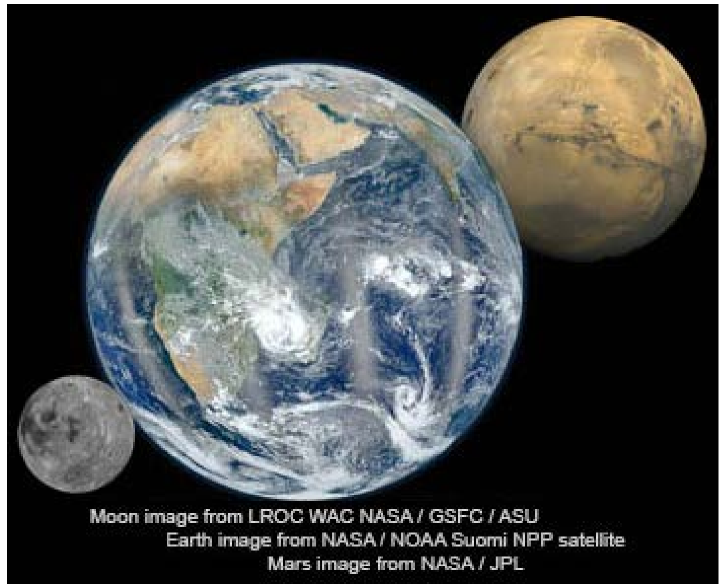
Headline Article

November 11, 2016

Searching for Ancient Solar System Materials on the Moon, Earth, and Mars



--- The early history of the Solar System is recorded by meteorites falling now, but also by those that fell hundreds of millions to billions of years ago, preserved in lunar samples, sedimentary layers on Earth, and even sitting on the surface of Mars.

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The Moon is a proven collector of rambling objects from throughout the Solar System, as summarized in a review article by Katherine Joy (University of Manchester, England) and colleagues at the University of London, the Lunar and Planetary Institute (Houston), NASA Johnson Space Center, and Western Ontario University. Their article summarizes the record of small bodies impacting the Moon. The lunar record includes chemical signatures in rocks formed by large impacts early in lunar history and rare, hard-to-find fragments of the impactors. Other studies have shown that layers of old sedimentary rocks on Earth also contain fragments of the types of meteorites falling to Earth today. Birger Schmitz (Lund University, Sweden) and coworkers at the University of Hawaiʻi, and the University of California, Davis have found a record of in-falling L-chondrites in limestone deposits formed during the Ordovician period (around 500 million years ago). Consistent with meteorite studies, these fossil meteorites indicate that the L-chondrite parent asteroid was demolished by the impact of a chemically different type of asteroid, which sent a plethora of objects into the inner Solar System to intersect Earth hundreds of millions of years ago. Surprisingly, this collection includes a new type of meteorite, suspected to be a piece of the impacting body that disrupted the L-chondrite parent asteroid 470 million years ago. Mars also collects meteorites, as summarized by James Ashley (Jet Propulsion Laboratory) who compiled a list of iron and stony-iron meteorites found by three different rovers on the Martian surface.

References:

- Ashley, J. W. (2015) The Study of Exogenic Rocks on Mars—An Evolving Subdiscipline in Meteoritics, *Elements,* v. 11, p. 10-11. [**abstract**]
- Joy, K. H., Crawford, I. A., Curran, N. M., Zolensky, M., Fagan, A.F., and Kring, D. A. (2016) The Moon: An Archive of Small Body Migration in the Solar System, *Earth Moon Planets,* v. 118, p. 133-158, doi: 10.1007/s11038-016-9495-0. [**abstract**]
- Schmitz, B., Yin, Q.-A., Sanborn, M. E., Tassinari, M., Caplan, C. E., and Huss, G. R. (2016) A New Type of Solar-System Material Recovered from Ordovician Marine Limestone, *Nature Communications,* v. 7, doi: 10.1038/ncomms11851. [**abstract**]

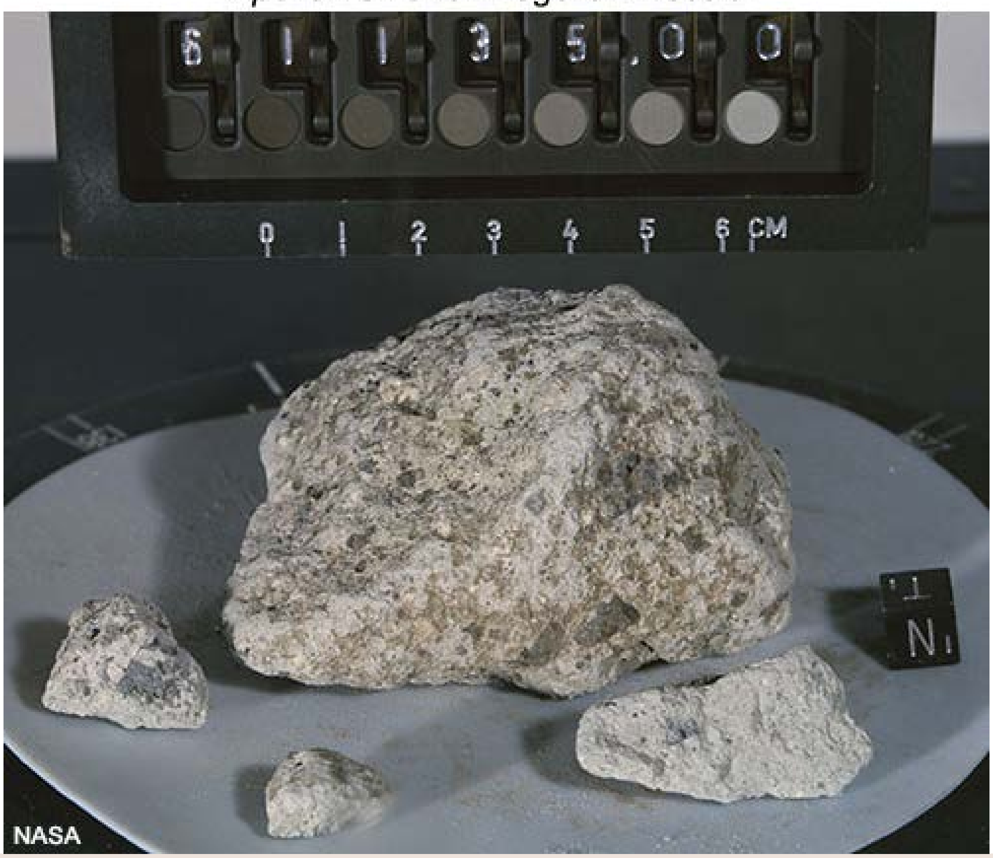
- **PSRDpresents:** Searching for Ancient Solar System Materials on the Moon, Earth, and Mars --**Short Slide Summary** (with accompanying notes).

The Lunar Warehouse of Solar System Artifacts

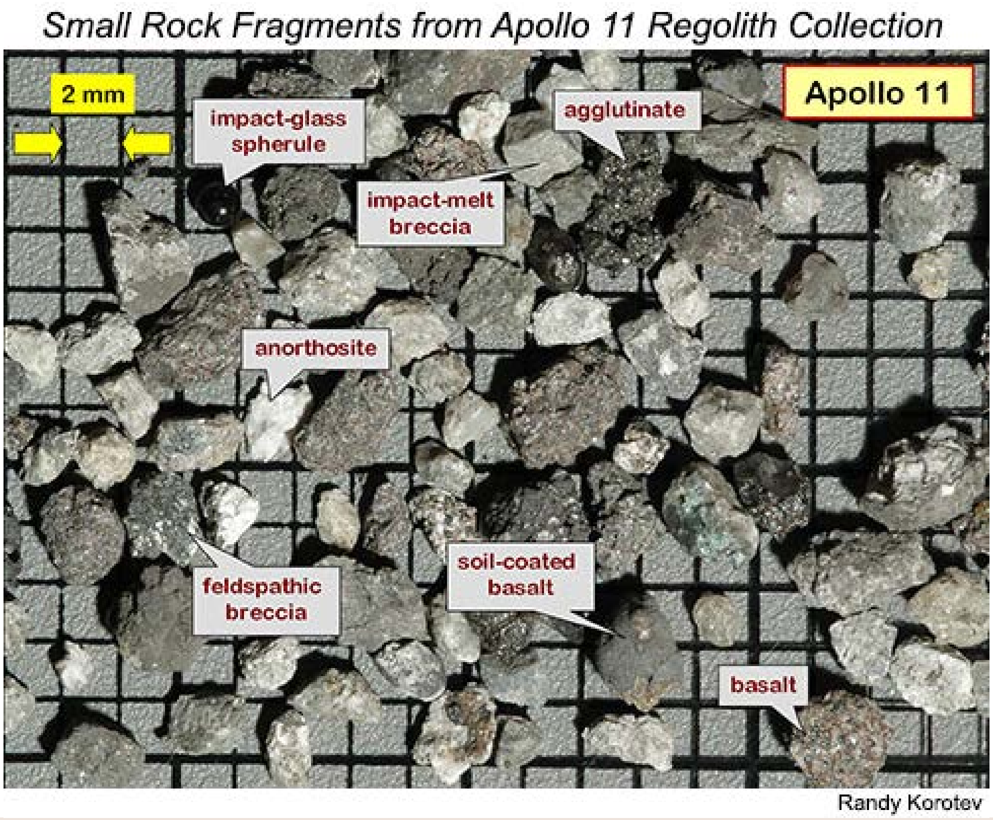
A prominent scientist used to call the Moon "a burnt out cinder." He meant it as an insult, but the fact that the Moon's internal engine substantially wound down by a couple of billion years ago is actually a virtue. In contrast to Earth and its frenzied geologic machine (plate tectonics, mountain building, volcanism, weathering and erosion, hurricanes and tornadoes), the Moon preserves a geologic record dating from over four billion years ago to now. Besides recording its own geologic evolution, the Moon is a collector of objects from throughout the Solar System, and it has been collecting them for billions of years. (Hint: Earth is not so bad at collecting Solar System artifacts after all, as explained in the next section.)

The downside is that the lunar artifact storage facility is more than a bit disorganized. The exo-lunar relics we wish to study do not land softly on the Moon. They smash into the lunar surface fast enough to make a crater and are mostly destroyed in the process. The surviving fragments are mixed with new and existing fragmental crater debris (creating **breccias**), so it takes careful study of samples to identify them hidden among fragmental indigenous lunar rocks. Some artifacts exist only as chemical components in lunar samples; these are interesting, but we'll focus on little pieces you can see in a microscope. The images below show the types of material Katie Joy and other investigators examined to find potential extra-lunar materials.

Apollo 16 Lunar Regolith Breccia

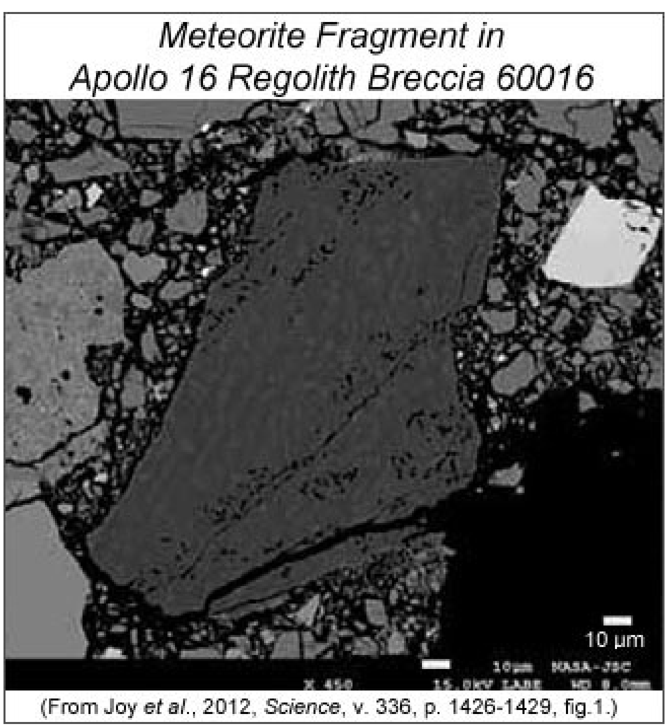


Lunar regolith breccia 61135 was collected at Plum Crater at the Apollo 16 landing site. This rock was consolidated from loose surface materials between 3.4–3.8 billion years ago (determined on the basis of the abundance of argon isotopes). In 2012, Katie Joy and coworkers reported finding ten fragments of chondritic rocks in 61135, and 20 samples in other Apollo 16 breccias; see PSRD article: Leftovers from Ancient Lunar Impactors.

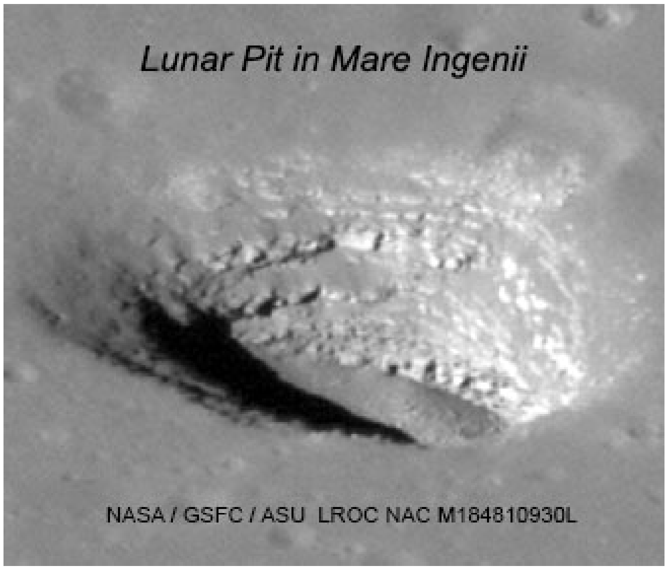


This photo shows Apollo 11 regolith sieved to the 2–4 mm size range. The diversity of colors, shapes, and textures shows the complexity of lunar regolith. No non-lunar rocks were found in this collection, but to know that for sure, every fragment had to be examined in detail, including chemical compositions. Gridlines are space 2 mm apart. Photo courtesy of Randy Korotev (Washington University in St. Louis).

So far, investigators have found fragments with compositions resembling carbonaceous and ordinary **chondrites**, enstatite chondrites, stony-iron **meteorites**, iron meteorites, and possibly differentiated meteorites. (The review by Katie Joy and colleagues has an informative table of discoveries so far.) The search of the Moon's archive of Solar System artifacts is still in its early stages. Joy and coworkers point out that future missions could target potential specific features of the lunar archive, such as **regolith** developed between lava flows. Because the lava flow ages could be determined, we would know when the regolith formed, hence the time of arrival of any extra-lunar materials found in it.



This backscattered electron image of a thin section of Apollo 16 sample 60016,83 shows one of the meteorite fragments identified by Joy and colleagues (in the center of the image) surrounded by regolith-breccia matrix. The grey patterns in the meteorite fragment are due to intergrowths of the minerals olivine and pyroxene.

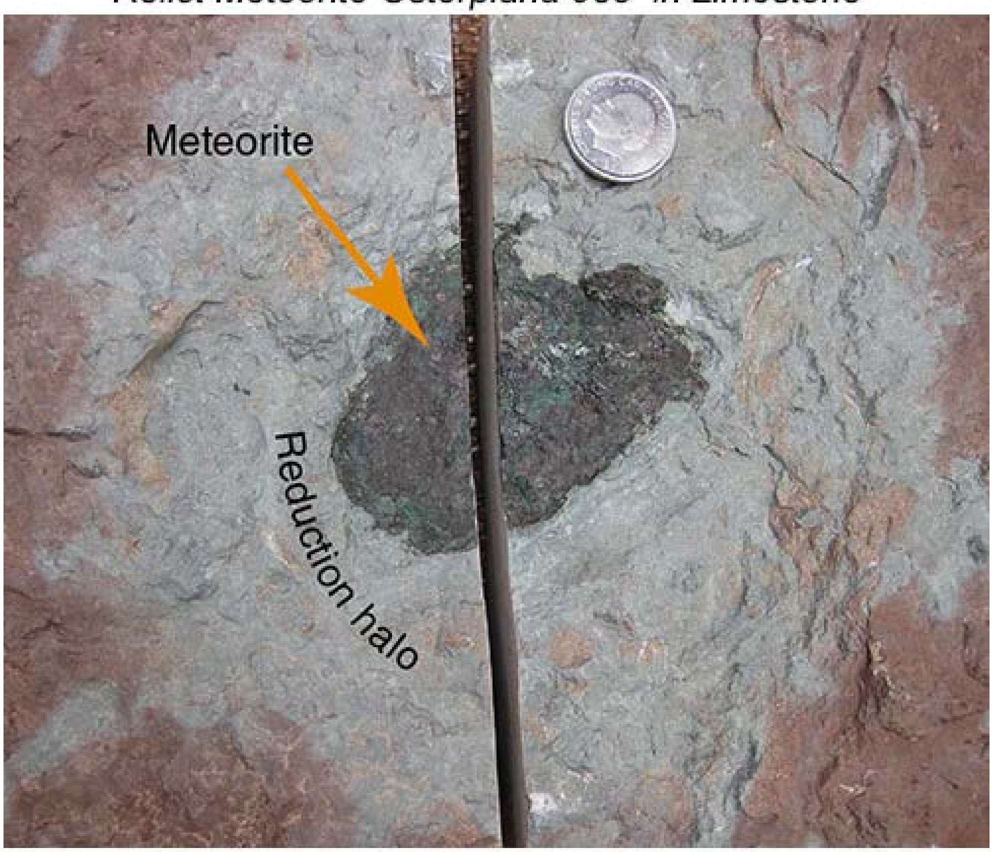


The Narrow Angle Camera on NASA's Lunar Reconnaissance Orbiter took this image of an oblique view into a pit in Mare Ingenii. The pit is about 130 meters across and about 45–65 meters deep. Note the layers of basalt lava flows revealed by the collapse. Regolith layers may exist between the flows, so determining the flow ages can bracket the age of the regolith. Thus, any non-lunar samples found in the regolith would have arrived at the Moon during a known time interval, thereby helping us understand the flux of different types of asteroids through time.

Ancient Meteorites in Sedimentary Rocks on Earth

One time, 470 million years ago, when Sweden was covered by a shallow sea with nautiloids swimming in it, and when Sweden was not even where it is today because nothing is stable on our active planet, meteorites occasionally splashed into the sea. It was a relatively serene environment, allowing finely-bedded limestone to form. However, during a period of about a million years, a bunch of meteorites fell into the soft carbonate sediment. (See **PSRD** article: **Tiny Traces of a Big Asteroid Breakup**.) The meteorites, though mostly altered by the surrounding sea water, contain a clear record of the type of meteorite falling. One of these fossilized meteorites, named Österplana 065 [**Data link** from the Meteoritical Database], is distinctly different from the others.

Relict Meteorite Österplana 065 in Limestone

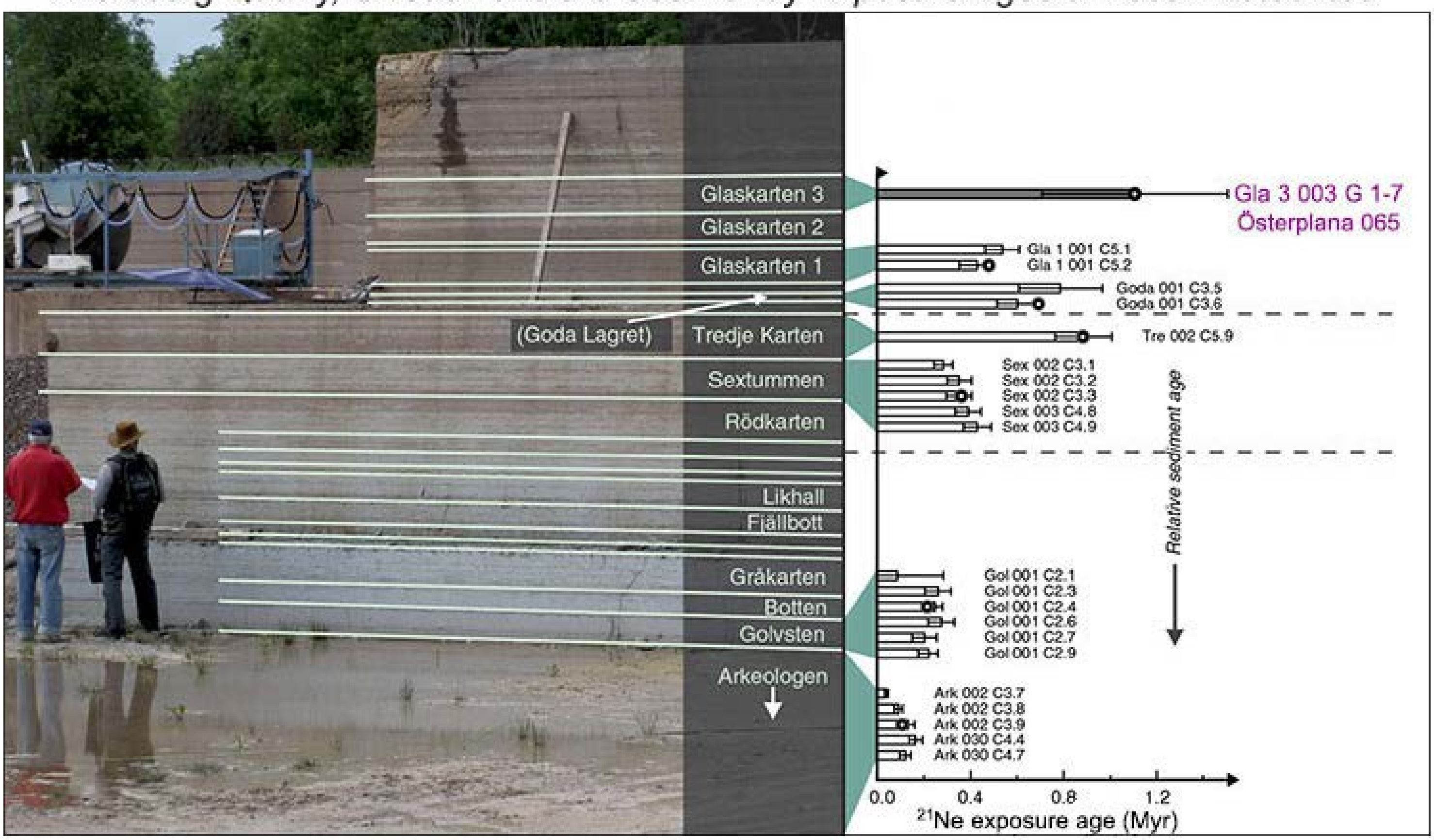


(From Schmitz *et al.*, 2016, *Nature Communications*, v. 7, doi: 10.1038/ncomms11851.)

Photograph of the Österplana 065 meteorite from the Thorsberg quarry in southern Sweden. The meteorite is surrounded by a gray zone caused by reduction of iron in the red limestone. The coin has a diameter of 2.5 cm. Although the meteorite was weathered on the Ordovician sea floor, slower-to-weather minerals such as chrome spinel survive and contain a unique chemical signature.

Österplana 065 was found in the Thorsberg quarry, along with more than 100 other fossil meteorites. The limestone-encased meteorites occur throughout a vertical face in the quarry. Surprisingly, the neon-21 (^{21}Ne) **cosmic-ray exposure ages** of the meteorites, a measure of the time the objects were in space as meter-sized or small objects, *increases* from the bottom of the section to the top, with Österplana 065 the top most sample. This age progression implies that the meteorites could all have been derived from the same event on an asteroid, with some drifting to Earth in a shorter time than others. (Cosmic-ray exposure ages are determined by measuring the abundance of a product of cosmic-ray nuclear reactions between cosmic rays (mostly protons) and rock. Interaction between magnesium, aluminum, silicon, and iron, for example, produces neon isotopes. It is all complicated, but well calibrated.)

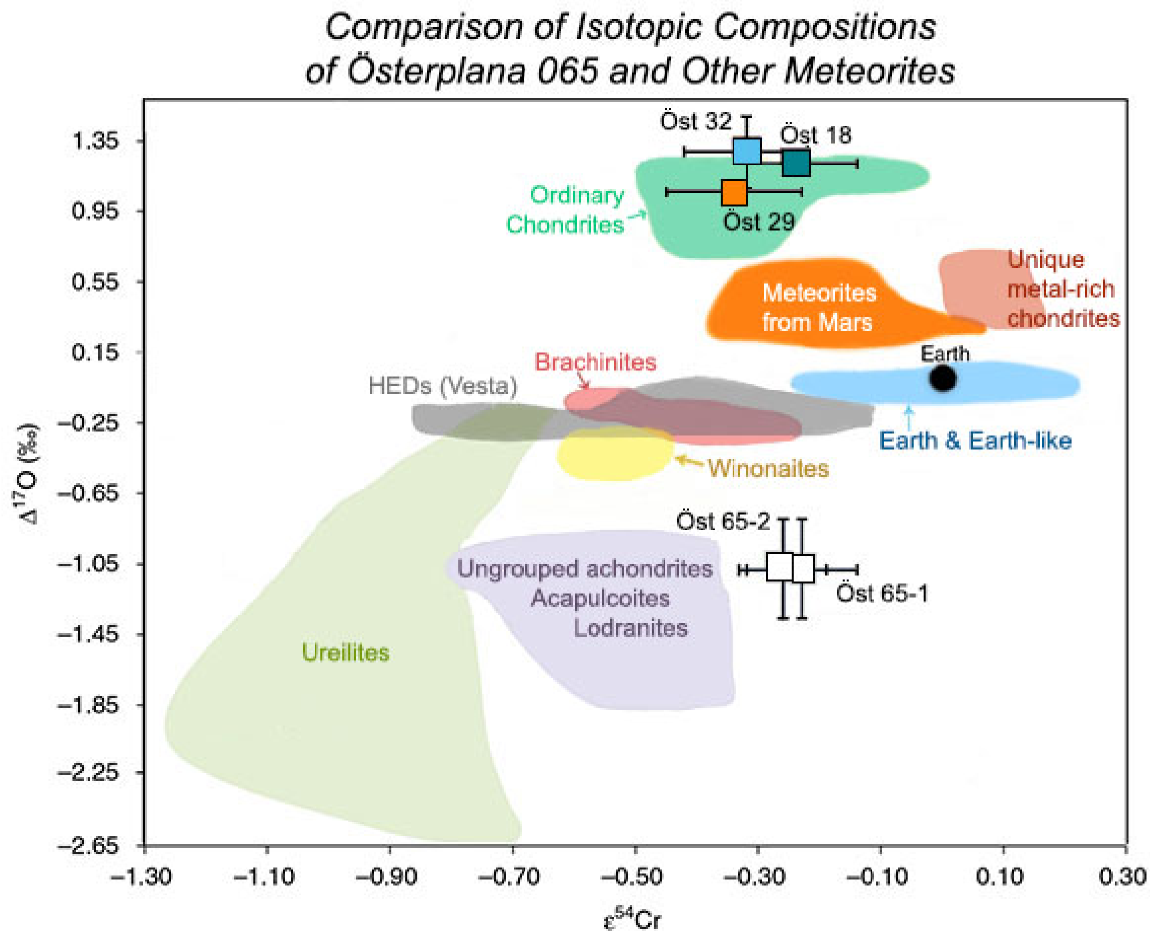
Thorsberg Quarry, Sweden and the Cosmic-ray Exposure Ages of Fossil Meteorites



(From Schmitz *et al.*, 2016, *Nature Communications*, v. 7, doi: 10.1038/ncomms11851.)

The photo on the left is of a quarried face in the Thorsberg quarry. It shows thin layers of limestone, with layers given names to help keep track of their relative positions. The layers formed during small changes in deposition conditions in the Ordovician sea. Lines are drawn at layer boundaries. The right side of the diagram shows where identified fossil meteorites came from, with bars ending at a neon-21 cosmic ray exposure age (scale at the bottom). Though not a perfect correlation, the space exposure time of the meteorites *increases upwards*, indicating a progressively longer trip from the asteroid belt to the Ordovician Earth. The enigmatic names are field names given to the samples. The uppermost sample labeled "Gla 3 003 G 1-7" has been given the official meteorite name Österplana 065. The age difference of the sediments from the upper beds where Österplana 065 was found to the bottom is about 1–2 million years.

Birger Schmitz and colleagues separated chromium-bearing spinel from the otherwise substantially altered meteorites. Spinel is a compositionally-complicated group of oxide minerals containing, besides oxygen, iron, magnesium, aluminum, titanium and chromium. Chrome spinels contain a lot of chromium, with one extreme case being the mineral chromite, $FeCr_2O_4$. Birger Schmitz and colleagues separated chrome spinels from the fossil meteorites by dissolving much of the rock, leaving behind the relatively insoluble chrome spinels and chromites. The compositions of these minerals vary among groups of known meteorites, but groupings are not as strong as we'd like. So, Schmitz and team measured the abundances of chromium and oxygen isotopes in an effort to pin down what type of meteorites most resemble those found in the limestone quarries of southern Sweden. The results on the diagram below show clearly that all but one of the meteorites plot near the field defined by ordinary chondrites, especially L-chondrites. The one exception is Österplana 065, two samples of which plot all by themselves in the lower right of the diagram.



(Adapted from Schmitz *et al.*, 2016, *Nature Communications*, v. 7, doi: 10.1038/ncomms11851.)

Oxygen isotopic composition (in delta notation) plotted against chromium isotopic composition (in epsilon notation, which is fundamentally $^{54}Cr/^{52}Cr$ normalized to this ratio in terrestrial rocks). Note the wide ranges in Solar System materials. Three Öst meteorites plot among the ordinary chondrites, specifically L-chondrites at the top of the graph. Österplana 065 (2 white squares) plots by itself to the right of the achondrite field.

Österplana 065 has a unique combined chromium and oxygen isotopic composition. Schmitz and colleagues show that element concentrations in the chrome spinels are also different from known meteorite types, as are some textural features of the chrome-spinel grains. In short, the grains in Österplana 065 are distinctly different from the L-chondrites found beneath it in the quarry. This is important because most of the samples we have of the L-chondrite parent body were shock-heated by a collision, a big event that reset the potassium-argon ages of many of the meteorites. One of the mysteries of this group of shock-damaged rocks from L-chondrite parent asteroid is that no pieces of the body that impacted it have been found—until now. Birger Schmitz argues that this unique meteorite is a piece of the impactor, which was completely destroyed by the event. It appears that Earth does not receive pieces from it now, but it did during the Ordovician period, as revealed by fossil meteorites in a quarry. How many other unique meteorites recording other dynamic events in Solar System history are resting quietly in ancient sediments on Earth?

Meteorites on Mars

Spirit, Opportunity, and Curiosity rovers and their high-tech instruments have shed considerable light on the geological history of Mars. This is not too surprising as that was what they are supposed to do. But finding meteorites on Mars? Now there's a bonus. James Ashley summarizes all the meteorites discovered on Mars by the rovers so far, and provides a useful list of references. All are iron or stony-iron meteorites. An interesting scientific use of the meteorites found on Mars is that metallic iron oxidizes easily, providing a way to monitor the planet's past climate. Such studies are still young, but the concept that nature has dropped climate monitors on Mars is fascinating. Even more intriguing is the possibility that future exploration on Mars might reveal chunks of asteroids in ancient sediments, like those found in Sweden. This might have to wait for people to start living on Mars and exploring its sedimentary treasures.

This image from the Mast Camera on NASA's Mars Science Laboratory Curiosity rover taken on October 30, 2016 shows an iron-nickel meteorite (about the size of a golf ball) in the center of this scene of the Martian surface. Curiosity's ChemCam laser instrument confirmed the composition of the meteorite (and left behind the visible grid of shiny bright spots on the rock). Click the image for more information from the Jet Propulsion Laboratory. The first meteorite of any type ever identified on another planet was also an iron-nickel (about the size of a basketball) found on Mars in January 2005 by NASA's Mars Exploration Rover Opportunity.

Researchers have found pieces of asteroids that struck the Moon and Earth long ago, providing important information about the flux of objects from the asteroid belt, and perhaps beyond. Not yet recognized is the possibility of finding on the Moon pieces of the ancient Earth that were blasted off by large impacts on our planet, perhaps dating to the time when life was just getting started. Looking at rocks is like traveling in time!

Additional Resources

Links open in a new window.

- **PSRDpresents:** Searching for Ancient Solar System Materials on the Moon, Earth, and Mars --**Short Slide Summary** (with accompanying notes).

- Ashley, J. W. (2015) The Study of Exogenic Rocks on Mars—An Evolving Subdiscipline in Meteoritics, *Elements*,v. , p. 10-11. [**abstract**]

- Joy, K. H., Crawford, I. A., Curran, N. M., Zolensky, M., Fagan, A.F., and Kring, D. A. (2016) The Moon: An Archive of Small Body Migration in the Solar System, *Earth Moon Planets,* v. 118, p. 133-158, doi: 10.1007/s11038-016-9495-0. [**abstract**]

- Martel, L. M. V. (March 2004) Tiny Traces of a Big Asteroid Breakup, *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Mar04/fossilMeteorites.html**.

- Martel, L. M. V. and Taylor, G. J. (June 2012) Leftovers from Ancient Lunar Impactors, *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/June12/Moon-chondritic-impactors.html**.
- Schmitz, B., Yin, Q.-A., Sanborn, M. E., Tassinari, M., Caplan, C. E., and Huss, G. R. (2016) A New Type of Solar-System Material Recovered from Ordovician Marine Limestone, *Nature Communications*, v. 7, doi: 10.1038/ncomms11851. [**abstract**]

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