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Asteroidal Lava Flows

--- Meteorite studies indicate that we have pieces of lava flows from at least five asteroids.

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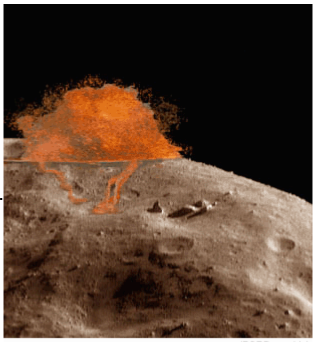


(PSRD graphic)

Some meteorites are pieces of lava flows. They have the expected minerals present and the crystals are intertwined in a characteristic way indicative of crystallization in a lava flow. This shows that lavas erupted on at least some asteroids. Age dating indicates that the eruptions took place 4.5 billion years ago. Planetary scientists have recognized three main groups of asteroidal lava flows, each distinctive enough to show that they must come from different asteroids. The most abundant are the eucrites, which might actually hail from asteroid 4 Vesta. Mesosiderites are complex mixtures of smashed up volcanic rock and metallic iron. Angrites have a distinctive group of minerals in them, but also clearly formed by volcanism. Recent studies increase the number of groups to five.

David Mittlefehldt (Johnson Space Center) and colleagues Marvin Killgore (Southwest Meteorite Lab) and Michael Lee (Hernandez Engineering, Houston, Texas) show that the five known angrites probably represent at least two different asteroids. Four of the angrites are fairly similar to each other in chemical composition, but a fourth, Angra dos Reis, was very different and may come from an entirely different asteroid. (This is ironic as the group derives its name from Angra dos Reis.) Akira Yamaguchi (National Institute of Polar Research, Tokyo, Japan) and colleagues in Japan at the University of Chicago show that a recently found eucrite, Northwest Africa 011 (NWA 011 for short), has a quite different composition of its oxygen isotopes than the rest of the eucrites. They suggest that NWA 011 comes from a different asteroid than the other eucrites. Thus, it appears that we have samples of lava flows from five different asteroids.

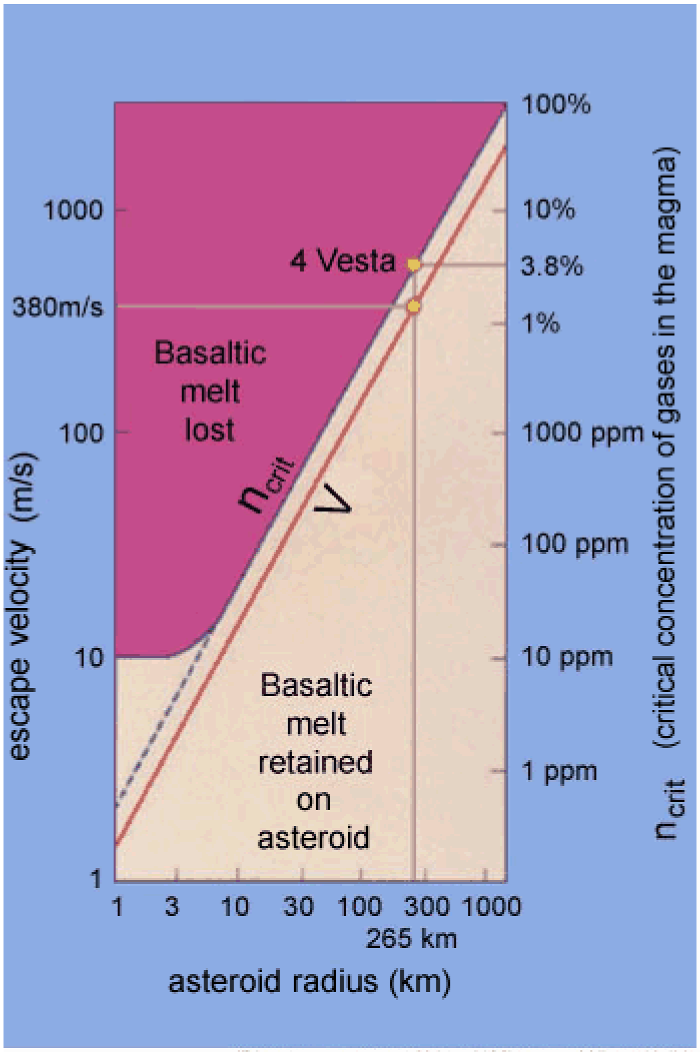
References:

Yamaguchi, A., Clayton, R. N., Mayeda, T. K., Ebihara, M., Oura, Y., Miura, Y., Haramura, H., Misawa, K., Kojima, H., and Nagao, K. (2002) A new source of basaltic meteorites inferred from Northwest Africa 011. *Science,* vol. 296, p. 334-336.

Mittlefehldt, D. W., Killgore, M., and Lee, M. T. (2002) Petrology and geochemistry of D'Orbigny, geochemistry of Sahara 99555, and the origin of angrites. *Meteoritics and Planetary Science,* vol. 32, p. 345-369.

Lava Flows and Eruptions on Asteroids

Even big asteroids have fairly puny gravitational fields. This means that we have to modify how we think magma is transported inside these little planets and how lava is erupted. This is not a one-way street, however. Making the adjustments sharpens our understanding of how magma transport and eruptions happen on larger planets. These comparisons are one of the great benefits of planetary science to understanding the Earth.



(Diagram courtesy of Lionel Wilson and Klaus Keil.)

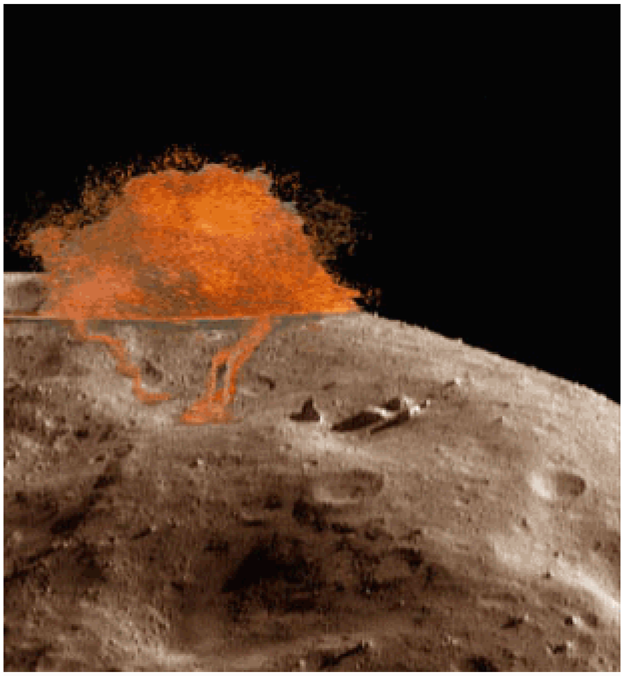
Lionel Wilson (Lancaster University, Brown University, and the University of Hawai'i--we estimate Lionel's average position as somewhere in the Eastern United States) has studied eruptive processes for many years. He has found that low gravity can lead to explosive volcanism on asteroids if even relatively small quantities of gases are present. The explosive eruptions propel drops of disrupted magma so fast that they exceed the escape velocity of many asteroids. This means that the lava is completely lost from the asteroid.

There is a complicated interplay of the amount of volatile substances (which produce the gases that drive the powerful eruptions) and the size of an asteroid (which defines the escape velocity), as shown in the illustration on the left. This process might explain why we have pieces of lava from so few asteroids--it was lost from those smaller than about 200 kilometers in diameter. Of course, there are always other explanations: it is also possible that countless impacts chipped away thick accumulations of lava from asteroids during the billions of years since they erupted.

LEFT: Lionel Wilson and Klaus Keil (Univ. of Hawai`i) have calculated the velocities of lava droplets erupted on asteroids of various sizes. The diagram shows that on small asteroids (x-axis shown in kilometers) with even moderate amounts of volatiles such as carbon dioxide, sulfur dioxide, and other gases (y-axis shown in ppm), the droplets will erupt so fast that they will be lost into space (area shaded dark pink). The line labeled "n_{crit}" defines the critical case when volatile content of the lava is enough to disrupt the melt into a spray of droplets lost to space. The line labeled "V" shows the escape velocity for reference.

Though modified by impact and metamorphism, the rocks that make up the eucrites began as lava flows on an asteroid. Matches between the spectrum of light reflected from eucrites in the laboratory and asteroid Vesta led Thomas McCord (then at the University of Hawai`i) and his colleagues to propose in 1970 that the eucrites hail from Vesta. This idea has been firmed up considerably by Richard Binzel (Massachusetts Institute of Technology) and his colleagues. Over the past decade or so, they have found numerous smaller asteroids that also resemble Vesta and the eucrites and whose orbital parameters are related to Vesta. So it seems we have samples of lava flows from a known asteroid. Vesta is large (265 kilometers in radius), so would have retained the lava unless it contained more than 3.8 wt% of volatiles, far higher than found in eucrites. The eruptions would still produce high fountains, but these would fall back to the surface and coalesce into lava flows.

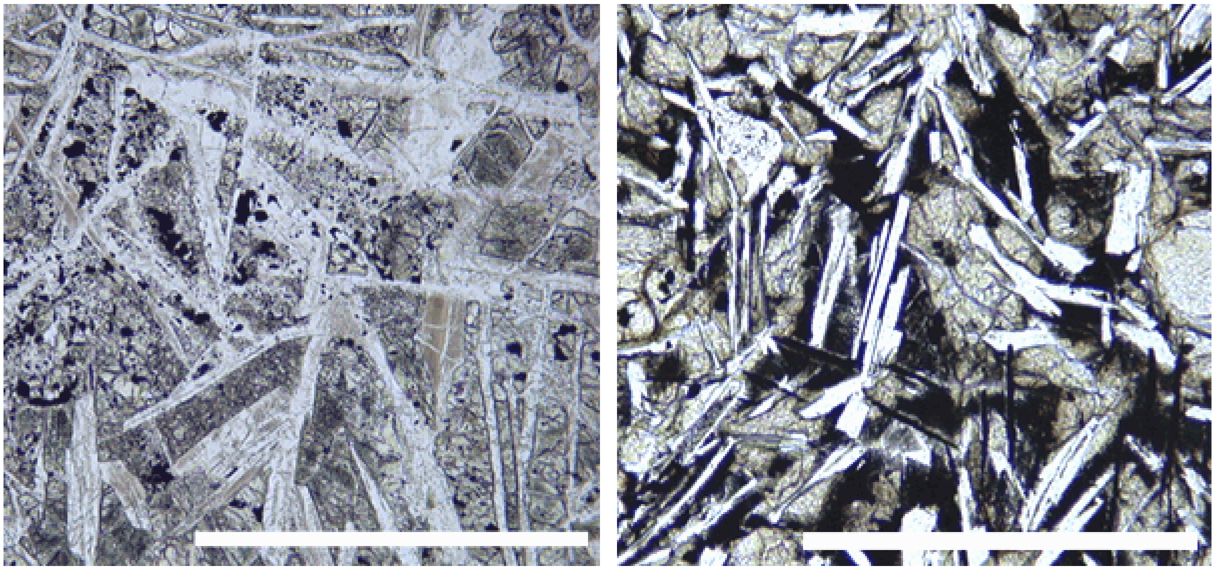
RIGHT: Lava flows on asteroids would likely originate from fountains of lava. The fountains would be higher and broader than on Earth. From the work by Wilson and Keil, we'd expect the fire fountains on an asteroid to be relatively wide, about double their height, because the materials move out nearly ballistically.



(PSRD graphic)

Pieces of individual lava flows from Vesta look a lot like terrestrial lava flows. In fact, Rachel Lentz (University of Tennessee) and I have found that eucrites most closely resemble pahoehoe lava flows, rather than \`a\`a flows. Pahoehoe flows are relatively smooth, whereas \`a\`a flows are very rough. These are only the superficial differences, however. The important difference lies in how they were emplaced on the surface. The lava inside a flowing pahoehoe flow is insulated, which leads to formation of fewer but larger crystals than in \`a\`a flows. In contrast, \`a\`a flows are rapidly flowing, usually incandescent streams of lava. This leads to formation of a greater number of crystals than in pahoehoe. The resemblance of eucrites to pahoehoe flows suggests that lava flows on Vesta are insulated. They might flow slower or be thicker than on Earth. Whatever the details, the striking similarity between eucrites and terrestrial lava flows (see figures below) shows that the eucrites almost certainly formed from lava on the surface of the asteroid.

BELOW: These two photomicrographs show the similarities between a eucrite meteorite called Millbillillie (left) and a Hawaiian pahoehoe lava flow (right). The grayish mineral is plagioclase feldspar; more colorful mineral is pyroxene. The similarities indicate that eucrites formed in lava flows. Scale bars are 1 millimeter.



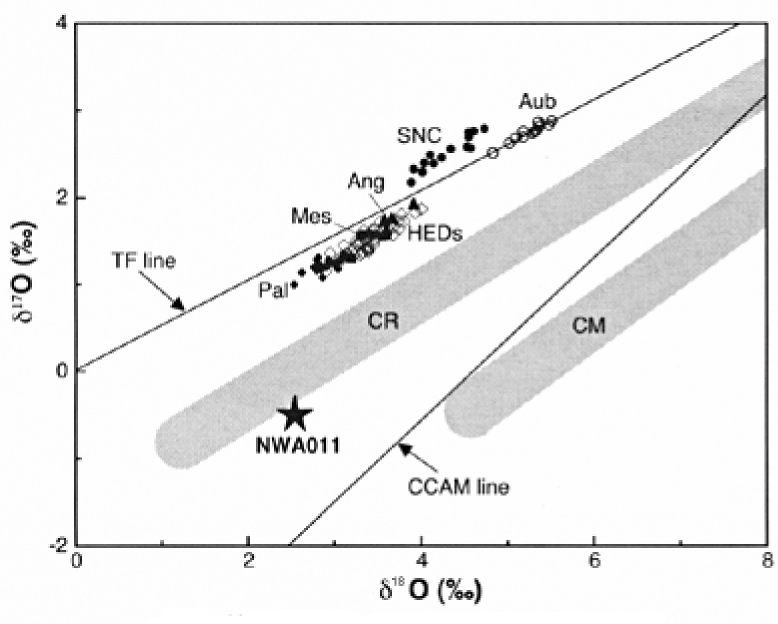
(G. Jeffrey Taylor) (G. Jeffrey Taylor)

Most eucrites did not simply form in a lava flow and then rest peacefully on the eucrite parent body. The ones that erupted earliest were buried deeply by subsequent flows and warmed up by heat escaping from the body below them, forming metamorphic rocks. Only the latest lavas to erupt escaped this heating. On top of that the surface of the flows were pummeled by projectiles early in the history of the solar system, converting the original works of volcanic art into debris piles. Because impacting and volcanism occurred at the same time, the debris piles from the impacts were also buried by younger flows and subsequently metamorphosed.

Sound complicated? Not compared to the mesosiderites. These are baffling rocks composed of rocky debris and metallic iron. Much, though not all, of the rocky material is some kind of volcanic rock. The volcanic rock, which formed on the surface of the mesosiderite asteroid, was mixed with metallic iron, which made up its core, or the core of an impacting asteroid. Somehow during all this, little or none of the mantle of either body was added to the mix. These mysterious meteorites will be the subject of a future PSRD article. For now, the important point is that there was another asteroid with a surface covered with lava flows.

Not All Eucrites Come from Vesta

One of the distinctive features shared by all eucrites is their oxygen isotopic compositions. They all fall on one line in a plot of oxygen-17/oxygen-16 vs. oxygen-18/oxygen-16 (see diagram below). Other groups of meteorites, the Earth and Moon (which share a common trend), and Mars (as represented by Martian meteorites) also plot in specific locations on the diagram. Planetary scientists use oxygen isotopic composition as a fingerprint. Rocks that derive from the same body have the same composition. If two rocks have different compositions they probably come from different asteroids or planets. (This assumes that all parts of a body have the same oxygen composition, which may not be strictly true. It is most likely to be true in the case of bodies that melted substantially. The melting would help iron out any differences in oxygen isotopic composition between different parts of the body.) Of course, having the same oxygen isotopic composition does not prove that two types of meteorites come from the same asteroid.



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LEFT: The oxygen isotopic compositions of several groups of meteorites plot in distinct regions on this plot of ^{17}O / ^{16}O vs. ^{18}O / ^{16}O. The lines for each group are parallel because on each body the oxygen isotopes were separated according to their masses, when the rocks formed. Cosmochemists measure the ^{17}O / ^{16}O and ^{18}O / ^{16}O ratios in terms of deviations in parts per thousand from a standard (delta ^{18}O and delta ^{17}O). The usual standard is mean ocean water, abbreviated SMOW, for Standard Mean Ocean Water.

The star symbol shows where meteorite NWA 001 plots. The abbreviations: HEDs = a class of differentiated meteorites (howardites, eucrites, and diogenites), Ang = angrites, Mes = silicate inclusions in mesosiderites, Pal = pallasites, SNC = Martian meteorites, CR and CM = carbonaceous chondrites, TF line = terrestrial (Earth and Moon) fractionation line, and CCAM line = carbonaceous chondrite anhydrous (water-free) mineral line.

Akira Yamaguchi and his colleagues used the oxygen isotope fingerprint idea to identify a eucrite that is not a eucrite. They studied a meteorite classified logically as a eucrite by its appearance, even in the microscope. It was found in Northwest Africa, and given the name NWA 011. Although the rock does indeed resemble eucrites, it has a distinctive oxygen isotopic composition, falling far from the eucrites and other rocks associated with them (nicknamed the HED meteorites, for howardites, eucrites, and diogenites). NWA 011, Yamaguchi and his colleagues conclude, comes from a different asteroid than the other eucrites. A distinct difference in the ratio of iron oxide to manganese oxide in the mineral pyroxene also indicates a different place of origin.

The new type of eucrite seems to have had a similar history to most of the main group of eucrites. It formed in a lava flow, was smashed up to form an impact deposit, then buried and metamorphosed. This suggests to Yamaguchi that NWA 011 formed in a body about the size of Vesta, but perhaps no longer exists. A team of astronomers led by D. Lazzaro (National Observatory, Brazil) have found a Vesta-like asteroid whose orbital parameters show that it is not related in any way to Vesta.

The Angrites and Their Odd Namesake

So now we are up to four asteroids that provide us with volcanic meteorites: two types of eucrites, the baffling mesosiderites, and the angrites. However, David (Duck) Mittlefehldt and his colleagues show that Angra dos Reis does not seem to be related to the other five angrites, in spite of lending its name to the entire group. Perhaps we have a fifth asteroid represented here.

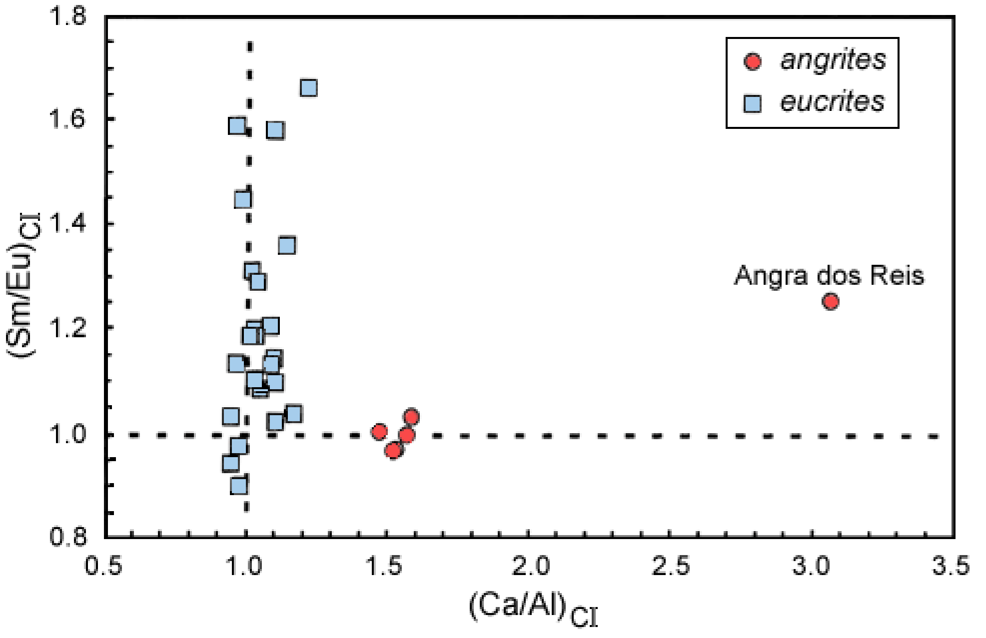
Mittlefehldt and his coworkers made a detailed study of a new angrite named D'Orbigny, a 16.6-kilogram meteorite found in Argentina. They also did chemical analyses of Sahara 99555, a 2.7-kilogram meteorite found in northern Africa, and compare these new data to what we knew previously about the angrites. The new angrites appear to be volcanic rocks, as shown by the shapes and intergrowths of minerals (see photograph below) and the way the mineral olivine is chemically zoned and rich in calcium. Zoning usually indicates that a crystal has grown fairly rapidly from a magma that cooled too fast to allow formation of minerals uniform in composition.

(From Mittlefehldt *et al.*, 2002, *Meteoritics and Planetary Science*, v. 32, p. 345-369.)

ABOVE: This microscopic view is of the meteorite D'Orbigny. Light gray and white mineral grains are plagioclase feldspar, blue grains are olivine, and red, greenish and tanish ones are pyroxene. The colors are caused by interference of light waves due to viewing a thin (35 micrometers) slice of the meteorite in polarized light. As for eucrites, the shapes of the individual crystals and the way in which they are intergrown indicates that the rock crystallized in a lava flow.

The chemical composition in individual olivine crystals varies in a complicated way. The interiors are uniform in composition, but about half way to the rims the composition begins to change, with the ratio of magnesium to iron and the concentration of chromium decreasing while calcium increases. There are even some reversals in the chemical zoning patterns. Mittlefehldt suggests that the complicated zoning patterns are caused by the crystallization of pyroxene in the lava because pyroxene incorporates different amounts of iron, magnesium, calcium, and chromium compared to the amounts incorporated in olivine. There may be an added effect due to the addition of fresh (uncrystallized) magma to the crystallizing portion of the lava.

The chemical compositions of angrites are strikingly different from those of the eucrites. Mittlefehldt and his coworkers illustrate this by drawing attention to the ratio of calcium to aluminum. The angrites have Ca/Al ratios larger than those found in carbonaceous chondrites, which are thought to represent the relative abundances of most elements in the solar system. The eucrites, in contrast, have Ca/Al ratios the same as in carbonaceous chondrites. This shift in Ca/Al cannot be attributed solely to a mineral with a low Ca/Al ratio separating from the angrite magma. For example, the likely mineral is plagioclase feldspar. If this mineral separates, it also affects the ratio of samarium (Sm) to europium (Eu). In eucrites, which seem to have been affected by plagioclase removal somehow, Sm/Eu varies widely. This ratio is quite uniform in angrites, suggesting that there is some other cause for the high Ca/Al. Mittlefehldt suggests it might have been caused by the presence of a mineral rich in aluminum (such as spinel) in the interior of the angrite asteroid, where the angrite magmas were created by partial melting. Angra dos Reis plots in a drastically different place from the other angrites, suggesting it formed in a different asteroid or in a very different region on the same asteroid.



(From Mittlefehldt *et al.*, 2002, *Meteoritics and Planetary Science*, v. 32, p. 345-369.)

ABOVE: This plot shows the ratio of samarium to europium (Sm/Eu) versus the ratio of calcium to aluminum (Ca/Al) in eucrites and angrites. Both ratios have been divided by the ratio in carbonaceous chondrites. Angrites are clearly enriched in Ca relative to Al. This enrichment is not caused by addition or separation of plagioclase feldspar, which would affect the Sm/Eu ratio even more, as shown by the eucrites. Note that Angra dos Reis is much different in both Ca/Al and Sm/Eu than the other angrites. This suggests that Angra dos Reis may have formed on a different asteroid.

The angrites seem to consist of two different groups: Angra dos Reis is all by itself in one group. The other five meteorites make up the other group. Angra dos Reis has been metamorphosed, whereas the others have not been. Angra dos Reis is also chemically distinctive. These factors point to an origin on a different asteroid. If so, perhaps it has a different mix of oxygen isotopes than do the other angrites, allowing us to use the same argument for distinctive origin as Akira Yamaguchi used to identify a new type of eucrite. No such luck. All six angrites have the same mix of oxygen isotopes. Mittlefehldt and coworkers suggest that the oxygen isotope test might not be definitive in this case because quite a few different meteorite groups have oxygen isotopic compositions in this region of the oxygen isotope plot. (Angrites are labeled "Ang" in the oxygen isotope plot above.)

Diverse Histories of Asteroidal Lava Flows

We cannot be sure that the angrites represent two separate asteroids, but the case is pretty strong. This means we may have pieces of lava flows from five different asteroids. All originated in volcanic eruptions, but some groups seem to have been smashed up by impacts more than others, and some have been metamorphosed by burial and others have not been, as shown in the table below.

Meteorite Group	Volcanic?	Brecciated by Impacts?	Metamorphosed?
Eucrites	Yes	Almost All	Almost All
Eucrite-2 (NWA 011)	Yes	Yes	Yes
Angrites (except one)	Yes	No	No
Angra dos Reis	Yes	No	Yes
Mesosiderites	Yes	Yes	Yes

Why do the five asteroids have such different histories? One possibility is that we do not have enough samples from some of them to be sure that the observations apply to an entire asteroid. We have plenty of eucrites and mesosiderites, but only one NWA 011 eucirte and six angrites, including Andra dos Reis. Lets assume that these meteorites are representative of the asteroids on which they formed. If so, why did the two angrite asteroids escape impact bombardment? Or did just a surviving remnant of it escape impact reworking and that is the piece providing us with meteorites. Why are all of them except the angrites (excluding Angra dos Reis) metamorphosed? Were their parent asteroids large enough for this to occur on? If the angrite asteroid was smaller, why did it retain the erupting lava? Answers to these questions await discoveries of additional meteorites in each category, detailed astronomical observations of asteroids, and perhaps missions (including sample-return missions) to a bunch of asteroids.

Additional Resources

Lentz, R. C. F. and Taylor, G. J. (2002) Petrographic textures and insights into basaltic lava flow emplacement on Earth, the Moon, and Vesta. *Lunar and Planetary Science Conference XXXIII,* abstract 1332.pdf.

Mittlefehldt, D. W., Killgore, M., and Lee, M. T. (2002) Petrology and geochemistry of D'Orbigny, geochemistry of Sahara 99555, and the origin of angrites. *Meteoritics and Planetary Science,* vol. 32, p. 345-369.

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