ASSESSING LUNAR RARE EARTH ELEMENT RESOURCES. L. Keszthelyi[1], L. Pigue[1], K. Bennett[1], C. Neal[2], J. Coyan[3], and R. Elphic[4] [1]U.S. Geological Survey, Astrogeology Science Center, Flagstaff, AZ, USA; [2]University of Notre Dame, Notre Dame, ID, USA; [3]U.S. Geological Survey, Geology, Minerals, Energy, and Geophysics Science Center, Spokane, WA, USA; NASA Ames Research Center, Moffett Field, CA, USA.

Introduction: Rare Earth Elements (REEs) are increasingly attracting attention globally due to their pivotal role in enhancing the performance of various high-tech devices. Small amounts of these elements greatly improve the performance of materials, making magnets stronger, lenses clearer, lights brighter, batteries last longer, etc. Here we examine the notion that REEs from the Moon might compete with mining on Earth.

Resource Assessments: Various methods exist for assessing mineral resources and their economic potential. Here, we follow the method suggested by [1] that adjusts the USGS methods for mineral assessments on Earth for application to the Moon (Fig. 1). However, the available data do not allow us to fully complete a quantitative assessment. There are more complex resource classification schemes for lunar resources [e.g., 2] but these also await new data.

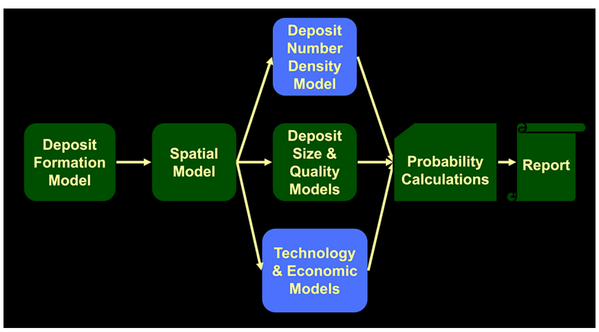

Fig.1 Flowchart for USGS lunar resource assessments [1]. Current data allow us to proceed ~50% across this workflow.

Deposit Formation Model: REEs on the Moon are found in higher concentrations in a type of rock that is also rich in potassium (K) and phosphorus (P) and is therefore named "KREEP." The concentration of these elements is thought to be related to the last stages of magma ocean crystallization; the primary KREEP deposit is ancient and deep in the lunar crust. KREEP materials have been brought to the surface by volcanic and impact processes where they have been modified and redistributed by impact gardening.

This long and complex geologic history has produced a variety of KREEP samples affected by varied mixes of igneous and impact processes. The Apollo missions returned a substantial collection of lunar samples, which have been instrumental in conducting detailed geochemical analyses. While these analyses have provided valuable insights into the Moon's composition, they are limited to specific locations and scales, leaving broader questions about lunar geology unanswered. Despite these limitations, the available data are sufficient to construct a preliminary KREEP deposit formation model.

Mapping KREEP: The next step in the assessment flowchart is to produce a spatial model that indicates where KREEP deposits are geologically plausible. Global mapping is done most effectively using orbital remote sensing and the instrument that could most directly detect REEs is the neutron spectrometer onboard the Lunar Prospector mission [3].

Some REEs are good absorbers of lower-energy "thermal" neutrons and there are regions of the Moon that emit relatively fewer thermal neutrons. Elphic et al. [3] were able to match the observations using neutron transport and absorption models and compositions constrained by Apollo samples. Figure 2 shows their map of inferred samarium (Sm) concentration.

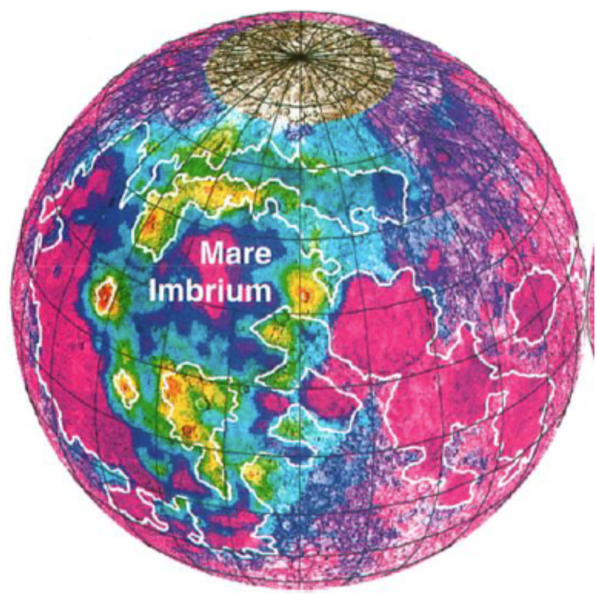

Fig.2 Map of inferred Sm abundance after [3]. Values range from <5 ppm (pink) to >45 ppm (orange).

These model results can be verified by comparing to maps of thorium (Th) on the Moon (Fig. 3). Thorium is not a REE but behaves chemically similarly in rocks and is elevated in KREEP samples. Thorium's natural radioactivity allows it to be detected by orbiting gamma ray spectrometers. The excellent match between the Sm and Th maps, derived from data collected by separate instruments with independent analyses, gives us great confidence that we have a robust spatial model of where KREEP materials are most abundant on the Moon.

REE Concentrations: The next model considers the quality (or grade) of the deposits. From the KREEP-rich lunar samples, we can estimate the concentration of the various REEs. A useful way to express these concentrations is to compare them to the average composition of our solar system, which is estimated from the compostion of a class of meteorites called “chondrites.” Figure 4 shows these values and compares them to those of a variety of REE ore deposits on Earth. The key take away is that known KREEP samples have compositions that partially overlap compositions of deposits that are economical to mine on Earth.

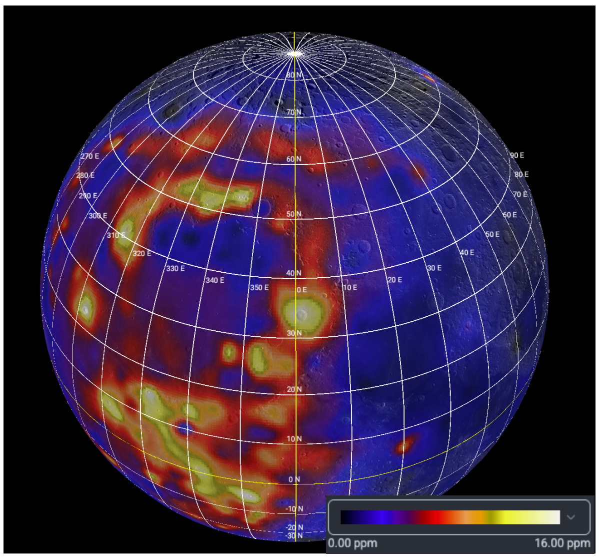

Fig.3 Map of thorium abundance after [4].

Other Deposit Models: To conduct a quantitative resource assessment, it is essential to develop probability distributions for key parameters such as the number, size, and concentration of deposits. This approach allows for a comprehensive understanding of the resource potential and associated uncertainties. This is where current data are lacking. The orbital neutron and gamma ray data have a spatial resolutions of tens of kilometers per pixel and the Apollo samples are, at best, decameters in size. These types of data do not allow us to measure the dimensions of individual deposits nor do they allow us to properly quantify the variability within and between deposits. There is good reason to suspect that there are deposits with higher concentrations of REEs than have been identified in the Apollo samples or via orbital mapping. [7] considered the hypothesis that KREEP may be concentrated within some geologic units and concluded that thorium (and presumably REE) concentrations may be locally ~12 times higher than indicated in the low resolution maps. This possibility is shown as “Fedorov Unit” in Figure 4, providing much greater overlap with ores on Earth.

Locating and characterizing the best REE deposits will require exploration across kilometers with a spatial resolution of decameters. Realistically, this can only be done with rovers. The VIPER rover is one example of a vehicle capable of resource exploration at this scale, but VIPER is designed to operate at the lunar poles where there is no indication of KREEP. However, NASA’s CLPS CP-21 mission is slated to land in 2028 at the Gruithuisen Domes – a region that [7] suggests may have the some of the highest concentrations of thorium (and presumably REEs) on the Moon. The CP-21 payload includes the rover-borne Lunar-VISE package that has instruments to characterize the chemistry, mineralogy, and surface properties of REE deposits.

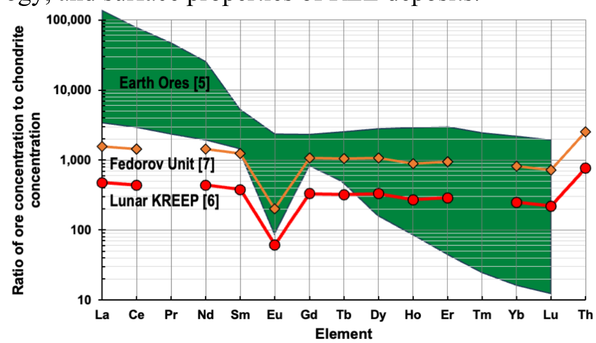

Fig.4 REE concentration in KREEP and Earth ores [5,6,7].

Economic Models: To assess if the lunar REE resources include reserves, it is necessary to consider if the REEs can be recovered economically. This depends critically on the capabilities and robustness of the transportation infrastructure between the Earth and the Moon, irrespective of exactly how much ore refinement is done on the Moon versus the Earth. USGS assessments often consider a 30-year timeframe, which allows for a wide range of possible scenarios for the development of the cislunar transportation infrastructure and changes in REE economics.

Summary: REE deposits do exist on the Moon and it is plausible that they could include reserves within a 30-year timeframe. There are two major steps needed to develop lunar REE reserves: (1) in-depth resource exploration of key locations already identified from orbit and (2) development of a robust transportation infrastructure between the Earth and Moon.

References: [1] Keszthelyi, L. et al. (2023) *USGS Circular* 1507. [2] Espejel, C. D. et al. (2023) *Handbook of Space Resources*, p. 999-1022. [3] Elphic, R. C. et al. (2000) *J. Geophys. Res., 105*, 20333-20345. [4] Lawrence, D. J. et al. (2007) *Geophys. Res. Lett.*, *34*, L03201. [5] Schulz, K. J. et al. *USGS Prof. Paper* 1802. [6] Warren, P. H. and Wasson, J. T. (1979) *Rev. Geophys. Space Phy., 17*, 73-88. [7] Hagerty, J. J. et al. (2006) *J. Geophys. Res., 111*, E06002.