Lunar and Martian Meteorites

Aleksi Mattila
aleksi.mattila@student.oulu.fi

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Contents

1 Introduction

Meteorites have fascinated and frightened people throughout the history. In the poems of Kalevala a fiery spark falls from the sky causing fires, death, and darkness. This might be a description of the event where a meteorite hit the island of Saaremaa in Estonia, and created the Kaali crater. In prehistoric times meteorites have had a significant effect on evolution on Earth. The Yucatan impact 65 million years ago is thought to have caused the mass extinction event that wiped out the dinosaurs. Asteroids and comets impacting the Earth might have brought the water essential to the formation of life.

Meteorites are material from the times of the formation of the solar system. Their study gives us information of the conditions of the early solar system, which is otherwise very difficult to obtain. Some meteorites tell us about the compositions of asteroid classes they correspond to. Martian meteorites are the only samples of the Martian terrain we have on Earth, at least until a probe or a manned flight brings back some rocks.

I will first explain a little background information in the section 2.1. Then in section 2.3 I will talk about different meteorite types and their numerous subtypes. In section 3 I will go on to Martian meteorites and tell about their different classes. How their origins were determined is briefly explained in section 3.5. In section 4 I will talk about classification and recognition of lunar meteorites. Finally, in section 5 I explain how the ejection from Mars and Moon has been studied using simulations, and what the impact conditions must be to launch material into orbit.

Figure 1: "Meteor of 1860" by Frederic Church.

2 About meteorites

2.1 What is a meteorite?

Meteorites are natural objects that have fallen into Earth from space. They are often confused with meteors, meteoroids, and asteroids. The difference between an asteroid and a meteoroid is that meteoroids are usually smaller, and there has been enough observations of asteroids that their orbital elements can be calculated. Meteors are meteoroids that have entered Earth's atmosphere and are visible as streaks of light or fireballs. Meteorite is a meteor that has fallen all the way to the ground (Karttunen et al., 2016).

How do you know if a rock is a meteorite or just a regular stone? Most of them have fusion crust. It is usually a thin dark layer that was formed when molten surface of the meteorite cooled and solidified near the end of the fall through the atmosphere. Sometimes the fusion crust is eroded away because of terrestrial processes like rain and wind. Some meteorites have thumbprint-like impressions of varying sizes on their surface (figure 2). These impressions are called regmaglypts, and they are formed when molten material is ejected off the meteorite when it is passing through the atmosphere. There are of course other signs too, the meteorite can be visibly metallic, or the mineral composition may be different from the rocks on Earth. Usually the fusion crust, especially with regmaglypts, is sufficient to determine if a rock is or is not a meteorite. (Norton, 2002)

Figure 2: Mundrabilla iron meteorite sample with thumbprint-like regmaglypts. (Image credit: NASA/KSC, 2002)

2.2 Where to find meteorites?

Most meteorites are found in deserts, where vegetation cannot cover them. Also in Antarctica there is a large meteorite searching program called Antarctic Search for Meteorites, or ANSMET (Case Western Reserve University, 2019). They have found over 22000 meteorites. As the meteorites fall into the ice, they are carried by moving glaciers. In some areas, like near mountain ranges, the glacier stops. Then wind erosion exposes the meteorites from the ice. Because of this, there are some locations in the Antarctica where meteorites are found more than everywhere else. Dark meteorites are also relatively easy to see in the white snow. Meteorites are also often found in the deserts of Africa and the Arabian Peninsula.

2.3 Meteorite types

There are many ways that meteorites can be categorized into different groups. One method of classification separates meteorites to stones, irons and stony irons, and each of these has subgroups and they have more subclasses. This classification is coarse and mostly gives an initial description of the meteorites. Here chondrites and achondrites are subgroups of stony meteorites, but that is not always the case.

A more detailed classification system is described in the book Meteorites and the Early Solar System by Lauretta and McSween, 2006. There the meteorites are divided to three main groups: chondrites, primitive achondrites, and achondrites. Again, each of these are divided into many classes, groups, and clans. This is the classification system used in this paper.

2.3.1 Chondrites

Chondrites are the most numerous of meteorites. Their defining characteristic is that they all have small spherical chondrules, depicted in figure 3, in their matrix. The four major classes of chondrules are carbonaceous (C) chondrites, ordinary (O) chondrites, enstatite (E) chondrites, Rumuruti (R) chondrites. In addition to these groups, there are ungrouped chondrites. Chondrites formed in the early solar system. As such they are primitive and non-differentiated.

Carbonaceous chondrites usually (but not always) have high abundances of carbon, which makes them very dark. They have a large range of chondrule sizes, from 100 μm to 2 mm. C chondrites have 8 recognized groups: CI, CM, CO, CV, CK, CR, CB, CH (Lauretta and McSween, 2006). The groups have different abundances and sizes of chondrules, abundances of metals, and other compositional differences. All C chondrites show signs of aqueous alteration, and they contain more volatile elements than other meteorite types (Norton, 2002). Some C chondrites, like CO and CV contain less carbon than some ordinary chondrites.

Figure 3: Cut through of Allende carbonaceous chondrite. The light spots are chondrules. (Image credit: NASA/ARC, 1971)

CI chondrites do not have any chondrules. Still, they are considered chondrites because their overall composition is very similar to CM chondrites (Norton, 2002).

Ordinary chondrites are the most numerous of chondrites. They have higher abundance of chondrules, and lower abundance of matrix compared to other chondrites. O chondrites are divided into three groups based on their abundances of Fe and the ratio of metallic Fe and FeO. These groups are H, L, and LL, from the highest abundance of iron to the lowest (Lauretta and McSween, 2006). Mean chondrule sizes for the different groups are 300 µm for H, 500 µm for L, and 600 µm for LL (Norton, 2002).

Enstatite chondrites are primarily composed of enstatite. It is a magnesium based pyroxene mineral, that is sometimes used as a gemstone. E chondrites also have a high content of metallic iron, and they have very little oxidised iron but 5-17% iron sulfides. Of the stony chondrites only CH chondrites are richer metal. E chondrites have two groups: EH and EL. EH chondrites have on average 30% total iron, and EL chondrites have 25%. Average size of chondrules for EH is 220 µm, and 550 µm for EL. (Norton, 2002)

Rumuruti chondrites are brecciated with light clasts, or fragments of rock, embedded in dark matrix. They are mostly composed of Fe-rich olivine, with some plagioclase and small amounts of other minerals. R chondrites have the highest iron oxidation of all chondrites, and they have almost no free metallic iron. Mean chondrule diameter of R chondrites is 400 µm. (Norton, 2002)

2.3.2 Primitive achondrites

Primitive achondrites' textures suggest that they were at least partially molten, melt residues, or otherwise recrystallized. They have petrologic, chemical, and O-isotopic compositions and characteristics that are similar to chondrites, from which primitive achondrites presumably formed. At some point in their lifetime they exceeded their solidus temperature, meaning that the solid material can melt (or can start to melt) at least partially. Primitive achondrite groups are Ureilites, Acapulcoite-Lodranite Clan, Brachinites, and Winonaites and IAB and IICD Iron Clan. (Lauretta and McSween, 2006)

Ureilites are monomict, or polymict breccias. This means that they are composed of single or multiple minerals. Breccias are formed of shattered minerals and rock cemented together by a matrix. Their textures and other features indicate that they are highly fragmented rocks from an achondrite parent body. (Lauretta and McSween, 2006)

2.3.3 Achondrites

The class of achondrites contains irons, stony irons and stones that most probably have originated from differentiated parent bodies. When one asteroid collides with another, usually fragments are chipped off. Those fragments then might eventually fall to Earth and become meteorites. Iron meteorites are thought to originate from the cores of differentiated asteroids. Achondrites' hierarchical terms are not applied as rigorously as with chondrites. Achondrites are sorted into many smaller groups, unlike chondrites, which have few classes with multiple clans, groups, and subgroups. (Lauretta and McSween, 2006)

2.4 Distribution of meteorite parent bodies in the Solar System

Most of the meteorites found on Earth can be associated with a type of asteroid. Asteroids are classified according to their spectral properties. Minerals in the surface of an asteroid absorb specific wavelengths of sunlight. From that we can learn much about their composition. Most asteroid parent bodies are located in the Main Asteroid Belt, at 2-4 AU. Even though it would seem like a chaotic and homogeneous system, there is structure in the distribution of different asteroid types in different parts of the belt.

In the inner belt, at around 2-2.5 AU, most of the asteroids are E and S type asteroids. E asteroids correspond to aubrites, which are a type of achondrites. S asteroids are possibly ordinary chondrites, but that is not certain. The middle belt has a high population of C asteroids, with some S and P asteroids. This is also where most of the M asteroids are, even though they are only about 15% of the population. C asteroids are thought to be parent bodies of CM carbonaceous chondrites. P and M asteroids are associated with E chondrites and iron meteorites. The highest concentration of P asteroids is in the outer belt. Parent bodies of other C subtype meteorites can be found almost anywhere in the main belt. This information is gathered into table 1. (Norton, 2002)

Table 1: Some of the primary asteroid spectral types with their corresponding meteorite classes and locations in the solar system (Norton, 2002).

Type	**Meteorite association**	**Location**
E	Aubrites	Inner Belt
S	Possibly OC, mesosiderites	Middle to inner belt
M	E chondrites, irons	Central belt
P	E chondrites, irons, lower albedo	Outer belt
C	CM carbonaceous chondrites	Middle belt, 3.0 AU
B/F/G	C subtypes	Inner to outer belt

2.5 Naming convention

Meteorites are named after the location and the year they were found. If multiple meteorites have been found in the same area, the name is usually followed by a number (Norton, 2002). For example ALH84001, a well-known Martian meteorite, was found in Allan Hills region, Antarctica, and it was the first meteorite found in 1984.

3 Martian meteorites or SNCs

Martian meteorites are very rare, and only 231 have been found at the time of this writing. That is under 0.01% of all meteorites found (Meteoritical Bulletin Database, 2019). The first Martian meteorite was the Chassigny meteorite, which was found in 1815. After that, there were the Shergotty meteorite in 1865, and the Nakhla meteorite in 1911. All Martian and Lunar meteorites are members of the achondrite group. Their Martian origin was not clear until it was all but proved in the year 2000, thanks to the evidence the meteorite EETA79001 provided. More on this later in the chapter.

The name SNC comes from the three most common types of Martian meteorites: shergottites, nakhlites, and chassignites. The names of these three groups come from the locations where they were first discovered. Shergottites are named after the Shergotty meteorite found in Shergotty, India. Nakhlites after the Nakhla meteorite from El-Nakhla, Egypt. And chassignites after the Chassigny meteorite from a French town of Chassigny. These are only the most common types of Martian meteorites, and there are meteorites that do not fit into any of these three groups (Treiman et al., 2000).

3.1 Shergottites

Shergottites are the most common type of Martian meteorites, and they can be classified into various groups based on their mineral structure and crystal size, rare-earth element (REE) content, or other criteria. Usually they are divided into following three groups: basaltic, lherzolitic, and olivine-phyric shergottites (Nyquist et al., 2001,Goodrich, 2002).

Basaltic shergottites consist of mostly of basalts, such as augite and pigeonite. Some basaltic shergottites have a structure that has a matrix of clinopyroxene with olivine xenocrysts, foreign crystals included in an igneous body (Nyquist et al., 2001). Some examples of basaltic shergottites are Shergotty and NWA 480. (Goodrich, 2002)

Lherzolitic shergottites are composed of maskelynite and pigeonite with coarse-grained olivine and chromite crystals in orthopyroxene. Examples of lherzolitic shergottites are ALH77005 and LEW88516 (Nyquist et al., 2001).

Olivine-phyric shergottites are sometimes called "mixed shergottites", "transitional shergottites", and various other names. They are somewhat like basaltic shergottites, in that their groundmass is clinopyroxene. What makes them different, is that they have crystals or grains much larger than the surrounding matrix, called megacrysts, of orthopyroxene and chromite, in addition to olivine. Examples of this type are EETA79001 (lithology A) and NWA 1195 (Goodrich, 2002).

3.1.1 Shergottite ages

The ages of shergottites, and other meteorites and stones, can be determined by radiometric dating. When the rocks are formed from liquid magma, some radioactive impurities get incorporated in the rock. Then as the impurities decay, the abundances of decay products can be measured. From that we can estimate the age of the rock.

All shergottites have crystallized approximately 165-475 million years ago. This means that they are relatively young compared to the average age of the Martian surface. This presents a problem, as most of the SNCs are shergottites, and most of the surface of Mars is very old. The precentage of shergottite-aged surface is under 10% of the total Martian surface. This is known as the shergottite age paradox, and it remains a mystery (Nyquist et al., 1998).

Most of shergottites were probably ejected in a relatively recent impact. One exception being Dhofar 019, with an ejection age of about 20 million years. Lherzolites were ejected 3.8-4.7 million years ago, six basalts have ejection ages of 2.4-3.0 million years, five olivine-phyrics about 1.2 million years, and EETA79001 0.73 ± 0.15 million years. Ejection ages can be determined by measuring how long the meteorites have been exposed to cosmic radiation, which can cause nuclear reactions that produce various unstable nuclides. The cosmic-ray exposure (CRE) age can then be determined by measuring the abundances of these radionuclides (Nyquist et al., 2001, Lauretta and McSween, 2006).

3.2 Nakhlites

Nakhlites are composed of mostly clinopyroxene, which is a common component of basalts. All nakhlites have moderately high contents of volatiles and are enriched in light rare-earth elements (LREE). Their compositions are different from those of shergottites, which indicates that they have formed from different magmas. Nakhlites are cumulates, which means that when the magma cools down and forms crystals, they either sink to the bottom of the magma pool, or in some cases float to the top. Either way, this creates layers of accumulated crystals (Nyquist et al., 2001,Treiman, 2005). If the cooling is too rapid this cannot happen, because the minerals do not have enough time to settle into differentiated layers.

Mineral chemistry and patterns of nakhlites are similar to terrestrial, lunar and asteroidal basalts but they contain about 75% augite, a pyroxene mineral often found in basalts. Their overall microstructure is very similar to terrestrial basalts, and almost identical volcanic and basaltic rocks have been found on earth (Treiman, 2005).

Nakhlites formed about 1.3 billion years ago. In addition to the material crystallized directly from magma, nakhlites contain iddingsite, which is a form of basalt weathered by liquid water. The presence of iddingsite in nakhlites confirms that there has been liquid water on mars (Nyquist et al., 2001). All nakhlites were ejected in the same impact about 10.6 million years ago (Lauretta and McSween, 2006).

3.3 Chassignites

Chassignites are relatively rare among the Martian meteorites. Only three have been found (Meteoritical Bulletin Database, 2019). They are composed of mostly olivine, and are cumulates like nakhlites (Treiman et al., 2000). Chassignites and Nakhlites have many other similarities too. Both are enriched in LREE, but their abundances are different, which indicates that they have formed from different magmas. They both formed around the same time, 1.3 billion years ago. It is also possible that they were ejected in the same impact event. Chassignites' ejection ages are 11.1 $\pm$ 1.6 million years (Nyquist et al., 2001, Lauretta and McSween, 2006).

3.4 Some interesting individual meteorites

3.4.1 ALH84001

The Allan Hills 84001 meteorite is drastically different to SNCs in its composition, being mostly low-calcium orthopyroxene. It is the oldest known Martian meteorite, having been formed about 4.5 billion years ago (Nyquist et al., 2001), and its ejection age is 15 million years (Lauretta and McSween, 2006). It is also the only orthopyroxene Martian meteorite found.

It contains spherical carbonate deposits that formed when the atmosphere of Mars was denser and conditions milder. The deposits are surrounded by magnesium and iron rich compounds. These structures are very similar to ones that some bacteria on Earth can produce. So in 1996 it was announced that proof of life on Mars had been found.

Other features that suggest microbial life in the carbonate deposits are polycyclic aromatic hydrocarbons or PAHs. They can form when dead micro-organisms are heated. These might originate from cooked Martian bacteria, or they could just be contamination from Earth and Antarctic ice, or even from carbonaceous chondrites, which often contain PAHs. It might be possible that the Martian surface had been contaminated with residual PAHs from C chondrites. But the precise origin of PAHs in ALH84001 is still unclear. There are also bacteria-like structures in the carbonate deposits (figure 4). The structures are a lot smaller than bacteria found on Earth, and they would probably be too small to support life as we know it.

Moreover, similar structures can form without biological processes, and there are compounds that have been shown to be terrestrial contaminants. Nowadays it is generally thought that these structures and other evidence are not enough to prove that Mars has or had bacterial life. Until we can get uncontaminated rocks from Mars, we cannot really be sure either way. (Lauretta and McSween, 2006, Norton, 2002)

3.4.2 EETA79001

The previously mentioned shergottite EETA79001 is unique. It has two different rock types, called lithologies A and B. Both lithologies are considered shergottites, but A is olivine-phyric and B is basaltic. Most of the meteorite is composed of lithology A. The lithologies have a nonbrecciated contact, which means that it was

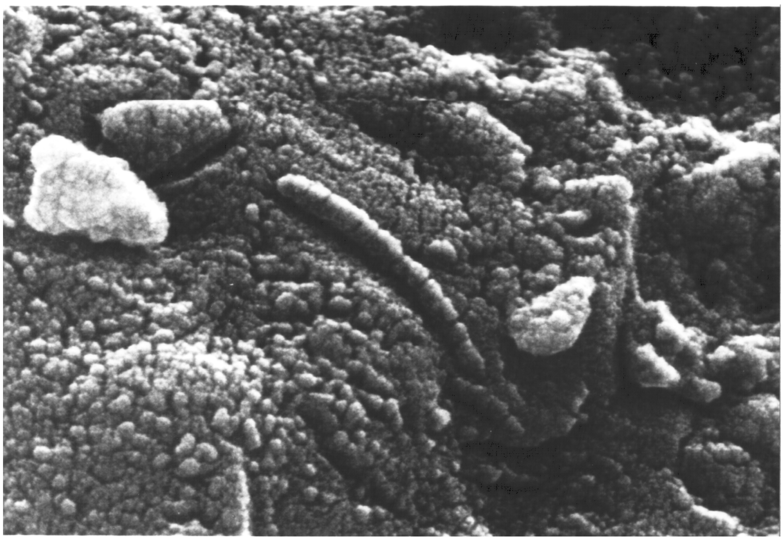

Figure 4: Electron microscope image of a bacteria-like structure on ALH84001 meteorite. The structure is 100 nm long. (Image credit: NASA/JSC/Stanford University, 1996.)

formed in an igneous process. This makes it different from most meteorites. It has been suggested that lithology A is an impact melt. (Goodrich, 2002)

When EETA79001 was found, it was classified as basaltic shergottite. After other meteorites similar to lithology A were found, the olivine-phyric shergottite group was created (Goodrich, 2002). EETA79001 also has glassy inclusions that contain trapped gases from Martian atmosphere, which proved that SNC meteorites actually are from Mars (Norton, 2002).

3.5 Origins

But how can we be sure that these meteorites are from Mars and not from some other celestial body? Since we do not have any return samples from Mars, we have to find other evidence of their origin. This evidence includes the composition of trapped gases, geochronology and other factors. Content of this section relies on Treiman et al., 2000.

The most convincing evidence of their origin comes from the trapped gases. The composition of Martian atmosphere was analysed by the Viking landers in 1976. The abundance ratios of CO_2, N_2, and noble gases differ from other atmospheres and reservoirs in the solar system. The SNC meteorites contain trace amounts of volatiles trapped in glass inclusions produced in the impact. Comparing the abundance ratios of the trapped gases and the Martian atmosphere (figure 5) we can see that they are nearly identical. Ratios also differ substantially from solar abundance and all other reservoirs, such as CI carbonaceous chondrites, Venus, and Earth.

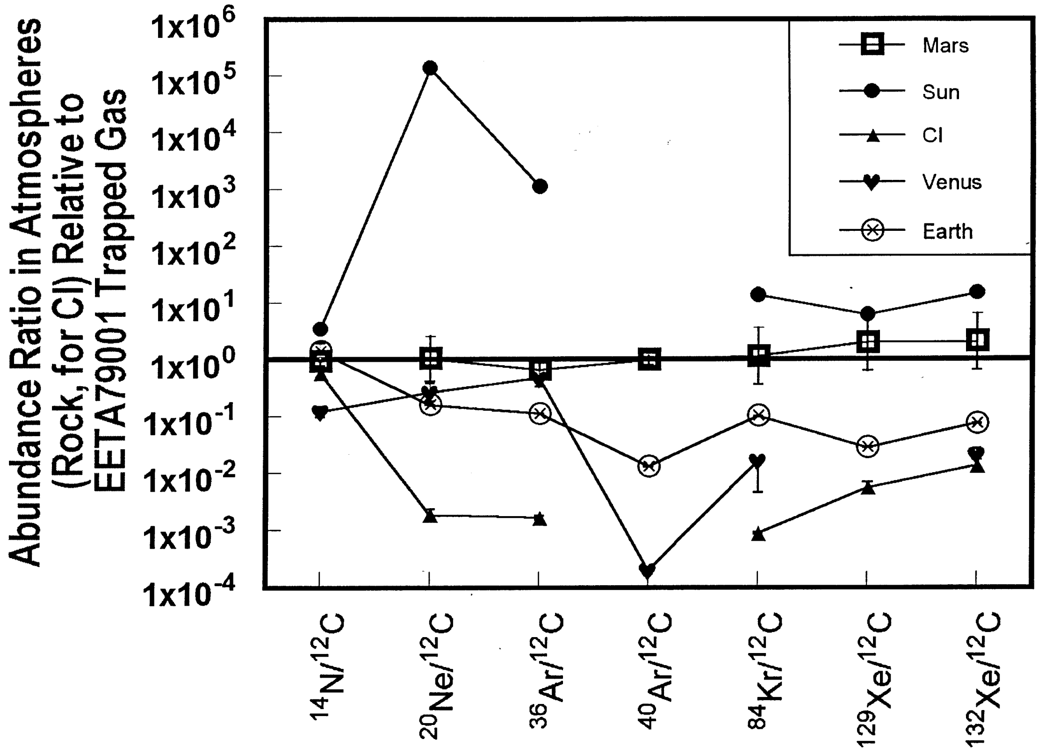

Figure 5: Abundances of elements in solar system atmospheres compared to trapped gas found in shock-glass nodules of Martian meteorite EETA79001. (Figure from Treiman et al., 2000.)

4 Lunar meteorites

The first lunar meteorite, called ALH81005, was recognized in 1982. There were other meteorites found before that but they were not recognized as lunar meteorites until later. Meteorites from the Moon are more common than Martian meteorites, but they contribute less than 0.01% of all meteorites. They are very similar to the samples brought back to Earth by lunar missions (Lauretta and McSween, 2006). Their ejection ages are up to 10 million years. Lunar meteorites can come from all over the Moon, unlike the rocks brought back by Apollo missions, which were gathered from a relatively small area. So the meteorites give us more information of the general composition of the Moon (Norton, 2002).

4.1 Classification

Lunar meteorites can be classified by their mineralogy, texture, petrology, and chemistry. Rocks are also divided by different areas of lunar surface. The two principal types of terrain are the mare, or the seas, and the terra, or highlands. These terrain types correspond to the most common lunar meteorite types, which are mare basalts and regolith breccias (Norton, 2002). Regolith is the loose surface soil covering the solid bedrock.

Rocks from the highlands are mostly anorthosites, which are composed of mostly calcium-rich plagioclase. Plagioclase is a type of feldspar, and feldspars are one of the most common minerals on Earth and the Moon. Rocks from the maria are basalts that consist of mostly pyroxene and plagioclase (Korotev, 2018). The basaltic rock and the maria formed when magma erupted into the basins created by impacts in the early lunar history. Some lunar rocks are breccias. They are composed of fragments of rock cemented together by a finer material, such as glass, densely packed dust, or crystallized melt. There are many types of breccias depending on their composition and the way they were formed (Norton, 2002).

Generally, most rocks from the lunar highlands are breccias. The highlands crust is very old and heavily cratered, so there has been a lot of time for the impact breccias to form. The reason why most of the mare rocks are not breccias is that when the maria formed the impact rate had already dropped. Mare basalt meteorites are much rarer than the regolith breccias from the highlands, as the maria cover only under a fifth of the lunar surface (Norton, 2002).

4.2 Origin

The lunar origin of the first recognized lunar meteorite, ALH81005, was determined by its anorthositic composition, and ratios of MnO and FeO. Anorthosites are common in lunar highlands, and ALH81005 and rocks brought back by Apollo 16 have very similar glass compositions. The FeO/MnO ratio of pyroxene in ALH81005 is similar to lunar rocks (Marvin, 1983).

The breccia of the meteorite contains glass spherules, and its fusion crust has vesicular patches, which were formed when the glassy parts melted on atmospheric entry. These properties indicate that it has originated in lunar regolith. Another indication of it is that ALH81005 has trapped gas particles from the solar wind in its matrix. This indicates that the material must have been on a surface exposed to the solar wind before the breccia's formation (Marvin, 1983, Bogard and Johnson, 1983).

5 Launch and delivery of meteorites from Mars and Moon

5.1 Ejection from the Martian surface

The material presented in this section relies on Head et al., 2002. They used simulations of impacts of different sized objects into various types of Martian terrain to see which kind of craters might be sources for Martian meteorites. Those simulations were then be used to estimate the impact conditions required to send material to orbit.

From the meteorites found on Earth, several constraints can be applied. Shergottites are relatively young and basaltic, so they must originate from a region on Mars where there is less loose Martian surface soil, regolith, covering the bedrock. Namely, on young Martian surfaces the thickness of regolith is about one meter. Older surfaces have had more time to accumulate regolith, and their regolith thickness can be tens of meters. The most ancient meteorites, such as ALH84001, come from heavily cratered terrain that today can have hundreds of meters of regolith.

The sizes of fragments ejected from Mars can be determined by studying the ablation of different types of meteorites in the Earth's atmosphere. It has been shown that most of the Martian meteorites found on Earth were less than half a meter in diameter before entering Earth's atmosphere.

Some estimates for the shock pressures experienced in the impact can also be made. Shock pressures are usually around 30-45 GPa, but the estimates are uncertain. It can be assumed that the shock pressures are less than 60 GPa, as that would be enough to completely melt the rocks.

The rocks also lack evidence for cosmic rays coming from only one direction, as it would be the case for a rock on a planetary surface. Therefore it can be concluded that the material has been shielded from cosmic rays while being Mars. The Martian soil absorbs almost all cosmic radiation fairly efficiently at 1 meter depth. Therefore it is likely that the Martian meteorites found on Earth originate from at least 1 meter depth on Mars. To be safe, in the simulations by Head et al, 2002, all material up to 2 meters from the surface was excluded from the results.

Finally, the amount of ejected Martian objects that reach the Earth within 10 million years is about 5% of all ejected material. The meteorites stay on the surface of Earth for a limited time, which is usually about 10^4 years before they erode away. Then, the surface area of Earth that is actively being searched for meteorites is less than 0.1%. The most searched areas being Antarctica and the deserts of Africa and the Arabian Peninsula. Most of our planet is covered by oceans and finding meteorites from them is very difficult. By combining all these factors, Head et al. estimated that the probability of finding a Martian meteorite on Earth is between 10^{-6} and 10^{-7}.

Based on these constraints conditions can be formulated for impacts on Mars that can launch material to orbit. The ejection velocity must be higher than the escape velocity of 5 km/s, material must come from the depth of 2 m or more, shock pressures must be less than 60 GPa, and fragments must have a diameter larger than 3 cm, and there must be more than 10^6 fragments ejected in an impact. The simulations by Head et al. were made to meet these criteria.

According to the simulations, it can be estimated that the impacts required for a fragment to reach the escape velocity of Mars typically create craters at least 3.1 km in diameter. Craters that small require a homogeneous basalt surface hit by a projectile 150 m in diameter travelling at 10 km/s. The largest crater this simulation could create is 6.7 km in diameter, with an impactor of 400 m in diameter. These impacts create fragments that are almost the correct size for Chassignites and Nakhlites. Thus it can be estimated that the minimum diameter of craters for those meteorites is 7 km. (Head et al., 2002)

The thickness of regolith affects the size of craters and velocity of ejected material. A thick layer of regolith dampens the shock wave of impact more efficiently than solid rock. As a result, the velocity of fragments falls faster when the distance from the impact point increases, than it would with solid basalt. This means that meteorites from older regions of Mars require larger impact events, as can be seen in figure 6. Then again, if an impact happened billions of years ago, the layer of regolith might have been thinner. Then the impacts possibly would not have had to be so large.

The number of source craters can be determined by using the equation

$$N = t_{CRE} \times f_p(D) \times R \times \text{area} \times f_{sfc} \tag{1}$$

where N is the number of source craters, t_{CRE} is the ejection age of a meteorite, which is the sum of cosmic-ray exposure age and terrestrial residence age, $f_p(D)$ is a lunar crater production function for craters with diameter D or larger. R is the ratio of Mars/Moon impact flux, "area" is the surface area of Mars, and f_{sfc} is the fraction of Martian surface of specific age. Using the equation we get two to four source craters for shergottites, one to two for nakhlites and Chassigny, and about one for ALH84001. These numbers fit the hypothesis that the Martian meteorites come from several small craters. (Head et al., 2002)

It must also be noted that shergottite producing events can happen with smaller intervals than the terrestrial delivery age, and larger impacts that produce the more ancient material like ALH84001, are much rarer. So a steady influx of shergottites can be expected, while the ancient material might have come from large single impacts. This might be a possible solution for the shergottite age paradox.

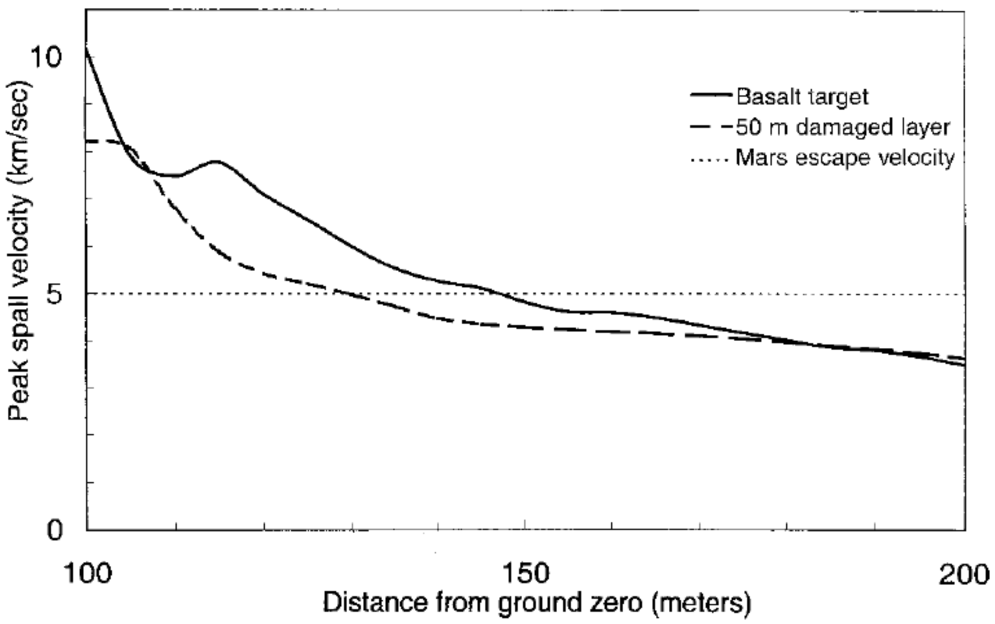

Figure 6: The velocity of ejected material, called spall velocity, as a function of distance from the impact location in identical impacts. Solid line is for the velocity of ejected material from an impact with solid basalt, and dashed line represents the velocities when there is a layer of regolith 50 meters thick above the basalt. (Figure reproduced from Head et al., 2002.)

5.2 Lunar ejections

Compared to Mars, ejection from the Moon requires smaller impacts. The escape velocity of the Moon is only about 2.4 km/s, which is just under half of the escape velocity of Mars. Like the Martian ejections, lunar ejections have been studied using simulations by Head, 2001. He showed that the smallest craters produced by impacts that can eject material of correct size to orbit are 1.1 km in diameter. However, he concludes that smaller craters are possible sources too, as they eject fewer 10 cm fragments, but enough fragments smaller than that to be the source of lunar meteorites.

Furthermore, the number of 1.1 km impact events in the last 10 million years is estimated to be 10, and only one in the last 0.1 Ma. At the time this study was made, there were 7 impact events represented in the meteorites found with CRE ages of 0.1 Ma or less. If the minimum crater size was 450 m, the expected number of impacts in 0.1 Ma is 6, which seems more reasonable. So the minimum crater size is probably around 450 m.

Good regolith models have not been incorporated in the study. A layer of regolith did not seem to significantly affect the ejection velocities and shock pressures. On Mars, the layer of regolith lowers the number of fragments ejected at 5 km/s, but more fragments are ejected at 2.5 km/s. So the regolith on the Moon might have a different effect than on Mars.

5.3 Other sources?

So why have we not found meteorites from other planets, like Venus or Mercury? Technically it is possible, but the chances of finding a meteorite originating from Venus, Mercury, or other planets or moons are very small. In case of Venus, the escape velocity is 10.4 km/s, and the planet's thick atmosphere makes reaching such velocities difficult. This means that significantly larger impacts are required in order to eject as much material as on Mars, as the probability of a fragment hitting Earth is proportional to the number of fragments ejected.

Mercury on the other hand has a little lower escape velocity than Mars, but the distance from Mercury to Earth is so large that the probability of an ejected meteoroid hitting Earth is very low. But if we get really lucky, it could be possible to find meteorites originating from Venus, Mercury, or even some moons of the gas giants (Lauretta and McSween, 2006).

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