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Data are of moderate spectral resolution, they still provide in-
SSI are critical.

Within constraints discussed below, these moderate spectral resolution
and (3) the maturity or exposure age of the soils based upon the
0.40/0.56-μm (UV/VIS) ratio, (2) mafic mineral abundance based upon the 0.76/0.99-μm ratio,
and (3) the maturity or exposure age of the soils based upon the
0.56-0.76-μm continuum and the 0.76/0.99-μm ratio. Within

These fundamental differences cause immature lunar materials to
be optically different from their mature counterparts. Immature
materials would be a very poor source of solar-wind-
implanted components and iron-rich agglutinates. Moderate spec-
tral 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; these
are (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 left-hand 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 spectrome-
ter, 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 left-hand 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 other radiometrically calibrated visible or near-infrared 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.

state (mature soil) abundance of absorbing soil alteration (aging) products and grain-size distribution, the albedo of anorthositic highland material would be expected to be controlled by the abundance of feldspar, which in turn also controls the Al/Si value due to its Al-rich nature. On the other hand, two types of lunar material do not follow a simple direct relationship between albedo and Al/Si. One of these materials is mare soil. These soils, plotting at normal albedos of less than approximately 106 DN in Fig. 3, are not expected to follow such a direct relationship since the range of plagioclase abundance is limited while the amount of albedo-controlling opaques varies extensively. The other type of lunar material that diverges from the linear relationship is material excavated by recent highland impact events (points lying to the right of the linear trend). The points labeled "Proclus" and "Alfraganus" in Fig. 3 are fresh highland impact craters. The high albedo of most types of recently excavated feldspathic material is normally not due to extremely high aluminum content, but rather due to the fact that the material has not been exposed long enough to have appreciably darkened by accumulation of agglutinates and other processes (i.e., [4,5]). If the correlation between Al/Si and normal albedo is expected for regions observed by SSI by employing the normal albedo of the SSI data, Al/Si is estimated as follows.

Finally, using the normal albedo of the SSI data, Al/Si is estimated for other areas by using quantitative SSI reflectance at 0.56 μm for the areas where concentrations cannot be calculated using the procedure described in the text. Brighter grey levels correspond to higher relative Al concentrations. O = Orientale Basin, H = Hertzsprung Basin, sp = South Pole-Aitken Basin, and ss = Schiller-Schickard.

Fig. 3. Scatterplot of Al/Si from the Apollo X-ray spectrometer [6] vs. lunar normal albedo [7]. DN values are from the La Jolla Consortium data. The line marked "highland soils" illustrates the linear trend of the mature highland soils. Points marked "Proclus" and "Alfraganus" are fresh impact craters. Direction of immature highland materials is indicated by the arrow.

Relative depletions of aluminum occur in the South Pole-Aitken region and the Schiller-Schickard cryptomare region. This is expected for Schiller-Schickard if less aluminous mare soils were indeed mixed with more aluminous highland soils in this area. Relative concentrations of aluminum occur in the Bailly, Korolev-Hertzsprung, and Orientale regions. The finding of high concentrations of aluminum in the Orientale region is supported by the discovery of anorthosite-rich massifs in the Inner Rook Mountains [8,9].

Conclusion: The simple techniques described above can be used to derive a surprising wealth of general information about a number of critical lunar resources. Although simple in nature, the importance of these techniques should not be underestimated as they rely only upon existing technology and very spectrally limited data. The proposed lunar Discovery/Scout-class missions to the Moon may provide a mechanism for quickly obtaining global basic lunar resource information with a moderate spectral resolution, high-spatial-resolution visible, and near-infrared imaging system.

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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 $^{222}$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 intergranular 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 outgassing event such as an eruption. 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 $^{212}$Po. 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.