The history of research on meteorites from Mars

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Abstract: It has been almost 25 years since the widespread acceptance of the presence of meteorites from Mars in the world's collections. The martian meteorites differ from meteorites from the asteroid belt in that they have crystallization ages younger than 4.568 billion years; evidence for a martian origin rests on the presence of trapped martian atmospheric gases within the specimens. The first three martian meteorites, Shergotty, Nakhla and Chassigny, gave their names to the groups into which the specimens were all placed: the SNCs. Since then this group has grown to over 30 members, and is divided into seven subgroups. The acronym 'SNC' is no longer appropriate, and the meteorites are simply referred to as 'martian'. The meteorites are all igneous, most are shocked and many show evidence of martian aqueous activity. Study of martian meteorites is a valuable complement to spacecraft observations of Mars, and helps in the understanding of primary magmatic and secondary alteration processes occurring on Mars.

Early in the morning of 5 October 1815, in the tiny village of Chassigny, near Langres, Haute Marne in France, the local villagers were disturbed by the rattle of musketry and the sound of cannon-fire. Startled, they rushed to see the cause – only to find that their village had been invaded, not by retreating soldiers from Napoleon's defeated army as had been their first thought, but by visitors from further afield. What happened in Chassigny that morning was the fall of a shower of meteorite stones. So disturbed were the citizenry, that they persuaded the local doctor, M. Pistollet, to collect some of the stones and convey them to l'Académie des Sciences in Paris, thus preserving the material for future generations (Pistollet 1816). We now believe that the meteorite fall of 1815 was our first recorded messenger from Mars, arriving on Earth in a storm of (albeit local) publicity. Fifty years later, quietly and with little fuss, a second visitor from the red planet arrived, landing over the remote Indian village of Shergotty, in Bihar district on the fringe of the Patna hills (Costley 1865). The third uninvited guest was also a newsworthy event, when it arrived early on a summer morning in 1911 in the Egyptian village of El Nakhla el Baharia on the borders of the Nile delta (Hume 1911; Prior 1912). The shower of stones appeared out of a cloud, accompanied by loud detonations. It was claimed that one of the stones killed a village dog, but this is likely to have been one of the local chiefs trying to ensure that his village became part of the event, as the timing and location of the claim do not fit with eyewitness accounts of the meteorite fall (Hume 1911).

These eventful passages mark the start of a fascinating story of exploration of our neighbouring planet. Meteorites from Mars have landed all over Earth, bringing with them information about Mars' atmosphere, both now and in the past, about the surface of Mars and the waters that once flowed there, and the deep reservoirs of magma that form the roots of the mightiest volcanoes in the solar system. This paper is an account of how martian meteorites came to be recognized, and what we have learnt about Mars from them.

Early interpretations of SNC meteorites

Lead–lead age dating of meteorites found that chondritic (i.e. non-melted) meteorites had very old ages, approximately 4.55 billion years. This was taken to be the age of the solar system, and the time at which asteroids formed (Patterson 1956). Shortly after the antiquity of meteorites was established, one of the first K–Ar studies carried out identified Shergotty as being much younger than other achondrites (i.e. melted meteorites) (Geiss & Hess 1958). The reason for this was not known, but the possibilities of

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0305-8719/06/$15.00

either addition of potassium through contamination or loss of argon through solar heating whilst in orbit were considered and rejected by the authors. As age-dating became an established and relatively routine procedure, several more igneous meteorites with anomalously young crystallization ages were recognized (e.g. Gale *et al.* 1975; Nyquist *et al.* 1979; Nakamura *et al.* 1982). These young meteorites also had related oxygen isotope compositions that differed from other meteorite groups (Clayton & Mayeda 1983), and thus they were grouped together as the SNCs, named after the first three falls described in the opening paragraph (Shergotty, Nakhla and Chassigny). Chassigny and the nakhlites had Rb–Sr ages around 1300 Ma, whilst shergottites were even younger, at around 165–200 Ma (Nyquist *et al.* 1979). The most straightforward explanation of these relatively recent ages was crystallization from a melt. However, this then implied that igneous activity had continued long after it had been assumed the asteroids had cooled and solidified. There were many ad hoc attempts to explain the ages, including scenarios that proposed secondary heating and melting episodes brought about by impact (e.g. Nyquist *et al.* 1979; Vickery & Melosh 1983) or complex magmatic histories (e.g. Shih *et al.* 1982). By 1980 there had been several suggestions that the SNC meteorites came from a much larger body than an asteroid, and that such a body had to be planetary (McSween *et al.* 1979; Walker *et al.* 1979; Wasson & Wetherill 1979). It was not known whether the diverse group of rocks, now grouped together as the SNCs, came from one or multiple parent bodies. Several authors, almost simultaneously, proposed that Mars would be the most logical and likely place from which the SNCs originated (e.g. Wood & Ashwal 1982). But dynamical considerations argued strongly against their origin from Mars, mainly because the ejection mechanism was thought to be via volcanic eruption (e.g. McSween & Stolper 1980).

A new chapter opened in the story of the SNC meteorites when ALH A81005 was returned from the Allan Hills region of Antarctica, and classified as a lunar meteorite. Description of this small (31.4 g) specimen were remarkably consistent, and acceptance of its lunar origin was unanimous (Marvin 1983). The reason that consensus could be achieved so readily was because ALH A81005 could be compared with the *Apollo* and *Luna* samples returned directly from the Moon. The lunar meteorite was identical to *Apollo* and *Luna* samples in mineralogy, mineral chemistry and isotopic composition. Cratering of planetary surfaces by asteroidal impact had been considered as an important process for modifying planetary surfaces (e.g. Hartmann 1977), but from the dynamics of such a process, the ejection of large amounts of material was thought to be unfavourable (Melosh 1984). Identification of ALH A81005 as lunar showed that material could indeed be removed from the Moon and land on Earth. Critics of a martian origin for SNCs had argued that if meteorites could come from Mars, then they would certainly come from the Moon, and did not seem to have done so. With acceptance of a lunar origin for ALH A81005 came realization that one of the most fixed arguments against martian meteorites, that of the lack of lunar meteorites, had been removed. Even so, this observation was not sufficient to assign the SNCs to a martian parent.

The martian origin explained

As described above, the SNC meteorites were recognized on the basis of their young crystallization ages being different from asteroidal meteorites, long before their martian origin was accepted. There are melted and differentiated meteorites from the asteroid belt, but, although they are younger than the primitive, unmelted chondrites, they still have crystallization ages within about 10 Ma or so of chondrites (e.g. Wadhwa & Russell 2000). In contrast, all but one of the SNCs seem to have crystallization ages of between 165 and 1300 Ma (Nyquist *et al.* 2001). In other words, they have come from a body that may have supported molten rocks as recently as 165 Ma ago. This cannot be the asteroid belt. There are few rocky bodies in the solar system to which this applies: Venus, Earth, the Moon, Mars and some of the satellites of the giant planets. In order to be convinced that Mars is the parental source it is possible, by a process of elimination, to discount many potential source regions within the solar system.

The SNCs are all igneous rocks, i.e. they emanate from regions of molten rock. Comets and Kuiper Belt objects (including Pluto) can thus be eliminated from consideration, on the grounds that they are primitive undifferentiated objects, i.e. they have never been molten. The gas giants (Jupiter and Saturn) and the ice giants (Uranus and Neptune) are eliminated on the logical grounds that they are made of predominantly gas, or gas and ice, rather than rock. Although these planets no doubt do have rocky layers, they are so deep within the gravitational well of each planet that ejecta would be unable to survive escape, even assuming that an object were able to survive passage down through the atmosphere to encounter rock. There were several large impacts on Jupiter in 1994, when comet Shoemaker-Levy/9 hit the planet in a series of collisions over a period of several hours. The energy of the largest impact has been calculated as *c.* 25×10^{18} MJ (Carlson *et al.* 1997); the resulting plume of ejecta was detected as a column that rose approximately 3000 km above the top of the atmosphere, before mostly falling back (Hammel *et al.* 1995; for comparison, the energy of the atomic bomb exploded over Hiroshima was *c.* 60×10^6 MJ, with an ejecta plume that rose approximately 17 km). No large blocks of ejecta resulting from the impact have been reported. It might also be argued that there are rocky satellites of the giant planets from which solid ejecta could be removed – and this is, indeed, true. However, given the enormous gravitational pull of the parent planets (e.g. Jupiter's effect on Io is so great that it keeps the innermost part of the satellite molten, making Io the most volcanically active body in the solar system), it is logical that any debris thrown up during impact would be drawn immediately into the planet.

So much for the outer part of the solar system. The inner, rocky, planets are much more feasible sources of the SNC meteorites than the outer giants, on the basis of composition and relative size. Given that the asteroids have been eliminated on the basis of crystallization age, that leaves five objects to consider: Mercury, Venus, Earth, the Moon and Mars. There have been calculations that show how much material is exchanged between bodies in the inner solar system (Melosh & Tonks 1993; Love & Keil 1995; Gladman *et al.* 1996). Mercury's small size, low escape velocity (4.3 km s^{-1}) and lack of atmosphere are all characteristics that combine to allow fairly ready removal of material from its surface (Love & Keil 1995). However, the main barrier to meteorites coming from Mercury is its location so close to the Sun – not only will potential impactors be more likely to fall into the Sun than onto Mercury, but ejecta excavated from the surface will also be more likely to be pulled towards the Sun than projected outwards. There are different problems associated with removing ejecta from Venus' surface. Venus is a similar size to the Earth, and has a similar escape velocity of 10.4 km s^{-1}, so it is immediately more difficult to remove material from Venus than Mercury. Size, however, is not the determining factor, but the presence of an atmosphere. Venus has a thick atmosphere (*c.* 90 bar) of CO_2. Any incoming impactor is (a) decelerated and (b) ablated during passage through this atmosphere, resulting in a less energetic collision by a smaller body than would be the case if a similar-sized body impacted Mercury. Following on from this, the ejecta removed from Venus' surface will also be ablated and decelerated as it is projected back up through the atmosphere. Finally, the high escape velocity of Venus causes a large proportion of ejecta to fall back to its surface. Thus, for different reasons, there is only a very small, but finite, chance of material arriving on Earth from either Mercury or Venus. There was a suggestion that the unusual basaltic meteorite NWA 011 might be from Mercury (Palme 2002), because this meteorite has an oxygen isotopic composition different from any other meteorite group (Yamaguchi *et al.* 2002), but the suggestion has been neither verified nor taken seriously by meteoriticists. Even so, it is not possible to discount Mercury and Venus as sources of the SNCs, although, as will be shown in a later section, there is more compelling evidence that eliminates them as source objects.

The Earth–Moon system might also be considered as a source of the SNCs. But there are convincing arguments against both bodies. For the Moon, there are *Apollo* and *Luna* samples that were returned directly to Earth by astronauts; the samples all have older ages than the SNCs, and are mostly fragmental breccias rather than igneous cumulates and basaltic flows (e.g. Taylor, 1982). On logical grounds, Earth could be the source of SNC meteorites: there are plenty of young igneous rocks on Earth and, dynamically, it is possible to produce a crater from which ejecta fall back at the speeds required to produce a fusion crust (Melosh & Tonks 1993). Arguments based on composition, rather than dynamics, are how the Earth and the Moon are eliminated as parental sources.

Impactors frequently hit the Earth, so it could be argued that the SNC meteorites were broken from the Earth's surface with insufficient energy to escape totally. The counter-argument to this is that all oxygen-bearing rocks from the Earth show a characteristic variation in composition of the three stable oxygen isotopes (see Fig. 1). The line on which data from SNC meteorites fall is displaced from that for terrestrial samples, indicating that the SNCs cannot come from the Earth (Franchi *et al.* 1999). Data from the SNCs also fall on a single line indicating that they all come from the same planet. The Moon is heavily cratered and none of the dynamic arguments applied to either Venus or Mercury apply to the Moon. But, as discussed in the previous section, material does come from the Moon and has been identified by its close similarities to *Apollo* samples. The composition of lunar meteorites is very different from

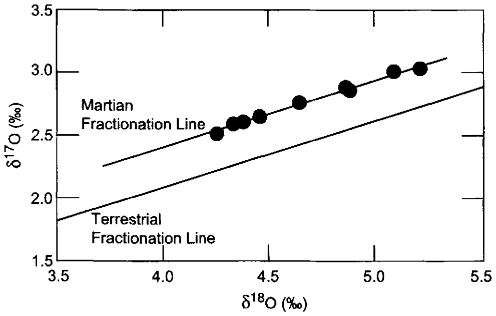


Fig. 1. Oxygen isotopic composition of martian meteorites (after Franchi *et al.* 1999).

that of the SNC meteorites. Also, the oxygen in lunar rocks lies on the same isotopic trend as terrestrial rocks (Clayton & Mayeda 1996 and Fig. 1). So the SNC meteorites cannot come from the Moon. By default, then, the SNC meteorites most probably originate from Mars. Additional evidence that makes the case for Mars irrefutable comes from one particular SNC meteorite, EET A79001. This is a shergottite that was collected in Antarctica in 1979 (Cassidy & Rancitelli 1982). When it was cut open, it was found to contain inclusions of black glass scattered throughout its mass (Score & Reid 1981) (Fig. 2a). These pockets of glass were 1–2 cm across, and formed by shock melting of mineral grains, presumably during the impact event that lofted the meteorite from the surface of its parent body. Small quantities of gas were also trapped within the glass during the impact shock; analysis of this gas showed it to be identical in chemical and isotopic composition to that of the atmosphere on Mars (Bogard & Johnson 1983) (Fig. 2b). The only way that this could happen is if EET A79001 came from Mars. As (on the basis of their oxygen isotopic composition, see above) all the other SNC meteorites come from the same parent as EET A79001, then they too must come from Mars.

The different martian meteorite groups

It was an amazing stroke of fortune that the original three meteorites seen to fall should be sufficiently different to form the type specimens of a subgroup, yet be related by their common parental source. However, the acronym 'SNC' is no longer accurate, as collection of additional martian meteorites from Antarctica and the Sahara Desert has extended the number of subgroups to seven. For the remainder of this paper, the meteorites will be referred to as 'martian', and not as 'SNCs'. At the time of proof correction (December 2005), 34 martian meteorites (57 separate named or numbered pieces) have been recognized. Of these, only four have been observed to fall, and a further two have been found in non-desert locations. It is possible that deserts have been such a rich source of martian meteorites because elsewhere on Earth the martian rocks, which after all are of a planetary nature, are more difficult to distinguish from equivalent terrestrial materials. An up-to-date list of martian meteorites can be found at http://www2.jpl.nasa.gov/snc/index.html, and there is a comprehensive and authoritative bibliography at http://www-curator.jsc.nasa.gov/curator/antmet/mmc/mmc.htm. All the martian meteorites are igneous rocks – they

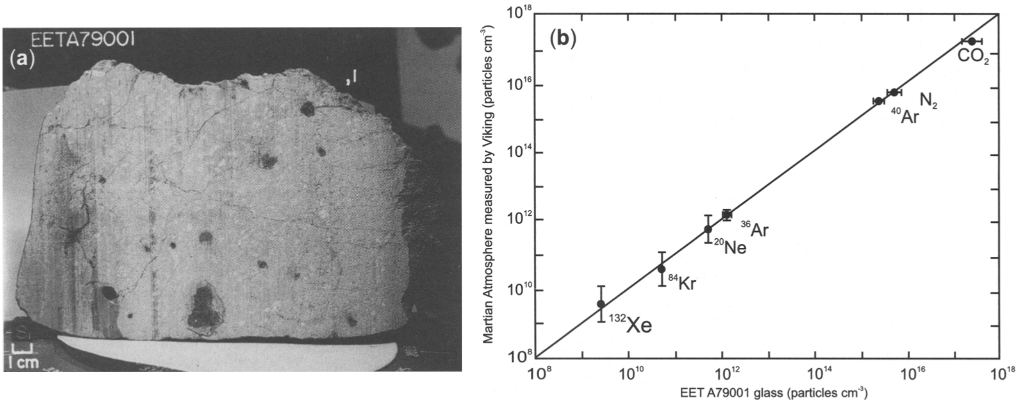


Fig. 2. (**a**) Saw-cut face of EET A79001, showing the patches of shock-produced glass that contain gas trapped within them. Image from NASA. (**b**) Composition of gas from EET A79001 compared with that of the martian atmosphere, as measured by *Viking* in 1976 (Nier *et al.* 1976) (after Pepin 1985).

have solidified from magma at or below Mars' surface (Fig. 3). The different groups represent crystallization at different depths; on Earth, geologists would have labelled them lherzolite, pyroxenite, dunite or basalt, etc. Some of the rocks have been altered by fluids, others appear to be dry. Many have been shocked to pressures of between 30 and 50 GPa.

Shergottites

The 24 shergottites are silicate rocks that are currently divided into three subgroups, with different formation localities. The most numerous group (10 in total), the *basaltic shergottites*, are fine-grained cumulate rocks (Fig. 3a), composed of subequal amounts of clinopyroxene (augite and pigeonite) and plagioclase (e.g. McSween 1994). The plagioclase has been converted, by shock, to maskelynite glass. Alignment of the minerals indicates that the rocks originated in a lava flow (dyke or sill). The second group (with six members), the *lherzolitic shergottites*, are also cumulates, but are more coarse-grained than the basaltic shergottites, indicating a slower cooling rate; they formed deeper below the martian crust than the basaltic shergottites, and their terrestrial equivalent would be a peridotite (McSween 1994). The main silicate is orthopyroxene, enclosing olivine grains, with minor plagioclase. Members (eight in total) of the most recently recognized subgroup, *olivine-phyric shergottites*, are composed of large olivine and orthopyroxene grains set in a finer-grained clinopyroxene matrix (Goodrich 2003). They are thought to be from olivine-saturated magmas that were parental to those from which basaltic shergottites crystallized. Based on Sm–Nd and Rb–Sr dating, all three groups of shergottites have crystallization ages of between 165 and 450 Ma (Nyquist *et al.* 2001). However, Pb–Pb ages imply an older history, with crystallization around 4.0 Ga ago (Bouvier *et al.* 2005). The shergottites were ejected from Mars in several separate impact events (see below).

Nakhlites

As of August 2005 there were seven nakhlites. In contrast to the different shergottites groups, the nakhlites are all clinopyroxenites that vary mainly in grain size rather than composition. They are almost unshocked rocks that formed at or near the martian surface in a slowly cooled, thick cumulate pile (Fig. 3b), with the various members of the group deriving from different depths within the intrusion (e.g. Lentz *et al.* 1999; Mikouchi *et al.* 2003). Although they solidified from melts about 1.3 billion years ago, and were ejected from the planet about 10–12 Ma ago (Nyquist *et al.* 2001), the rocks still bear traces of low-temperature aqueous processes that can be used to infer conditions on the martian surface. The meteorites have been altered by weathering, leading to the production of secondary minerals (clays, carbonates and sulphates) associated with which are low concentrations of martian organic material (Carr *et al.* 1985; Bridges & Grady 1999, 2000). It has thus been suggested that nakhlites might contain evidence for a martian biology (Wright *et al.* 1989).

Chassignites

Chassigny was the first of the non-desert Martian meteorites to fall; only in early 2005 was a second member of this subgroup recognized (Beck *et al.* 2005; Mikouchi *et al.* 2005). The chassignites are cumulate rocks, almost completely composed of olivine (Fig. 3c) that crystallized about 1.3 billion years ago; although they have the same crystallization age as the nakhlites, they may not have emanated from the same magma source (Wadhwa & Crozaz 1995). The closest terrestrial analogue to chassignites is dunite, a rock formed by crystallization at some depth (several kilometres) below the Earth's surface, or by very slow cooling in a large magma chamber.

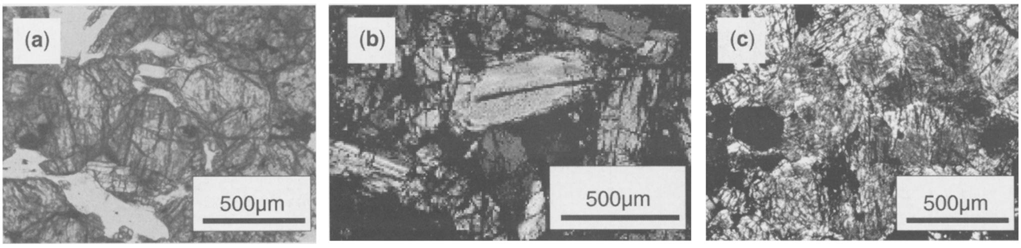


Fig. 3. Optical photomicrographs of (**a**) Zagami, (**b**) Nakhla and (**c**) Chassigny showing the different textures of the three main martian meteorite rock types.

ALH 84001

Allan Hills 84001 (ALH 84001) is currently the only member of its subgroup. It is the oldest of all the martian meteorites, having crystallized about 4500 Ma ago (Nyquist *et al.* 2001). It has had a long and complex history of shock and thermal metamorphism (Treiman 1998), and also contains carbonate minerals, indicating that at some stage in its history it has been in contact with martian water (Romanek *et al.* 1994). As few hydrated minerals (such as are found in clays on Earth) have been identified amongst the alteration products in ALH 84001, it has been proposed that the carbonates were produced at the surface of Mars in a region of restricted water flow, such as an evaporating pool of brine (McSween & Harvey 1998; Warren 1998). This hypothesis satisfactorily accounts for the chemical and isotopic characteristics of the carbonates and is also a mechanism that is compatible with an environment in which micro-organisms might survive.

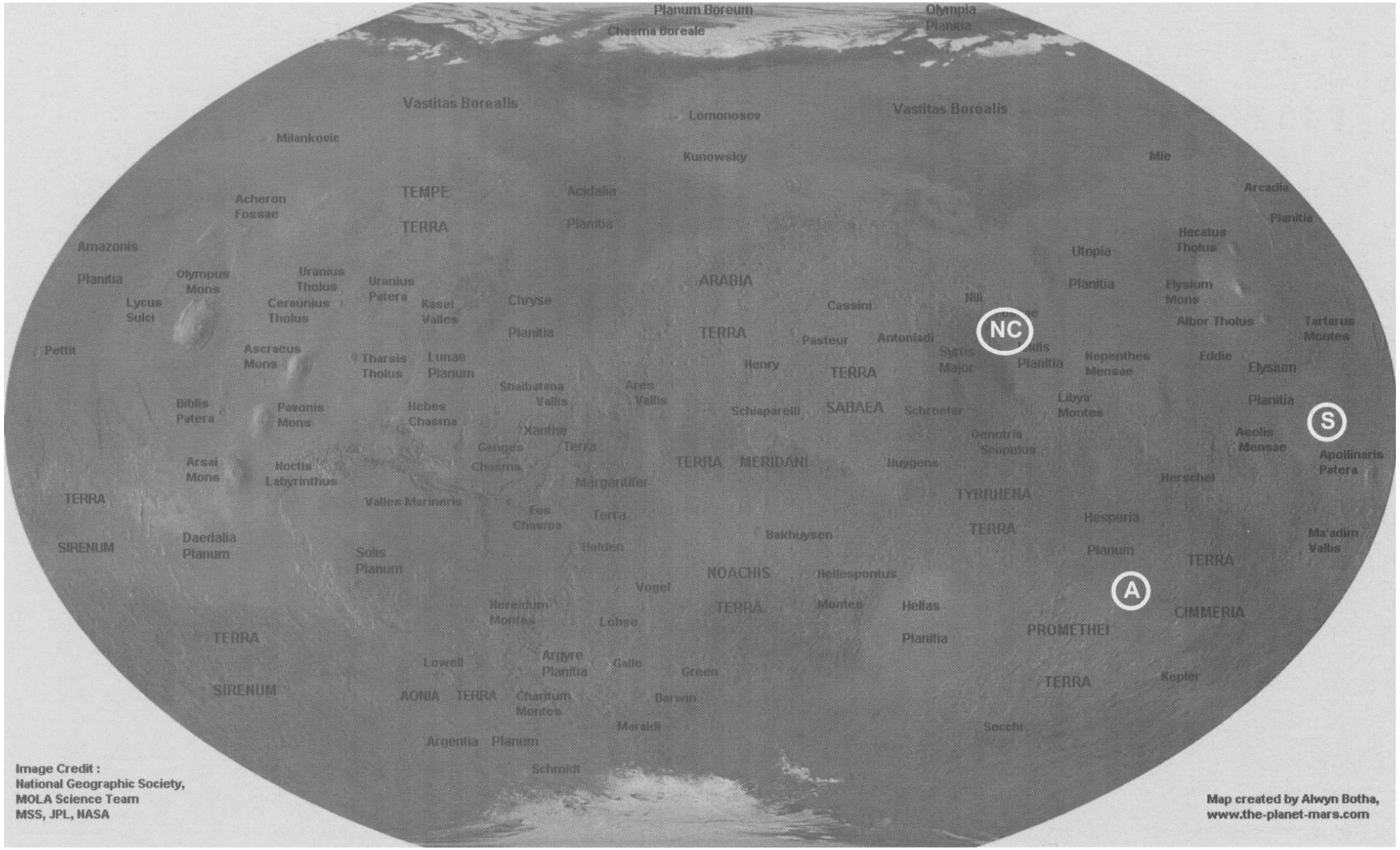
Origin on Mars

Although the Martian origin of the meteorites is no longer doubted by most of the scientific community, it is not yet possible to identify with certainty the specific region of Mars from which they have been derived. We know from the mineralogy and chemistry of the subgroups that they are rocks that formed in different locations at or below the martian surface and thus cannot all have come from a single impact event. Relative crater intensities matched with lithology have given us a martian timescale divided into three great epochs, each matched with specific igneous provinces and events across the planet (Tanaka 1986; Hartmann & Neukum, 2001). The most ancient epoch, the Noachian, is probably more than 3.8 Ga old; the middle epoch, the Hesperian, is 1.3–3.8 Ga, whilst the most recent is the Amazonian (<1.3 Ga). Knowledge of the cratering history of Mars allows inference of which areas are more likely to be parent regions of the meteorites. Cratering dynamics were thought to require either oblique impacts on the Martian surface (e.g. Nyquist 1983) or craters with diameters of more than 10 km (Mouginis-Mark *et al.* 1992). However, more recent calculations have indicated that smaller craters (>3 km) could also produce ejecta with sufficient velocity to escape (Head *et al.* 2002), giving a greater number of potential source craters. The crystallization age of the meteorites also constrains from which regions of Mars they might be derived, whilst cosmic-ray exposure (CRE) age (the length of time that a specimen is exposed in space, also taken as to be the length of time since the body was broken or ejected from its parent) constrains the number of ejection events that have occurred. The CRE ages of martian meteorites fall into four groups, with ejection events at around 2, 3, 11 and 15 Ma ago. By itself, this might imply that all the meteorites were ejected by four impact events, but there are other parameters to consider, including crystallization age. Once this is taken into account, it seems that a total of between six and eight ejection events are required for the 34 currently known martian meteorites (Nyquist *et al.* 2001; Eugster *et al.* 2002).

Figure 4 shows the approximate regions from which martian meteorites might have originated, based on cratering statistics and relative chronologies of the landforms. ALH 84001, with its ancient crystallization age of 4500 Ma and oldest CRE age of 15 Ma (Nyquist *et al.* 2001; Eugster *et al.* 2002), must be from the heavily-cratered Noachian terrains of the southern hemisphere, possibly the edge of Hesperia Planitia (Barlow 1997). The nakhlites and Chassigny have the same crystallization age (1300 Ma) and CRE age (11 Ma) (Nyquist *et al.* 2001; Eugster *et al.* 2002), implying ejection from a common location by a single impact event into early Amazonian rocks (Treiman 1995). Harvey & Hamilton (2005) suggested that the NE region of the Syrtis Major shield volcano might be the source area. The number of ejection events for shergottites is more problematic than for the older martian meteorites. There are at least three different mineralogical subgroups, with a range of crystallization ages (165–450 Ma) and CRE ages (0.6–5 Ma), although if the recently reported ancient Pb–Pb ages (Bouvier *et al.* 2005) are correct, there are alteration, rather than crystallization ages. The minimum number of impacts required to launch the shergottites has been estimated as between four and six (Nyquist *et al.* 2001; Eugster *et al.* 2002). The Cerberus Plains region of southern Elysium has been identified as a possible source area (Plescia 1999).

What have we learnt about Mars from martian meteorites?

Results from remote observations of Mars by spacecraft have allowed a detailed history and geology (areology?) of the planet to be constructed. However, without absolute ages for different regions, it is difficult to construct a



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Map created by Alwyn Botha,
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Fig. 4. Map of Mars, showing approximate potential source regions of martian meteorites. (A) ALH 84001 (Barlow 1997), (NC) Nakhlites and Chassigny (Harvey & Hamilton 2005) and (S) Shergottites (Plescia 1999).

complete history of the planet's evolution. Martian meteorites allow us to obtain absolute ages, but the random nature of their arrival on Earth and their specific provenance on Mars only allow additional pieces of the puzzle to be added, rather than a complete picture to appear. Analyses of martian meteorites provide information about processes that have occurred on Mars. These can be considered as a progression of events that trace primary (magmatic) events, through secondary alteration to tertiary shock events.

Primary processes

All the martian meteorites are igneous rocks; they therefore have been produced by magmatic processes. The different mineralogical compositions of the rocks are evidence of their differing petrogenetic histories. Determination of mineral composition allows the composition of the melt from which the rocks crystallized to be inferred. This in turn leads to deduction of crystallization depth and oxygen fugacity. Matching the different rocks with different igneous provinces on Mars (Fig. 4) helps to refine the relative chronology, but does not make it absolute.

Secondary processes

Secondary processes on Earth are very much tied to the hydrological cycle: weathering and erosion of primary magmatic rocks by water (and wind) leads to transport of sediment, its subsequent deposition, then, eventually, lithification. Images of features on Mars' surface have long been interpreted as being caused by the action of fluids (water or ice), and pictures of the five sites where spacecraft have landed all show landscapes of rocks that appear to have been weathered by wind, frost and water. So secondary processes have clearly affected the surface of Mars. These processes can also be traced within martian meteorites, where the igneous rocks have been altered. The nakhlites show most evidence of secondary weathering, with primary magmatic silicates broken down to clay minerals. In the nakhlites, the pyroxene and olivine grains are cut by veinlets of smectite associated with gypsum, halite and iron-rich carbonate. The assemblage is the type of mixture associated with deposition from an evaporating brine, and different extents of alteration within the nakhlites has allowed an alteration sequence of the meteorites to be recognized, which might be tied to depth of extraction from the nakhlite magma flow (Bridges & Grady 2000; Bridges *et al.* 2001). The orthopyroxenite ALH 84001 is unique in its possession of large (up to approximately 1 mm) rosette-shaped patches of mineralogically zoned carbonates, including Fe-, Mg- and Ca-rich components (Fig. 5a). Measurement of the chemical and isotopic composition of the carbonates, especially the rosettes in ALH 84001, have allowed inferences to be drawn about the temperature and salinity of the water from which the carbonates were deposited (e.g. Romanek *et al.* 1994; Leshin *et al.* 1998).

Tertiary processes

Within asteroidal meteorites, tertiary processes generally include shock transformation of minerals and brecciation caused by collisions between asteroids. Martian meteorites do not appear to be brecciated, but they do exhibit features associated with impact shock. These features are inferred to have been caused by the

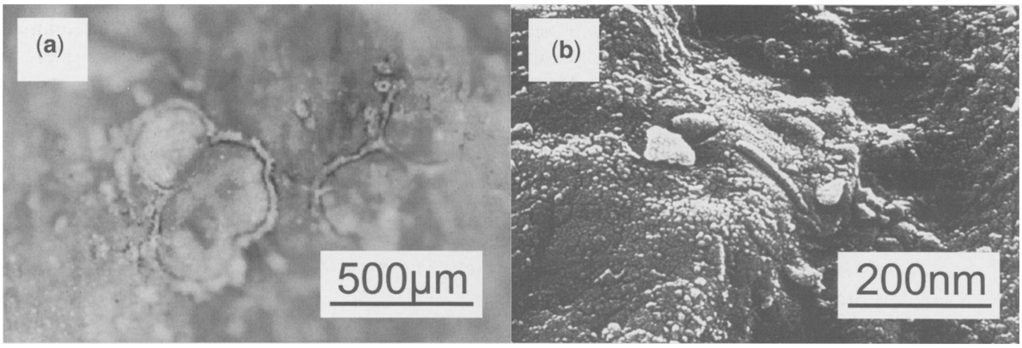

Fig. 5. (**a**) Optical image of patches, or rosettes, of carbonate minerals on a broken surface of the ALH 84001 orthopyroxenite. Image from NHM, London. (**b**) Scanning electron microscope image of a structure within a carbonate rosette in ALH 84001. The structure was identified by McKay *et al.* (1996) as a primitive martian microfossil. Image from NASA.

impacts that ejected the meteorites from Mars' surface, and include transformation of some crystalline minerals to glass, and mosaicism and deformation of other grains (e.g. Stöffler *et al.* 1986; Nyquist *et al.* 2001). As discussed in the section on 'The martian origin explained', it was the extraction and analysis of gas trapped in the shock-produced glass in EET A79001 that provided the defining criterion for establishing a martian origin for the meteorites. ALH 84001 is the oldest of the martian meteorites, and seems to have had the most complex history, suffering repeated episodes of shock and metamorphism (Treiman 1998). There has been a suggestion that this meteorite contains samples of Mars' atmosphere trapped within it from an earlier epoch than the final event that removed it from Mars' surface (Murty & Mohapatra 1997; Grady *et al.* 1998). Thus, martian meteorites provide a possible opportunity for examining how the martian atmosphere has evolved through time.

Life on Mars?

One of the main reasons for the great importance attached to the study of Mars is the possibility that the planet has for harbouring life. Satellite images and surface explorations have shown that Mars is a rocky planet, over which rivers of water and ice have flowed, and where seas might have formed (e.g. Murray *et al.* 2005). The cluster of huge volcanoes in the western hemisphere of Mars indicate an extensive thermal history. The presence of water and energy are two of the major requirements for life to survive, and their presence on Mars is an indicator that life might well have arisen at some time in Mars' past, even if it is not extant today. None of the probes that has landed on Mars' surface has, as yet, detected unequivocal signs of life, and any such claims from planned future missions will be subject to detailed levels of scrutiny. Assuming that life on Mars, should it exist, is at the trace-fossil/micro-organism level, rather than as a macro-flora or macro-fauna, then observations made remotely at Mars' surface will always be difficult to verify.

An alternative approach is to search for traces of life that might have been preserved within martian meteorites. On the face of it, igneous rocks are not the best place in which to search for fossils: on Earth, sedimentary rocks are the source of macro- and microfossils. But there is evidence that the martian rocks have been altered by fluids, and that secondary minerals were formed under conditions favourable for micro-organisms to survive. It is therefore possible that any such micro-organisms might have left behind evidence of their presence. This was the rationale underlying the claim that the fossilized remains of primitive martian organisms had been found inside a patch of carbonates within the ALH 84001 meteorite (Fig. 5b) (McKay *et al.* 1996).

Explanations of the findings that led to McKay *et al.*'s (1996) conclusions have been published elsewhere, as have alternative interpretations of the observations (e.g. presentations made at the 1998 workshop in Houston, Texas: 'Martian meteorites: where do we stand and where are we going?' http://www.lpi.usra.edu/meetings/marsmet98/pdf/program.pdf). Nine years after publication of McKay *et al.*'s paper, there is little acceptance by the scientific community that the features they described were of indigenous martian micro-organisms. But this does not mean that we rule out the possibility that life does not, or did not, exist on Mars. The building blocks of life were undoubtedly present on the planet. It has had a thicker atmosphere in the past, allowing water to flow on its surface: we can still see the dried up remnants of water channels on satellite images. However, when Mars lost its atmosphere, the surface waters also disappeared. Mars is now a dry and sterile planet, its surface bathed by the Sun's ultraviolet radiation. However, we do not know what lurks below the surface. One of the problems associated with identification of fossils from micro-organisms is that great care must be taken not to confuse the traces produced by biology with those produced abiotically by chemistry. This confusion has recently led to great debate about interpretation of trace features within ancient rocks on Earth (e.g. Brasier *et al.* 2004). On Earth, it is possible to revisit a sample locality and view it in its spatial and chronological context. Specimens can be analysed directly by the most sophisticated and sensitive of analytical techniques. And it is still found to be difficult to identify with certainty the origin (biogenic/abiogenic) of features in rocks. Given that there is this problem with potential terrestrial microfossils, the prospects of finding unassailable evidence for fossilized micro-organisms on Mars' surface by remote techniques is, at best, a challenging prospect. This does not give us an excuse, however, for not looking.

Summary

At the time of proof-checking (December 2005) there were 34 martian meteorites subdivided into seven groups. Their crystallization ages may range from 165 to 4500 Ma, and thus span almost all of Mars' active magmatic history. Although they are all igneous rocks, they have different compositions and mineralogies, and so emanate from a variety of locations across Mars. Cratering statistics, crystallization ages and CRE ages imply that they have been ejected from Mars by between six and eight impacts.

The last 25 years has seen an evolution from discussion about the unlikelihood of rocks from Mars arriving as meteorites on Earth, to full acceptance of martian meteorites as valuable materials from which deductions can be made about processes on Mars. One can only speculate as to what advances will be made in this field over the next 25 years – and hope that this period will see results from directly returned martian samples for comparison with those rocks returned by fate.

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