

tion of Na, S, and K during lunar volcanism was a subject of some interest during the early days of lunar sample analysis [e.g., 25,26].

The marked depletion of S in lunar volcanic glasses compared to the crystalline mare basalts has been attributed [21] to either (1) strong degassing of magmas during the fire fountaining that produced the volcanic glasses compared to the quiescent fissure eruptions that produced the mare basalts or (2) major differences in the S abundance within the mantle source regions. While our data strongly indicate that the former mechanism certainly contributed to this difference between mare basalts and volcanic glasses, additional constraints [27] suggest that the picritic magmas that produced the volcanic glasses were generated from different source regions than most of the mare basalts.

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RESOURCE AVAILABILITY AT TAURUS-LITTROW. Larry A. Haskin and R. O. Colson, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis MO 63130, USA.

What constitutes a lunar resource? Presumably, anything available on or from the Moon (e.g., [1]) is a resource. Our knowledge of the Moon's resources stands to be enhanced markedly through further exploration. A resource is not necessarily an ore, i.e., an economical source of a desired product. For commercial lunar extraction or manufacture, we require a resource, a need for the product, and reason to believe a lunar source is economical, i.e., that for some time period costs of mining, processing, fabrication, and delivery can be done more cheaply than from Earth or another extraterrestrial source.

During the next few decades, a lunar source is likely to be economical only for materials used in large quantities on the Moon or in near-Earth space, where the Moon's low gravity may offer an edge over Earth in transportation cost (e.g., [2]). Even so, lunar soils are potential ores for key products (fuel, metal, construction materials). Also, there are two plausible exceptions. One is souvenirs; the other is ^3He , plentiful on the Moon but not on Earth, proposed as fuel for commercial fusion reactors [3].

Long-duration experience in reduced, but nonzero, gravity is a "product" that may be cheaper to obtain on the Moon than elsewhere. This product, research, includes experience with physiological ef-

fects of long-term exposure to low gravity, problems of living, means of exploring, and coping with another environment. It includes experience in mining, extraction, and manufacturing. The Moon, because it is nearby, is probably the most economical extraterrestrial site for this research, especially if astronauts as well as automated equipment are involved. It is not clear that the experience in mining, extraction, production, handling, and storage on a planetary surface can be adequately simulated on Earth or in orbit. Mining and manufacturing can probably be done more cheaply with astronauts to assist in set-up, adjustment, maintenance, and repair of equipment rather than in wholly automated mode.

The complexity of carrying out even simple tasks on the Moon is a taxing overhead on proposed mining and manufacturing processes. The Moon lacks abundant and cheap air, water, and fossil fuels. It has no known common ores and no developed infrastructure. Differences between lunar and terrestrial conditions are so great that simple transplantation of terrestrial technologies is unworkable [2]. Economical use of lunar materials requires invention, demonstration, and development of methods appropriate to the Moon. We contend that lunar technologies for the next few decades must be simple and highly automated or teleoperated, and require minimal tending by astronauts. Processes requiring astronaut attention during nominal operation or for frequent repairs and maintenance will be regarded as labor intensive, and lunar labor will be expensive. Full automation is not obviously an inexpensive substitute, however; the successful Viking landers were a costly means of doing simple laboratory tasks inflexibly.

Early lunar technologies [2] will probably use a common lunar material as ore. They will be robust to minor fluctuations in feedstock composition and will not require appreciable feedstock beneficiation (see Beneficiation in references) such as rock grinding or mineral concentration. Technologies using unprocessed soil and indifferent to its composition will have the advantage. Nevertheless, the size and grade of the ore body must be confirmed for even the most indiscriminate process. Simple uses such as heaping unprocessed lunar soil for thermal insulation or radiation shielding onto a habitat require that we know the depth of the regolith, the size distributions of its soils, the locations of large boulders, and the ease of excavation. Costs of detailed site surveys trade against restrictions on site selection and conservative engineering design to accommodate unknown conditions of a poorly explored site.

Given the above considerations, we consider briefly some abundant lunar materials, their proposed uses, and technologies for their preparation, with particular attention to the Taurus-Littrow site. Relatively few papers are referenced in this text; references to two bibliographies [4,5] and to numerous, mainly more recent papers grouped according to subject area are compiled at the end of this abstract.

The Taurus-Littrow site has its fair share of the most common lunar resources, which are clinging soil; high vacuum; extreme temperatures ($\sim -170^\circ$ to 120°C); half-time sunlight; long, hot days ($\sim 14 \times 24$ hours); and long, cold nights [1]. With experience, we will come to view them as assets rather than just as obstacles. Harnessing the Sun's energy requires reflectors, pointable mirrors, photovoltaic and other devices for converting radiation to electrical energy, and heat engines. Vacuum is handy in casting molten materials. Proposed uses for unprocessed soil include thermal insulation, radiation shielding, and spacecraft ballast. Exactly how to use the soil, dig it up, and pile it on remain research topics.

Converting soil to structural material with adequate mechanical strength adds complexity. Proposed forms include bricks [6-8], cast basalt products (see Glass and Ceramics), glasses (see Glass and

Ceramics), cement, and concrete [9] (see Concrete). Sintering with solar ovens and with microwaves has been proposed [7,10,11]. Molten soil can be cast in the same manner that basalt is cast on Earth to produce pipes. Quenched rapidly, it will yield glass. Items drawn, spun, and cast from molten soil may become the main structural materials of near-Earth space. Glasses produced and used in a water-free vacuum will be somewhat stronger than their counterparts exposed to water [12-15]. Concrete may prove useful on the Moon; it need contain as little as ~1.5 wt% hydrogen. Cohesive lunar rock can serve as aggregate, but gravel appears to be scarce in the regolith [1] and is probably too valuable to use this way. Destructive distillation of lunar soil at very high temperature produces refractory materials that, on fine grinding, might make decent cement. Distillation, grinding, collection of aggregate, mixing, forming, and pouring make concrete use a multistep, probably labor-intensive process, however.

The Apollo 17 site has a good range of soil compositions [1,16], although it lacks the highly feldspathic soils typical of most lunar highlands. Major elemental constituents of lunar soils can be extracted chemically. At the Taurus-Littrow site, typical soil concentrations in weight percent are as follows: Si, 18-21; Ti, 0.8-6; Al, 3-5.5; Fe, 6.5-14; O, ~44 [1,16].

Oxygen production has received the most attention because O₂ makes up the bulk of H₂-O₂ propellant. Oxygen is also crucial to life support. Proposed extraction methods include reduction of ilmenite or glass by H₂, C, or CO (e.g., [17-22]; see Oxygen and Water), chemical dissolution of soil (e.g., [23-25]), electrolysis of molten soil, with or without added electrolyte (e.g., [26-29]), and destructive distillation of soil in a solar furnace (e.g., [31,32]). Gas reduction and electrolytic methods are understood best because the most experiments have been done on them. Early gas reduction studies centered on ilmenite, which is abundant (up to ~25 wt% in basalts) at the Taurus-Littrow site. Cumulus deposits of ilmenite may occur. Compositions of most Taurus-Littrow soils are also within the range (12-22% Al₂O₃) required by electrolytic methods.

Some less abundant materials are possible ores. Lunar volcanic ash has low overall lunar abundance, but is concentrated in relatively few locations (e.g., [33]). The orange soil ash from station 4 indicates that the Taurus-Littrow site may have useful deposits. A deposit would need to be proven by three-dimensional survey before a process using it was selected.

Abundant but dilute materials may be considered as ores if extraction of a product is simple. Solar-wind-implanted elements (SWIE) H, N, C, and noble gases can be extracted by heating soils to >700°C (e.g., [1,34-41]). Concentrations in mature Apollo soils (H and N, ~50 µg/g; C, ~100 µg/g; He, ~10 µg/g) are sufficient that a small operation by terrestrial mining standards could supply life-support needs of a substantial lunar base and enough H₂ for propellant for all operations in near-Earth space [34]). If ³He is ever mined for export to Earth, the other SWIE will be abundant byproducts; their potential future value demands that these materials be collected and stored if this can be done at low cost.

High concentrations of SWIE are favored by the presence of crystalline ilmenite (e.g., [42]), small grain size (e.g., [43]), and high soil maturity (average duration of exposure to solar wind). Unfortunately (in this context), soils of high maturity and small grain size tend to have low proportions of surviving minerals, including ilmenite. The soils collected from the Taurus-Littrow site that have the greatest maturity and highest SWIE are not the high-TiO₂ mare soils (e.g., [16,39,44-46]). Most sampled mare soils were collected near relatively fresh craters, however, and may be less mature than average Taurus-Littrow mare soils. Concentrations of SWIE and maturities at

the tops of cores and drive tubes are not indicative of conditions a few centimeters lower (e.g., [39,44-46]. Thus, ore certification is essential for efficient mining of SWIE. The Taurus-Littrow site has some mature soils with competitively high SWIE concentrations (i.e., >50 µg/g H).

The minor elements P and S may be present in high enough concentrations in KREEPY materials and basalts that those materials can be considered seriously as potential ores if economical methods for their extraction can be developed [1,47]. If so, the Taurus-Littrow site is favorable for S; typical soil concentrations are 0.03-0.1 wt% [1,16]. Higher concentrations, typically, <0.1 wt%, are found in high-Ti mare basalts. Ores of higher grade may occur, however, based on evidence for S mobilization on the Moon as well as theoretical reasons to expect it [48]. Small quantities of H₂S are released when SWIE elements are vaporized from soils [49]. The Apollo 17 orange soil is probably a poor ore despite its sulfide coatings; the bulk S concentration of the orange soil is only ~0.07 wt% [1]. Taurus-Littrow soils are 0.015-0.03 wt% P, several times lower than Fra Mauro soils [1]. Vapor mobilization may have produced P ores [48]. It may be a good economic gamble to search for concentrated ores of P and S rather than to use common rocks or soils.

There may be ores of less abundant elements, owing to the extensive chemical fractionations known to have occurred during formation and evolution of the Moon's crust. This is speculative, prediction of sites of deposition of such ores is speculative, and survival of specialized ores through meteoroid impacts is speculative, so we dare not rely on their presence until we evaluate this through further exploration and sampling. Lunar volcanic ash, and especially the orange glass at the Taurus-Littrow site, is sometimes suggested as a source for relatively volatile elements, as these coat the individual spherules and may be easy to extract. However, except for Zn, bulk concentrations of vapor-mobilized elements (VAPS [1]) are not especially high relative to soil concentrations at several landing sites.

The principal materials required for survival and basic human activity are present on the Moon, if one chooses to imagine oneself a lunar pioneer and chemist [50]. The common materials of construction and the general style of life will differ in interesting ways from what we are used to. The Taurus-Littrow site has adequate supplies of the most common lunar resources.

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A SPECTRAL SURVEY OF THE SERENITATIS BASIN REGION OF THE MOON. B. R. Hawke¹, C. A. Peterson¹, P. G. Lucey¹, D. T. Blewett¹, J. F. Bell III², and P. D. Spudis³, ¹Planetary Geosciences, SOEST, University of Hawaii, Honolulu HI 96822, USA, ²NASA Ames Research Center, Moffett Field CA 94035, USA, ³Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, USA.

Introduction: The returned lunar samples contain much petrological and compositional information for small, select portions of the surface of the Moon. Many of the highland samples returned from the Apollo landing sites are somehow related to lunar multiringed impact basins, either as primary ejecta or reworked local material. These highland samples cannot always be related to a basin directly, and it is extremely difficult to characterize the composition and lithology of basin ejecta based on a small number of returned samples. However, the Apollo orbital geochemistry instruments and Earth-based remote sensing techniques provide compositional data for large portions of the lunar surface, including basin ejecta deposits. These data provide a regional framework within which to interpret the significance of the returned samples as well as information concerning the stratigraphy of the lunar crust [1].

In recent years, we have utilized the Apollo orbital geochemistry datasets and Earth-based spectral reflectance data to investigate the composition of highland units associated with lunar multiring basins. These include Imbrium [2], Orientale [3,4], and Nectaris [1,5] Basins. We have also analyzed a large number of near-IR reflectance spectra and multispectral images in an attempt to answer a variety of questions concerning the Serenitatis Basin. These questions include (1) What is the composition of highland units in the region and how do these compositions vary as a function of position around and distance from Serenitatis? (2) What was the crustal stratigraphy of the Serenitatis preimpact target site? (3) How do the Apollo 17 samples relate to geologic units in the surrounding highlands? (4) What is the nature and origin of light plains deposits in the region? (5) Do cryptomare occur in the Serenitatis region? The purpose of this paper is to present the preliminary results of our analyses of spectral data obtained for the Serenitatis Basin region.

Method: Near-infrared reflectance spectra (0.6-2.5 μm) were obtained at the 2.24-m telescope of the Mauna Kea Observatory during a series of observing runs using the Planetary Geosciences indium antimonide spectrometer. The lunar standard area at the Apollo 16 landing site was frequently observed during the course of each evening, and these observations were used to monitor atmospheric extinction throughout each night. Extinction corrections were made using the methods described by McCord and Clark [6], and spectral analyses were made using the techniques described by McCord et al. [7]. The multispectral images used in this study were described by McCord et al. [8] and Bell and Hawke [9].

Results and Discussion: *Taurus-Littrow region.* Spectra were obtained for various portions of the North and South Massifs at the Apollo 17 site. Analysis indicates that they exhibit "1- μm " bands that are centered at 0.92 μm and have band strengths of ~6%. These characteristics indicate a feldspar-bearing mineral assemblage with a

mafic component dominated by low-Ca orthopyroxene. The areas for which these spectra were obtained contain abundant anorthositic norite.

Spectra were also collected for various areas of Littrow Crater. The dominant lithology is anorthositic norite. However, spectra for a small, fresh crater on the north rim of Littrow as well as the floor of Littrow have "1- μm " bands centered at slightly longer wavelengths (~0.94 μm) than the spectra obtained for the Apollo 17 massifs. The highland-rich soil in the floor of Littrow may contain minor amounts of dark mantle material of pyroclastic origin.

Both localized (LDMD) and regional dark mantle deposits (RDMD) of pyroclastic origin occur in the Taurus-Littrow region. The Taurus-Littrow RDMD occurs west of the Apollo 17 site, and the thickest portion covers an area of 4000 km² [10,11]. We have obtained near-IR spectra for several portions of this RDMD. The spectra exhibit very steep continuum slopes and broad, shallow 1.0- μm absorption bands. Band analysis suggests that olivine is the most abundant mafic mineral. Previous studies have demonstrated that the black spheres from the rim of Shorty Crater are the characteristic ingredients and dominate the spectra of the Taurus-Littrow RDMD [11-14]. These dark pyroclastic spheres, which contain abundant ilmenite and olivine, are the quench-crystallized chemical equivalents of the homogeneous Apollo 17 orange glasses. This RDMD exhibits very weak echoes on 3.8-cm radar images; a lack of surface scatterers (fragments 1-50 cm in size) is believed to be responsible for the low radar returns [11,12]. Previous studies of lunar RDMD have suggested that they would be excellent sites for lunar outposts and that the pyroclastic debris could be a source of several valuable resources [15].

The dark floor deposit in Vitruvius Crater was mapped as an LDMD by Wilhelms and McCauley [16]. The spectrum obtained for this deposit falls in LDMD group 2 as defined by Hawke et al. [10]. These spectra closely resemble those obtained for mature mare.

Plinius-Dawes region. The preliminary results of analyses of CCD imaging and spectroscopy data obtained for the Plinius-Dawes region was recently presented by Bell and Hawke [9]. Dawes (18 km) has a symmetrical band centered at 1.0 μm that is deeper than that of the surrounding mare, indicative of a lesser degree of soil maturity. In addition, Dawes has little or no highland signature in its six-color spectrum. In contrast, Plinius Crater (43 km) spectra exhibit more complex 1- μm bands. Spectra for the southwest wall and southwest floor have bands that appear rather symmetrical and are centered near 1.0 μm . The bands are not as deep as those exhibited by the Dawes spectra or those of surrounding mature mare surfaces. The 1- μm bands of the Plinius central peak and northeast wall spectra are clearly composed of two features: a short-wavelength component centered near 0.92 μm and a longer wavelength component centered near 1.0 μm . The 0.92- μm feature is weaker than the 1.0- μm band in the northeast wall spectrum, suggesting that this is primarily mare material with a minor highland component. However, the 0.92- μm band is much more prominent in the central peak spectrum, suggesting that the peak is primarily noritic highland material with minor mare contamination [9]. Our linear mixing model studies of the six-color CCD images verify and extend the spectral interpretations. The Plinius central peak and several regions of the floor clearly have a substantial highland signature, and small outliers of highland material can be seen in the northwest ejecta. In addition, several regions of the floor and south-southwest rim exhibit a spectral signature more like that of the low-Ti Serenitatis mare than the Tranquillitatis basalts.

Montes Haemus region. The Haemus Mountains form one segment of the mare-bounding ring of the Serenitatis Basin. Menelaus Crater straddles the mare-highlands border, and the interior and