



The SNC meteorites are from Mars

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Abstract

The 14 SNC meteorites are all igneous rocks, either basalts or basaltic cumulates. They are inferred to be from Mars, based on direct comparison with Martian materials and on consistency with inferences about Mars. Most telling is that the SNC meteorites contain traces of gas which is very similar in elemental and isotopic compositions to the modern Martian atmosphere as measured by Viking landers on Mars and spectroscopy from Earth. The Martian atmosphere appears to have a unique composition in the solar system, so its presence in the SNCs is accepted as strong direct evidence that they formed on Mars. Independent of this link, the SNC meteorites must be from a planet with a significant atmosphere because they contain several abundant gas components, one of which carries large isotopic fractionations characteristic of atmospheric processing. Further, the elemental compositions and oxidation state of the SNC meteorites are consistent with data from in situ analyses of Martian soils and rocks, and are quite distinct from compositions of other meteorites, rocks from the Earth, and rocks from the Moon. The range of formation ages for the SNC meteorites, 4.5–0.18 Ga, is consistent with the varied ages of the Martian surface (based on its cratering record) and inconsistent with surface ages on any other solar system body. The extreme chemical fractionations in the SNC meteorites suggest complex internal processes on a large planet, which is inconsistent with an asteroidal origin. Some SNCs were altered by aqueous solutions at < 0.7 Ga, consistent with the recent presence of liquid groundwater in Mars inferred independently from the geology of its surface. There seems little likelihood that the SNCs are not from Mars. If they were from another planetary body, it would have to be substantially identical to Mars as it now is understood. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Planning for Mars Sample Return has been, and will continue to be, strongly influenced by claims that Martian life has been detected in meteorites from Mars (McKay et al., 1996, 1999). Until 15–20 years ago, it was difficult to imagine that some meteorites might actually be rocks from Mars. But data from these meteorites, the SNC meteorites, are now the foundations for much of our present understanding of Mars (e.g., McSween, 1994).

The importance of the SNCs in Mars exploration has increased dramatically since they were reviewed last (McSween, 1994). Since then, four new SNC meteorites have been discovered (Yamato 793065, QUE94201, Dar al Gani

476, and Dar al Gani 489), and McKay et al. (1996, 1999) reported putative signs of Martian life in two SNCs. These new developments have initiated an avalanche of new data on the SNC meteorites and their implications for the geology, atmosphere, and history of Mars. But, as shown by debates at the SOCFI conference in Paris, France (February 1–5, 1999), there is still some uncertainty in the international scientific community about the link between SNC meteorites and Mars (e.g., Jagoutz, 1999; Ott, 1999).

We feel it is useful to explore and restate the evidence linking the SNC meteorites with Mars, because so much mission planning for Mars Sample Return ultimately rests on inferences from these meteorites. First, we will give a short overview of the SNC meteorites themselves and why they are thought to have formed on a single parent body. The compendium of Meyer (1998) gives a full review of the “Martian meteorites” and their properties. The remainder of the paper will summarize the evidence and arguments linking the SNCs to Mars: trapped atmospheric gases, bulk chemistry, geochronology, and hydrology.

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Table 1
The SNC meteorites

| Name | Rock type | Where found |
|----------------------|---|---------------------------------|
| Chassigny | Dunite (Olivine-rich) | Haute Marne, France |
| Shergotty | Basalt | India |
| Nakhla | Pyroxenite (high-Ca pyroxene) | Egypt |
| Lafayette | Pyroxenite (high-Ca pyroxene) | Indiana, USA |
| Governador Valadares | Pyroxenite (high-Ca pyroxene) | Brazil |
| Zagami | Basalt | Nigeria |
| ALHA77005 | Lherzolite (Olivine-Pyroxene-Plagioclase) | Antarctica, Transantarctic Mts. |
| EETA79001 | Basalt | Antarctica, Transantarctic Mts. |
| LEW88516 | Lherzolite (Olivine-Pyroxene-Plagioclase) | Antarctica, Transantarctic Mts. |
| ALH84001 | Pyroxenite (low-Ca pyroxene) | Antarctica, Transantarctic Mts. |
| QUE94201 | Basalt | Antarctica, Transantarctic Mts. |
| Y793605 | Basalt | Antarctica, Yamato Mts. |
| Dar al Gani 476 | Lherzolite (Olivine-Pyroxene-Plagioclase) | Libya |
| Dar al Gani 489 | Lherzolite (Olivine-Pyroxene-Plagioclase) | Libya |

2. Why S+N+C?

The SNC meteorites are 14 samples of basaltic rock and cumulate rocks derived from basaltic magma, that share a common geochemical and isotopic heritage (Table 1). The acronym SNC comes from the three classes of meteorite involved: S is for shergottites, which are basalts and peridotites, named for the type meteorite Shergotty; N is for nakhlites, which are clinopyroxenites, named for the type meteorite Nakhla; and C is for Chassigny, which is a unique dunite. ALH84001, an orthopyroxenite, is also grouped with the SNC meteorites. This meteorite classification is awkward, and it has been proposed that all SNCs be called “Martian meteorites” (Mittlefehldt, 1994). Although this proposal has gained some acceptance, it is not appropriate where we are evaluating proposed links between these meteorites and Mars. Thus, in this paper we refer to the meteorites as SNCs (Table 1).

The chemical, isotopic, and geological properties of the SNC meteorites have been reviewed in detail (McSween, 1985, 1994; McSween and Treiman, 1998; Meyer, 1998). Here, we excerpt portions of that literature to provide basic data and evidence that the meteorites should be considered together. The reader is strongly urged to consult these reviews and original sources for a more complete discussion of the data sets.

2.1. Petrology

The SNC meteorites are basaltic and ultramafic rocks that are essentially unbrecciated and have retained their original igneous textures. The shergottites (S) include basaltic and peridotitic (olivine-rich) igneous rocks that have abundant plagioclase-composition glass (produced by shock from original crystalline feldspar) and low-calcium pyroxenes. The basaltic shergottites are quickly cooled lavas, with nearly the same compositions as the magmas from which they formed. The peridotitic shergottites

represent liquid magma plus earlier-formed crystals (cumulates), which settled and cooled together more slowly in large (or deep) magma bodies. However, even the so-called basaltic shergottites contain moderate proportions of entrained (or previously crystallized) material, mostly pyroxene. The nakhlites (N) are clinopyroxene-rich cumulates that also formed from basaltic magmas. Chassigny (C) is composed principally of olivine, and is petrologically related to the nakhlites. The ALH84001 meteorite is composed almost entirely of low-calcium pyroxene and chromite.

Basaltic meteorites (achondrites) are common, comprising ~ 5% of all meteorites. Three classes of basaltic meteorites have been linked to specific parent bodies: SNCs linked with Mars; lunar meteorites are substantially identical to returned samples from the Moon; and the eucrite clan, or HEDs, has been linked to the asteroid 4 Vesta. ALH84001 is so similar to the diogenites (D in HED) of the eucrite clan that it was first classified as such. Olivine-rich meteorites, besides Chassigny, are classified into several different groups of achondrites, such as ureilites, brachinites, lodranites, etc. These meteorites likely originated from small differentiated asteroids. The nakhlites are unique among known achondrites, as are the shergottites.

2.2. Mineralogy

The mineralogy and mineral compositions of the SNC meteorites were initially used to differentiate them from other meteorite groups. The most telling single parameter in the mineralogy is oxidation state — the SNC meteorites record conditions significantly more oxidizing than any other meteorite group. Among sulfide minerals, the SNCs feature the relatively oxidized minerals pyrite (FeS₂) and pyrrhotite (Fe_{1-x}S) rather than the reduced mineral troilite (FeS), which is the dominant sulfide in iron meteorites, chondrites, and other basaltic meteorites (e.g., eucrites, angrites, and brachinites). Iron oxide minerals and iron-

bearing silicate minerals in the SNC meteorites contain significant or detectable ferric iron, the oxidized form, which has not been noted in the other basaltic meteorites. Feldspars in the SNC meteorites are more sodic than in other achondrites or lunar basalts. Nearly all SNC meteorites contain minute grains of hydrogen-bearing amphibole, which indicates that their parent magmas contained some water. Amphiboles are not known from other basalt meteorites, and have been described in only a few other meteorites.

Most SNCs contain low-temperature alteration minerals, such as carbonates, salt and clay minerals, that did not form on the Earth (vis. Gooding, 1992; Mittlefehldt, 1994). Most meteorites, including the SNCs, do contain low-temperature alteration minerals that formed on Earth (e.g., Gooding, 1986; Barrat et al., 1998). However, some of these low-temperature minerals in the SNC meteorites are clearly not terrestrial, as they are faulted along shock-induced fractures, melted into the fusion crust (which forms as meteorites traverse the Earth's atmosphere), and/or have non-terrestrial chemical or isotopic compositions (e.g., Gooding et al., 1991; Treiman et al., 1993; Farquhar et al., 1998). Such pre-terrestrial alteration minerals are not seen in other types of basaltic meteorites, although they are abundant in some chondrites.

2.3. Geochemistry

The bulk elemental compositions of the SNC meteorites are also distinctive, and separate them from other basaltic and non-basaltic meteorites. These distinctions are best seen in the ratios of abundances of certain elements, which are not changed by formation of basalt magma or by its subsequent cooling and crystallization (e.g., Wänke et al., 1981; Drake, 1980; Treiman et al., 1986; Wänke and Dreibus, 1988; Longhi et al., 1992). The most useful of these ratios involve elements that can be significantly fractionated from each other early in a planet's history, for instance during planet accretion and core formation. Planetary bodies appear to undergo unique differentiation histories and so should preserve distinct ratios for these element pairs. For instance, iron and manganese behave nearly identically during basalt formation and crystallization, but can be strongly fractionated from their initial (chondritic?) ratio during core formation. Similarly, potassium and lanthanum behave identically during formation and early crystallization of basalt, but potassium is much more volatile at high temperature, and so can remain in the interplanetary gas (or be lost to the gas) during early planet formation. These effects produce distinct element abundance ratios in a planet's mantle, which are then preserved through subsequent igneous events.

Several groups have applied this element ratio technique to the SNCs, and have found that the SNC meteorites all show similar values for a series of important ratios (e.g., Treiman et al., 1986; Longhi et al., 1992). This has helped to establish the consanguinity of the SNC clan, and also

establishes their uniqueness among all achondrite groups. Later in this paper we will apply these ratios to establish direct links between the SNCs and Mars.

2.4. Oxygen isotopes

Oxygen is the most abundant element in solid bodies of the solar system, and has three stable isotopes: ^{16}O , ^{17}O , and ^{18}O . The proportions of these isotopes differ slightly among planets and asteroids (Clayton and Mayeda, 1983, 1996), in a manner that is not affected by normal chemical reactions and equilibria (i.e., without photochemistry or nucleosynthesis). Oxygen isotope ratios of anhydrous silicate and oxide minerals in SNC are all similar and consistent with them having formed on the same parent planet (e.g. Clayton and Mayeda, 1996; Franchi et al., 1997).

Surprisingly, however, the low-temperature and alteration minerals in the SNC meteorites have different proportions of oxygen isotopes, such that they could not be derived from the anhydrous silicates and oxides (Karlsson et al., 1992; Farquhar et al., 1998). It will be seen that this finding is consistent with the sharp differences between atmospheric and internal volatiles on Mars.

3. Volatile components

Initially, the idea that the SNC meteorites might be from Mars was based on indirect evidence — comparing characteristics of the meteorites in hand with reasoned hypotheses about Mars' rocks (e.g., Wood and Ashwal, 1981). These indirect arguments were augmented in 1983 by the recognition of Martian atmosphere gas trapped in the SNC meteorites. These gases constitute the strongest direct evidence that the SNC meteorites are from Mars. In comparing SNC volatiles to the Martian atmosphere and other volatile reservoirs in the solar system, one must consider the elemental and isotopic data collectively. Single element or isotope systems in the SNC volatiles may resemble other (non-Martian) volatiles in the solar system, but the full elemental and isotopic composition of the SNC volatiles is similar only to that of the current Martian atmosphere.

3.1. Atmospheric gases

The SNC meteorites contain modest concentrations of volatiles that are very similar in elemental and isotopic composition to the current atmosphere of Mars, but differ in detail from compositions of other volatile reservoirs (Bogard and Johnson, 1983; McSween, 1985, 1994). The composition of the Martian atmosphere has been analyzed by Earth-based spectroscopy and by mass spectrometry on the Mars Viking spacecraft (Owen et al., 1977), and it is significantly different in relative abundances of CO_2 , N_2 , and noble gases, and in isotopic ratios of noble gases from other volatile reservoirs known in the solar

system (vis Pepin, 1991). In contrast, Bogard and Johnson (1983) found abundances of noble gases trapped in the shergottite EET79001 to closely resemble the Martian atmosphere. This finding was confirmed and extended to N_2 and CO_2 as well (e.g., Bogard et al., 1984; Becker and Pepin, 1984, 1986; Carr et al., 1985; Ott and Begemann, 1985; Swindle et al., 1986; Wiens et al., 1986; Wiens and Pepin 1988; Drake et al., 1994; Marti et al., 1995; Bogard and Garrison, 1998; Garrison and Bogard, 1998). Because the Martian atmospheric composition is distinctive, these results were quickly adopted as direct evidence that EET79001 and the other SNC meteorites had come from Mars (McSween, 1985, 1994). In shergottite meteorites, the atmospheric gases are concentrated in silicate glass produced on the Martian surface by shock (impact) melting, although shocked non-glass phases also contain this gas (Bogard and Garrison, 1999). Laboratory experiments have shown that it is relatively easy to shock-implant ambient gases into silicates, and the gas implantation efficiency is appreciable even at relatively modest shock pressures of 20 GPa (Bogard et al., 1986; Wiens and Pepin, 1988). This shock-implantation in the laboratory occurs without isotopic fractionation and with only minimal elemental fractionation.

The close similarity between trapped SNC gas and the Martian atmosphere can be demonstrated in several ways. Table 2 gives the elemental compositions of several major volatile reservoirs in the solar system, including measurements of Mars' atmosphere and SNC shock-glass. Note that only the compositions of atmospheric reservoirs are given in Table 2, and these reservoirs for earth and Mars differ greatly in relative abundances of some components, e.g. H_2O and CO_2 , compared to the whole planet abundances; e.g. Turekian and Clark (1975).

Fig. 1 (after Wiens et al., 1986) shows that relative elemental abundances of eight different volatile species are essentially identical in the trapped SNC gas and the Martian atmosphere, even though the concentrations of these species vary across many orders of magnitude. It is very difficult to imagine any process that could take one or more volatile components having different relative abundances of these eight species and produce in SNCs the close correlation demonstrated by Fig. 1.

In addition to having compositions similar to each other, it is equally important to show that trapped volatiles in SNC shock-glass and the Martian atmosphere have compositions that are distinct from other known gas reservoirs. Fig. 2 shows abundances of selected isotopes of various volatile species relative to ^{12}C for several major reservoirs of solar system volatiles — the Sun, Earth's atmosphere, Venus' atmosphere, C1 carbonaceous chondrites, and the Martian atmosphere. These abundance ratios are normalized to the values measured in shock glass of EETA79001. The abundance ratios 'Martian atmosphere'/'EETA79001 shock-glass gas' are nearly unity (within error), meaning that their gas compositions are nearly identical. In contrast, relative abundances for solar and C1 chondrites differ

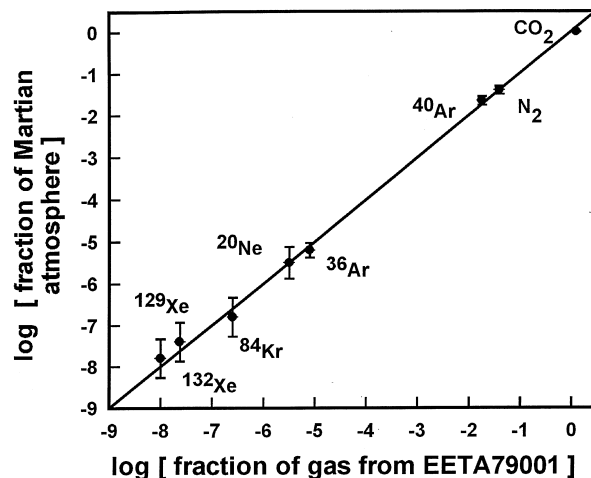


Fig. 1. Abundances of gas species and isotopes in the Martian atmosphere and in the trapped gas found in shock-glass of the EETA79001 shergottite meteorite. Martian atmosphere after Owen et al. (1977) and Owen (1992); SNC trapped gas after Pepin and Carr (1992). Both axes are particles per cubic centimeter (Wiens et al., 1986).

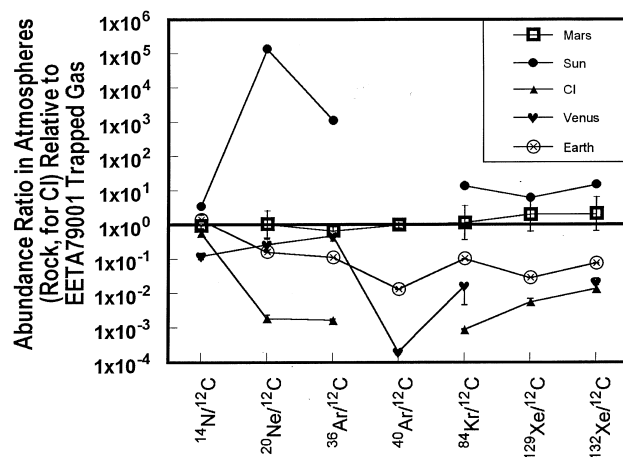


Fig. 2. Elemental abundances in solar system atmospheres compared to the SNC shock-glass component (defined from analyses of EETA79001), normalized to abundances of ^{12}C in the gas. Note that ratio scale is logarithmic. A gas identical to the SNC trapped component would plot with all its components having an abscissa ratio of unity. Gas in the shock glass resembles the Martian atmosphere, but not the other volatile reservoirs. Data for the sun is normal solar wind, Mars atmosphere is Viking lander analyses, and CI chondrites are the AVCC gas component. Error bars are as listed by original authors, and propagated through the calculation. Error bars for sun, Earth, and CI chondrites smaller than symbols. Carbon-12 was chosen for normalization because of its abundance and availability of analyses. Data collated from Owen et al. (1977), Pollack and Black (1982), Donahue and Pollack (1983), Donahue (1986), Swindle (1988), Wiens and Pepin (1988), Pepin (1989), Pepin and Carr (1992), Owen (1992), Bogard (1997), Bogard and Garrison (1998), and Jones and Swindle (1998).

Table 2
Compositions of solar system gases and condensates^a

| | SNC ^b | Mars ^c | Earth | Sun ^d | Venus | Jupiter | Saturn | Uranus | Neptune | Comet ^e |
|--------------------|------------------|-------------------|---------|------------------|---------|---------|----------|-----------|---------|--------------------|
| H ₂ % | — | — | 0.6 ppm | 90 | — | 86 | 96.3 | 82.5 | ~ 80 | — |
| He % | — | 1.1 ppm | 5 ppm | 10 | — | 14 | 3.25 | 15.2 | 19 | — |
| CH ₄ % | — | < 20 ppb | 1.8 ppm | 0.039 | — | 0.2 | 0.5 | 2.3 | ~ 1.5 | — |
| NH ₃ % | — | < 5 ppb | — | 0.010 | — | 0.03 | ~ 0.01 | < 0.1 ppm | — | 4.3 |
| CO ₂ % | 95 | 95.32 | 0.035 | — | 96.5 | — | 0.3 ppb | < 0.3 ppb | 0.5 ppb | 17.1 |
| N ₂ % | 2.5 | 2.7 | 78.05 | — | 3.5 | — | — | — | — | 1.4 |
| Ar % | 1.5 | 1.6 | 0.93 | 4.4 ppm | 0.007 | < 0.001 | — | — | — | — |
| H ₂ O % | — | ~ 0.03 | < 4 | 0.079 | — | < 0.057 | ~ 10 ppb | ~ 7 ppb | ~ 2 ppb | 67.2 |
| SO ₂ % | — | < 100 ppb | — | 18 ppm | 0.0015 | — | — | — | — | 9.8 |
| O ₂ % | — | 0.13 | 20.95 | — | — | — | — | — | — | — |
| Ne ppm | ~ 3 | 2.5 | 18 | 0.013 | 12 | < 26 | — | — | — | — |
| Kr ppm | ~ 0.3 | 0.3 | 1.1 | — | ~ 0.025 | < 0.005 | — | — | — | — |
| Xe ppm | ~ 0.08 | 0.08 | 0.087 | — | ~ 0.002 | < 0.01 | — | — | — | — |

^aData for atmospheres of Earth, Venus, Jupiter, Saturn, Uranus, and Neptune as compiled in Lodders and Fegley (1999). Values for Earth, Mars, and Venus are atmospheres only, and do not include volatiles trapped in crust, mantle, or ocean.

^bEETA 79001 shock-glass gas, calculated for $p = 7$ mbar by addition of CO₂.

^cOwen (1998), Krasnopolsky et al. (1994).

^dAs compiled in Lodders and Fegley (1998), recast to 100% as H₂, He, H₂O, CH₄, NH₃, Ar, SO₂.

^eDelsemme (1997). Volatile fraction of comet 1P/Halley recast as CO₂, H₂O, NH₃, SO₂, N₂.

substantially from the Martian atmosphere and EET79001 gas compositions. Although the earth's atmosphere and EET79001 gas show generally similar elemental abundances of the noble gas species, the abundances of nitrogen and carbon relative to noble gases differ considerably. In the following section we show that differences in isotopic composition also exist. Similarly, Table 2 shows that cometary ice and atmospheres of outer-solar-system bodies are quite distinct from the SNC shock-glass gas.

3.2. Isotopic ratios

Beyond their similar elemental compositions, volatiles in Mars' atmosphere and in some SNCs also have generally similar isotopic compositions. Table 3 compares several isotopic ratios in a variety of gas reservoirs, including Mars' atmosphere and the shock-glass component in the SNCs. Unfortunately, many isotopic measurements made by Viking were not of high precision, and these data have significant uncertainties. The Viking mass spectrometers were optimized for analyses of organic molecules, not atmospheric gases. In fact, because much more precise isotopic measurements have been made of gases in SNC shock-glass, the latter are commonly adopted as the best available measures of the isotopic composition of the recent Martian atmosphere. For example, the argon isotopic composition reported by Viking was $^{40}\text{Ar}/^{36}\text{Ar} = 3000 \pm 500$ and $^{36}\text{Ar}/^{38}\text{Ar} = 5.5 \pm 1.5$ (Owen, 1992). Recent evaluations of SNC data give lower ratios: $^{40}\text{Ar}/^{36}\text{Ar} \leq 1900$ and $^{36}\text{Ar}/^{38}\text{Ar} \leq 4.0$ (Bogard, 1997; Garrison and Bogard, 1998). Among Viking's other attempted measurement of noble gas isotope ratios, only $^{129}\text{Xe}/^{132}\text{Xe}$ was reported. The same $^{129}\text{Xe}/^{132}\text{Xe}$ ratio measured by the Viking landers is measured in the shergottites, but to much higher precision. Although not discussed by

Owen et al. (1977), the Viking mass spectrum of Kr isotopes suggest excess ^{80}Kr and ^{82}Kr relative to ^{84}Kr . Similar excesses are also seen in Kr in the SNC shock-glass gas, and probably reflect neutron capture on Br (Bogard et al., 1984; Becker and Pepin, 1984; Swindle et al., 1986).

Some additional isotopic ratios measured by Viking resemble those measured in SNC shock-glass (Table 3, Fig. 3). The D/H ratio measured in Mars' atmosphere by earth-based spectroscopy is similar to D/H measurements in some SNC phases (Watson et al., 1994). In the case of the $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ isotopic ratios, uncertainties in the Viking measurements (~ 5% for each) are generally larger than the total range of measurements of these isotopic ratios in different phases of SNC meteorites. The $^{15}\text{N}/^{14}\text{N}$ ratio measured by Viking is a more accurate determination of the Martian atmospheric value than the EETA79001 data, because analyses of Martian N in SNCs always include additional N components (e.g., ^{15}N from spallation) and thus only define a lower limit for the atmospheric $^{15}\text{N}/^{14}\text{N}$. However, the $^{15}\text{N}/^{14}\text{N}$ measurements on SNC shock-glass define a mixing line that passes near the composition measured by Viking (see Fig. 4; Marti et al., 1995; Miura et al., 1994). Thus, an overall similarity exists in isotopic composition between gas trapped in SNC shock-glass and the Martian atmosphere.

In addition to major solar system reservoirs of volatiles (e.g., Table 2), there also exist other volatile components. We can consider to what extent these may have contributed to SNC volatiles to produce a Mars-like composition. Xenon-129 and ^{40}Ar are monoisotopic gas components that form from radioactive decay of ^{129}I and ^{40}K , respectively, and these components are clearly present in SNCs and the Martian atmosphere (Fig. 2; vis. Swindle, 1988). Direct production of ^{129}Xe by in situ decay of ^{129}I in most SNCs appears very unlikely because of the short

Table 3
Isotopic compositions of gases and condensates^a

| | SNC ^b | Mars ^c | Earth | Venus | Comets ^d |
|---------------------|---------------------------------------|-----------------------|-----------------------|---------|------------------------|
| D/H | 8.4×10^{-4e} | 8.6×10^{-4f} | 1.56×10^{-4} | 0.016 | $0.5-5 \times 10^{-4}$ |
| δD | 4400‰ | 4500‰ | 0‰ | 10,000‰ | |
| $^{12}C/^{13}C$ | > 86 ^g | 92 ± 5^h | $\sim 89 CO_2$ | 88 | ~ 70 |
| $\delta^{13}C$ | > 36‰ | -33 ± 45 | $-7‰$ | $-7‰$ | |
| $^{14}N/^{15}N$ | < 188 ⁱ | 170 ± 15 | 272 | 273 | > 200 |
| $\delta^{15}N$ | > 450‰ | $620 \pm 160‰$ | 0‰ | 0‰ | |
| $^{16}O/^{18}O$ | 489–473 ^g | 510 ± 25^h | 489 CO_2 | 500 | 435 ± 125 |
| $\delta^{18}O$ | +4–+36‰ | $-37 \pm 45‰$ | +4.2‰ | $-18‰$ | |
| $^{16}O/^{17}O$ | — | 2655 ± 25 | 2520 CO_2 | — | — |
| $\delta^{17}O$ | — | $-50 \pm 20‰$ | +2.2‰ | — | — |
| $^{36}Ar/^{38}Ar$ | 4.1 ± 0.2^j < 4 ^{k,l} | 5.5 ± 1.5 | 5.32 | 5.1–5.6 | — |
| $^{40}Ar/^{36}Ar$ | $\sim 1800^l$ | 3000 ± 500 | 296 | 1.0 | — |
| $^{129}Xe/^{132}Xe$ | 2.6 ^m | 2.5_{-1}^{+2} | 0.98 | — | — |

^aValues for Earth, and Mars, and Venus are atmospheres only, and do not include volatile components trapped in liquid and solid materials of planets.

^bShock-glass gas component (see text).

^cViking Lander analyses, as in Owen (1988), except where otherwise noted.

^dVanysek (1991)

^eWatson et al. (1994).

^fKrasnopolsky et al. (1998).

^gJakosky (1991), Hutchins and Jakosky (1997).

^hKrasnopolsky et al. (1996).

ⁱMiura and Sugiura (1994).

^jBecker and Pepin (1984), Weins et al. (1986).

^kBogard (1997).

^lBogard and Garrison (1998).

^mBogard and Garrison (1998).

half-life of ^{129}I (18 Myr) and the relatively young formation ages of the meteorites (see later section). The shergottites also contain excess radiogenic ^{40}Ar in far greater amounts than those expected from in situ decay of ^{40}K (Shih et al., 1982; Bogard and Garrison, 1999), a situation not observed in other meteorites. Cosmic ray interactions produce a nuclear, or cosmogenic, component of generally predictable isotopic composition that does not resemble gases in SNC shock-glass. Some primitive nucleosynthetic components only affect isotopes of particular elements, such as xenon-HL, xenon-S, or krypton-S (Anders, 1988; Swindle, 1988). A range of pre-solar carbon components have been identified and found to be associated with some of the exotic gas components above (Anders, 1988). Most, however, have $\delta^{13}C$ values too large for that of the Martian atmosphere ($> 340‰$ vs. $< 36‰$), and none have permissible values of both $\delta^{13}C$ and $\delta^{15}C$ (Table 3). (The δ isotopic notation describes the difference between an isotope ratio and that of a standard in parts per thousand. Thus, $\delta^{13}C = +100‰$ means that the $^{13}C/^{12}C$ ratio in the analyzed substance is 10% greater than that in the standard.) Fission of heavy

elements ($^{244}Pu, ^{238}U, ^{235}U$) produces distinctive spectra of xenon isotopes, but these are not like xenon in the SNC meteorites (although they may be precursor components; Swindle and Jones, 1997). It would require a complex and contrived mixture of many such exotic components to even begin to reproduce, unsuccessfully we believe, the isotopic composition of volatiles in SNC shock-glass.

Some SNC and Martian volatiles (those lighter than Kr) are significantly enriched in the heavier isotopes compared to other volatile reservoirs. This enrichment is particularly obvious in N and H, but also occurs for $^{36}Ar/^{38}Ar$ (Table 3). The isotopic enrichment in these Martian atmospheric species is interpreted to result from mass fractionation during atmospheric loss over geologic time (Pepin, 1994; Jakosky et al., 1994; Jakosky and Jones, 1997; and references therein). The same explanation has been offered for the high D/H ratio in Venus' atmosphere (Donahue, 1995). Of course, enrichments of the heavier isotopes could also arise, in principle, from mass fractionation produced in other ways. Martian volatiles such as C and O do not show isotopic fractionations nearly as large as N,

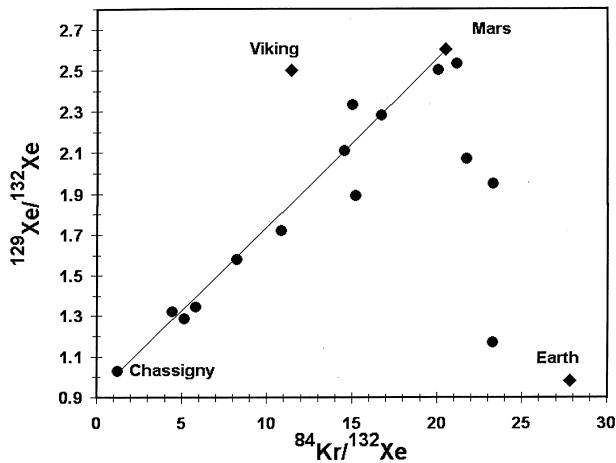


Fig. 3. Component mixing relation between the $^{129}\text{Xe}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios measured in samples of shergottites EET79001, Shergotty, Y793605, and ALH77005 and in Chassigny. Also shown are these ratios for the Earth's atmosphere, for the Martian atmosphere from Viking Lander data, and the SNC shock-glass gas composition. See text for references.

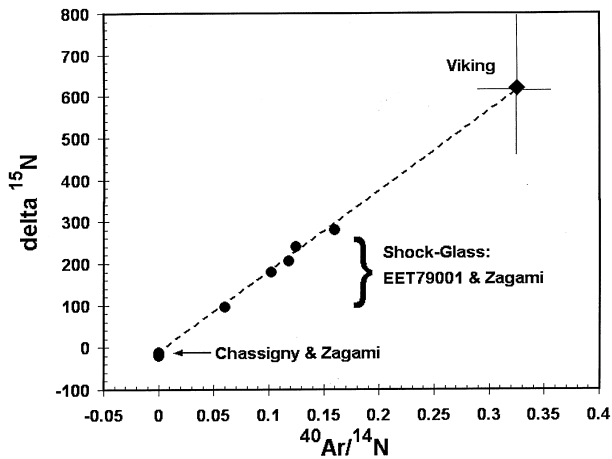


Fig. 4. Component mixing relation between $\delta^{15}\text{N}$ and $^{40}\text{Ar}/^{14}\text{N}$ for five shock-glass samples of shergottites EET79001 and Zagami, and for non-glass samples of Chassigny and Zagami. The Viking measurements are also shown. See text for references.

probably because atmospheric C and O are buffered by exchange with larger reservoirs of these elements in the Martian crust. A few meteorites have N isotopic compositions as heavy or heavier than the Martian atmosphere (Prombo and Clayton 1985), but their other gas species are unlike those in the Martian atmosphere or in SNC shock-glass gas (Anders, 1988). Cometary ices can have elevated D/H ratios, but not so extreme as in the Martian atmosphere (Table 3; Delsemme, 1997). The fact that escape from a planetary atmosphere can account for appreciable mass fractionation in some volatiles, and buffering with crustal species can account for much smaller mass fractionation in other volatile species, would appear to be specific to plane-

tary processes. Thus, the general isotopic similarity of SNC volatiles and Martian atmospheric volatiles implies that the SNC volatiles experienced a similar planetary history.

3.3. Evidence for a planet with an atmosphere

Independent of the exact compositions of the Martian atmosphere and of other gas reservoirs in the solar system, the trapped SNC gases themselves seem to require evolution on a planetary body with a significant atmosphere. With this constraint, the SNC parent body could not be an asteroid or comet, Mercury or the Moon, or all but a few of the moons in the outer solar system. Most smaller bodies in the solar system never possessed significant atmospheres. Even if we had only a knowledge of the Earth's atmosphere and its processes, the trapped gases in the SNCs would strongly suggest that they formed on Mars. We infer four lines of evidence that the SNC gases require a planet-sized body with an atmosphere: high abundances of an 'atmospheric component', strong depletions of light isotopes in the 'atmospheric component', multiple gas components, and the presence of a component derived from the 'atmospheric component' by elemental fractionation.

3.3.1. Gas abundances

First, the SNC gas component found in shock-glass and identified with the Martian atmosphere is extremely abundant in some samples of the SNC meteorites. For example, shock-glass inclusion EETA9001,27 contains this component in an abundance equivalent to an isovolumetric aliquot of Martian atmosphere gas at ~ 7 millibars pressure (e.g., Wiens and Pepin, 1988). Such a high gas abundance, notably rich in CO_2 , N_2 , and noble gases, requires that a separate reservoir of these gases was sampled and injected into the glass at the time of its formation, which most probably was within the past 0.2 Gyr (see later section). Chemical evidence has been presented for a significant Martian regolith component in the EET79001 shock-glass (Rao et al., 1999), and Martian atmosphere associated with this regolith is an obvious source for these shock-implemented volatiles. The only somewhat similar case among other meteorites is that of the ureilites, where noble gases already adsorbed by graphite was incorporated into diamond produced from the graphite during shock (Göbel et al., 1978). The ureilite noble gases closely resemble gases in primitive meteorites, however, and not those in shergottites.

3.3.2. Atmospheric isotopic fractionation

Second, the isotopic composition of the shock-glass gas component is strongly fractionated in a manner consistent with atmospheric processing. As shown in Table 3, the shock-glass gas is strongly enriched in the heavy isotopes of several atmospheric species, most notably H, N, and Ar, compared to the bulk solar system, the bulk Earth, and to

most gases in meteorites. Isotopic abundances of C and O are less fractionated, but they could reasonably be buffered by other reservoirs on the parent planet (e.g., carbonate and silicate minerals). This consistent enrichment in heavy isotopes suggests the loss of light isotopes, and escape from an atmosphere to interplanetary space provides a pathway for this enrichment (Donahue, 1986; Pepin, 1994; Jakosky et al., 1994; Jakosky and Jones, 1997; and references therein).

Mars' is not the only planetary atmosphere that has changed by loss of light isotopes. Venus' atmosphere is strongly depleted in hydrogen (^1H) relative to deuterium (^2H), presumably through thermal escape to space (Donahue and Pollack, 1983; Donahue, 1995). In addition, the atmosphere of Titan is depleted in ^{14}N relative to ^{15}N , although the putative escape processes are non-thermal (Lunine et al., 1999). In the case of Mars' atmosphere, several atmospheric escape mechanisms are possible or possibly required (Pepin, 1994); the common theme among them is that the residual gas left at the planet can become strongly enriched in heavier isotopes.

3.3.3. Elementally fractionated gas with atmospheric signature

A third argument for the existence of an atmosphere on the SNC parent body is that the nakhlites and ALH84001 contain noble gases which can be related to the shock-glass component by elemental fractionation. This gas component consists of noble gases with isotopic ratios resembling those of the shock-glass component, but with significantly different elemental abundance ratios (Drake et al., 1994; Gilmour et al., 1998). At least some of this gas component is associated with secondary (low-T alteration) minerals, and its elemental fractionation pattern is consistent with selective adsorption on grain surfaces, possibly during aqueous alteration (Drake et al., 1994; Bogard and Garrison, 1998; Gilmour et al., 1998). The isotopic ratios of both gas components seem to require an origin in an atmosphere (see preceding paragraph), and it seems simplest to infer that this nakhlite (and ALH84001) gas component has the same source as the shock-glass component, which we have identified as the Martian atmosphere. Again, this process requires a distinct reservoir of atmospheric gases (i.e., an atmosphere) and a planet with active complex geochemistry to allow that component to be adsorbed onto solids, fractionated in the process, and stabilized there.

3.3.4. Multiple volatile components

A final argument for the existence of an atmosphere on the SNC parent body is the observation that SNC meteorites contain volatiles derived from at least two distinct components that occur in varying proportions. One component is the shock-glass (= Mars atmosphere) gas discussed above (Tables 2, 3; Figs. 1, 2), present both as 'pristine' and elementally fractionated' forms. The second component is represented by trapped gas in the Chassigny meteorite (Ott,

1988; Swindle, 1995; Marti et al., 1995; Bogard and Garrison, 1998). These two gas components have very different elemental and isotopic abundances of the noble gases, N, and H (and to a lesser extent O and C), and so must have been formed and preserved separately. The simplest way to justify separate gas reservoirs (as has been done for the SNCs) is to attribute one component to an atmosphere on the parent body and the other to the silicate rock mantle and crust.

These two SNC gas components are best revealed in their heavy noble gases and nitrogen. Fig. 3 shows the mixing relation between the $^{129}\text{Xe}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios for analyses of shergottites EET79001, Shergotty, Y793605, and ALH77005. One end member gas composition is that measured for Chassigny (Ott, 1988). From this plot and analogous data for Ar, Bogard and Garrison (1998) deduced the other end member component (abundant in shock-glass) to be that of the Martian atmosphere, having an elemental composition of $^{36}\text{Ar}/^{132}\text{Xe} = 900 \pm 100$ and $^{84}\text{Kr}/^{132}\text{Xe} = 20.5 \pm 2.5$. These two ratios for Chassigny are only ~ 15 and ~ 1.2 , respectively. The Martian atmosphere (and shock-glass) gas components have $^{129}\text{Xe}/^{132}\text{Xe} = 2.6$ (Table 3), whereas Chassigny has $^{129}\text{Xe}/^{132}\text{Xe} = 1.03$. The Chassigny component has been inferred to be the residue of solar nebula gas accreted into the SNC parent body. However, whereas the Xe isotopic composition in Chassigny is very similar to solar gas, the Chassigny Ar/Kr/Xe elemental ratios are very highly mass fractionated relative to solar gas (Ott, 1988). Clearly, the Martian atmosphere and mantle gas components have very different evolutionary histories. A few analyses in Fig. 3 plot off of the SNC atmosphere/mantle trend and indicate significant contamination with terrestrial air, which has a distinctive noble gas composition (Bogard and Garrison, 1998). The analysis reported by Viking is similar in its $^{129}\text{Xe}/^{132}\text{Xe}$ measurement, but differs by a factor of two in its $^{84}\text{Kr}/^{132}\text{Xe}$ from the Martian atmospheric composition deduced from SNC data. Although Owen et al. (1977) suggested an uncertainty of $\pm 20\%$ in the Viking Kr and Xe measurements, the SNC data suggest that the actual uncertainty was greater.

The atmospheric and mantle components in SNCs also have distinctly different nitrogen isotopic abundances. Fig. 4 shows $\delta^{15}\text{N}$ values (defined as deviations of $^{15}\text{N}/^{14}\text{N}$ from terrestrial N in parts per thousand) plotted against $^{40}\text{Ar}/^{14}\text{N}$ ratios for five shock glass samples of EET79001 and Zagami (Becker and Pepin, 1984; Wiens et al., 1986; Marti et al., 1995). Also plotted are analyses of Chassigny and a non-glass sample of Zagami (Marti et al., 1995; Mathew and Marti, 1999), and the Viking analysis of the Martian atmosphere (Owen et al., 1977). The SNC data have been corrected for ^{40}Ar from in situ decay of ^{40}K and for ^{15}N produced from cosmic-ray interactions. The corrected shock-glass data all lie on a two-component mixing trend between the end member compositions defined by the Viking analysis of the Martian atmosphere and by gas in the Chassigny and non-glass Zagami samples for the mantle component. Additional measurements of shergottite

shock-glass show $\delta^{15}\text{N}$ values up to $\sim 520\text{‰}$, greater than the values plotted in Fig. 4 (Wiens et al., 1986; Marti et al., 1995; Miura and Sugiura, 1994; Murty and Mohapatra, 1997; Mathew et al., 1998; Grady et al., 1998). However, $^{40}\text{Ar}/^{14}\text{N}$ ratios were not measured for some of these analyses, so they are not plotted. These variations in $\delta^{15}\text{N}$ are closely related to similar variations in the noble gases (e.g., Fig. 3) and are produced by mixing of the same two atmospheric and mantle gas components.

Hydrogen isotopic ratios in SNC samples also vary widely, although their variations have not been clearly correlated with those of N and noble gases. H-bearing minerals in SNC meteorites have D/H ratios up to 8.4×10^{-4} , or $\delta D \sim 4400\text{‰}$ (Watson et al., 1994). This value is nearly as high as the Martian atmosphere's D/H ratio of 8.6×10^{-4} , or $\delta D \sim 4600\text{‰}$ (Krasnopolsky et al., 1998). Such extreme mass fractionation was undoubtedly produced during loss of the Martian atmosphere, a phenomenon also observed for Venus (Donahue, 1995). However, other H-bearing minerals in SNCs yield D/H ratios as low as 1.8×10^{-4} , $\delta D \sim 150\text{‰}$ (Boctor et al., 1999) and gas released from Chassigny samples at high T yield D/H of 1.48×10^{-4} – 1.65×10^{-4} , $\delta D \sim 50\text{‰}$ – $+50\text{‰}$ (Leshin et al., 1996). Such broad variations in δD suggest that the SNCs contain at least two H-bearing components, and that the heavier (higher δD) component is the Martian atmosphere.

In addition to these major variations in the elemental and isotopic abundances of N, H, and the noble gases, SNCs exhibit smaller variations in the isotopic compositions of O and C which suggest separate volatile reservoirs on their parent planet. Because the observed O and C isotopic variations are smaller, we must also consider that isotopic fractionation which naturally results from chemical reaction and isotopic exchange among different phases. Using the $^{18}\text{O}/^{16}\text{O}$ ratio as a monitor of such equilibrium isotopic differences, the $^{17}\text{O}/^{16}\text{O}$ ratios for some SNC analyses indicate the existence of two or more separate oxygen reservoirs not in isotopic equilibrium. One reservoir is represented by primary silicate minerals, and another is represented by volatile-containing phases such as carbonates, clay minerals, apatite etc. (Karlsson et al., 1992; Watson et al., 1994; Romanek et al., 1998; Farquhar et al., 1998). Presumably, the oxygen in these volatile-containing phases derived from atmospheric O and did not equilibrate with O in the silicate. Again this is consistent with two gas reservoirs that evolved separately.

Carbon also shows a significant range in $^{13}\text{C}/^{12}\text{C}$ ratios in SNCs. To account for the $^{13}\text{C}/^{12}\text{C}$ variations that reflect chemical equilibria, however, we must identify all major C-containing phases. On earth, the $^{13}\text{C}/^{12}\text{C}$ ratio typically varies by $\sim 10\text{‰}$ among atmospheric CO_2 , carbonate rocks, and carbon in mantle rocks, whereas organic carbon extends the range of $^{13}\text{C}/^{12}\text{C}$ to $\sim 30\text{‰}$. In SNC meteorites, $\delta^{13}\text{C}$ shows a large total range of $+41\text{‰}$ to $\sim -60\text{‰}$. The reason for the more negative values of $\delta^{13}\text{C}$ are not understood and may even represent terrestrial contaminants (Wright

et al., 1997a). However, values of $\delta^{13}\text{C}$ among SNC carbonates and associated phases apparently vary from $+41\text{‰}$ to -11‰ (e.g., Grady et al., 1994; Romanek et al., 1994; Jull et al., 1997; Wright et al., 1997b; and references therein). The explanation for the larger variation in $\delta^{13}\text{C}$ for SNC carbonates compared to the earth may be Martian organic compounds (Wright et al., 1998) to separate reservoir components not in isotopic equilibrium.

The presence of two or more isotopically distinct volatile components in a single SNC meteorite requires several distinct sources of volatiles in its parent planet. For these different volatile components to have become sited in altered, shocked igneous rocks implies that the components must have evolved as distinct gas reservoirs within the parent body, and this indicates a complex, differentiated body. The shock-glass component is undoubtedly atmosphere, and the others probably represent crustal or mantle gases which have never been exposed on the mass fractionation processes of the atmosphere. Presence of multiple indigenous gas components is nearly unique to the SNC meteorites (ignoring cosmic-ray-produced gases, whose isotopic composition is distinctive). The only similar case is in meteorites that contain a gases component acquired during meteorite formation and a solar component acquired during solar wind irradiation at parent body surfaces. The gas components in SNCs do not show solar-like elemental abundances, although they may have been derived originally from solar-like gases.

3.4. Summary

The SNC meteorites contain two or more trapped volatile components with distinct compositions. One gas component is nearly identical in elemental and isotopic composition to the Martian atmosphere as measured by Viking. It is distinct from other known gas reservoirs in the solar system and its composition is characteristic of processing in a planetary atmosphere, a condition consistent with Mars but not with smaller solar system parent bodies. In fact, this SNC gas composition, rather than the Viking *in situ* analyses, is generally adopted as a precise measure of the Martian atmospheric composition for the noble gases (e.g., Pepin, 1989; Jakosky, 1991; Pepin and Carr, 1992; Bogard, 1997; Jakosky and Jones, 1997; Swindle and Jones, 1997; Bogard and Garrison, 1998). Some SDNC meteorites contain a variant of this atmospheric component, particularly among alteration and low-temperature minerals. The isotopic composition of this variant is similar to the atmosphere component, but its elemental abundance ratios are consistent with fractionation of atmospheric gas during absorption onto mineral surfaces. A second component represents volatiles acquired during accretion of the planet and still trapped in its interior. In the case of N, the noble gases, and H, this mantle component is elementally and isotopically very different from the

atmosphere. Variations in the isotopic compositions of H and O among silicate and volatile-containing phases of some SNCs implies that separate reservoirs of these elements are also present, although differences between these reservoirs are much less striking than for the noble gases, H, and N. Several characteristics of SNC volatiles indicate processing through a planetary atmosphere, a condition consistent with Mars but not with smaller solar system parent bodies. It appears highly unlikely that complex combinations of gas reservoirs or processes that produce gas components could independently generate within SNC meteorites a range of volatile compositions so similar to that measured directly for Mars.

4. Chemical composition

The Viking and Mars Pathfinder landers produced chemical analyses of soils and rocks on the Martian surface, and these analyses provide additional links between the SNC meteorites and Mars. From the beginning, the Viking analyses of Martian fines were compared to the Shergotty meteorite (Clark et al., 1982), and that similarity is still cited (e.g., Rieder et al., 1997).

Many geochemical parameters are useful in distinguishing basaltic materials that come from the various solar system bodies, like oxidation state and element abundance ratios, but few of the critical elements have been analyzed in Mars surface materials (e.g., La, U, Rb, Cs, Ni, Co, Ga, Ge; Laul et al., 1972b; Stolper et al., 1979; Wänke, 1981; Smith et al., 1984; McSween, 1985; Treiman et al., 1986; Drake et al., 1984; Malvin and Drake, 1987; Wänke and Dreibus, 1988; Longhi et al., 1992). To use these elements in geochemical tests of Martian origin, we would need in situ trace element analyses of Martian materials, or Martian samples returned to Earth. For now, we can only discuss the parameters that involve elements analyzed by the Viking and Mars Pathfinder landers.

4.1. FeO vs. MnO

For more than 25 years, the abundance ratio FeO/MnO has been used as a discriminant for the origin and classifications of planetary basalts (Laul et al., 1972a, 1986; Wänke et al., 1973; Stolper et al., 1979; Drake et al., 1989). Fig. 5 shows ranges of FeO and MnO contents of basaltic materials from planets and meteorites. Basalts from the Earth have FeO/MnO near 60; lunar basalts have slightly higher values near 70–75. Eucrite basalts, SNC meteorites and Mars materials (from Mars Pathfinder) have distinctly lower values of FeO/MnO, mostly near 35. The eucrites center tightly at that value, and the SNC meteorites and Mars materials tend to have a slightly higher value near ~ 40 , but the statistical significance of this difference is not clear. From the perspective of FeO/MnO ratio, the SNCs could be Martian, and are

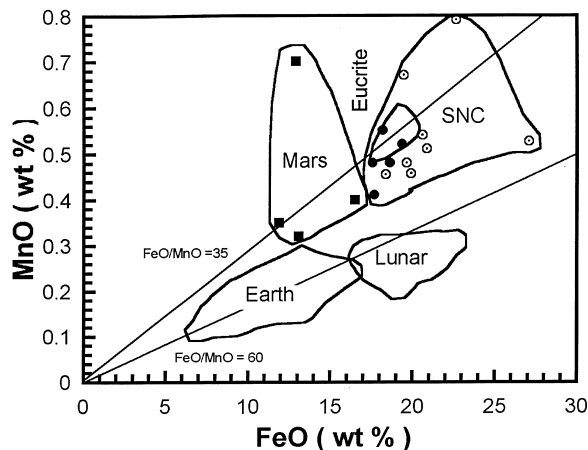


Fig. 5. Weight percentages of FeO and MnO in solar system basalts and Martian materials. Filled circles are SNC basalts, open circles are other SNC meteorites, filled squares are Mars surface materials. SNC meteorites have essentially the same FeO/MnO ratio as do Mars surface materials and eucrite basalts. Lunar and terrestrial basalts are similar to each other, and quite distinct from SNCs. Only the Chassigny SNC meteorite has a comparable FeO/MnO ratio to terrestrial basalts; this difference arises because Chassigny is an olivine cumulate rock, not strictly a basalt. Data sources are: SNC meteorites, Meyer (1998); Mars surface materials, Clark et al. (1982), Banin et al. (1992), Rieder et al. (1997), Dreibus et al. (1999), Wänke (1999); solar system basalts, BVSP (1981), Dungan et al. (1989), and Barnes et al. (1983).

definitely not terrestrial or lunar. It remains unclear, from FeO and MnO whether the SNCs could be eucritic.

4.2. Cr vs. Mg*

The proportion of chromium abundance to Mg*, the molar ratio Mg/(Mg + Fe) differs among basalts from planetary bodies (Stolper et al., 1979; BVSP, 1981; Laul et al., 1986; Wänke and Dreibus, 1988; Drake et al., 1989). Fig. 6 shows these parameters for a variety of solar system basalts; cumulates have been excluded because of the likelihood that chromite fractionation would obscure magmatic trends. Chromium data from Mars Pathfinder must be regarded as preliminary, as its calibration continues (Dreibus et al., 1999; Wänke, 1999). It is clear that the SNC basalts and the Mars Pathfinder rocks are part of the same trend (Fig. 6), along with lunar and eucritic basalts. Terrestrial basalts are clearly distinct from the other solar system basalts. It may be that there are significant distinctions among the non-terrestrial basalts on this diagram, but it should be clear that the Cr vs. Mg* test is consistent with the SNC having formed on Mars.

4.3. Na vs. Al

Solar system bodies differ in their contents of volatile elements, presumably reflecting volatility-controlled processes during accretion. This difference has been used in many

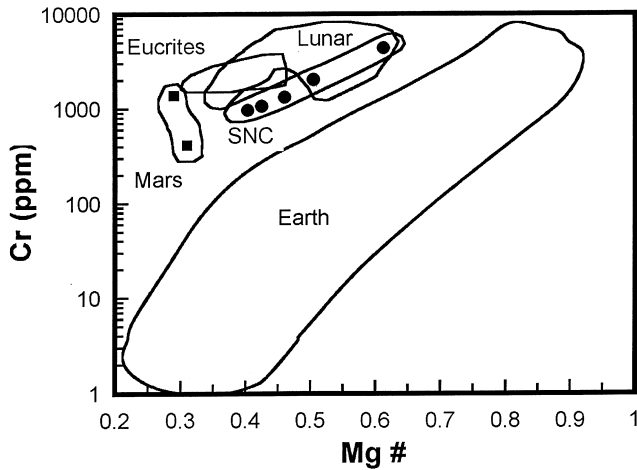


Fig. 6. Weight percentages of Cr compared to molar Mg/(Mg + Fe) ratio, Mg#, in solar system basalts and Martian materials. Filled circles are SNC basalts, other SNC not shown because of the possibility of chromite accumulation, filled squares are Mars surface materials. SNC meteorites have essentially the same Cr vs. Mg# trend as do Mars surface materials, eucrite basalts, and lunar basalts. Terrestrial basalts have significantly less Cr for a given Mg#. Data sources as in Fig. 5.

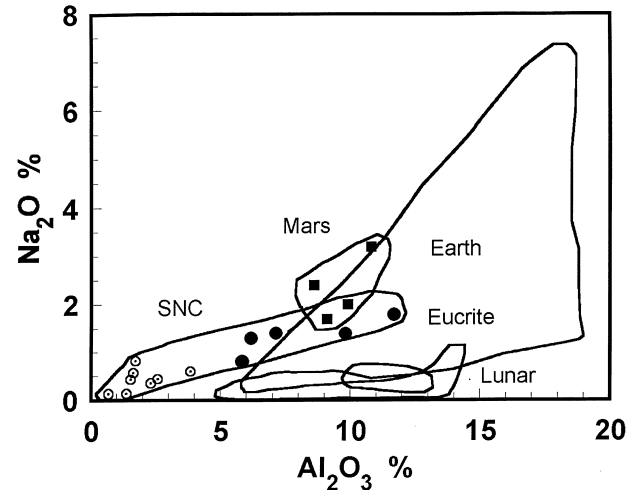


Fig. 7. Weight percentages of Na₂O and Al₂O₃ in solar system basalts and Martian materials. Filled circles are SNC basalts, open circles are other SNC meteorites, filled squares are Mars surface materials. SNC meteorites have essentially the same Na₂O/Al₂O₃ ratios and trend as do Mars surface materials. Terrestrial basalts show a wide range of Na and Al contents, presumably reflecting the long and complex petrogeneses possible on Earth. Lunar and eucrite basalts have significantly less Na and generally more Al than do SNC basalts and Mars surface materials. Data sources as in Fig. 5.

planetary discriminators by comparing abundances of a volatile element to a refractory element of comparable geochemical behavior. Alkali elements tend to be quite volatile, so elemental ratios like K/U, Cs/La, etc. have been used extensively (e.g., Stolper et al., 1979; Wänke, 1981; Smith et al., 1984; McSween, 1985; Treiman et al., 1986; Wänke and Dreibus, 1988; Longhi et al., 1992). This approach is difficult for the Martian rocks, at present, because the in situ analyses of alkalis are fairly uncertain, and because we have no analyses of highly incompatible elements like U or La.

Abundances of the remaining alkali element, Na, are closely correlated with Al abundances in the SNC meteorites (Treiman et al., 1986), so the Na/Al ratio may be useful. This ratio is not ideal, as Na and Al can have significantly different behaviors in basaltic systems depending on whether an Al-rich mineral (plagioclase, spinel, or garnet) was retained in the source region or whether plagioclase crystallized and separated from the basalt magma. Even with these cautions, comparison of the abundances of Na₂O and Al₂O₃ in solar system basalts and related rocks (Fig. 7) shows: (1) the wide range Na₂O and Al₂O₃ abundances and ratios in Earth basalts, reflecting a complex geologic history; (2) the relative constancy of Na/Al ratios in the SNC meteorites; and (3) the very low Na abundances (and therefore Na/Al ratios) in the eucrite and lunar basalts. Fig. 7 also shows that Martian materials have Na/Al ratios like SNC meteorites and unlike ratios in the other bodies. Thus, Na/Al ratios are consistent with the SNC meteorites having formed on Mars.

4.4. FeO/MnO vs. Na/Al

In the graphs of FeO vs. MnO and Na₂O vs. Al₂O₃, the SNC meteorites plot with Martian materials, and are distinct from some other solar system basalts (Figs. 5–7). Kring et al. (1995) noted that combinations of several ratios can provide stronger discriminants than single ratios. Kring's best example was Fe/Mn vs. Ga/Al, which together were sufficient to distinguish all known groups of solar system basalts; on this diagram, the SNC meteorites plot together, orders of magnitude distant from any other group of basalts. The Martian surface materials have not been analyzed for Ga, but we can use the Na/Al ratio (Fig. 7) in its stead, as shown in Fig. 8. From that figure, it is clear that the SNC and Martian materials are quite comparable, in the sense of having nearly identical FeO/MnO ratios (reflecting similar oxidation states during core formation) and nearly identical Na₂O/Al₂O₃ (reflecting similar temperature histories during planetary accretion). Further, it can be seen that the SNC and Mars samples are completely distinct from eucrite basalts, lunar basalts, angrite basalts, and brachinite 'basalts'. The SNC and Martian materials are mostly distinct from terrestrial basalts in having lower FeO/MnO values (Fig. 5). Again, the combination of these chemical ratios is consistent with the SNC meteorites having formed on Mars.

4.5. Oxidation state

A test of rather different character is provided by the oxidation states of Mars and the SNC meteorites. Among

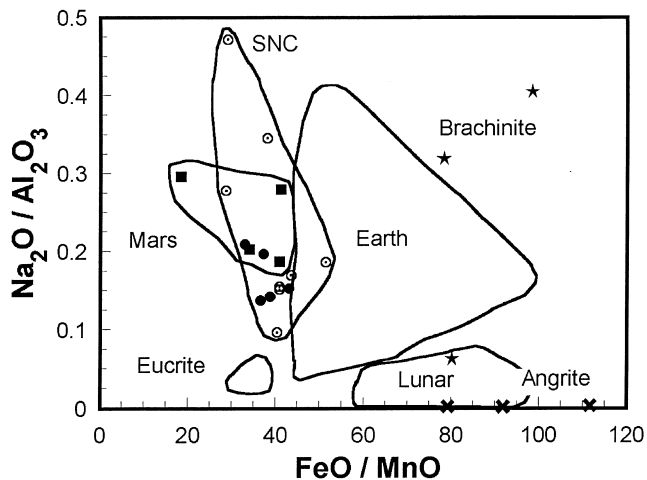


Fig. 8. The abundance ratios FeO/MnO versus $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ in solar system basalts and Martian materials. Also shown are angrite basalts as “X”s and brachinite basalts as stars (both asteroidal meteorites). Following Kring et al. (1995), pairs of element abundance ratios can be better planetary discriminators than individual ratios or parameters. Here, SNC basalts and Mars surface materials are nearly coincident (showing their geochemical similarity), and clearly distinct from lunar basalts, eucrite basalts, angrite basalts, and brachinites. Only the Chassigny SNC meteorite has a comparable FeO/MnO ratio to terrestrial basalts; this difference arises because Chassigny is an olivine cumulate rock, not strictly a basalt. Data source as in Fig. 5.

meteorite basaltic rocks, only the SNCs and the angrites containing significant proportions of ferric iron (Fe^{3+}) and ferrous iron (Fe^{2+}); the other meteoritic basalts contain only ferrous iron and iron metal (vis. Papike, 1999). Thus, oxidation state clearly differentiates the SNCs from the eucrite meteorites, which have similar FeO vs. MnO and Cr vs. Mg^* .

The relatively oxidizing nature of the SNCs is consistent with what is known of Mars surface mineralogy, although it along obviously cannot distinguish a Martian origin from terrestrial or Venusian origins. Mars is reddish to the eye, and that color is universally thought to reflect the presence of ferric iron in the surface materials (e.g., Banin et al., 1992; Bell III, 1996). The reddish color is thought to derive principally from ultrafine (nanophase) hematite, a ferric iron oxide, and from ferric iron oxyhydroxides (Banin et al., 1993). Similarly, Viking lander analyses of the Martian soil indicate that it is strongly oxidized and oxidizing (Klein et al., 1992).

4.6. Summary

Chemical analyses of the SNC meteorites are consistent with a Martian origin, recognizing that we have analyses of only a few Martian materials for only a few elements at relatively poor levels of accuracy and precision. Yet, even with these cautions, it is clear that the SNC meteorite and Martian materials are closely similar and are not similar to the other analyzed basalts in the solar system: terrestrial, lunar, eucritic, angritic, and brachinitic. The chemical links

between the SNCs and Martian rock and soil is not as strong as the atmospheric gas link because of the relative imprecision of the Martian in situ analyses. Yet we emphasize again that bulk compositions of the SNC meteorites are consistent with an origin on Mars.

5. Geochronology and history

One important part of the earlier, indirect arguments linking the SNC meteorites to Mars (Wood and Ashwal, 1981) was their chronological histories. Although a significant amount of additional data have been obtained, these arguments remain (for the most part) as valid as they were in the early 1980s. The young isotopic ages of the SNCs and their extreme chemical fractionations, the mix of young and old ages, and evidence for recent aqueous alteration, are all consistent with Mars as the source planet.

5.1. Young ages, extreme fractionations

The young formation ages of the SNC meteorites were a key argument that they were from Mars (Wood and Ashwal, 1981). Radiometric ages for all known SNCs at that time were 1.3 Ga or younger (McSween, 1985), while nearly all other meteorites had formation or crystallization ages near 4.5 Ga. These young ages were assumed, by and large, to represent times of igneous crystallization or subsequent shock metamorphism. This bespoke a geologically active planet, one that was large enough to retain the heat needed for volcanism at least to 1.3 Ga ago. Extreme depletions in certain trace elements, inferred from their isotopic compositions to be a characteristic of the mantle source regions, suggested extreme or repeated chemical fractionations in the planet where they were produced (e.g., Smith et al., 1984; Borg et al., 1997). Such processes seemed highly unlikely on an asteroid-sized body.

However, difficulties have arisen in interpreting the SNCs precise chronology from the radiometric data, especially for the shergottite meteorites. For the nakhilites and Chassigny, many radio-isotope systems (Rb–Sr, Sm–Nd, K–Ar, U–Th–Pb) yield ages of about 1.3 Ga. ALH84001 also records a relatively simple radioisotope chronology, despite its complex geological history (Treiman, 1998): formation from magma at 4.5 Ga; shock metamorphism, brecciation and emplacement of secondary carbonates at ~ 3.9 Ga, ejection into space at 15 Ma, and impact onto Earth 13,000 years ago.

5.1.1. The shergottites

Radio-isotope systematics for the shergottite meteorites are more complex. Whole-rock Rb–Sr data for the shergottites yield an isochron of 4.5 Ga with an initial Sr isotopic ratio like that of the basaltic asteroids (Shih et al., 1982). However, Rb–Sr data for minerals in individual shergottites yield isochrons with apparent ages ranging

from 360 to 160 Ma (Shih et al., 1982; Jagoutz, 1991; Nyquist et al., 1995; Borg et al., 1997). Early whole-rock Sm–Nd data for the shergottites (Wooden et al., 1982; Shih et al., 1982) appeared to yield an isochron age of ~ 1.3 Ga, comparable to the crystallization ages of the nakhlites and Chassigny. However, Sm–Nd data for minerals in individual shergottites also suggest young ages comparable to the Rb–Sr internal (mineral) ages. Data on U–Th–Pb systems are consistent with the Rb–Sr system, indicating an early fractionation event in the mantle source at about 4.5 Ga and young formation ages of ~ 200 Ma (Chen and Wasserburg, 1986, 1993; Jagoutz, 1991). Jones (1986) concluded that an igneous age of ~ 180 Ma for all shergottites was most consistent with available isotopic data. Ar–Ar ages (a proxy for K–Ar), yield apparent ages between 0.3 and 5 Ga (Bogard et al., 1979; Bogard and Garrison, 1999), but these are false ages due to the presence of trapped Martian atmosphere rich in the daughter isotope ^{40}Ar . By considering the presence of Martian atmosphere, the release spectra of Ar from Shergotty has been deconvolved to reveal an age of 167 Ma, more or less concordant with the other isotopic systems (Bogard and Garrison, 1999). One shergottite, QUE94201, is somewhat older at 330 Ma (Borg et al., 1997).

The young ages of the shergottites are widely accepted as igneous events, i.e., the times of solidification of lavas from inside a planet (Jones, 1986; McSween, 1994). If so, their ages are consistent with a Martian origin for the SNCs. Other possible interpretations, however, may not require a Martian origin. Instead, the young ages could represent the times of impact melting and metamorphism, or of hydrothermal alteration with no melting.

The earlier suggestion that the radiometric age of ~ 180 Ma represented impact ejection of shergottites from their parent planet is no longer tenable. The strong correlation of radiometric exposure ages and lithologies (e.g., Eugster, 1997; Eugster et al., 1997; Nyquist et al., 1998) suggest that the exposure ages are ejection ages. Orbital dynamics also suggests that rocks ejected from Mars would evolve to be Earth-crossing or be ejected from the solar system on timescales < 20 Myr (Gladman, 1997).

In the first alternative, the shergottites could represent crystallized impact melts formed when an asteroid hit the parent planet at ~ 180 Ma (Chen and Wasserburg, 1986; Nyquist et al., 1995; Mittlefehldt and Lindstrom, 1999). This would presumably require that QUE94201 (age of 330 Ma) have formed in a different impact than the other shergottites. This model does not sever the link between the SNCs and Mars; it still requires a major geochemical event at 1.3 Ga, the time of nakhlite/Chassigny formation.

In the second alternative, the isotopic and radiochronologic characters of the SNC meteorites were set by processes that did not involve silicate crystal and liquid. Jagoutz (1997, 1999) and Blichert-Toft et al. (1999) invoked this model to explain the extreme fractionations — Sm from Nd, U from Pb, Lu from Hf — that are required in the SNC's isotopic histories. These fractionations are so

extreme that repeated partial melting and melt extraction would be required (e.g., Borg et al., 1997), and Jagoutz (1997, 1999) suggested this was unlikely. Jagoutz (1997, 1999) suggests rather that the SNC meteorites formed from magma at 4.5 Ga; much more recently, hydrothermal solutions introduced or removed the most mobile components (e.g., Rb, Nd, U), to produce the young ages.

In Jagoutz's view, the events of this second alternative do not require that the SNCs formed on Mars, and may not be consistent at all with a Martian origin. Extreme fractionations among elements are a fact among the SNC meteorites, as are isotopic correlations requiring mixing between two or three distinct isotopic reservoirs on their parent planet (Jones, 1989; Jagoutz, 1989). These extreme fractionations are a challenge to explain using conventional petrologic approaches and may require other processes, possibly including hydrothermal alteration. In our opinion, the need to invoke such complex processes actually strengthens the link between the shergottites and Mars! Non-igneous processes require abundant volatile components (like water and carbon dioxide) for chemical transport, and would have required a source of heat to mobilize them within the last 1.3 Ga. While one can imagine these processes occurring in a volatile-rich asteroid early in the solar system, Mars does contain the requisite volatiles and heat sources in the recent past (e.g., Carr, 1996; Hartmann et al., 1999).

5.2. *Young and old ages*

Despite many complications in the geochronology of the SNC meteorites, the mere fact of having ancient and young ages represented together seems uniquely consistent with a Martian origin. Of the terrestrial planets, Mars alone has surface geologic units that span the whole age of the solar system — from ~ 4.5 Ga (Tanaka et al., 1992) to the recent (Hartmann et al., 1999). Mercury has been geologically inactive for ~ 4 billion years (Spudis and Guest, 1988). The Moon has been largely inactive through the past ~ 3 billion years, although basalts in some limited areas may be as young as 1 billion years (BVSP, 1981; Spudis and Hood, 1988). Venus has been largely resurfaced within the last few hundred million years (e.g., Phillips et al., 1992), while no rocks are preserved from the Earth's first 500 million years (e.g., Bowring et al., 1990).

The radiometric record of the SNC meteorites fits with a Martian origin in retaining ages stretching from earliest planet formation at 4.5 Ga to magma crystallization and/or hydrothermal events at 0.18 Ga. The most ancient history of the SNC parent body is recorded in radioisotope traces of early core formation and differentiation into an enriched crust and depleted mantle (Harper et al., 1995; Lee and Halliday, 1997; Borg et al., 1997; Blichert-Toft et al., 1999). The crystallization age of the ALH84001 meteorite (4.5 Ga) is consistent with the presence of ancient crust in the Martian cratered highlands (Breuer et al., 1993). Mars' retention

of early record was apparently permitted by the absence of recycling crust into the mantle and by inefficient convective mixing in the mantle (Harder and Christensen, 1996). Magma ocean processes, including sinking of dense phases like majorite garnet and liquid into the lower mantle combined with olivine flotation above the transition zone, appear to be a realistic scenario for early stratification and differentiation of the Martian mantle and crust (Bertka and Fei, 1997) and are consistent with SNC chemistry. Siderophile element and Re–Os isotopic data for SNCs may suggest that may late chondritic veneer accreted to Mars was not incorporated into its mantle (Birck and Allegre et al., 1994; Birck and Allegre, 1994; Brandon et al., 1998), consistent with the absence of plate tectonics and with dynamical models that suggest Mars accreted quickly (Wetherill, 1986). Mars was too large to crystallize abundant plagioclase like the Moon, but too small, and therefore unable to retain enough water at its surface, to sustain any kind of major plate tectonic associated differentiation necessary to form a siliceous crust as on Earth. In the SNC meteorites, there is likewise no evidence for significant plagioclase flotation (e.g. Eu anomalies) or KREEP reservoirs, as on the Moon. The presence of evolved Earth-like crustal components in some SNC meteorites is probably best thought of as a ‘cryptic’ signature, although presence of more evolved rocks on Mars has been implicated from evidence for high silica rocks in the Pathfinder data (Rieder et al., 1997).

6. Aqueous alteration

All of the SNC meteorites were altered or modified by water-borne solutions before they arrived at Earth (e.g., Bunch and Reid, 1975; Gooding and Muenow, 1986; Gooding et al., 1988; Gooding, 1992; Romanek et al., 1994). While many asteroidal meteorites show similar signs of aqueous alteration (e.g., Zolensky and McSween Jr, 1988), alteration of the SNC meteorites was relatively recent (Gooding, 1992; Swindle et al., 1997; Shih et al., 1998), except for ALH84001 (Borg et al., 1999). Of the planets, Mars is the likely site for these alterations, as its atmosphere and polar caps contain abundant water, parts of its surface were sculpted by liquid water relatively recently (Carr, 1996), and water-mediated alteration and cementation appear important in its subsurface (Treiman et al., 1995; Carr, 1996).

7. From Mars to The Earth

Although once very controversial, it is now generally accepted that rocks can be ejected from Mars, and can traverse the solar system to land on Earth. Before the mid-1980s it was not clear how unmelted, unvaporized material (i.e., rock) could be ejected from a planetary surface. That problem was solved by the first recognition of a meteorite from

the Moon (Mason, 1982; Treiman and Drake, 1983) and by recognition of the physical ejection mechanism of spallation (Melosh, 1989). There also was doubt that rocks from Mars (once ejected) could traverse interplanetary space and arrive at Earth within the durations that SNC meteorites had been exposed to cosmic rays. This issue has now been resolved satisfactorily (Gladman et al., 1996; Gladman, 1997).

8. Conclusion

At this point, everything known about the SNC meteorites is consistent with the constraints we know or can reasonably surmise about Mars. The presence of Martian atmosphere gas (or an identical facsimile) in the SNC meteorites is the most telling link between the SNCs and Mars. The presence of distinct atmospheric and crust/mantle gas components in the SNCs are consistent with their source on a differentiated planet with an atmosphere, and seems to exclude small bodies and those without atmospheres as possible sources. The geochemistry of the SNCs matches that of Martian materials analyzed on Mars. The ages of the SNCs, both very young and very old, seem uniquely consistent with the surface geology of Mars. Relatively recent alteration by liquid water, not on the Earth, is similarly consistent with a Martian origin. If the SNC meteorites are not from Mars, they are from a planet-sized body in our solar system that is identical to Mars in all these aspects. It is conceivable, however remotely, that such an object does exist among the asteroids. It is also conceivable, however remotely, that Mars is substantially different from the scientific community’s understanding, based on the available remote and in situ data. In that sense, a returned Mars sample will provide the most rigorous test of the theory that the SNC meteorites are from Mars. Returned samples would permit analyses of many trace elements, of atmospheric isotope ratios (especially C, H, O, N, and the noble gases), and of formation ages. In our opinion, it is a near certainty that these analyses will confirm the link between Mars and the SNCs.

Perversely, the most exciting sample science would arise if the SNCs were NOT found to be Martian. If Martian rocks were irreconcilably different from the SNCs, the scientific community would then have to find a likely source for the SNCs besides Mars: a rocky body with an atmosphere, recently active volcanism, both old and young crust, and active groundwater in the recent past. In addition, we would have to explain: how the ‘unique’ composition of the Martian atmosphere could arise on two bodies; how an asteroid (or other small body) could remain hot enough to produce melts and aqueous alteration to nearly the present day (< 180 Ma); how the extreme differentiation in the SNCs (possibly involving high-pressure minerals such as garnet) could arise on an asteroid; and how traces of bacterial organisms (if confirmed) could arise on an asteroid. However exciting this scenario might be, evidence in hand seems to

leave little doubt that the SNC meteorites formed originally on Mars.

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