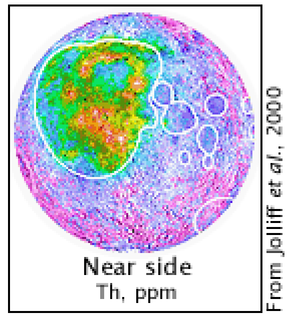
Hot Idea posted August 31, 2000

A New Moon for the Twenty-First Century



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Thirty years of lunar sample studies supplemented by spotty remote sensing and geophysical data gave us the broad outline of the nature and geologic history of the Moon. Many cherished beliefs are now being questioned on the basis of global data returned by two bargain-basement missions sent to the Moon in the 1990s, Clementine and Lunar Prospector. These data are being integrated with new and old lunar sample data, to give us new, though still controversial, ideas about the nature of the Moon. Two articles in a special section of the Journal of Geophysical Research (Planets) illustrate the point. Brad Jolliff and his colleagues at Washington University in St. Louis, Jeff Gillis, Larry Haskin, Randy Korotev, and Mark Wieczorek (now at the Massachusetts Institute of Technology) divide the Moon's crust into distinct geochemical provinces quite different from the traditional highlands (or terra) and maria. In a separate paper, Randy Korotev presents a detailed analysis of a common rock type among the samples returned by the Apollo missions. This rock type, nicknamed enigmatically "LKFM," was thought by many of us to represent the composition of the lower crust everywhere on the Moon. Korotev argues that it is confined to only one of Jolliff's provinces. If correct, this changes our estimates of the composition of the lunar crust, hence of the entire Moon. Although other lunar scientists will scrutinize these new views of the Moon, it is clear that some long-held ideas about the Moon might be modified significantly, if not tossed out completely.

References:

Jolliff, Bradley L., Gillis, Jeffrey J., Haskin, Larry A., Korotev, Randy L., and Wieczorek, Mark A. (2000) Major lunar crustal terranes: Surface expressions and crust-mantle origins. *Journal of Geophysical Research,* vol. 105, p. 4197-4216.

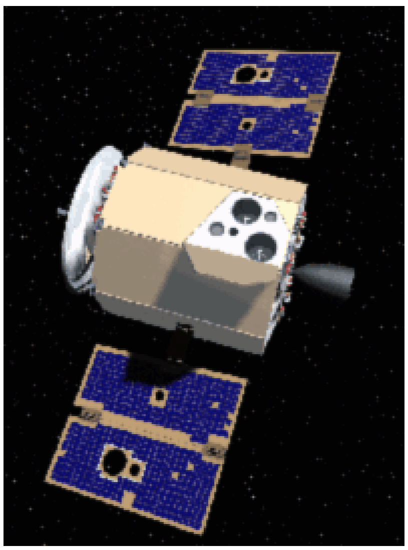
Korotev, Randy L. (2000) The great lunar hot spot and the composition and origin of the Apollo mafic ("LKFM") impact-melt breccias. *Journal of Geophysical Research,* vol. 105, p.4317-4345.

Blending Lots of Data

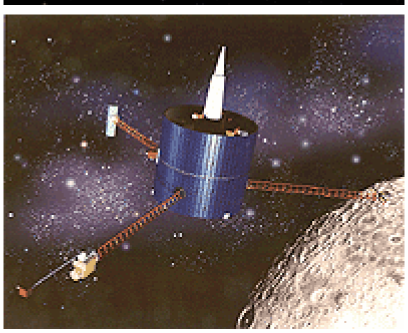
We now have a huge amount of data about the Moon, and lunar scientists are using all of it. Interdisciplinary teams composed of experts in lunar-sample studies, remote sensing, and geophysics are doing much of the new research. Even more important, many individual scientists are becoming experts in using many types of data. This research was sparked by new orbital missions to the Moon and an initiative, "New Views of the Moon," organized by the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM). The interdisciplinary nature of the work is illustrated by the author list in Jolliff's paper: Jolliff is a geochemist and mineralogist, Haskin and Korotev are geochemists, Gillis is a photogeology and remote sensing specialist, and

Wieczorek is a geophysicist. The data come from several sources:

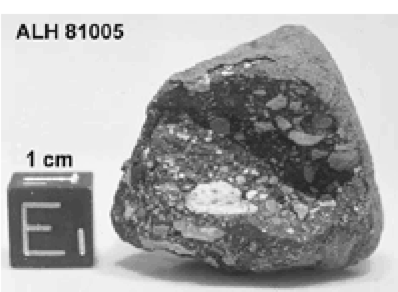
The magnificent Apollo program returned 380 kilograms of rock and dirt from the Moon from mid-1969 to late 1972. The samples have been studied in great detail, but the job is not yet done. New analytical techniques have been developed, necessitating new analyses. The mountains of data returned by Clementine and Lunar Prospector have sparked numerous new analyses of the samples. The Apollo missions returned samples from only six locations on the Moon, all relatively close together on the Earth-facing side of the Moon. The sampling was expanded somewhat by unpiloted, robotic missions sent by the Soviet Union in 1971, 1972, and 1976. These missions returned about 150 grams of lunar soil. One of the most important aspects of lunar samples is that they come from known locations on the Moon, thereby providing calibration points for remote sensing data. The Apollo missions also brought back remote sensing observations for a tantalizing 20% of the lunar surface and set up geophysical stations at the six landing sites.



The Clementine mission (1994) was developed and funded by the Department of Defense as a test of sensor systems. NASA joined forces with DOD to provide funding for a science team and for data analysis. Clementine carried a laser altimeter, which produced the first global topographic map of the Moon. It also had cameras equipped with filters to view the Moon in several wavelengths. The images returned can be converted to maps of the FeO and TiO_2 concentrations and mineralogy of the surface [See **PSRD** article: Moonbeams and Elements].



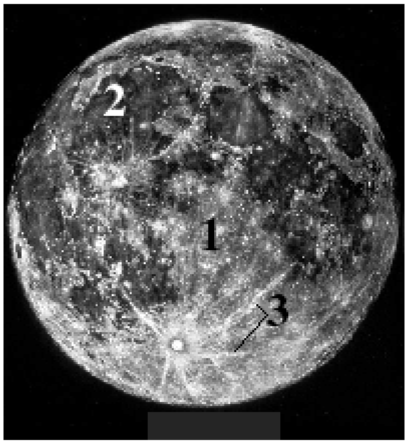
Lunar Prospector (1998-1999) was the first competitively selected mission in NASA's Discovery Program. It aimed a number of remote sensing instruments at the Moon. A gamma-ray spectrometer provided data on the thorium concentration of the surface, and will eventually provide maps of iron and possibly titanium. The neutron spectrometer measured the abundance of hydrogen on the surface, finding enrichments at the poles; the enrichments are probably due to the presence of water ice. The neutron spectrometer is also providing information about the amounts of iron and titanium, a useful check on the techniques used to extract the concentrations of these elements from the Clementine data. Lunar Prospector also measured the weak magnetic field of the Moon.



Lunar meteorites were first recognized in 1982. There are now about 15 of them. Impacts blast rocks off the Moon, and some land on Earth. These samples are very important for understanding the composition of the lunar crust because most probably come from places far from the Apollo landing sites.

Major Crustal Terranes

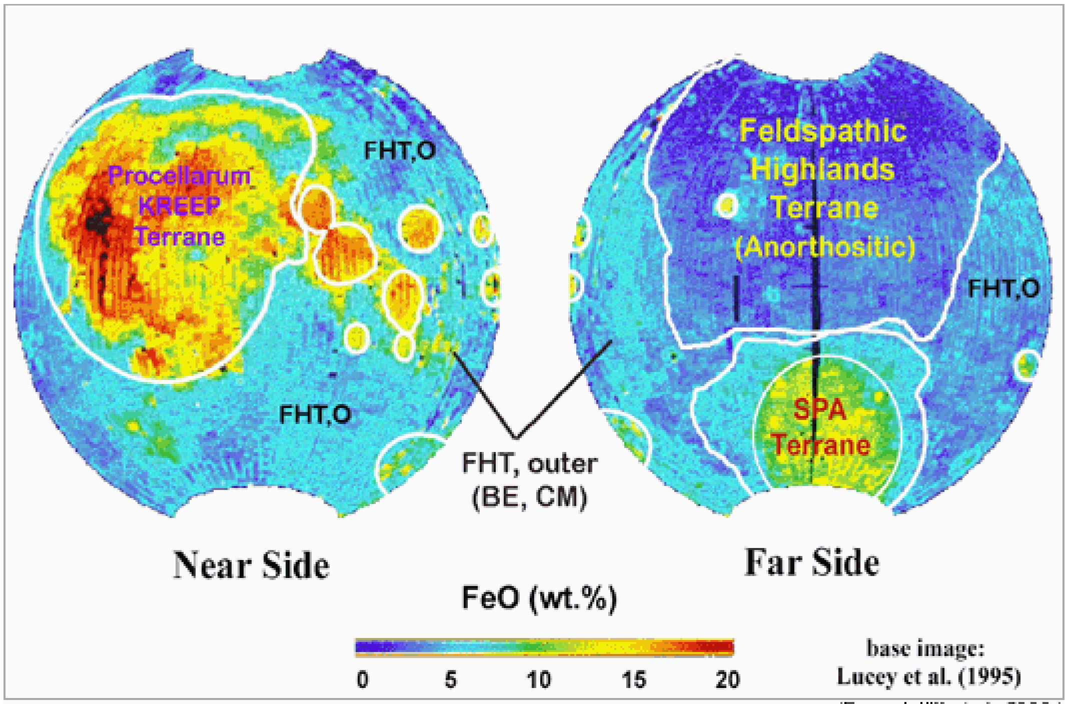
Since Galileo first peered at the Moon through his homemade telescope in the early 1600s, lunar scientists have divided the lunar surface into two major terranes, terra and maria. The terra (usually called "highlands") are heavily cratered, light colored, and higher than the maria, which are less cratered (hence younger), darker, and lower. Galileo thought these two terranes represented continents (terra, for land) and oceans (maria, for seas). The maria are not and never were seas because the Moon is bone dry. Instead, the maria are thin (no more than a kilometer or two) deposits of lava that flowed into the low areas on the Moon.



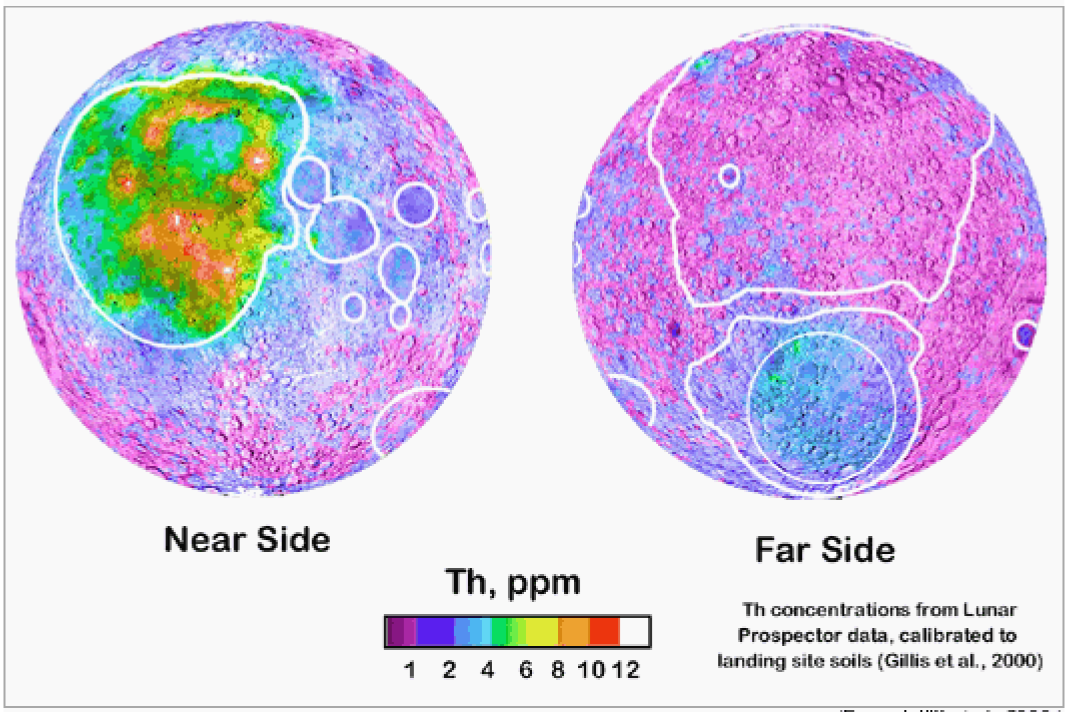
Traditionally, the Moon has been divided into two major geological terranes, the highlands (1) and the maria (2). The highlands are more cratered and higher in elevation than the darker maria. (The number three points to rays from the crater Tycho; this photo is used in a hands-on classroom activity available online at Exploring Planets in the Classroom.)

This division served us well for a long time. The highlands are composed of different rock types than are the maria, and formed long before the maria were created by volcanic eruptions. One abundant type of highland rock, called anorthosite, made up the initial lunar crust when feldspar crystallized from a globe-encircling ocean of magma and floated to the top to create huge masses of anorthosite. Other magmas subsequently intruded into this primary crust. Mare lavas formed by melting of accumulated dense minerals from the magma ocean, erupting from fissures, and flowing across the stark lunar surface.

Things are not actually so simple, as Jolliff and coworkers show. There are prominent regions on the Moon defined by chemical characteristics, specifically by the concentrations of iron oxide (FeO) and thorium (Th), not just morphology and color. Iron and thorium are particularly useful elements when distinguishing rock types from each other and in monitoring geochemical processes. Feldspar-rich anorthosites do not contain much FeO, but mare basalts contain lots of it. Thorium behaves like a large number of elements, such as the rare earth elements, that are not incorporated into common minerals. As a result, when magma crystallizes, Th becomes more abundant in the left over magma; after 99% of a magma has crystallized, it contains about 100 times as much Th as the original magma contained.



(From Jolliff *et al.*, 2000.)



(From Jolliff *et al.*, 2000.)

Brad Jolliff and his colleagues have defined three major terrranes on the Moon, see images above: **(1)** The Feldspathic Highlands Terrane (FHT) which includes its somewhat different outer portion (FHT,O); this terrane has low FeO and Th. **(2)** The Procellarum KREEP Terrane (PKT), characterized by high Th. **(3)** South Pole Aitken Terrane (SPA Terrane), which has modest FeO and Th. These do not correspond to the traditional divisions into highlands and maria.

The anorthositic part of the Feldspathic Highlands Terrane (FHT-anorthositic) corresponds to much of the lunar highlands and is characterized by low FeO (4.2 wt% on average) and very low Th (0.8 parts per million). It is composed of anothosite and related feldspar-rich rocks, and represents a pure form of the ancient, primary lunar crust. Jolliff and coworkers also identify a related terrane, which they call the outer Feldspathic Highlands Terrane (FHT,O). This is similar to FHT, but contains more FeO (5.5 wt%) and Th (1.5 parts per million). The Jolliff team believes that FHT,O is FHT modified by the addition of ejecta from huge impact basins and some mare basalt deposits. Together, these highland terranes cover 65% of the lunar surface.

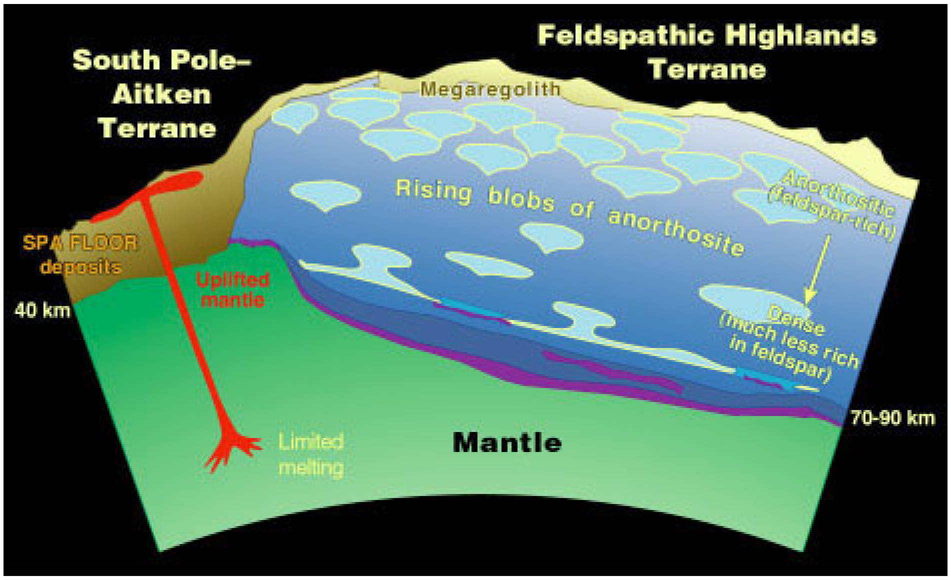
The Procellarum KREEP Terrane (PKT) dominates the nearside of the Moon. "KREEP" is an acronym for lunar rocks that are high in potassium (K), rare earth elements (REE), and phosphorus (P). The PKT is a mixture of assorted rocks, including most of the mare basalts on the Moon, and is characterized by high Th (about 5 parts per million on average). This region has also been called the "high-Th Oval Region" and the "Great Lunar Hot Spot" by two of the authors of the Jolliff paper. PKT occupies about 16% of the lunar surface.

The final major terrane is associated with the immense South Pole Aitken Basin, a huge impact crater on the southern farside of the Moon. Jolliff divides the area into SPAT-inner and SPAT-outer. SPAT-inner has moderate FeO (average of 10.1 wt%) and Th (1.9 parts per million). SPAT-outer has less FeO (5.7 wt%) and Th (1.0 parts per million).

The Lower Crust

The remotely-sensed data used by Jolliff and coworkers determines compositions of the uppermost surface of the Moon (upper micrometer to several centimeters). Can we figure out anything about the material below that? Definitely: Meteoroids have pummeled the Moon for billions of years, digging holes up to tens of kilometers deep. The crushed rock tossed out of impact craters and the impact-melted deposits on crater floors provide windows into the lunar crust. Impact craters are natural drill holes.

Even the largest craters in the FHT-An and FHT-O excavate nothing but low-FeO rock, implying great thicknesses of feldspar-rich rock. Using geophysical data, crater sizes, and geological relationships, Jolliff and colleagues estimate that the FHT represents a layer 50 kilometers thick in the pure FHT-An and 30 kilometers thick in the FHT-O areas. Because FHT-O material is composed largely of debris from gigantic impacts, Jolliff and coworkers believe that the region is underlain by a layer about 40 kilometers thick with a composition like that of FHT-O. They believe that almost all the FHT-An and FHT-O formed from the lunar magma ocean. The somewhat higher FeO of the lower portion of the crust (represented by the composition of FHT-O) may be due to the presence of denser rocks trapped in the growing anorthosite crust.

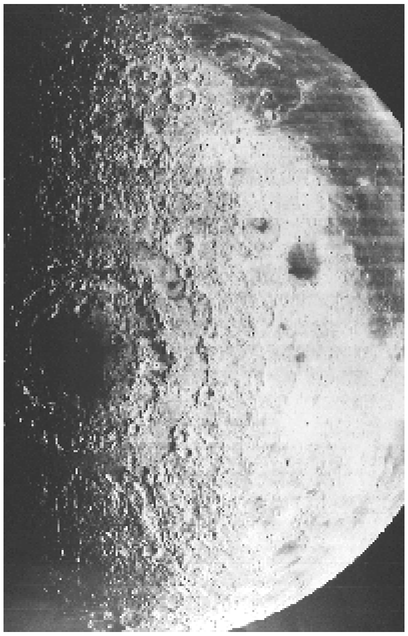


(Graphic by Brooks G. Bays, Jr. based on diagram by Brad Jolliff.)

Brad Jolliff and his coauthors present this schematic of the anothositic region of the Feldspathic Highlands Terrane (FHT), which makes up the thickest part of the lunar crust and is composed of feldspar-rich (anorthositic) rock. The uppermost part of the terrane is impact-generated megaregolith, which may be dominated by ejecta from South Pole Aitken basin. As the FHT crust formed from the magma ocean, concentrations of the magma were trapped, forming rocks richer in FeO. Because such rocks would have been denser than the surroundings, they would sink through the other rocks to concentrate nearer to the base of the crust (dark blue and purple layers). The portions of these trapped magmas that were rich in low-density feldspar would rise. This process may explain the slight increase in FeO with depth. In Jolliff's view, the SPAT may actually be excavated lower crust typical of the FHT.

The nature and origin of the PKT is controversial. A common rock type among Apollo samples is nicknamed "LKFM." As Randy Korotev reviews in his paper, this acronym has had a long and confusing history. It stands for "Low-K Fra Mauro" basalt. The K stands for potassium, and the low was added to distinguish it from medium and high-K varieties. The original samples were not basalts, which are lava flows. Instead, they were impact-produced glasses in the lunar soil. Rocks of the right composition were found in abundance at the Apollo 15, 16, and 17 sites, and they were all impact melt breccias (fragments of assorted rocks and minerals bound together by magma made during an impact). Originally an adjective, LKFM began to be used as a noun--the name for a rock type--and the acceptable amount of potassium began to be stretched. Though baffling to newcomers to the field, most of us happily used "LKFM" and knew what it meant. It had FeO and Al_2O_3 contents of about 10 and 18 wt%, respectively, a range in potassium concentrations, and characteristic relative abundances of trace elements. Korotev knew what it meant, too, but always hated the term and tried to get the rest of us to stop using it. It was not a very successful campaign! His current suggestion is to call rocks with the LKFM characteristics "thorium-rich, mafic impact melt breccias," but is forced to refer to them as LKFM in his paper so the rest of us will know what he's talking about.

In 1977, Graham Ryder and John Wood of the Smithsonian Astrophysical Observatory (Ryder is now at the Lunar and Planetary Institute in Houston) proposed that the LKFM rocks at the Apollo 15 and 17 landing sites were produced by melting during the formation of the Imbrium and Serentatis impact basins. These impressive structures, making up the Man in the Moon's right and left eye, respectively, would have melted much of the lower crust of the Moon. So, Ryder and Wood proposed that the lower crust of the Moon is composed of rock with the composition of LKFM. A decade later, Paul Spudis and Phil Davis of the U. S. Geological Survey Astrogeology Branch (Spudis is now also at the Lunar and Planetary Institute in Houston) used Apollo remote sensing data to show that the amount of LKFM-like rock in basin ejecta increases as the size of the basin increases. Because the depth of excavation increases with crater diameter, this implies that the lower crust is richer in LKFM.



Large impact basins on the Moon, like the 900-km Orientale basin shown here, excavate materials from depth. Paul Spudis and Phil Davis suggest that the amount of LKFM excavated increases with basin size, hence with depth of excavation. This implies that the lower lunar crust has a composition similar to LKFM. Randy Korotev questions this conclusion and suggests that it applies only to the Procellarum KREEP terrane.

Most of us latched onto this idea and it became part of the lore of lunar science. We extrapolated the observation to the entire Moon. (Outlandish extrapolations are not uncommon in planetary science!) A lower crust like LKFM became a basic component in estimates of the composition of the Moon. Most recently, my colleagues and I here in Hawai`i claimed that the floor of South Pole Aitken basin was composed largely of LKFM, though we noted other possibilities. A lower crust with the composition of LKFM is convenient and simple. But is it right?

Randy Korotev has always been something of a heretic when it comes to LKFM. Not only has he preached against use of the term, but he has disputed the conclusion that it represents the composition of the lower part of the lunar crust. In his recent paper he makes the case on the basis of the compositions of LKFM rocks. He suggests that they represent the most abundant rock type in the PKT and cannot be used to estimate the composition of the lower crust elsewhere on the Moon.

He tackles the problem by calculating the proportions of various rock types that go into the LKFM mix. The first step is to define average compositions of assorted subdivisions of LKFM, which is relatively straightforward. The next step is harder. Korotev had to decide what rock types he would try to mix together mathematically to reproduce the LKFM chemical composition. He tried several logical choices, finally settling on four: (1) KREEP norite, as represented chemically by basalt fragments found at the Apollo 15 landing site. Basalts, which are lava flows, would not be present in the LKFM amalgam. Instead, it would include a non-erupted equivalent of basalt, called norite. It is reasonable to assume that a lot of the magma that erupted to form KREEP basalts was trapped deep beneath the surface, hence ready to be incorporated into LKFM impact melts. (2) Dunite, a rock type that consists of little else but the mineral olivine, which has compositions between Mg_2SiO_4 and Fe_2SiO_4; in this case the olivine was close to Mg_2SiO_4. (3) Feldspathic upper crust, similar to the FHT-An and obtained from the compositions of lunar meteorites. (4) Iron-nickel metal, to represent a meteorite component derived from impacting projectiles.

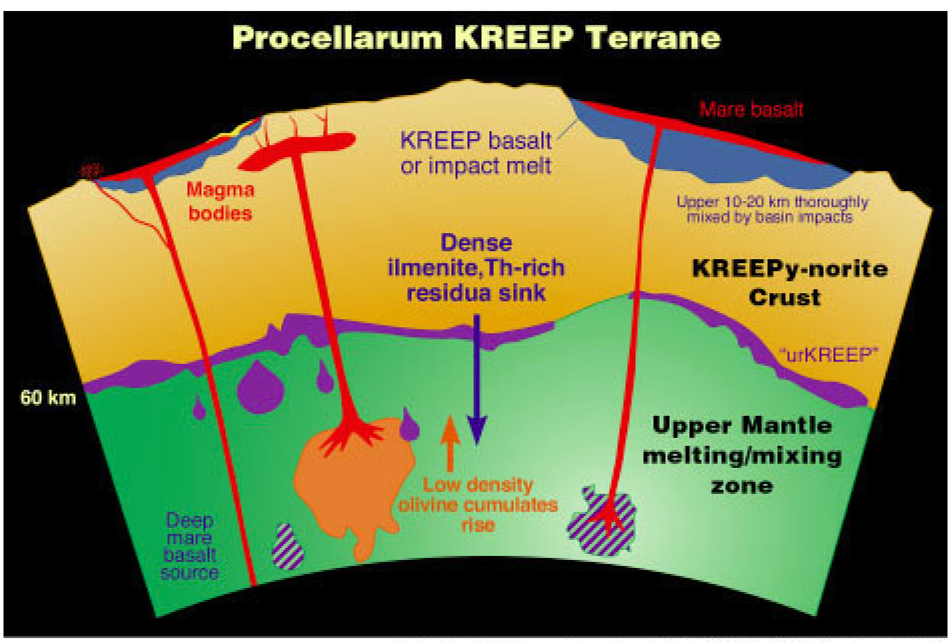
The mixing calculations were done using a technique called "least squares modeling." The idea is to calculate a composition of a mixture of the components and compare it to the composition of the real rock being modeled. A good mix is obtained when the difference between the concentrations of the elements in the calculated and real rock is minimized. (Korotev used the concentrations of 33 elements.) The calculations indicate that LKFM, on average, is a mixture composed of 58% KREEP basalt, 13% dunite, 29% feldspathic crust, and a fraction of a percent iron-nickel metal. Some individual samples contain up to 95% KREEP basalt. Korotev contends that the calculations indicate that the PKT was composed mostly of KREEP basalt and related rocks, and that such rocks are confined to that area. To support that conclusion, he points out that the SPAT (South Pole Aitken Terrane) ought to be composed mostly of lower crustal rocks, but does not contain enough Th to be LKFM as the prevailing view requires.

Korotev points out that his calculations are not unique: "Mathematical success of a mass-balance model such as that described here supports but does not and cannot prove the hypothesis that the breccias are actual mixtures of the lithologies represented by the components of the model. Models involving other components may provide equivalently good or better fits..." Nevertheless, he assumes for the moment that the model represents reality and concludes that the PKT is the home of LKFM, not the entire lower lunar crust. This conclusion is almost certain to be debated vigorously and is likely to be refined as more research is done on the combination of lunar samples, lunar meteorites, and the data from Clementine and Lunar Prospector, but Korotev's renegade view is gaining momentum.

PKT, the Lunar Mantle, and Mare Basalts

Jolliff, Korotev, and their coauthors focus most of their attention on the nature of the PKT, the immense lunar hot spot. The important thing about the PKT is that it contains high concentrations of not only thorium, but other radioactive elements that behave geochemically like it, namely potassium and uranium. When these elements decay they release heat, raising the temperature of the surroundings. This can lead to melting to produce magmas and igneous rocks.

Another important observation about the PKT is that it contains most of the mare basalt on the Moon. These formed by melting in the lunar interior, and much of the heat for the melting may have come from the decay of all that thorium, uranium, and potassium concentrated in the PKT. This is the subject of a detailed study published in the *Journal of Geophysical Research* by Mark Wieczorek and Roger Phillips (Washington University in St. Louis).



(Graphic by Brooks G. Bays, Jr. based on diagram by Brad Jolliff.)

Schematic diagram, above, shows a cross section of the PKT. For reasons not yet completely clear, the dregs of the magma ocean, nicknamed urKREEP in the diagram, concentrated in one area of the Moon, destined to become the PKT. The urKREEP would have been associated with other late products of the magma ocean, including dense rocks rich in ilmenite. The dense rocks could sink, interacting with the underlying mantle, forming hybrid rocks suitable for the production of mare basalts [See PSRD article: The Surprising Lunar Maria.] At the same time, low density rocks formed by accumulation of olivine would rise. The rising rocks could melt as they encountered lower pressure, and form magmas. This is in reality a complex system involving both the crust and the mantle of the Moon.

Jolliff and his colleagues think that the PKT is a complex system involving both the crust and the underlying mantle in the region. It formed when the last dregs of the magma ocean concentrated in the area where the Imbrium basin would form. This late-crystallizing magma would be rich in thorium, potassium, rare earth elements, etc. (the KREEP elements), and be associated with ilmenite-rich rocks. Ilmenite is a dense mineral, so the rocks would sink, dragging some KREEP with it, modifying the underlying mantle. This dynamic mixing process could have continued for hundreds of millions of years, producing the characteristics of the PKT.

Jolliff and colleagues believe the PKT, like the FHT, formed in a global magma ocean. Paul Warren and John Wasson (University of California, Los Angeles) recognized the existence of this division, though the lack of global data made it less secure. They suggested that it was caused by heterogeneous crystallization of the lunar magma ocean, with the anothositic highlands (FHT in Jolliff's terminology) representing a huge, ancient super continent. Jolliff and coworkers suggest that the last dregs of the magma ocean might have been squeezed to the side of the super continent, producing the PKT. The details of such a process and the cause of the heterogeneous crystallization clearly need to be explored in detail.

New Moon

Interdisciplinary studies of the Moon are guaranteed to change the way scientists view it. The division into three major geochemical terranes and the consequences of their existence on mare basalt production, the composition of the lunar mantle and crust, and our understanding of how planetary-scale magma systems crystallize is only the beginning of a new era in understanding the geologic history of the Moon. The interdisciplinary study of the Moon is a model for how other planets need to be explored.

Additional Resources

Exploring the Moon, from the Lunar and Planetary Institute.

Jolliff, Bradley L., Gillis, Jeffrey J., Haskin, Larry A., Korotev, Randy L., and Wieczorek, Mark A. (2000) Major lunar crustal terranes: Surface expressions and crust-mantle origins. *Journal of Geophysical Research,* vol. 105, p. 4197-4216.

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Lunar meteorites, from the Dept. of Earth and Planetary Sciences, Washington University at St. Louis.

Lunar Prospector mission homepage.

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