

and transport. The near-vacuum conditions will result in outgassing 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 plant, and support facilities for COMINCO of Canada. The Polaris lead and zinc mine is located 90 miles north of the Arctic Circle and 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 production. However, the Moon presents unique processing challenges. One of the unique problems on the Moon is that the ore or feedstock is being characterized at the same time that processing design decisions need to be made. Various authors have rated the favorability of different oxygen production processes. There is no general agreement on the best process or the most desirable feedstock [1]. Processes such as pyrolysis, electrolysis, and hydrogen reduction have been cited as being the most feasible. The process finally chosen will depend on the type of feedstock and will dictate the number of operating units, the reagents, and the power supply required. Since the required facilities and some materials will need to be transported from the Earth at great expense, at least initially, careful decisions must be made for process selection and plant design.

The feedstocks most often cited as resource material are bulk soil and ilmenite. However, we cannot choose a process that requires ilmenite unless we know that there are sufficient reserves at and below the surface. The consistency of the bulk soil composition, the impurities, and the grain size of the bulk soil at proposed mining sites also need to be determined if lunar regolith is to be used as the feedstock.

The ore or feedstock grade and the areal and depth distribution of the ore will control the amount and type of mining equipment needed to supply the process plant. Hypothetically, an ore with 5% ilmenite might require 20 mining and transport vehicles, while an ore with 20% ilmenite might require 5 vehicles.

**Remote Sensing of Lunar Resources:** Various remote sensing methods have been devised to assess lunar resources, specifically ilmenite. Telescopic measurements from Earth with spatial resolutions of between 1 and 20 km have been our greatest source of mineralogical data. The telescopic measurements have been used in conjunction with chemical analyses of a very limited number of lunar samples. The information that will be needed for material processing will require even higher resolution.

Based on earlier work by Charette and others [2], Pieters [3] has graphed the  $TiO_2$  content of lunar samples from Apollo and Luna missions against the telescopic reflectance of those sample sites. These authors have found a distinctive relationship between the weight percent of  $TiO_2$  and the ratio of the spectral bands at 0.40- and 0.56- $\mu m$  wavelength. This relationship is only applicable to sites with mature regolith that contain abundant agglutinate and other glass. A linear relationship was found at higher concentrations of  $TiO_2$ . Johnson and others [4] have mapped surface ilmenite concentrations from telescopic reflectance measurements and have identified two regions with greater than 8 wt%  $TiO_2$ . The projected concentrations are based on concentrations

in returned lunar samples. Most of our knowledge of the chemical and mineralogical composition of the Moon has come from the 832 kg of samples returned during the Apollo missions from six sites.

To examine the lunar resource assessment process, a known mining area in northern California was selected as a lunar analogue. Bechtel contracted for a flight line of remote sensing data over the New Almaden mercury mine, south of San Francisco, near San Jose. This mine has produced 40% of the mercury mined in the U.S. The site was chosen because the area contains some rocks and minerals that are analogous to lunar rocks, including iron oxide minerals. The data were acquired with the Geoscan MkII Airborne Multispectral Scanner. The sensor has 24 spectral bands in the visible, near infrared, shortwave infrared, and thermal infrared parts of the spectrum. The spatial resolution on the New Almaden flight was about 5 m. Existing topographic and geologic maps were used in the resource assessment in conjunction with the remote sensing data.

By examining the spectral curves of minerals associated with the mercury ore, processing strategies were defined to map iron-stained silica carbonate rock and serpentinite. Two separate mappings were produced. The first indicated a conservative estimate of mineral distribution, and the second a less conservative estimate. From indications in the field, the true mineral distribution is somewhere between the two estimates. The remote sensing data are most effective when used together with field sampling and chemical and mineralogical testing. This will be especially important in the lunar resource assessment program.

**Conclusions:** It is essential to define the lunar ore material and assess its grade and areal and depth distribution. Experience with Canadian gold mines shows that two to three times as many mines fail as succeed. We cannot afford a failure on the Moon, and accurate resource assessment is a key part of the success strategy. The keys to the success of lunar mining operations are caution with new processes, the collecting and testing of bulk samples, and adequate ore reserve calculations.

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**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 channels provide a significant amount of general information about crucial lunar resources. The Galileo Solid State Imaging system (SSI) 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

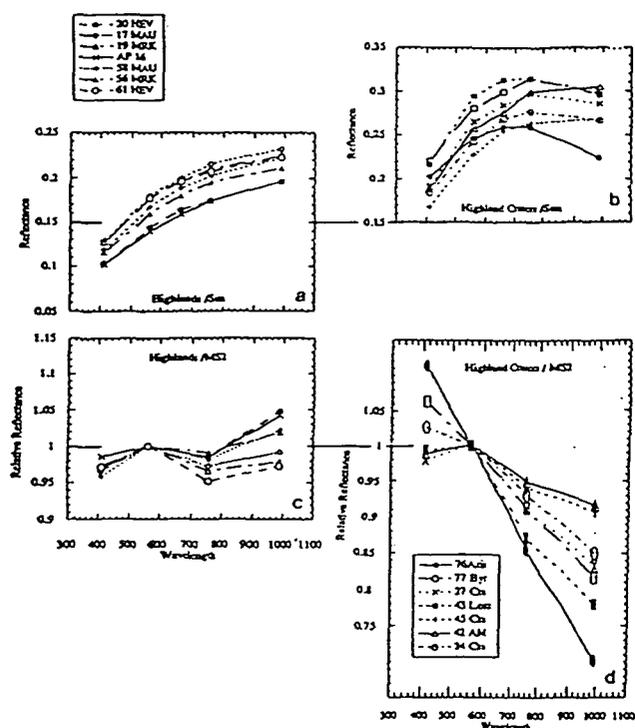


Fig. 1. Representative SSI spectra of mature ("highlands") and immature ("highland craters") highland materials. (a) and (b) are scaled to "Sun," thus preserving albedo information. (c) and (d) are scaled to the Mare Serenitatis standard area MS2 and  $0.56 \mu\text{m}$ , accentuating color differences.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

relative ease. Because quantitative-albedo data are necessary for these kinds of analyses, data such as those obtained by Galileo SSI are critical.

SSI obtained synoptic digital multispectral image data for both the nearside and farside of the Moon during the first Galileo Earth-Moon encounter in December 1990 [1]. The data consist of images through seven filters with bandpasses ranging from  $0.40 \mu\text{m}$  in the ultraviolet to  $0.99 \mu\text{m}$  in the near-infrared. Although these data are of moderate spectral resolution, they still provide information for the following lunar resources: (1) titanium content of mature mare soils based upon the  $0.40/0.56\text{-}\mu\text{m}$  (UV/VIS) ratio, (2) mafic mineral abundance based upon the  $0.76/0.99\text{-}\mu\text{m}$  ratio, and (3) the maturity or exposure age of the soils based upon the  $0.56\text{--}0.76\text{-}\mu\text{m}$  continuum and the  $0.76/0.99\text{-}\mu\text{m}$  ratio. Within constraints discussed below, these moderate spectral resolution visible and near-infrared reflectance data can also provide elemental information such as Al/Si for mature highland soils.

**Soil Maturity from the SSI Data:** Immature soils, relatively unweathered in the lunar environment due to their young exposure age, are fundamentally different from mature soils. For example, immature soils are coarser and contain fewer aging products such as agglutinates (derived from micrometeorite impact) and solar-wind-implanted components such as hydrogen and helium. These fundamental differences cause immature lunar materials to be optically different from their mature counterparts. Immature soils associated with fresh impact craters are particularly useful for the study of vertical and horizontal crustal heterogeneity since they have much higher spectral contrast and thus provide excellent information on mineralogical composition. On the other hand,

immature materials would be a very poor source of solar-wind-implanted components and iron-rich agglutinates. 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  $0.56 \mu\text{m}$ , 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  $0.56\text{--}0.76\text{-}\mu\text{m}$  continuum, and (3) the  $0.76/0.99\text{-}\mu\text{m}$  ratio. Immature highland materials are characterized by higher albedos, lower  $0.76/0.56\text{-}\mu\text{m}$  ratios, and higher  $0.76/0.99\text{-}\mu\text{m}$  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  $0.76/0.56\text{-}\mu\text{m}$  and  $0.76/0.99\text{-}\mu\text{m}$  ratios to distinguish immature and mature highland materials in this study. Figure 2 illustrates the relationship between the  $0.76/0.56\text{-}\mu\text{m}$  and  $0.76/0.99\text{-}\mu\text{m}$  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  $0.76/0.56\text{-}\mu\text{m}$  ratios lower than a certain value and  $0.76/0.99\text{-}\mu\text{m}$  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-

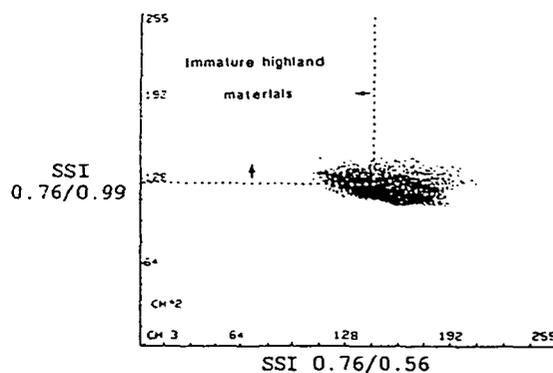


Fig. 2. Scatterplot of the  $0.76/0.56\text{-}\mu\text{m}$  continuum ratio vs. the  $0.76/0.99\text{-}\mu\text{m}$  ratio for the Galileo SSI lunar coverage. Immature highland materials systematically lie in the upper lefthand quadrant of this plot. Axis values are in DN's.

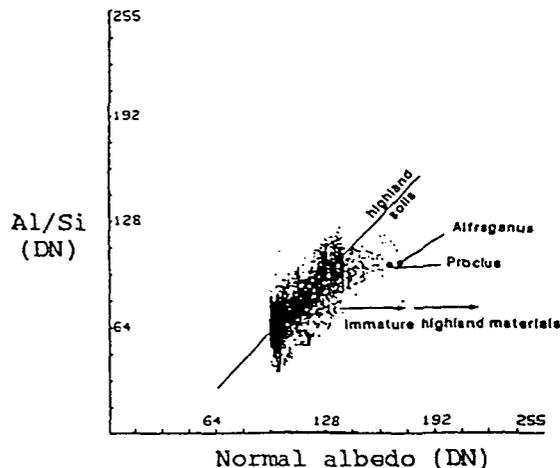


Fig. 3. Scatterplot of Al/Si from the Apollo X-ray spectrometer [6] vs. lunar normal albedo [7]. DN values are from the La Jolla Consortium data. The line marked "highland soils" illustrates the linear trend of the mature highland soils. Points marked "Proclus" and "Alfraganus" are fresh impact craters.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

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 albedo and Al/Si is corrected for the mare soils and immature material, then the linear relation can be utilized to calculate Al/Si. The mare soils can easily be excluded simply on the basis of albedo. The immature highland materials are identified and removed using the 0.76/0.56- $\mu\text{m}$  and 0.76/0.99- $\mu\text{m}$  ratios, as discussed above. Although 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/

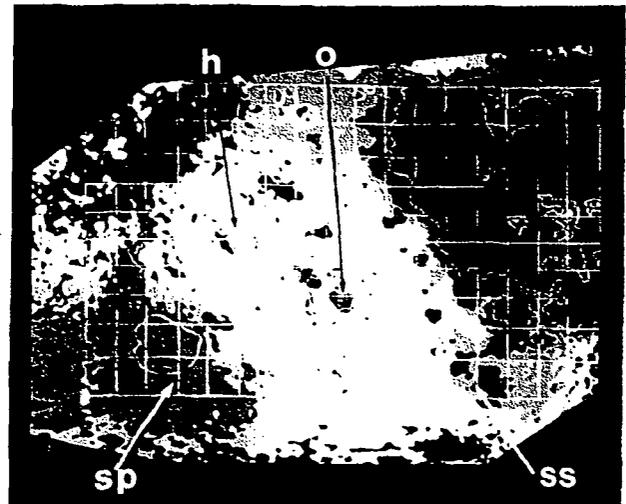


Fig. 4. Three-slice map of relative Al concentration for the highland soils observed by SSI (overlain by the La Jolla Consortium grid). Black corresponds to regions (mare and immature soils) for which Al concentrations cannot be calculated using the procedure described in the text. Brighter grey levels correspond to higher relative Al concentrations. o = Orientale Basin, h = Hertzprung Basin, sp = South Pole-Aitken Basin, and ss = Schiller-Schickard.

Si [6] and normal albedo [7] for the mature highland soils for which the two types of data exist (portions of the eastern nearside and limb). This relationship is illustrated by the straight line in Fig. 3. The values on the axes are in DN's as per the La Jolla Lunar Consortium data. Conversion to actual Al/Si and other values will be undertaken in the future. Then, normal albedo is calculated for the SSI data from an empirical relationship between normal albedo and SSI reflectance at 0.56  $\mu\text{m}$  for the areas where the two types of data overlap (most of the western nearside). Finally, using the normal albedo of the SSI data, Al/Si is estimated for the mature highland soils observed by SSI by employing the relationship quantified in step 1.

From this analysis we find that large-scale variations in aluminum content occur throughout the highlands observed by SSI (Fig. 4). 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-Hertzprung, 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  $^{222}\text{Rn}$  and its decay product  $^{210}\text{Po}$  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  $^{222}\text{Rn}$  was in excess of what would be in equilibrium with  $^{210}\text{Po}$  [1]. At other locations, such as Grimaldi Crater and the edges of circular maria, the decay rate of  $^{210}\text{Po}$  was in excess.

The half-life of  $^{222}\text{Rn}$  is 3.8 days. The time to reach decay equilibrium between  $^{222}\text{Rn}$  and  $^{210}\text{Po}$  is largely controlled by the 22.3-year half-life of the intermediate isotope  $^{210}\text{Pb}$ . 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  $^{222}\text{Rn}$ , 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.