

Now in its 19th year

METEORITE

MARCH 2013
VOLUME 19, No.1

Vesta and The Search for a Meteorite Parent Body

A New Dawn SEE PAGE 5

Vesta's Children

SEE PAGES 12 and 17

**A Parent Through the
Eyes of its Children**

SEE PAGE 22 and 28

**Siblings? Eucrites and
mesosiderites** SEE PAGE 33

*The Chelyabinsk
Fireball*
SEE PAGE 37

THE INTERNATIONAL QUARTERLY OF METEORITES AND METEORITE SCIENCE



An ancient magnetic field on asteroid Vesta

Roger R. Fu and
Benjamin P. Weiss

Figure 1: Backscattered scanning electron microscopy map of the ALHA81001 enclite. Dark gray lineations are plagioclase crystals, while the wider light gray lathes are pyroxene crystals. Very fine, zebra stripe striations of darker gray within the pyroxenes represent exsolution textures and indicate slow cooling at low temperatures. This image is 0.35 mm across.

In the space of less than just 10 million years, a tiny fraction of the 4.5 billion year age of the sun, the inner solar system evolved from a disk of gas mixed with micrometer-sized dust particles to a cosmic raceway of many Moon-sized and larger protoplanets. One of these protoplanets, Mars, is still with us today. And the protoplanet that would eventually grow into the Earth was taking recognizable shape. Understanding the processes that led to this rapid formation of planetary bodies is one of the most active areas in planetary science, with many fundamental questions remaining open. One conclusion that seems virtually certain is that Moon and Mars-sized protoplanets did not coagulate out of small particles directly. Rather, between these two stages of planet formation, there existed a generation of 100 to 1000 km diameter bodies known as planetesimals, a fraction of which survived until today as asteroids.

The first several million years of the solar system may therefore be called the epoch of planetesimals. During this time, the terrestrial planet region must have been swarming with these tiny bodies. The coagulation of more than 25,000 bodies of diameter 500 km is necessary to make one Earth. By understanding the nature of these planetesimals, we can answer some key questions about this brief but important period in the solar system's history. In what ways were the planetesimals similar to the cold dust clumps from which they accreted? In what ways did they foreshadow the terrestrial planets, including the Earth, that they were destined to form?

Two classes of observations offer us a glimpse into the properties of ancient planetesimals. First, a number of planetesimals have survived into the present day in the form of asteroids and are available for study by telescopes and spacecraft. Second, we can analyze samples from some planetesimals in the form of meteorites that have been naturally delivered to the Earth.

In the case of asteroid Vesta, both of these approaches can be applied to the very same planetesimal. With a mean diameter of ~530 km, Vesta is the second most massive body in the asteroid belt. Discovered in 1807, it was once thought to be a piece of an ancient planet shattered in the distant past. We now know that the size of Vesta indicates that this is not the case; such a large object is very unlikely to have been shattered by a catastrophic collision during the history of the solar system. Rather, Vesta has survived largely intact from the formation stage of our solar system.

Telescopic observations of Vesta have led to a profound insight: the single largest clan of achondrites, the howardite-

euclite-diogenites (HEDs), have compositions nearly indistinguishable from those of the Vestan surface. Recently, close up observations from the Dawn spacecraft, in orbit around Vesta between July 2011 and September 2012, have shown that distinct regions on the surface of Vesta correspond most closely to each of the three meteorite groups in the HED clan, thereby providing even stronger evidence that the HED meteorites indeed originate from the asteroid Vesta.

Vesta is therefore the only asteroid confidently identified to be the parent body of known meteorites. The more than one thousand known HED meteorites have provided an invaluable source of knowledge of processes on early Vesta and, by extension, on the first planetesimals. Radiometric dating of these meteorites demonstrates that Vesta must have formed within

the first 2-3 million years after solar system formation, squarely in the middle of the epoch of planetesimals. The elemental composition of the HED meteorites indicates that Vesta, like the terrestrial planets, underwent differentiation into a metallic core, an olivine-rich mantle, and a less dense basaltic crust. The existence of this core has been verified by the Dawn spacecraft, which has shown that Vesta is too dense to be made from silicate rocks alone.

The liquid, metallic cores in Earth and Mercury generate a large-scale planetary magnetic field in a process known as the geodynamo. Tur-

bulent, convective motion of the electrically conductive liquid metal converts kinetic energy into magnetic energy and sustains strong magnetic fields detectable on the surfaces of these planets. The existence of a metal core in Vesta opens the possibility that it too may have sustained an active magnetic dynamo during its early history.

Due to its small size, Vesta cooled off quickly compared to Earth, such that any liquid core in Vesta must have frozen solid long ago. Therefore, Vesta cannot be generating a magnetic field today. However, ancient magnetic fields can sometimes leave their signature in rocks that survive over billions of years to the present day. Grains of magnetic minerals occur in nearly any natural rock and can be thought of as tiny bar magnets. When a rock cools in the presence of a magnetic field, the electrons within these magnetic grains align their spin axes preferentially in the same direction as the background magnetic field. Once the rock has cooled to low temperatures, the orientations of electrons in these magnetic grains are preserved. This preferential alignment leads to the entire rock behaving like a very weak magnet, a property we refer to as "magnetization." Laboratory measurements of this magnetization can recover both the orientation and strength of the ancient fields that produced it. For a given rock, stronger observed magnetization implies stronger ancient magnetizing fields.



Figure 2: Crossed polars transmitted light micrograph of large relic pyroxene grains (light blue and orange in upper left) in ALHA81001. Their fractured textures suggest that ALHA81001 is an impact melt. The surrounding dark blue matrix that makes up most of the meteorite crystallized quickly after the impact event.

In this way, paleomagnetists have studied Earth rocks to probe the magnetic field of the Earth in the past. In particular, we now know that the Earth's dynamo has existed since at least 3.5 billion years ago. Furthermore, paleomagnetic studies of lunar rocks returned by the Apollo missions and Martian meteorites naturally transferred to Earth have established the past presence of ancient global, dynamo-generated magnetic fields on those bodies.

Meteorites from early planetesimals have also been found to be magnetized, suggesting that their parent bodies also generated dynamo magnetic fields. A study by Benjamin Weiss and colleagues in 2008 showed that meteorites from a rare group of achondrites known as angrites cooled in a magnetic field with >20% of the strength of the present-day Earth field. Moreover, that magnetic field lasted for several million years in the early solar system with nearly constant intensity. Such a strong and stable magnetic field could have been generated only by a magnetic dynamo in the angrite parent body. Although no asteroid has been identified as the parent body of the angrites, this study showed that small, asteroid-sized bodies were capable of internal magnetic field generation.

The HED meteorites might also provide evidence for any early Vestan dynamo. Although paleomagnetic studies of HED meteorites have been pursued for more than 30 years, most of the results have been difficult to interpret. A major reason for this difficulty lies in their cooling histories. Most HED meteorites crystallized on long timescales, lasting up to millions of years in the case of some diogenites. Such long crystallization times result in coarse magnetic mineral grains. This is problematic for paleomagnetic studies because finer magnetic mineral grains generally carry more stable magnetization. Coarse-grained rocks like most HEDs typically do not faithfully retain records of ancient fields because their magnetizations are easily reset by exposure to the Earth's field and shock waves from meteoroid impacts. Another major problem for paleomagnetic studies of HED, as well as all other meteorites, is the application of hand magnets by collectors. Just touching a meteorite with a rare earth magnet usually completely destroys any ancient magnetic records within! As a result, huge numbers of meteorites, particularly hot desert finds, have lost nearly all scientific value for paleomagnetic studies.

The key to unlocking the magnetic history of Vesta is to find an exceptional HED meteorite not exposed to a hand magnet and that underwent very fast cooling. Luckily, at least one such eucrite has been documented in the literature. This is ALHA81001, retrieved in the Allan Hills of Antarctica in 1981. Although it is not a large eucrite specimen, with a total mass of only 52.9 g, its fine-grained texture is unique among the eucrites. Its $\sim 1 \mu\text{m}$ wide plagioclase grains (thin, dark lineations in Fig. 1) indicate that the initial cooling of the melt down to $\sim 1150^\circ\text{C}$ took place over a period of only 1 hour, orders of magnitude faster than most other HEDs.

How did the melt that formed ALHA81001 cool so quickly when virtually all other eucrites cooled over much longer timescales? Examination of a small population of pyroxene crystals, which make up only about 1% of ALHA81001 by mass, provides the answer. These large, highly fractured relict crystals (Fig. 2) experienced strong shock and were incorporated into the surrounding quickly-cooled melt. As described below, this event, almost certainly a meteoroid impact, probably occurred at 3.7 billion years ago.

The most likely formation scenario of ALHA81001 is as follows. First, a typical, coarse-grained eucrite near the surface of Vesta was subjected to heavy shock in an impact event, which led to melting of all but $\sim 1\%$ of the target material. The unmelted 1% survived as the large pyroxene grains. The melt then cooled extremely quickly, either because it was flung temporarily into space, or because it was injected into adjacent cold, unmelted rock.

This rapid formation process insured that ALHA81001 would have a fine-grained texture that could faithfully record ambient magnetic fields on Vesta. However, continued rapid cooling of the rock down to ambient space temperatures poses another problem. Very energetic impacts may be able to generate an ionized cloud of vaporized rock. Electric currents in this ionized medium may lead to strong magnetic fields that last for upwards of about 20 minutes on Vesta. If ALHA81001 cooled down to ambient temperatures in such a short amount of time, it may have recorded a mixture of this ephemeral magnetic field in addition to any background field that existed on Vesta, complicating any interpretation of its magnetic record.

However, close examination of the minerals in ALHA81001 rules out the recording of impact-generated fields. Zebra stripe patterns in the meteorite's pyroxene crystals (light colored lathes in Fig. 1) show that cooling below $\sim 800\text{--}1100^\circ\text{C}$ occurred slowly, over the course of several hundred years. Magnetism in rocks containing Fe-Ni metal is recorded only during the stage of cooling below 780°C , which means that any magnetism in ALHA81001 was recorded in a time interval of several hundred years and therefore could not have been due to impact-generated fields. In short, the cooling history of ALHA81001 places it in a Goldilocks zone: it crystallized quickly enough to contain fine-grained magnetic minerals that faithfully record the ambient field but not so quickly that it could have recorded transient impact-generated fields.

Although we have established that ALHA81001 was capable of having recorded ancient, stable magnetic fields on Vesta, it is still possible the magnetism in ALHA81001 was reset after landing on Earth. The mere act of resting in the Earth's magnetic field leads to the acquisition of contaminating magnetization in the rock. At the same time, terrestrial oxygen and water can attack and alter the magnetic minerals in meteorites, erasing their extraterrestrial magnetic record. Finally, as we mentioned above, hand magnets and electronic devices very often generate powerful magnetic fields that

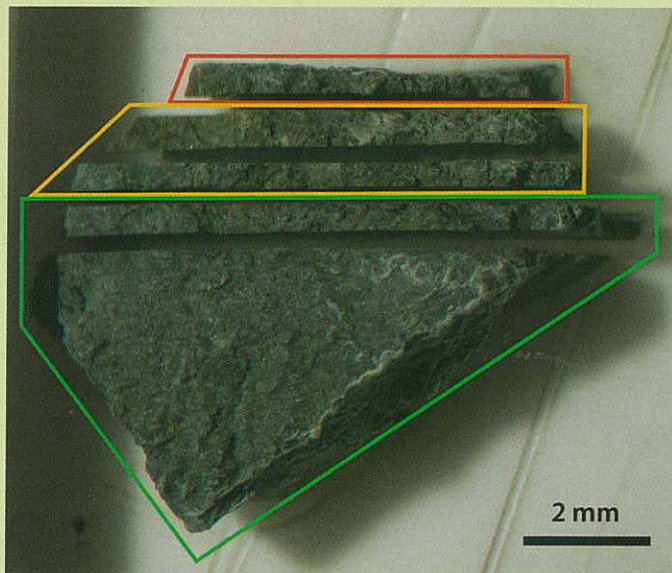


Figure 3: A piece of the ALHA81001 after four cuts parallel to the fusion crust surface (top of piece). Heating during atmospheric entry results in full (red), partial (yellow), or no remagnetization (green) of the rock based on the sample's distance from the fusion crust. The magnetism of each individual piece is then measured to perform the fusion crust baked contact test. In this test, the distribution of magnetization in the interior and near-fusion crust pieces is used to constrain the extraterrestrial or post-terrestrial origin of the magnetization in the deep interior.

overwrite the natural magnetic remanence in meteorites.

Another potential source of contamination is the passage of the meteorite through the Earth's atmosphere. During atmospheric entry, not only does the surface layer of the meteorite melt to form a fusion crust but also the near surface material is heated to a depth of 2-3 mm. The extraterrestrial magnetism in this thin layer is partially or fully replaced by magnetization acquired in Earth's magnetic field. However, material deeper than this "baked zone" fully retains its original, extraterrestrial magnetization.

Paradoxically, the mixed terrestrial and extraterrestrial magnetization of baked zone samples can be used to our advantage. Any magnetization that is acquired after arrival of the meteorite on Earth is expected to exist in both the near-surface material heated during atmospheric entry as well as the unheated interior material. In contrast, extraterrestrial magnetization would be carried only in the interior material, but not in samples taken within 2-3 mm of the surface. Therefore, by observing the distribution of magnetization in samples taken from different parts of the meteorite, we can distinguish between an extraterrestrial versus post-terrestrial origin of observed magnetism in the deep interior. This analysis, called the fusion crust baked contact test, is one of the most powerful tools available for establishing the extraterrestrial origin of an observed magnetization.

To perform this test on ALHA81001, we cut a number of thin samples parallel to the fusion crust surface (Fig. 3). The magnetism of each piece was then measured on our MIT laboratory's superconducting rock magnetometer, which is capable of detecting single microscopic magnetic grains. We progressively demagnetized each sample in discrete steps using a device similar to a very finely calibrated magnetic tape eraser. By measuring the magnetization of the sample after every step of the demagnetization process, we can peel back the magnetic history of the sample and identify multiple components of magnetization acquired during different events in the history of the sample.

In the case of ALHA81001, this stepwise demagnetization procedure yielded two distinct magnetization components in all samples of the meteorite. The first, lower stability component has the same direction in all samples, regardless of where the sample originated relative to the fusion crust (Fig. 4, left panel). This magnetization was therefore acquired after the meteorite's arrival on Earth. In this case, the relative ease of removing this component suggests that it was acquired simply by being in the Earth's magnetic field for perhaps thousands of years in Antarctica.

More interestingly, a second, more stable component of magnetization (Fig. 5, right panel) shows clearly distinct directions between samples from near the fusion crust and interior samples unheated during arrival on Earth. This component of magnetization in the interior material is therefore most likely to be extraterrestrial in origin. In this way, we isolated a reliable recording of a magnetic field on Vesta in an HED meteorite. Our further experiments showed that the field strength on Vesta in which

ALHA81001 cooled was likely around 12 μT , or about one fourth of the typical strength of the magnetic field at the Earth's surface.

The final question is what generated this magnetic field on Vesta. To answer this, we must turn to the thermal history of ALHA81001 as recorded by its radioisotopes. A rock can record magnetization no older than the last time it was heated to high temperature. The isotope potassium-40, found as a constituent of common rock-forming minerals, decays to the noble gas argon-40 with a half-life of 1.25 billion years. The argon-40 accumulates until the rock is heated, upon which the argon is released, and the process of accumulation begins anew. Therefore, by measuring the amount of argon-40 in a meteorite, we can

infer the timing of the most recent heating event. In the case of ALHA81001, its argon-40 content indicates that it was strongly heated 3.7 billion years ago and that no significant heating has occurred thereafter. The extraterrestrial magnetization in ALHA81001 therefore dates to 3.7 billion years ago.

This is a very interesting age for a magnetic field on Vesta. Because Vesta is such a small body, any liquid metal core must have frozen solid by this time, which is 800 million years after its formation. No active magnetic dynamo was therefore possible on Vesta at that time. The only other way to generate a temporally stable magnetic field on a planetary body is remanent magnetization of the crust. In this process, the rocks at the surface of a body were themselves magnetized by an earlier magnetic field. These rocks in turn generate their own magnetic field that persists long after the original field had decayed away. This phenomenon is widely observed as crustal magnetic anomalies on Mars, the Moon, and Earth, each of which had past (or in the case of Earth, active) dynamos. The magnetization detected in ALHA81001 suggests that Vesta had a magnetized crust that generated a magnetic field 3.7 billion years ago.

But the crust of a planetary body cannot become magnetized spontaneously; an earlier magnetic field is required. Based on the strength of the magnetic field generated by the Vestan crust, this earlier magnetic field could have only been due to an internally generated dynamo. Other field sources, such as early nebular fields or impact generated fields were too weak or too evanescent to magnetize the crust of Vesta to the necessary level.

The magnetic fields on Vesta recorded in ALHA81001 therefore imply that Vesta generated an early dynamo. This in turn implies that Vesta not only formed a liquid metallic core, but that the core was vigorous stirred as it cooled, analogous to the motion inside a lava lamp.

It turns out that astronomical observations provide additional evidence for magnetic fields on Vesta. As discussed above, the origin of HED meteorites on Vesta is indicated by the close match between their compositions as inferred from astronomical and laboratory spectra. However, the similarity of



Figure 4: The authors' 2G superconducting rock magnetometer. It is one of the most sensitive devices available for measuring the magnetization of geological samples.

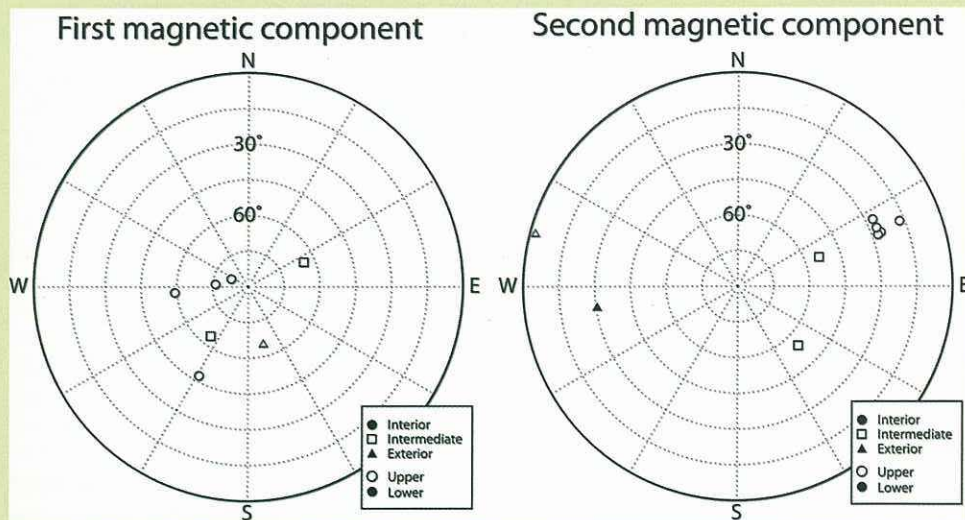


Figure 5: Equal area stereonet diagrams indicating the directions of the two magnetization components measured in individual, mutually oriented samples of the ALHA81001 eucrite. Hollow symbols indicate magnetization vectors that are pointing upward and solid symbols indicate downward magnetization. Note that the first magnetic component (left panel) points in the same direction regardless of whether the sample contains fusion crust (exterior), is from deep inside the meteorite (interior), or from in between these two zones (intermediate). In contrast, for the second magnetic component (right panel), the interior samples clearly carry a distinct magnetization, strongly suggesting that this component of magnetization is extraterrestrial in origin.

Since the surface of Vesta has also been exposed to the space environment for millions of years, we may expect its surface to show a more subdued spectrum similar to that of the moon. However, the spectral features of the Vestan surface are unexpectedly strong. One possible explanation for this is that Vesta has a crustal magnetic field protecting its surface from the bombardment of the solar wind. Because ions in the solar winds are charged, they are deflected by planetary magnetic fields. By a similar process, the Earth's magnetic field protects artificial satellites from damage by the solar wind. The lack of visible space weathering on the surface of Vesta may provide evidence for the existence of magnetic fields on modern Vesta. The only magnetic fields that can persist on Vesta to the present day are generated by a magnetized crust,

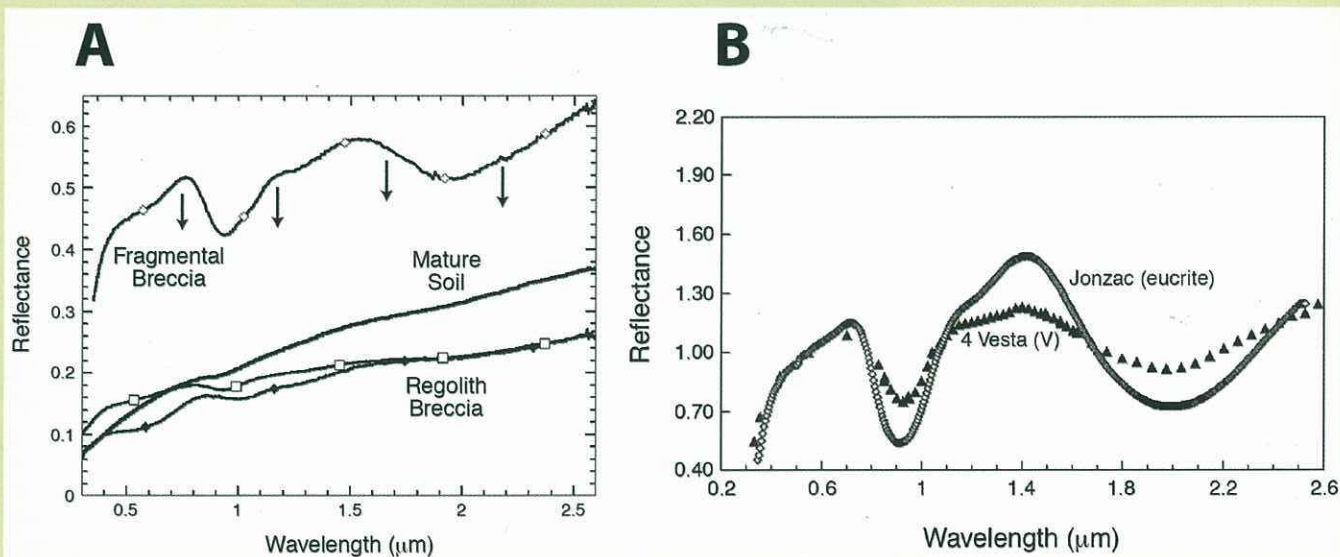


Figure 6: Infrared wavelength spectra of (A) the lunar surface and a moon rock (fragmental breccia) and (B) the Vestan surface and a eucrite (Jonzac). As the lunar surface is exposed to the space environment, the spectral features of fresh moon rocks become attenuated and the surface becomes darker. In contrast, this effect is much less pronounced on Vesta. Magnetic fields may be the agent that is protecting the surface of Vesta from undergoing the same spectral transformation as the moon. From Clark et al. (2002), in *Asteroids III*, Univ. Arizona Press.

their spectra is a little bit *too* close. For example, the spectra of moon rocks sometimes look quite different than that of similar rocks on the lunar surface (Fig. 5). The same is true for S-type asteroids, which are the likely parent bodies of the ordinary chondrites. The reason for the discrepancy between the spectra of hand samples and the object's surface is a collection of effects called space weathering. When a rocky surface is exposed to the space environment for thousands or even millions of years, the chemistry of the near surface layer changes gradually until the spectrum of the weathered surface bears almost no resemblance to the original, fresh surface.

just as inferred from our experiments with ALHA81001.

We have shown that, at least magnetically, planetesimals like Vesta were very much like miniature versions of the terrestrial planets that they eventually accreted to form. Many planetesimals even produced core dynamo generated magnetic fields that sheltered their host planetesimals in a magnetosphere, similar to that found around the present day Earth. The early solar system during the epoch of planetesimals may be a more familiar place than previously thought.