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RADON AS A TRACER FOR LUNAR VOLATILES.

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Introduction: Radon and its decay product polonium can be used as tracers to search for lunar volatiles. One effective technique to look for them would be by using alpha-particle spectrometers from lunar orbit.

Alpha spectrometers were flown in the Apollo Service Modules during the Apollo 15 and 16 missions, and did observe ^{222}Rn and its decay product ^{210}Po on the lunar surface from orbit [1,2]. This demonstrates that radon and polonium can be observed from orbit; what must next be shown is that such observations can reveal something about the locations of volatiles on the Moon.

How Radon and Polonium Can Act as Tracers for Volatiles: What must first be understood is that radon released in the lunar regolith has a very low probability of reaching the surface before it decays, if it must do so under its own power, by random walk. Under the extreme vacuum of the Moon, the mean free path of a radon atom's random walk is not determined by collisions with other gas molecules, but rather by collisions with soil grain surfaces. The problem the atom faces is that it has such a high heat of adsorption that when it collides with a soil grain surface, it tends to stick very tightly to that surface, and thus remain there for a comparatively long time before it takes the next hop. This slows down the diffusion process so much that almost all of the radon atoms random walking in this way will decay before they reach the lunar surface [3]. On top of that, radon atoms may have difficulty getting "unstuck" from their production sites into the intergrain volume for even the first hop [2].

For these reasons, if radon or its decay product polonium are seen on the lunar surface in significant amounts, the radon was almost certainly swept out by some other outflowing gas or gases. The Apollo 15 and 16 orbital alpha spectrometer results indicate another reason to suspect that radon is brought to the surface by sweeping rather than by random diffusion: the radon and polonium decay rates observed were not in equilibrium with each other [1,2]. At Aristarchus Crater during Apollo 15, the decay rate of ^{222}Rn was in excess of what would be in equilibrium with ^{210}Po [1]. At other locations, such as Grimaldi Crater and the edges of circular maria, the decay rate of ^{210}Po was in excess.

The half-life of ^{222}Rn is 3.8 days. The time to reach decay equilibrium between ^{222}Rn and ^{210}Po is largely controlled by the 22.3-year half-life of the intermediate isotope ^{210}Pb. Thus the disequilibria between decay rates of radon and polonium indicate that outflow rates of radon at these locations on the Moon have varied on timescales of days to years. Indeed, given the short half-life of ^{222}Rn, the radon observed at Aristarchus during Apollo 15 must have been coming out of the Moon during the time of the mission, or within a few days before. This is a further argument in favor of a sweeping mechanism for bringing the radon to the surface, rather than a steady diffusion. In this connection, it is worth noting that the sites where higher-than-average radon and polonium decay rates were observed—Aristarchus, Grimaldi, and edges of circular maria—are among those most frequently cited as locations for lunar transient events (LTE), as summarized by Middlehurst and Moore [4,5]. For these reasons, it has previously been suggested [6] that radon and polonium can act as a tracer system for recent geologic activity on airless planetary bodies.

But radon and polonium activity can trace not only where activity is taking place, but where volatile deposits are. For in order for a "sweeping" mechanism to bring radon to the surface, there must be volatile reservoirs as well as activity to bring it up. So observing major amounts of radon and/or polonium at some location on the surface would be a strong indicator of a source of volatiles beneath that location.

Where might such sources of volatile materials lie, and how might they have gotten there? One possibility is that, even though analysis of returned samples indicates that the near-surface layers of the Moon are extremely depleted in water and other volatiles, deposits of volatiles may exist at greater depths. Our present understanding of the Moon's formation and history is not yet complete enough to rule this out. Another concept, mentioned by Smith [7] and Feldman et al. [8], is that some fraction of the water from comets impacting the Moon may be driven down into the regolith and megaregolith by the impact process, to be trapped in pores and fractures or to form hydrated minerals, and remain buried for geologically significant periods of time.

The latter idea, if correct, would make understandable the association of many LTE with young bright ray craters, such as Aristarchus.

Such potential pockets of buried cometary volatiles represent another place to search for useful volatile materials, in addition to the frequently mentioned idea of ice deposits in permanently shadowed craters at the lunar poles [9]. We should keep in mind that no one presently knows for certain that such polar ice deposits exist.

We don't know, of course, whether any pockets of cometary volatiles exist elsewhere, either. And in fact, Smith's suggestion runs counter to estimates by Chyba [10] and others that volatiles from objects impacting the Moon would be almost completely lost. The point is that any significant lunar source of, for example, water or carbon dioxide or nitrogen would have enormous value for life support at a manned lunar settlement, so much value that we should use every reasonable search technique, and look everywhere we can think of, in our efforts to find sources of useful volatiles on the Moon. Even if the likelihood of success is small, the potential payoff justifies a significant search effort.

One attraction of using radon as a tracer is that it doesn't matter if the idea of cometary implantation of volatiles is wrong. This technique does not depend on any assumptions about how volatiles got into place. If volatiles are present, and if they are coming to the surface, they will bring radon with them. The radon—or its polonium descendant—can then be observed from lunar orbit.

The Apollo 15 and 16 alpha spectrometer results already give us strong reason to suspect that deposits of volatiles do exist at some locations within the Moon, from which "burps" occasionally come to the surface in an episodic fashion.

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