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Headline Article

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The Oldest Volcanic Meteorite: A Silica-Rich Lava on a Geologically Complex Planetesimal

Meteorite NWA 11119

(Srinivasan *et al.*, 2018, *Nature Communications*, v. 9:3036, doi: 10.1038/s41467-018-05501-0.)

--- A volcanic meteorite is the oldest igneous meteorite identified so far, erupting onto its parent body only about 3 million years after the Solar System began to form.

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A meteorite found in Mauritania, named Northwest Africa (NWA) 11119, held some surprises for a team of researchers led by Poorna Srinivasan (University of New Mexico, UNM) and co-workers at UNM, Arizona State University (ASU), and NASA Johnson Space Center. The investigators determined that the rock formed by a volcanic eruption only about 3 million years after the first solids formed in our Solar System, hence requiring that its parent body was assembled and heated soon after the Solar System started to form. Equally amazing, the rock is high in silica (SiO_2), a characteristic of evolved igneous rocks, not the common basalt composition (characterized by low silica) usually displayed by igneous meteorites. Oxygen isotopic compositions of NWA 11119 are different from basaltic meteorites except for two, namely NWA 7325 and Almahata Sitta, perhaps linking all three to the same geologically-complex parent planetesimal.

Reference:

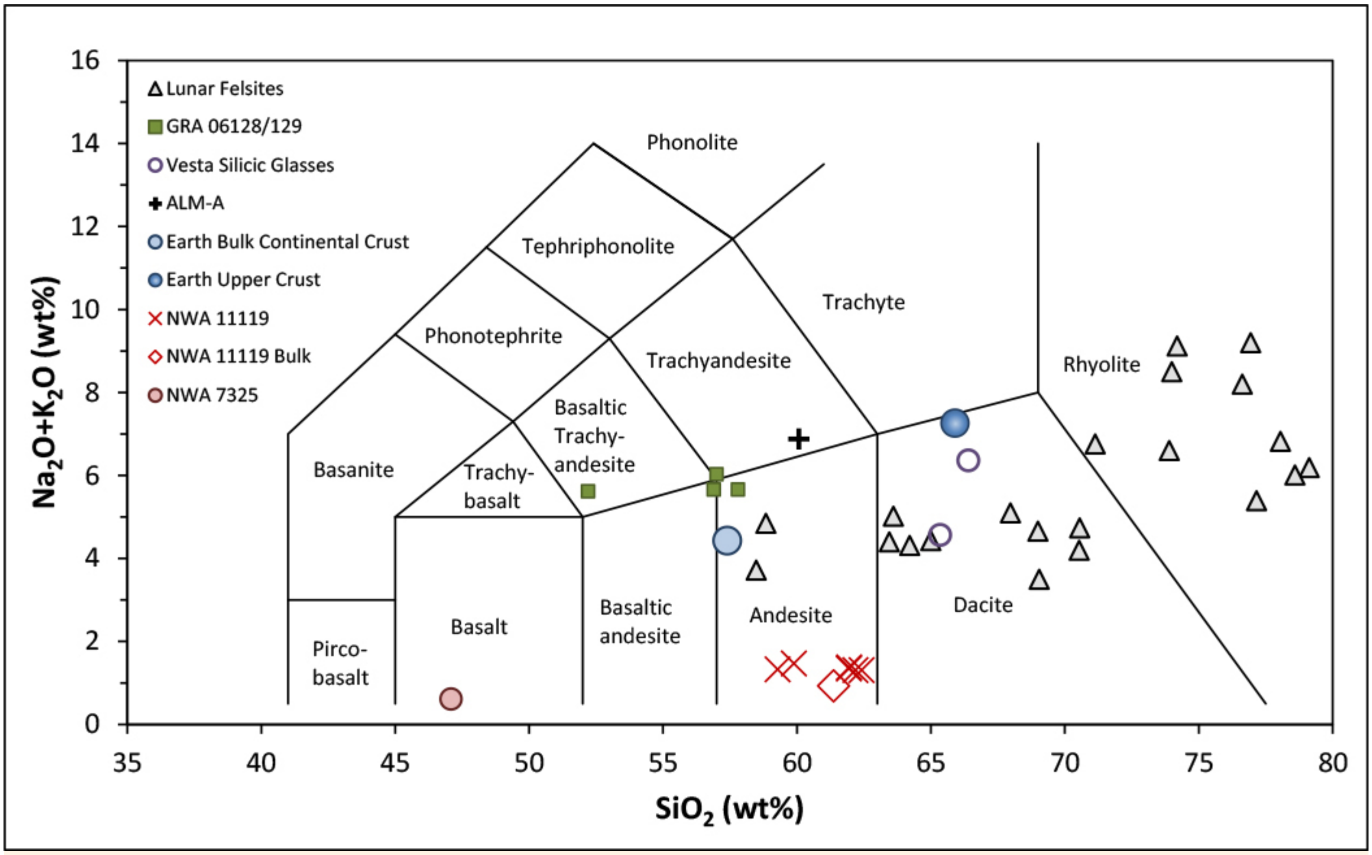
- Srinivasan, P., Dunlap, D. R., Agee, C. B., Wadhwa, M., Coleff, D., Ziegler, K., Zeigler, R., and McCubbin, F. M. (2018) Silica-rich Volcanism in the Early Solar System Dated at 4.565 Ga. *Nature Communications,* v. 9, doi: 10.1038/s41467-018-05501-0. [**article**]
- **PSRDpresents:** The Oldest Volcanic Meteorite: A Silica-Rich Lava on a Geologically Complex Planetesimal --**Short Slide Summary** (with accompanying notes).

Silicic Rocks: Common on Earth, Rare Elsewhere, Important Everywhere

Rocks rich in silica are of special interest to geologists and cosmochemists because they are so evolved compared to **basalts**. Let's see where they occur. Silicic rocks are not abundant in our Solar System, except for on Earth. The continents on which most people live are compositionally different from the basalts making up the sea floor. Continents are made mostly of **igneous** rocks that contain more SiO_2 (silica) than do the ocean-floor basalts. These compositions can be viewed in a classification based on silica versus the sum of sodium and potassium oxides, called the Total Alkalis and Silica, or TAS, diagram. In the TAS diagram shown below, the average composition of Earth's total (or "bulk") continental crust and of the upper continental crust appear as blue dots. (Data are from the excellent summary of planetary crusts by Ross Taylor and Scott McLennan.)

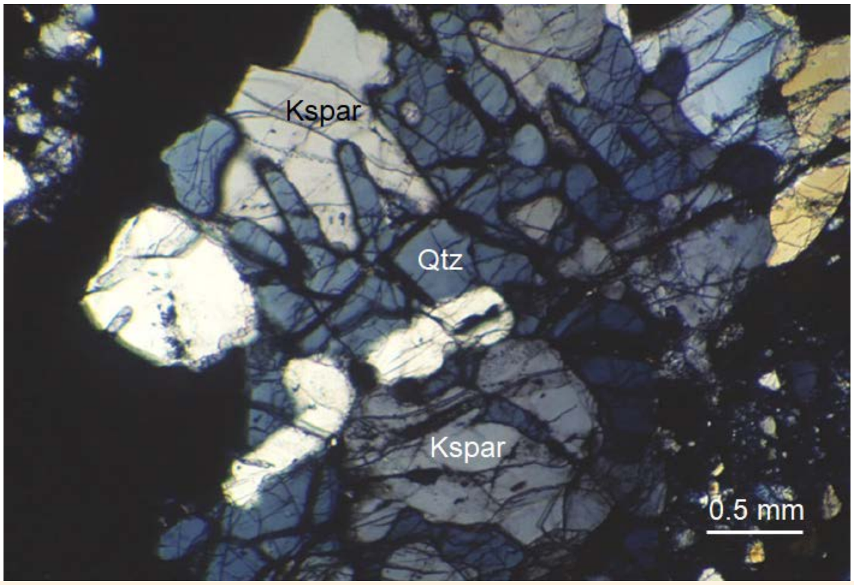
Terrestrial silicic rocks, whether volcanically erupted onto the surface or formed underground (**intrusive**), are usually heterogeneous of at range of scales. This variation is one of the features that makes the famous Yosemite landmark El Capitan (pictured below) such a striking outcrop of rock. The huge rock face varies in color, a consequence of different rock compositions, but all are more silicic than the **andesite** range in the TAS diagram below (El Capitan data are not shown in the diagram). The variation results from the complex origin of terrestrial silicic rocks, which involves interactions between huge **tectonic** plates, the **subduction** of water-rich oceanic crust downward, water-rich fluids migrating upwards into the overlying **mantle**, partial melting of that mantle, mixing of **magmas** of different compositions, and crystallization of magmas in big magma chambers, to name a few of the processes operating when plates collide. The important point is that formation of the terrestrial continental crust involves plate tectonics, water, and a lot of time.

El Capitan, a famous landmark in Yosemite National Park, in the heart of the Sierra Nevada in eastern California, is composed of a variety of silicic rocks. Note the lighter and darker areas. These represent silicic rocks of differing SiO_2 concentrations, indicating the complex origin of the magmas near the base of the crust in a subduction zone created when the Pre-Pacific Farallon Plate slid beneath the margin of the North American plate.



This TAS diagram, a favorite of petrologists, shows total alkalis (oxides of potassium and sodium) versus silicon dioxide concentration (all in weight percent) for all the samples discussed in this article. The fields show where different types of terrestrial volcanic rocks plot. (Magmas that do not erupt plot in these fields, too, but the rocks have different names. For example, the non-volcanic version of rhyolite is granite.) The exotic names were created for terrestrial studies, but seem to work fine for extraterrestrial ones, too. Those plotting on the right half of the diagram, say from 55 wt% SiO_2 or more, are often termed "evolved" rocks. Such rocks are found on the Moon, asteroid 4 Vesta (in meteorites called Howardites), and in some meteorites, including NWA 11119 [Data link from the Meteoritical Database]. The sample labeled ALM-A is one separated rock fragment from the Alamhata Sitta meteorite [Data link from the Meteoritical Database], which might be related to the evolved rocks in NWA 11119. The two blue dots represent the average compositions of Earth's bulk continental crust and the upper continental crust.

The prominence of silicic rocks on Earth leads planetary scientists to take note when such rocks are found elsewhere. If found on another body does it mean that the same plate tectonic processes operated there? Or are other processes involved? The first clear case of silicic rocks (also called felsites) occurring on another planetary body was in the **Apollo** collection of lunar samples. A photomicrograph of one is shown below, and all that have been analyzed are plotted in the TAS diagram above (as triangles). The compositions are highly evolved, ranging from andesite to rhyolite. So, their compositions are sort of Earthy.



Piece of a lunar granite (called felsite to prevent confusion with the granites that make up mountains on Earth) in Apollo 14 fragmental breccia 14321. This view of a thin section of the little rock shows that it is composed mostly of quartz (Qtz) and potassium feldspar (Kspar). The photomicrograph was taken in cross-polarized light. The uniform color of the quartz shows that it is likely to be one crystal. Lunar rocks like this range in their concentrations of SiO_2, but all can be called "silicic" or "evolved" igneous rocks.

The lunar felsites differ in one important way from terrestrial silicic rocks: there is no evidence that the lunar rocks formed as whole mountain ranges or in big magma chambers. In 1983, Paul Warren (now at UCLA) and others estimated the rock pictured above weighs only 1.8 grams, which they described in the title to a paper as "large"! The little rocklets are not very abundant either, although remote sensing studies suggest that some small volcanic domes may be rich in silica. The little silicic lunar rocks likely formed by **fractional crystallization** of an original basaltic magma. This process also happens on Earth in layered intrusions, now observed as large, layered bodies of igneous rocks. The last materials to crystallize are silicic and form within the upper layers of the intrusion. The silicic materials are not very abundant compared to the entire stack of crystallized rock.

Silicic domes on the Moon, such as the small ones decorating the smooth plains of Oceanus Procellarum, may have involved formation by one of the processes involved in producing some silicic rocks on Earth, namely partial melting of the lunar crust by the intrusion of hot, basaltic magma. This process, often called underplating, has been shown to work experimentally and produces more silicic magma than does fractional crystallization. Nevertheless, it does not produce long mountain ranges the way plate tectonics do on Earth.

Glassy volcanic spherules have been found in samples from the **HED** parent body, which is almost certainly asteroid 4 Vesta. (See **PSRD** article: **The Complicated Geologic History of Asteroid 4 Vesta**.) Most of the volcanic glasses have compositions like basalts common on Vesta, but two (plotted in the TAS diagram as open circles) are silicic. This suggests that fractional crystallization operated on Vesta, too, though some form of magma underplating might also have operated.

Another interesting set of silicic rocks is found in a meteorite named Graves Nunatak 06128 and 06129 [**Data link** from the Meteoritical Database]; see **PSRD** article: **More Evidence for Multiple Meteorite Magmas**. These paired meteorites contain rocks that have higher sodium and mostly elevated silica (see green squares plotted in the TAS diagram). There is some range in silica concentration among samples analyzed, but none is typical of basalt.

The NWA 11119 Silicic Rock

Poorna Srinivasan and colleagues studied a newly-identified extraterrestrial silicic volcanic rock, a meteorite named NWA 11119 [**Data link** from the Meteoritical Database]. It is linked by its oxygen **isotopic** composition to other igneous meteorites so might have formed in the same complicated parent body. And, perhaps most important, it has an extremely old age, as discussed below.

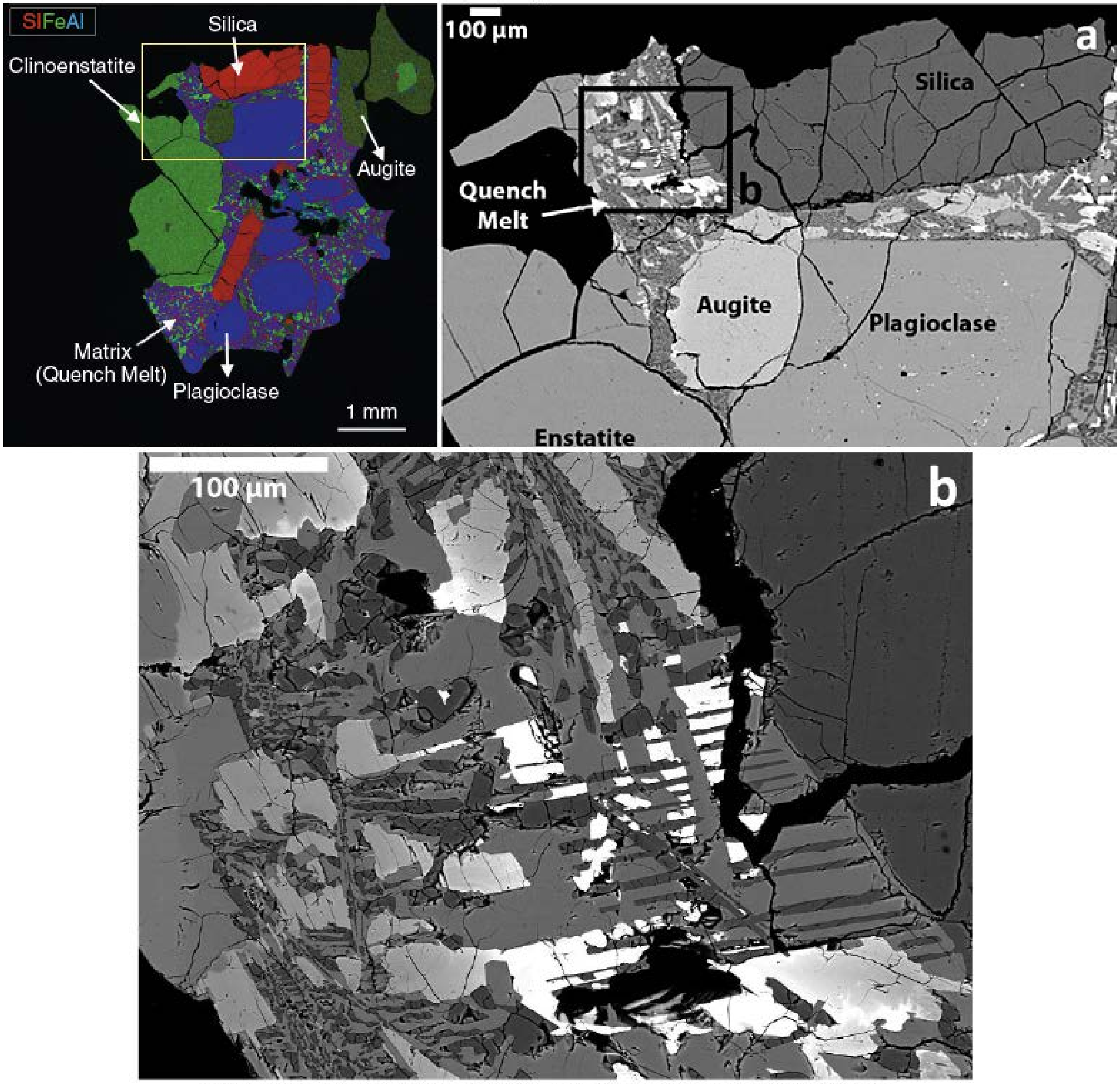
NWA 11119 has an unusual appearance in thin section. It has a light green fusion crust and large crystals of greenish augite (high-calcium **pyroxene**), **plagioclase feldspar**, and tridymite (SiO_2). It has a characteristic volcanic texture in which large mineral grains are surrounded by a fine-grained intergrowth of the same minerals (though in different proportions). There is no evidence for impact-melting to have been involved. NWA 11119 is a volcanic rock. It is silicic, with the composition of an andesite, but lower in alkali elements (plotted as red X and diamond in the TAS diagram above). The composition of the bulk rock is similar to that of the matrix, suggesting that there has not been extensive fractionation of the coarse-grained minerals while surrounded by magma before it erupted. Another striking aspect of NWA 11119 is its low alkali concentration, much lower than any of the other silicic igneous rocks.

Meteorite NWA 11119

(Srinivasan *et al.*, 2018, *Nature Communications*, v. 9:3036, doi: 10.1038/s41467-018-05501-0.)

Hand specimen of a sample of NWA 11119. The green mineral is pyroxene (greenish tint comes from about a percent of Cr_2O_3 in the sample), gray is a silica polymorph that Poorna Srinivasan and colleagues identified as tridymite, and whitish is plagioclase feldspar. The rock contains on average 50% plagioclase, 27% tridymite, 12% pyroxene, and 11% matrix.

Texture and Mineralogy of Meteorite NWA 11119

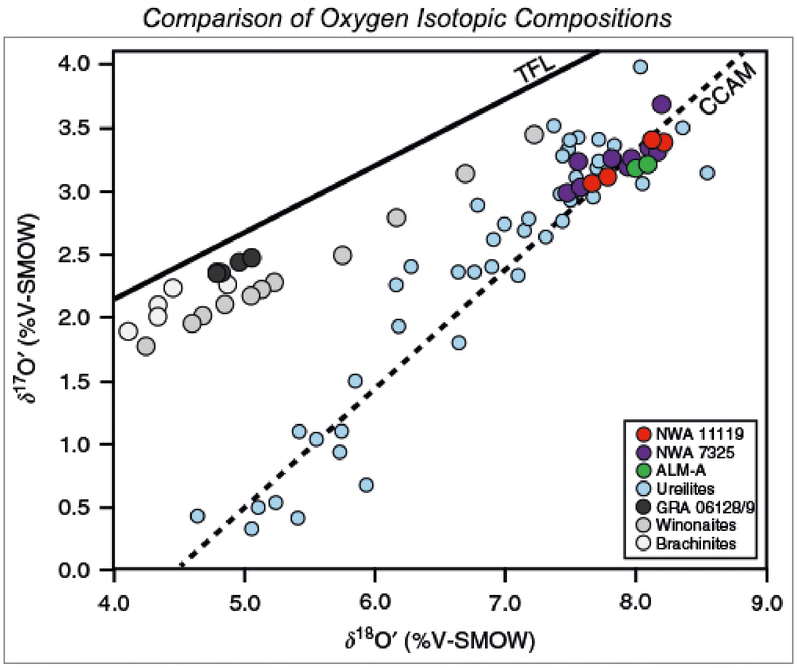


(Srinivasan *et al.*, 2018, *Nature Communications*, v. 9:3036, doi: 10.1038/s41467-018-05501-0.)

[Top Left] False-color X-ray map of a piece of NWA 11119 as seen in a polished thin section. Minerals are labeled. **[Top Right]** Backscattered electron image enlargement of the area outlined by yellow box. In both images, larger crystals are embedded in a fine-grained, continuous matrix (which in igneous rocks is usually called the groundmass). **[Bottom]** Backscattered electron image enlargement of the area outlined in black box showing a classic texture for rapidly-cooled, hence volcanic, rocks. Darkest grains are silica (tridymite), medium gray are plagioclase, and brightest are enstatite (low-calcium pyroxene) and augite (high-calcium pyroxene).

Oxygen **isotopic** composition is an important fingerprint of parent body origin. Most rock suites vary in oxygen isotope abundances. For example, Earth rocks plot along a line (TFL in the oxygen isotope plot below), which is distinct from the linear array of Martian meteorites, the separate array for rocks from Vesta, and different **chondrite** groups. An exception is that the Moon lies on the terrestrial line, suggesting a close cosmochemical kinship. Anhydrous primitive components such as **chondrules** and **CAIs** lie along a separate line called the Carbonaceous Chondrite Anhydrous Minerals (CCAM) line. The Graves Nunatak silicic samples (GRA 06128/9) lie close to the terrestrial fractionation line, along with other **achondrite** groups. However, NWA 11119, the silicic Almahata Sitta rock fragment (ALM-A), and the **ureilites** lie along the CCAM line.

Ureilites comprise a complicated suite of related meteorites. Many are rich in **olivine** and low-calcium pyroxene and resemble rocks from which a basaltic component has been removed by partial melting. The rocks also contain a carbon-rich matrix, and shock (by an impact) has converted graphite to diamonds typically smaller than a micrometer. Ureilites vary in Fe/Mg in olivine and in the ratio of olivine to pyroxene, and some contain distinctive basaltic rock clasts, indicating extensive impact mixing. This complexity is also shown by the Almahata Sitta meteorites and the little asteroid that deposited them. The meteorite is dominated by ureilites, but also contains ALM-A, which plots in the ureilite array along the CCAM line in the oxygen isotope plot shown below. Basaltic meteorite NWA 7325 (the only point in the basalt field on the TAS diagram above), also plots on the CCAM line, as do the NWA 11119 samples, suggesting that all these meteorites might come from the same parent body that exhibited extensive igneous activity to produce basaltic magma (NWA 7325, and others), more evolved magma (NWA 11119), and an assortment of partial melt residues.



(Srinivasan *et al.*, 2018, *Nature Communications*, v. 9:3036, doi: 10.1038/s41467-018-05501-0.)

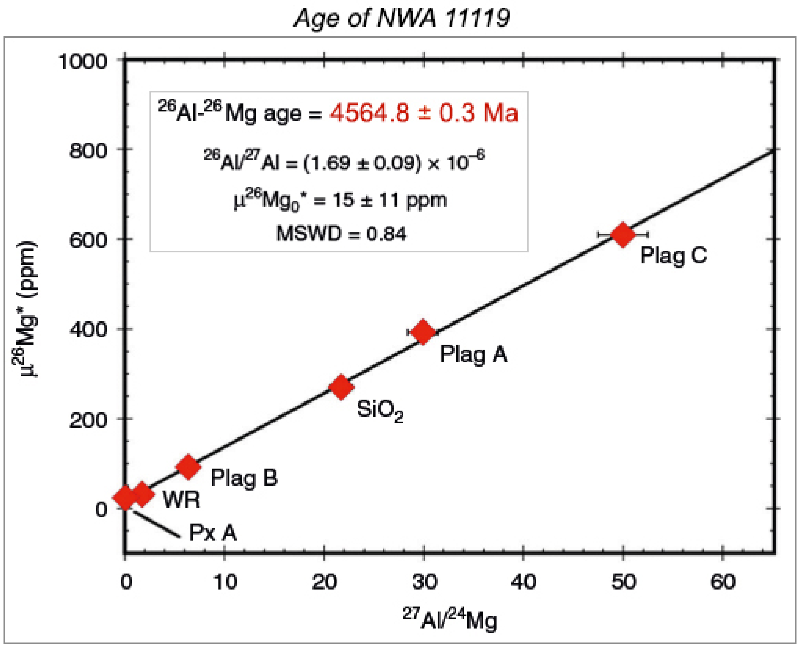
Oxygen isotope plot for evolved igneous rocks in meteorites (except for NWA 7325, which is a basalt), ureilites, ALM-A (from Almahata Sitta), and three other types of meteorites whose parent bodies experienced enough heating to melt at least partially. TFL is the terrestrial fractionation line where samples from Earth plot. The dashed line labeled CCAM shows where anhydrous components in carbonaceous chondrites plot. The clear correspondence of NWA 11119, ALM-A, NWA 7325, and ureilites suggests that they might all be from the same parent asteroid. For a brief primer on the oxygen isotope plot see PSRD article: Oxygen Isotope Plot.

An Amazingly Old Silicic Rock

NWA 11119 and the other rocks that may be related to it formed by some combination of partial melting and fractional crystallization, probably on an asteroid-sized body (say 100–300 kilometers in diameter). Unknowns are the precise chemical and mineralogical composition of the body, the oxidation state, whether any H_2O was present, and whether the melting was at equilibrium or not. Seems like a lot of variables to pin down. Potential solutions are explained by Srinivasan and colleagues. An introduction to the arguments can be found in see **PSRD** article: **More Evidence for Multiple Meteorite Magmas**.

It takes lot of rock processing to produce an evolved rock like NWA 11119. The time includes how long it took to accrete the parent body and then heat it up by the decay of short-lived isotopes. How long did it take? The lunar felsites have ages from about 3.8 to 4.35 billion years. Hence the oldest of them formed 217 million years after CAIs. That is a lackadaisical pace compared to NWA 11119.

To find out how long it took to make the silicic rocks in NWA 11119, coauthor and ASU PhD candidate Daniel Dunlap separated minerals from the rock to measure the compositions of aluminum and magnesium. When our Solar System formed, the short-lived isotope ^{26}Al was still alive. This allows precise isotopic dating of events in the early Solar System because its **half-life** is only 730,000 years. The data all plot on a precise line (**isochron**) in the diagram below, which determines the amount of decayed ^{26}Al by the excess in the ^{26}Mg (the decay product of ^{26}Al) compared to ^{27}Mg. By assuming the initial amount of **radioactive** ^{26}Al is the same as in CAIs, the slope of the line gives the age, which is 4564.8 ± 0.3 million years. This is only 2.4 million years younger than the oldest CAI (4567.2 million years). Taking some uncertainties into account, Srinivasan and coauthors conclude that the evolved **lithology** represented by NWA 11119 formed only 2.5–3.5 million years after CAIs.



(Srinivasan *et al.*, 2018, *Nature Communications*, v. 9:3036, doi: 10.1038/s41467-018-05501-0.)

This diagram shows the variation in the amount of aluminum versus magnesium (the x-axis, which plots two non-radioactive isotopes) versus the amount of excess magnesium-26 compared to magnesium-24 for whole rock (labeled WR) and mineral separates (labeled by mineral) of NWA 11119. (The μ notation means that the y-axis is in parts per million and that it represents the excess ^{26}Mg divided by the amount of ^{24}Mg). The excess ^{26}Mg derives from the decay of ^{26}Al, which has a half-life of only 730,000 years. The slope gives the age by assuming an initial ^{26}Al/^{27}Al ratio (derived from Calcium-Aluminum-Inclusions, CAIs, the first solids to form in the Solar System). The age is 4564.8 ± 0.3 million years. For comparison, the oldest CAIs have an age of 4567.2 million years, only about 2.2 million years older than the volcanic rock in NWA 11119.

So, in 2.5 to 3.5 million years, the parent body of NWA 11119 accreted, probably with a roughly chondritic composition, and began to melt. Heating was driven by the decay of ^{26}Al (which left behind a record of its decay, allowing the time to be determined). This led to different amounts of heating in different places, and probably different amounts of melt migration throughout the body. The importance of NWA 11119 is that some of the rapid early melting produced an evolved igneous rock whose manufacture did not require the existence of carousing tectonic plates on a big planet.

Additional Resources

Links open in a new window.

- **PSRDpresents:** The Oldest Volcanic Meteorite: A Silica-Rich Lava on a Geologically Complex Planetesimal -- **Short Slide Summary** (with accompanying notes).

- Srinivasan, P., Dunlap, D. R., Agee, C. B., Wadhwa, M., Coleff, D., Ziegler, K., Zeigler, R., and McCubbin, F. M. (2018) Silica-rich Volcanism in the Early Solar System Dated at 4.565 Ga. *Nature Communications,* v. 9, doi: 10.1038/s41467-018-05501-0. [**article**]
- Taylor, G. J. (June, 2009) The Complicated Geologic History of Asteroid 4 Vesta. *Planetary Science Research Discoveries.* **www.psrd.hawaii.edu/June09/Vesta.granite-like.html**.
- Taylor, G. J. (Feb, 2009) More Evidence for Multiple Meteorite Magmas. *Planetary Science Research Discoveries.* **www.psrd.hawaii.edu/Feb09/asteroidalMagmas.html**.
- Taylor, S. R. and McLennan, S. M. (2009) *Planetary Crusts: Their Composition, Origin, and Evolution.* Cambridge University Press, New York, 378 pp. [**book**]
- Warren, P. H., Taylor, G. J, Keil, K., Shirley, D. N., and Wasson, J. T. (1983) Petrology and Chemistry of Two "Large" Granite Clasts from the Moon. *Earth and Planetary Science Letters,* v. 64, p. 175-185, doi: 10.1016/0012-821X(83)90202-9. [**article**]