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Hot Idea

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The Biggest Hole in the Solar System

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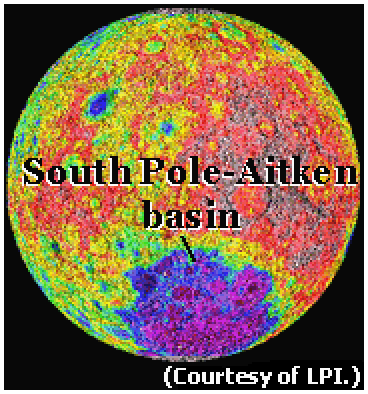


There's a huge splotch on the southern hemisphere of the farside of the Moon. This megasmudge is South Pole-Aitken (SPA) basin, 2500 km in diameter and over 12 km deep. It is darker and richer in iron than the rest of the lunar highlands. Such immense craters formed by impact onto the lunar surface. Calculations indicate that the floor of SPA basin ought to be composed mostly of rock derived from the mantle of the Moon, but using spacecraft data Paul Lucey (University of Hawaii) and his co-workers suggest it is at most half mantle, half crust. Taking a different approach, Carle Pieters (Brown University) and her colleagues suggest that no mantle is present. Why is so little mantle present? Is our understanding of the formation of craters incomplete? Was there something unusual about the impact, such as the projectile striking the Moon at a low angle? What's going on?

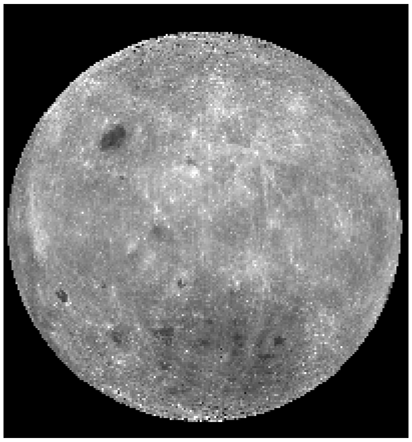
References:

Pieters, Carle M. and others (1997) Mineralogy of the mafic anomaly in the South Pole-Aitken Basin: Implications for excavation of the lunar mantle. *Geophysical Research Letters* vol. 24, p. 1903-1906.

Lucey, P. G. and others (1998) FeO and TiO2 concentrations in the South Pole-Aitken basin: Implications for mantle composition and basin formation. *Journal of Geophysical Research* vol. 103, p. 3701-3708.

The Big Hole

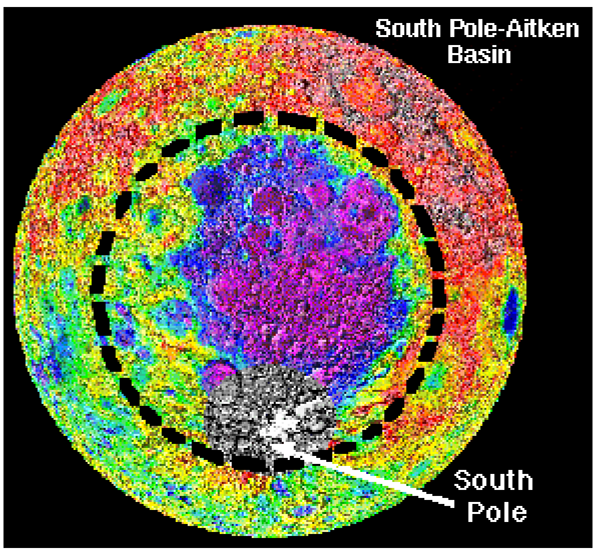
The existence of the SPA basin was suspected as early as 1962, but global photography by the Lunar Orbiter Program in the mid-1960s confirmed its existence. The first complete map was published in 1978 by D. Stuart-Alexander of the U. S. Geological Survey. The basin was not the center of very many studies after that because we knew so little about it, until spacecraft returned to the Moon in the 1990s. First the Galileo spacecraft flew by the Earth and Moon in 1992 as it was gaining speed for its long trip to Jupiter, where it is now. Its camera snapped away at the Moon, revealing that SPA was a distinctly dark smudge on the farside of the Moon and that its composition was unusually enriched in iron-bearing material. The Defense Department's Clementine mission was sent to the Moon early in 1994. Clementine returned global images at 11 wavelengths and measured elevations over most of the Moon. It confirmed the Galileo observations that SPA is darker than its surroundings, and surprised lunar scientists by revealing that the basin is not only wide (2500 km in diameter), but also deep, at least 12 km lower than the surrounding highlands. The only impact basin close to SPA in size is the Chryse Basin on Mars.



(Courtesy of Lunar and Planetary Institute.)

South Pole-Aitken basin is distinctly darker than its surroundings, as shown in this black-and-white image taken by a camera on the Clementine spacecraft. When this dark anomaly was first observed by the Galileo spacecraft, scientists figured it was probably due to the presence of rocks with more iron-bearing minerals than rocks in the rest of the lunar highlands.

The Clementine spacecraft carried a laser altimeter, a device that sent a laser pulse at the Moon and measured how long it took to detect the laser light reflected from the surface -- the longer the time, the deeper the spot where the laser hit the Moon. By sending the laser pulses to the surface lots of times, the Clementine science team could produce a map of elevations for the entire Moon.



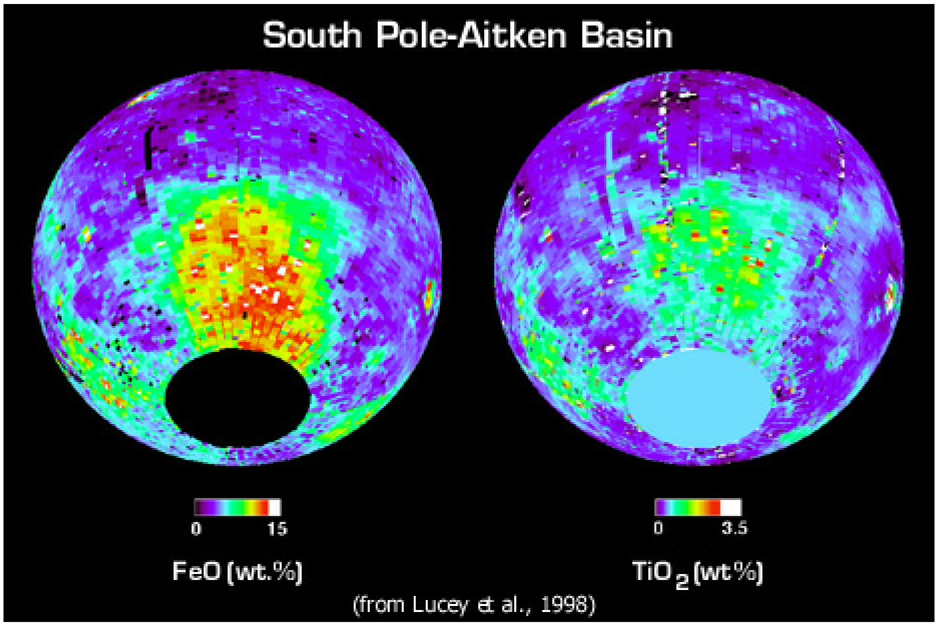
(Courtesy of Lunar and Planetary Institute.)

In this Clementine topographic map of the Moon (rotated to be centered on the SPA basin) red=high, purple=low -- each color equals 500 meters of elevation. It shows the extent of the South Pole-Aitken basin and shows that the basin is quite deep, at least 12 km deeper than its surroundings.

Planetary scientists love deep holes, especially those made by huge impacts. We want to know how they form, how the energy of a high-speed projectile is converted to explosive excavation of crushed and melted rock, how much of the target is melted, and how deep the rocks now on the surface came from. A hole the size of SPA is especially exciting as it might have dug well into the mantle of the Moon. Mantles are important. They are deeper and compositionally different from the crust which forms the surface of a planet. Crusts are typically tens of kilometers thick (perhaps up to 100 km on the lunar farside). Mantles contain information about a planet's total composition, a key parameter in understanding planet formation and how the planets vary in composition with distance from the Sun. It's no wonder so many of us are interested in South Pole-Aitken basin, possibly the biggest of all holes!

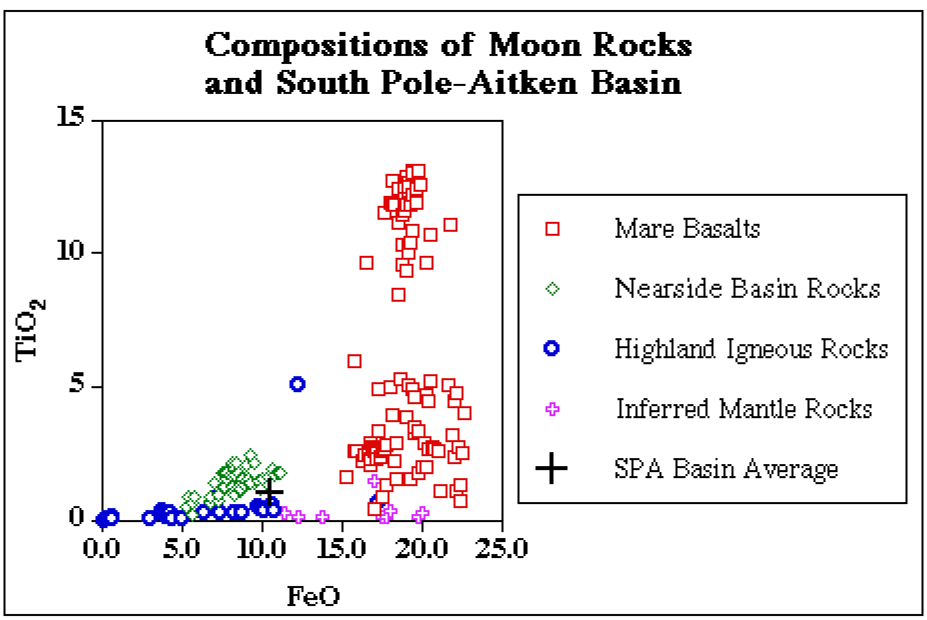
The Big Hole's Composition

The amount of light reflected off the Moon at different wavelengths was measured by the Clementine camera system. The data have been converted into information about the iron and titanium concentrations of the floor of SPA basin. (The concentrations are expressed as iron oxide, FeO, and titanium oxide, TiO_2 because those elements are bound to oxygen inside minerals.) The remarkable feat of converting ratios of reflected light to elemental concentrations was described in **PSR Discoveries** article: Moonbeams and Elements.



South Pole-Aitken Basin is clearly different from the surrounding lunar highlands, as shown by these maps of the FeO and TiO_2 concentrations in SPA. Paul Lucey and his colleagues produced the maps. The basin contains more FeO and TiO_2 than typical of the lunar highlands. Possibilities for the distinctive chemical composition are: the presence of an unusual rock type or types, widespread distribution of ponds of iron-rich basalts like those in the lunar maria, exposure of lower crustal rocks with a different bulk composition from the surface, or the presence of rocks dug up from the lunar mantle.

How does the composition of SPA basin compare to lunar rocks? The samples returned by the Apollo missions provide an important framework for comparison, because we think we know something about their origin and limited distribution on the Moon. The graph below plots the concentration of TiO_2 against that of FeO for key categories of moon rocks.



(PSRD graphic)

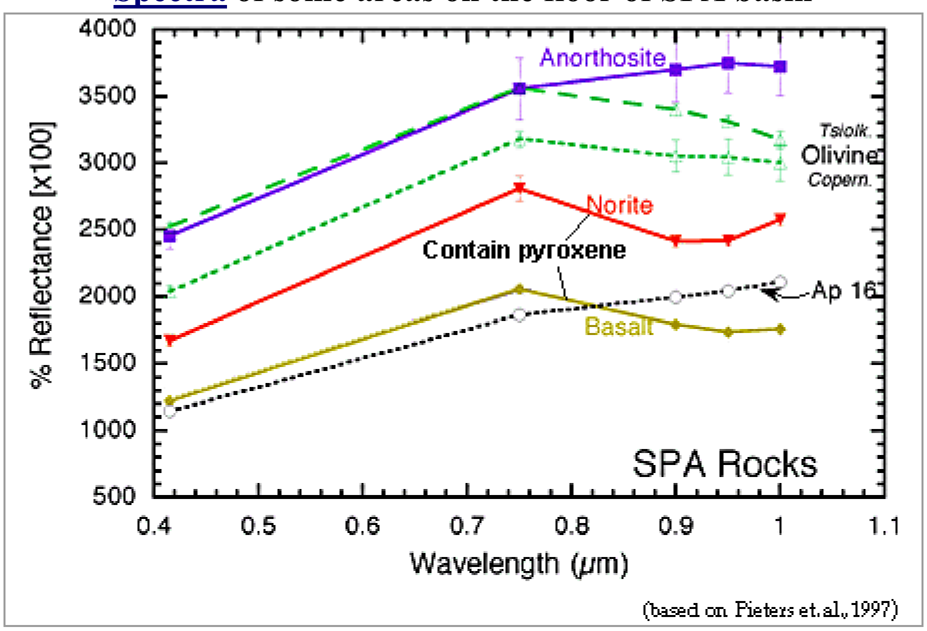
The rocks highest in FeO are basalts from the lunar maria (shown in red). These formed as lava flows on the surface, and occur mostly on the nearside of the Moon, though they occur elsewhere as well, including as ponds inside SPA basin. Igneous rocks from the lunar highlands (shown in blue) are quite low in TiO_2 and generally low in FeO, though they range up to about 10%. One group of rocks, shown in green, is common at the Apollo 15 and 17 landing sites. The rocks were located on or near the rims of large impact basins. This suggests they were brought up from great depth, so most lunar scientists think these rocks represent the composition of the lower crust, though that is not certain.

We also think we know a bit about the mantle of the Moon. The Apollo missions did not return any pieces of the mantle, but that does not discourage a good planetary scientist! One way of probing the mantle is to study rocks that crystallized from magmas that came from the mantle. The mare basalts are the best bets: almost all the basalts on the planets, including the Earth, formed when a planet's mantle partially melted. The liquid rock, being less dense, separated from the remaining solid like water squeezed from a sponge, and made its way to the surface. If not too much happened during its journey, it retained a chemical finger print of its original location. The finger print is deciphered in various ways, including by squeezing a basalt to high pressure and temperature in laboratories. (Such apparatus was described in **PSR Discoveries** article The Martian Interior.) I used the results of such experiments to estimate the composition of the lunar mantle for a variety of basalt compositions, and these are shown as lavender crosses on the graph.

The large, black cross on the diagram shows the average of the Clementine data for the SPA basin. It falls between the rocks representing the nearside basin materials, the highest FeO highland igneous rocks, and the mantle rocks. From this, Lucey and co-workers inferred that the SPA floor was composed of about equal amounts of lower crustal rocks and mantle rocks. However, they could not rule out the possibility that it was composed of a type of highland rock not collected during the Apollo missions.

Carle Pieters and her colleagues tested the idea that mantle was exposed in SPA by examining the mineralogy across the basin. One mineral they searched for is olivine, a greenish mineral notable for containing iron and magnesium, and almost certainly abundant in the mantle. (The Earth's upper mantle, for example, is composed of about 70% olivine, 25% pyroxene, and 5% other minerals.) Many minerals can be identified by the way they reflect light. Minerals which contain iron in their crystal structure absorb light in the part of the spectrum near 1 micron (just *where* depends on the particular mineral). We can distinguish rocks dominated by olivine from those dominated by pyroxenes, and from those that contain little of either. For example, the diagram below shows the amount of reflected light at different wavelengths for a variety of materials in SPA basin. For comparison, the graph also shows the spectra for two places that contain lots of olivine, the central mountains of in the craters Tsiolkovsky and Copernicus.

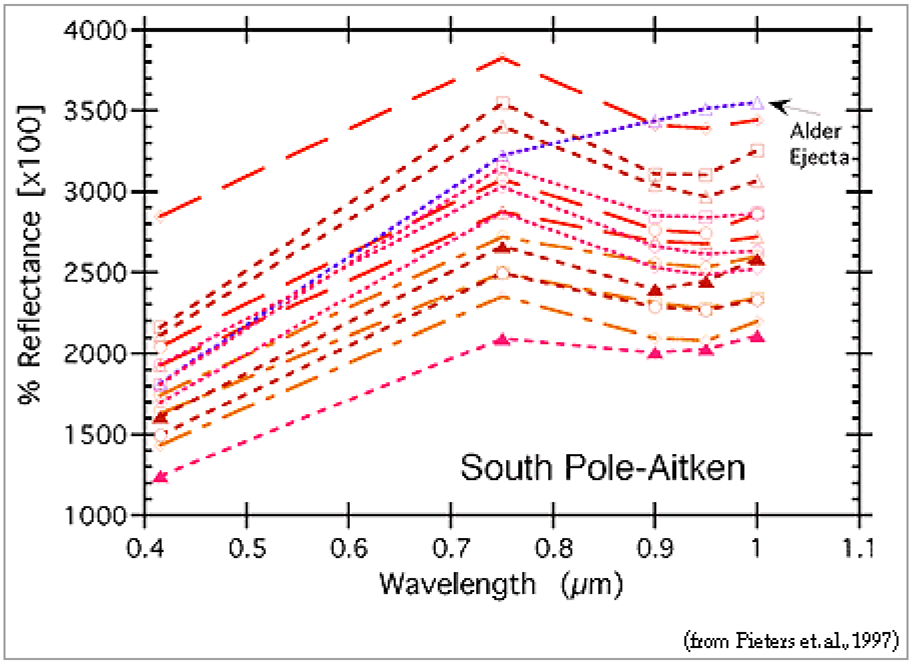
Spectra of some areas on the floor of SPA basin



Those labeled "norite" and "basalt" contain pyroxenes, which have a curvy appearance between 0.9 and 1 microns. This is completely different from "anorthosites," which are very low in iron and are the most common rock in the highlands, and different from the olivine-rich spectra from the craters Tsiolkovsky and Copernicus, which do not have the bowed-down shape between 0.9 and 1 microns.

Pieters and her colleagues measured spectra of large and small fresh craters in a traverse from the south rim of the SPA basin to just beyond the center and several large craters elsewhere in the basin. They examined numerous spots, and found none that gave a clear-cut indication that olivine was present. All were dominated by pyroxene, except for one anorthosite area (labeled "Alder ejecta"). They concluded that no mantle was exposed on the floor of the basin. Detailed analysis of the spectra indicates that the pyroxene is of the type common in rocks from the lower crust which is quite different from the pyroxene that dominates basalts.

Spectra of fresh craters inside SPA basin



Except for the anorthosite exposed by the crater Alder, all spectra indicate the presence of rocks with crustal pyroxene. None is remotely like an olivine-rich rock, suggesting that no mantle rocks are exposed on the floor of this huge basin. Furthermore, none of the pyroxene is like that in basalts except at the few small ponds of mare material.

Not Much Mantle in SPA - What's it Mean?

Is the floor of SPA basin a mixture of half mantle and half lower crust, as Lucey prefers, or all lower crust, as Pieters prefers? Why do the two approaches not agree? Well, actually, they do not disagree all that much. For one thing, the technique used by Pieters and co-workers cannot detect olivine in the presence of pyroxene unless its abundance is greater than about 30%. Lucey and his buddies suggest that the floor is half mantle and half lower crust. If the mantle is 50% olivine, then the average floor would only contain 25% olivine, below the amount Clementine measurements can detect. In other words, if the materials of SPA floor are very well mixed, we can't tell if the floor contains no mantle rock, or is half mantle and half crust.

Perceptive readers will wonder if this is a useful conclusion. After all, it does seem like a huge difference. It turns out to be incredibly useful because computer models of crater formation predict that the floor of a basin the size of SPA should consist of nothing but mantle rock! Pieters says none, Lucey says no more than half, and impact theory says all. Now there's a disagreement! Is everything we know about the physics of impact wrong?

Geophysicists expert in impact dynamics are convinced that a normal impact could not have produced SPA without digging up vast amounts of mantle materials. In fact, Peter Schultz (Brown University), a crater specialist who has been pondering the huge size of SPA for decades, is astonished that there is not a huge, uplifted plug of mantle material in the central portion of the basin, and wonders why the Moon was not shattered by such a huge impact. He suggests that it was not a typical, high-velocity impact. He hypothesizes that SPA was formed by the impact of a low-velocity projectile that hit at a low angle (about 30 degrees or less), hence did not dig very deeply into the Moon. During a low-angle impact, not all the energy is available for digging a crater.

Pete Schultz also points out that the impactor decapitates and sends much of the debris back into space surrounding the Moon and Earth. This may have provided a source of projectiles to make other lunar basins, many of which may have been made in a narrow time interval between 3.85 and 3.95 billion years ago. So, the consequences of figuring out the amount of mantle present on the floor of the SPA basin are enormous. The final answer is not in yet. Fortunately, more data are being obtained by the Lunar Prospector mission, now in orbit around the Moon. The Lucey and Pieters papers are not the last we'll see about the largest hole in the Solar System.

Additional Resources

Clementine mission information from the National Space Science Data Center.

Galileo mission information from the Jet Propulsion Lab.

Lucey, P. G., G. J. Taylor, B. R. Hawke, P. D. Spudis (1998) FeO and TiO2 concentrations in the South Pole-Aitken basin: Implicantions for mantle composition and basin formation. *Journal of Geophysical Research* vol. 103, p. 3701-3708.

Lunar Prospector mission from NASA Ames Research Center.

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Summary of missions to the Moon from the National Space Science Data Center.

Visualizations of the Moon from Clementine data, produced by the Scientific Visualization Studio.

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