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SNC meteorites: Igneous rocks from Mars?

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"... when you have excluded the impossible, whatever remains, however improbable, must be the truth."

The Adventure of the Beryl Coronet
Arthur Conan Doyle

Abstract—Three classes of achondrites, comprising 9 stones, are anomalous in having crystallization ages of 1.3 b.y., more than 3 b.y. younger than any other meteorite. These meteorites—shergottites, nakhlites, and chassignites (SNC)—are unbrecciated augite to olivine igneous cumulates that are volatile-rich, have complex rare earth element patterns, equilibrated near the quartz-fayalite-magnetite buffer, and formed in a magnetic field-free region of the solar system. Although SNC meteorites have been suggested as being related to eucrites, the young SNC ages and other unique characteristics make that connection exceedingly unlikely. Additionally, current understanding of the thermal evolution of asteroids is such that igneous processes as recent as 1.3 b.y. ago are difficult to envision. Mars is the only plausible parent body for SNC meteorites, as previously suggested, although the mechanism for the escape of unmelted surface material from Mars is not yet clearly understood. Assuming that SNC meteorites are Mars samples allows inferences on the history and evolution of the planet. Model ages and isotopic systematics imply that Mars formed and underwent a major chemical differentiation (core formation and/or magma ocean?) 4.6 b.y. ago. The crystallization 1.3 b.y. ago of SNC igneous rocks from four or more chemically distinct sources suggests that volcanism was vigorous late in martian history, as predicted by some crater count calibrations. Mars had only a weak or possibly no magnetic field when SNC meteorites formed, consistent with the apparent absence of a present-day field of Mars. Overall, the chemical characteristics of SNC meteorites are remarkably similar to terrestrial igneous rocks suggesting similar processes and perhaps evolution for the mantles of these two planets.

INTRODUCTION

All dated meteorites have formation ages of 4.4 to 4.6 b.y. (Sears, 1978), except for nine achondrites which crystallized 1.3 b.y. ago (Table 1). These meteorites—shergottites, nakhlites, and chassignites (SNC)—also differ chemically, petrologically, physically, and magnetically from other meteorite types, suggesting a unique origin. We propose, extending previous tentative suggestions (Wasson and Wetherill, 1979; Nyquist *et al.*, 1979a; Walker *et al.*, 1979; McSween and Stolper, 1980), that SNC meteorites are igneous rocks from Mars, and additionally, using the characteristics of SNC meteorites, we speculate on specific events in the history of Mars.

SNC METEORITES

Mineralogy and chemistry

SNC meteorites are rare members of the achondrite class of igneous meteorites, but differ substantially from eucrites, the most common (n ~ 40) achondrite type. Eucrites are composed mainly of calcic plagioclase and low-Ca pyroxene (pigeonite) that apparently originated ~4.5 b.y. ago on one of more volatile-poor bodies of asteroidal size (Duke and Silver, 1967; Stolper, 1977; Consolmagno and Drake, 1977).

Shergottites, nakhlites, and chassignites have distinguishing characteristics (see below and Table 2) but are generally uniform in their differences with eucrites and other meteorites. Compared to eucrites, SNC meteorites are enhanced in overall volatile

Table 1. SNC meteorites.

Meteorite	Type	Fall Date	Location	Crystallization Age (10^9 yrs)	Ref.	Exposure Age (10^6 yrs)	Ref.
Shergotty	S	1865	India	1.34 ± 0.06		2.1; 2.4	11; 12
Zagami	S	1962	Nigeria	Sm–Nd	1; 2	2.5	12
ALHA 77005	S	Find	Antarctica	(W.R.)		7 ± 1	13
EETA 79001	S	Find	Antarctica	?		?	
Nakhla	N	1911	Egypt	1.37 ± 0.02	3	8 ± 0.8	5
				Rb–Sr			
				1.24 ± 0.01	4	10.1	11
				Rb–Sr			
				≤1.3 Ar–Ar	5		
				1.3 ± 0.2	6		
				U–Pb			
				1.27 ± 0.06	6		
				Sm–Nd			
Lafayette	N	Find	Indiana	1.33 ± 0.03	5	6.5 ± 0.6	5
				Ar–Ar		10.5; 11.2	11; 14
Governador Valadares	N	Find	Brazil	1.33 ± 0.01	7	8 ± 1	8
				Rb–Sr			
				1.32 ± 0.04	8		
				Ar–Ar			
Chassigny	C	1815	France	1.39 ± 0.17	9	8.9 ± 0.5	9
				K–Ar			
				1.27 Ar–Ar	10		
Brachina	C	Find	Australia	?		?	

S = shergottite; N = nakhlite; C = chassignite.
References: 1—Nyquist *et al.*, 1979a; 2—Shih *et al.*, 1981; 3—Papanastassiou and Wasserburg, 1974; 4—Gale *et al.*, 1975; 5—Podosek, 1973; 6—Nakamura *et al.*, 1977; 7—Wooden *et al.*, 1979; 8—Bogard and Husain, 1977; 9—Lancet and Lancet, 1971; 10—Bogard and Nyquist, 1979; 11—Fuse and Anders, 1969; 12—Heymann *et al.*, 1968; 13—Kirsten *et al.*, 1978; 14—Ganapathy and Anders, 1969.

Table 2. Comparison of eucrites and SNC meteorites.

	Eucrites	Shergottites	Nakhlites	Chassignites
Cryst. Age	~4.6 b.y.	←	~1.3 b.y.	→
Exposure Age	2–40 m.y.	2.5 m.y.	8–11 m.y.	9 m.y.
Dominant Phase	Pig. + Plag.	Pig. + Aug.	Augite	Olivine
Fspar. Comp.	An_{80-95}	An_{40-60}	$An_{34} + Or_{77}$	$An_{16-37} + Or_{70}$
Oxidation	free metal	←	Fe–Ti oxides	→
Hydrous Phases	none	none	iddingsite	kaersutite
K/U	3,000	10,000	25,000	25,000
REE/chond.	flat	LREE depleted	← LREE enriched	→
$\delta^{18}O/\delta^{17}O$	2.9–3.7/1.2–1.7	4.2/2.2	4.4–4.7/2.5–2.6	3.7/1.8
Shock Level	~unshocked	300 kbar	unshocked	0–~175 kbar
Texture	brecciated	←	unbrecciated	→
Examples	Juvinas	Shergotty	Nakhla	Chassigny
	Chervony Kut	Zagami	Lafayette	Brachina
	Moore County	ALHA 77005	Governador Valadares	
	+ 39 others	EETA 79001		

content, ratio of high-Ca pyroxene to low-Ca pyroxene, alkali content in feldspar, and oxidation state (Stolper *et al.*, 1979).

The shergottites Shergotty and Zagami are quite similar to each other (Table 3), containing ~70% pigeonite and augite (~1:1), ~22% maskelynite, with a few percent titanomagnetite (Stolper and McSween, 1979). Maskelynite was recognized in Shergotty

Table 3. Chemical compositions and modes of SNC meteorites.

	Shergotty[1]	Zagami[1]	ALHA 77005	EETA 79001	Nakhla[2]	Lafayette[3]	Governador Valadares[4]	Chassigny[2]	Brachina[5]
SiO_2	50.4	50.8			48.24	46.9	49.5	37.0	38.04
TiO_2	0.81	0.77			0.29	0.33	0.35	0.07	0.12
Al_2O_3	6.89	5.67			1.45	1.55	1.74	0.36	2.12
Cr_2O_3	0.21	0.30			0.42	0.18	0.21	0.83	0.58
FeO	19.1	18.0			20.64	22.7	19.74	27.44	23.69
MnO	0.50	0.50			0.54	0.79	0.67	0.53	0.34
MgO	9.27	11.0			12.47	12.9	10.9	32.83	27.27
CaO	10.1	10.8			15.08	13.4	15.8	1.99	2.10
Na_2O	1.37	0.99			0.42	0.36	0.82	0.15	0.63
K_2O	0.16	0.14			0.10	0.09	0.43	0.03	0.08
P_2O_5					0.12			0.04	0.27
H_2O									0.26
C									0.07
(Fe, Ni, Co)S									4.20
Total	98.8	99.0			100.77	99.1	100.16	101.27	99.77
					[8]	[3]	[9]	[10]	[5,11]
Pigeonite	36.3[1]	36.5[1]	26[6]	major[7]					
Augite	33.5	36.5	11	minor	78.6	major	major	5.0	6
Olivine			52	+	15.5	minor	minor	91.6	79
Plagioclase	23.3*	21.7*	10*	minor*	3.7	+	+	1.7	10
Magnetite				+	1.9	+			
K-Feldspar					1.1				
Chromite			1	+				1.4	0.8
Titanomagnetite	2.25	2.1				+	+		
Troilite				+	+	+	+		4
Mesostasis Intergrowth	4.0	2.1							

Note: * = maskelynite.
References: [1]Stolper and McSween, 1979 (average of two point count estimates). [2]McCarthy *et al.*, 1974. [3]Boctor *et al.*, 1976. [4]Burragato *et al.*, 1975. [5]Johnson *et al.*, 1977. [6]Ma *et al.*, 1981. [7]Reid, 1981. [8]Bunch and Reid, 1975. [9]Berkley *et al.*, 1980. [10]Floran *et al.*, 1978. [11]Nehru *et al.*, 1979.

more than 100 years ago by G. Tschermak, and is now known to be a shock-produced alteration of plagioclase (Binns, 1967). Chemical details are not yet published for the two shergottites discovered in Antarctica (ALHA 77005 and EETA 79001). ALHA 77005 has only 37% pigeonite and augite (~2:1), 10% maskelynite, and 52% olivine, and may be similar to the peridotitic source material from which Shergotty and Zagami were derived (McSween *et al.*, 1979; Ma *et al.*, 1981). EETA 79001 is unique in containing two different (but related) lithologies separated by a geologic contact (Reid, 1981). About 10% of the meteorite closely resembles Shergotty but the remainder is a shocked but unbrecciated pyroxenite with pyroxene as the major phase but also containing maskelynite, Mg–Al chromite, iron sulphide, possible ilmenite, a few large olivines, and melt glasses (Reid, 1981). The main mass of EETA 79001 appears to be unique, containing maskelynite like the other shergottites, but its chromite and iron sulphide are reminiscent of chassignites.

The three nakhlites (Nakhla, Lafayette, and Governador Valadares) are fairly uniform, being nearly monomineralic (augite with minor olivine) cumulates (Bunch and Reid, 1975). Unlike shergottites, the plagioclase has not been shocked to maskelynite and occurs in both potassic and sodic phases. A hydrous alteration product of olivine, probably iddingsite, is found in nakhlites and appears to be of pre-terrestrial origin (Reid and Bunch, 1975; Berkley *et al.*, 1980).

The two known chassignites (Chassigny and Brachina) are also nearly monomineralic cumulates with olivine being the dominant phase (80–90%) and minor augite (5–6%) (Johnson *et al.*, 1977; Floran *et al.*, 1978; Nehru *et al.*, 1979). Feldspar compositions (sodic plagioclase plus minor potassic feldspar) are nearly identical to those of nakhlites, and kaersutite, a primary hydrous amphibole, occurs in melt inclusions within olivine (Floran *et al.*, 1978).

Rare earth elements

Rare earth element (REE) patterns (Fig. 1) for most eucrites are nearly flat and cluster at 8–10 times chondrites with no Eu anomalies (Drake, 1979). A few eucrites have lower abundances with positive Eu anomalies, and others have higher abundances with negative Eu anomalies. In contrast, SNC meteorites are characterized by highly fractionated REE patterns, with no appreciable Eu anomalies (Fig. 1). Nakhla and the chassignites exhibit subparallel, strongly light REE enriched patterns, with the chassignites about 5 times lower in chondrite-normalized abundance than Nakhla (Nakamura and Masuda, 1973; Mason *et al.*, 1975; Johnson *et al.*, 1977; Boynton *et al.*, 1976). A genetic relationship for the nakhlites and chassignites based on igneous differentiaton has been suggested by Mason *et al.* (1975) and Nakamura and Masuda (1973). Similarly, shergottites have subparallel light REE depleted patterns, with ALHA 77005 about 5 times lower in abundances than Shergotty and Zagami. Although a genetic relationship among these meteorites is possible (Ma *et al.*, 1981), their isotopic compositions indicate that they cannot be comagmatic, as discussed subsequently.

Potassium/uranium ratios

The K/U ratios for SNC meteorites have been compared to those of the Earth, Moon, and eucrites by McSween *et al.* (1979). Eucrite K/U values cluster around $2–4 \times 10^3$, similar to ratios for lunar rocks, whereas shergottites and chassignites are centered at 10^4, the average value for terrestrial rocks. Nakhlites are slightly higher at $1.5–3 \times 10^4$, at the upper end of the range for terrestrial samples.

Oxidation state

Experiments (Delano and Arculus, 1980) demonstrated that the oxidation state of the Nakhla parent body was comparable to that of the Earth's upper mantle, near the wüstite-magnetite (WM) buffer. Coexisting ilmenite and Ti-magnetite analyses for Sher-

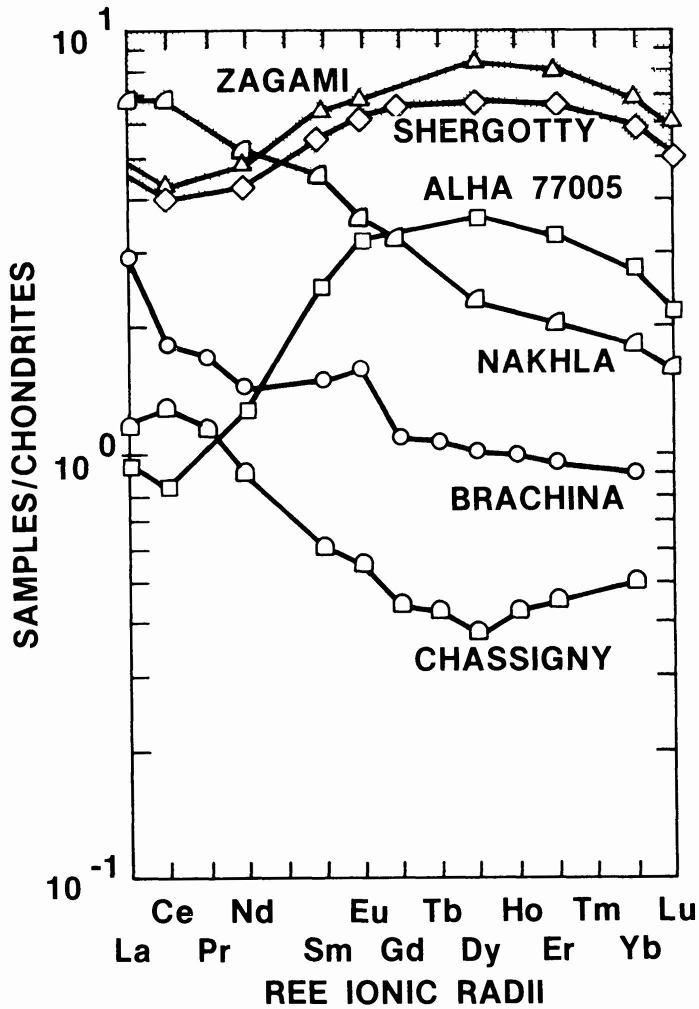

Fig. 1. Rare earth abundance patterns for SNC meteorites, normalized to chondrites. For comparison a portion of the eucrite field (Drake, 1979) is indicated by the pattern. Most eucrites are flat and 8–10 times chondrites but the range is 4–16 times chondrites, and some eucrites have pronounced Eu anomalies. Data sources: Zagami, Shergotty, and ALHA 77005-Shih *et al.*, 1981; Nakhla-Nakamura and Masuda, 1973; Brachina-Johnson *et al.*, 1977; Chassigny-Mason *et al.*, 1975.

gotty indicate an oxygen fugacity between the quartz-fayalite-magnetite (QFM) and WM buffers (Smith and Hervig, 1979). These results are consistent with the occurrence of accessory oxide phases (magnetite, ilmenite and/or Fe^{3+}-rich chromites) in various SNC meteorites suggesting equilibration near the QFM buffer (Bunch and Keil, 1971; Floran *et al.*, 1978; Stolper and McSween, 1979). Eucrites crystallized under considerably more reducing conditions (as evidenced by the presence of metallic iron) than SNC meteorites, and have oxygen fugacities similar to lunar basalts (Stolper *et al.*, 1979).

Oxygen isotopes

Meteorites have been classified by oxygen isotopes into groups that (as far as is presently understood) cannot be derived from one another by chemical processes such as fractionation (Clayton *et al.*, 1976). Eucrites and other basaltic achondrites plot in a different section of the three-isotope plot of oxygen isotopic abundances (Fig. 2) than Shergotty, Zagami, Nakhla, and Lafayette (Clayton *et al.*, 1976; Clayton, pers. comm., 1981), although Chassigny plots within the eucrite field. It should be noted that despite the high

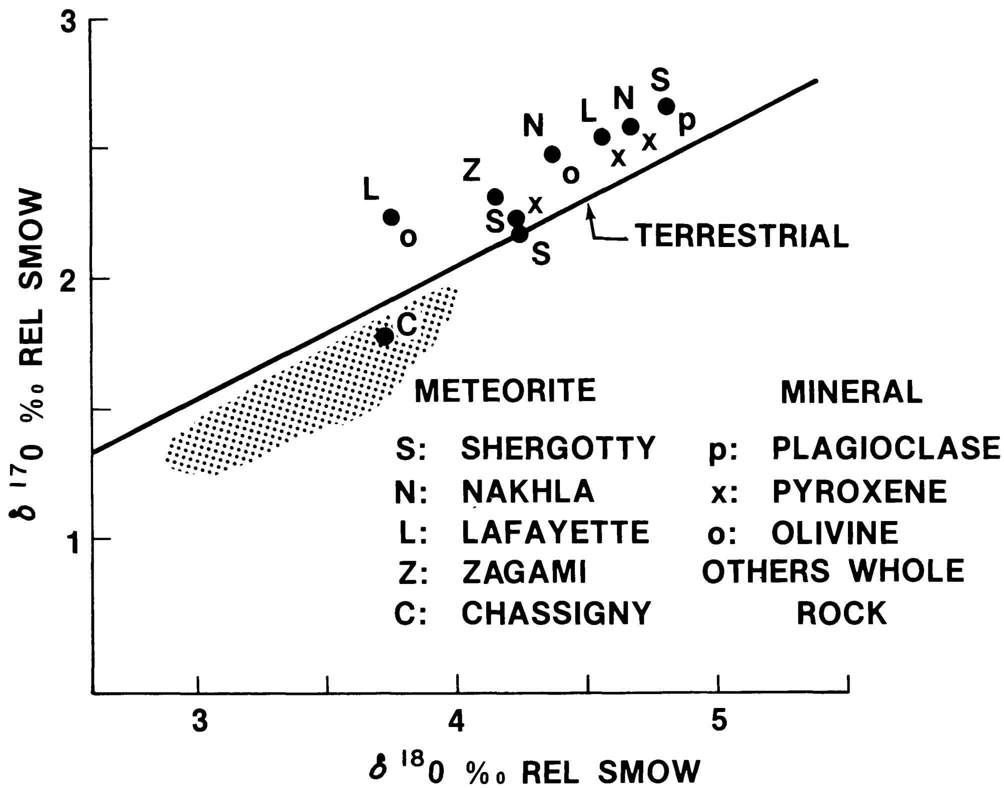

Fig. 2. Three-isotope plot (both x and y values are normalized to ^{16}O) of variations in oxygen isotopic abundances for SNC meteorites and basaltic achondrites (pattern). All data from Clayton *et al.*, 1976 and Clayton, pers. comm., 1981. Diagonal line is mass-fractionation trend defined by terrestrial and lunar materials. SMOW is standard mean ocean water.

precision of these measurements there appears to be considerable variability in replicate analyses: Clayton *et al.* (1976) give two determinations for pyroxenes from Shergotty—one plots above the terrestrial fractionation line near Zagami, but the other falls below the line, within the extreme limits of the eucrite field. Replicate analyses of Chassigny and determinations for Brachina are necessary to check whether chassignites have significantly different isotopic compositions from shergottites and nakhlites.

Ages and isotopic evolution

Ages of SNC meteorites (Table 1) average 1.31 b.y. (11 independent measurements), and have been interpreted as the time of primary crystallization. Evidence for this includes the concordancy of ages from four isotopic systems for Nakhla and from two isotopic systems for Governador Valadares and Chassigny (Table 1). Shih *et al.* (1981) have obtained a whole-rock Sm–Nd isochron of 1.34 ± 0.06 b.y. for three shergottites, but there is some uncertainty about the significance of this age because evidence exists that the samples are not comagmatic (Ma *et al.*, 1981). Rb–Sr isotopic analyses of these shergottites plot on or close to a line corresponding to an age of about 4.6 b.y. (Shih *et al.*, 1981), which may be interpreted as the time at which source regions with distinctly different Rb/Sr were produced. This event, however, cannot have produced differences in Sm/Nd among the shergottite sources, since the samples have the same initial $^{143}Nd/^{144}Nd$ ratio at the presumed crystallization age of $\sim$1.3 b.y. Sm/Nd isotopic data for Nakhla (Nakamura *et al.*, 1977) suggest that its source had a high initial Nd ratio at 1.3 b.y. compared to a chondritic uniform reservoir (CHUR) and hence was depleted in light REE. Since the shergottite source has a low initial Nd ratio (light REE enriched) compared to CHUR at this time (Shih *et al.*, 1981), it may be argued that the nakhlite and shergottite source regions were complementary with respect to chondritic or bulk planetary evolution. This assumes, of course, that Nakhla and the shergottites were derived from the same parent body. The shergottites cannot be comagmatic with each other or with two nakhlites (Nakhla, Governador Valadares) because of the disagreement of whole-rock ages between Sm–Nd and Rb–Sr systems, and also because of the distinct differences in initial Sr ratios and/or initial Nd ratios at the presumed time of crystallization (Shih *et al.*, 1981; Nakamura *et al.*, 1977; Wooden *et al.*, 1979; Papanastassiou and Wasserburg, 1974; Gale *et al.*, 1975). In summary, the available isotopic data for SNC meteorites are consistent with a model whereby their distinctly different source regions were produced by a large-scale chemical differentiation event soon after planetary accretion. One possibility for such an event is a magma ocean, as proposed for the early evolution of the outer portions of the Moon (Wood *et al.*, 1970).

The internal isotopic systems of the shergottites have been disturbed, presumably by a shock event between 165 and 187 m.y. ago, which transformed plagioclase into maskelynite (Shih *et al.*, 1981; Wooden *et al.*, 1979; Bogard *et al.*, 1979; Nyquist *et al.*, 1979b). This event may have ejected the meteorites from the gravitational field of their parent body. Distinct differences in initial $^{87}Sr/^{86}Sr$ ratios at this time preclude an origin for these meteorites by crystallization from a shock melt, because impact melts effectively homogenize chemical variations in the target rocks (Simonds *et al.*, 1976).

Cosmic ray exposure ages, which measure the length of time a meteorite was exposed to space within a fragment smaller than a few meters, are less than 10 m.y. for SNC meteorites (Table 1). Shergotty and Zagami have essentially equal exposure ages of 2.5 m.y., and the other analyzed SNC meteorites cluster around 8.5 m.y. ago, suggesting two different collisions, possibly while the stones were in Earth-crossing orbits.

Magnetism

Paleomagnetic studies of meteorites have demonstrated that great variations in magnetic field strength existed when different classes of meteorites formed. Nagata (1979) has found the following average paleointensities: carbonaceous chondrites—1.02 Oe; ordinary chondrites—0.1 to 0.4 Oe; and eucrites and other basaltic achondrites—0.11 Oe. More recently a paleointensity of 0.01 Oe has been determined for the shergottite ALHA 77005 (Nagata, 1981). Cisowski (1981 and pers. comm.) found no substantial extraterrestrial magnetization associated with Shergotty, whereas Zagami's weak remanence appears to be related to a shock event that postdated the formation of maskelynite. Additionally, the thermomagnetic curves for Shergotty and Zagami are quite similar to unoxidized to slightly oxidized terrestrial basalts (Cisowski, 1981). Thus, the magnetic properties of the three SNC meteorites investigated so far suggest that they were derived from a parent body with a very small to nonexistent magnetic field, in contrast to all other meteorite types.

Shock and texture

The existence of maskelynite in shergottites demonstrates that these meteorites experienced about 300 kbar of shock (Schaal and Hörz, 1977; Nyquist *et al.*, 1979b). Deformation of olivine, pyroxene, and feldspar indicate a shock pressure of ~200 kbar for Chassigny (Floran *et al.*, 1978), but Brachina is unshocked (Johnson *et al.*, 1977). No evidence of shock is found in Nakhla (Bunch and Reid, 1975) and deformed twin lamellae in Lafayette augite suggest only weak shocking, if any at all, for that meteorite (Boctor *et al.*, 1976). None of the SNC meteorites are brecciated, indicating that they are unlikely to have been derived from an impact dominated regolith, in contrast to the eucrites and most other meteorites. This conclusion is supported by the observation that SNC fragments have not been found as clasts in other brecciated meteorites.

WHERE DO SNC METEORITES COME FROM?

There is no certainty about the specific provenance of any meteorite; all proposed sources must be plausible in terms of (a) likely chemical and petrological affinity, and (b) ease of dynamical derivation. Many of the characteristics of SNC meteorites reviewed above argue for their source being a large body, however, removal of meteorites from large bodies is dynamically difficult. Additionally, there is a strong bias against suggestions that meteorites are derived from any body other than asteroids, especially since no meteorites appear to come from the Moon. Some researchers, stressing general chemical similarities, have proposed that shergottites come from the eucrite parent body (Stolper *et al.*, 1979; Stolper and McSween, 1979; Feierberg and Drake, 1980), although others, stressing the age differences with eucrites and other meteorites, have suggested Mars as the parent of shergottites, or even of all SNC meteorites (Wasson and Wetherill, 1979; Nyquist *et al.*, 1979a; Walker *et al.*, 1979; McSween and Stolper, 1980). Based on our review of SNC characteristics, and arguments presented by the above authors, we believe Mars is the most likely source of the SNC meteorites. We now briefly consider (and reject) all plausible alternative sources including the other terrestrial planets (including Earth), other asteroids, and comets. The latter type of body can presumably be ruled out, because comets appear to be very primitive (and small) bodies that should not have experienced igneous activity 1.3 b.y. ago.

Mercury and Venus

Mercury is unlikely to be the SNC parent body on both dynamical and compositional grounds. Following Consolmagno and Drake (1977), the estimate of a maximum of 6% FeO on the surface of Mercury (deduced from reflectance spectra by Adams and McCord, 1977) contrasts with measured values of ~20% FeO in SNC meteorites (Table 3). Additionally, Mercury is thought to be a volatile-poor, anhydrous planet (Consolmagno and Drake, 1977), unlike SNC meteorites. Although Mercury's relatively small gravitational field would enhance escape of crater ejecta, the planet's small mass, and location deep within the sun's gravitational well, would diminish the probability of ejecta being perturbed to the Earth. Venus is a volatile-rich planet with a minute quantity of water in its atmosphere (e.g., Oyama *et al.*, 1980) and might be a compositionally acceptable SNC parent body, but its dense atmosphere and large gravitational field would make escape of any material very difficult. Furthermore, samples derived from the surface of Venus should show evidence of extensive alteration, due to the interaction between the hot venusian troposphere and the surface rocks (Barsukov *et al.*, 1980).

Earth and Moon

In many respects Earth is the most likely SNC parent body. McSween and Stolper (1980, p. 56) comment that shergottites and terrestrial basalt "are so similar in composition and mineralogy that it is difficult to conceive that the shergottites could have originated elsewhere in the solar system." Furthermore the oxidation state, hydrous phases, REE patterns, K/U ratios, and thermomagnetic curves of SNC meteorites are also consistent with an origin on the Earth. But as McSween and Stolper (1980) point out, there are a number of compelling reasons for rejecting this intriguing hypothesis, the most significant being the systematic differences in oxygen isotopes between terrestrial material and SNC meteorites (Clayton *et al.*, 1976). Additionally, the negligible magnetic paleointensity of SNC meteorites (Nagata, 1981; Cisowski, 1981) argues against their cooling within the Earth's magnetic field. Finally, the Earth's strong gravitational field makes escape of ejecta very difficult. If, however, SNC meteorites were somehow ejected from the Earth and cooled in space, it would be necessary to store them for 165–187 m.y. before they fell back to the Earth. There is no simple way to store Earth ejecta for such prolonged periods.

The Moon was seriously considered as a source of meteorites (Urey, 1959; Wänke, 1968) until the first lunar samples were demonstrated to be different isotopically and chemically from all meteorites, including SNC's.

Eucrite parent body

Because they have igneous textures and lack chondrules, SNC meteorites have been considered to be related to eucrites and other basaltic achondrites. Stolper *et al.* (1979) discussed the possible derivation of SNC meteorites from a protoeucrite source peridotite by addition of volatiles, but they did not suggest a mechanism to account for SNC meteorites being 3 b.y. younger than eucrites, nor for the different oxygen isotopic compositions. Drake and co-workers (Drake, 1979; Consolmagno and Drake, 1977; Feierberg and Drake, 1980) have argued that eucrites come from Vesta, the only asteroid with a reflection spectrum closely matching eucrites, and thus concluded that the shergottites probably did as well. This proposal is difficult to substantiate, and indeed, the spectral reflectance data for Vesta do not match the spectrum of the shergottites (Feierberg and Drake, 1980). Wetherill (1978) has further pointed out that Vesta is far from any resonance position in the asteroid belt and thus derivation of any meteorites—eucrites or SNC's—would be difficult. Although SNC's and eucrites are both classes of achondrites, they are sufficiently dissimilar (Table 2) such that an origin on the same parent body is highly unlikely.

Asteroids, in general, are unlikely to be parent bodies of SNC meteorites because they are too small to produce igneous activity 3 b.y. after their formation (e.g., Minear *et al.*, 1979), and no asteroid >25 km in diameter has a spectrum that matches SNC meteorites (Drake, 1979). Impact melting on an asteroid can be rejected as a possible source of SNC meteorites. Studies of terrestrial and lunar impact melt sheets suggest that cooling of the melts occurs rapidly enough by thorough mixing with cold clastic debris that the formation of cumulates is prevented (Simonds *et al.*, 1976). The SNC meteorites are cumulate rocks with variable initial Sr ratios at their time of crystallization, and are thus exceedingly unlikely to have been derived from any single impact melt on an asteroid. That different asteroids experienced major melt-producing impacts 1.3 b.y. ago and fed meteorites to Earth seems implausible.

Mars

To account for the young crystallization ages, various investigators (Walker *et al.*, 1979; Nyquist *et al.*, 1979a; Wasson and Wetherill, 1979; McSween and Stolper, 1980) have recently proposed that shergottites come from a planet large enough to have experienced igneous activity 1.3 b.y. ago. Mars is the obvious candidate because of its apparently young volcanism, and because of the close compositional similarites of Shergotty and martian soil (when corrections are made for likely weathering products; Baird and Clark, 1981). We concur that Mars is the most likely parent body for shergottites, and, because of the general chemical similarities of all SNC meteorites, and their common crystallization age, we endorse the proposal (Wasson and Wetherill, 1979) that nakhlites and chassignites also come from Mars. In addition to the arguments based on youthful volcanism, various characteristics of SNC meteorites are consistent with the present understanding of Mars. Absorption bands in reflection spectra of martian dark regions have been reinterpreted as due to augite clinopyroxenes (Singer, 1981) such as dominate (Table 2) shergottites and nakhlites. The olivine-rich chassignites have cumulate texture and most likely represent material crystallized in magma chambers, and thus would not be expected on the martian surface.

The occurrences of primary and possibly secondary hydrous phases in chassignites and nakhlites, respectively, imply that water was brought to the surface of Mars, consistent with photogeologic evidence for fluvial activity (e.g., Milton, 1973; Carr and Schaber, 1977) and the detection of atmospheric water vapor (Farmer *et al.*, 1977). Martian lava flows are very long by terrestrial standards, suggesting dense, fluid melts. This conclusion, previously reached on the basis of estimates of the density of the martian mantle (McGetchin and Smyth, 1978), is consistent with inferred melt rheology, calculated from the chemistry of SNC meteorites (Bottinga and Weill, 1970; 1972). Assuming Brachina to have essentially the same composition as its melt (as suggested by Johnson *et al.*, 1977), and that the range of reconstructed melt compositions for Chassigny (Boynton *et al.*, 1976) are correct, we calculate viscosities of 2 to 45 poise, and densities of 2.8 to 3.1 gm/cm^3, for anhydrous compositions at 1150°C. For comparison, common terrestrial basalts have viscosities of 10^2 to 10^3 poise, and densities of 2.6 to 2.7 gm/cm^3 at the same temperature (Murase and McBirney, 1973). The negligible paleointensity measured for shergottites (Nagata, 1981; Cisowski, 1981) is compatible with the current weak to non-existent martian magnetic field (Russell, 1979).

Derivation of meteorites from Mars

The previous section demonstrated that Mars is the most likely parent body for SNC meteorites, based on age, chemical, and physical considerations. However, a satisfactory mechanism has not been demonstrated to explain how rocks escaped the surface of Mars without melting and evolved into Earth-crossing orbits on a time scale consistent with observed shock or exposure ages. Wasson and Wetherill (1979) have speculated that SNC meteorites may be ejecta from a cratering event on Mars. They hypothesized that martian subsurface permafrost, explosively released by an impact, could aerodynamically accelerate ejecta to escape velocity (5 km/sec). Ejecta would not be shock melted because its velocity would be similar to that of the volatiles surrounding it. The hypothesis of entrainment of ejecta within a gas is very similar to models derived by volcanologists (Wilson, 1976) to explain how terrestrial volcanic bombs can travel greater distances from the vent than predicted by ballistic calculations. On Mars, the weak gravity field and low density atmosphere would favor this process.

This model is supported by experiments in which 3 mm pyrex projectiles traveling at 2.2 km/sec impacted a target of solid wax floating on liquid wax (J. Fink, pers. comm.) In one run, in which air bubbles were accidently trapped between the solid and liquid layers, a large column of material jetted from the crater center. Other experiments, with targets lacking air bubbles, did not produce the energetic central jet, suggesting that the presence of gases in the target may dramatically change ejection characteristics. Further experiments are clearly needed to evaluate the importance of these effects.

That a significant mass of ejecta would have sufficient energy to escape from the surface of Mars is indicated by calculated relations between the mass and velocity of impacting and ejected material (O'Keefe and Ahrens; 1977). For impact velocities of ~20 km/sec (Shoemaker, 1977) martian rocks with a total mass about 0.1 times the impacting meteorite mass would achieve escape velocity (Fig. 3). The ejecta mass would equal meteorite mass for impact velocities greater than ~30 km/sec, i.e., for comet impacts. Thus, experiments and calculations support the hypothesis that significant volumes of ejecta from impact into a volatile-rich target could escape Mars' gravitational field. The orbital evolution of such material has not been investigated. Presumably much of it would be reaccreted by Mars or ejected to the outer solar system, but some fraction would be perturbed by close approaches to Mars into eccentric orbits that would finally become Earth-crossing. Based on Wetherill's (1974) estimate that Apollo asteroids (already in Earth-crossing orbits) have lifetimes of 10^6–10^7 years before colliding with Earth; the time required for a random walk evolution of a small body initially near Mars into an Earth-crossing orbit is probably ~10^8 years (R. Greenberg, pers. comm. 1981), a period commensurate with the 165–187 m.y. shock ages of shergottites.

This concordance of orbital evolution and shock age is disturbed, however, by models accounting for diffusive resetting of Rb–Sr and Ar–Ar isochrons by the 165–187 m.y. shock event (Nyquist *et al.*, 1979b; Bogard *et al.*, 1979). According to these analyses, the shock event buried Shergotty (and presumably the other shergottites) under a few

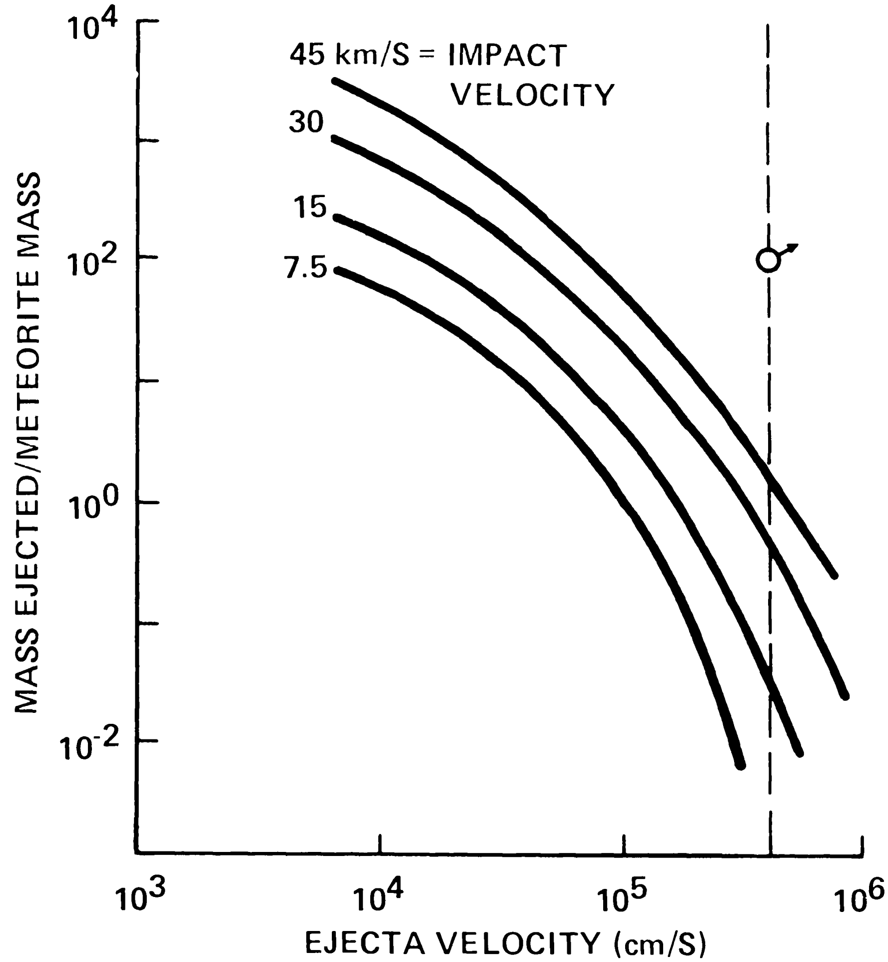

Fig. 3. Relations between velocity and mass of impacting meteorite and crater ejecta. For impact velocities greater than 15 km/sec, a significant quantity of Mars rocks will achieve escape velocity (5 km/sec). Graph from O'Keefe and Ahrens, 1977.

hundred meters of warm (300°–400°C) overburden for 10^3–40^4 years, during which time the diffusive resetting of ages occurred. Wasson and Wetherill (1979) pointed out that ejecta blocks hundreds of meters in diameter were unlikely to have escaped Mars and thus that serious difficulties beset the meteorites from Mars hypothesis. This objection is valid, but its assumptions may not be. The models quantifying ejecta dimension and isotopic resetting by shock are conceptually satisfying, but rely on parameters that are poorly known, and generally assume that severely shocked meteorite minerals behave similarly to unshocked materials for which diffusion rates, etc., are available. The models may or may not be correct, but they do not, in any case, affect the possible martian origin of SNC meteorites. We propose that the event at 165–187 m.y. did not necessarily eject material from the surface of Mars (although it may have if the diffusive models are incorrect); that may have been accomplished by a later impact, which left no shock signature. This proposal is consistent with (a) the lack of shock in nakhlites, and only minor shock recorded by chassignites, and (b) the observation that no meteorite known to us has equal shock and exposure ages. The significance of (b) is that exposure ages record the time since a meteorite fragmented from a larger body by a collision which did not engender a shock signature. For SNC's, exposure ages range between 2 and 11 m.y. (Table 1). Thus, we infer that the impact which launched igneous rocks from Mars occurred between 165 m.y. ago and 11 m.y. ago. An earlier date is more consistent with orbital evolution requirements.

Our conclusion that SNC meteorites are derived from Mars is apparently weakened by the lack of meteorites from the Moon, a much closer and gravitationally weaker world than Mars. The reason lunar meteorites are not found on Earth, however, may be related to the following observations: (1) Cratering on a large enough scale to eject material from the Moon has been statistically rare during the last few million years, and travel time to the Earth is only days to a few years (Hartung, 1981). These facts, and the observation that stony meteorites are rendered unrecognizable by erosion within a few tens to tens of thousands of years (Hartmann, 1972, p. 208) imply that lunar meteorites should rarely be found on the Earth. (2) The Moon would be less likely than Mars to yield meteorites if a volatile-rich target is required for the formation of unmelted, high-velocity ejecta.

MARTIAN EVOLUTION IMPLIED FROM SNC SAMPLES

However counter to intuition, Mars appears to be the most logical source for SNC meteorites. Assuming this to be true, SNC meteorites are Mars samples and thus offer the first detailed knowledge of that planet's history and evolution.

Model ages of ~4.6 b.y. (Shih *et al.*, 1981) for SNC samples show that by that time Mars had formed and undergone large scale differentiation that produced source regions with distinct Rb/Sr values. The early formation of Mars disagrees with gravitational accretion models of planetary formation which require more than 10^9 years for Mars to form (Weidenschilling, 1976), and also disagrees with the suggestion that Mars may have escaped early global differentiation (Hostetler and Drake, 1980). Planetary differentiation, resulting from accretional heating or core formation, may have produced a magma ocean, with subsequent formation of a low density crust—a remnant of which may have survived as the isostatically high, heavily cratered martian southern hemisphere.

The next event recorded by SNC samples is their crystallization 1.3 b.y. ago, supporting those crater-count calibrations (Hartmann, 1973; 1978; Soderblom *et al.*, 1974; Soderblom, 1977; Neukum and Hiller, 1981) which predict that volcanism extended into the last third of martian history. Initial Sr and Nd ratios at 1.3 b.y., and various chemical considerations require that four or more distinct source regions were producing magmas at 1.3 b.y., suggesting that a major episode of volcanism may have occurred at that time. Crater counts (based on the Soderblom and Hartmann chronologies) imply that the oldest lava flows on the periphery of Olympus Mons and the Tharsis shields are about 1.1 to 1.6 b.y. old (Schaber *et al.*, 1978), thus SNC meteorites may be samples of lavas from the onset of the Tharsis volcanic episode (Fig. 4). Comparison of these crater counts with a photogeologic map of volcanic units (Greeley and Spudis, 1981) suggests that no other region on Mars is young enough to be the source of SNC samples. About 165–187 m.y. ago an impact crater formed in this area of young martian volcanism, shocking the lavas sufficiently to convert plagioclase to maskelynite. This impact or perhaps a later one ejected the SNC samples off the surface of Mars.

Chemically, the most remarkable feature of Mars, as revealed by the SNC samples, is the Earth-like character of its igneous rocks. The similarities include minor and trace element abundances (McSween and Stolper, 1980), Rb/Sr and K/U ratios and REE patterns (Papanastassiou and Wasserburg, 1974), oxidation state (Delano and Arculus, 1980; Bunch and Keil, 1971), and thermomagnetic characteristics (Cisowski, 1981). These similarities must reflect similar patterns of activity and evolution for the upper mantles of the two planets, a remarkable conclusion, considering their different masses and tectonic styles. There are, however, differences which are consistent with our knowledge of Mars. Chassignites have a much higher Fe/Mg ratio than terrestrial olivine-rich rocks (Floran *et al.*, 1978), consistent with the high estimates (3.3–3.6 g/cm^3) for the zero-pressure density of the martian mantle (Arvidson *et al.*, 1980). The Fe-rich magmas produced igneous rocks that are more mafic than common on Earth, with the resulting very long lava flows.

The K/U ratio is an important quantity for understanding the thermal history of a planet (e.g., Toksöz and Hsui, 1978; Morgan and Anders, 1979). For Mars the SNC samples imply K/U values from $\sim 8 \times 10^3$ to $\sim 3 \times 10^4$ (McSween *et al.*, 1979), considerably higher than the ratio (2.2×10^3) used in Morgan and Anders' (1979) calculation of the

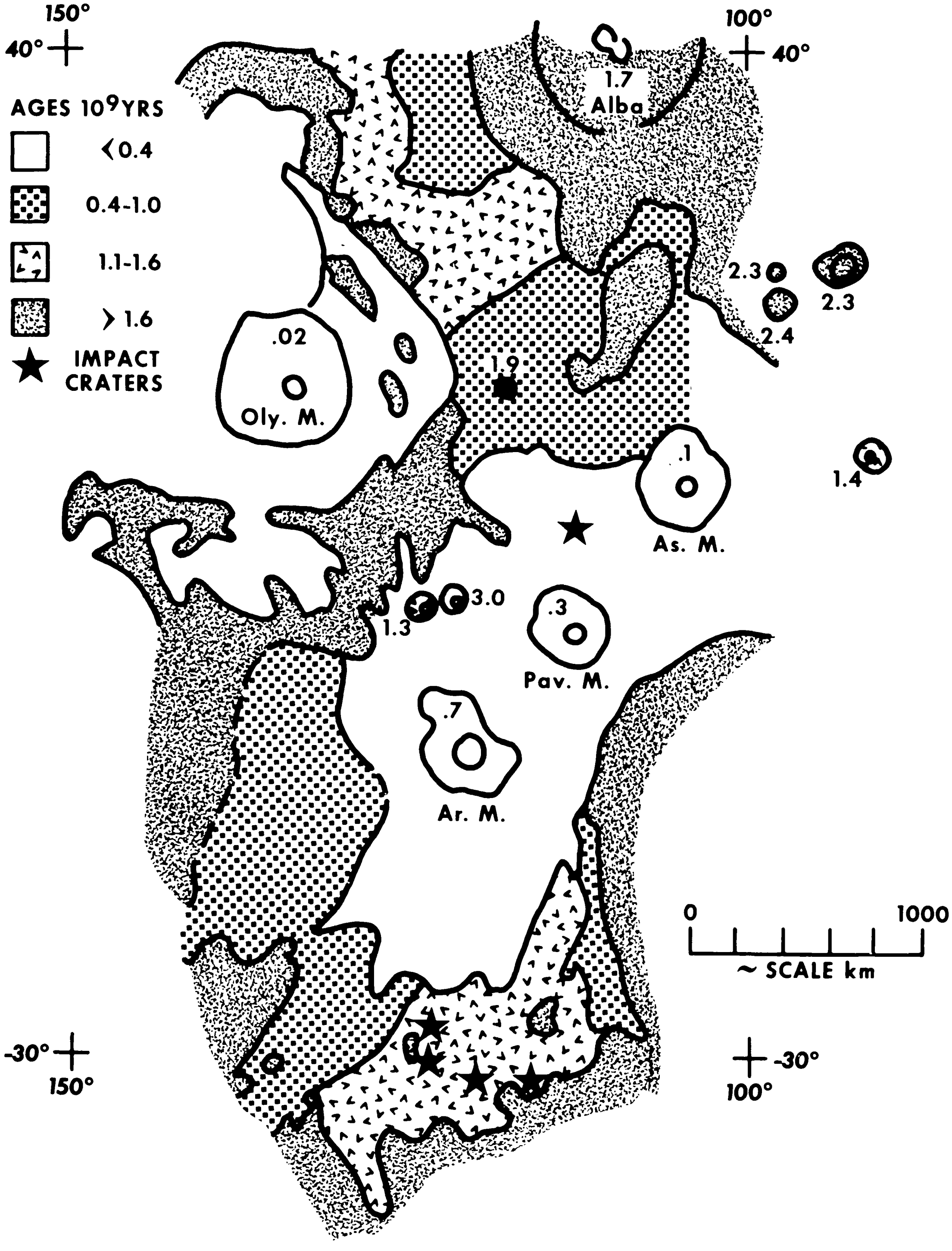

Fig. 4. Chronological map of volcanic units in the Tharsis region of Mars; compiled from crater count data by Schaber *et al.*, 1978 and Plescia and Saunders, 1979. SNC meteorites may be samples of oldest volcanic unit (1.1 to 1.6 b.y.) which is exposed on margins of region and presumably underlies younger units.

chemical composition of Mars, but comparable to values (2.5×10^4) assumed by Toksöz and Hsui (1978). Measurements of K/U by the Soviet Mars 5 spacecraft have been analyzed and calibrated repeatedly; the latest value of 6.7×10^3, with an uncertainty of about 50% (Surkov *et al.*, 1981), approaches the SNC ratio. The earth-like K/U ratio of the SNC samples implies that Mars has a volatile abundance more like the Earth than the Moon.

Currently Mars has a very weak to non-existent magnetic field (Russell, 1979), and paleo-intensity measurements on SNC meteorites (Nagata, 1981; Cisowski, 1981) provide no evidence for a field 1.3 b.y. ago. These data suggest that Mars does not have a convecting liquid core and has not had one during the last third of its history, and support thermal models such as that of Toksöz and Hsui (1978) in which core formation occurred in the first billion years of martian evolution, and not in the last billion years (e.g., Solomon, 1979).

CONCLUSIONS

The chemical and physical characteristics of SNC meteorites argue strongly against their origin in association with the eucrites, the most closely related class of meteorites. Additionally, plausible thermal models of asteroid evolution preclude igneous activity due to internal processes, and impact derived melt sheets on asteroids are not likely to yield the cumulate textures and isotopic variability of SNC meteorites. Instead, SNC meteorites were derived from an Earth-like parent body which we believe to be Mars. This conclusion, based on compilation of all available evidence, is sufficiently intriguing and important (especially since documented sample return from Mars is unlikely in the next decade) that the possible mechanisms of transport of materials from Mars to Earth should be seriously investigated. More specifically, the role of target gases and volatiles in producing unmelted ejecta from impacts on large planetary objects should be thoroughly evaluated through both theory and experiment. Calculations of the yield and travel time of Earth-crossing ejecta from Mars should also be carried out.

The prospect that we may have martian samples on Earth justifies an intensive program of SNC analysis to provide as many constraints as possible regarding the origin and evolution of Mars. Petrologic and geochemical work may define the depths of origin of the melts from which the SNC samples crystallized. Much can be learned of the SNC source regions by experimental petrological investigations at high pressures appropriate to the martian upper mantle (10–25 kbar). Further stable and radiogenic isotopic studies may clarify the relations between individual SNC meteorites, and the complex histories they seem to have experienced.

The possibility that other meteorites in terrestrial collections may have come from Mars should not be overlooked. Samples of other regions of Mars may also have been ejected into Earth-crossing orbits. Recognition and study of samples from the geologically diverse terrains of Mars are crucial to the development of a broad understanding of its evolution.

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