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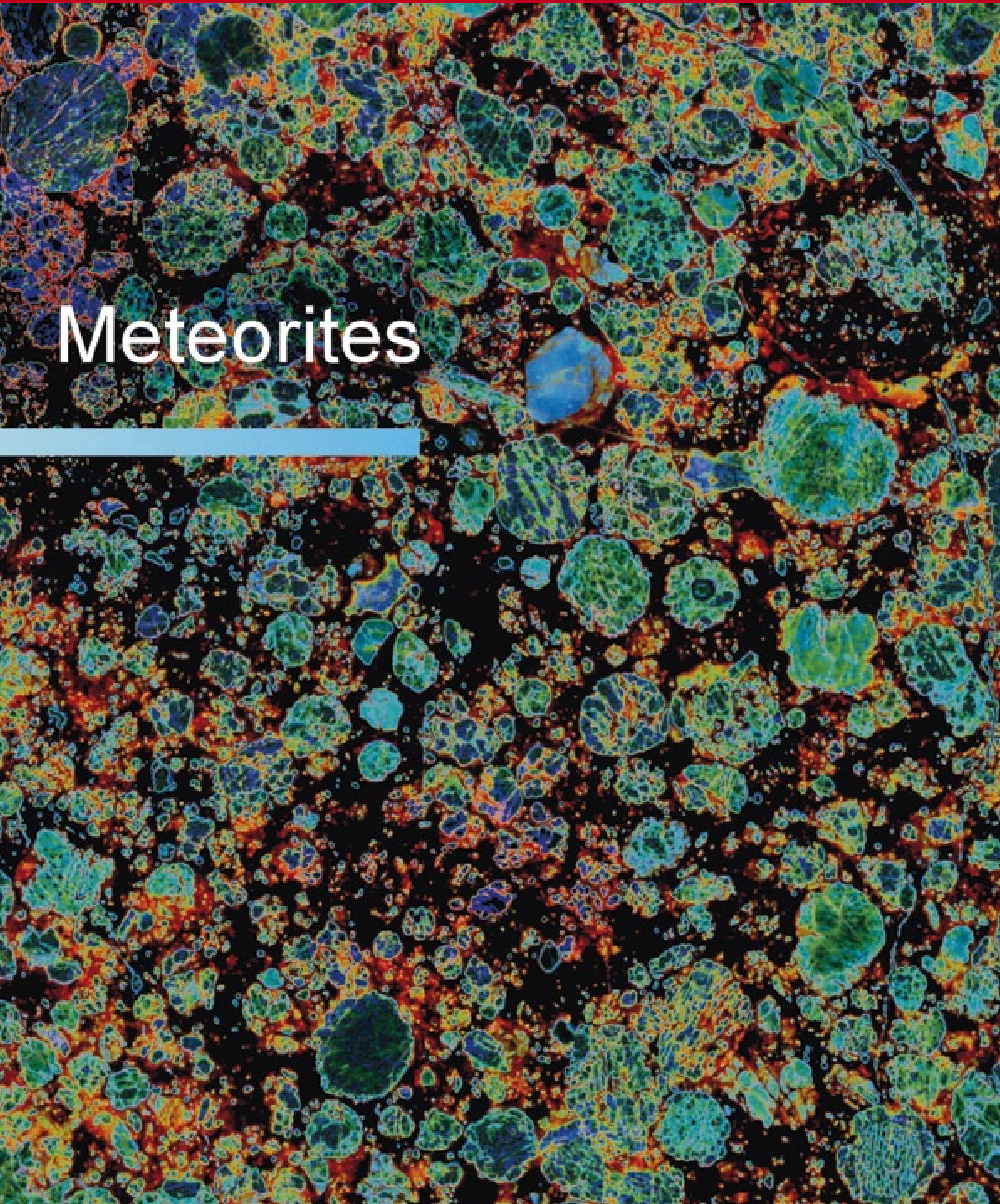

Meteorites

Editorial

Earth's long history is not a quiet Sunday morning's tale, but rather a sequence of apocalyptical disasters with calmer phases in between. The same is true for the evolution of life on Earth. Repeatedly, such global catastrophes wiped out successfully developing species. Fortunately though, life is not the static result of a unique creative act, as was current wisdom when Charles Darwin saw the light of the day 200 years ago (and certain minds still believe to this day). Meticulous observations on a trip along the coast of South America provided him with seminal insights into the secrets of life: the permanent mutation of genetic properties combined with a relentless selection in favour of the fittest must be the driving force for Nature's overwhelming evolutionary capabilities.

We do not know what made such catastrophes happen, but the impact of large meteorites is thought to be a strong option: the innumerable craters on the Moon's pale face bear telling witness of cosmic bombardments in the distant past, which certainly did not spare the Earth. Now, intriguingly, the earliest traces of life on Earth date back just to the end of that fiery epoch. Scientists, therefore, argue that large meteorite impacts on the young Earth could have created the conditions that allowed complex organic molecules to develop which later evolved to higher forms of life. If this is the case, meteorites play pivotal roles with regard to evolution: on the one hand to launching life from the unenlivened early Earth and on the other to extirpate some of the species emerged so far thereby offering open niches for new forms of life. Even the human race is thought to owe its existence to such a dramatic event some 65 million years ago.

The present issue of Spatium is devoted to meteorites, more specifically however to the good-natured class of small extraterrestrial bodies that continue reaching the Earth without doing major harm. Science has learned to appreciate them as cosmic messengers that faithfully recount the billion year history of our solar system. This role of meteorites was the topic of an exciting lecture by Dr. Beda Hofmann (Natural History Museum of Bern and Institute for Geology, University of Bern) for the Pro ISSI audience on 28 October 2008. We are indebted to Dr. Hofmann for his kind permission to publish herewith a summary of his talk in our *Spatium* series and to forward some of the meteorites' stunning messages to you, our dear reader.

Hansjörg Schlaepfer
Brissago, February 2009

Impressum

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Front Cover
This image shows an artist's interpretation of a typical thin section of a chondrite found in the Jiddat al Harasis area, Oman. Chondrites are stony meteorites. The spheric chondrules therein have diameters of up to 2 mm and were formed in the protosolar nebula 4.57 billion years ago as freely floating silicate melt drops.

METEOROITES[1]

Dr. Beda Hofmann, Bern

Introduction

Meteorites have been known since the antique. Throughout the ages, they were venerated as sacred objects by ancient civilizations. The spectacular fall of a meteorite, accompanied by light and sound phenomena, such as fireballs, smoke, thunder, and sonic booms, has always kindled the human imagination, evoking fear and awe in everyone who witnesses such an event. For obvious reasons, the remnants of these incidents, the actual meteorites, were often kept as sacred stones or objects of power. They were worshiped and used in religious ceremonies.

The historically oldest meteorite falls from which material is still preserved occurred in Japan (Nogata, 861) and in Alsace (Ensisheim, 1492). Here, on November 7, 1492 – the year when Columbus discovered the New World – a huge stone landed with much noise in a wheat field outside the small town at that time belonging to Germany and the Holy Roman Empire. A boy who had witnessed the fall led a crowd of curious people to the place where a black stone lay in a meter-deep hole. After they had pulled it out, people began chipping off pieces of the rock as good-luck talismans, until they were stopped by the town magistrate. He ordered that the unusual stone be transported to his residence in an effort to protect it from his careless citizens. Today, this famous meteorite can be admired in the Regency Palace of Ensisheim as the centrepiece of a most remarkable meteorite collection, **Fig.1.**

During the Enlightenment meteorites lost their popularity. It was only at the beginning of the 19th century that meteorite falls and the connection between meteoritic stones and the fiery observations of meteors in the sky once again received broader attention. Since then, research on meteorites has flourished and has provided crucial contributions to our knowledge of the solar system: meteorites now belong to the best-investigated rocks.

Fig. 1: The Donnerstein (the "thunder stone") of Ensisheim, France is the oldest preserved meteorite in Europe (1492). It features a mass of about 55 kg. (Credit: Sternwarte Singen e.V.)

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[1] The present issue of *Spatium* is based on a lecture by Dr. Beda Hofmann, Natural History Museum Bern and Institute for Geology, University of Bern on 28 October 2008 for the Pro ISSI audience.

The Nature of Meteorites

The Origins

What are the origins of meteorites? Where do they come from? What are they made of? In order to unveil their secrets we have to step back to the beginnings of the solar system: the Sun together with its planets formed out from a huge primordial cloud of dust and gas that collapsed some 4.6 billion years ago[2]. Most of the matter contained in that cloud condensed into what later was to become the Sun, but some material was left over and circled the Sun. During the following millions of years this matter combined and formed bodies of various sizes amongst which are the planets. Still, a very small part of the original primordial matter remained which under the gravitational effect of Jupiter and Mars was mostly concentrated on orbits between these two planets. This became the asteroid belt, **see Fig. 2.**

Amongst the matter incorporated in the emerging bodies there was radioactive material. Its decay caused the bodies to heat up and some became molten. Now, the mass content of a sphere is proportional to its diameter to the power of three while its surface is only proportional to its diameter to the power of two. This means that bulky bodies, such as planets and a few large asteroids had large heat contents as compared to their surfaces. It took them a long time to radiate heat off and cool down. This in turn kept them liquid for a sufficient period of time to allow the heavier elements, such as iron, to sink to the body's centre while the lighter elements, such as silicates, wandered towards the surface. This process is called differentiation. With further cooling the silicate-rich crust solidified while the iron-core may have remained liquid as is still the case for example with the Earth. The same law, on the other hand, made small bodies generate less heat which was radiated off fast. Therefore, many asteroids merely heated up and then re-crystallized only partially

But what prompts a piece of matter to suddenly leave its parent body? Basically, all meteorites are collision products, be it from collision among asteroids **(see box Asteroids)** or between a large meteorite and a planet. During such incidents tremendous amounts of energy are released. This in turn may accelerate a chunk to such an extent that it escapes the parent body's gravitational field. As it is easier to escape from a small body with a small gravitation than from a large body, most meteorites are produced by the collision of asteroids. In contrast, the impact of

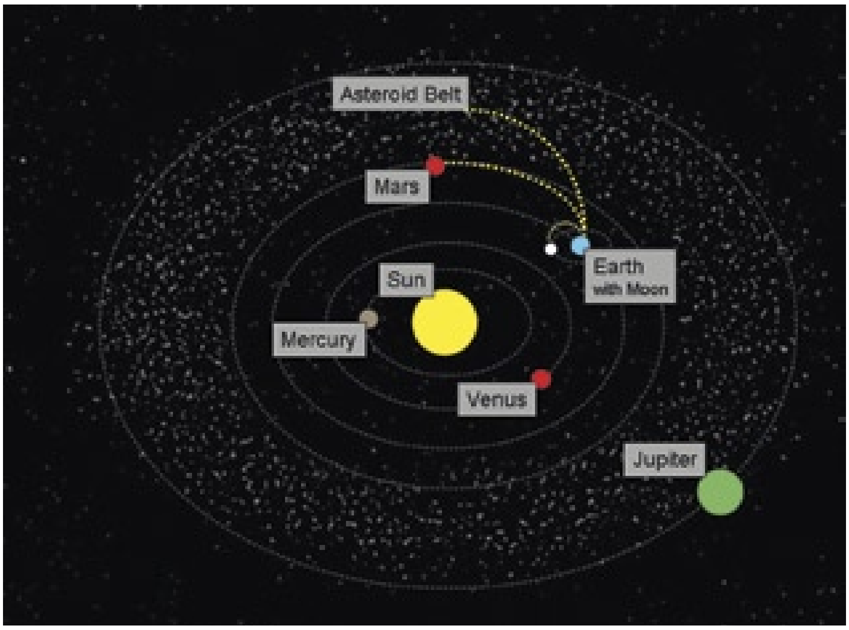


Fig. 2: The origins of meteorites. Most meteorites stem from the asteroid belt, an aggregation of primordial chunks circling the Sun between Mars and Jupiter. A minority of meteorites come from the Moon and Mars as the result of major impact events with large meteorites.

[2] See Spatium 6: From Dust to Planets

very large meteorites on a planet such as Mars or on the Moon is required to provide the required energy for meteorites to escape their stronger gravitation. Hence only a small percentage of meteorites stem from Mars or the Moon.

Asteroids circle the Sun on various orbits leading to collisions every now and then. If the bodies involved are small, as are the majority of asteroids, they are not differentiated and their fragments will hence contain the primordial cocktail of iron and silicates. The collision of small bodies leads to what are called ordinary chondrites. If, however, larger asteroids are involved that have undergone differentiation, their cores will mostly contain iron and their crust silicates. Fragments generated by such collisions will therefore consist of either iron or silicates and the resulting meteorites will be of the iron and stony type respectively.

Arriving on Earth

We have now identified the three main sources of meteorites as depicted in **Fig. 2.** Meteoroids, as they are called before entering the Earth's atmosphere, may now quietly travel through the void of space for millions, even billions, of years. Eventually they may get on a collision course with our home planet and enter its atmosphere at an incredible speed of between 11,000 and 72,000 m/s. This high velocity corresponds to a high kinetic energy content of which a part will be converted into heat during entry. This heat results in the melting of some of the meteorite's surface which will be ablated on the trajectory and create the well-known ephemeral meteorite trail on the night sky. The track coordinates may be calculated exactly from detailed observations during atmospheric entry such as photographs obtained from networks of cameras operated specifically for this purpose. Such observations led to the find of a number of meteorites so far, most recently in Saskatchewan, Canada (fall of 20 November 2008).

Meteorites Scars

Meteorites range in size from dust particles to large bodies exceeding 10 km in diameter. While the small samples are burnt completely during entry, larger meteorites will reach the Earth's surface and excavate major impact craters similar to those we can observe on the lunar surface. The fact that all bodies in the solar system with an old surface display meteorite craters demonstrates that meteorites are common in time and space. So, it was to be expected that sooner or later even NASA's Mars Exploration Rovers would detect a meteorite on the surface of Mars, as was the case recently, **see Fig. 3.**

On Earth about 175 impact craters are known, a low number compared to the Moon whose surface is saturated with craters. In contrast to the Moon, however, the Earth's surface is very dynamic and subject to continued erosion and tectonic forces. These processes eliminate most impact craters within just a small fraction of the Earth's age.

Asteroids

The Asteroid Belt is an aggregation of chunks circling the Sun between Mars and Jupiter. It constitutes the leftovers from the primordial solar nebula that formed the solar system 4.6 billion years ago. More than half the mass of the asteroid belt is contained in the four largest objects: Ceres, Vesta, Pallas, and Hygiea. While Ceres has a diameter of some 950 km, most other asteroids are much smaller ranging down to the size of dust particles.

Vesta is the second most massive object in the asteroid belt, with a mean diameter of about 530 kilometres and an estimated mass of 9% of the mass of the entire asteroid belt. Vesta is of specific interest as it underwent a major collision less than a billion years ago resulting in a high number of fragments that have fallen on Earth which are a rich source of evidence about the asteroid.

Fig. 3: A meteorite on Mars. NASA's Mars Exploration Rover Opportunity has found a meteorite on Mars, officially named "Meridiani Planum", the first meteorite ever identified on another planet. The football-sized object is mostly made of iron and nickel and has its origins in the core of a large asteroid. (Image credit: NASA/JPL/Cornell)

The largest impact crater known on Earth is the Vredefort crater in South Africa measuring some 300 km in diameter. It was created by a 15 km meteorite impact some 2 billion years ago. But there are also much younger craters, such as the Wolfe Creek crater in Australia formed a mere 300,000 years before the present, **Fig. 4.**

Frequency of Meteorite Falls

The intensity of meteorite bombardment on Earth and the Moon (and on the other bodies of the solar system) was much stronger about 4 billion years ago than today. There are indications for a period of particularly heavy bombardment about 3.9 billion years before present. Then, the intensity strongly declined and remained approximately at the present level. The current fall density of meteorites with a mass exceeding 10 gr is estimated at 80 falls per million square kilometres and year, or about 40,000 falls per years for the whole Earth. This estimate is based on the observation of meteors by camera networks. It corresponds to 3.3 falls/year on the surface of Switzerland. The fact that the last freshly fallen meteorite was recovered in 1928 in Utzenstorf near Bern demonstrates that most meteorite falls are not noticed.

Fig. 4: The Wolfe Creek crater in Australia. It represents one of the largest "fresh" meteorite craters on Earth: it is nearly circular with a diameter of some 900 m and an estimated age of some 300,000 years. Thanks to the environmental conditions prevailing in the Australian desert it has retained most of its original structure, although the bottom has been filled in with wind-blown sand. Rainfall is retained in the whitish gypsum areas on the central crater floor, permitting plants to grow. (Credit: Lund Observatory, Sweden)

Finding Meteorites

Due to their rare appearance, only a few hundred meteorites had been discovered until the beginning of the 20th century. Most were iron and stony-iron meteorites, which are easily distinguished from local rocks. When scientists became aware that meteorites must be much more common on the surface of the Earth, systematic search missions were launched. A few meteorites were found by field parties in Antarctica between 1912 and 1964. Then in 1969, a Japanese Antarctic Research Expedition happened to find nine meteorites. With this discovery came the realization that appropriate movements of the ice sheets might act to concentrate meteorites in certain areas. After a dozen other specimens were found in the same place in 1973, another Japanese expedition was launched in 1974 specifically dedicated to the search for meteorites. This team recovered nearly 700 meteorites. Later, teams from all over the world began to explore Antarctica for meteorites. Today there are over 30,000 meteorite finds in the world's collections.

Fig. 5: The Arabian Peninsula as seen from space. The most promising area for meteorite search is encircled by a thin white line.

At the same time as meteorites were discovered in the cold desert of Antarctica, meteorite hunters found them also in the hot deserts of Australia. Several dozen were retrieved in the Nullarbor region of western and southern Australia. Systematic searches located over 500 more. The meteorites can be found in this region because the land presents a flat, featureless plain covered with limestone. In the extremely arid climate, there has been relatively little weathering or sedimentation on the surface for tens of thousands of years, allowing meteorites to accumulate without being buried or destroyed. The dark coloured meteorites can be recognized easily among the very different looking limestone pebbles and rocks. The same is true for the Sahara deserts, especially the northwestern parts, that provide a rich flow of meteorites to this day.

Another region with attractive meteorite finds is Oman in the southeastern part of the Arabian Peninsula. The suitable area in Oman forms a strip approximately 200 km wide by 500 km long between the sands of the vast Rub Al-Khali desert and the Arabian Sea, **see Fig. 5.** The gravel plains in the Dhofar and Al Wusta regions of Oman have yielded several thousand meteorites of which over 2,000 have been officially named. As a significant number of meteorites stem from the Moon (55) and from Mars (12), Oman is a particularly important area for meteorite hunters. While early expeditions to Oman were done by commercial meteorite dealers and private collectors in the meantime, the government of the Sultanate of Oman has granted the University of Bern the rights to execute systematic meteorite search missions on its territory. A team from several Swiss institutions has been the only one working in collaboration with Omani authorities since 2001.

Meteorite Search in Oman

Geologists from the University of Bern have been active in field work in Oman for many years. They paved the way for the first specific meteorite search project undertaken in 2001. Its success led to the establishment of a long-term project in collaboration with the Directorate General of Minerals, Ministry of Commerce and Industry in Muscat, Sultanate of Oman. The project is supported by the Swiss National Science Foundation and represents the only long-term meteorite search project outside Antarctica. Up to 2008, seven campaigns in Oman yielded over 5,000 meteorite samples representing about 340 different fall events. The situation of Oman is unique worldwide because it is the only large desert area where a very large number of meteorites has been recovered while maintaining a high standard of documentation. The exact place of a meteorite find is a key issue when it comes to assessing its origins: During entry, meteorites often break into various pieces that land at different places. The exact position information of each find is required to identify their common ancestor. This is in contrast to the current flow of large numbers of meteorites from north-west Africa which lack precise location information. It is likely that Oman will become the best-documented large meteorite recovery area outside Antarctica and the only one where all fall locations are known. This allows unprecedented interpretations concerning pairing, the abundance of large strewn fields and meteorite weathering under hot-desert conditions.

In the Oman desert meteorites are searched for visually because they are dark and form a strong contrast against the nearly white limestone surface prevailing in this area, **see Fig. 6.** In the laboratory, the finds are classified based on polished thin sections. Among the parameters determined are meteorite type, degree of metamorphism due to heating of the parent asteroid, degree of impact shock and intensity of terrestrial weathering.

Meteorite search field trips give students hands-on experience on how meteorites are found, providing invaluable experience supporting the interpretation of data obtained in the laboratory. In the following chapters we will elaborate on what information can be extracted from meteorites with a strong focus on finds made in Oman. This includes data from numerous collaborating scientists.

Fig. 6: Omani geologist Ali Al-Kathiri observing a meteorite in the vast monotony of the desert, east of Ghaba, central Oman.

The Secrets of Meteorites

Meteorites are classified according to the nature of their main components. As we have seen above, the stony type prevails by far of which 90% are chondrites **(see Geological Dictionary I)** and 10% are achondrites. Iron and stony iron meteorites are much rarer.

Geological Dictionary I

Achondrites are stony meteorites consisting of material similar to terrestrial igneous rocks. Compared to the chondrites, they were differentiated and reprocessed due to melting and re-crystallization within the meteorite's parent body. As a result, achondrites have distinct textures indicative of igneous processes.

Breccias are rocks composed of angular fragments of several minerals or rocks in a matrix that is a cementing material that may be similar or different in composition to the fragments. A breccia may have a variety of different origins, as indicated by the named types such as impact breccia.

Calcium-aluminium-rich inclusions (CAI) are centimetre-sized light-coloured calcium- and aluminium-rich parts found in carbonaceous chondrite meteorites. CAI's consist of minerals that are among the first solids condensed from the cooling protoplanetary disk of the solar system. CAI's were formed at much higher temperatures than the associated chondrules, and may have survived many high-temperature events, whereas most chondrules are the product of a single transient melting event.

Chondrites are stony meteorites that have not been modified due to melting or differentiation of the parent body. They formed when various types of dust and small grains that were present in the early solar system accreted to form primitive asteroids. Prominent among the components present in chondrites are the enigmatic chondrules, millimetre-sized objects that originated as freely floating, molten or partially molten droplets in space. The term chondrule is derived from the Greek chondros, grain.

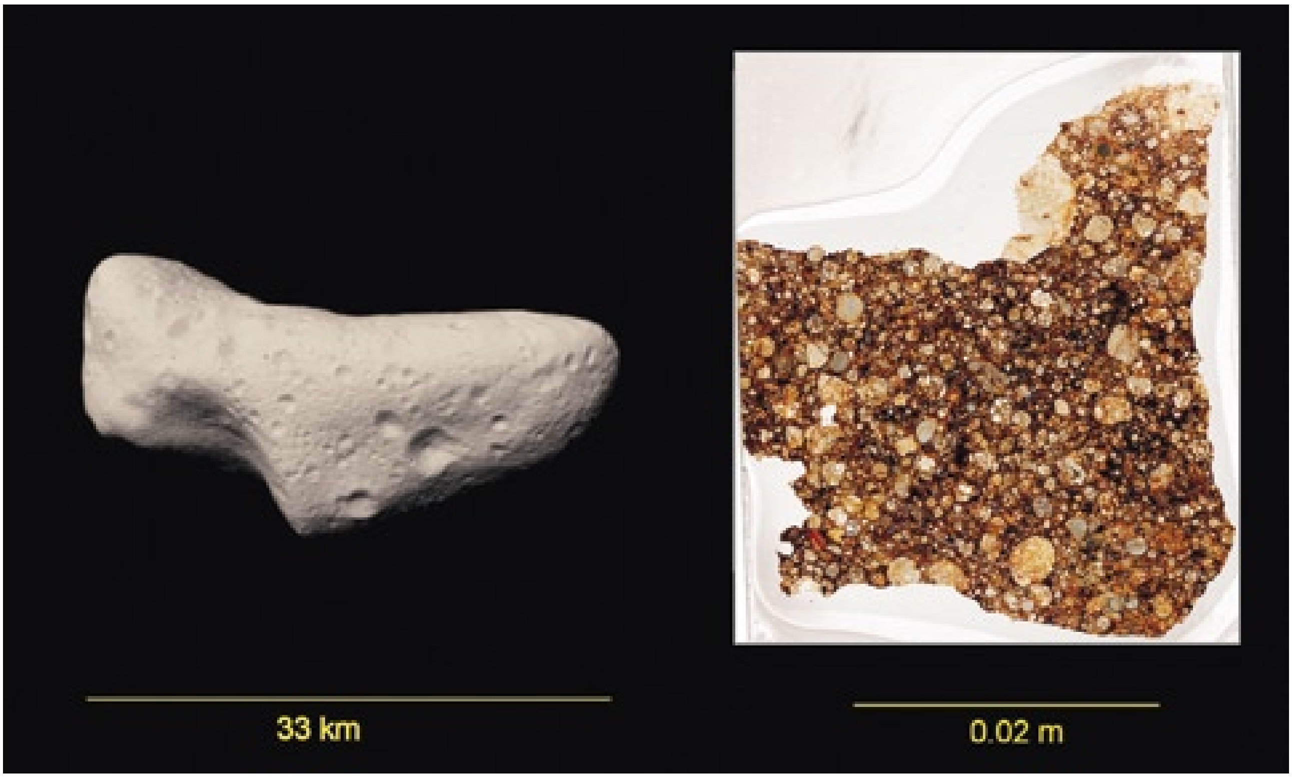


Fig. 7: A typical thin section image of a chondritic meteorite. This is the mixture most asteroids consist of. On the left a reconstruction of a typical asteroid (Eros) as seen by NASA's NEAR spaceprobe is shown (Credit: NASA)

Stony Meteorites

Undifferentiated Meteorites: Chondrites

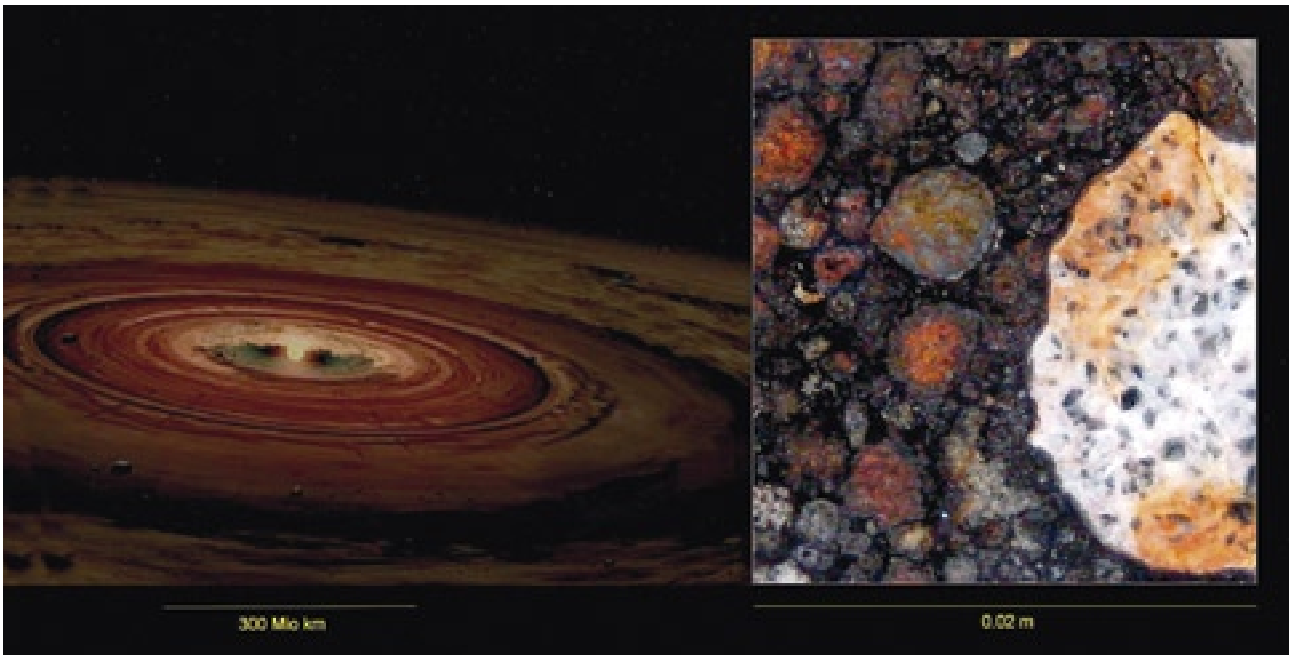
Most of the observed falls are chondrites, **see Fig. 7.** These are meteorites essentially composed of millimetre-sized silicate chondrules. Chondrules are droplets of former silicate melt, heated to temperatures above 1,500 °C while floating in the forming solar nebula. After cooling and partial crystallization, chondrules, along with un-molten dust, metal particles and some other minor constituents, accumulated to bodies reaching several kilometres in diameter. Chondrites also contain stardust, that is small traces of mineral grains formed earlier in other stellar environments that survived the fiery events in the early solar system.

Due to the presence of fast-decaying radionuclides, such as ^{26}Al, the asteroids were heated and underwent re-crystallization, a process that blurred and finally destroyed the chondritic texture. After cooling, only impact processes further altered the asteroidal parent bodies of meteorites. Evidence of such impacts can be found in the form of breccias and high-pressure minerals.

Calcium-Aluminium-Rich Inclusions (CAI's)

In carbonaceous chondrites one can find abundant calcium-aluminium-rich inclusions **(see Fig. 8)** that constitute the oldest material from the solar system condensed from the solar nebula at temperatures as high as 1,750 °C. Such CAI's consist of Ca-Al-oxides and Ca-Al-rich silicates. Radiometric dating of CAI's using the uranium-lead method has yielded an age of 4,567 million years confirming the absolute oldest age of solar system material. The matrix of carbonaceous chondrites contains organic matter in the form of aromatic, polymer-like material of non-biological origin.

Fig 8: Details of carbonaceous chondrite Sayh al Uhaymir 202 with a large calcium-aluminium-rich inclusion (CAI) which contains the oldest material in the solar system. On the left an artist's rendering of the proto-solar cloud with the early Sun. (Credit: NASA)



Iron Meteorites

The heating of asteroids by the decay of incorporated radioactive elements soon after their formation sometimes led to their complete fusion. This mainly occurred in the case of larger asteroids which formed very early as both scenarios increase the decay heat of radionuclides. As we have seen above iron meteorites represent pieces of the metal cores of asteroids. A lot of information about the parent bodies can be read out of these irons: The variability among iron meteorites collected so far suggests as many as 50 different parent asteroids. The time of solidification of the iron cores is typically only a few million years less than the age of the solar system: the cooling occurred at a rate of 0.5 to more than 100 °C per million years, indicating parent body diameters ranging from 400 km down to about 20 km. The time iron meteorites spent in space as small bodies is typically orders of magnitude higher (several 100 million years) than that of chondrites (a few to tens of million years), probably due to the higher strength of irons during collisional events.

The iron meteorite Shisr 043 is the only one found so far in Oman. This is a common type of iron meteorite with a nickel content of 8%. After cutting and etching of the metal, an intriguing structure of iron crystals is revealed: the Widmannstätten pattern, **see Fig. 9.** During slow cooling of the asteroidal core, the homogeneous iron crystal that formed initially decayed into a nickel poor (kamacite) and a nickel-rich (taenite) iron phase. Profiles of nickel concentration in taenite, due to solid-state diffusion, can be used to deduce a cooling rate that corresponds to an asteroidal diameter of approximately 50 kilometres. Noble gases and cosmogenic isotopes (^{40}Ca) measured on Shisr 043 indicate that it travelled in space as a small meteoroid for 290 million years, and fell to Earth not more than 10,000 years ago.

Fig. 9: The inside of an iron meteorite. A cut and etched slab of the iron meteorite Shisr 043 shows the Widmannstätten pattern characteristic for the type of iron meteorites called octahedrites.

Geological Dictionary II

Diogenites are achondritic stony meteorites that originate from deep within the mantle of the asteroid 4 Vesta. Diogenites are composed of igneous rocks of plutonic origin, having solidified slowly enough deep within Vesta's crust to form crystals which are larger than in the eucrites. These crystals are primarily magnesium-rich orthopyroxene with small amounts of other silicate materials. Diogenites are named after Diogenes of Apollonia, an ancient Greek philosopher, who was the first to suggest an outer space origin for meteorites.

Eucrites are achondritic stony meteorites of basaltic composition that originate from the crust of the asteroid Vesta. Eucrites are named from a Greek word meaning "easily distinguished".

Pyroxenes are a group of important rock-forming silicate minerals found in many igneous and metamorphic rocks. The name pyroxene comes from the Greek words for fire and stranger. Pyroxenes were named thus because of their presence in volcanic lavas, where they are sometimes seen as crystals embedded in volcanic glass; it was assumed they were impurities in the glass, hence the name "fire strangers". However, they are simply early forming minerals that crystallized before the lava erupted.

Achondrites from Vesta

The light silicate portions of asteroids that melted a short time after their formation are the origins of a class of meteorites called achondrites. These meteorites are quite similar to terrestrial igneous rocks and have a similar origin, as they crystallized from magma (molten rock) either at some depth in the asteroids, or at their surface in the course of volcanic eruptions. There are several different groups of achondrites that are derived from different asteroids. The most common type, comprising 2.5% of the observed falls, are meteorites from asteroid 4 Vesta **(see box on p. 5)**. The link of these meteorites with Vesta is given by the similarity of the infrared spectra of Vesta and the Eucrite meteorite family **(see Geological Dictionary II)**. Similar to iron meteorites, Vesta formed very early, only a few million years after the origin of the solar system.

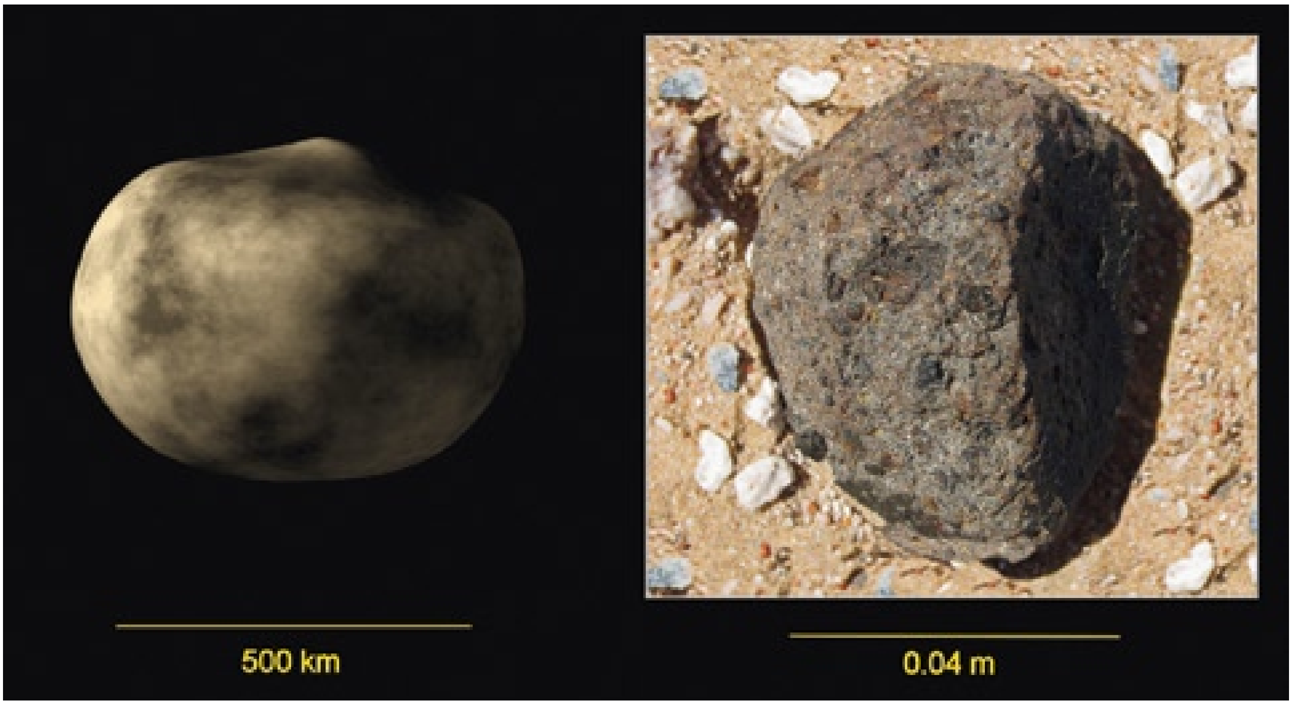
Meteorite Jiddat al Harasis 335 **(Fig. 10)** is a diogenite breccia. It is dominantly composed of large pyroxene fragments **(see Geological Dictionary II)** derived from deep inside the silicate mantle of Vesta, but were excavated by a large meteorite impact and transformed into a breccia. Fragments of eucrites are present among the pyroxenes due to the mixing of different rock types during one or several impact events.

Mars Meteorites

While Mars is a prime target of space missions due to its relative proximity to Earth no samples of Martian material have been returned so far. Nevertheless, nearly 100 kg of Mars rock are available for research in the form of Mars meteorites. Volcanic and magmatic rock types are represented. The most common Mars meteorites have ages of only several hundred million years. This indicates relatively recent magmatic activity which is possible only on a large planet, while small bodies such as asteroids have cooled down relatively shortly after their formation.

Sayh al Uhaymir 094 is a Mars meteorite found in Oman during the first Omani-Swiss campaign in 2001, **see Fig. 11.** In the area of the find, several other Mars meteorites

Fig. 10: Diogenite Jiddat al Harasis 335 as found in the desert. Dark minerals are large pyroxene crystals originally formed in the mantle of asteroid Vesta while the brighter material has a eucritic component. To the left, a computer model of asteroid 4 Vesta is depicted based on images by the Hubble Space Telescope (Credit table on the left: NASA).



were found and it is clear that they are paired, i.e. the result of atmospheric fragmentation of one single meteoroid entering the Earth's atmosphere. Detailed investigations of SaU 094 and paired meteorites showed that this rock formed from cooling magma on Mars, 445±18 million years ago. This age is far younger than any igneous rock from an asteroid (all close to 4,500 million years old) and proves that the rock must have formed on a large, internally hot, geologically active body. Within the reach of Earth, only the planets Mars, Venus and Mercury are thus possible. A Martian origin is supported by direct chemical comparison with rocks analyzed in situ during several NASA missions and by tiny gas inclusions in other Mars meteorites that show a composition strongly resembling that of the Martian atmosphere, as analyzed by the Viking landers in 1976.

But Sayh al Uhaymir 094 has much more to say: During a large meteorite impact on the Martian surface the rock was so highly shocked that feldspar crystals **(see Geological Dictionary III)** were transformed into glass, and part of the rock started to melt as a whole. Some of the Martian surface material reached the escape velocity of 5.0 km/s. Analyses of noble gas contents in SaU 094 showed that the ejection from Mars occurred 1.4 million years ago. Based on radioactive dating with ^{14}C and ^{10}Be, the terrestrial age is just 13,000 years, indicating a fall during the last ice age. At that time the present Omani desert likely was a savannah.

Geological Dictionary III

Feldspar is the name of a group of rock-forming minerals which make up as much as 60% of the Earth's crust. Feldspars crystallize from magma in igneous rocks, and they also occur in many types of metamorphic rock. The name Feldspar is derived from the German Feld, field, and Spat, a rock that that shows specular cleavage planes.

Lunar Meteorites

A lot is known about the Earth's moon not least thanks to the samples returned by the Apollo and Luna missions. A number of meteorites have subsequently been iden-

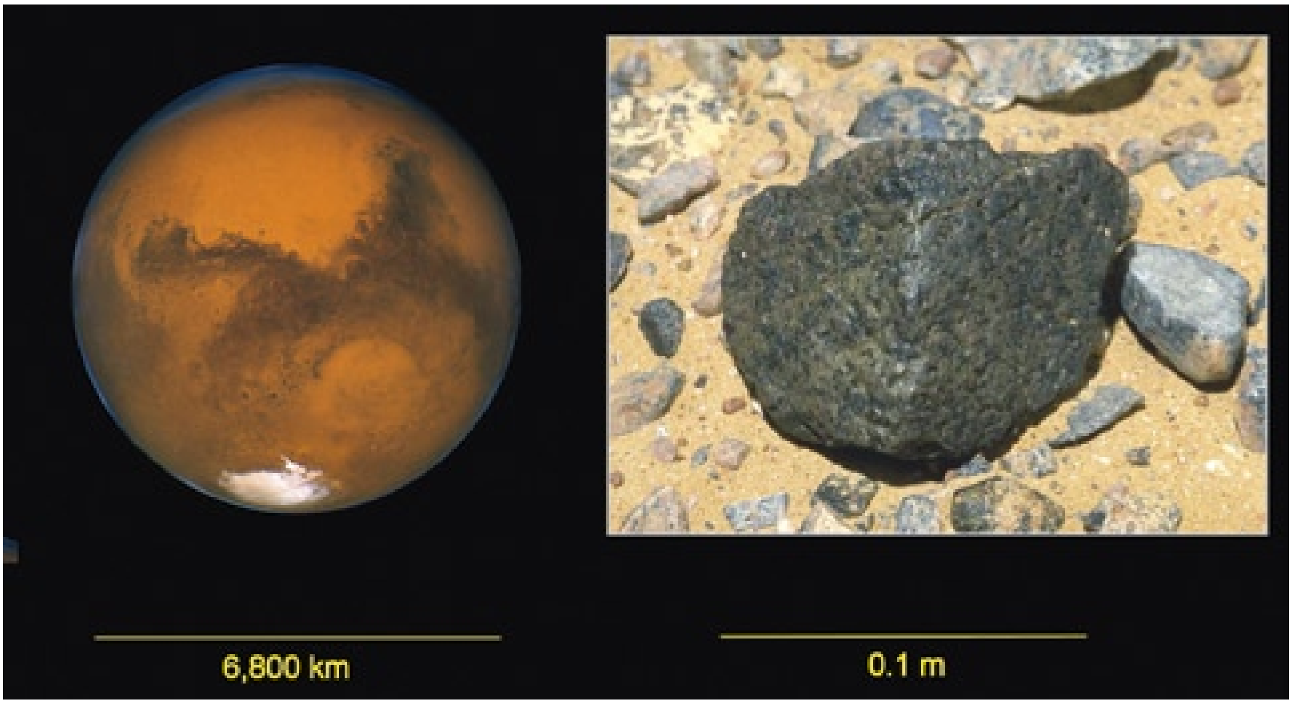


Fig 11: Mars meteorite Sayh al Uhaymir 094 on the Omani desert soil. The slightly greenish colour is characteristic for most Mars meteorites; the red colour of the Martian surface is due to a thin layer of iron oxides. (Credit: Peter Vollenweider). On the left an image from Mars by the Hubble Space Telescope is shown. (Credit: STScI)

tified as being of lunar origin. These meteorites greatly enhance our knowledge of the Moon, as the space missions could only cover a small part of the surface. The Moon is a large differentiated body, intermediate in size between asteroids and planets. Not surprisingly, its magmatic activity was much more extended than on asteroids but nevertheless ended more than one billion years ago.

Meteorite SaU 169 is a rather unusual lunar rock, **see Fig. 12.** Its origin is related to one of the very large impact events that formed the Moon's large basins. The rock is an impact melt breccia, a mixture of molten and unmolten rocks present at the impact site. SaU 169 shows the highest concentrations of uranium and thorium among all meteorites. This allows it to be linked to a relatively small area on the lunar surface thanks to the mapping of element-specific radioactivity performed by NASA's Lunar Prospector Orbiter in 1998-1999. Only very small areas of the lunar surface are as highly enriched in radioactive elements as SaU 169. Together with the characteristics of adhering lunar soil, the origin of SaU 169 could be constrained to an area near the crater Lalande. The age of the impact that formed the SaU 169 main lithology was dated at 3,909±13 million years, closely corresponding to the age of the Imbrium impact basin as determined independently. Large amounts of ejecta from the Imbrium impact event likely were transferred to Earth at that time, but the near-complete lack of terrestrial geological record of this time makes it unlikely that their traces will ever be found. SaU 169, however, remained on the Moon for a further 3.9 billion years until it was ejected during the formation of a rather small (probably a few kilometres in diameter) crater. It travelled in space for a maximum time of 340,000 years and fell in present-day Oman approximately 10,000 years ago.

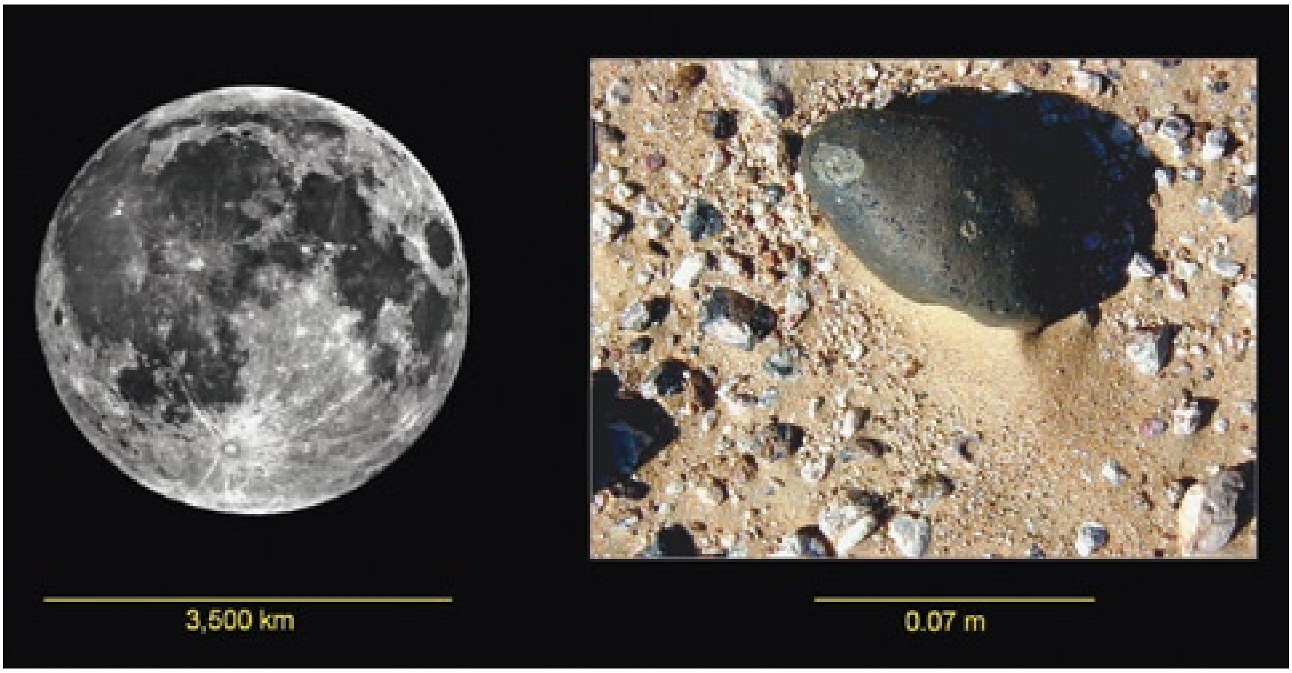


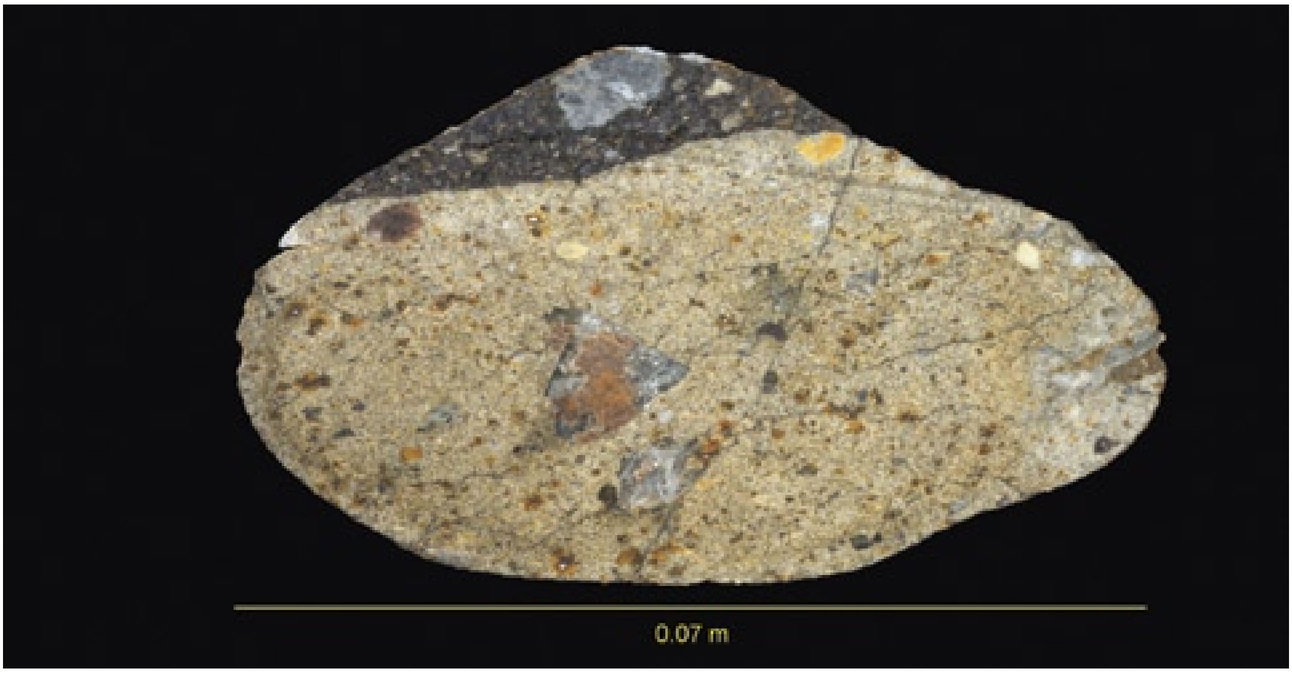
Fig. 12: Lunar meteorite Sayh al Uhaymir 169 as found in the desert (right). This meteorite likely stems from the Mare Imbrium on the upper centre of the lunar surface (left) from where it was expelled about 3.9 billion years ago. (Credit table on the left: Lick Observatory)

Outlook

Meteorites are very exciting and rare samples of other bodies in the solar system. They reveal detailed information about the history of their parent bodies and greatly enhance our knowledge about the origin and evolution of the solar system. Meteorites allow a hands-on investigation of asteroids, Mars and Moon and are complementary to information gathered by space missions. All opportunities to gather meteorites should be realized as it is the least costly way of getting more or less pristine extraterrestrial material. These include observed falls, systematic searches in Antarctica and in hot deserts, but also raising the awareness of the public about the scientific value of meteorites.

Among the hot desert areas, the Sultanate of Oman is in a unique situation as this country has very large areas suitable for meteorite recovery, and for 10 years all finds have been reported carefully with detailed localities. It is likely that Oman, perhaps with adjacent areas of the Arabian Peninsula, will become the prime area in the world where ancient meteorite finds are recovered at their site of fall.

Fig. 13: Cut slab of the same lunar meteorite Sayh al Uhaymir 169. Two distinct lithologies can be identified: the main part, an impact melt with fragments of older rocks, likely stems from the large meteorite impact that created the Imbrium crater on the Moon 3.9 billion years ago. The darker part is regolith, i.e. the remains of the lunar surface with many fragments of mare basalts (Credit: P. Vollenweider).



The Author

Beda Hofmann grew up in Neuhausen in Canton Schaffhausen near the Rhine Falls. With his father, a geologist, he started exploring and collecting rocks and minerals at the age of five during the time of the early manned space programs. Career plans thus shifted between geology and becoming an astronaut. He soon developed a fascination for meteorites and the first (unsuccessful) meteorite searches were performed on a field close to home. He started to study mineralogy and geology at the University of Bern in 1979 and concluded his PhD in 1988 working on the genesis and recent rock-water interaction in a uranium deposit in the Black Forest, Germany. During a post-doctoral stay at the U.S. Geological Survey in Denver from 1988 to 1990 he investigated altered organic matter in uranium deposits, effects of low-T redox geochemistry and uranium-series disequilibria in meteorite oxide fragments from the Cañon Diablo crater, Arizona. His search for meteorites in the Colorado plains remained unsuccessful. Beda Hofmann then moved back to Bern where he took the position as head of the Earth science department at the Natural History Museum Bern. He also started teaching at the Institute for Geological Sciences at Bern University.

Two lines of research have evolved since: I) Signatures of past microbial life from deep subsurface environments; and II) Meteorites. The first subject, based on both museum collections and fieldwork in California, Iceland and Switzerland, added Earth's unique factor life to purely inorganic mineralogy and has led to an involvement in projects searching for life on Mars and Astrobiology in general. He helped to found the European Astrobiology Network Association (EANA) where he is involved in ESA's planned ExoMars mission.

His early interest in meteorites evolved only slowly until meteorites started to be found in Oman in 1999. Based on existing collaborations between the University of Bern and the Sultanate of Oman, a first (finally successful) Omani-Swiss meteorite search campaign was carried out in 2001. So far nine search campaigns have been conducted in Arabia, making this the most continuous scientific meteorite search project outside Antarctica. The fascination of discovering rocks from space in the desert, and of deciphering their secrets remains unbowed. He also likes the chance to conduct scientific work in the frame of a different culture. To keep an eye on Switzerland, he has worked on the Swiss meteorite Twannberg.

Beda Hofmann likes contacts with the broad public at the Natural History Museum and enjoys to pass on some of the fascination for rocks, be they terrestrial or from space. He lives in a village near Bern and likes hiking, biking, camping and fire-making in the wilderness, with his three sons, a friend, or in solitude.