and transport. The near-vacuum conditions will result in outgas-
ing of materials and difficulties with lubrication around bearings
and seals.

Some extreme conditions that provide construction challenges
are also found on Earth. Bechtel Corporation has successfully
designed, engineered, and constructed the Polaris mine, processing
and transporting coal over 600 miles from the North Pole. The entire processing plant
was built on a single barge and delivered to the site during the
last high tide, before the end of the six-week-long ice-free shipping season. It was docked in a dredged area, frozen in place, and has
operated year round.

We can take advantage of our resource processing experience
in the terrestrial environment in planning for lunar oxygen pro-
duction. However, the Moon presents unique processing chal-


LUNAR RESOURCES USING MODERATE SPECTRAL RESOLUTION VISIBLE AND NEAR-INFRARED SPECTROSCOPY: Al/Si AND SOIL MATURITY. Erich M. Fischer, Carlé M. Pieters, and James W. Head, Department of Geological Sciences, Brown University, Providence RI 02912, USA.

Introduction: Modern visible and near-infrared detectors are
critically important for the accurate identification and relative
abundance measurement of lunar minerals; however, even a very
small number of well-placed visible and near-infrared bandpass
cells provide a significant amount of information about
many lunar resources. The Galileo Solid State Imaging system
(SS1) multispectral data are an important example of this. Al/Si
and soil maturity will be discussed below as examples of significant
general lunar resource information that can be gleaned from
moderate spectral resolution visible and near-infrared data with
Infrared spectroscopy provides a valuable tool for studying the surface composition of the Moon. The Moon's surface is composed of different materials, each with unique spectral properties. Moderate spectral resolution visible and near-infrared spectroscopy can be used for distinguishing between mature and immature soils. Illustrated in Figs. 1a through 1d are representative SSI spectra of mature highland soils and immature highland materials. The spectra in Figs. 1a and 1b have been scaled to "Sun," thus keeping the albedo information, while those in Figs. 1c and 1d have been scaled to the Mare Serenitatis standard area MS2 and also to 0.56 μm, allowing color differences to be discerned more easily. These figures illustrate three critical optical/spectral properties that differ between immature and mature highland soils: (1) albedo, (2) the 0.56-0.76-μm continuum, and (3) the 0.76/0.99-μm ratio. Immature highland materials are characterized by higher albedos, lower 0.76/0.56-μm ratios, and higher 0.76/0.99-μm ratios relative to their mature counterparts. Because the albedos of mature and immature highland materials overlap to some extent, we have decided to use only the 0.76/0.56-μm and 0.76/0.99-μm ratios to distinguish immature and mature highland materials in this study. Figure 2 illustrates the relationship between the 0.76/0.56-μm and 0.76/0.99-μm ratios for the Galileo SSI lunar coverage. Although not obvious from this figure, there are very useful and systematic relationships between these two ratios. As described above, most immature highland materials can be characterized well as having 0.76/0.56-μm ratios lower than a certain value and 0.76/0.99-μm ratios higher than a certain value; thus they plot in the upper lefthand portion of the scatterplot. Using these two criteria, the immature highland materials observed by SSI can be identified.

Al/Si Calculated from the SSI Data: While the mineralogical information normally associated with visible and near-infrared multispectral data is clearly pertinent to the assessment of lunar resources, this type of data can provide additional compositional information with which it is not usually associated. An example is derived from the important positive relationship that was observed between Al/Si measured by the Apollo X-ray spectrometer, and normal albedo [2,3]. The linear portion of the relationship between albedo and Al/Si, shown by the line in Fig. 3, appears to be dominated by mature lunar highland soils. Near the low albedo values of the mare, the linearity may to some extent be affected by mare/highland mixing. This linear relationship for mature highland soils is intuitively expected because, for a steady...

Fig. 1. Representative SSI spectra of mature ("highlands") and immature ("highland craters") highland materials. (a) and (b) are scaled to "Sun," thus preserving albedo information. (c) and (d) are scaled to the Mare Serenitatis standard area MS2 and 0.56 μm, accentuating color differences. Figure adapted from [10].

Fig. 2. Scatterplot of the 0.76/0.56-μm continuum ratio vs. the 0.76/0.99-μm ratio for the Galileo SSI lunar coverage. Immature highland materials systematically lie in the upper lefthand quadrant of this plot. Axis values are in DNs.
The distinct advantage of the SSI data in this case is their extensive spatial coverage. The first step is to quantify the linear relationship between Al/Si and normal albedo. Quantitative albedo can be derived from SSI data. The line marked "highland soils" illustrates the linear trend of the mature highland soils. Points marked "Proclus" and "Alfraganus" are fresh highland impact craters. Direction of immature highland materials is indicated by the arrow.

The Apollo X-ray spectrometer data cover only 9% of the lunar surface, if the same correlation between albedo and Al/Si is valid for the mature highland soils of the rest of the Moon, then Al/Si can be estimated for other areas by using quantitative albedo information. Quantitative albedo can be derived from SSI or other radiometrically calibrated visible or near-infrared data. The distinct advantage of the SSI data in this case is their extensive spatial coverage.

Since the Apollo X-ray and current SSI data do not overlap to a great extent, in order to compute Al/Si for regions observed by SSI, a three-step process is used to relate the two datasets. The first step is to quantify the linear relationship between Al/Si and normal albedo. Quantitative albedo can be derived from SSI or other radiometrically calibrated visible or near-infrared data. The distinct advantage of the SSI data in this case is their extensive spatial coverage.

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RADON AS A TRACER FOR LUNAR VOLATILES. Larry Jay Friesen, Lockheed Engineering and Sciences Company, P.O. Box 58561, Houston TX 77258, USA.

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 Rn and its decay product 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 intergran 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 Rn was in excess of what would be in equilibrium with Po [1]. At other locations, such as Grimaldi Crater and the edges of circular maria, the decay rate of Po was in excess.

The half-life of Rn is 3.8 days. The time to reach decay equilibrium between Rn and Po is largely controlled by the 22.3-year half-life of the intermediate isotope 210Po. 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 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.