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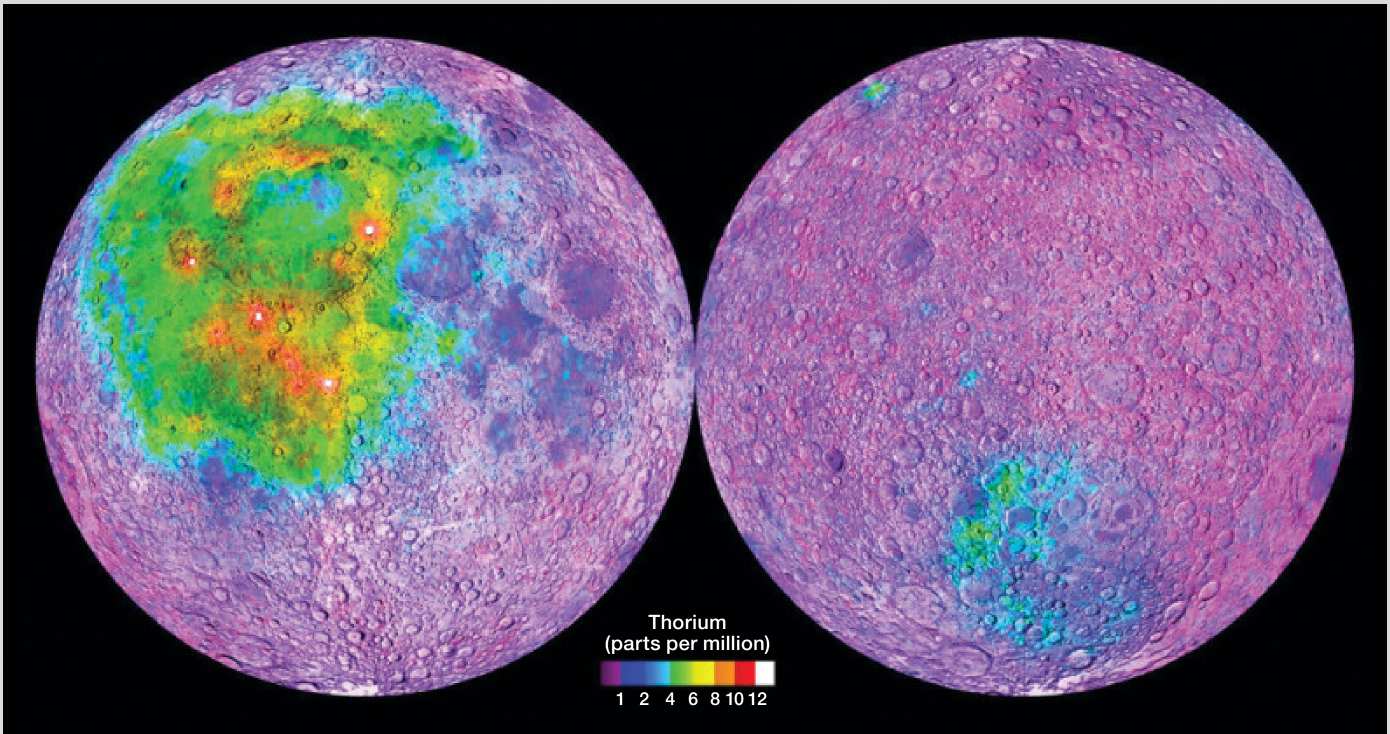
KREEPy Rocks and Terrane

Understanding the Moon requires looking beyond the visible.

The Procellarum KREEP Terrane (PKT) is a 21-year-old discovery that is critical to our modern understanding of the Moon but is hardly known to amateur astronomers. Up until the spacecraft era, our knowledge of lunar geology depended on visual observations and photographs of the lunar surface. Although these are still powerful and important tools, discoveries made using ultra-high-resolution images and the flood of new data from beyond the visible spectrum produced by a host of spacecraft have radically changed what we once thought we knew. A single map can longer depict everything we can glean about our nearest neighbor — that requires the integration of data across multiple disciplines.

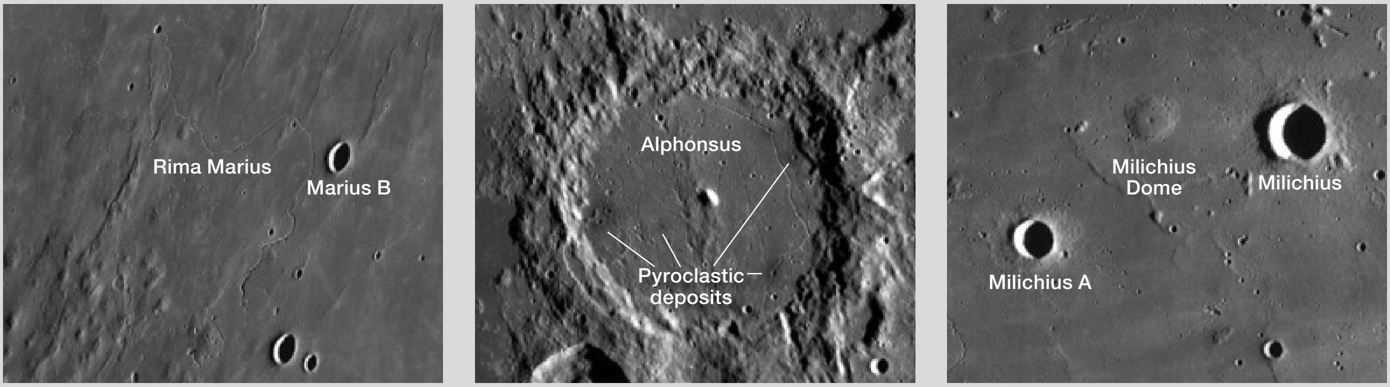
The very first lunar orbiting spacecraft (aptly named the Lunar Orbiter series) accidentally discovered that the strength of lunar gravity isn't homogenous. Mission controllers noticed that the Orbiters were pulled closer to the lunar surface as they passed over maria, demonstrating that there must be more mass beneath their surfaces than is present under the highlands. These *mascons* (mass concentrations) have been mapped with increasing precision ever since this serendipitous discovery.

Following the telescopic photography campaigns in the 1960s that used filters to isolate different parts of the visible spectrum, spacecraft have mapped the Moon across the entire electromagnetic spectrum, revealing the chemical and mineralogical compositions of different lunar materials. The occurrence of the radioactive-element thorium mapped with gamma-ray spectrometers reveals that the interior of the Moon isn't the same everywhere. Other sensors measured thermal, topographical, and magnetization properties — characteristics that are invisible to traditional photography. In addition, the analysis



This map depicts the concentrations of thorium on the lunar surface recorded by NASA's Lunar Prospector. The large colorful area on the nearside (left) is known as the Procellarum KREEP Terrane.

NASA



▲ Sinuous rilles (left) are almost exclusively found in the KREEP terrane, whereas pyroclastic deposits (center) and volcanic domes (right) occur in most nearside maria.

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and dating of samples collected during the Apollo missions provided ground truth to accurately calibrate the lunar crater counts used to estimate the ages of maria.

One of the major discoveries from these multitudes of data was of the PKT in 2000 by Brad Jolliff and colleagues at Washington University in St. Louis, Missouri. Scientists had previously discovered basalts, anorthosite-rich highlands materials, and other, less-common rock types from Apollo samples. But they also found an unexpected suite of rocks (called KREEP) rich in certain elements, especially radioactive potassium (atomic symbol K), phosphorous (P), and rare-earth elements (REE) — the so-called incompatible elements that don't bond readily with those in most rocks and so are the last to form when magma solidifies.

KREEP was found in many Apollo samples as brecciated (fragmented) rocks, but also in non-brecciated volcanic rocks in Apollo 15 samples from the **Hadley Rille** area of **Mare Imbrium**. This finding suggests that the source of all KREEP materials is buried in the Hadley Rille region. Presumably, the formation of the Imbrium impact basin brecciated and ejected bits of KREEP basalt, scattering debris all over the Moon. But data from the NASA Lunar Prospector's gamma-ray spectrometer shows that high-radiation levels (as identified by thorium measurements) were almost entirely concentrated in the area covered by **Oceanus Procellarum**, Mare Imbrium, the western half of **Mare Serenitatis**, and the Imbrium ejecta northwest of the crater **Ptolemaeus**. Jolliff and his colleagues recognized that this area is unique and called it the PKT. So have all lunar scientists ever since.

The thorium map shows that the PKT includes most of the maria on the Moon. Only the eastern maria, including **Crisium**, **Tranquilitatis**, **Nectaris**, and **Fecunditatis** are excluded. On the farside there are fewer maria, and only the ones inside the South Pole-Aitken basin have any significant levels of thorium. Another surprising characteristic of the PKT is that, although most of the lunar maria formed between about 3.8 and 3.2 billion years ago, only the basalts in the PKT have crater-count ages as young as 2 to 1 billion years. The PKT is the only area of the Moon that had voluminous quantities of magma for a prolonged period. The older PKT mare rocks appear chemically similar to other mare rocks found over much of the Moon, but the younger lavas that originate in the PKT have nearly twice as much titanium as older rocks outside of the PKT. This means that the source region or processing of the younger magmas had changed since the time of earlier eruptions.

PKT magma also favored the formation of sinuous rilles carved by flowing lava — nearly all of which occur in the PKT. However, domes (another volcanic landform) are common in the PKT as well as elsewhere, such as in the eastern maria, especially Tranquillitatis. Similarly, pyroclastic deposits, such as volcanic ash, are also widespread both in and beyond the PKT, especially in floor-fractured craters.

Models of the various styles of lunar volcanic eruptions by Lionel Wilson at Lancaster University, Lancaster, UK, and James Head, at Brown University, Providence, Rhode Island, help explain these differences. They found that sinuous rilles form when eruption rates and volumes are large, whereas domes (small shield volcanoes) form from small-volume activity. The sinuous-rille distribution may imply that PKT eruptions were generally larger than those in other regions. And the more widespread occurrence of pyroclastic deposits and domes may be explained by noting that the beginning of all eruptions is driven by escaping gases, while the end phases produce smaller eruptions with lavas that flow only short distances and sometimes build up small domes. Pyroclastics are deposited at beginnings of eruptions, and domes form during declining periods, with sinuous rilles occurring any time a lot of magma erupts quickly.

Next time you observe the Moon with your telescope, try to appreciate the impact of the PKT on all aspects of lunar volcanism — each rille, dome, and ash deposit you detect tells you something about local eruption conditions billions of years ago. To fully embrace your role as lunar volcanism explorer, you may want to wear a hard hat and leather boots while observing.

■ Contributing Editor **CHUCK WOOD** sees hints of lunar history every time he views the Moon.