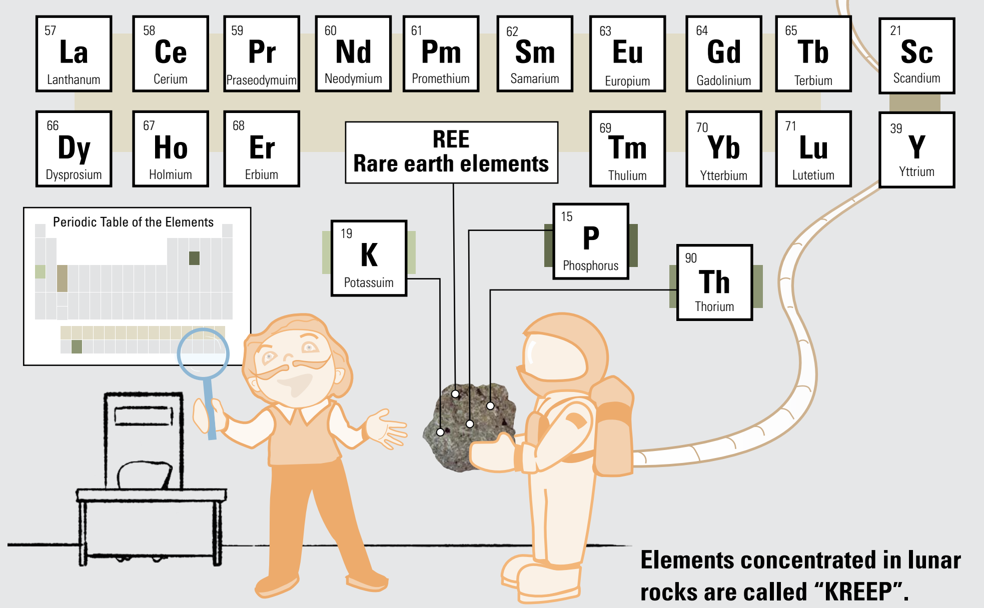
Rare Earth Elements on the Moon

Image showing KREEP basalt, Sample 15386, the largest fragment of KREEP extracted from the lunar regolith. Photograph from NASA.

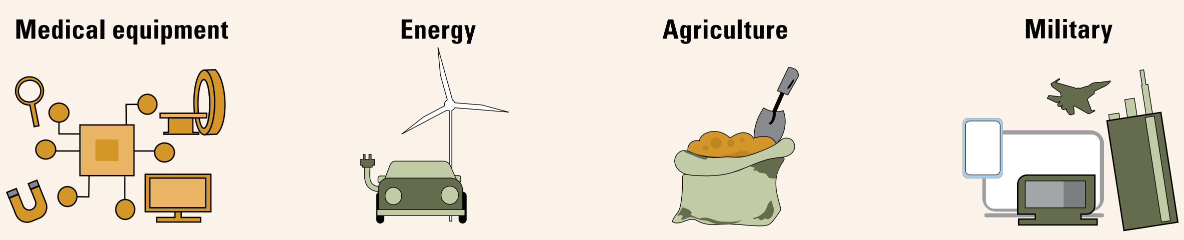
Rare earth elements (REEs) are a scarce but vital resource for our modern economies and lifestyles. Since the late 1990s, China has supplied the vast majority of the world’s refined REEs. Increasing global demand has broadened the search for REE deposits to unconventional places, including the Moon. Although most lunar rocks have very low REE concentrations, Apollo samples showed that one type of lunar rock containing potassium (K), REEs, and phosphorus (P)—known by the acronym KREEP—has high concentrations of REEs. Data from orbiting satellites have identified locations where substantial deposits of KREEP are likely. The viability of mining these deposits depends on the evolution of REE economics, the development of the Earth-Moon infrastructure, and the findings from future lunar mineral exploration missions.

What are Rare Earth Elements?

Near the bottom of the periodic table lies a group of elements called the lanthanides. There are 17 elements typically considered REEs: the lanthanides group, along with scandium and yttrium. Compounds containing REEs have countless applications, from industrial processes to the medical field. The addition of REEs provides performance improvements such as making magnets stronger, camera lenses clearer, lights brighter, batteries last longer, and television screens more vibrant. REEs increase economic prosperity, improve medical treatments, and are necessary for defense systems that protect our Nation.

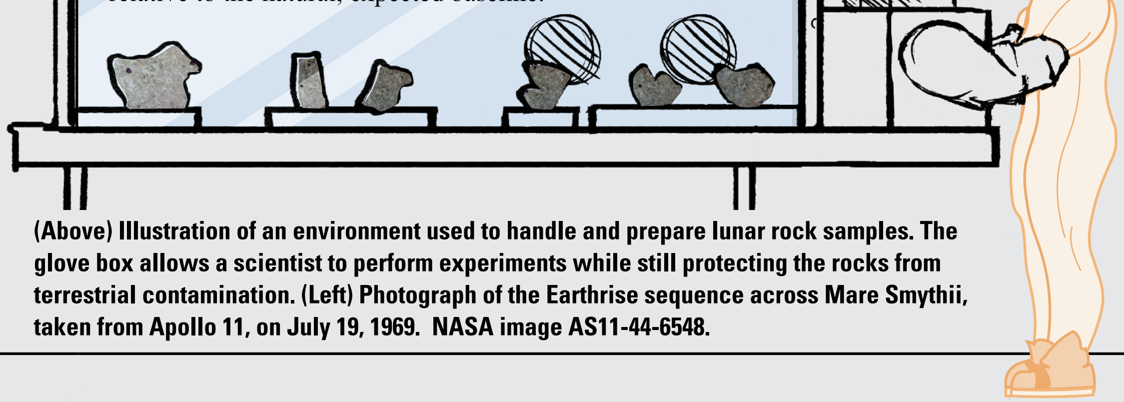


Elements concentrated in lunar rocks are called “KREEP”.



Examples of uses for rare earth elements.

Scientists make sense of the concentrations of elements in a rock sample, referred to as the bulk chemical composition, by comparing them to other rocks. For REEs, geologists compare concentrations to a particular type of meteorite, called a chondrite. Chondrites preserve a "snapshot" of the bulk chemical composition of materials that were present when the Solar System was formed, providing us with a Solar System average composition. Comparing the concentrations of REEs in a rock sample to the concentrations of REEs in chondrites allows us to determine if a rock has a higher or lower amount of REEs relative to the natural, expected baseline.



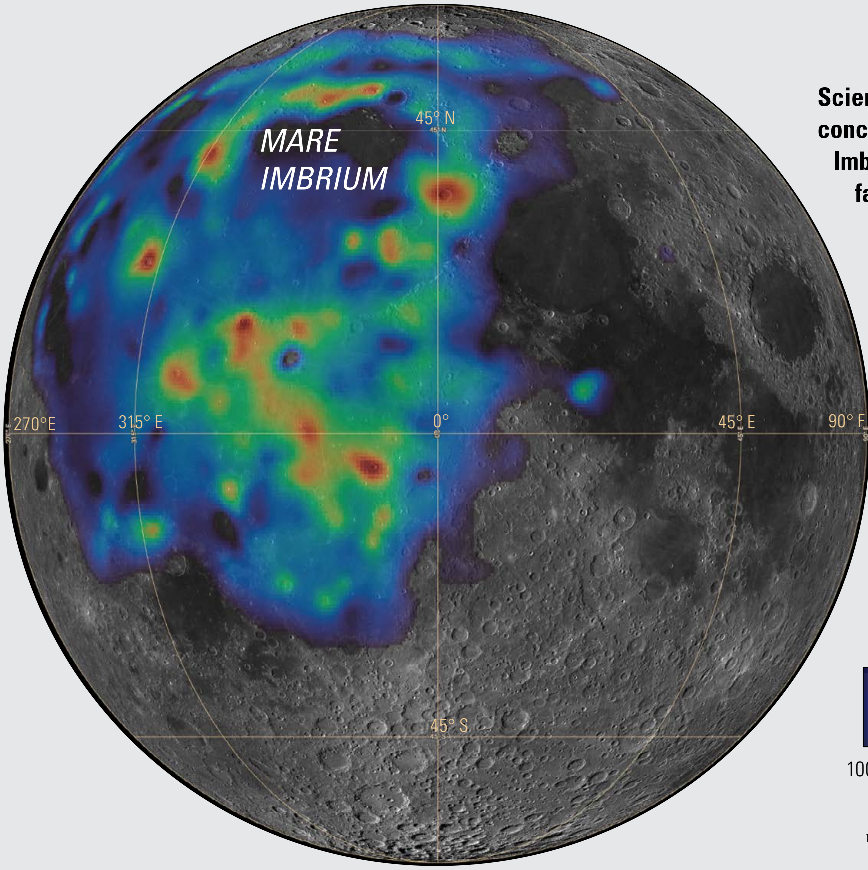
(Above) Illustration of an environment used to handle and prepare lunar rock samples. The glove box allows a scientist to perform experiments while still protecting the rocks from terrestrial contamination. (Left) Photograph of the Earthrise sequence across Mare Smythii, taken from Apollo 11, on July 19, 1969. NASA image AS11-44-6548.

Hunting for Lunar Rare Earth Elements

The Moon's surface has been pounded by meteorite impacts for billions of years, creating a layer of loose crushed rocks and dust known as regolith. Samples of regolith, returned to Earth by Apollo astronauts, show that most rocks in the places they visited have very low REE concentrations. However, detailed analysis of these samples found small rock fragments with relatively high concentrations of REEs. The fragments also have increased amounts of potassium (abbreviated K on the periodic table) and phosphorus (abbreviated as P), giving us the acronym "KREEP." But the small KREEP fragments could have come from practically anywhere on the Moon—the impacts that formed regolith also blasted material far and wide across the surface. Other instruments are needed to locate the larger mounds or layers of KREEP that the fragments originated from.

Mapping KREEP on the lunar surface has been challenging, but scientists have devised two methods to find KREEP using satellite-based instruments. The first method combines data from neutron spectrometers and numerical models to estimate concentrations of REEs (Elphic and others, 2000). The second method maps the element thorium (Th), which acts chemically similar to REEs in rocks and is therefore also concentrated within KREEP. Thorium is sufficiently radioactive and abundant that its radiation can be mapped by orbiting gamma-ray spectrometers. These two independent methods produce similar maps of KREEP distribution, giving us confidence that we know where REE-rich rocks can be found on the Moon.

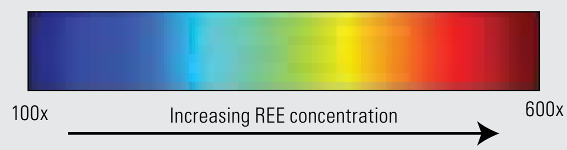
Image of former USGS employee and NASA astronaut, Harrison Schmitt, collecting regolith samples using a lunar rake. Photograph taken by Commander Eugene Cernan on December 11, 1972, during extravehicular activity (EVA) 1 of the Apollo 17 mission. NASA image AS17-134-20425.



Scientists have discovered that elevated thorium concentrations are mostly in a ring around the Imbrium basin, located on the nearside (Earth-facing side) of the Moon. This region covers roughly 2 million square miles—an area that represents about 16 percent of the moon's total surface area and is more than twice the size of Greenland. Data available in the Lunar QuickMap; image created using default base map and orthographic (nearside) projection, centered at lat 0°, long 0°.

EXPLANATION

Thorium[1] concentration of KREEP rocks compared to Solar System Average



[1]Thorium data from https://doi.org/10.1029/2006GL028530.

How Rich are the Deposits?

Even though the maps reliably show where KREEP-rich rocks are located on the Moon, they do not provide the best constraints on the concentrations of REEs within KREEP. The orbital mapping techniques report average abundances over large areas (approaching ten thousand square kilometers), but individual deposits are likely to be much smaller (less than a thousand square kilometers). Additionally, the small fragments of KREEP in the Apollo samples have been mixed and diluted with more common rocks that have low REE abundance. Thus, the estimated REE concentrations from samples and orbit (about 200–600 times higher than the Solar System average) are both probably underestimates. In fact, one study combining the low-resolution orbital data and the highly localized Apollo sample results suggests that there are locations with Th concentration twelve times what was estimated for KREEP from just the orbital data (Hagerty and others, 2006). Since REE and Th concentrations are correlated, we can infer that there may be at least a few lunar deposits with REE concentrations over 1,000 times the Solar System average—a concentration similar to that found in ores mined for REEs on Earth.

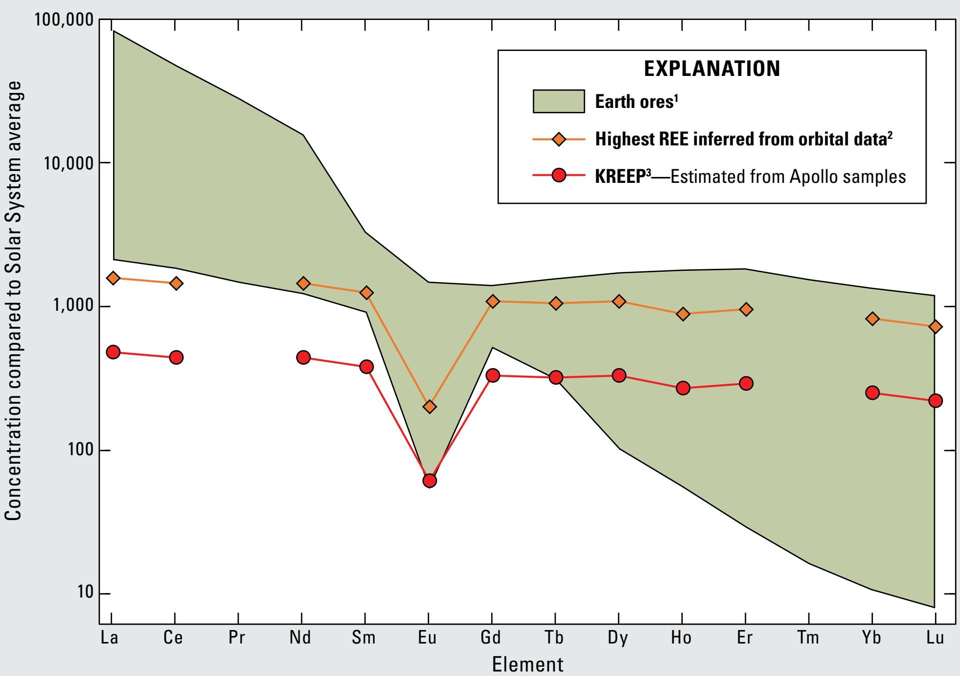


Diagram showing the relative concentrations of REEs compared to the Solar System average, for both terrestrial REEs and lunar REEs.

[1]Earth ore data from https://doi.org/10.3133/pp1802O.

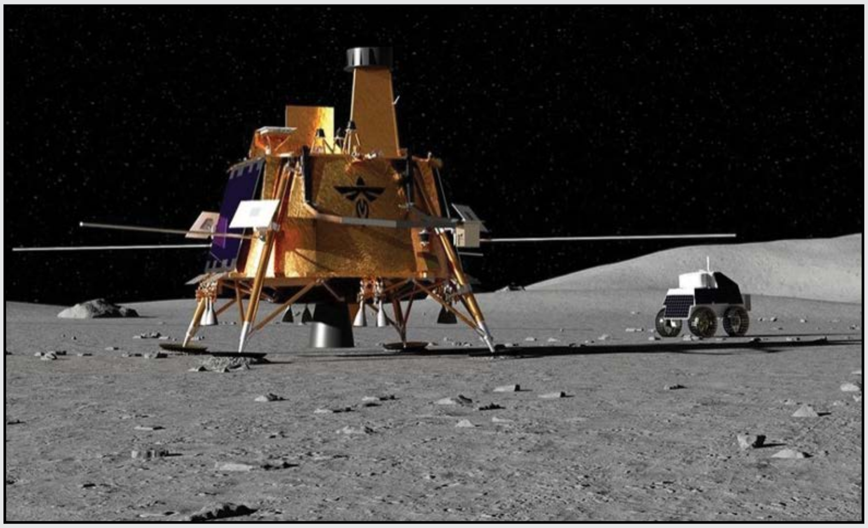
[2]KREEP estimate from https://doi.org/10.1029/RG017i001p00073.

[3]REE estimate from https://doi.org/10.1029/2005JE002592.

Technology and Economics

Although the technology to mine REEs from the Moon does not currently exist, the engineering challenge is relatively modest compared to some other space resources. Robotic excavators have been developed to efficiently move the pulverized rock that covers the lunar surface, and vehicles designed to transport many tons between the Earth and Moon are currently being developed. In short, there is no obvious technical reason why mining REEs on the Moon cannot be accomplished in the coming years. However, even if deposits with high concentrations of REEs are found on the Moon, their usefulness is not automatically guaranteed. For lunar REE mining to be economically viable, the price of REEs from the Moon would need to be competitive with REEs already mined on Earth. Economic viability could be possible in the future if the prices of REEs rise or if lunar infrastructure develops, lowering transportation costs. Since both possibilities are plausible, the idea of mining REEs on the Moon is no longer pure science fiction.

Excavator designed for lunar use undergoing testing at the NASA Kennedy Space Center. Photograph from Keszthelyi and others (2023), used with permission.



Artistic rendering of Firefly's Blue Ghost 3 lander with rover; credit to Firefly Aerospace, used with permission.

What Next?

Scientists have yet to directly explore the features on the Moon with the highest concentrations of REEs. Fortunately, the National Aeronautics and Space Administration (NASA) has already prioritized some of the KREEP-rich localities observed from orbit for scientific exploration, including the Aristarchus plateau, an area with a wide variety of volcanic features. Another high-interest area is the Gruithuisen domes, the target for the NASA Lunar Vulkan Imaging and Spectroscopy Explorer (Lunar-VISE) payload, planned for delivery in 2028. The Lunar-VISE payload will include instruments that can characterize the chemistry, mineralogy, and surface properties of the soil and rocks at a high resolution, all essential for REE prospecting.

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