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SNC Meteorites: Clues to Martian Petrologic Evolution?

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The shergottites, nakhlites, and Chassigny (SNC meteorites) are apparently cumulate mafic and ultramafic rocks that crystallized at shallow levels in the crust of their parent body. The mineralogy and chemistry of these meteorites are remarkably like equivalent terrestrial rocks, although their ratios of Fe/(Fe + Mg) and certain incompatible elements and their oxygen isotopic compositions are distinctive. All have crystallization ages of 1.3 b.y. or younger and formed from magmas produced by partial melting of previously fractionated source regions. Isotope systematics suggest that the SNC parent body had a complex and protracted thermal history spanning most of geologic time. Some meteorites have been severely shock metamorphosed, and all were ejected from their parent body at relatively recent times, possibly in several impact events. Late crystallization ages, complex petrogenesis, and possible evidence for a large gravitational field suggest that these meteorites are derived from a large planet. Trapped gases in shergottite shock melts have compositions similar to the composition measured in the Martian atmosphere. Ejection of Martian meteorites may have been accomplished by acceleration of near-surface spalls or other mechanisms not fully understood. If SNC meteorites are of Martian origin, they provide important information on planetary composition and evolution. The bulk composition and redox state of the Martian mantle, as constrained by shergottite phase equilibria, must be more earthlike than most current models. Planetary thermal models should benefit from data on the abundances of radioactive heat sources, the melting behavior of the mantle, and the timing of planetary differentiation. Calculated depletion of chalcophile elements in source regions indicates a core dominated by sulfides, and paleomagnetic measurements suggest the presence of a weak magnetic field within the last several hundred thousand years. Concentrations of volatile elements indicate that the SNC parent body was not volatile depleted, and trapped atmospheric components measured in shock melts may be useful in understanding planetary degassing. By providing comparisons for spectral reflectance data and Viking soil analyses, these meteorites may also constrain surface mineralogy and weathering mechanisms.

CONTENTS

INTRODUCTION

Within a span of 2 decades, we have witnessed the transformation of planets and satellites from remote astronomical objects into almost familiar geological worlds. With the notable exception of our moon, this shift of scientific turf has been accomplished solely through spacecraft remote sensing. However marvelous these second-hand observations may be, there is still much that could be learned from direct analysis of physical samples, as was amply demonstrated by the staggering amount of otherwise unobtainable information contained in Apollo rocks and soil [e.g., *Taylor*, 1982].

Of these newly unveiled geological terranes, one of the most interesting is the planet Mars (reviewed by *Arvidson et al.* [1980]). However, our understanding of Martian history and the processes that shaped it are less complete than we might like because of the absence of sample data. Must the resolution of some Martian geological problems wait decades for a possible sample return mission? Possibly not. A small group of achondritic meteorites (shergottites, nakhlites, and the unique meteorite Chassigny) have characteristics that suggest they may be Martian samples. The information contained in these meteorites is the subject of this review. Because the complexity of these rocks exceeds that of most other meteorites, this paper will first summarize their petrologic and chemical properties and what is known or surmised about their petrogenesis. Some common misconceptions about these meteorites will also be corrected. We will then consider the evidence for a Martian origin, as well as some problems encountered in obtaining planetary samples. Finally, the implications that can be drawn about Mars, assuming that it is the shergottite parent body (SPB), will be explored.

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CLASSIFICATION

The shergottites, nakhlites, and Chassigny are collectively called "SNC meteorites." Meteorites are conventionally classified by their petrography or chemistry into groups with little internal variation, a serviceable but simplistic system that may overlook genetic relationships, at least in the case of igneous meteorites (achondrites). Despite this potential problem, the present classification system will be retained to avoid the confusion of a new terminology.

The shergottites are mostly medium-grained basalts, or more properly diabases. Their name derives from several stones that fell in Shergotty, India, in 1865 (originally described by *Tschermak* [1872]). A second shergottite fell in Zagami, Nigeria, in 1962. The Elephant Moraine (EETA) 79001 meteorite, found in Antarctica in 1979, is actually a layered stone containing two distinct shergottite lithologies (termed A and B). Allan Hills (ALHA) 77005, another Antarctic find from the 1977 field season, is a feldspathic harzburgite closely related to the shergottites.

Nakhlites are pyroxenites. They take their name from a shower of about 40 stones that fell in El Nakhla el Baharia, Egypt, in 1911 (described by *Prior* [1912]). One of these supposedly struck and killed a dog. Two other finds from Lafay-

TABLE 1. Modal Compositions of SNC Meteorites (vol %)

	Shergotty (Ref. 1)	Zagami (Ref. 1)	EETA 79001,A (Ref. 2)	EETA 79001,B (Ref. 2)	ALHA 77005 (Ref. 3, 4)	Nakhla (Ref. 5)	Lafayette (Ref. 6)	Governador Valadares (Ref. 7)	Chassigny (Ref. 8)
Pigeonite	36.3	36.5	59.3	39.5	26				
Augite	33.5	36.5	6.1	20.0	11	78.6	major	major	3.8
Orthopyroxene			5.4						4.0
Olivine			8.9		52	15.5	minor	minor	88.5
Plagioclase[a]	23.3 (m)	21.7 (m)	17.1 (m)	29.1 (m)	10 (m)	3.7	trace	trace	2.6
K feldspar						1.1	trace	trace	trace
Oxides[b]	2.3 (ti, il)	2.1 (ti, il)	3.0 (ti, il, cr)	3.5 (ti, il)	1 (il, cr)	1.9 (ti)	trace (ti)	trace	1.2 (cr, il)
Sulfides[c]	trace (po)	trace (po)	trace (po)	trace (po)	trace (tr)	trace	trace (py, tr, ch, mr)	trace	trace (pe, mr)
Phosphates[d]	trace (wh, ap)	trace (wh, ap)	0.2 (wh, ap)	0.4 (wh, ap)	trace (wh)	trace (ap)	trace	trace	trace (ap)
Mesostasis[e]	4.0	2.1	0.1	0.7	trace				

References in column headings: 1, *Stolper and McSween* [1979]; 2, *McSween and Jarosewich* [1983]; 3, *Ma et al.* [1981]; 4, *McSween et al.* [1979*a*]; 5, *Bunch and Reid* [1975]; 6, *Boctor et al.* [1976]; 7, *Burragato et al.* [1975]; 8, *Nehru et al.* [1983].

[a]The letter m indicates maskelynite.

[b]Oxides include titanomagnetite (ti), chromite (cr), and ilmenite (il).

[c]Sulfides include troilite (tr), pyrrhotite (po), pyrite (py), chalcopyrite (ch), marcasite (mr), and pentlandite (pe).

[d]Phosphates include whitlockite (wh) and chlorapatite (ap).

[e]Mesostasis includes fayalite, tridymite, baddelyite, and other accessory phases.

ette, Indiana, and Governador Valadares, Brazil, complete this group.

The Chassigny meteorite is a dunite that fell in France in 1815. Circumstances surrounding this fall were summarized by *Jeremine et al.* [1962]. The only other dunite meteorite, Brachina, is not part of this association [*Clayton and Mayeda*, 1983; *Nehru et al.*, 1983].

Despite their petrographic diversity, members of the SNC group form a coherent association that is distinct from all other achondrites in terms of mineral chemistry, redox state, oxygen isotopic composition, and radiometric ages. These characteristics will be discussed in detail in later sections. Petrographic, chemical, and radiometric age data for each meteorite are summarized in Tables 1, 2, and 3.

MINERALOGY

The most complete mineralogical descriptions of SNC meteorites can be found in the following references: shergottites and ALHA77005 [*Binns*, 1967; *Duke*, 1968; *Ishii et al.*, 1979; *McSween et al.*, 1979*a*; *Smith and Hervig*, 1979; *Stolper and McSween*, 1979; *Steele and Smith*, 1982; *McSween and Jarosewich*, 1983; *Smith et al.*, 1983]; nakhlites [*Bunch and Reid*, 1975; *Boctor et al.*, 1976; *Berkeley et al.*, 1980; *Smith et al.*, 1983]; *Chassigny* [*Floran et al.*, 1978; *Smith et al.*, 1983]. Major mineral compositions, taken from the above references, are summarized in Figure 1.

Shergottites and ALHA77005

Shergottites consist predominantly of clinopyroxenes (pigeonite and augite) and maskelynite (a diaplectic glass of plagioclase composition). Both pyroxenes are strongly zoned with Fe-enriched rims. Typical core and rim compositions are $En_{60}Fs_{28}Wo_{12}$–$En_{21}Fs_{61}Wo_{18}$ (pigeonite) and $En_{48}Fs_{20}Wo_{32}$– $En_{25}Fs_{47}Wo_{28}$ (augite). Minor elements (Al, Ti, Cr, Mn) in pyroxenes are also strongly zoned. Maskelynite is zoned from $Ab_{43}An_{56}Or_1$ cores to $Ab_{56}An_{41}Or_3$ rims. Other phases include titanomagnetite ($Mt_{37}Usp_{63}$), ilmenite ($Ilm_{95}Hem_5$), pyrrhotite ($Fe_{0.94}S$), fayalite (Fa_{90-93}) or pyroxferroite, tridymite, whitlockite, chlorapatite, and baddeleyite. Patches of glassy mesostasis containing minor phases occur between some crystals. Trapped melt inclusions in pyroxenes contain small grains of chromite and kaersutite [*Treiman*, 1985*a*], one of only two occurrences of hydrous amphibole in meteorites (the other is in Chassigny).

EETA79001,A contains large xenocrysts of olivine, orthopyroxene, and chromite in addition to the conventional shergottite minerals that comprise its groundmass. Clinopyroxenes in this groundmass are slightly more magnesian and maskelynite is slightly more calcic than other shergottites, but these differences are minor. The compositions of xenocrysts are similar to the same minerals in ALHA77005. Olivines and orthopyroxenes in both meteorites are zoned from Fo_{81-55} and $En_{82}Fs_{16}Wo_2$–$En_{58}Fs_{30}Wo_{12}$, respectively. Chromites enclosed by silicate minerals have compositions of $Fe_{0.97}Cr_{1.61}Al_{0.30}Ti_{0.02}O_4$ and are unzoned. Those not armored by silicates are strongly zoned to more ulvöspinel-rich compositions. Augite and pigeonite are more magnesian in ALHA77005 than in other shergottites, but the compositions of maskelynite, Fe-Ti oxides, and phosphates are similar. Troilite rather than pyrrhotite is the sulfide phase in this meteorite, possibly because of shock reduction.

Nakhlites and Chassigny

Nakhlites consist primarily of augite ($En_{39}Fs_{23}Wo_{38}$) grains with slightly Fe enriched overgrowths. Large olivines have

TABLE 2. Chemical Compositions of SNC Meteorites

	Shergotty	Zagami	EETA 79001,B	EETA 79001,A	ALHA 77005	Nakhla	Lafayette	Governador Valadares	Chassigny
SiO_2, %	51.36	50.8	48.58	49.03	43.08	48.24	46.9	49.5	38.16
TiO_2, %	0.87	0.8	0.64	1.12	0.44	0.29	0.33	0.35	0.10
Al_2O_3, %	7.06	6.4	5.37	9.93	2.59	1.45	1.55	1.74	0.69
FeO, %	19.41	19.0	18.32	17.74	19.95	20.64	22.7	19.74	27.1
MnO, %	0.53	0.50	0.47	0.45	0.46	0.54	0.79	0.67	0.53
MgO, %	9.28	11.1	16.31	7.38	27.69	12.47	12.9	10.9	31.6
CaO, %	10.00	10.6	7.05	10.99	3.35	15.08	13.4	15.8	0.60
Na_2O, %	1.29	1.21	0.82	1.66	0.44	0.42	0.36	0.82	0.13
K_2O, %	0.164	0.14	0.033	0.065	0.027	0.10	0.09	0.43	0.041
P_2O_5, %	0.80		0.54	1.31	0.36	0.12			0.06
Cr_2O_3, %	0.20	0.29	0.59	0.18	0.96	0.42	0.18	0.21	0.63
S, %	0.13		0.16	0.19	0.06				0.01
Total	101.09	100.84	98.88	100.05	99.41	100.77	99.10	100.16	99.65
Fe/(Fe + Mg)	0.73	0.69	0.59	0.76	0.48	0.68	0.70	0.70	0.53
Ref.	(1)	(2)	(1)	(1)	(1)	(3)	(4)	(5)	(1)
Li, ppm	5.6	3.82	2.21	4.54	1.31	3.8			1.3
C, ppm	620		98	36	82	696			847
F, ppm	41.6		30.9	39	21.9	57.1			14.7
Cl, ppm	108		48	26	14	1145			34
Sc, ppm	58.9	57	50.5	36.1	21.1	46			5.4
V, ppm		312	206	210	158	192			34
Co, ppm	39.0	36.4	31.1	47.3	69.5	54.0			126
Ni, ppm	83	67	46	158	335	90	94	80	480
Cu, ppm	26.0				5.5	18.3			2.6
Zn, ppm	83.0	61.7	120	81	71	64	72		74
Ga, ppm	14.7	14.1	24.4	12.6	7.5	3.4			0.7
As, ppb	25	46	12	44	22	260			8
Se, ppm	0.41	0.32	0.42	0.43	0.15	0.09	50		
Br, ppm	0.60		0.25	0.14	0.07	4.08	0.17		0.07
Rb, ppm	6.84	5.69	1.78	1.04	0.63	3.15	3.25		
Sr, ppm	51.0	45.9	67	57	100	51.4			
Ag, ppb	110	31	6.3	19	4.4	40	58		
Cd, ppb	340	61	70	37	6.0	71	98		
In, ppb	23	22	68	46	11		20		
Sb, ppb	5	12	16	10	0.68		103		
Te, ppb	3.2	1.0	7.4	5.9	0.5		<5.2		
I, ppb	50		960	<100	1720				<100
Cs, ppm	0.41	0.38	0.13	0.075	38	0.49	0.35		
Ba, ppm	35.5	25.3	14.0	<10		31.3			5
La, ppm	2.29	0.90	0.80	0.37	0.32	2.28			0.59
Ce, ppm	5.54	3.75	3.1	1.4	1.09	6.20	4.21		
Nd, ppm	4.5	2.89	2.9	1.4	1.15	4.06	3.12		0.7
Sm, ppm	1.37	0.76	1.56	0.75	0.42	0.86			0.16
Eu, ppm	0.56	0.44	0.73	0.35	0.20	0.28	0.19		0.05
Tb, ppm	0.44	0.22	0.64	0.30	0.17	0.13	0.10		0.04
Dy, ppm	2.94	1.7	4.58	2.11	0.96	0.81			0.27
Ho, ppm	0.56		0.99	0.50	0.22	0.17			0.06
Tm, ppm	0.38		0.37	0.21	0.08				
Yb, ppm	1.69	0.98	2.14	1.12	0.52	0.40	0.31		0.12
Lu, ppm	0.25	0.13	0.30	0.15	0.07	0.06	0.06		0.02
Hf, ppm	1.97	1.7	1.93	0.93	0.55	0.29			<0.1
Ta, ppm	0.25	0.2	0.09	0.03	0.03	0.09			<0.02
W, ppb	480		155	83	84	176			46
Ir, ppb	0.4		<3	<2	3.5	0.3	.05		2.4
Au, ppb	14	2.2	1.1	2.8	0.3	0.7	66.2		1.0
Tl, ppb	12	12	7.9	6.9	1.7	3.1	6.8		
Bi, ppb	2.0	5.1	0.76	0.67	<0.7	0.5	5		
Th, ppb	390	270	<200	<100	59	239			<200
U, ppb	116	154	<100	<60	18.1	56	44.2		<100
Ref.	(1, 2)	(2, 6)	(1, 2)	(1, 2)	(1, 2, 7)	(8, 9, 11)	(10, 12)	(5)	(1)

References: 1, *Burghele et al.* [1983]; 2, *Smith et al.* [1984]; 3, *McCarthy et al.* [1974]; 4, *Boctor et al.* [1976]; 5, *Burragato et al.* [1975]; 6, *Shih et al.* [1982]; 7, *McSween et al.* [1979*b*]; 8, *Nakamura et al.* [1982*a*]; 9, *Weinke* [1978]; 10, *Dreibus et al.* [1982]; 11, *Laul et al.* [1972]; 12, *Treiman et al.* [1985].

compositions of Fo_{35-32}. Interstitial mesostasis contains variolitic plagioclase ($Ab_{60-68}An_{23-26}Or_{3-9}$) and alkali feldspar ($Ab_{20-42}An_{4-6}Or_{52-76}$), Fe-rich pigeonite and augite, and fayalite (Fo_{23}). Other phases are titanomagnetite with ilmenite lamellae, chlorapatite, silica, and sulfides (pyrite, troilite, and chalcopyrite). Iddingsite, a mixture of smectite clays and hydrated iron oxides, probably represents a preterrestrial alteration product of olivine in nakhlites [*Reid and Bunch*, 1975].

TABLE 3. Chronological Data for SNC Meteorites

Meteorite*	Crystallization Age, 10^9 years	Ref.	Shock Age, 10^6 years	Ref.	Exposure Age, 10^6 years			Ref.
					^{3}He	^{21}Ne	^{38}Ar	
Sh	0.35 ± 0.05 (Sm-Nd)	(1)	165 ± 11 (Rb-Sr)	(2)	2.1	2.6	2.5	(15)
Sh, Za, AL	1.34 ± 0.06 (Sm-Nd)	(2)	180 ± 4 (Rb-Sr)	(2)	2.6	2.9	2.2	(15)
			192 ± 20 (Rb-Sr)	(2)	3.0	1.9	2.8	(15)
Sh, Za, AL, EE/A, EE/B	1.27 ± 0.04 (Sm-Nd)	(3)	173 ± 10 (Rb-Sr)	(14)	0.5	0.6	0.4	(15)
Sh, Za, AL, EE/A, EE/B	0.18 ± 0.02 (Rb-Sr)	(4)	185 ± 25 (Rb-Sr)	(14)	0.5	0.7	1.0	(15)
Na	1.37, 1.24 ± 0.02 (Rb-Sr)	(5, 6)			10.7	11.9	11.7	(15)
Na	≤1.3 (Ar-Ar)	(7)						
Na	1.26 ± 0.07 (Sm-Nd)	(6)						
Na	1.28 ± 0.05 (U-Pb)	(8)						
La	1.33 ± 0.03 (Ar-Ar)	(7)			10.8	11.9	10.5	(15)
GV	1.33 ± 0.01 (Rb-Sr)	(9)			9.7	9.2	6.3	(15)
GV	1.32 ± 0.04 (Ar-Ar)	(10)						
Ch	1.39 ± 0.17 (K-Ar)	(11)			11.8	9.6	9.8	(15)
Ch	1.27 (Ar-Ar)	(12)						
Ch	1.23 ± 0.12 (Rb-Sr)	(13)						

References: 1, *Jagoutz and Wänke* [1985]; 2, *Shih et al.* [1982]; 3, *Nyquist et al.* [1984]; 4, *Jones* [1985]; 5, *Papanastassiou and Wasserburg* [1974]; 6, *Gale et al.* [1975]; 7, *Podosek* [1973]; 8, *Nakamura et al.* [1982*a*]; 9, *Wooden et al.* [1979]; 10, *Bogard and Husain* [1977]; 11, *Lancet and Lancet* [1971]; 12, *Bogard and Nyquist* [1979]; 13, *Nakamura et al.* [1982*b*]; 14, *Wooden et al.* [1982]; 15, averages of all data in the work of *Bogard et al.* [1984].

*Sh, Shergotty; Za, Zagami; AL, ALHA 77005; EE/A, EETA 79001,A; EE/B, EETA 79001,B; Na, Nakhla; La, Lafayette; GV, Governador Valadares; Ch, Chassigny.

Olivine (Fo_{32}) is the dominant mineral in the Chassigny meteorite. Subordinate grains of augite ($En_{45}Fs_{12}Wo_{43}$) and orthopyroxene ($En_{71}Fs_{27}Wo_2$) each contain exsolution lamellae of the other. Chromite is similar in composition to that in ALHA77005, and grains not enclosed by olivine exhibit a similar enrichment in ulvöspinel component at their rims. Interstitial phases include plagioclase and alkali feldspars (with highly variable compositions from andesine to orthoclase), chlorapatite, pyrrhotite ($Fe_{0.88}S$), marcasite, pentlandite, ilmenite, rutile, and baddeleyite. Marcasite may be a terrestrial alteration product of other sulfides. Melt inclusions in Chassigny olivines also contain kaesutite.

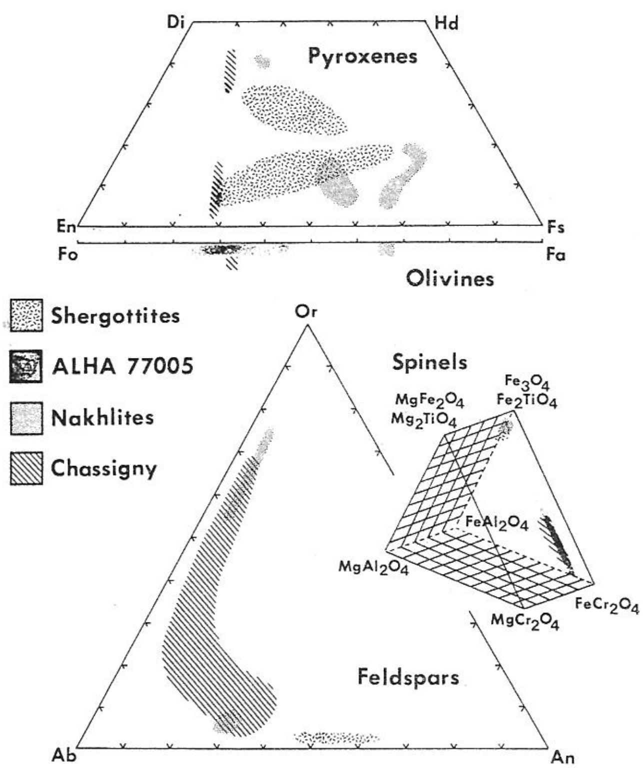

Fig. 1. A summary of the compositions of major minerals in SNC meteorites. All diagrams are in molar units.

Implications

The mineralogy of SNC meteorites can be used to infer something about their petrogenesis:

1. It is clear that they all crystallized under relatively oxidizing conditions. The compositions of coexisting Fe-Ti oxides in shergottites define temperatures and oxygen fugacities close to the QFM buffer [*Smith and Hervig*, 1979; *Stolper and McSween*, 1979]. The occurrence of magnetite or Fe^{3+}-bearing chromite (up to 10 mol % of the Fe is ferric) in other SNC meteorites [*Floran et al.*, 1978; *McSween et al.*, 1979*a*] indicates that they are also oxidized, although their redox states are unquantified. Olivine in SNC meteorites contains Ni, also a result of high oxidation state [*Smith et al.*, 1983].

2. The presence of magmatic amphiboles in shergottites and Chassigny and preterrestrial iddingsite in nakhlites indicates that these achondrites formed from hydrous magmas. This characteristic, as well as the oxidation state, sets SNC meteorites apart from all other achondrites.

3. The high Fe/(Fe + Mg) ratios of ferromagnesian minerals and high alkali contents of feldspars suggest that all SNC meteorites crystallized from fractionated liquids. Ultramafic SNC meteorites are unlikely to be refractory residues from partial melting, as suggested for ALHA77005 by *McSween et al.* [1979*a*] and *Smith et al.* [1984].

4. The Fe/Mn ratios of pyroxenes and olivines in most SNC meteorites are lower than those in other extraterrestrial samples [*Stolper and McSween*, 1979; *Smith et al.*, 1983]. This ratio serves as a useful cosmochemical discriminant, because Fe and Mn can be separated by volatility but not by magmatic processes at modest pressures. Early crystallizing augites in nakhlites are slightly displaced from the shergottite Fe/Mn trend, possibly implying that these meteorite groups are not directly related [*Smith et al.*, 1983], though late-stage pyroxenes in nakhalites have Fe/Mn ratios that match those in shergottites.

5. All SNC meteorites show evidence of disequilibrium in the form of mineral zonation or differences in the compo-

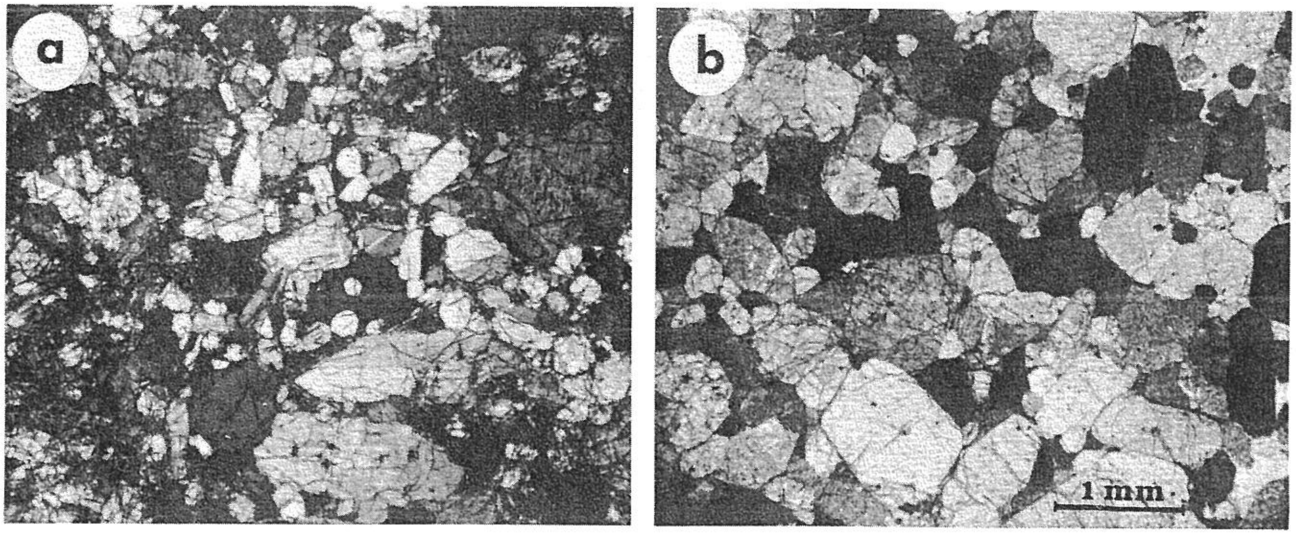

Fig. 2. Photomicrographs of (*a*) Nakhla and (*b*) Chassigny, illustrating the cumulate textures of these meteorites. Scale as in Figure 2*b*.

sitions of early and late crystallizing phases. This plus the presence of glassy or devitrified mesostasis demands fairly rapid cooling. These rocks must have formed near (though not necessarily on) the surface of their parent body. The high Ca contents of SNC olivines also suggest crystallization at low pressure [*Smith et al.*, 1983]. The stability of magmatic amphiboles suggests load pressures in excess of 1 kbar [*Treiman*, 1985*a*]; however, these grains were trapped within cumulus minerals and probably crystallized before final magma emplacement.

Petrography and Crystallization Histories

The minerals described above are combined in various modal proportions to form SNC meteorites, as indicated in Table 1. Photographs of some of these meteorites are shown in Figures 2, 3, and 4.

Cumulate Textures

A common link among most SNC meteorites is the occurrence of cumulate textures. The terms cumulate refers to a framework of touching crystals that were concentrated by fractional crystallization of their parental magma [*Irvine*, 1982]. Cumulate rocks usually consist of cumulus crystals, possibly with postcumulus overgrowths, and interstitial spaces filled by other postcumulus phases. Petrofabric studies of the optical orientations of cumulus augite in nakhlites [*Berkeley et al.*, 1980] and of cumulus olivine in ALHA77005 [*Berkeley and Keil*, 1981] indicate that these meteorites possess planar foliations with superimposed lineations (Figure 5). Such fabrics suggest accumulation while in the process of magmatic flow, which entrained elongated cumulus minerals parallel to flow directions and produced associated foliations defined by alignment of broad crystal faces parallel to flow lines. Cumulus olivines in Chassigny apparently have no directional fabric [*Floran et al.*, 1978] and thus may have formed in stagnant magma. Shergottites are not amenable to rigorous petrofabric analysis because pigeonite and augite cannot readily be distinguished optically because of shock effects. However, counts of pyroxene grain contacts encountered on oriented traverses in shergottites show that these meteorites are well foliated [*Stolper and McSween*, 1979; *McSween and Jarosewich*, 1983]. The presence of lineations could not be determined by this method, but these are not apparent from inspection of sections cut at various orientations. Therefore the shergottites also presumably crystallized in quiescent magma bodies.

Crystallization Patterns

The crystallization history of nakhlites inferred from their textures began with augite accumulation. These cumulus grains may have been slightly enlarged by growth from trapped interstitial liquid. Large olivine grains either formed as cumulus crystals [*Reid and Bunch*, 1975], crystallized later to fill some pore spaces [*Berkeley et al.*, 1980], or are xenocrysts [*Treiman*, 1985*b*]. Remaining intercumulus melts were then quenched to form a mesostasis of small crystallites and glass. *Berkeley et al.* [1980] suggested that pore fluids were flushed through the crystalline network, resulting in a highly fractionated mesostasis that may not represent the liquid complementary to the cumulus grains. *Treiman* [1985*b*] questioned this interpretation, arguing that similarities in inferred trace element partition coefficients for Nakhla with experimental values indicated closed-system accumulation. Finally, olivines were partly altered to iddingsite, presumably by deuteric processes.

Olivine, chromite, and possibly small amounts of augite were cumulus phases in Chassigny. Growth of pyroxenes from intercumulus liquid, possibly in communication with the larger magma column, produced a poikilitic texture in which large pyroxenes enclose olivine grains. A limited amount of liquid was trapped as melt inclusions within olivines [*Floran et al.*, 1978] or ultimately solidified as small interstitial pockets.

The crystallization sequence for ALHA77005 was similar to nakhlites and Chassigny but apparently involved less cumulus material. Early crystallization of olivine and chromite, joined later by orthopyroxene, produced a poikilitic intergrowth. The rounded shapes of olivine grains and zoning in chromites indicate that these minerals reacted with intercumulus liquid at lower temperatures. The residual liquid ultimately solidified as a network of plagioclase, augite, pigeonite, and accessory minerals [*McSween et al.*, 1979*a*]. On the assumption that orthopyroxene and other pyroxenes in the meteorite crystallized together, *Ishii et al.* [1979] calculated an equilibration (final solidification?) temperature of 1160°C.

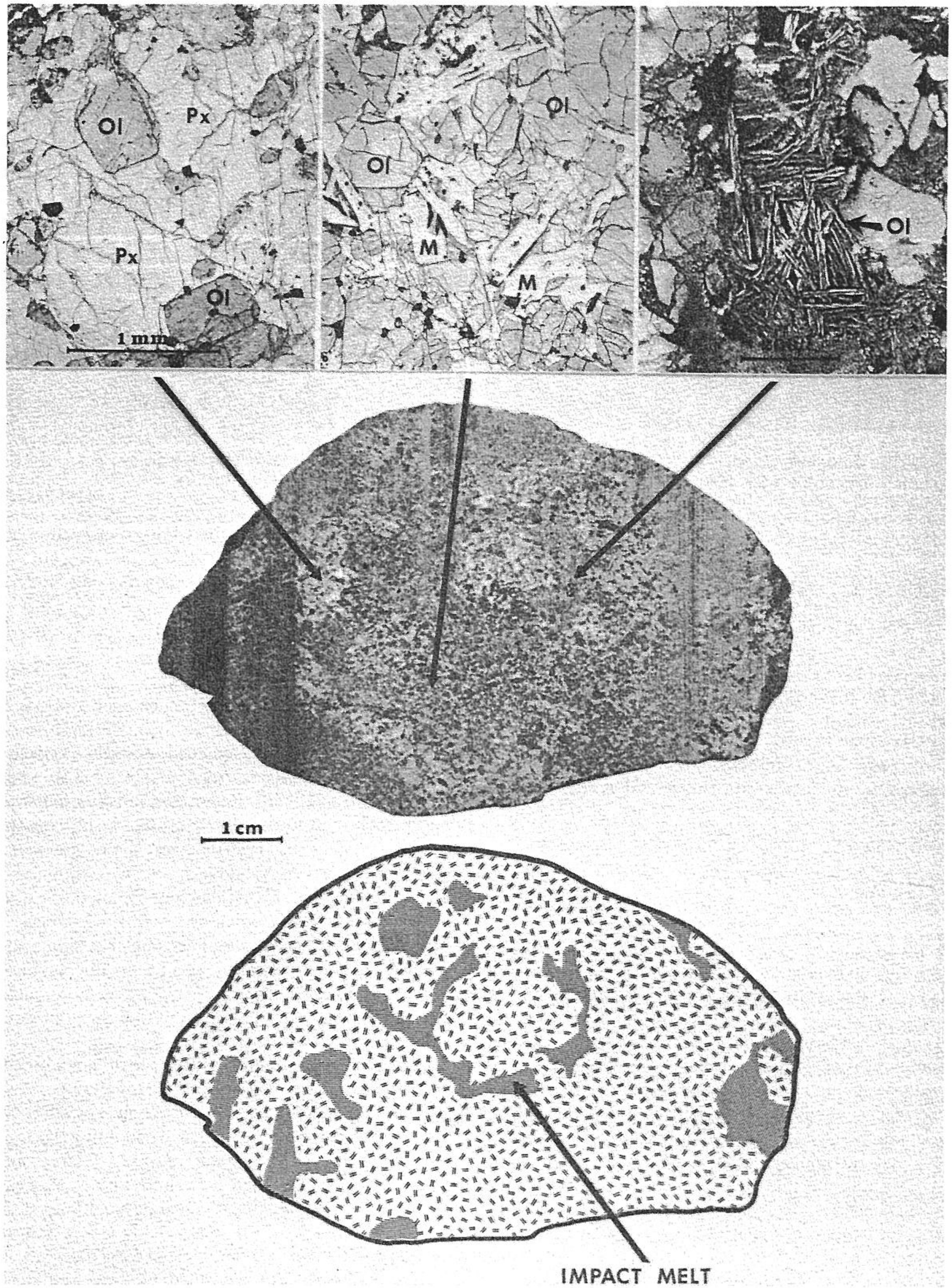

Fig. 3. Photographs of the ALHA77005 meteorite, showing the petrographic complexity of this stone. Lighter colored patches on the cut face consist of olivine (Ol) and chromite (opaque) poikilitically enclosed by orthopyroxene (Px); darker interstitial areas contain olivine, maskelynite (M), and other accessory phases; gray, vesicular pockets of impact melt have crystallized skeletal olivine.

Shergottites contain cumulus pigeonite and augite, and other phases fill interstices between the pyroxene prisms. It is not known whether accumulation involved only the magnesian pyroxene cores [*Stopler and McSween*, 1979] or larger, already zoned phenocrysts [*Smith and Hervig*, 1979]. Melting experiments using Shergotty and Zagami compositions by *Stopler and McSween* [1979] indicated accumulation temperatures of 1140°C for their preferred model or 1105°C for Smith and Hervig's model. The intercumulus liquid compositions for both meteorites were similar. The restriction of plagioclase to interstitial spaces between pyroxenes, as well as measured Al variations in pyroxenes, suggests that the onset of plagioclase crystallization occurred after pyroxenes accumulated. This was followed by the precipitation of accessory

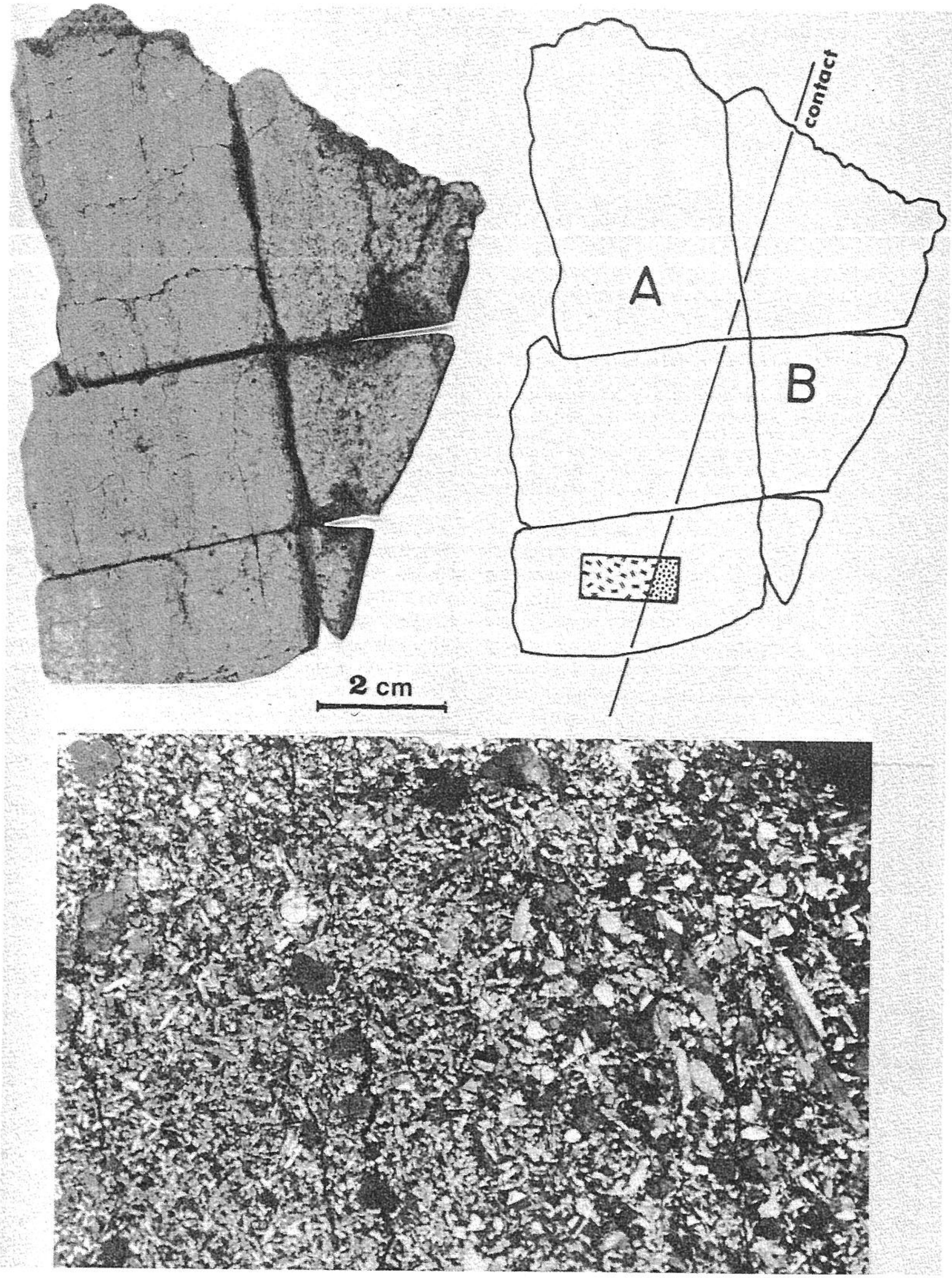

Fig. 4. Photographs of the EETA79001 meteorite, which contains two distinct shergottite lithologies (A and B) separated by a planar contact, apparently of igneous origin. The thin section photomicrograph below (width of 1 cm) straddles this contact. Lithology A is finer grained and contains irregular xenocrysts that have reacted with the host magma; B exhibits a texture similar to other shergottites, with oriented prisms of clinopyroxenes. Dark veins crosscrossing the slab above are shock-melted glass.

phases from interstitial melts, the last vestiges of which were quenched as mesostasis. Final solidification occurred at 1060°C [*Stolper and McSween*, 1979].

The EETA79001 shergottite shows a more complex crystallization history. Embayments in large xenocrysts of olivine and orthopyroxene in lithology A cut across primary zoning patterns [*Steele and Smith*, 1982], indicating that these were derived from some complex mixing process, either assimilation

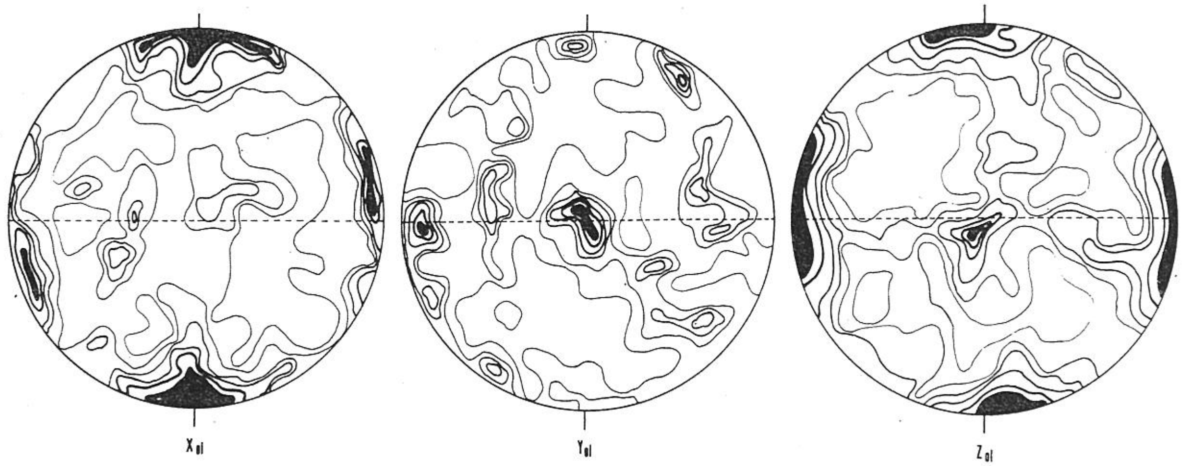

Fig. 5. Stereographic projections of the orientations of olivine optical axes (X, Y, Z) in ALHA77005. These data demonstrate that the meteorite has a foliation defined by alignment of broad crystal faces (the trace of which is represented by the horizontal dashed line) and a lineation of elongated grains (which lies in the foliation plane and is normal to the page). This cumulate rock probably solidified in the act of flow and crystal accumulation. Contour lines represent 1–6% in 1% of the areas. After *Berkeley and Keil* [1981, Figure 2]; reprinted by permission of the Mineralogical Society of America.

of solid harzburgite or admixture of another magma containing these phases as phenocrysts. The minerals comprising the groundmass of lithology A are similar to those in EETA79001,B and other shergottites, and their crystallization histories are inferred to be the same. The contact between lithologies A and B is sharp and planar (Figure 4). *McSween and Jarosewich* [1983] interpreted these to be separate magma pulses.

Grain Sizes

The diameters of cumulus augite grains in nakhlites are generally 1–3 mm. Cumulus olivines in Chassigny range from 1 to 1.5 mm. ALHA77005 contains cumulus olivines that range up to 2 mm in size. Shergottites are somewhat more variable but are generally comparable in grain size. Cumulus pyroxenes in Shergotty and EETA79001,B are 1–2 mm in length; Zagami and EETA79001,A pyroxenes are about half that size. Note that all of these meteorites are fine- to medium-grained rocks.

Implications

The cumulate textures of SNC meteorites and the ultramafic compositions of nakhlites, Chassigny, and ALHA77005 have led to the commonly held but probably erroneous view that these are plutonic rocks akin to those found in massive layered igneous complexes on earth. The modest grain sizes and mineralogical evidence for rapid cooling are not consistent with such an interpretation. SNC parent magmas must have been emplaced in shallow, tabular chambers or were extruded as phenocryst-laden lava flows. This is not meant to imply, however, that SNC meteorites represent liquid compositions. Crystallization experiments on shergottites show clearly that they are not multiply saturated [*Stolper and McSween*, 1979], as would certainly be expected for fractionated liquid compositions. Addition of cumulus crystals, probably by gravity settling in flowing or stagnant magmas, must have played a role in producing these meteorites.

CHEMICAL COMPOSITIONS

The following references report and interpret major, minor, and trace element abundances in SNC meteorites: shergottites [*Duke*, 1968; *Easton and Elliott*, 1977; *Stolper and McSween*, 1979; *Shih et al.*, 1982; *Burghele et al.*, 1983; *McSween and Jarosewich*, 1983; *Smith et al.*, 1984; *Laul et al.*, 1985]; ALHA77005 [*McSween et al.*, 1979*b*; *Ma et al.*, 1981; *Shih et al.*, 1982; *Burghele et al.*, 1983; *Smith et al.*, 1984]; nakhlites [*McCarthy et al.*, 1974; *Burragato et al.*, 1975; *Boctor et al.*, 1976; *Boynton et al.*, 1976; *Weinke*, 1978; *McSween et al.*, 1979*b*; *Dreibus et al.*, 1982; *Nakamura et al.*, 1982*a*]; and Chassigny [*McCarthy et al.*, 1974; *Mason et al.*, 1975; *Boynton et al.*, 1976; *McSween et al.*, 1979*b*; *Burghele et al.*, 1983]. Major, minor, and trace element abundances for individual meteorites selected from the above references are given in Table 2.

Major Elements

The major element abundances of SNC meteorites are similar to those of analogous terrestrial rocks except in one regard. All have high indices of differentiation (Table 2), defined as 100 Fe/(Fe + Mg). Although this probably reflects the fact that these meteorites formed from differentiated parent magmas, the indices still seem anomalously high. This characteristic could also arise from fusion of source rocks with high Fe/(Fe + Mg).

Most of these meteorites are quartz normative. Olivines appear to have been in reaction relationship with intercumulus liquids, and feldspathoids are absent. These characteristics indicate that parental magmas for SNC meteorites were tholeiitic. However, the crystallization of olivine and pyroxene before plagioclase in all SNC meteorites is unlike terrestrial tholeiites and may suggest picritic (ultramafic) magmas of tholeiitic affinity.

One of the most perplexing features of shergottite bulk compositions is that they apparently define linear arrays. The compositions of Shergotty, Zagami, and EETA79001,A can be approximated by mixing ALHA77005 and EETA79001,B in various proportions, as illustrated in Figure 6. This observation supports the inference from xenocrysts in EETA79001,A that mixing processes may have partly controlled the compositions of these rocks.

Minor and Trace Elements

Abundances of minor and trace elements in shergottites are remarkably similar to those in average terrestrial basalts

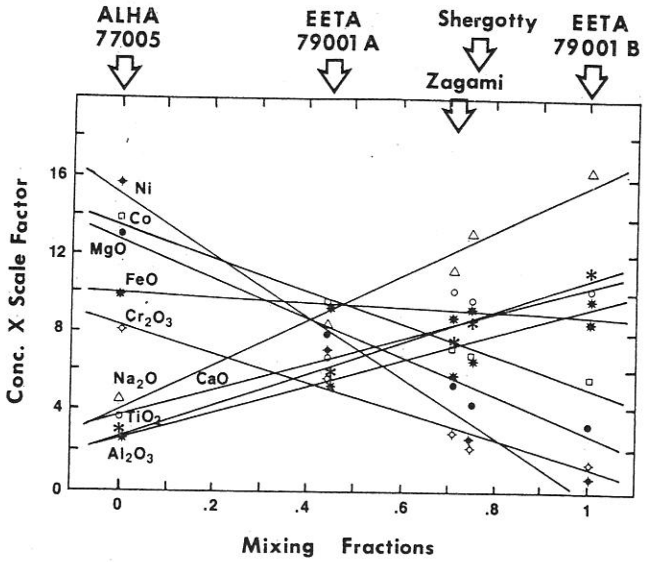

Fig. 6. Colinearities in the compositions of major and some minor elements among shergottites, after *Ma et al.* [1982]. ALHA77005 and EETA79001,B can be combined in various proportions to produce the approximate compositions of the other shergottites. All elements are expressed as wt % oxides, except Ni and Co which are in ppm. Scale factors are as follows: Al, Ca (1.0); Fe, Mg (0.5); Na, Cr, Ti (10); Ni (0.05); Co (0.2).

[*Stolper*, 1979; *Stolper and McSween*, 1979], and those in ALHA77005, nakhlites, and Chassigny mimic terrestrial peridotites [*McSween et al.*, 1979*b*; *Ma et al.*, 1981; *Nakamura et al.*, 1982*a*]. One example is illustrated in Figure 7. This coherence is somewhat surprising because these elements exhibit wide variations in geochemical behavior. SPB magma source regions must have had overall abundances of these elements similar to the earth's upper mantle, the source region for terrestrial basalts. However, there are some minor, though petrogenetically important, differences between trace element abundances in SNC meteorites and equivalent terrestrial rocks, mostly in siderophile and chalcophile elements. Their likenesses have probably been overemphasized in the literature, although it is undeniable that the two classes of materials

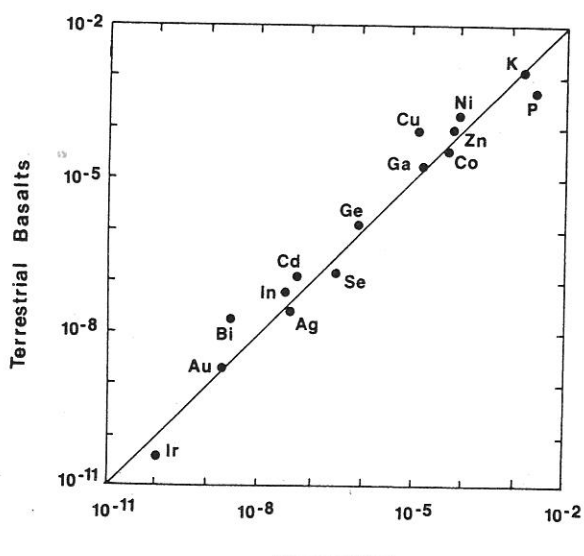

Fig. 7. Trace element abundances in shergottites versus those in average terrestrial basalts, after *Stolper* [1979]. An exact correlation would lie along the diagonal line. Data sources are given in Stolper's paper. All units are weight fractions.

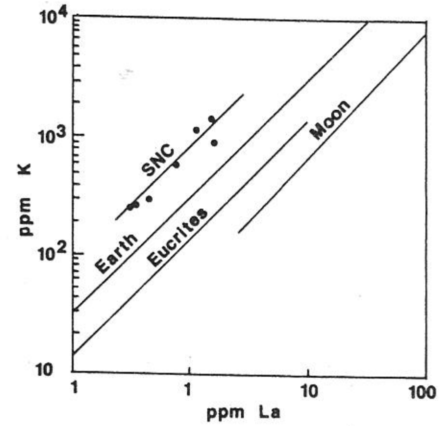

Fig. 8. Correlation between K and La in SNC meteorites, after *Burghele et al.* [1983] and *Smith et al.* [1984]. The correlation line is distinct from those for terrestrial and lunar rocks and other achondrites and serves as a chemical fingerprint for the SPB.

are grossly similar and distinct from other extraterrestrial samples. One example of the distinctive chemical signature of SNC meteorites is their K/La ratios, as shown in Figure 8. The coherent behavior of these two elements demonstrates a rather important aspect of the geochemistry of cumulate rocks: more information is carried in ratios of incompatible elements than in their absolute abundances. *Wänke and Dreibus* [1984] also noted other unique chemical features, as well as similarities with terrestrial rocks, that provide important insights into the composition of SPB source regions.

The highly fractionated rare earth element (REE) abundance patterns in SNC meteorites are particularly unusual and informative. Shergottites and ALHA77005 are light REE depleted, whereas nakhlites and Chassigny show light REE enrichments (Figure 9). Significant differences in reported REE abundances for specific meteorites, e.g., Shergotty [*Stolper and McSween*, 1979; *Dreibus et al.*, 1982; *Shih et al.*, 1982; *Smith et al.*, 1984; *Laul et al.*, 1985], are probably due to analyses of small, unrepresentative samples in which REE are distributed heterogeneously. Measured abundances in mineral separates indicate that REE are strongly concentrated in small, nonrandomly distributed grains such as phosphates [e.g., *Smith et al.*, 1984]. The published REE patterns for whole-rock samples of SNC meteorites are probably only representations of true values.

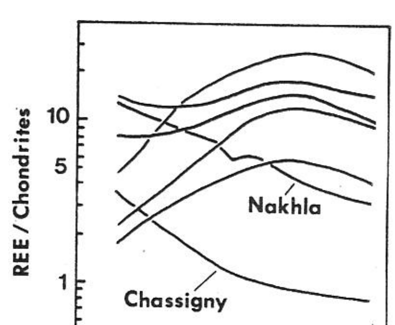

Fig. 9. Rare earth element patterns for SNC meteorites, after *Shih et al.* [1982] and *Nehru et al.* [1983]. Nakhla and Chassigny are light REE enriched, whereas the shergottites and ALHA77005 (unlabeled lines) are light REE depleted.

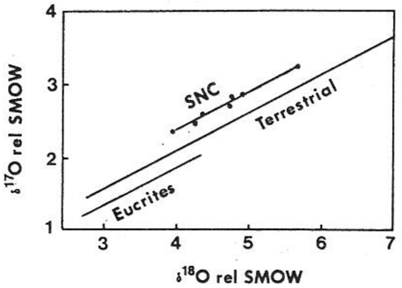

Fig. 10. Oxygen isotopic compositions for SNC meteorites define a mass fractionation line displaced from those of terrestrial (and lunar) rocks and the eucrite association. After *Clayton and Mayeda* [1983].

Stable Isotopes

Oxygen isotopic compositions of SNC meteorites [*Clayton and Mayeda*, 1983] define a mass fractionation line displaced from both the terrestrial-lunar line and that for other achondrites (the eucrite association), as shown in Figure 10. This distinctive isotopic composition also serves as a chemical fingerprint for the SPB.

SNC meteorites appear to have been contaminated with terrestrial carbon, but measurements of C isotopes at high extraction temperatures probably record indigenous components. *Carr et al.* [1985] reported $\delta^{13}C$ values of about −30‰ for the high-temperature fraction, very different from terrestrial mantle carbon at approximately −5‰. However, δD values are similar to those of terrestrial hydrogen [*Fallick et al.*, 1983; *Yang and Epstein*, 1985].

Implications

The chemical compositions of SNC meteorites are similar to those of equivalent terrestrial mafic and ultramafic rocks in many respects. However, some distinctive chemical and stable isotopic ratios serve to distinguish these meteorites from all terrestrial and extraterrestrial materials. Petrogenetic implications of these data will be discussed in a later section.

Shock Metamorphism

Shergottites and ALHA77005

Intense shock effects in the shergottites and ALHA77005 are indicated by phase transformations. Plagioclase in all these meteorites has been completely converted to maskelynite, a diaplectic glass. The absence of maskelynite crystal structure is indicated by optical isotropism and the failure to produce diffraction lines in long-exposure X ray powder photographs [*Binns*, 1967]. Ringwoodite and majorite, the high-pressure polymorphs of olivine and pyroxene, respectively, were tentatively identified within shocked veins in EETA79001 [*Steele and Smith*, 1982].

Shock effects in pyroxenes and olivines were described by *McSween and Stöffler* [1980], *McSween and Jarosewich* [1983], *Mori and Takeda* [1984], and *Ostertag et al.* [1984, 1985]. Both phases are commonly fractured and exhibit mosaicism and patchy extinction. Planar fractures and multiple sets of polysynthetic mechanical twins occur in pyroxenes. Olivines display planar fractures, planar elements, and lamellar deformation bands, as well as minor granulation at grain boundaries. High densities of dislocations within olivines occur in association with microcracks. Olivines in ALHA77005 also exhibit a pronounced brown color due to the presence of Fe^{3+}. The coloration was clearly preterrestrial in origin, because brown olivines are bleached where they were in contact with hot impact melt. This unusual feature possibly resulted from shock-induced oxidation on the SPB [*Ostertag et al.*, 1984], as observed in olivine experimentally shocked in oxidizing atmospheres, or from thermal metamorphism under dry, oxidizing conditions [*Smith and Steele*, 1984].

Localized melting of maskelynite in Shergotty is suggested by flow structures and vesicles in a few grains. Incipient melting of pyroxenes adjacent to incompressible opaque phases has also been observed. More advanced melting in EETA79001 and ALHA77005 [*McSween and Stöffler*, 1980; *Rietmeijer*, 1983; *McSween and Jarosewich*, 1983] is indicated by thin veins and rounded pockets of impact-melted glass (Figures 3 and 4). These highly vesicular glasses contain relict crystals and in some cases secondary skeletal olivine and pyroxene crystallites. The compositions of glasses are generally similar to bulk rock compositions except that the former are enriched in the plagioclase component. Maskelynite was apparently preferentially melted, as also indicated by insets of relict olivine, pyroxene, and spinel, but not maskelynite, in the glasses. In EETA79001, distinct impact melts formed from fusion of the two lithologies and were injected along veins across the boundary, where they comingled. Ambient atmospheric gases on the SPB were apparently implanted in these impact melts by shock [*Bogard and Johnson*, 1983; *Becker and Pepin*, 1984].

Shock Conditions for Shergottites

Estimates for peak shock pressures in these meteorites are based on the formation of maskelynite and in some cases partly melted plagioclase, mosaicism and granulation of olivine, and the production of bulk rock melts. Shergotty and Zagami experienced shock pressures of 30–35 GPa [*Steele and Smith*, 1982; *Ostertag et al.*, 1985]. Peak pressures of 35–45 GPa occurred outside of melt regions in ALHA77005 and EETA79001 [*McSween and Stöffler*, 1980; *McSween and Jarosewich*, 1983], but bulk rock melting may have required local pressures in excess of 80 GPa. Such high-stress concentrations may have been achieved by reverberation within the target, possibly near highly incompressible minerals. The shergottites and ALHA77005 were clearly shock metamorphosed during a large impact event, almost certainly on the SPB.

Heating experiments on Shergotty maskelynite [*Duke*, 1968] suggested that postshock thermal effects were minimal. Decrease in maskelynite refractive index, unobserved in these meteorites, occurs in annealing experiments above 400°C. The small degree of dislocation recovery in EETA79001 olivine [*Mori and Takeda*, 1984] is also consistent with fairly low temperatures. *Lambert* [1983] suggested that postshock temperature estimates were invalid because shergottites experienced more than one shock event, but the normal refractive indices of maskelynite in Shergotty argue against a second shock overprint [*Ostertag et al.*, 1985].

Nakhlites and Chassigny

Chassigny olivines exhibit planar shock features and irregular fractures, and pyroxenes show some minor shock damage [*Floran et al.*, 1978]. Small insets of impact-melted glass also occur in olivines. *Melosh and Treiman* [1983] estimated that peak shock pressures of 15–56 GPa were necessary to produce such olivine melts.

It is generally accepted that nakhlites are virtually un-

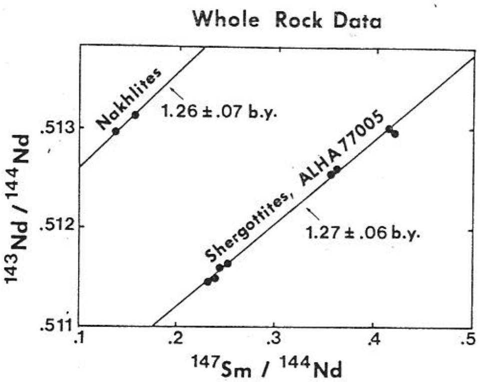

Fig. 11. Sm-Nd whole-rock isochrons for SNC meteorites, after *Wooden et al.* [1982] and *Nakamura et al.* [1982*a*]. The nakhlite isochron is further constrained by mineral separates (not shown). Differences in initial Nd isotopic ratios between nakhlites and shergottites suggest distinct source regions, but both meteorite groups give the same apparent age.

shocked. *Berkeley et al.* [1980] attributed lamellar twins in augites of the Governador Valadares meteorite to mild shock. However, the pervasive effects of shock metamorphism that characterize other SNC meteorites are clearly absent.

Chronology

A great deal of effort has been expended in radiometric age determinations for SNC meteorites. References and the results of these studies are summarized in Table 3.

Igneous Crystallization Ages

Crystallization ages for nakhlites are constrained to approximately 1.3 b.y. from concordant results using Rb-Sr, Sm-Nd, U-Pb, and ^{40}Ar-^{39}Ar isotopic methods. The Sm-Nd isochron and whole-rock data points for nakhlites are shown in Figure 11. Chassigny crystallized at approximately the same time, as indicated by concordant Rb-Sr, ^{40}Ar-^{39}Ar, and K-Ar data.

The crystallization ages for shergottites and ALHA77005 are extremely difficult to estimate because of the pronounced overprint of shock metamorphism. Internal Rb-Sr isochrons for all of these meteorites and a Sm-Nd internal isochron for Zagami apparently define a 180 m.y. event, which *Shih et al.* [1982] arttributed to complete resetting during shock. Argon 40–argon 39 plateau ages for maskelynite in all these meteorites fall in the range of 250–260 m.y., and whole-rock samples give complex Ar release patterns. *Bogard et al.* [1979] and *Shih et al.* [1982] interpreted the Ar data to reflect only partial resetting of this isotopic system during shock metamorphism. The Sm-Nd system does not appear to be as easily reset because of the decreased mobility of REE compared to volatile alkalis and noble gases. A whole-rock Sm-Nd age of 1.27 b.y. for all of the shergottites and ALHA77005 (Figure 11) may give the time of crystallization if the Sm-Nd ratios of precursor mantle materials were the same. This age was revised by *Nyquist et al.* [1984] from an earlier 1.34 b.y. estimate [*Shih et al.*, 1982] that did not include data from EETA79001. *Nyquist et al.* [1984] considered this to be a "best estimate" upper limit on the time of crystallization. Their best estimate lower limit, based on ^{40}Ar-^{39}Ar ages of mineral separates, ranged from 0.9–1.2 b.y. for different SNC meteorites.

Jagoutz and Wänke [1985] constructed an internal Sm-Nd isochron from pyroxene mineral separates (cores and rims) in Shergotty. Because zoning in pyroxenes has been preserved, they argued that the pyroxenes behaved as closed systems since the time of crystallization. The age obtained from the pyroxene isochron was approximately 350 m.y., which they interpreted as a crystallization age.

Jones [1985] suggested that the 180 m.y. event recorded by Rb-Sr internal isochrons represents the igneous crystallization age of shergottites. In this scenario the apparent Sm-Nd whole-rock isochrons are mixing lines with no chronologic significance, and shock metamorphism after 180 m.y. ago did not alter any isotopic systems. His argument rests partly on the assumption that shock should not have mobilized Sr, but data reported by *Jones et al.* [1985] show that Sr has a homogeneous distribution within maskelynite, even though most trace elements are zoned. *Jones* [1985] also noted that migrating shock melts in EETA79001 do not appear to have exchanged Sr isotopes with their host lithologies, and isotopic homogenization between two solid phases may be even more difficult.

It is not possible at the present time to eliminate any of the postulated crystallization ages. The 1.3 b.y. age remains an attractive possibility, because it agrees with the crystallization ages unambiguously determined for the nakhlites and Chassigny. However, there is no reason why the shergottites must have the same crystallization age as other SNC meteorites. Of the two younger suggested ages, the 350 m.y. age seems most plausible, because it is difficult to rationalize ^{40}Ar-^{39}Ar ages older than the igneous crystallization age. It also appears unlikely that the intense shock metamorphism observed in shergottites would not disturb some isotopic systems.

Parent Body Differentiation

Whole-rock Rb-Sr model ages ranging between 4.4 and 5.1 b.y. for shergottites and ALHA77005 have been interpreted to indicate early global differentiation of the SPB at approximately 4.6 b.y. ago [*Shih et al.*, 1982; *Wooden et al.*, 1982]. Rb-Sr data for nakhlites also fall along this model isochron (Figure 12). U-Pb data for several shergottites intercept the concordia curve at 4.5 b.y. and at 165 m.y. [*Chen and Wasserburg*, 1985]. The older intercept corroborates the time of differentiation inferred from Rb-Sr systematics, and the

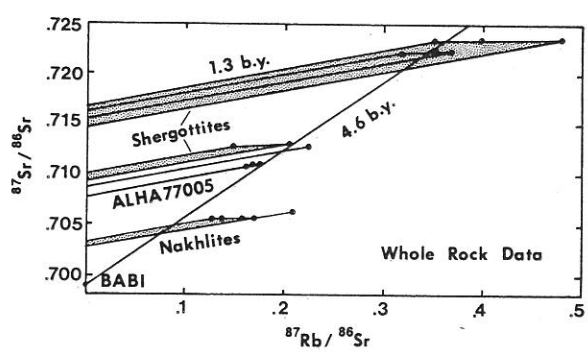

Fig. 12. Rb-Sr evolution diagram for SNC meteorites, after *Ashwal et al.* [1982]. Data points are extrapolated along reference isochrons corresponding to assumed crystallization ages of 1.3 b.y. to show distinct initial Sr isotopic ratios among these meteorites. The initial Sr isotopic ratio for Chassigny is similar to that for Nakhla [*Nakamura et al.*, 1982*b*], but whole-rock data for this meteorite have not been published. The spread in data points for individual meteorites is probably due to unrepresentative samples. A reference isochron of 4.6 b.y. with an initial Sr isotopic ratio of 0.69898 (BABI) passes through the ranges of whole-rock data points, suggesting that the SPB was differentiated at that time.

younger intercept indicates a time of lead loss, possibly due to shock.

Internal differentiation of the SPB did not end at 4.5–4.6 b.y. ago, however. The initial planetary differentiation apparently did not directly produce the source regions from which SNC meteorites were derived. These must have formed later. U-Pb data for Nakhla suggest that the age of its source region was not greater than 4.3 b.y. ago [*Nakamura et al.*, 1982*a*]. *Shih et al.* [1982] concluded that more than one stage of REE fractionation was required to produce the Sm-Nd patterns in shergottites. They could only constrain the time of formation for shergottite source regions to some time earlier than 1.3 b.y. ago.

Shock Ages

If the Rb-Sr system in shergottites was completely reset by shock, as advocated by *Shih et al.* [1982], then the 180 m.y. event recorded by this system represents an impact event that produced the pervasive shock metamorphism in these rocks. The younger intercept on the U-Pb concordia curve for some shergottites [*Chen and Wasserburg*, 1985] probably represents lead loss and is also consistent with a shock event.

Cosmic Ray Exposure Ages

Exposure ages calculated from cosmogenic nuclide (^{3}He, ^{21}Ne, ^{38}Ar) concentrations in SNC meteorites are summarized in Table 3. Determinations of the amounts of other cosmic-ray-produced nuclides are hampered by contamination and analytical uncertainty [*Bogard et al.*, 1984]. Exposure ages based on all three isotopes are similar (2.6 m.y.) for Shergotty, Zagami, and ALHA77005, but those for EETA79001 are lower (0.5 m.y.). The nakhlites and Chassigny have longer exposure ages of 11 m.y. Data analysis by *Bogard et al.* [1984] indicated that different amounts of shielding were unlikely to diminish the number of exposure groups.

Rajan et al. [1984] reported a minor proportion of phosphate grains in the EETA79001 shergottite that have substantially more fission tracks than can be accounted for by in situ decay of U over 1.3 b.y. These extra tracks may have been acquired through neutron-induced fission, possibly by exposure to cosmic rays in the SPB regolith prior to ejection.

Implications

The chronological data outlined above describe a parent body active over most of solar system history. It was differentiated approximately 4.6 b.y. ago, formed several distinct magma source regions at unspecified times between 4.3 and 1.3 b.y. ago, and experienced further igneous activity at 1.3 b.y. ago and possibly later.

Shock metamorphism may have affected the shergottites and ALHA77005 at 180 m.y. ago. Because cosmic ray exposure ages are significantly less than the inferred time of shock metamorphism, this major impact event may not have ejected the meteorites from their parent body. Moreover, the three distinct groups of cosmic ray exposure ages measured for SNC meteorites suggest that all of these were not contained in the same immediate parent object. Each group presumably experienced a different impact event, either in space or on the SPB, that initiated exposure.

PETROGENESIS

Petrogenetic models for SNC meteorites can provide important insights into parent body processes, but construction of such models is fraught with difficulty. Arbitrary assumptions must be made about initial compositions, element distribution coefficients, mechanisms and degree of melting and fractionation, and other factors. Petrogenetic models for terrestrial rocks are contentious enough, even with the added constraints of adequate sampling and field relations.

We will begin this discussion with the premise that SNC meteorites are not impact melts, in contrast to a position taken by *Singer and Melosh* [1982]. The absence of angular lithic clasts, the presence of cumulate textures, and the chemical and isotopic heterogeneity of SNC meteorites are inconsistent with the impact melt hypothesis [*Ashwal et al.*, 1982]. The following discussion presumes that SNC meteorites formed from magmas generated by melting of source rocks in the interior of the SPB.

Source Regions

The source region for the nakhlites and Chassigny was neither ancient (4.6 b.y. old) nor primitive (chondritic in composition). The isotopic evidence for several periods of differentiation to produce the nakhlite source region [*Nakamura et al.*, 1982*a*] has already been discussed. A 6.5 b.y. Sm-Nd model age for Nakhla is the direct result of a nonchondritic Sm/Nd ratio in its source region at the time of melting. This source region was depeleted in light REE, as well as other incompatible lithophile elements like K, Rb, and Ba, relative to chondritic abundances [*Nakamura et al.*, 1982*a*]. The Chassigny source region had similar characteristics [*Boynton et al.*, 1976; *Nakamura et al.*, 1982*b*].

Trace element models for the shergottites and ALHA77005 also require light REE-depleted sources [*Shih et al.*, 1982; *Wooden et al.*, 1982]. However, the Sm-Nd systematics of these meteorites necessitate time-averaged subchondritic Sm/Nd ratios (enrichment of light REE) since 4.6 b.y. ago, so the light REE-depleted shergottite source region must have formed comparatively late. Early planetary differentiation must have produced a light REE-enriched proto-source with high Rb/Sr, which was later remelted to form the immediate shergottite source region [*Shih et al.*, 1982].

The overall similarity in trace element abundances between SNC meteorites and terrestrial basalts or peridotites has already been mentioned as an indication that SPB source regions were chemically similar to the earth's upper mantle. *Stolper et al.* [1979] used crystallization sequences and calculated normative mineralogies to infer that the SPB and terrestrial source regions were also broadly similar in major element composition.

Differences in initial ^{87}Sr/^{86}Sr isotopic ratios (intercepts on the ordinate of Figure 12, based on assumed 1.3 b.y. crystallization ages) between various SNC meteorites have been cited as evidence that each of these meteorites (except Shergotty, Zagami, and nakhlites, Chassigny) was derived from a distinct source region [*Shih et al.*, 1982; *Wooden et al.*, 1982]. This argument may be countered by petrologic mixing models discussed below. However, the chemical differences between the shergottites and ALHA77005 versus the nakhlites and Chassigny appear to require at least two distinct source regions for these groups.

Melting and Fractional Crystallization

Partial melting of the nonchondritic source regions discussed above produced SNC primary liquids, but details of the melting process cannot be accurately specified because these magmas were fractionated prior to solidification. The amount of fractionation required to model measured trace element abundances varies inversely with the degree of partial melting assumed for the source. Thus published models are obviously not unique solutions. *Nakamura et al.* [1982*a*] estimated that at least 50% fractionation crystallization of the primary magma was necessary to produce the REE abundances in Nakhla, based on an assumed minimum degree of melting of 5%. Shergottite models have generally assumed higher degrees of partial melting (20%, *Shih et al.* [1982]; up to 40%, *Smith et al.* [1984]) but still require extensive fractionation. Because degrees of partial melting outside this range are probably unreasonable, these models emphasize the major role of fractional crystallization in the petrogenesis of these meteorites.

Such highly fractionated magmas probably carried entrained phenocrysts upward to their emplacement locations, perhaps accounting for the pervasive development of cumulate textures in these meteorites. This is supported by calculations of *Grimm and McSween* [1982], which suggested that the small pyroxene phenocrysts in shergottites would have been difficult to decouple from moving magmas. Fractional crystallization in SNC meteorites might best be viewed as the result of mechanical processes which created crystal mushes rather than mostly solid networks of touching crystals. The volume proportions of cumulus grains in shergottites are apparently too low to support free standing piles of crystals [*Stolper and McSween*, 1979], and textural evidence in nakhlites and ALHA77005 suggests solidification around suspended crystals in active flow regimes [*Berkeley et al.*, 1980; *Berkeley and Keil*, 1981].

Petrologic Mixing Processes

The observation of partial resorption or reaction of xenocrysts of olivine, orthopyroxene, and chromite with enclosing magma in EETA79001,A prompted suggestions that these crystals represent remnants of partially assimilated xenoliths of spinel harzburgite [*Steele and Smith*, 1982; *McSween and Jarosewich*, 1983; *Nyquist et al.*, 1984]. The protolith for these xenocrysts would have been mineralogically similar to ALHA77005. The resulting hybrid magma composition would lie on a mixing line between the compositions of the original magma and the assimilated solids. If the uncontaminated magma had the composition of EETA79001,B, the colinear relationships between these compositions (Figure 6) would be explained by this process. The calculated proportion of ALHA77005 that would have to be assimilated to produce this hybrid was estimated at 36 wt % based on major element chemistry [*McSween and Jarosewich*, 1983] and 44 wt % based on Sr isotopic compositions [*Nyquist et al.*, 1984]. However, the high proportion and refractory composition of harzburgite required to satisfy the assimilation model impose severe (probably insurmountable) thermal constraints [*McSween*, 1983]. Assimilation would require that the xenoliths were heated to very high temperatures prior to incorporation in the magma, and the magma itself would probably have to be heated many hundreds of degrees above its liquidus temperature. Based on the terrestrial experience, this model seems unlikely.

Mixing of different magmas may offer a more plausible explanation for the observed colinear compositions. In this case the xenocrysts in EETA79001,A would represent phenocrysts that formed in one of the original magmas. After mixing, the phenocrysts were no longer in equilibrium with the resulting hybrid magma and reacted with it.

Chemical colinearities with Shergotty and Zagami (Figure 6) are also consistent with such a mixing process. However, the situation is more complicated, because isotopic constraints rule out formation of all these meteorites by mixing of the same two end-members. The initial Sr isotopic compositions of Shergotty and Zagami (Figure 12) do not fall between those of the two postulated end-members (EETA79001,B and ALHA77005).

Proposed olivine xenocrysts in Nakhla [*Treiman*, 1985*b*] may also suggest some role for petrologic mixing during its magmatic evolution. However, not enough information exists to evaluate this possibility.

Relationships Between SNC Meteorites

It is always tempting to try to relate all meteorites of the same group through a common origin or common processes. The literature on SNC meteorites contains many such attempts. However, the data discussed above indicate that the petrogenesis of the SNC meteorite group was extremely complex. The shergottites and ALHA77005 appear to have formed from a different source region than the nakhlites and Chassigny, although there are some similarities. The parental magmas for each group, probably formed by varying degrees of partial melting, were subsequently modified by fractional crystallization and possibly magma mixing prior to final solidification. The complexity of SNC petrogenesis appears to preclude the definition of simple relationships between these meteorites.

EVIDENCE FOR MARTIAN ORIGIN

Arguments for the formation of SNC meteorites on Mars have been reviewed by *Wood and Ashwal* [1981] and *McSween* [1984]. Most of these lines of reasoning support the idea that the SPB is a large planet, but the identity of this body is unspecified. *Ashwal et al.* [1982] took the opposite tact, citing the evidence against an asteroidal origin. If the SPB is large, Mercury and Venus are less likely candidates than Mars, based on dynamical and compositional grounds [*Wood and Ashwal*, 1981].

The late crystallization ages for SNC meteorites are difficult to explain if the SPB is (or was) of asteroidal size. An apparent relationship between the duration of igneous activity and planetary size (Figure 13) suggests that late volcanism is confined exclusively to planets. The heat source for asteroidal melting was presumably the decay of short-lived radionuclides, but this mechanism could not remain effective long enough to explain SNC crystallization at 1.3 b.y. ago or later. However, igneous activity on large planets could persist because their insulating properties permit decay of long-lived radionuclides to be an effective heat source. The crystallization ages of SNC meteorites prompted the first suggestions that they might be planetary samples [*McSween et al.*, 1979*b*: *Nyquist et al.*, 1979; *Walker et al.*, 1979; *Wasson and Wetherill*, 1979]. Mars was thought to be the most plausible candidate, because of its relatively small size, proximity to earth, and active volcanism at that time.

The complexity of SNC petrogenesis, as deduced from isotopic and REE data, is also probably not consistent with an asteroidal parent body. Several periods of melting and differentiation, spanning most of geologic time, are required to produce the observed isotopic and trace element fractionations. Partly on this basis, *Ma et al.* [1981], *Shih et al.* [1982], *Nakamura et al.* [1982*a*], and *Smith et al.* [1984] proposed a planetary origin.

Ma et al. [1981] and *Wooden et al.* [1982] suggested that

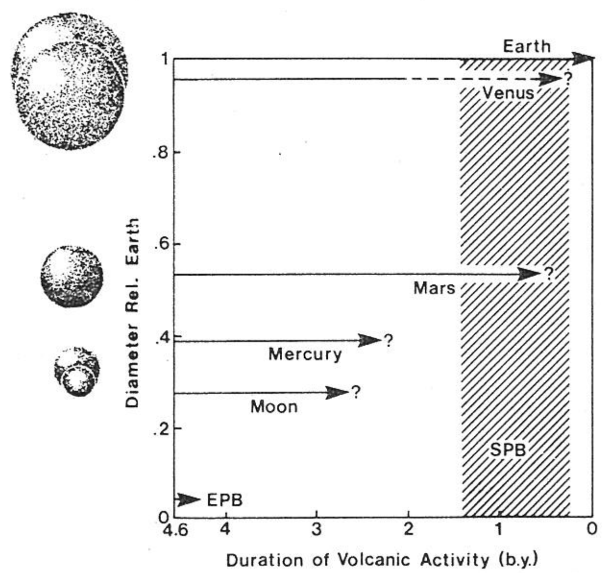

Fig. 13. Apparent relationship between the duration of volcanic activity and planetary size. Crystallization ages for SNC meteorites range from 1.3 b.y. to possibly as late as 180 m.y., overlapping only large planets like Mars. The duration of volcanism on these planets has been estimated from crater counts of volcanic plains.

small amounts of residual garnet in the shergottite source region might be required to produce the extreme REE fractionations; otherwise, unrealistically small degrees of partial melting ($\leq 0.1\%$) might have to be invoked. *Smith et al.* [1984] indicated that these patterns could be accounted for by fractional crystallization of phases other than garnet. Their conclusion depends critically on the choice of REE distribution coefficients, and experimentally determined coefficients [*McKay and Wagstaff*, 1985] apparently provide some reasons to question this model. From retention of Al relative to Ca in the nakhlite source region, *Treiman* [1985*b*] inferred that either garnet or spinel was present. Garnet and in some cases spinel are high-pressure phases in rocks of ultramafic composition, and neither is stable in bodies of asteroidal size. However, given the uncertainty in these REE fractionation models, the suggestion of high-pressure melting should be considered a weak constraint at best.

Burghele et al. [1983] also cited the low K/Rb and Rb/Cs ratios of SNC meteorites as evidence for a large planetary body. They reasoned that preferential loss of the more volatile alkalis in each pair would have occurred on a small body with a low gravity field. This idea is supported by the high values of these ratios for other achondrites presumably derived from asteroids and the low ratios for terrestrial basalts.

A more direct way of assessing the SPB gravitational field is through modeling its effect on cumulus crystals in magmas. Numerical models of crystal accumulation in shergottites were formulated by *Grimm and McSween* [1982]. These calculations suggested that the small pyroxene phenocrysts in these meteorites could have segregated from their parent magmas only under the influence of a large (planetary) gravity field.

The only evidence that ties SNC meteorites directly to Mars is the composition of gases in impact melt glasses of the EETA79001 and ALHA77005 meteorites. *Bogard and Johnson* [1983] discovered a trapped gas component in these glasses which they attributed to shock implantation of SPB atmosphere. The unusual relative abundances and isotopic compositions of Ar, Kr, Xe, and N in this trapped component are unique among meteorites but closely resemble the composition of the Martian atmosphere analyzed by Viking [*Bogard et al.*, 1984; *Becker and Pepin*, 1984; *Swindle et al.*, 1984]. Isotopic ratios are consistent with dilution of a Martian atmospheric component by adsorbed terrestrial atmosphere or by indigenous gases from the minerals of the rock, as illustrated in Figure 14. Although these data are the most compelling evidence for a Martian origin for SNC meteorites, this interpretation is not without its detractors [*Ott and Begemann*, 1985]. These authors note some perplexing inconsistencies for noble gas patterns in bulk rock samples of various SNC meteorites (rather than shock melts), but their data are also not explained by an asteroidal parent body.

In summary, the evidence for several complex differentiation events that culminated in late igneous activity, for magma genesis under possible high-pressure conditions, and for a large gravitational field all support the hypothesis that the SPB is a large planet. The unusual composition of trapped atmospheric gases in shock melts of several meteorites suggests that this planet is Mars. Other arguments for a Martian origin that have been cited previously (summarized by *McSween* [1984]) are only permissive and will not be included here. All this does not prove a Martian origin for SNC meteorites, but it makes a strong case. Proof will probably require a Martian sample return, because the geochemical and isotopic signature of the SPB requires higher analytical precision than spacecraft instrumentation can deliver. Analysis of oxygen isotopes in the Martian atmosphere likewise would require more advanced technology than is currently available.

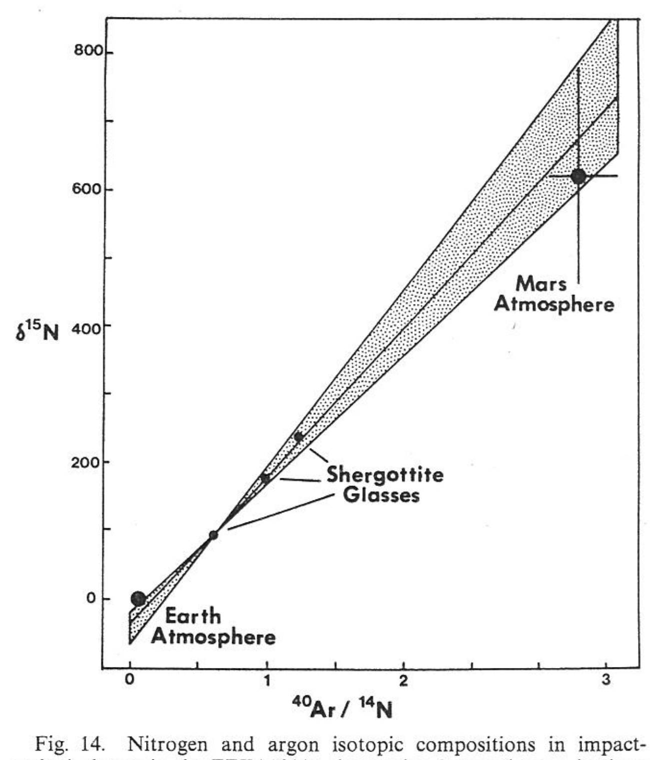

Fig. 14. Nitrogen and argon isotopic compositions in impact-melted glasses in the EETA79001 shergottite. Trapped gases in three glass samples lie on or near an apparent mixing line between the composition of the Martian atmosphere, as measured by Viking, and a composition near that of the earth's atmosphere. The latter point may represent volatiles from the Martian interior. These and other noble gas data [*Bogard et al.*, 1984] suggest an atmospheric component implanted during shock on the SPB. After *Becker and Pepin* [1984], with additional data from R. O. Pepin (personal communication, 1985). Nitrogen 15 is in per mil units.

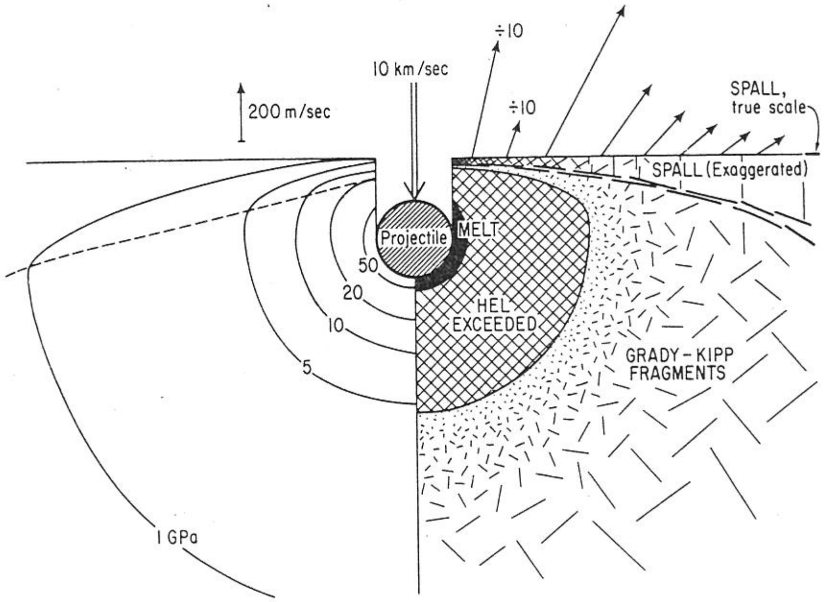

Fig. 15. A schematic diagram illustrating the fragmentation-ejection model for large impact craters on Mars. Pressure contours in gigapascals are shown in the left half of the figure. The dashed line represents the lower boundary of the near-surface region in which stress wave interference occurs. The right half of the figure illustrates the nature of the fragmentation expected. Fragments of decreasing size are produced at higher shock pressures, and the Hugoniot elastic limit (HEL) is exceeded at 4.5 GPa. The spall zone is illustrated with exaggerated thickness; its true scale is shown in the upper right. Spalls would be ejected as illustrated by the direction and magnitude of the surface vectors. After *Melosh* [1984]; reprinted by permission of Academic Press.

The Problem of Martian Sample Acquisition

Meteoroid impact is the only plausible means of ejecting fragments from the Martian surface, as the entropy of expanding volcanic gases is insufficient for this purpose [*Melosh*, 1985]. Prior to several years ago, a persuasive argument against the Martian origin of SNC meteorites was the apparent absence of lunar meteorites. If impacts onto the surface of the moon had not ejected rocks into earth-crossing orbits, how could they have escaped the gravitational grasp of an even larger body? This particular argument is no longer valid because of the recent discovery of lunar meteorites in Antarctica [e.g., *Marvin*, 1984]. However, the dynamical difficulties in accelerating rocks to Martian escape velocity (≥5 km/s) remain a formidable problem.

Sizes of Martian Ejecta

The sizes of ejected SNC rock fragments provide an important constraint on impact models. Unfortunately, this question has not been resolved. *Bogard et al.* [1979] suggested that such fragments were large on the basis of postshock Ar diffusion in shergottites. That estimate has now been at least partly refuted [*Bogard et al.*, 1984], as it depended critically on an assumed postshock temperature [*Nyquist*, 1982].

Cosmic ray exposure ages provide a means of determining how long fragments of less than a few meters in diameter were orbiting in space. Exposure ages for SNC meteorites occur in groups of 0.5, 2.6, and 11 m.y. (Table 3). *Bogard et al.* [1984] discussed three scenarios to explain these exposure histories. In the first, relatively large objects were ejected by a major shock event at 180 m.y. ago. Cosmic ray exposure was initiated by collisional breakups in space at much later times. In the second model, small fragments were ejected by three recent, independent events and immediately were exposed to cosmic rays. The third model calls for preirradiation of some samples on the Martian surface to generate most of the cosmogenic products, followed by ejection as small fragments in a single event 0.5 m.y. ago.

The first model suffers under the strain of having to account for large ejected fragments, and the second, from the necessity of having three events within the last 11 m.y. Measurements of ^{26}Al in SNC meteorites suggest that the third model, involving preirradiation, may not be viable [*Bogard et al.*, 1984]. A combination of the first two seems most reasonable. In this case, one event at 11 m.y. ago could eject a number of small to moderately sized fragments from various locations around the crater perimeter. The smaller ones immediately recorded cosmic ray exposure, but the larger ones were unaffected until subsequent breakup in space at 2.5 and 0.5 m.y. ago. In this model, ejected fragments would be in the size range of approximately 1–20 m, and the major impact that caused shock metamorphism in the shergottites would not have been the ejection event.

Possible Ejection Mechanisms

Calculated relationships between the mass and velocity of impacting and ejected material indicate that a significant quantity of Martian ejecta could be accelerated to escape velocity during large impacts [*O'Keefe and Ahrens*, 1977], but most of this material would be pulverized or even vaporized. Several novel hypervelocity impact mechanisms have been proposed to account for larger Martian ejecta. *Wasson and Wetherill* [1979] took advantage of the Martian subsurface permafrost layer as a possible means of propulsion. They speculated that the expanding gases derived from vaporization of these ices by a large impact might provide enough additional acceleration to propel rocks to escape velocity. Calculations of the magnitude of this effect [*Singer*, 1983] suggest that fairly large chunks (≥10-m diameter) might be aerodynamically accelerated to the required velocity.

Nyquist [1982] proposed that oblique impacts might produce fragments which were entrained with the ricocheting pro-

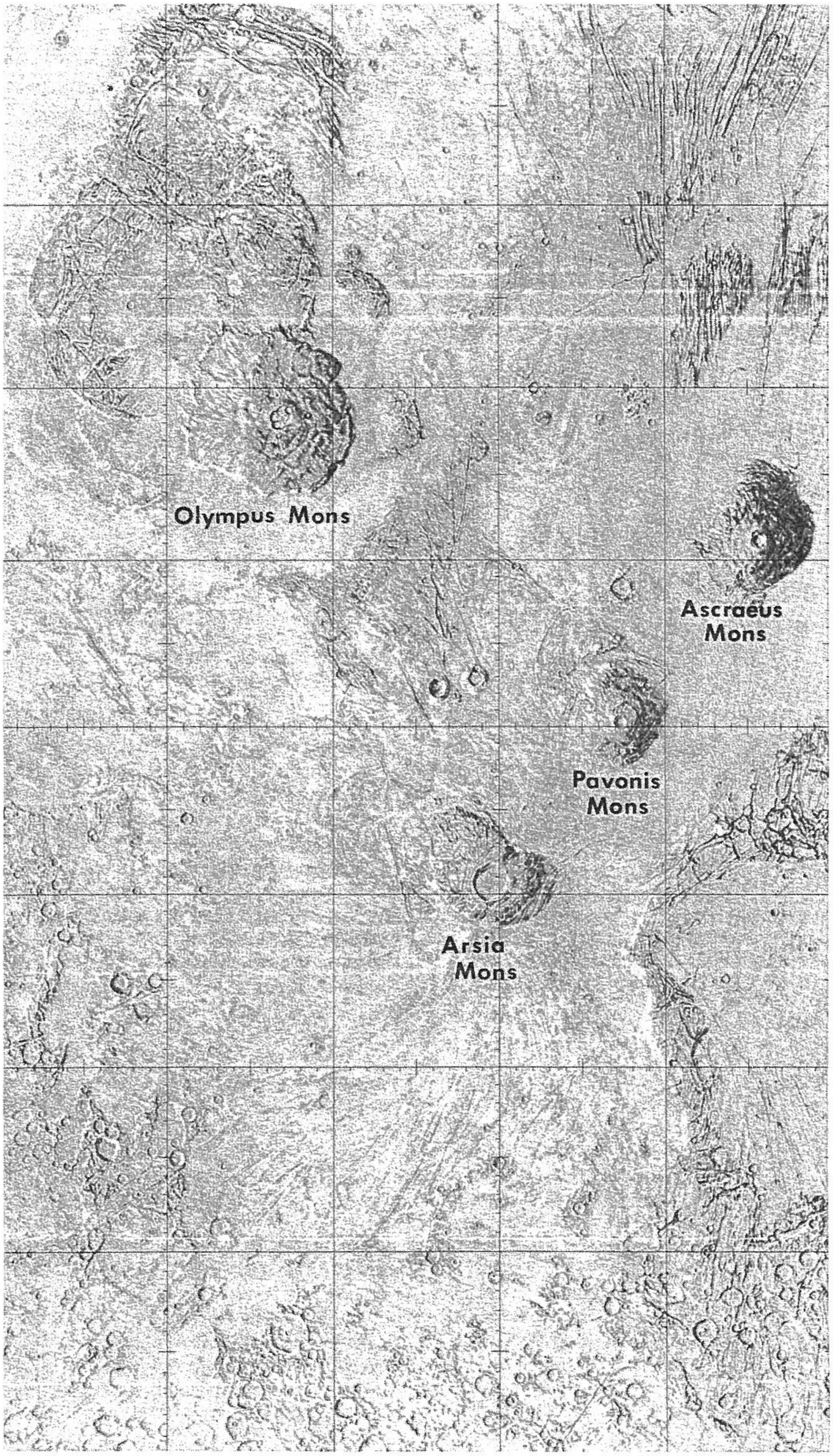

Fig. 16. Shaded relief and geologic sketch maps (the latter modified from *Schaber et al.* [1978] and *Wood and Ashwal* [1981]) of the Tharsis region of Mars. The ages of surface units were estimated from crater counts. This may be the only region with volcanic units young enough to be the source of SNC meteorites. The locations of superimposed large craters which could possibly represent impacts that ejected these meteorites from the planet are also illustrated for units younger than 1.6 b.y.

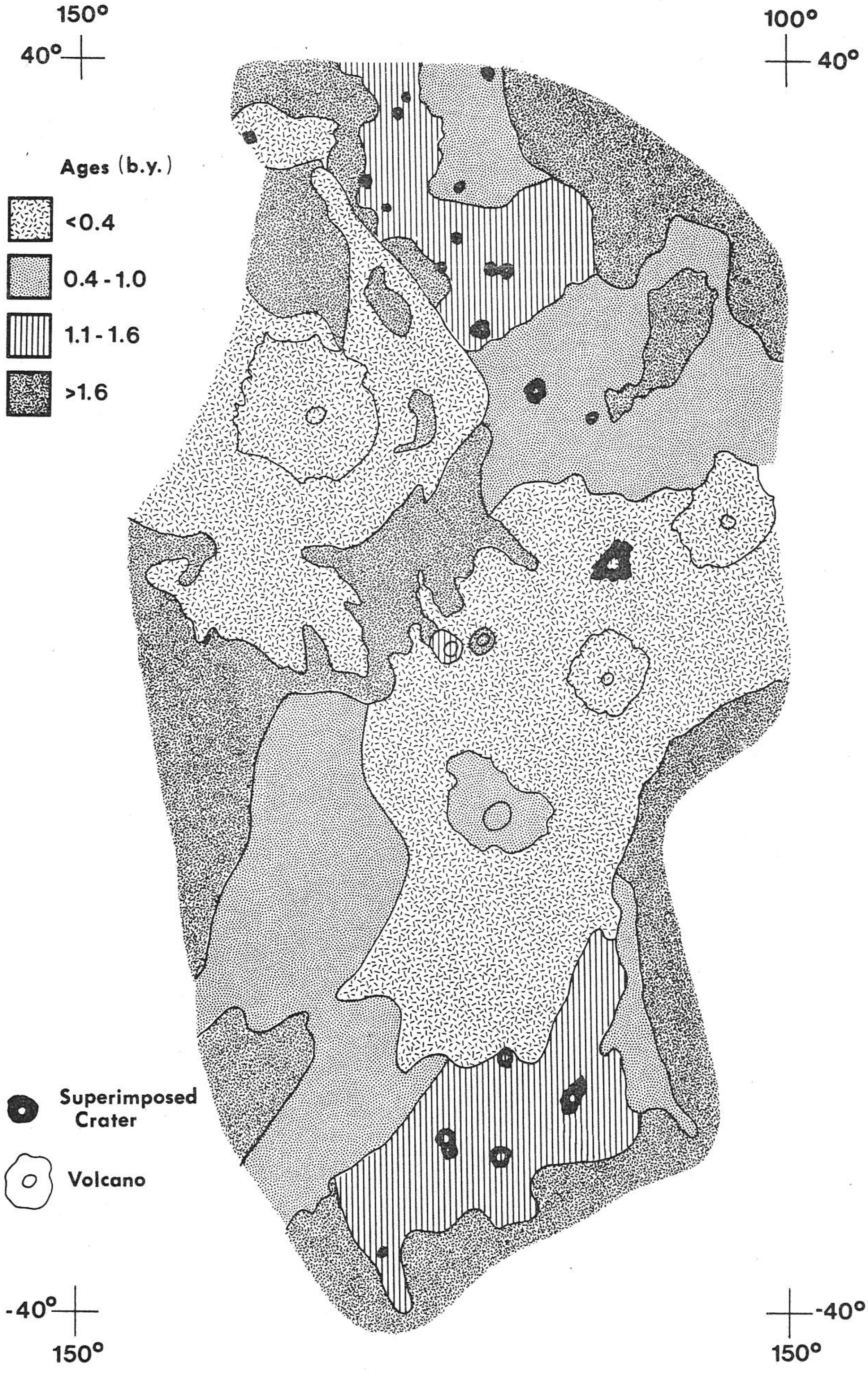

Fig. 16. (continued)

jectile. At high impact velocities the ricocheting object may be vaporized, and the entrained material would then be accelerated by fluid dynamic drag. On the basis of the results of experimental studies of oblique impacts, Nyquist argued that some ejecta could achieve escape velocity. Some large Martian craters have highly asymmetrical ejecta patterns that suggest they were produced by low-angle impacts.

The problem with any mechanism that releases fragments from a planetary body may be the physical state of the ejecta. In general, the material ejected earliest from a crater is the fastest moving, but it is also the most highly shocked and finely comminuted. This poses a dilemma for SNC meteorites, because all are of moderate size and the nakhlites are hardly shocked at all. However, detailed calculations suggest that some of the fast-moving ejecta escape shock effects [*Ahrens and O'Keefe*, 1978; *Melosh*, 1984]. Stress wave interferences can produce fragments of surficial rocks that show no detectable shock metamorphism [*Melosh*, 1985]. Figure 15 illustrates how these spalls form. Spalls ejected from a 30-km-diameter crater (corresponding to the largest crater in the young terrain of Mars) might possibly range up to a few tens of meters in size [*Melosh*, 1984]. In this model the near-surface spalls that have been spared intense shock are the only materials to escape the planet. Therefore shock metamorphism that affected the shergottites would presumably represent an event that preceded the impact that ejected the meteorites from the SPB. This is consistent with the absence of shock effects in some SNC meteorites and the short cosmic ray exposure ages in all of them.

Possible Martian Impact Sites

It probably seems presumptuous to think that sufficient information exists to identify plausible locations on Mars from which SNC meteorites may have been extracted; however, the distribution of volcanic units approximately 1.3 b.y. old or younger appears to be quite limited. *Schaber et al.* [1978] determined crater densities on volcanic plains in the Tharsis region. Those with 1730–2400 craters/10^6 km^2 were assigned ages of 1.15–1.60 b.y. Distributions of these volcanic units are shown in Figure 16. There is considerable uncertainty in the calibration of cratering count ages for Mars, but these crater densities appear to be of the right magnitude based on currently accepted chronologies. *Wood and Ashwal* [1981] compared this crater density interval with a photogeologic map of Martin volcanic units and suggested that no Martian terrain outside of Tharsis is young enough to have provided SNC meteorites. This is supported by age relationships compiled by the *Basaltic Volcanism Study Project* [1981*a*]. Distributions of young volcanic units in the Tharsis region are shown in Figure 16.

The locations of large craters within these units are also illustrated in Figure 16. *Melosh*'s [1984] ejection mechanism would require craters of these sizes to provide spalls of up to 1–20 m in size. *Nyquist* [1982] also noted the presence of at least two oblique impact structures in the Tharsis region. Both lie outside the mapped region of Figure 16, but each is situated on relatively young volcanic units. Regardless of whether any of these craters represent the exact formation locations of SNC meteorites, the realization that these may be samples of the Tharsis plateau could be useful in assessing the implications of these samples for Martian evolution.

Transit to Earth

Wetherill [1984] investigated the orbital evolution of material ejected from Mars into heliocentric orbits. Whether ejecta was initially small, or of moderate size and was subsequently fragmented in space, a large fraction (35%) of the Martian ejecta that would ever reach earth is calculated to do so within 10 m.y., in agreement with the observed short cosmic ray exposure ages.

The velocity at which Martian ejecta would enter the earth's atmosphere is only slightly above the earth's escape velocity [*Wetherill*, 1984]. Consequently, ablation mass loss should be of the order of only 50% [*Revelle*, 1979]. The immediate preatmospheric masses of SNC meteorites were thus not greatly different from their masses at recovery, which range from 158 g to 40 kg, fractions of a meter in size.

IMPLICATIONS FOR MARTIAN HISTORY

So much effort has been focused on trying to determine whether or not SNC meteorites are Martian samples that the implications these may have for the geologic evolution of Mars have been largely overlooked. One notable exception is a paper by *Wood and Ashwal* [1981], in which some ramifications were discussed. An appeal by *Ryder* [1982] for more such studies was perhaps made too early, as the Martian parent body hypothesis had not yet found wide acceptance. However, reluctance to accept this idea has been ameliorated somewhat by the evidence presented earlier. This section will explore some topics of global importance in more detail.

Constraints on Planetary Composition

Bulk compositions of Mars have been estimated from theoretical models of condensation or chondrite mixing and from empirical models based on geophysical and geochemical parameters. Six such compositions were tabulated by the *Basaltic Volcanism Study Project* [1981*b*], and an additional composition was reported by *Goettel* [1983]. The silicate fractions of these compositions are commonly taken to represent mantle plus crust compositions. The Martian crust is perhaps only 50 km thick [*Phillips et al.*, 1973], probably an insignificant component corresponding to only 3% of the total Martian silicate mass. Stable mineral assemblages in the model system CaO-MgO-Al_2O_3-SiO_2 at various pressures were used by *Stolper* [1980] to predict the mantle mineralogies expected for each of these compositions, as illustrated in Figure 17. Magma compositions derived from these mineral assemblages at various pressures can be predicted from experiments by *Presnall et al.* [1978].

Shergottites crystallized from fractionated magmas, but their parental liquids must have been tholeiitic in character [*Stolper et al.*, 1979]. This conclusion provides at least a qualitative test for Martian compositional models. Projected onto Figure 17 are the seven published Martian compositions alluded to previously (indicated by solid circles). At pressures below 5 kbar, none of these mantle compositions would produce tholeiitic liquids on partial melting. However, at pressures of about 5–15 kbar, all of these models except the model of *Ringwood* [1977] (the point that projects outside the triangle) appear to be capable of producing tholeittic parental melts. In the pressure range of 15–25 kbar, all models except the model of *Goettel* [1983] (the point nearest the composition of the earth's mantle) would produce alkali olivine basalts. Melts formed at pressures above about 25 kbar would likewise have alkalic affinities, with the exception of Goettel's model. The conclusion reached by *Stolper* [1980] was that Martian melts produced at higher and lower pressures than the stability field of spinel lherzolites (5–15 kbar) would generally be more aluminous and silica undersaturated than terrestrial magmas produced at the same pressures.

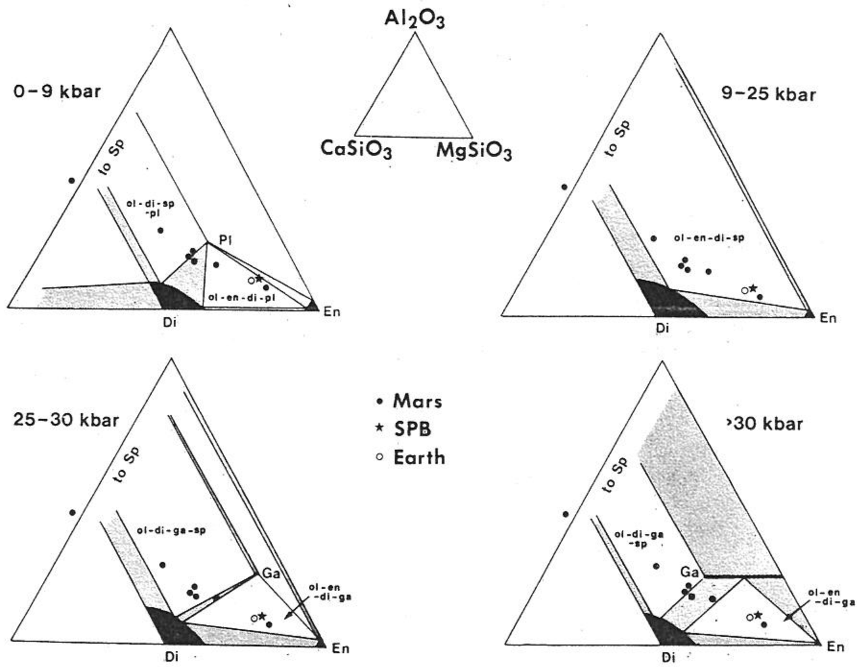

Fig. 17. Near-solidus phase diagrams showing stable minerals coexisting with olivine at pressures ranging from 1 atm to 50 kbar, after *Stolper* [1980]. Estimates of the mantle compositions of Mars [*Basaltic Volcanism Study Project*, 1981*b*; *Goettel*, 1983], earth [*Stolper*, 1980], and the SPB [*Dreibus and Wänke*, 1985] are projected from olivine into this diagram using procedures outlined by *Stolper* [1980].

The estimated composition of the SPB mantle plus crust (Table 4, *Burghele et al.* [1983], and *Dreibus and Wänke* [1985]) is more earthlike than any published Martian models except the model of *Goettel* [1983]. The SPB composition (indicated by a star) is compared with an average terrestrial mantle composition from *Stolper* [1980] (open circle) in Figure 17. Partial melts produced from this composition would be tholeiitic at less than 15 kbar, alkalic at 15–25 kbar, and probably picritic with tholeiitic affinity at greater than 25 kbar. Thus the SPB composition, unlike most Martian models, permits tholeiitic melts to form at high pressures within the stability field of garnet lherzolites.

We have already seen that the extreme REE fractionation patterns in SNC meteorites might be explained by garnet in

TABLE 4. Bulk Composition of the Shergottite Parent Body (SPB)

	Composition
Mantle and Crust	
MgO, %	30.2
Al_2O_3, %	3.02
SiO_2, %	44.4
CaO, %	2.45
TiO_2, %	0.14
FeO, %	17.9
Na_2O, %	0.50
P_2O_5, %	0.16
Cr_2O_3, %	0.76
MnO, %	0.46
K, ppm	315
Th, ppb	56
U, ppb	16
Core	
Fe, %	77.8
Ni, %	7.6
Co, %	0.36
S, %	14.24
Core mass, %	21.7

From *Dreibus and Wänke* [1985].

their source regions. Garnet is stable in ultramafic compositions only at pressures exceeding about 25 kbar. At 25–30 kbar, only the estimated SPB composition and the Martian compositions of *Goettel* [1983] and possibly *Morgan and Anders* [1979] contain garnet (Figure 17). At higher pressures, several other Martian compositions form garnet as the compositional field of this phase expands, but the low enstatite components in these models make the production of tholeiitic melts increasingly difficult. *Thurber and Toksoz* [1978] and *Solomon et al.* [1979] estimated that the thickness of the elastic lithosphere under Olympus Mons exceeded 150 km, from consideration of the topographic and fracturing effects of mass loading. The magma source region would presumably lie below the lithosphere. On the basis of the assumption that lavas erupted from the summit of Olympus Mons were supported by hydrostatic load, *Phillips and Ivins* [1979] estimated that the depth to the source region for these magmas was at least 210 km. The pressure at 210-km depth would be approximately 25 kbar. Thus there is independent evidence for high-pressure melting on Mars, at least in the Tharsis region.

These data suggest that the interior of Mars may be more earthlike than most published Martian compositions would permit. The composition of the SPB (Table 4) may be the most tightly constrained Martian composition. The phase equilibria on which this conclusion is based depend on the assumption that small degrees of partial melting did not exhaust any minerals from the source region residues. Similarities of trace element abundances in SNC meteorites and analogous terrestrial basalts and peridotites also indicate that the Martian and terrestrial mantles must have had similar initial compositions and have been affected by similar evolutionary processes.

Terrestrial and lunar samples analyzed for oxygen isotopes lie along the same mass fractionation line. *Taylor* [1982] suggested that this coincidence resulted from the fact that the earth and moon accreted enough nebular materials that any oxygen isotopic fluctuations were swamped by the volume of these components. The SNC meteorites define a mass fractionation line clearly distinct from, though close to, the terrestrial-lunar line [*Clayton and Mayeda*, 1983]. If these are Martian samples, Taylor's reasoning could not be correct. The distinct oxygen isotopic compositions of the earth-moon system and Mars would then indicate that each formed from isotopically dissimilar materials in a heterogeneous nebula.

Redox State of the Martian Interior

The high measured moment of inertia factor (0.365) and low estimated uncompressed density (3.72–3.78 g/cm^3) for Mars suggest a relatively oxidized planet containing an FeO-rich mantle, denser than that of the earth, and possibly an oxidized iron core, somewhat smaller than that of the earth [*Goettel*, 1981]. Simple condensation-based models for Mars [*Lewis*, 1972; *Goettel*, 1983] suggest that its oxidation state should be higher than that of the earth, but this conclusion is model dependent. Intrinsic oxidation state depends to some degree on core fractionation and volatile degassing (both considered below), which in turn may be controlled by planetary size and thermal history. Because some of these variables cannot be specified with any confidence, the redox state of the Martian interior is not really known.

There is presently some debate about how accurately the redox conditions of basalts reflect those of their source regions. Evidence compiled by the *Basaltic Volcanism Study Project* [1981*c*] suggested that basaltic mineral assemblages which are sensitive to oxygen fugacity (mostly Fe-Ti oxides) provide approximate measures of source region oxidation states, if crystallization was sufficiently rapid. Measurements of intrinsic oxygen fugacity in basalts [e.g., *Arculus and Delano*, 1980] give different results, consistently more reducing than the conditions indicated by Fe-Ti oxides in the same samples, but there is some uncertainty as to what is actually recorded in intrinsic fugacity experiments. Although it may not be possible to specify exactly the redox conditions of a planetary interior based on the characteristics of its magmatic products, there is little disagreement that gross differences in the redox states of basalts (of the magnitude of terrestrial versus lunar rocks) reflect distinct redox conditions in their source regions. The oxidizing conditions recorded in SNC meteorites are similar to those of terrestrial basalts. This is consistent with an oxidized Martian interior which would resemble that of the earth more than the moon or eucrite parent body.

Thermal History and Timing of Planetary Differentiation

Uncertainty in the amounts of radioactive heat sources in the Martian interior is one of the primary limitations in formulating planetary thermal models. Because radioactive elements have very different volatilities, large variations in their abundances are expected among planets. However, the large ionic radii of these elements cause them all to be partitioned similarly during igneous processes. Therefore the ratios of these elements may remain constant, even in cumulate rocks like SNC meteorites, although their absolute abundances may vary. The measured K/U ratios for SNC meteorites indicate that the earthlike K/U values sometimes assumed for Martian thermal models may be more correct than the more frequently specified chondritic ratio. *Nakamura et al.* [1982*a*] calculated absolute abundances of K, Th, and U in the nakhlite source regions, and *Burghele et al.* [1983] reported similar data for the SPB mantle plus crust (Table 4). These data sets are critically dependent upon either choice of partition coefficients or element correlations but are nevertheless in substantial agreement. The abundances of these heat-generating elements appear to be comparable to those of the earth's mantle and are distinctly nonchondritic.

The mechanical rigidity and positive buoyancy of the Martian crust may have prevented tectonic plate movements, but this need not have necessarily suppressed thermal convection at depth [*Basaltic Volcanism Study Project*, 1981*d*]. If convection occurred in Martian past history, it would of course have profound consequences for heat transport in the interior (explored by *Toksoz et al.* [1978]). Some isotopic data for shergottites may bear on this question. Assuming that the 180 m.y. event recorded by the Rb-Sr systems of all shergottites is a shock age, it seems likely that all of these meteorites were located in the same geographic (i.e., target) area on the SPB. Differences in the initial Sr isotopic ratios for different meteorites [*Shih et al.*, 1982] could therefore reflect heterogeneities in the mantle beneath this region. The occurrence of distinct, long-lived isotopic reservoirs would place some limits on mantle convection and recycling. However, the possibility that these isotopic differences might reflect crustal contamination has already been introduced, and this would eliminate the requirement for a stratified mantle.

Thermal models of Mars must allow differentiation to form its crust and core within a reasonable time frame. Crustal differentiation must have been completed by the end of heavy bombardment (prior to 3.5 b.y. ago), as suggested by old basinal features that appear to be isostatically uncompensated [*Basaltic Volcanism Study Project*, 1981*d*]. However, the timing of core formation is constrained only by rather uncertain thermal models that permit a range of ages from 4.5 b.y. [*Solomon*, 1979] to 0.9 b.y. [*Solomon and Chaiken*, 1976]. The absence of crustal compressional features restricts consideration to thermal models that do not predict significant global cooling in the last billion years or so of Martian history.

Isotopic systematics of SNC meteorites provide more definitive information on planetary differentiation. Rb-Sr model ages for all these meteorites are approximately 4.6 b.y., and the older intercepts of the U-Pb concordia curve for shergottites are 4.5–4.6 b.y. This must represent the time of planetary differentiation and presumably core formation. Such early differentiation should provide an important constraint for thermal models and has implications for planetary heat sources as well. It suggests that heating by accretion [*Hanks and Anderson*, 1969] and decay of short-lived radionuclides [*Toksoz and Hsui*, 1978] should be important factors in establishing base temperatures for thermal models; the possible contributions of electromagnetic induction and tidal dissipation [*Hostetler and Drake*, 1980] are not known. Early differentiation also wreaks havoc with accretionary models for Mars that require up to 1 b.y. for its formation [*Weidenschilling*, 1976].

The melting behavior of the Martian interior depends on a number of factors that can only be guessed at or ignored in thermal models, but SNC meteorites allow some insights into this complicated process. The earthlike mineralogy of the Martian mantle inferred earlier suggests that the predicted mantle solidus should be lowered by as much as 25°–50°C in the low (<9 kbar) and high (>25 kbar) pressure regimes (cf. Figure 5 of *Stolper* [1980]). Current thermal models also assume anhydrous melting, but the presence of magmatic amphiboles in SNC meteorites indicates that their source regions were not dry. Anhydrous melting behavior could be a valid assumption if water concentrations were too low to affect

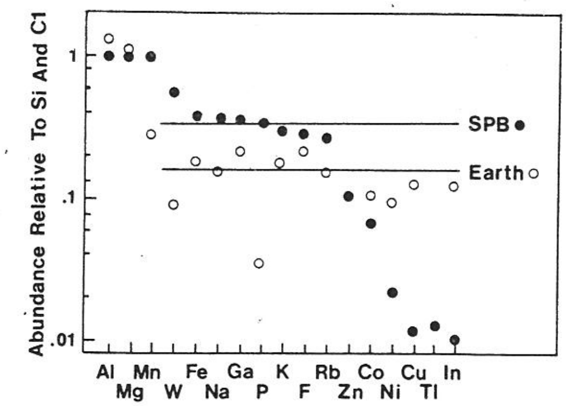

Fig. 18. Comparison of the estimated mantle plus crust compositions for the SPB and the earth, after *Dreibus and Wänke* [1985]. The horizontal lines represent the proportions of C1-like component used in constructing the models. The SPB mantle is more depleted in elements with high sulfide-silicate partition coefficients (Zn, Co, Ni, Cu, Tl, In) and less depleted in elements with high metal-silicate partition coefficients (W, Ga, P) than the earth's mantle, suggesting a SPB core dominated by sulfides.

phase equilibria, but even small amounts of water could have an effect at low degrees of partial melting. The high Fe/(Fe + Mg) ratios of SNC meteorites (0.52–0.76) relative to comparable terrestrial rocks may be due in part to derivation from source regions with abundant oxidized iron, which would also affect melting relationships. All of these factors suggest that the Martian mantle may possibly have the lowest solidus temperatures of any of the terrestrial planets.

The Martian Core and Magnetic Field

Condensation models predict that Mars should have a small core (1350- to 2200-km diameter), comprising perhaps 12–25% of the planet's mass [*Basaltic Volcanism Study Project*, 1981*b*]. A core of this size is consistent with the limited available geophysical information on internal structure [*Johnson and Toksoz*, 1977; *Arvidson et al.*, 1980; *Goettel*, 1981]. Most models predict that the Martian core should consist primarily of FeS-NiS [e.g., *Goettel*, 1977], but there is little direct information on which to speculate about the core composition. SNC meteorites provide such data. *Dreibus and Wänke* [1985] found substantial similarities between the calculated mantle plus crust compositions for the earth and the SPB; however, some significant differences occur in the abundances of many siderophile and chalcophile elements (Figure 18). The distributions of these elements in the terrestrial mantle were presumably dominated by metal-silicate partitioning during the formation of its core. *Wänke and Dreibus* [1984] explained the SPB abundances as resulting from extraction of elements from the Martian mantle during core formation approximately according to their sulfide-silicate partition coefficients (which are low for W, Ga, and P and high for Zn, Co, Ni, Cu, Tl, and In). This conclusion, corroborated by *Treiman et al.* [1985], is a strong argument for a Martian core dominated by sulfides. *Burghele et al.* [1983] estimated that the mass fraction of the SPB core was 21.7%. Its calculated composition is given in Table 4.

Thermal models disagree on whether the Martian core should be solid [*Young and Schubert*, 1974] or liquid [*Toksoz and Hsui*, 1978]. Because a dipole magnetic field is generally thought to result from a dynamo operating within a fluid core, the presence of such a field could aid in answering this question. Unfortunately, the magnetic field of Mars is the least understood of all the terrestrial planets. The only magnetometer carried aboard a U.S. spacecraft was on Mariner 4, and its flyby distance was too great for meaningful measurements. Magnetic data obtained by at least three Soviet orbiters were somewhat better but included no low-altitude measurements. The Soviet data have been interpreted to indicate a dipole moment 0.0003 times that for the earth, tilted 15°–20° with respect to the rotational axis and oriented in the opposite sense to that of the earth [*Dolginov et al.*, 1976]. However, the quality of these data appear to be insufficient to prove that Mars currently posseses a magnetic field [*Russell*, 1978]. This controversy was reviewed by *Slavin and Holzer* [1982].

Paleomagnetic intensities measured for several shergottites [*Cisowski*, 1981, 1982] indicate values of less than 5000 γ, provided the meteorites carry thermal remanence. *Nagata* [1981] also published a paleofield estimate of 1000 γ for the ALHA77005 meteorite. The magnetizing event was probably shock metamorphism. If these meteorites cooled through the Curie temperature in an ejecta blanket on the SPB, the paleomagnetic data acquired at low temperature suggest a small planetary field, possibly at 180 m.y. ago. If cooling occurred within an ejected meteoroid in space, the low-temperature data would simply reflect the interplanetary field, but the high-temperature magnetization (also less than 5000 γ) could still relate to the Martian field.

No paleomagnetic data have been obtained for nakhlites. These meteorites are unshocked, and thus they offer the possibility of ascertaining whether or not the SPB had a magnetic field 1.3 b.y. ago. This important experiment might identify a convecting core at that time.

Volatile Inventory and Degassing History

Original interpretations of the Soviet Mars 5 orbiting γ ray experiment suggested that the global surface K/U ratio is significantly less than that of the earth, consistent with the hypothesis that Mars is volatile poor [*Anders and Owen*, 1977]. The hypothesis of a volatile-poor Mars is unsettling, because it violates the monotonic trend in volatiles with solar distance and severs the coupling between volatile content and oxidation state. However, more recent interpretations of this admittedly imprecise data indicate that permissible K/U values have error brackets which at least overlap terrestrial values [*Levskiy*, 1984].

The ratios of volatile K, Rb, Cs, and Tl to refractory U measured in SNC meteorites are high, generally equal to terrestrial values (Figure 19). Because it is difficult to separate these incompatible lithophile elements during igneous events, their ratios argue against a volatile-depleted Mars. Estimates of the absolute abundances of volatile halogens (Cl, B, I) in the SPB by *Dreibus and Wänke* [1985] exceed those of the earth by factors of 2 to 4, also consistent with this conclusion.

Viking analyses of the Martian atmosphere [*Owen et al.*, 1977] indicated that the relative abundance patterns of noble gases are similar to those of the earth's atmosphere and provide further evidence for the existence of a "planetary" component. However, the Martian noble gas absolute abundances are nearly 2 orders of magnitude lower. If Mars is not a volatile-depleted planet, possible explanations for the lower atmospheric abundances include: (1) noble gases (but not other volatiles) that were accreted into planets varied in abundances with solar distance, (2) most of the original Martian atmosphere has been catastrophically removed, and (3) Mars never experienced outgassing to the degree that the earth has. A systematic trend of decreasing atmospheric ^{36}Ar per gram

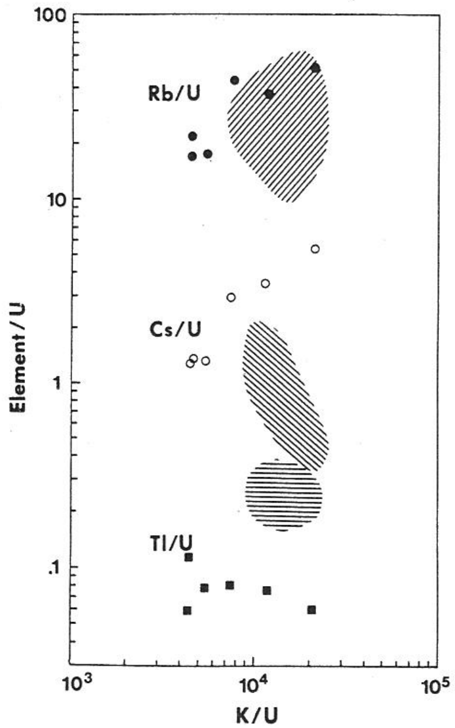

Fig. 19. Weight ratios of Rb/U, Cs/U, and Tl/U versus K/U for SNC meteorites (symbols; data from *Laul et al.* [1972], *Burghele et al.* [1983], and *Smith et al.* [1984]) and terrestrial igneous rocks (cross-hatched fields, from *McSween et al.* [1979*b*]). Because these elements are difficult to fractionate from each other during igneous process, similarities between SNC meteorites and terrestrial rocks in the ratios of each volatile element to refractory U suggest similar volatile element abundances in their respective source regions.

planetary mass of Venus, earth, and Mars might suggest fractionation of noble gases from other volatiles and thus support explanation 1 [*Arvidson et al.*, 1980]. However, the enrichment in Martian atmospheric $^{15}N/^{14}N$ over terrestrial values, the total CO_2 and N_2 to rare gas abundances, and the observational evidence for transient liquid water on the surface are all consistent with an earlier Martian atmosphere more massive than the present one [*McElroy et al.*, 1976; *Owen and Biemann*, 1976]. Widespread volcanism certainly suggests that ample opportunity existed for degassing, but it is not clear that atmospheric loss alone could sufficiently account for the depletion in heavy noble gases.

The trapped atmospheric component in quenched shergottite impact melts provides an independent (and in some cases more precise) measure of some atmospheric components. Viking analyses found that $^{15}N/^{14}N$, $^{40}Ar/^{36}Ar$, and $^{129}Xe/^{132}Xe$ ratios were distinctly different from terrestrial values but were unable to make accurate abundance measurements for Xe and Kr or even give precise values for ratios of their isotopes [*Owen et al.*, 1977]. Shergottite data [*Becker and Pepin*, 1984; *Bogard et al.*, 1984; *Swindle et al.*, 1984] not only confirmed the high N, Ar, and Xe isotopic ratios of Viking (this is of course a circular argument), but also provided more precise data on Xe and Kr isotopes. The trapped Xe does not differ substantially from terrestrial Xe, except for a large ^{129}Xe excess and a small depletion of lighter isotopes. *Swindle et al.* [1984] suggested that the depleted light Xe isotopes were part of a single trapped component (called "xenon M" for Mars), the composition of which may provide information on Martian atmospheric history. This component may have formed by fractionation of several other Xe components known from chondrites, possibly with addition of fission Xe. Krypton shows a small enrichment of lighter isotopes compared with terrestrial Kr, possibly a neutron capture component in the Martian atmosphere. Ne may possibly contain a high $^{20}Ne/^{22}Ne$ component, although there is significant terrestrial contamination of this element. Helium measurements are not significant, because all ^3He can be accounted for by cosmic ray interactions, and the ^4He abundance is consistent with in situ decay of U and Th.

Ott and Begemann [1985] also measured noble gases in bulk samples of Shergotty, Nakhla, and Chassigny. The proportion of impact melt glasses in these meteorites is negligible, so the gases they contain are presumably not implanted atmosphere. These authors noted that wherever variations in isotopic abundance ratios are found in terrestrial samples, rocks always contain higher proportions of radiogenic nuclides than does the atmosphere. However, their data for SNC meteorites suggest that this situation must be reversed. Preferential degassing of radiogenic Xe could explain this observation.

The Martian inventories of H_2O and CO_2 have been predicted from cosmochemical models and geologic constraints (reviewed by *Arvidson et al.* [1980]). SNC meteorites provide very little direct information on this problem. *Dreibus and Wänke* [1985] suggested a bulk concentration of 12 ppm water in the SPB. This amount of water would form a layer 51 m deep covering the Martian surface. However, this value is highly model dependent, as are others already published.

The Martian Regolith

The properties of Martian soil are best matched by an assortment of smectite clays with salts and magnetic iron oxides [*Toulmin et al.*, 1977]. These materials would presumably have formed from bedrock by ultraviolet-activated reactions [*Huguenin*, 1974] or by interactions of magmas with subsurface water [*Soderbloom and Wenner*, 1978]. *Gooding* [1978] questioned this mineralogic composition on thermodynamic grounds, suggesting that mafic minerals would be converted to oxides and carbonates, rather than clays, under prevailing Martian conditions. SNC meteorites contain no recognizable regolith components, and the alteration observed in Antarctic samples appears to be of terrestrial origin [*Smith and Steele*, 1984]. Although they cannot address this question directly, understanding whether these weathering products formed under open- or closed-system conditions would provide a possible constraint for proposed alteration mechanisms, as well as assess whether or not fractionation of weathered products occurred in response to winds or other agents. The almost identical results in measured soil compositions from two Lander sites 6000 km apart suggests that fractionation has not been important, but similar results would also have been obtained if surface fines had been thoroughly homogenized during aeolian transport.

SNC meteorites provide a possible comparison for soil compositions, from which the degree of closed-system weathering can be ascertained. *McSween and Stolper* [1980], *Baird and Clark* [1981], and *Clark* [1983] found that Martian soil is strikingly similar in composition to shergottites. Furthermore, these meteorites contain titanomagnetite of approximately the right composition and modal abundance to match the magnetic oxide component of Martian soil [*Hargraves et al.*, 1977]. The only significant compositional difference is in the content of highly volatile elements (S, Cl, Br) in soils, which may have been added from volcanic exhalations. This apparent closed-system behavior suggests weathering processes with low ion mobility, i.e., those not invoking high fluid/rock ratios.

The mineralogy of SNC meteorites could also be important in interpreting spectral reflectance data from the dark, presumably unweathered, areas of the Martian surface. Earth-based infrared spectra of these regions have been interpreted to indicate the presence of olivine, pyroxenes, and plagioclase [*Huguenin and Jones*, 1985]. A knowledge of the modal proportions and mineral chemistry of SNC meteorites might be useful in constructing such spectral models.

Conclusions

SNC meteorites are apparently mafic and ultramafic cumulate rocks that probably crystallized at shallow levels in the SPB crust. Their mineralogies indicate fairly rapid cooling and crystallization from tholeiitic magmas that contained water and were highly oxidized. Lack of multiple-phase saturation in these highly fractionated rocks indicates that they do not represent liquid compositions. Solidification histories suggest early crystallization of pyroxenes and/or olivine and chromite, joined later by plagioclase and accessory minerals. Cumulate textures possibly formed by gravity settling in both moving and stagnant magmas. Trace element abundances of SNC meteorites have many similarities with equivalent terrestrial basalts and peridotites, but their Fe/(Fe + Mg) ratios and oxygen isotopic compositions are distinctive. Igneous crystallization ages are 1.3 b.y. or younger. However, radioactive isotope systematics suggest an extended geologic evolution for the SPB, involving initial differentiation at 4.5–4.6 b.y. followed by at least two periods of melting. Source regions for SNC parental magmas were distinctly nonchondritic in composition and formed between 4.3 and 1.3 b.y. ago. These parental magmas experienced complex fractional crystallization and petrologic mixing processes prior to final crystallization, precluding the definition of simple relationships between the resulting rocks. Many meteorites experienced intense shock metamorphism that culminated in high-pressure phase transformations and localized melting in some cases.

The characteristics of SNC meteorites are not compatible with impact melts; thus their young crystallization ages suggest derivation from a large planet, because of the absence of suitable internal heat sources on asteroids so late in solar system history. The required lithologic complexity of the SPB also suggests a large body. Tenuous evidence for high-pressure melting and a large gravity field further support this conclusion. Mars is the most probable planetary parent body, based on dynamical and compositional arguments. Inferred ages for Martian volcanic units are also consistent with this hypothesis and suggest that the Tharsis region is the most likely site for SNC meteorites. The elemental and isotopic abundances of atmospheric gases implanted in melts generated by shock metamorphism of shergottites match Viking measurements of the Martian atmosphere but are unlike any other known materials.

Although this circumstantial evidence is persuasive, the problem of extracting samples from Mars' gravitational field is formidable. Possible ejection mechanisms include acceleration by vaporization of permafrost or by oblique impacts. However, such ejecta should consist of small, heavily shocked fragments, except for possible spalls protected by stress wave interferences. A large impact event, possibly at 180 m.y. ago, that caused shock metamorphism in many SNC meteorites was unlikely to have liberated these meteorites from the SPB. Their short cosmic ray exposure ages indicate that they either were ejected much later or were parts of large fragments that broke up in space. The latter seems implausible because of the dynamical difficulties in accelerating large rocks to Martian escape velocity. Moreover, the exposure ages are similar to calculated transit times from Mars to earth, and atmospheric entry velocities were such that appreciable mass loss should not have occurred.

If SNC meteorites are actually Martian samples, they provide important information about the geologic evolution of that planet. Most published models of Martian bulk composition appear to be inconsistent with constraints imposed by shergottite phase equilibria. The Martian mantle must be more earthlike than previously believed, and it must have a redox state at least as oxidized as the earth. Information on the abundances of radioactive heat sources, the timing of planetary differentiation, and the melting behavior of mantle source regions also add fundamental constraints for planetary thermal models. Calculated abundances of siderophile and chalcophile elements in the SPB mantle argue for a core dominated by sulfides, and paleomagnetic measurements suggest the presence of a weak magnetic field at the time of shock metamorphism. Volatile element concentrations also indicate that Mars is not volatile depleted, as advocated by some models. The trapped atmospheric component in shergottites gives a precise measurement of certain noble gas isotopic abundances and fractionations, which may be useful in unraveling the planetary degassing history. These meteorites also provide a basis for comparison with spectral reflectance data and Viking soil analyses, which may help constrain surface mineralogy and proposed weathering mechanisms.

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