TABLE 1. Orbital remote sensing for lunar resources.

| Objective | Measurement | Technique | Precision and Resolution |
|---|---|---|---|
| Ilmenite abundance and distribution (relates to H, He, and $O_2$ potential; also to Ti and Fe production) | 1. $TiO_2$ concentration<br>2. Concentration of other major elements (Si, Al, Mg, Fe, Ca) | 1,2. X-ray fluorescence or gamma ray | 1. ±5%; 10s km spatial<br>2. ±5%; 10s km spatial |
| | 3. Modal abundance of ilmenite | 3a. Albedo<br>3b. UV spectroscopy | 3a. ±10%; 100 m spatial<br>3b. 0.1 to 0.7 $\mu$m; 100 m spatial |
| | 4. Regolith maturity | 4. Reflectance spectra | 4. Broad characterization; 5 narrow bands at 0.7, 0.9, 0.95, 1.0, and 1.5 $\mu$m (or imaging spectrometer); 100 m spatial |
| Regolith properties (relates to plans for mining, base construction, and ilmenite abundance) | 4. Regolith maturity<br>5. Regolith thickness<br>6. Block distribution | 4. Same as above<br>5. Imaging<br>6. Imaging | 4. Same as above<br>5. 2 m spatial<br>6. 1 m spatial |
| Unexpected enrichments of elements or minerals | 6. Concentrations of major elements (Si, Al, Mg, Fe, Ca, Ti) | 6. X-ray fluorescence | 6. ±5%; 1 km spatial |
| | 7. Concentrations of incompatible trace elements (U, Th, K) | 7. Gamma ray spectrometry | 7. ±5% (in 1–100-ppm range); 10 km spatial |
| | 8. Presence of unusual minerals (e.g., quartz) | 8. Imaging reflectance and emission spectroscopy | 8. Full spectral coverage, 0.1 to 50 $\mu$m |

around ilmenite reduction. In these cases, the key information is the abundance and physical state of ilmenite in the regolith. The ideal regolith contains a high abundance of ilmenite and has been reworked by impacts sufficiently to break up rocks, but not so much as to convert much of the regolith (including ilmenite) to glassy agglutinates. Thus, we need to know (1) the Ti concentration, which gives us the potential ilmenite concentration; (2) concentrations of other major elements for completeness and to help assess modal ilmenite by calculating normative ilmenite; (3) the modal abundance of ilmenite, which can be obtained directly, in principle, by spectral measurements in the UV and by albedo measurements; and (4) regolith maturity, to choose areas richest in ilmenite fragments. Hydrogen and helium concentrate in ilmenite. This effect overwhelms the effect of soil maturity, though both are important. Thus, the highest concentration of H and He are in high-ilmenite soils that have long exposure histories. So, in this case, the optimum soil would have high maturity, rather than the intermediate soil preferred for oxygen production by ilmenite reduction.

**Regolith—Shielding and Construction Material:** We probably already know enough about the lunar regolith to design equipment to excavate and transport it. However, for completeness, I list the properties that can be assessed from orbit (Table 1). Maturity was discussed above. Regolith thickness can be deduced from crater morphologies; thus high-resolution imaging is needed. Clearly, this cannot be done globally. Determining the abundance and distribution of blocks of rock also requires high-resolution imaging. How good the resolution needs to be is problematic; since block distributions tend to follow a power law (i.e., the size distribution is fractal), one can measure blocks larger than 1 m and deduce the distribution at smaller sizes.

**The Unexpected:** The absence of water on the Moon limits the potential for elemental concentrations and the production of unusual minerals. However, extreme igneous fractionation might have produced some materials rich in incompatible elements (U, Th, K, rare earths) and perhaps even certain volatiles such as halogens and the elements that might have formed complexes with them (e.g., Ge). The trick is to search for evidence for extensive igneous evolution: high Fe/Mg; enrichments in elements such as U, Th, and K; and the presence in moderate to high amounts of minerals such as quartz and alkali feldspar.

Reference: [1] Spudis P. D., this volume.

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**A COMBINED XRD/XRF INSTRUMENT FOR LUNAR RESOURCE ASSESSMENT.** D. T. Vaniman, D. L. Bish, S. J. Chipera, and J. D. Blacic, Los Alamos National Laboratory, Los Alamos NM 87545, USA.

Robotic surface missions to the Moon should be capable of measuring mineral as well as chemical abundances in regolith samples. Although much is already known about the lunar regolith, our data are far from comprehensive. Most of the regolith samples returned to Earth for analysis had lost the upper surface, or it was intermixed with deeper regolith. This upper surface is the part of the regolith most recently exposed to the solar wind; as such it will be important to resource assessment. In addition, it may be far easier to mine and process the uppermost few centimeters of regolith over a broad area than to engage in deep excavation of a smaller area. The most direct means of analyzing the regolith surface will be by studies *in situ*. In addition, the analysis of the impact-origin regolith surfaces, the Fe-rich glasses of mare pyroclastic deposits, are of resource interest [1,2], but are inadequately known; none of the extensive surface-exposed pyroclastic deposits of the Moon have been systematically sampled, although we know something about such deposits from the Apollo 17 site. Because of the potential importance of pyroclastic deposits, methods to quantify glass as well as mineral abundances will be important to resource evaluation.

Combined X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis will address many resource characterization problems on the Moon. Other means of chemical analysis (e.g., instrumental neutron activation analysis or laser-induced breakdown spectroscopy) would extend the suite of elements measured beyond

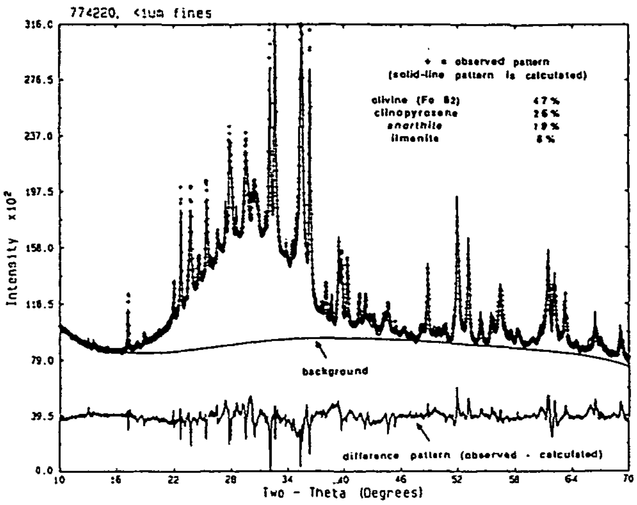


Fig. 1.

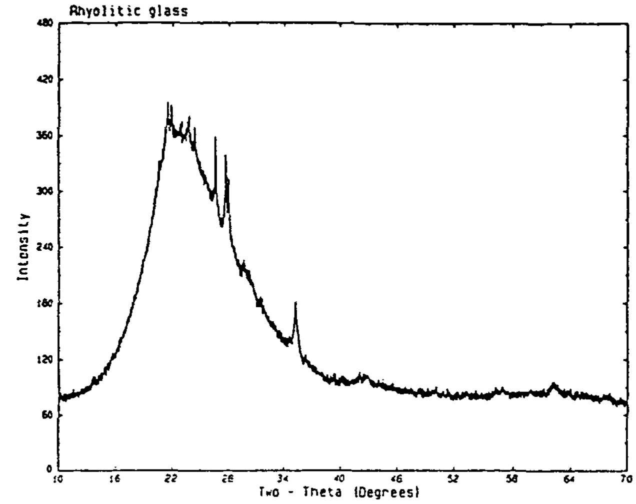


Fig. 2.

those detectable by XRF, particularly for elements lighter than Mg. However, XRF methods are valuable for obtaining full major-element abundances with high precision. Such data, collected in parallel with quantitative mineralogy, permit unambiguous determination of both mineral and chemical abundances where concentrations are high enough to be of resource grade.

Collection of both XRD and XRF data from a single sample provides simultaneous chemical and mineralogic information. These data can be used to correlate quantitative chemistry and mineralogy as a set of simultaneous linear equations, the solution of which can lead to full characterization of the sample. The use of Rietveld methods for XRD data analysis can provide a powerful tool for quantitative mineralogy [3] and for obtaining crystallographic data on complex minerals [4]. Rietveld methods applied to the XRD data will provide (1) enhanced accuracy for quantitative mineralogy, (2) a capability for crystal-chemical characterization of unstable minerals (e.g., the questionable lunar occurrences of lawrencite, $FeCl_2$ [5]) in their natural environment, and (3) a capability to recognize and characterize previously unknown minerals.

Ultimately, Rietveld methods can be used to determine glass abundances where the sample contains a particular type of glass. This approach will be most useful in the exploration of pyroclastic glass deposits. Figure 1 shows an XRD pattern obtained from the <1-μm fraction of pyroclastic sample 74220,19, obtained by settling in Freon. This pattern was collected from 17 mg of material. Rietveld analysis was used to obtain the abundances of crystalline constituents (normalized to 100%) as well as the olivine Mg/Fe ratio. When similar data are obtained on pure splits of the pyroclastic glass, then abundances of this glass (represented by the amorphous bulge between 17° and 46° 2Θ) can be determined. Other glasses, either known or exotic, can be modeled from diffraction data. Figure 2 illustrates the very different amorphous diffraction character of terrestrial rhyolitic glass in comparison with the basaltic pyroclastic glass of 74220 in Fig. 1. With appropriate library diffraction data, a wide variety of glasses and minerals can be determined quantitatively in lunar materials.

**References:** [1] McKay D. S. et al. (1991) *LPSC XXII*, 881–882. [2] Hawke B. R. et al. (1989) *LPSC XX*, 389–390. [3] Vaniman D. T. (1991) *LPSC XXII*, 1429–1430. [4] Vaniman D. et al. (1991) *Clay Min. Soc. 28th Ann. Mtg.*, 157; [5] Taylor L. A. et al. (1973) *Proc. LSC 4th*, 829–839.

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**LUNAR LAVA TUBE SENSING.** Cheryl Lynn York, Bryce Walden, Thomas L. Billings, and P. Douglas Reeder, Lunar Base Research Team, Oregon L5 Society, P.O. Box 86, Oregon City OR 97045-0007, USA.

Large (≥300-m-diameter) lava tube caverns appear to exist on the Moon and could provide substantial safety and cost benefits for lunar bases. Over 40 m of basalt and regolith constitute the lava tube roof and would protect both construction and operations. Constant temperatures of -20°C reduce thermal stress on structures and machines. Base designs need not incorporate heavy shielding, so lightweight materials can be used and construction can be expedited [1,2]. Identification and characterization of lava tube caverns can be incorporated into current precursor lunar mission plans. Some searches can even be done from Earth.

Earth-based sensing of major near-surface (200-m-deep) lunar lava tubes and their entrances at 25-m resolution may be possible using Earth-penetrating radar (EPR) interferometry [3]. From lunar orbit 1-m EPR resolution should be achievable. Radar, lidar, and optical and infrared imaging might spot an entrance candidate from lunar orbit without using power-intensive EPR. Lava tube entrances can also be found directly by surface explorers (human or machine). Multifunctional kinetic penetrators and high-resolution seismic arrays may detail likely sites. Any search for lunar ice or other captured volatiles should include sheltered lava tube entrances and skylights (spot roof collapses).

Interior volume mapping to 10-cm resolution should be possible using lidar, microwave, or optical imaging from a platform moving along the length of the cavern. Floor and ceiling detail in optical or lidar data could be evaluated for lunar geoscience and possible