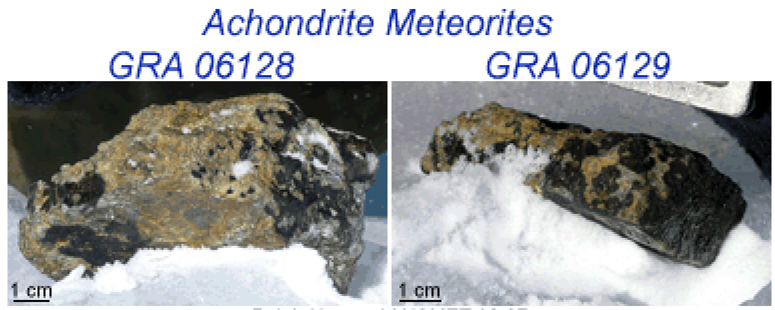
Hot Idea February 19, 2009

More Evidence for Multiple Meteorite Magmas



Ralph Harvey / ANSMET 06-07

--- Cosmochemists show that a pair of meteorites formed in an asteroid that erupted a newly-recognized type of asteroidal magma.

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Cosmochemists have identified six main compositional types of magma that formed inside asteroids during the first 100 million years of Solar System history. These magmas vary in their chemical and mineralogical make up, but all have in common low concentrations of sodium and other volatile elements. Our low-sodium-magma diet has now changed. Two groups of researchers have identified a new type of asteroidal magma that is rich in sodium and appears to have formed by partial melting of previously unmelted, volatile-rich chondritic rock. The teams, one led by James Day (University of Maryland) and the other by Chip Shearer (University of New Mexico), studied two meteorites found in Antarctica, named Graves Nunatak 06128 and 06129, using a battery of cosmochemical techniques. These studies show that an even wider variety of magmas was produced inside asteroids than we had thought, shedding light on the melting histories and formation of asteroids.

References:

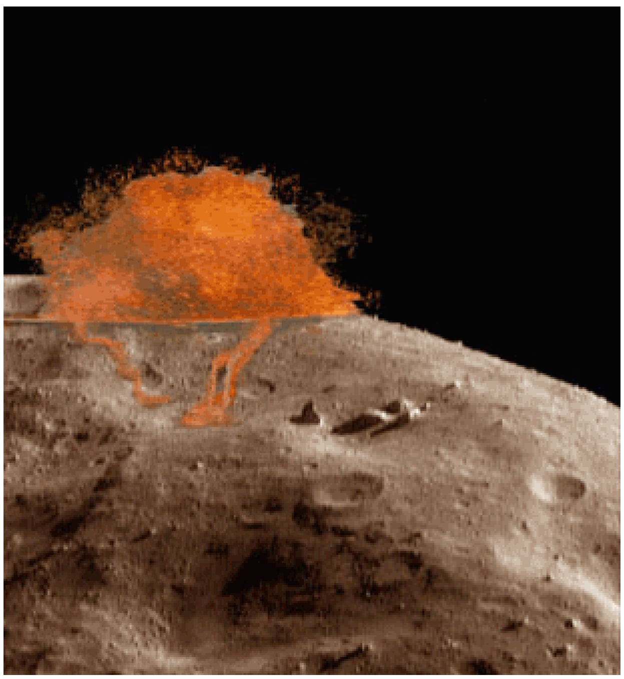
- Shearer, C. K., Burger, P. V., Neal, C. R., Sharp, Z., Borg, L.E., Spivak-Birndorf, L., Wadhwa, M., Papike, J. J., Karner, J. M., Gaffney, A. M., Shafer, J., Weiss, B. P. Geissman, J., and Fernandes, V. A. (2008) A Unique Glimpse into Asteroidal Melting Processes in the Early Solar System from the Graves Nunatak 06128/06129 Achondrites. *American Mineralogist*, v. 93, p. 1937-1940.
- Day, J. M. D., Ash, R. D., Liu, Y., Bellucci, J. J., Rumble, D., McDonough, W. F., Walker, R. J., and Taylor, L. A. (2009) Early Formation of Evolved Asteroidal Crust. *Nature*, v. 457, p. 179-182. doi:10.1038/nature07651.

PSRDpresents: More Evidence for Multiple Meteorite Magmas --Short Slide Summary (with accompanying notes).

Asteroidal Lava Flows

Lava flows are glowing works of performance art, both scary and mesmerizing. Cosmochemists are impressed by the show, but also by what lava flows represent geologically. Volcanic eruptions are an important part of how planetary crusts form, and lava flow compositions tell us about not only the composition of a planet's crust, but about the composition of its interior as well. Lava flows, even those that crystallized billions of years ago, are packed with information that can be unraveled by cosmochemical detective work.

Lavas erupted on all the rocky planets and on Io, a moon of Jupiter about the size of Earth's Moon. They also erupted on asteroids. See the artist's depiction below. Cosmochemists have previously identified samples of at least five of these (see **PSRD** article: Asteroidal Lava Flows), plus other meteorites that give us information about the effects of melting inside asteroids. We now have a distinctly different, sixth type of lava in the form of the Graves Nunatak (GRA) meteorites.



Lava flows on an asteroid could have constructed its crust. They might have erupted as broad, high fountains of lava, but also might have stalled beneath the surface and solidified underground.

(PSRD graphic)

The five lava types identified previously tell stories of melting inside their parent asteroids, eruptions as lava flows and magma intrusion beneath the surface, assault by impacts, and metamorphism from heat inside the asteroids or from impact--complicated stories. An interesting part of the stories is that each type's history is different. One type (called the angrites) was not metamorphosed or affected by impact bombardment. Another, the mesosiderites, are fragmented basalt lava flows mixed with metallic iron-nickel that then slowly cooled. The one thing they have in common is low concentrations of volatile elements like sodium and potassium. The GRA 06128/9 meteorite pair is loaded with such moderately volatile elements. It is a new type of asteroidal crust.

The ANSMET meteorite hunting team found GRA 06128 on blue ice in the Graves Nunatak region of Antarctica during the 2006/2007 field-season. This photograph was taken at the time of collection. The team gives each meteorite a unique field number (shown on the number counter) that is logged in the field notebook along with the rock's size and estimate of fusion crust (black surfaces) and preliminary classification. The meteorite's permanent name, GRA 06128, refers to its collection location (GRA), season (06) and laboratory analysis number (128).

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GRA 06128 and its pair, GRA 06129, are achondrite meteorites with compositions unlike any previously discovered Solar System materials. Image courtesy of Ralph Harvey (Case Western Reserve University), the Principal Investigator of the highly successful Antarctic Search for Meteorites (ANSMET) program. See **PSRD** articles: Searching Antarctic Ice for Meteorites and Meteorites on Ice for descriptions of the field work and some of the meteorite discoveries

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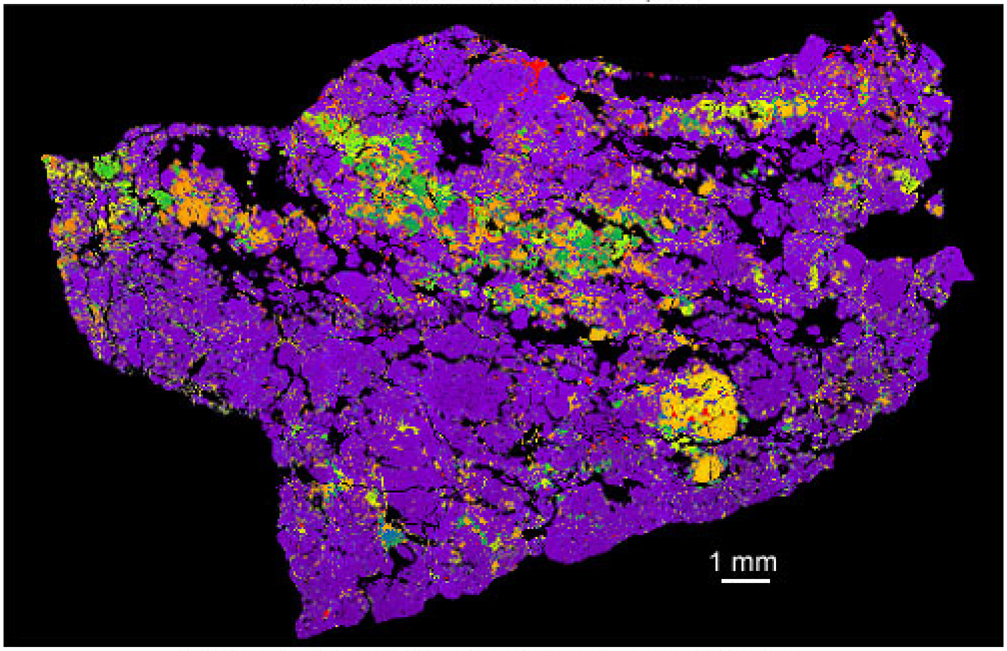
A New Meteorite Magma Type

The two GRA samples are paired, by which meteoriticists mean they were part of the same original meteoroid that blazed through Earth's atmosphere. The original fragment broke apart and the fragments fell to Earth. They usually fall in a relatively small area called a strewn field, so finding two samples from the same original asteroid chunk is not unexpected. Of course, cosmochemists pair them because the samples have so many properties in common. The small differences reflect heterogeneities in the rock, also not unexpected.

The first distinctive characteristic is that the GRA samples consist of more than 75% sodium-rich plagioclase feldspar. Plagioclase ranges in composition from a sodium-rich end member (albite, $NaAlSi_3O_8$) to a calcium-rich one (anorthite, $CaAl_2Si_2O_8$). The composition can be anything between these two extremes, which mineralogists express as the mole percentage of albite and anorthite. Plagioclase in GRA 06128/9 contains 85 mole percent albite and only 15 mole percent anorthite. In contrast, plagioclase in all the other asteroidal lavas described so far contains less than 25 mole percent albite, with most less than 15 mole percent. This must reflect a drastic difference in the composition of the interior of the GRA-type's parent asteroid compared to the others.

Meteorite GRA 06129,23



(From Shearer *et al.*, 2008, *American Mineralogist*, v. 93, p. 1937-1940.)

This is a false-color back-scattered electron image showing the abundance and distribution of plagioclase (purple), pyroxene (green), olivine (orange-yellow), phosphate minerals (blue-green), and in red, iron oxides (mostly terrestrial weathering products), iron sulfides, and metals.

The minerals in the GRA 06128/9 are uniform in composition. Their sizes and the way their grain boundaries are rounded is indicative of either slow cooling or, more likely, thermal metamorphism. It appears that they were heated after they formed, causing the minerals to even out their compositions (cosmochemists call this equilibration), and to change the mineral shapes from their original igneous shapes.

Meteorite GRA 06129 in cross-polarized light

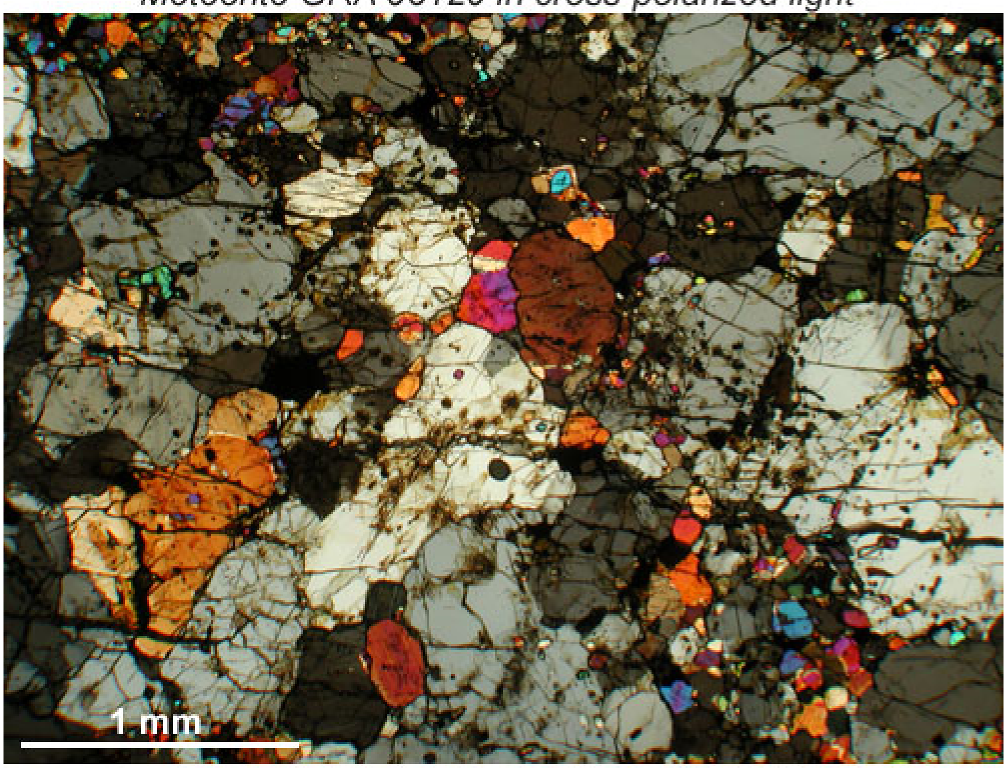
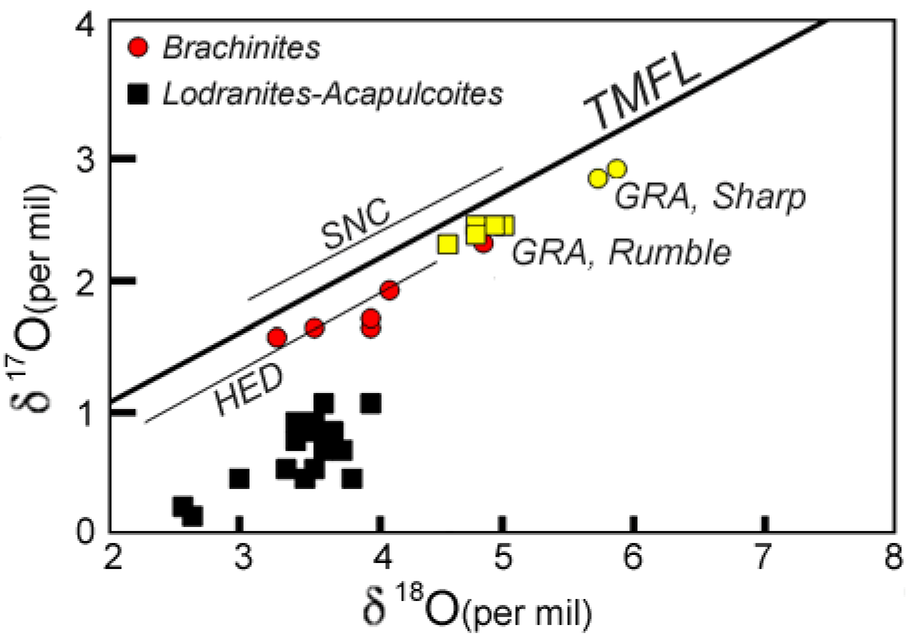


Image courtesy of Yang Liu (University of Tennessee).

Photomicrograph of a polished thin section of GRA 06129 in cross-polarized light. Both GRA 06129 and its pair, GRA 06128, have granoblastic textures and are composed predominantly of sodium-rich plagioclase (85 mole percent of the albite end member). White and grey grains are plagioclase. Other grains are olivine and pyroxene.

An important measurement made by both groups of investigators is the relative abundances of oxygen isotopes in the two GRA samples. Oxygen isotopes can often be used as a fingerprint to prove that samples of planetary materials come from the same body. Cosmochemists measure all three oxygen isotopes (^{16}O, ^{17}O, and ^{18}O; ^{16}O is most abundant). Plotting the ratio of ^{17}O to ^{16}O versus ^{18}O to ^{16}O shows that the data for both Earth and Moon fall on the same line (called the Terrestrial Mass Fractionation Line or TMFL). The line slopes in the way expected for chemical processing (crystallization, melting, alteration by water, and other processes). Data for meteorites, however, fall on other lines, indicating differences in the abundance of ^{16}O. Cosmochemists interpret this as evidence that oxygen isotopes were not distributed uniformly throughout the Solar System. Martian meteorites (SNC on the diagram below) are distinctly different from lunar and terrestrial samples, containing less ^{16}O than the Earth-Moon system. Other igneous meteorites contain more ^{16}O than do Earth and the Moon. The GRA samples plot along a line with a group of meteorites called brachinites, which are olivine-rich igneous rocks generally thought by cosmochemists to be residues left over after partial melting inside an asteroid.

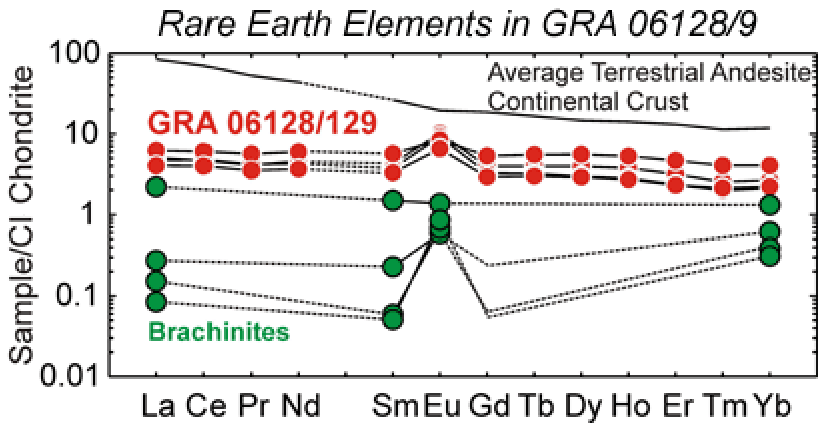


(From Shearer *et al.*, 2008, *American Mineralogist*, v. 93, p. 1937-1940.)

Oxygen isotopic composition of GRA samples (yellow symbols) measured in two different laboratories (Zachary Sharp at the University of New Mexico and Douglas Rumble at the Carnegie Institution of Washington). The points for the GRA samples fall close to the same line, indicating a common heritage. They appear to be related to a group of meteorites called the brachinites, but are distinctly different from other igneous meteorite groups, including Martian meteorites ("SNC"). The line labeled "HED" shows where typical eucrites and related rocks plot. TMFL is the Terrestrial Mass Fractionation Line on which data for Earth and Moon plot.

Processing an Asteroid

The connection between the GRA samples and the brachinite meteorites is intriguing. It shows up in their concentrations of rare earth elements (REE) as well. The diagram below shows the concentration of each rare earth element, with the concentrations divided by the concentrations in CI carbonaceous chondrites. (This normalization gets rid of the inherently zig-zaggy pattern shown by the rare earth elements because the abundances of elements with even atomic numbers are larger than elements with odd atomic numbers.) In general, the GRA samples have higher concentrations of REE than do the brachinites. This suggests a complementary relationship in which an asteroid heated up by decay of short-lived isotopes such as aluminum-26 (^{26}Al), and began to melt, forming a sodium-rich basaltic lava (the GRA 06128/9 samples) and leaving behind an olivine-rich residue to later become the brachinites. Alternatively, brachinites might have formed from the GRA magma by accumulation of olivine. More work needs to be done to figure out the details of brachinite formation.

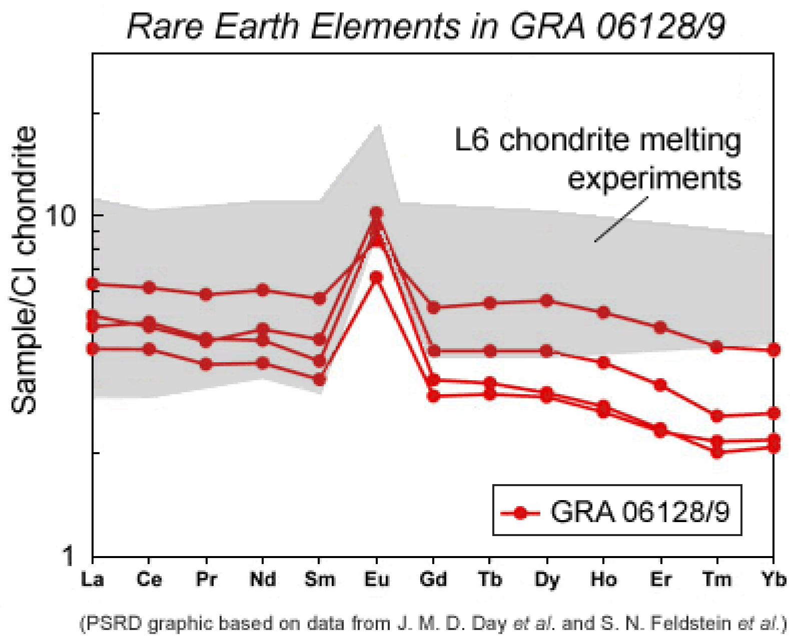


(From Day *et al.* (2009) *Nature*, v. 457, p. 179-182.)

Rare earth element abundances (normalized to CI carbonaceous chondrites) for GRA 06128/9 are higher than those in brachinites, hinting that brachinites could be complementary solid residues formed by removal of the GRA 06128/9 magma. Shown for comparison is average terrestrial continental andesite, which has major element concentrations somewhat like those of GRA 06128/9.

What was the starting material like? Two lines of evidence suggest it was a previously unmelted chondritic rock of some sort. One piece of the puzzle comes from melting experiments done by Rhian Jones, Chip Shearer's colleague at the University of New Mexico, and reported in a paper by Sharon Feldstein, Rhian Jones, and James Papike. They heated samples of an L6 chondrite to various temperatures and times (1 hour to 21 days), quenched the hot samples, and studied the distribution and composition of glass in the samples. The glass represents portions of the rock that were molten during the experiment, which averaged about 13 weight percent of partial melting. Feldstein measured the concentrations of major and trace elements in the glassy areas using electron microprobe and ion microprobe analysis.

The Feldstein experiments show that partially melting the L6 chondrite produces a sodium-rich melt with rare earth element concentrations in the range of concentrations measured for the GRA samples. A difficulty in the experiments was the loss of sodium and other volatiles during the experiments. Nevertheless, sodium loss was small for the short, one-hour experiments, showing that the melts were initially high in the molten material. (We recently discussed the importance of sodium loss, or lack of it, during chondrule formation in the **PSRD** article: Tiny Molten Droplets, Dusty Clouds, and Planet Formation.) The important point is that partial melting of an ordinary chondrite produces magma not unlike the magma represented by the GRA 06128/9 samples. The brachinites might represent the left over, unmelted rock.



This plot shows rare earth element abundances (normalized to CI carbonaceous chondrites) in the GRA 06128/9 samples measured by James Day and coworkers. The shaded area shows rare earth element abundances in experimental partial melts of an ordinary chondrite from Feldstein, Jones, and Papike.

The other clue to the composition of the GRA asteroid derives from the abundances of highly-siderophile elements. Siderophile means "iron loving," or, less romantically, elements that concentrate in metallic iron if it is present. Many siderophile elements will also concentrate in iron sulfide if it is present. ("Highly siderophile element" means that an element is obsessed with metallic iron, and that metal ought to take out a restraining order on it.) The concentrations of highly siderphile elements in GRA 06128/9 are not uniform as in chondritic meteorites. They are fractionated, with palladium (Pd), Platinum (Pt), and Iridium (Ir) depleted by about 70% compared to Rhenium (Re), Osmium (Os), and Ruthenium (Ru). James Day and his coworkers suggest that the fractionation among highly siderophile elements was caused by separation of two different sulfide minerals during migration of the GRA 06128/9 magma inside its parent asteroid. Most important, the fractionation does not reflect a widespread equilibration as would happen during core formation. When the asteroid melted to produce the GRA 06128/9 magma, it had not melted previously and contained metallic iron and sulfide minerals distributed throughout its rocky portion. That is, it resembled an ordinary chondrite.

On top of all the igneous processing to produce the GRA 06128/9 magma, it must have formed a thick lava flow or pooled beneath the surface to accumulate extra plagioclase. It consists of about 75 volume percent plagioclase, larger than the amount expected from partial melting of an ordinary chondrite, about 50 volume percent. The rock cooled slowly enough for low-Ca pyroxene to form inside high-Ca pyroxene (a process called exsolution). T. Mikouchi and M. Miyamoto (University of Tokyo) estimate from the compositions of the two pyroxenes a cooling rate of 10 to 20 ^{o}C per year, implying a burial depth of 15-20 meters beneath the surface.

Many Meteorite Magmas

The GRA 06128/9 magma type is distinct from the others cosmochemists have identified. GRA 06128/9 has a high sodium concentration, reflected in its plagioclase having a high albite concentration (over 80 mole percent, see table below). All the other magma types have plagioclase low in albite, typically 15 mole percent or less.

Meteorite Group	Volcanic?	Albite in Plagioclase	Brecciated by Impacts?	Metamorphosed?
Eucrites	Yes	5-25	Almost All	Almost All
Eucrite-2 (NWA 011)	Yes	15	Yes	Yes
Angrites (except one)	Yes	0.3	No	No
Angra dos Reis	Yes	13	No	Yes
Mesosiderites	Yes	7-9	Yes	Yes
GRA-type Sodic Magmas	Possibly	82-85	Maybe	Yes

Is the GRA 06128/9 type magma as rare as it seems? Possibly not. Groups of igneous meteorites also contain solidified partial melts with high-sodium plagioclase. Prominent examples are the lodranites-acapulcoites, winonaites, and the silicate (rocky) parts of IAB iron meteorites. An example of a rocky inclusion in a IAB iron meteorite (from Caddo County, Oklahoma) is shown below. Gretchen Benedix (University of Hawai'i at the time, now at the Natural History Museum, London) and coworkers studied these interesting rocks in detail. The large plagioclase is rich in sodium, like those in GRA 06128/9, averaging about 84 mole percent albite. This magma probably crystallized underground, not as a lava flow, but nevertheless shows that internal melting of metal-bearing chondritic meteorites can yield sodium-rich magma.

Meteorite Caddo County in cross-polarized light

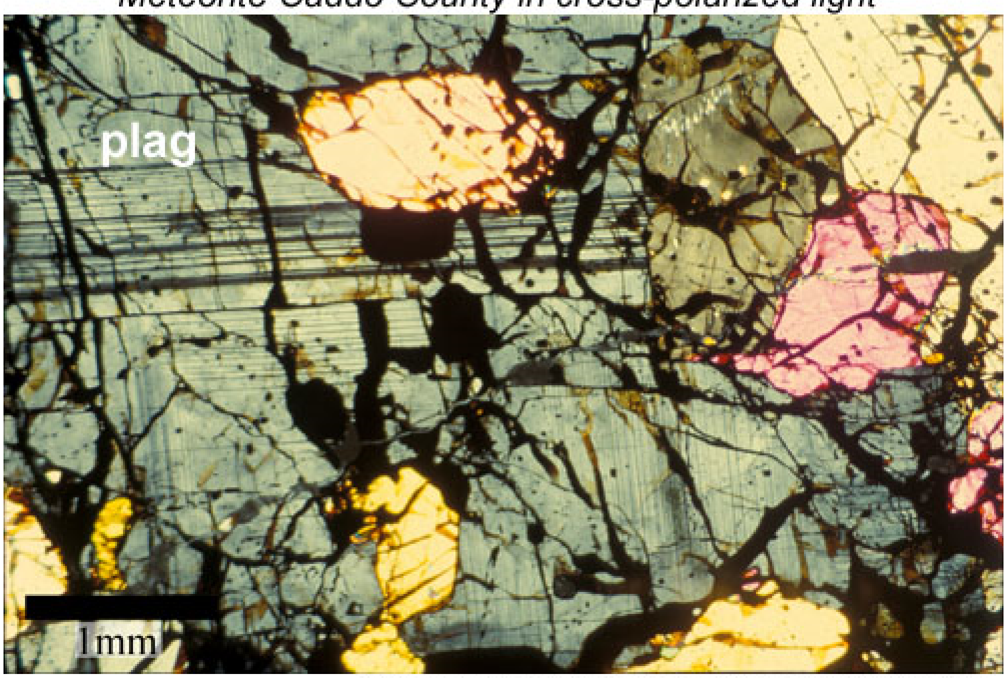


Image courtesy of Gretchen Benedix (Natural History Museum, London).

Photomicrograph of a polished thin section of Caddo County in cross-polarized light showing large sodic plagioclase grain (plag) enclosing and surrounded by olivine and pyroxene grains.

Cosmochemists have now identified at least six magma types in our meteorite collections. The magma types have different chemical compositions and impact and metamorphic histories, but the biggest difference is in sodium concentration. Most have small concentrations of sodium and other volatile elements. The GRA 06128/9 type has lots of it. Furthermore, it appears that the low-sodium types also melted substantially so that cores formed inside their parent asteroids. In contrast, the sodic GRA 06128/9 type formed by partial melting of an undifferentiated, previously unheated chondrite.

Why the difference? Timing might lead to big differences in asteroid composition and melting history. For example, asteroids that accreted early would contain more radioactive ^{26}Al, leading to substantial heating and core formation. Asteroids forming only a million years later would have much less ^{26}Al, thereby melting less. The temperature of the accreting material makes a big difference, too. The hotter the average temperature, the less volatiles an asteroid would contain. Thus, the GRA 06128/9 asteroid might have formed later and cooler than the asteroids giving rise to the other magma types.

Cosmochemists hope that further work on GRA 06128/9 and searching for additional magma types and new samples of the rarer ones will help us figure out the details of asteroid formation and melting. For now, we can just be amazed at the array of processes that produced magmas and lavas in our Solar System.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** More Evidence for Multiple Meteorite Magmas --Short Slide Summary (with accompanying notes).

- Benedix, G. K., McCoy, T. J., Keil, K., and Love, S. G. (2000) A Petrologic Study of IAB Iron Meteorites: Constraints on the Formation of the IAB-Winonaite Parent Body. *Meteoritics and Planetary Science*, v. 35, p. 1127-1141.
- Day, J. M. D., Ash, R. D., Liu, Y., Bellucci, J. J., Rumble, D., McDonough, W. F., Walker, R. J., and Taylor, L. A. (2009) Early Formation of Evolved Asteroidal Crust. *Nature*, v. 457, p. 179-182. doi:10.1038/nature07651.
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