

A STRATEGY FOR PROSPECTING FOR LUNAR RESOURCES USING REMOTE SENSING AND *INSITU* (XRF/XRD) CHEMICAL AND MINERALOGICAL ANALYSES. G. Jeffrey Taylor¹, Linda M. V. Martel¹, Kevin M. Cannon², Elizabeth B. Rampe³, D.F. Blake⁴, P. Sarrazin⁵. ¹Hawaii Inst. of Geophysics and Planetary Science, Univ. of Hawaii (gjtaylor@higp.hawaii.edu), ²Colorado School of Mines, ³NASA Johnson Space Center, ⁴NASA Ames Research Center, ⁵eXaminArt LLC.

Introduction: Permanent lunar settlements will require using resources found on the Moon. Lunar resources such as ice in permanently-shadowed places near the lunar poles may be exported to support scientific and commercial ventures throughout cis-lunar space and the entire inner Solar System. It is also possible that some resources will be valuable enough to mine, refine, and transport to Earth or other destinations. Here, we focus on prospecting for rare earth elements (REE). These elements are central to our modern electronic life. They are essential ingredients in silicon chips, computers, cell phones, batteries, ultra-strong magnets, x-ray machines and other medical devices, lasers, and low-emission fuel efficient vehicles [1]. It is an open question whether there are sufficient concentrations of the REE on the Moon to be classified as ore bodies [2,3] and if they exist that they could be transported to Earth to supplement the terrestrial supply and to decrease the terrestrial environmental hazards associated with their mining and refinement. Nevertheless, as McLeod and Krekeler [2] point out, the most promising areas on the Moon that might house REE ore deposits have not been examined at sufficiently high resolution to determine if high enough concentrations exist to classify them as ore deposits. It may turn out that there are no REE ore deposits on the Moon, but the prospecting approach we outline here can be used to search for other types of useful deposits.

Searching for REE in the Great Procellarum Hot Spot: As shown by Jolliff et al. [4] from global orbital measurements of Th concentrations using gamma-ray spectrometry, Th is distributed heterogeneously (Fig. 1). Because Th is a typical large-ion lithophile (LIL) element, all other LIL elements are likely to also be distributed heterogeneously. Studies of lunar samples confirm this. There is a strong correlation (Fig. 2) between Th and La, indicating that Th is a good guide for the global distribution of the REE on the lunar surface.

It is obvious from Fig. 1 that the PKT is the logical place to search closely for potential ore deposits of the REE. For example, the Apollo 14 landing site is inside one of the 60-km wide resolution elements that has the highest concentration of Th, ~12 ppm, corresponding to ~70 ppm of La (Fig. 2) and (not shown in Fig. 2) 180 ppm of Ce and 650 ppm of Zr.

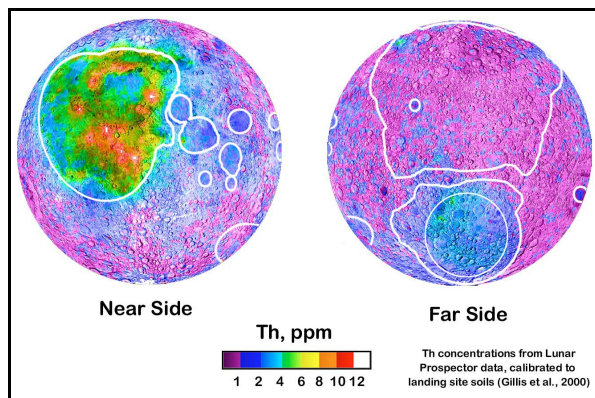


Fig. 1: Th concentration on the Moon. White lines outline the terranes identified by [4]. Large, high Th region on the nearside is the Procellarum KREEP Terrane (PKT), which has Th measured concentrations up to ~12 ppm. Each spatial resolution element is 60 km across, so it is likely that smaller regions have Th concentrations > 12 ppm.

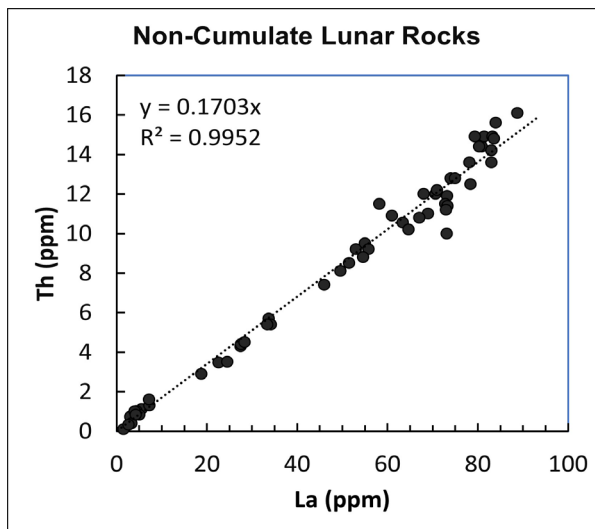


Fig. 2: Th is correlated with La (and other REE) abundances, showing the value of Th as a tracker of total REE abundances. Data from [5,6].

A rover could be landed inside a 60-km spatial resolution element, say near the Apollo 14 site. It could autonomously traverse an assigned region, making measurements of pertinent major and trace elements. Let us say it has an instrument (see below) capable of

measuring Zr or the REE (e.g., La or Ce) to high accuracy if it is present above the mean expected for 12 ppm of Th (70 ppm of La, 180 ppm of Ce, or 650 ppm of Zr). To fully understand the distribution, detection limits would need to be at least 10% of these values. Measurements could be made every 10 or 100 meters along a 2-dimensional grid. The data could be transmitted back to a central station or directly to orbiting satellites. The numerous analyses at known locations would allow planetary economic geologists to make contour maps of the abundance of Zr (or another diagnostic element), as illustrated in Fig. 3. Regions of exceptional concentrations would be investigated further, either by autonomous rovers or by humans.

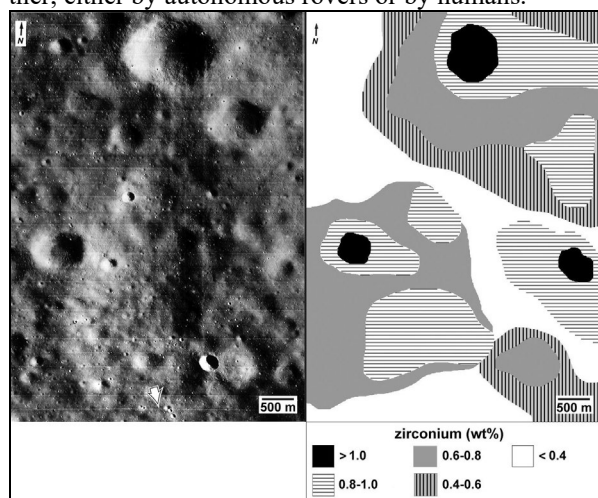


Fig.3: Example of map of elemental distribution obtained by an XRF instrument on a hypothetical rover on the Moon. Left: Portion of Lunar Orbiter photograph III-133-H2 of the region north of the Apollo 14 landing site (arrow near the bottom). Right: Map of the concentration of zirconium in this hypothetical example.

The REE are not, of course, distributed uniformly in the phases present in the lunar regolith. They concentrate in minerals with crystallographic sites suitable for hosting large ions such as the REE, Zr, Th, and U. This is an advantage for their use as a resource, assuming their host minerals can be identified and then extracted by mineral processing/beneficiation. Thus, it would be essential to include the capability of identifying which REE-bearing minerals are present in the lunar regolith along the exploration traverses. Apollo sample analyses show that several REE-bearing minerals are present in the PKT. Merrillite, for example, contains 6 to 10 wt% total REE in samples from the Apollo 11, 12, 14, 15, and 17 landing sites, plus lunar meteorite LAP022 [7]. Other common REE-bearing minerals are apatite (up to about 1 wt% total REE),

monazite, tranquillityite, zircon, and zirconolite [8]. A full survey of a potential ore deposit requires that these minerals be identified and their abundances determined with detection limits on the order of 1 wt%.

Potential Instrumentation for *In Situ* Analyses:

Mineral phases are best identified by X-Ray Diffraction (XRD) and bulk chemical analyses can be done accurately by X-Ray Fluorescence (XRF). For example, an instrument package [9] proposed to NASA's PRISM program combines both XRD and XRF (with other instruments). The XRD/XRF instrument is described by Blake et al. [10]. Instrument development is still in progress, but previous experience and calculations show that pertinent minerals will be detectable and their abundances quantifiable if present at >1 wt% and that most REE elements will be detectable and quantifiable at concentrations >2 ppm. Major elements (those with concentrations >0.1 wt%) will have detection limits of <0.01 wt%. Alternatively, the tried-and-true APXS instrument could measure REE concentrations as well and could be accompanied by an XRD instrument. The crucial point is that the combination of XRD and XRF analyses along traverses as shown in Fig. 3 will allow for a robust estimate of whether a given prospect can be classified as an ore deposit.

Summary: The approach outlined here for assessing a locale for its resource potential is feasible. The combination of using global remote sensing data to target potential mining sites, and *in situ* mineralogical and bulk chemical analysis of promising sites will be an effective way to start using lunar resources. Significant unknowns are the details of how REE-bearing minerals will be extracted efficiently and where the separation of the REE will be done (on the Moon or by shipping tons of REE to the Earth). An even greater unknown is the cost effectiveness of exporting lunar resources to the Earth. To address that issue, we need to determine where potential ore deposits exist and test how efficiently we can extract them with minimal harm to the lunar environment.

References: [1] Balaram, V. (2019) *Geosci. Frontiers*, 10, 90, 1285-1303. [2] McLeod, C. L. and Krekeler, M. P. S. (2017) *Resources*, 6, 40. [3] McLeod, C. L. and Shaulis, B. J. (2018) *Minerals*, 8, 455. [4] Jolliff, B. L. et al. (2000) *J. Geophys. Res.*, 105, p. 4197-4216. [5] *Lunar Sample Compendium*. [6] Korotev, R. L. (2000) *J. Geophys. Res.*, 105, 4317-4345. [7] Jolliff, B. L. et al. (2006) *Am. Mineralogist*, 91, 1583-1595. [8] *Lunar Sourcebook*, Chapter 5. [9] Rampe, E. B. et al. (2022) *LPSC LIII*, abstract #2093. [10] Blake, D. F. et al. (2022) *LPSC LIII*, abstract #1612.