PLANETARY SCIENCE RESEARCH PSRD Discoveries

Hot Idea

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Finding Basalt Chips from Distant Maria

--- Tossed chips of lava help fill in blanks in our knowledge of lunar basalts.

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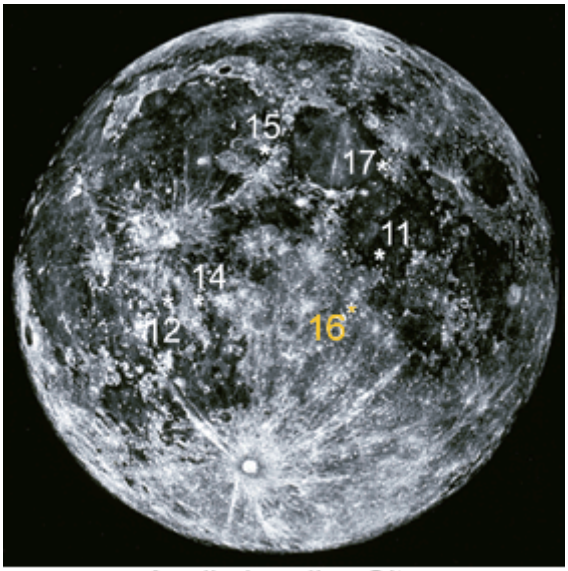


Apollo Landing Sites

The Apollo 16 landing site is in the lunar highlands, over 200 kilometers away from the nearest maria. Nevertheless, the Apollo 16 regolith contains a small percentage (<1%) of tiny fragments thrown to the site from distant maria. Ryan Zeigler, his colleagues at Washington University in St. Louis: Randy Korotev, Brad Jolliff, and the late Larry Haskin, and Jeffrey Gillis-Davis (University of Hawaii) made a detailed study of the chemical composition and mineralogy of fragments (only 2-4 millimeters across) of mare basalts. The basalts vary in composition, but are similar to other types identified previously. The team matched the compositions of the fragments to compositions of mare surfaces in the Apollo 16 region using remote sensing data from the Clementine mission. This blending of cosmochemical and remote sensing analyses allowed them to make educated guesses about where each of the basalt fragments may have originated. We now have a fuller understanding of the range of compositions of mare basalts and, because basalts record a wealth of information about planetary interiors, this research enlightens us about the diversity of rock compositions in the lunar mantle.

Reference:

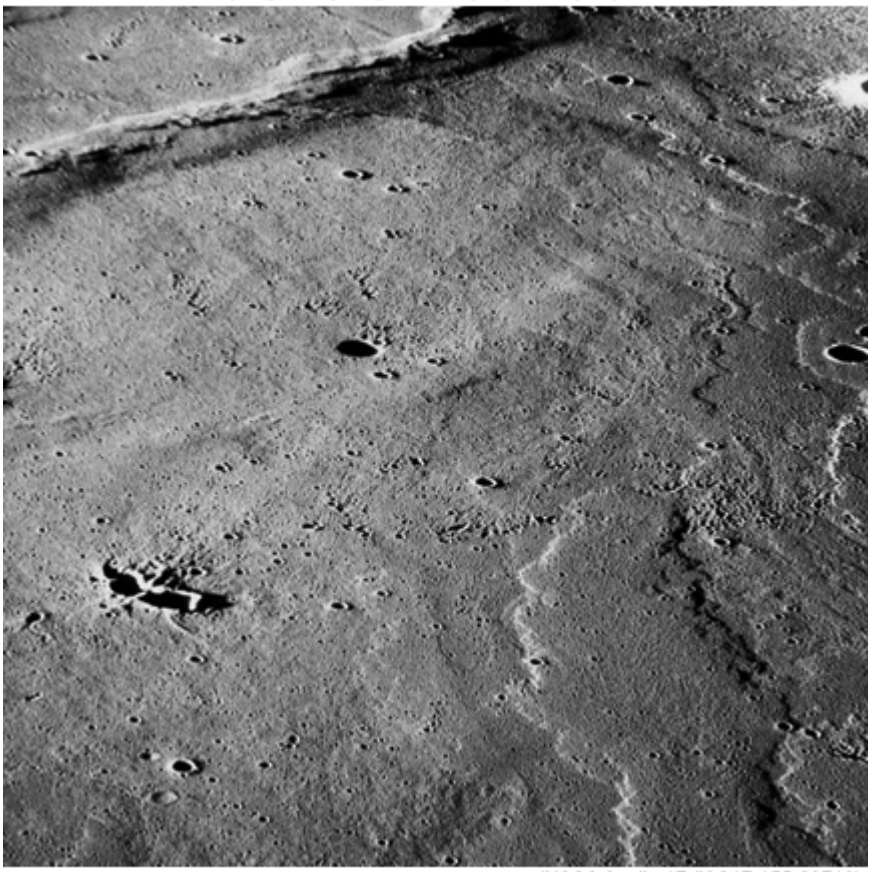
- Zeigler, Ryan A., Randy L. Korotev, Larry A. Haskin, Bradley L. Jolliff, and Jeffrey L. Gillis (2006) Petrography and geochemistry of five new Apollo 16 mare basalts and evidence for post-basin deposition of basaltic material at the site. *Meteoritics and Planetary Science*, vol. 41, p. 263-284.

The Maria and the Mantle

Lava flows contain a detailed record of the composition of a planet's interior and of the processes that affected the magma when it formed and as it oozed to the surface. The composition of planetary interiors is central to deciding among models of how the planets formed. In the case of the Moon, its composition holds the clues to the processes that operated during and soon after the giant impact with the still-assembling Earth that may have

created the Moon, as well as the composition of the impactor. If the Moon was not made by a giant impact, its composition still contains important information about the formation of moon-sized objects during planet formation.

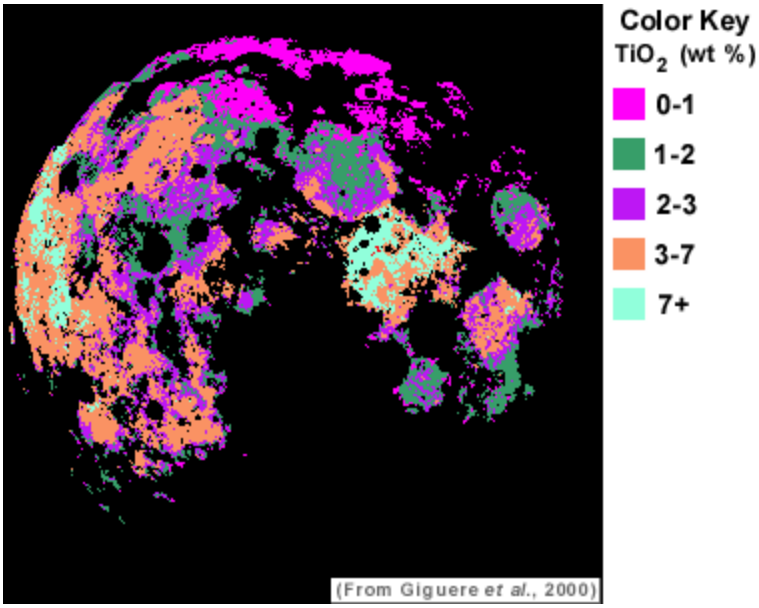
Lava Flows in Mare Imbrium



(NASA Apollo 17 #AS17-155-23713)

Several lava flows in Mare Imbrium are visible in this Apollo photograph taken from lunar orbit. The most prominent one comes from the lower right of the image and goes half way up the photograph. The light shines from the left, illuminating the left margin of the flows, and creating shadows on the right margins. Chemical compositions of lava flows provide information about the composition and mineralogy of the lunar interior.

The lunar maria (the dark regions as viewed from Earth) are composed of basalt lava flows. They generally fill up low-lying regions inside enormous impact basins, though the basalts flowed across the surface tens to hundreds of million years after the basins formed. Analysis of Apollo samples showed that there are several distinctive types of mare basalts, varying most prominently in their concentrations of TiO_2 (titanium dioxide). Carlé Pieters (Brown University) showed in 1978 that the Apollo collection only sampled about one-third of the types of mare basalts that occur on the Moon. Data from the Clementine mission revealed that there is a full range in titanium concentrations, not just low or high. However, the remote sensing data do not give us the entire story. We need to know how all the elements vary in abundance, both those present in large amounts (>1%, major elements) and those present in small amounts (down to about the parts per million range, called trace elements). For that type of information, we need samples. Ryan Zeigler and his colleagues searched for samples of maria not studied previously.

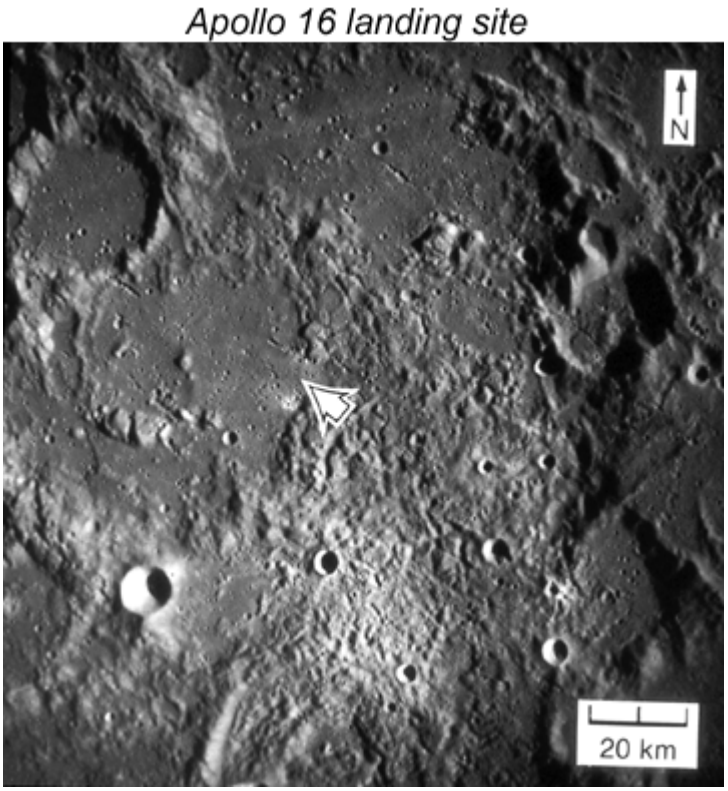


Map of TiO_2 concentrations in the lunar maria on the nearside of the Moon, determined from images obtained by the Galileo spacecraft. Highland areas (black) have been masked out.

Picking Small Rocks

The Apollo 16 landing site is in the lunar highlands, over 200 kilometers from the nearest mare surface. The large rocks collected by the crew are all highland rock types (much richer in feldspar, hence in aluminum, than mare basalts), so they contain no information about the maria. But the astronauts collected almost 20 kilograms of regolith from about 30 places. The regolith is the fragmental layer on the Moon. It formed from underlying rock by impact, with non-local rocks flung to the Apollo 16 site by distant impacts.

A few percent of the regolith consists of fragments of rock between 2 and 4 millimeters across. These are very useful samples because they are abundant (so we can find rare rock types) and because they are large enough to analyze in amazing detail. For example, the first anorthosites, which we now know make up most of the lunar highlands, were found among the 1-4 millimeter fragments in the Apollo 11 regolith samples. Apollo 11 did not land on the highlands--it landed on Mare Tranquillitatis. That's opposite to Zeigler and colleagues finding mare basalts at a highland site. Incidentally, the Apollo 11 anorthosite fragments led to the invention by John Wood (Smithsonian Astrophysical Observatory) of the magma ocean concept (see discussion of lunar magma ocean in **PSRD** article A Primordial and Complicated Ocean of Magma on Mars).



The Apollo 16 mission landed (arrow) in the lunar highlands. Everything in this picture is highlands. The site lies at least 200 kilometers from the nearest mare surface, yet small fragments of mare basalts are present in the regolith samples returned by Apollo 16 astronauts. Studies during the 1970s revealed the presence of mare basalts. The new research by Ryan Zeigler and his co-workers show that a fuller range of basalt types are present at the Apollo 16 landing site.

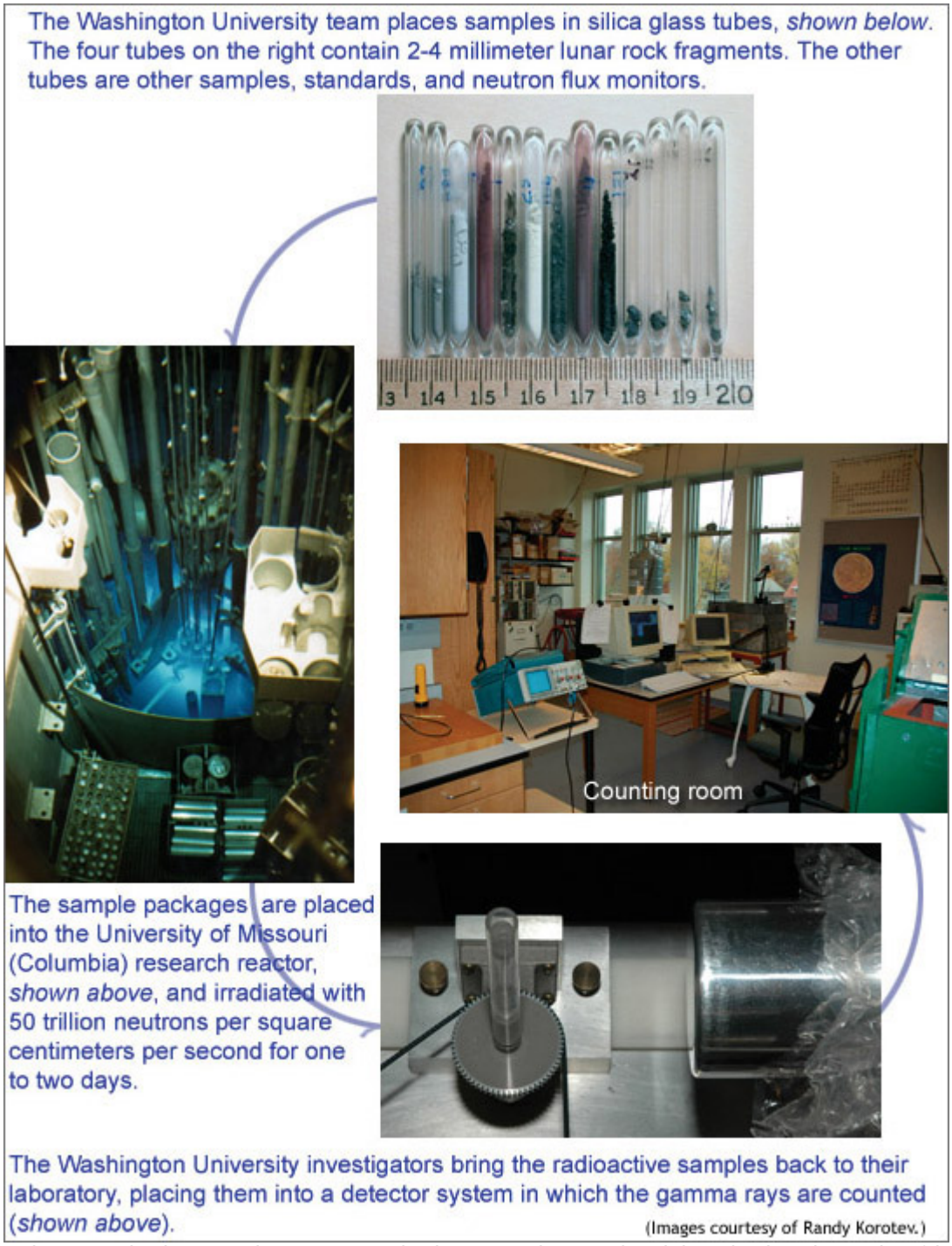
The lunar science group at Washington University is making a thorough study of 506 rock fragments in the 2-4 millimeter size range, selected from all sampling stations at the Apollo 16 site, except for those near the young North Ray Crater. As part of this heroic effort, they hand picked fragments from sieved samples containing many rock chips. The team was purposely trying to find a diversity of rock types, so the percentage of lithologic categories does not necessarily represent the proportions of rock types in the regolith. Of the 506 rock fragments, five were mare basalts, as distinguished by their chemical compositions (high iron, scandium, and chromium, and low aluminum).

Analyzing the Small Rocks

It has always amazed me what cosmochemists can do with even small samples (see, for example, **PSRD** article Analyzing Next to Nothing). In the case, it involved analyzing each fragment of basalt by neutron activation and then making polished thin sections of the same pieces for study by optical and electron microprobe analysis.

Neutron activation is a tried and true technique, and the Washington University team members are world-class practitioners, especially Randy Korotev, who has analyzed thousands of samples. In neutron activation analysis the samples are irradiated by neutrons in a nuclear reactor. Nuclear interactions take place, producing a bunch of radioactive isotopes. When the isotopes decay, they produce gamma rays with energies characteristic of the isotope, giving a measurement of the abundance of an element. Each package that goes into the reactor contains rock standards of known chemical composition and a monitor to measure the total number of neutrons that zapped the samples. The packages experience a rain of 50 trillion neutrons per square centimeter every second for 24 to 48 hours. The samples are taken back to the laboratory at Washington University and placed into

shielded detectors for gamma ray measurements. Typically, the concentrations of 25 to 30 elements are determined. Follow the steps of sample analysis in the pictures below, starting with the topmost picture and proceeding to the counting room at Washington University.



The detectors in the counting room are in the green box to the right. The box is made of lead lined with cadmium to shield the samples. Counts are accumulated by computer systems, which then make assorted corrections to convert gamma-ray counts to elemental concentrations.

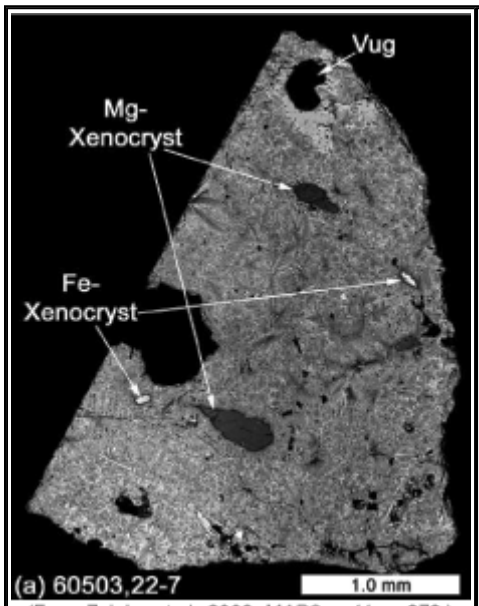
Neutron activation analysis done this way is called "Instrumental Neutron Activation Analysis," INAA for short, because it is done non-destructively. An even more sensitive method is called "Radiochemical Neutron Activation Analysis" (RNAA) because the samples are dissolved and groups of elements separated from each other chemically before counting (but after irradiation). INAA has the great advantage that cosmochemists can make thin sections from the same chips used for INAA.

Once the gamma-ray counting was done, which takes place at intervals over a period of about four weeks to allow interfering peaks to decay away, Zeigler and his colleagues made polished thin sections (30 micrometers, about 1/10,000 inch, thick). They studied the samples in the optical microscope and electron microprobe. If enough material remained after making the thin sections, they melted them into glass beads for analysis of major elements by electron microprobe. (They were able to do this for 4 of the 5 mare basalt fragments). In some cases the team also determined the bulk chemical composition for major elements by electron microprobe by using a broad beam (50 micrometers instead of the usual 1 micrometer) or by combining mineral abundances with average mineral compositions to calculate an overall chemical composition.

Five Important Little Rocks

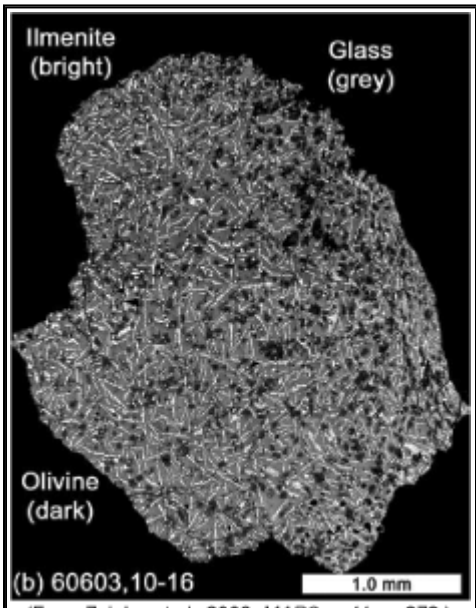
Ryan Zeigler and his coauthors found that the five basalt fragments differ from each other in chemical composition and mineralogy. Brief summaries of each rock fragment follow, but first a word about sample numbering. Note that the samples are labeled with numbers like this: 60603,10-16. This means that it is the 2-4 millimeter sieve fraction (labeled 60603) from bulk, unsieved regolith sample 60600. The ,10 means that it is from subsample #10, the pile of grains allocated to the Washington University team for chemical and mineralogical studies. The -16 indicates the sample number from the #10 subsample of 60603. There is great logic to numbering this way, and prevents confusion in the future if another investigator wished to analyze the samples by a different technique. Sample numbering over the years has resulted in the Apollo collection being subdivided into over 110,000 individually numbered subsamples!

The textural, chemical, and mineralogical properties of the five fragments are summarized in the table below, with a backscattered electron image of each sample. The compositional diagrams that follow are just the tip of the chemistry berg used by Zeigler and his coworkers to compare the samples to known types of mare basalts returned by the Apollo missions and the Luna (Russian unpiloted) missions.



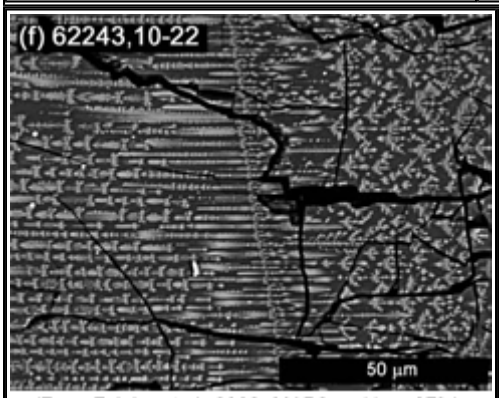
(From Zeigler *et al.*, 2006, *MAPS*, v. 41, p. 272.)

Fragment 60603,22-7 : *High-titanium basalt*
This is a fine-grained, hence rapidly cooled, fragment that contains vugs (irregular-shaped holes formed when the rock solidified around gas bubbles) and fragments of olivine. Most of the rock is composed of ilmenite and glass. Its composition shows that it is a high-titanium basalt. On the compositional diagrams (below, shown as point 22-7) it plots close to either the fields defined by Apollo 11 or Apollo 17 high-titanium basalts, or both, though overall it is a bit different from either type.



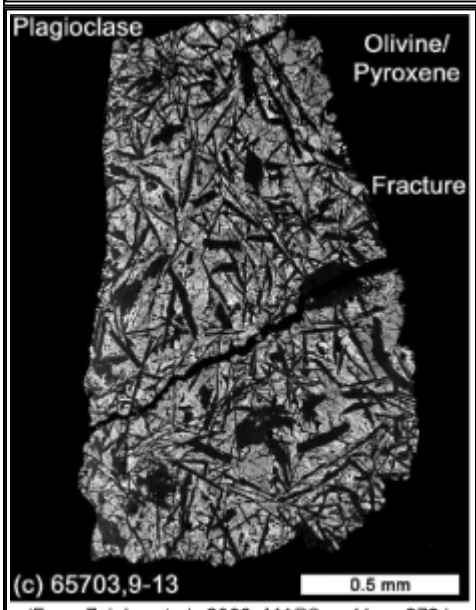
(From Zeigler *et al*., 2006, *MAPS*, v. 41, p. 272.)

Fragment 60603,10-16 : *Very-high titanium basalt*
This is a fragment of a rapidly-crystallized very-high titanium basalt. It consists of elongated, skeletal ilmenite crystals with olivine in a glassy or extremely fine-grained groundmass. Zeigler and his co-authors suggest that the finer-grained area on the right side, which contains numerous small cavities called vesicles, may be near the original surface of the lava flow. Its composition (see point 10-16 in the diagrams below) is different from known mare basalts, lying close to a group of volcanic glasses. It may be a crystalline form of volcanic glass.



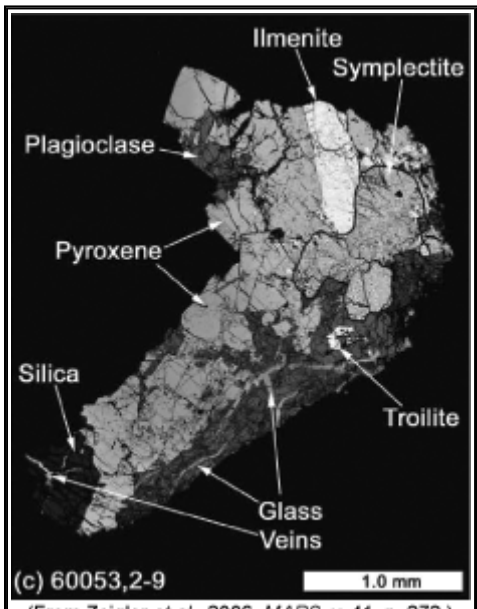
(From Zeigler *et al*., 2006, *MAPS*, v. 41, p. 273.)

Fragment 62243,10-22 : *Very-low titanium basalt*
This fragment was so full of fractures (no doubt caused by meteoroid impact) that it fell to pieces in the silica glass tube used for INAA. The picture (left) is of pyroxene that crystallized very rapidly. It is compositionally similar to Apollo 17 very-low titanium basalt (shown as point 10-22 in the diagrams below), but is finer grained than any of those samples (themselves fragments in the Apollo 17 regolith).



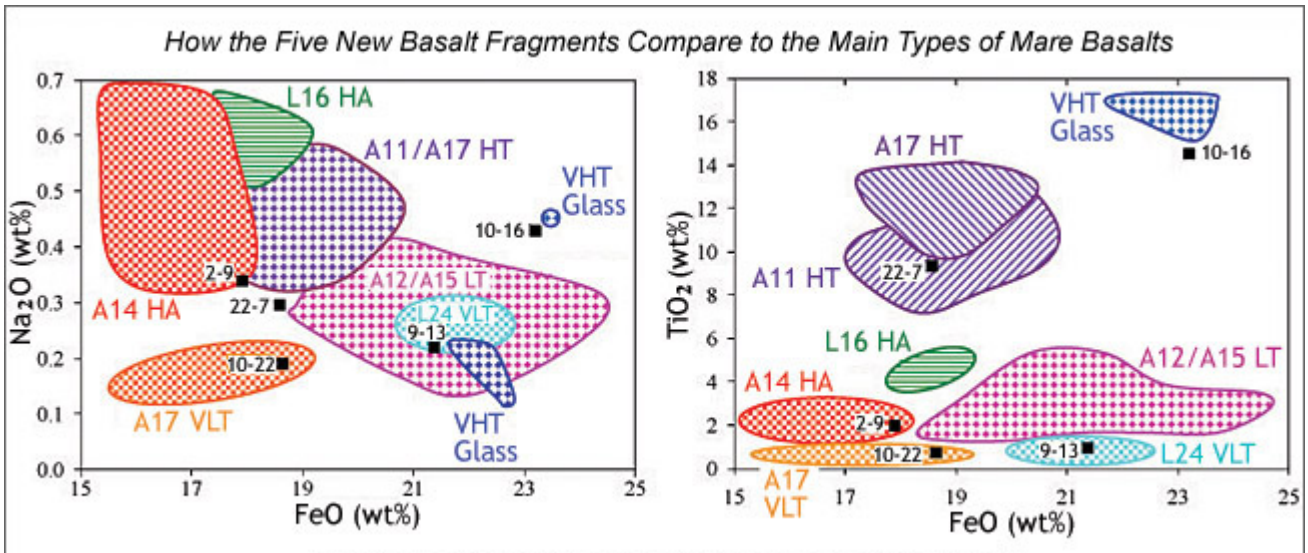
(From Zeigler *et al*., 2006, *MAPS*, v. 41, p. 272.)

Fragment 65703,9-13 : *Very-low titanium basalt*
Rock fragment 65703,9-13 is a crystalline basalt composed mostly of pyroxene and plagioclase, with small amounts of olivine. It is a compositional dead ringer to basalts returned by the robotic Luna 24 sample-return mission (see point 9-13 in the diagrams below).



(From Zeigler *et al.*, 2006, *MAPS*, v. 41, p. 272.)

Fragment 60053,2-9 : *High-aluminum, low-titanium basalt*
This coarse-grained rocklet is low in titanium, but relatively high in aluminum. Its coarse grain size and small overall size makes it difficult to obtain a good bulk chemical composition, but mineral compositions help indicate that it is most like one of the groups of basalts found in Apollo 14 fragmental impact breccias (see point 2-9 in the diagrams below).



(From Zeigler *et al.*, 2006, *Meteoritics & Planetary Science*, v. 41, fig. 5, p. 274.)

The two graphs shown above elaborate on the chemical variations among mare basalts. The colored areas in these diagrams show the compositions of the main types of mare basalts that have been defined by detailed studies of the Apollo (labels starting with A) and Luna (labels starting with L) sample collections. Note how they plot in well-defined fields. The five new basalt fragments studied by Zeigler and colleagues are plotted as black squares and are labeled with their subsample numbers. The left diagram shows the variation of Na_2O (sodium oxide) versus FeO (iron oxide); right diagram shows variation of TiO_2 (titanium dioxide) versus FeO.

Quite a few other lunar scientists had described mare basalts in the Apollo 16 regolith. However, all but one of these was discovered in a thin section, precluding analysis for trace elements, and in most cases the fragments were too small to obtain a reliable analysis for major elements. On the basis of the compositions of the minerals present, those investigators suggested that the fragments fell into high- and low- titanium categories, two of which were high in aluminum, too. Three of the particles might not even be mare basalts and their classification is inconclusive. The new results by Zeigler and colleagues expand those to include very-high titanium and very-low titanium basalts. Most important, the team reports trace element concentrations for all samples and can classify them unambiguously as mare basalts.

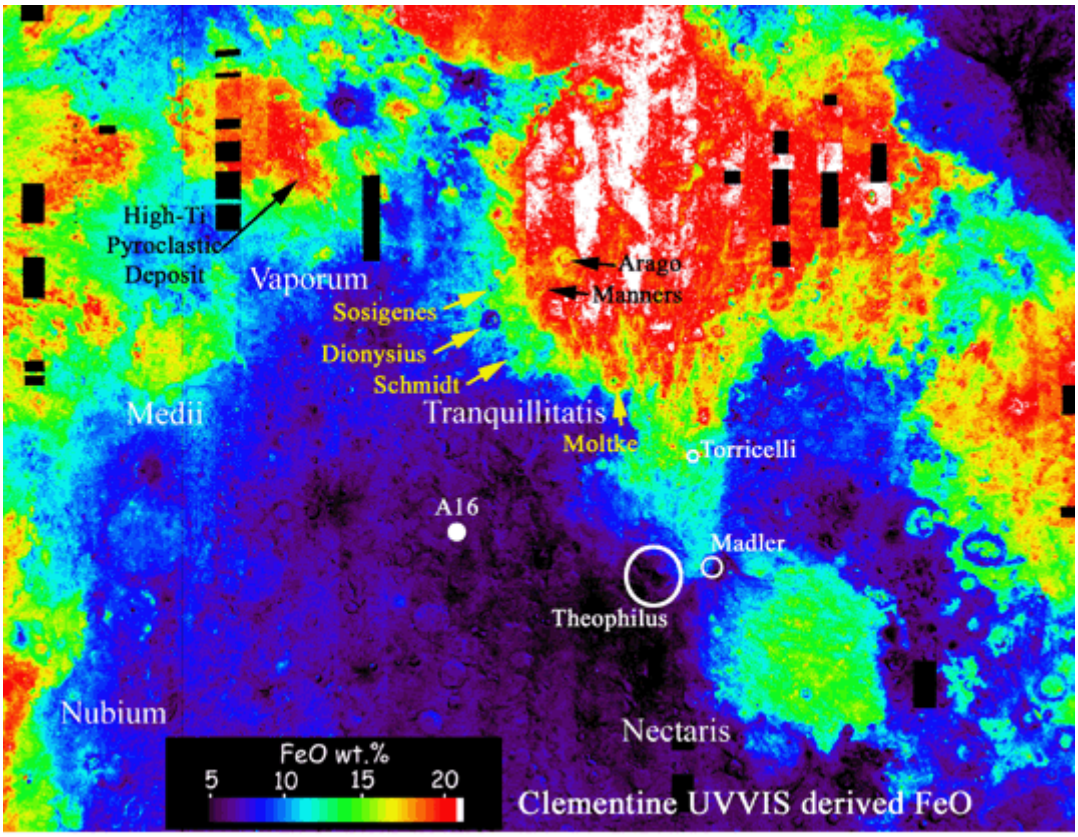
The most interesting of the five fragments may be 60603,10-16, the very-high titanium basalt with similarities

to very-high titanium pyroclastic glass. Pyroclastic glasses are frozen droplets of lava erupted in fire fountains [see **PSRD** article Explosive Volcanic Eruptions on the Moon]. Although they have the typical large range in titanium concentration seen in mare basalts, the pyroclastic glasses cannot be related in any simple way to a specific type of basalt. Yet the pyroclastic eruptions may have produced lava flows as well as dispersed piles of lava rain. Fragment 60603,10-16 might be a sample of partly crystallized rock related to a pyroclastic eruption. But which eruption? Where? In fact, where do any of these five basalt fragments come from? To answer those questions, Zeigler and his colleagues turned to remote sensing data.

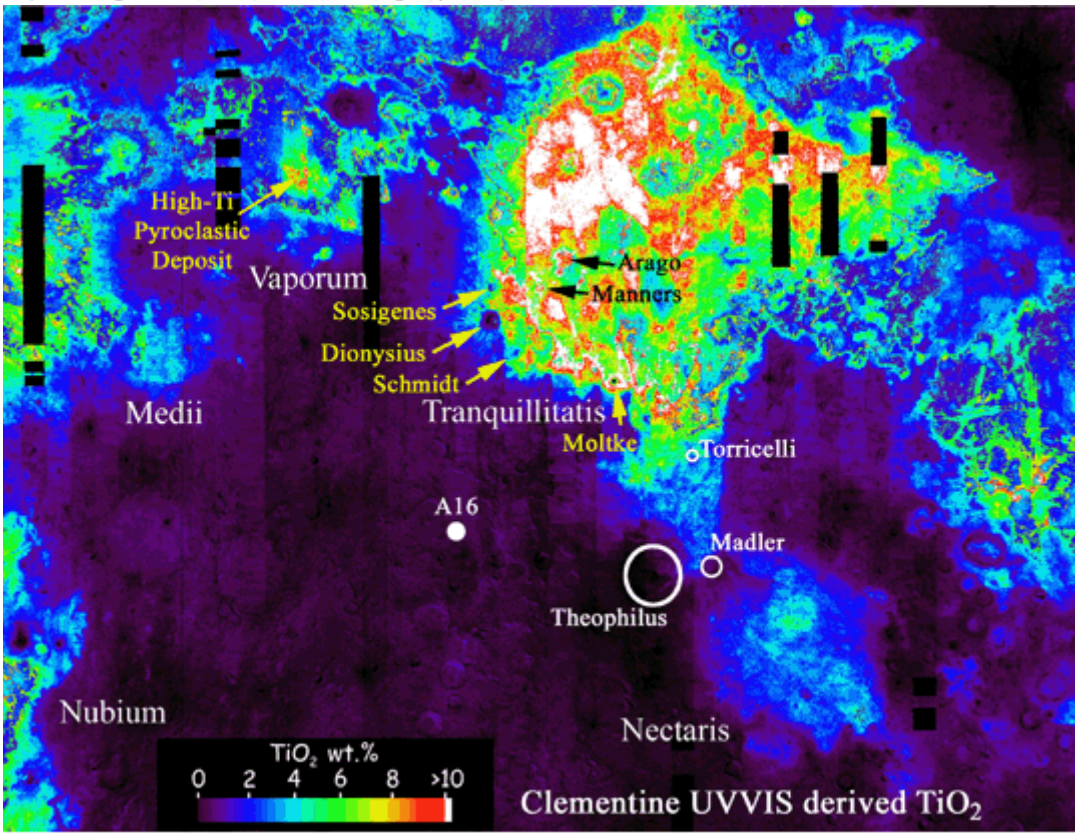
Where Did the Little Rocks Come From?

One possible source of the basalt fragments is ancient lava flows at the Apollo 16 site that were demolished by large local impacts or when ejecta was deposited from distant immense basins such as Imbrium, Serentatis, and Nectaris. If this were the case, then ancient impact breccias at the Apollo 16 site ought to contain mare basalt fragments. Such breccias contain fragments of mare basalt at the Apollo 14 and Apollo 17 sites. (This was an important discovery because it showed that lavas like those composing the surfaces of the maria began to erupt long before the visible maria formed.) However, detailed studies of Apollo 16 regolith breccias have not revealed the presence of any significant amount of mare basalt. Thus, even ejecta from Imbrium and Serentatis did not deliver mare basalts to the Apollo 16 site. The mare basalts at the Apollo 16 site most likely come from maria and other volcanic deposits formed after the large lunar basins. Zeigler and his cohorts conclude that impacts onto mare surfaces tossed the fragments to the Apollo 16 site.

But tossed from where, specifically? The team narrowed down the possibilities by using measurements obtained by the Clementine mission of the amount of light reflected at a few wavelengths. These data were converted to concentrations of FeO and TiO_2 (see maps below) using techniques developed by Paul Lucey (University of Hawaii) and modified by Jeff Gillis-Davis (formerly at Washington University, now at the University of Hawaii). For more information about how to convert the intensity of reflected light to element concentrations, see **PSRD** articles Moonbeams and Elements and Composition of the Moon's Crust.



(From Zeigler *et al.*, 2006, *MAPS*, v. 41, fig. 9, p. 280.)



(From Zeigler *et al.*, 2006, *MAPS*, v. 41, fig. 9, p. 280.)

Maps of the FeO (top) and TiO_2 (bottom) concentrations in the Apollo 16 region of the Moon. The Apollo 16 site is in the center (A16), surrounded by a vast area of highlands (low FeO and TiO_2) rock. Possible launching craters for mare basalts found at Apollo 16 are labeled. Black bands are places where there are no Clementine data.

Zeigler and coworkers argue that the high-Ti basalt fragments most likely originated in Mare Tranquillitatis, the large area to the northeast of Apollo 16 with the highest TiO_2 concentrations. Although there are other maria with somewhat high TiO_2, Mare Tranquillitatis has the highest and is closest to the Apollo 16 site. Deciding on what crater launched the fragments to Apollo 16 is trickier. There are several craters in western Tranquillitatis that could have done the job. The team gives Dionysius a slight edge because it has rays elevated in both FeO and TiO_2 that extend into the highlands towards the Apollo 16 site.

The closest low-Ti basalts are in Mare Nectaris, only about 220 kilometers east of Apollo 16. Mare Nectaris is closer than it seems on the FeO and TiO_2 maps because its eastern part was demolished by the formation of the relatively young, 100-kilometer crater Theophilus. In fact, Zeigler and colleagues think that Theophilus is a good candidate for the source crater for the low-Ti basalts at Apollo 16. It has secondary craters only 10 kilometers from the site, so it seems certain that it delivered some basalt. Other candidate craters may have, too, such as Madler and Torricelli. The important conclusion is that Nectaris is the most likely source for the low-Ti basalts.

The very-low titanium basalts may also come from Nectaris, again because it is closest to the site. Although Nectaris contains on average 2.5 wt% TiO_2, it may contain very-low titanium lava flows (possibly buried by younger low-Ti flows). This is the case in Mare Crisium, far to the northeast of the Apollo 16 site. The largest expanse of very-low-Ti basalt is Mare Frigoris, 1500 kilometers to the north. That's pretty far, so Zeigler and coauthors conclude that Nectaris is the best bet. The same candidate craters that might have flung the low-Ti basalts to the Apollo 16 site are candidates for the very-low-Ti basalts, too.

Very-high-Ti and high-Ti pyroclastic glasses have been found in Apollo 16 regolith samples. Fragment 60603,10-16 is compositionally similar to the very-high-Ti type. The largest expanse of high-Ti pyroclastic glass deposits is in the southern part of Mare Vaporum, about 500 kilometers from the Apollo 16 site. It occupies about 25,000 square kilometers. Zeigler and colleagues consider these deposits to be the most likely source, but could not identify any obvious source craters.

Stones Unturned

Research will continue on the rare rock types in the lunar regolilth (from all missions), helping us fill in the gaps in our knowledge of mare basalt compositions, hence in our knowledge of the lunar mantle. But it cannot all be done with existing samples. We need to collect some more.

There are two ways to collect samples. One is by sending unpiloted robotic spacecraft to collect samples from specific maria. A prime target would be the youngest lava flows on the Moon, such as those located near the crater Lichtenberg on the lunar nearside. This would provide absolute ages on those flows. They have been dated by counting the number of craters on them, but there are large uncertainties in this approach. Samples from such surfaces would help calibrate the crater counting method and give us the time when mare volcanism ceased on the Moon, an important parameter in understanding the variation of temperature with time of the lunar interior.

Besides mare basalts, there are probably other types of lava flows in the highlands. These may contain less iron and more magnesium than do mare basalts. These will be valuable probes of the portions of the mantle that have a high ratio of magnesium to iron [see **PSRD** article Gamma Rays, Meteorites, Lunar Samples, and the Composition of the Moon].

The other way to collect samples is by the human (gloved) hand. Human missions are scheduled to resume in about 2018. These may go to a few new places on the Moon before concentrating on a single base location. These missions could return valuable, well-selected samples of the lunar maria or of other types of lava flows.

Human Explorations on the Moon

NASA

Detailed studies of previously unsampled mare basalts will be done when astronauts return to the Moon. This artist's conception shows astronauts examining a lava tube.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Lunar Sample Laboratory Facility at Johnson Space Center. This web page also has a link for a virtual tour of the laboratory.
- Martel, L. (2004) Composition of the Moon's Crust. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Dec04/LunarCrust.html
- Taylor, G. J.(2006) A Primordial and Complicated Ocean of Magma on Mars. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Mar06/mars_magmaOcean.html
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- Weitz, Catherine M. (1997) Explosive Volcanic Eruptions on the Moon. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Feb97/MoonVolcanics.html
- Zeigler, Ryan A., Randy L. Korotev, Larry A. Haskin, Bradley L. Jolliff, and Jeffrey L. Gillis (2006) Petrography and geochemistry of five new Apollo 16 mare basalts and evidence for post-basin deposition of basaltic material at the site. *Meteoritics and Planetary Science,* vol. 41, p. 263-284.