good information over nearly all the surface of the Apollo 17 site on the sizes of craters and rocks on a submeter scale of resolution. However, we have very little information on variation in the third dimension, depth. We have only a single 3-meter core and a few drive tubes which penetrated less than 1 meter. Since mining would likely go to a depth of at least a few meters, knowledge of the regolith properties to that depth might be a requirement for resource evaluation.

From the Apollo 17 site at Taurus Littrow, we have the largest suite of samples and we also have the onsite observations of geologist-astronaut Jack Schmitt. By designing flexibility into mining and processing equipment, we can eliminate the need for some of the data normally required.

The chief feedstock at the Apollo 17 site would be the iron- and titanium-rich mare basalts. This "ore" could be scraped from the surface and provided as bulk material; oxygen and metallic iron could be extracted from it; and ceramics could be made from it—all with relatively simple mining, beneficiation, extraction, and processing procedures. However, even the simplest resource operations present difficulties on the lunar surface and require the support of a sophisticated transportation system and the presence of human beings.

Oxygen Production

All of the major rock types we have found on the Moon offer the potential for oxygen production in large quantities. However, ilmenite-rich mare basalts, such as those at the Apollo 17 site, seem to offer the widest range of production methods, including ilmenite reduction. Adequate

separation of the ilmenite from the silicates in these basalts could be a problem. Because the ilmenite-rich soils at this site derive from basalt flows, the ilmenite crystals are both fine-grained and intergrown with silicate crystals. An answer to this separation problem might be to use an oxygen production process (such as magma electrolysis or the carbothermal reduction of silicates) which does not require beneficiation (mineral concentration).

Metal Extraction

Iron seems to be the metal most easily obtained from lunar rocks. It can be obtained as a byproduct of the direct hydrogen reduction of ilmenite and possibly by other methods. Mare basalts, relatively rich in iron and titanium, provide the best large-scale source known on the lunar surface. The basalts at the Apollo 17 site are thus an adequate source of iron.

Bulk Material

While bulk material is available at virtually any lunar location, a site with a deep, relatively fine-grained regolith is preferred from the point of view of moving large amounts of material. The Apollo 17 site provides adequate access to this resource.

Other Site Considerations

Proximity to highlands: Although we anticipate that the first lunar resources used on the Moon will be obtained from mare soils, it may be that, in the long range, materials such as aluminum, lime,

and certain ceramics may best be obtained from highland rocks. Thus, selection of an initial lunar mining and processing site close to lunar highlands seems prudent. This requirement would also be satisfied by the Apollo 17 site (see fig. 14).

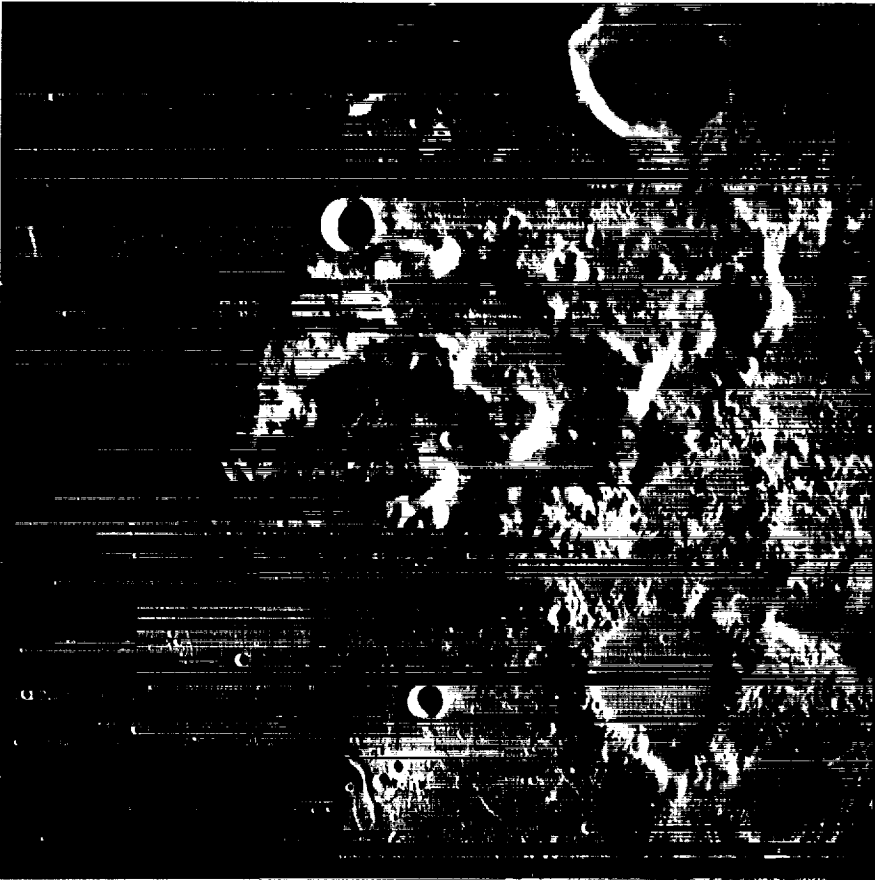


Figure 14

Orbital View of the Apollo 17 Site

Apollo 17 is an example of a site at a boundary between a mare and a highlands area. In this orbital view, Mare Serenitatis can be seen to the left and part of the western highlands to the right. Between these two features, to the right of center, is the Taurus Littrow Valley (note the landslide there). Such sites have a geological diversity that, besides being scientifically interesting, may offer many different types of usable materials.

ORIGINAL PAGE
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Specific siting of mine and plant: Optimum location of the first lunar mine and resource-processing plant will require additional site evaluation. Detailed characterization of the regolith is needed in order to construct an adequate ore body model. Further sampling to establish the necessary sampling grid would be a prime task for the next astronauts to occupy the Apollo 17 site. Their other chief concern will be to establish a base camp that can evolve into a permanent habitat.

New Sites

In terms of currently recognized lunar mineral resources, there is very little justification for developing a site other than an Apollo site. If, however, water were located in the polar regions, then a water-bearing site would have a higher priority than any other site. Evaluation of resources at a site or sites other than an Apollo site would require implementation of a regional exploration program. This program would include the discovery phase, presumably by an orbiter mission, in which a number of potentially favorable mining sites would be identified, each with multiple prospects. This phase would be followed by an unmanned surface mission or missions to several of the most favorable sites. Such a mission would include a Rover-type vehicle capable of obtaining regolith cores at least 2 meters deep and

returning the samples to Earth. Followup manned missions would land at one or two places from which candidate mining sites are accessible.

The objectives of the earliest manned missions would be to set up an exploration base and, operating from that base, to carry out a rigorous sampling and evaluation program at a small number (no more than 5 or 6) of the most favorable prospects. From this evaluation, all the prospects found to be ore bodies would be ranked from most to least favorable on the basis of mining and milling criteria. Final site acceptance would factor in accessibility, potential hazards, power requirements, and the myriad of site details required by any mining operation.

Conclusion

Any otherwise acceptable mining site on the Moon should have adequate resources to support a 10-year, 40 000-metric-ton-per-year operation. Of the sites sampled, that of Apollo 17 is the best characterized and should require the least pre-development work. Only a site having frozen water would be more desirable. Even though the Apollo 17 site is the best characterized of the sites, pre-development work involving extensive coring of the regolith is required to assess its physical and compositional variability.