One caution: Detecting radon or polonium from lunar orbit can reveal the existence and selenographic locations of volatile reservoirs within the Moon; however, such detections will not reveal the amount of volatile material within a reservoir, its composition, how deeply it is buried, nor how difficult it will be to gain access to the material. Thus this search technique may be of more value for the long term, for permanent human settlement of the Moon, than for an initial base.

Proposed Method of Search: It will surprise no one who has read this far that I am proposing to look for radon and polonium with an alpha spectrometer from lunar orbit, just as was done on Apollo 15 and 16. One important difference is that this time it should be done from lunar polar orbit in order to get a complete global survey of any significant radon sources.

It would be useful to narrow the selenographic resolution of detection, if feasible. The maps of ^{210}Po distribution produced from Apollo 15 and 16 data show ^{210}Po activity variations for blocks of the lunar surface 10° wide [11]. It would be very helpful to be able to locate volatile flows more precisely. By integrating over several orbits, it should be possible to improve the signal-to-noise ratio enough to do this [12].

Information of the sort I am proposing may be provided by the proposed Lunar Prospector mission [12], if and when it flies. That mission has an alpha spectrometer among its planned suite of instruments.

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ECONOMIC GEOLOGY OF THE MOON: SOME CONSIDERATIONS.

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Supporting any but the smallest lunar facility will require indigenous resources due to the extremely high cost of bringing material from Earth [1]. The Moon has also attracted interest as a resource base to help support near-Earth space activities, because of the potential lower cost once the necessary infrastructure has been amortized. Obviously, initial lunar products will be high-volume, bulk commodities, as they are the only ones for which the economics of lunar production are conceivably attractive. Certain rarer elements, such as the halogens, C, and H, would also be extremely useful (for propellant, life support, and/or reagents), and indeed local sources of such elements would vastly improve the economics of lunar resource extraction.

However, early scenarios for lunar resources, based on extracting many common elements from ordinary regolith [2], are probably unworkable. A survey of terrestrial mining experience indicates that the overwhelming criterion of a potentially economic deposit is its recoverable concentration of the desired element [3]. This results because separating elements is difficult and costly, and is indeed why "ores"—i.e., anomalous concentrations of the desired element—are worth seeking in the first place. In fact (and somewhat paradoxically), a high-grade ore is most critical for large-volume commodities, as those would be prohibitive to purify on the scale required. Hence, identifying the most concentrated sources of desired element(s) for local resource extraction should be an element of future lunar missions, and certainly should be a factor in siting a lunar base.

Few lunar geologic studies to this point, however, are directly relevant to exploration for potential ores, as they have been concerned with identifying large-scale, global processes. This focus has been appropriate, of course, given our *a priori* ignorance of the Moon. Moreover, quite apart from the Moon's scientific interest, serious concern about its resource value would also have been highly premature, for at least two reasons: (1) Useful constraints would be impossible without first knowing the basic geologic framework and (2) potential resources cannot be evaluated in a vacuum; their value depends on their possible uses. However, the broad-brush approach of planetological studies is opposite that of economic geology, because economic geology deals with the products of rare events. Ore deposits typically occur where by happenstance a rare process, or a fortuitous combination of processes, has run to an extreme. Such deposits are rare by their very nature; indeed, almost by their very definition. Nonetheless, they are worth seeking because of the extreme expense of separating elements, so that it is highly cost effective to let natural processes carry out as much separation as possible first. Hence, global characterizations such as typify traditional lunar studies are not immediately relevant for economic geology investigations. They merely set the geologic context, whereas economic geology lies in the unusual—and extremely local—variations from the norm.

It has been argued, especially in the popular literature, that the anhydrous nature of lunar materials precludes any ore deposits like those on the Earth. This is overstated. For one thing, the Moon is vastly more heterogeneous than had been thought even until relatively recently, as has been demonstrated by both ongoing studies of lunar petrology [4] and by remote sensing [5]. The Moon underwent protracted igneous activity, spanning hundreds of millions of years, during its early history, and this led to varied and large-scale differentiation and fractionation.

Second, the mere waterlessness of the lunar environment does not preclude all ore-forming processes. Although it is true that water is vital in forming many terrestrial ores, anhydrous magmatic differentiation is also capable of generating substantial element concentrations, and indeed has formed some terrestrial ore deposits. Such purely magmatic processes include partial melting, fractional crystallization, and phase separation (liquid unmixing or crystal settling). Examples of such magmatic ores on Earth include Cu-Ni sulfide ores from sulfide liquid immiscibility, chromite from cumulate settling, and magnetite ores crystallized from late-stage magmatic fluids extremely enriched in Fe [6]. Similar processes may occur on the Moon [7]. Yet other potential lunar processes may have no terrestrial analogues, as with the possibility of cold-trapped volatiles in permanently shadowed regions at the lunar poles [8].

To be sure, the lunar geologic environment is very different from the terrestrial, and the possible consequences of the Moon's low oxidation state and waterlessness for generating useful concentrations of elements must be addressed. For example, considering the behavior of the rarer elements under lunar conditions with a view to how (or whether!) they can become concentrated locally would be valuable. Many industrially important elements are highly incompatible and in a magma will tend to become concentrated in the residual melt, so that useful concentrations may form [7]. However, the enormous literature on lunar rare elements is focused instead on their use as tracers of large-scale geologic processes (e.g., partitioning of REE) and thus is not directly applicable to economic geology.

For example, much lunar Cr is present as Cr^{++}, due to the reduced character of lunar rocks [9], and Cr is enriched in the lunar crust relative to Earth. The mechanism of this enrichment seems somewhat obscure, however. Presumably, Cr^{++} is excluded from compact Fe-Mg silicates in the lunar mantle, as it is a large ion [10]; moreover, Cr^{++} has large Jahn-Teller effects and hence prefers distorted crystal sites. Hence the Cr on the surface probably arrived as Cr^{++} in residual melts originally fractionated out of the mantle. However, surface Cr commonly exists as Cr^{+++}, especially in chromite [11]. Data from reduced chromian slags indicate that at low temperatures CrO is unstable and will disproportionate into Cr metal and Cr_2O_3 [12]. As Cr metal is more electropositive than Fe, this suggests that some of the native Fe on the Moon may result from reduction by Cr^{++} oxidation, and textural relations support this interpretation [13]. In any case, understanding Cr mobility due to its varying redox behavior may allow finding areas enriched in it, and may also have implications for deposits of native Fe.

Moreover, as this example suggests, the slag literature seems to be a largely overlooked source of possible insights about the behavior of silicate melts under extremely reducing conditions. They may provide information on rare elements in particular. Many slags contain not only Cr^{++}, but Ti^{+++} or even Ti^{++} [12]. The ceramic literature may also be useful as many high-performance ceramics are anhydrous. Indeed, industrial experience has already provided extremely useful analogues for some non-terrestrial processes, e.g., Sill's [14] modeling of the role of sulfur in Venus cloud processes, using observations from Lunge's [15] industrial treatise on the obsolete lead-chamber process for commercially producing sulfuric acid, and Lee et al.'s [16] observations of molten sulfur flows in commercial mining operations to infer behavior of natural flows on Io. Such literature also seems an underused source for potential insights into lunar conditions.

Surface Signatures: It is not enough to predict mechanisms by which ores may be formed; they must also be found. Seeking a distinctive signature from orbital sensors is an obvious and relatively cheap approach; e.g., it has been commonly advocated for detecting whether cold-trapped polar volatiles exist. Many if not most ore deposits will be too small, however, to show up with the resolution proposed for probes such as the Lunar Observer. For example, a deposit of pure ilmenite 100 m on a side, which would be more than enough to support an initial lunar installation, would not be seen.

Detection of such small deposits must be more subtle, especially as global increases in resolution are not practical. Instead, the signature of potentially favorable geologic settings for concentration of the desired element must be sought; once such areas have been identified, they can be targeted for further investigation.

It seems underappreciated that this is how mineral exploration is carried out on Earth. For example, an explorationist seeking Au mineralization in Nevada does not begin by mapping the entire state at 1-m resolution. Instead, he or she focuses attention on promising areas identified on the basis of their general geologic setting, and maps them in detail. Similarly, small but promising areas on the Moon, initially found by remote sensing, can be later focused on in detail with high-resolution sensing, and in the case of the most favorable areas, actual samples can be collected.

Conclusion: In summary, a viable ore resource contains as high a concentration of the desired element as possible in a form that is as easy to recover as possible, and such deposits moreover are unusual, resulting from rare processes or unusual extremes of common processes. This will be true of lunar resources as much as terrestrial ones. To explore for lunar resources, therefore, the lunar geologic literature must be reevaluated with this perspective, using our knowledge of global lunar processes to establish geologic contexts, and then determining what element-concentration processes might occur locally in such contexts. Terrestrial analogues, such as magmatic ore formation, as well as lunar samples that seem to reflect unusual processes, should help identify such possibilities. Industrial experience with possibly relevant systems such as reducing slags or anhydrous ceramics may also provide insight on possible ore-forming processes. Once possibilities are established, then attention can be focused on promising lunar localities.

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THE TARGET: H_2O ON THE MOON.

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The importance of H_2O on the lunar surface has long been identified as a high priority for the existence of a human colony for mining activities and, more recently, for space fuel. Using the Earth as an analogue, volcanic activity would suggest the generation of water during lunar history. Evidence of volcanism is found not only in present lunar morphology, but in over 400 locations of lunar transient events catalogued by Middlehurst and Kuiper in the 1960s. These events consisted of sightings since early history of vapor emissions and bright spots or flares. Later infrared scan-