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Report

A survey of shergottite, nakhlite and chassigny meteorites whole-rock compositions

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Abstract–Literature data on major and trace elemental abundances and water contents of the shergottite, nakhlite, and chassigny (SNC) meteorites are compiled and evaluated. The individual members of the SNC group are relatively homogeneous, and representative average compositions for each meteorite can be computed from multiple data reported in the literature. Major element abundances are used to calculate normative compositions and densities. The data survey shows that our knowledge of whole rock abundances in SNC meteorites is very limited for many elements and that more basic analytical work is needed.

INTRODUCTION

The Mars Pathfinder mission and recent speculation about the existence of primitive life on Mars have intensified the interest in the shergottite, nakhlite and chassigny (SNC) meteorites, which are widely believed to originate from Mars. More than ten years have past since Treiman *et al.* (1986) summarized compositional data for SNC meteorites. Since then, four more SNC meteorites have been recognized and many more analytical data have become available in the literature. This data survey provides an overview of available bulk elemental data and mineralogical compositions for the SNC meteorites. These data are useful for modeling parent body mantle composition and structure, core-mantle differentiation, radioactive heat sources, and thermal evolution on the Shergotty parent body, (*i.e.*, Mars). Elsewhere, we have already used these data to model the bulk and mantle composition of Mars (Lodders and Fegley, 1997). This survey also shows that abundances of several key elements used in planetary modeling are poorly known. Future analytical work (*e.g.*, by inductively coupled plasma mass spectroscopy) is needed to obtain these data.

THE DATA SURVEY

The Shergottite, Nakhlite and Chassigny Sample

The 12 currently known members of the SNC meteorites are listed in Table 1 together with information about fall or find locations, recovery dates, and masses recovered. The major and minor abundant minerals that characterize each group are also indicated. The seven known shergottites are separated into two groups, basalts and lherzolites/harzburgites, depending on their principal mineralogy. Three of the nakhlites are characterized as clinopyroxenites and one member as an orthopyroxenite. The only chassignite currently known is characterized as a dunite. Detailed reviews about SNC meteorite mineralogy are given by McSween (1994) and Banin *et al.* (1992).

Bulk Elemental Abundances

The literature was searched for bulk analyses of SNC meteorites, and data from ~90 references were collected in a spreadsheet. All elements, except N and the noble gases, are considered. The references included in the database are listed in the appendix where it is also indicated which meteorite data are given in each reference.

The individual SNC meteorites are relatively homogeneous in composition, and mean concentrations ($\pm 1\sigma$ uncertainties) were computed for each element. Sometimes authors published the same data repeatedly, and these analyses were included only once in the computation of average values and standard deviations. For several elements, two bulk analyses are available for an individual meteorite. In these cases, the uncertainty reflects the range in values. In some cases (*e.g.*, Na, K, In, or halogens), analyses reported in the older literature are apparently discordant and these data were excluded from the calculation of the mean concentrations.

The bulk water abundances are derived from the published water analyses summarized in Table 2. Water abundances are listed as a function of release temperature during combustion or pyrolysis. Only the amount of water released at ≥300 °C, considered to be indigenous to the meteorite, was used to obtain the selected water values.

The computed average elemental abundances and water values for each SNC meteorite are listed in Table 3. Elephant Moraine 79001 has two distinctive lithologies and bulk data for each lithology

TABLE 1. Names, recovery locations, recovered masses, and principal mineralogy of the SNC meteorites.

Names	Locations	Major minerals	Minor minerals
Shergottites (basalts)			
EET 79001	Antarctica, 1979, 7.94 kg	pigeonite, augite	ilmenite, Ti-magnetite,
Shergotty*	India, 1865 August 25, 5 kg	maskelynite	whitlockite
QUE 94201	Antarctica, 1994, 12 g		
Zagami*	Nigeria, 1962 October 3, 23 kg		
Shergottites (lherzolites/harzburgites)			
ALH 77005	Antarctica, 1977, 480 g	cum. olivine,	opx, plagioclase,
LEW 88516	Antarctica, 1988, 13 g	chromite,	Ti-magnetite,
Y-793605	Antarctica, 1979, 18 g	pigeonite, augite,	ilmenite
Nakhlites (clinopyroxenites/wehrlites)			
Governador Valadares	Brazil, 1958, 160 g	cumulate augite, olivine	plagioclase, Ti-magnetite, ilmenite
Lafayette	USA, 1931, 600 g		
Nakhla*	Egypt, 1911 June 28, 40 kg		
Nakhlites (orthopyroxenites)			
ALH 84001	Antarctica, 1984, 1.93 kg	cumulate orthopyroxene	chromite, maskelynite, augite, olivine
Chassignites (dunites)			
Chassigny*	France, 1815 October 3, 4 kg	cumulate olivine	augite, plagioclase, chromite, ilmenite

* Observed fall.

TABLE 2. Water content in SNC meteorites (ppm by mass).

ppm released at T (°C)	<300	300	350	400 or >450	600	750 or 800	≥1000	total	≥300	references
EET 79001A	—	—	—	—	—	—	—	340	340	(2)
	—	—	—	—	—	—	—	380	380	(2)
	—	—	—	—	—	—	—	210	210	(2)
	260	—	240	—	90	—	50	640	380	(3)
	290	—	205	—	88	—	20	603	313	(5)
							selected value:		325 ± 70	
Shergotty	—	—	—	23.4	—	—	—	—	(23.4)	(1)
	—	—	—	—	—	—	—	200	200	(2)
	160	—	220	—	150	—	110	640	480	(3)
	—	—	—	—	—	167.4	72	—	239	(4)
	110	—	144	—	106	—	54	414	304	(5)
	325.8	—	70.2	—	41.4	—	~72	509.4	184	(6)
							selected value:		280 ± 120	
ALH 84001	284	—	293	—	221	—	32.4	832	547	(5)
							selected value:		547	
Zagami	140	—	150	—	70	—	60	420	280	(3)
	120	—	150	—	80	—	80	430	310	(3)
	—	—	187	—	99	—	92	380	380	(5)
							selected value:		320 ± 50	
Governador Valadares	344	419	—	—	329	—	1.8	1094	751	(5)
							selected value:		751	
Lafayette	1360	—	1310	—	910	—	290	3870	2510	(3)
	—	—	—	—	—	966.6	82.8	—	1049.4	(4)
	1793	752	—	581	468	—	293	3840	2047	(5)
	1813	601	—	517	488	—	306	3724	1912	(5)
							selected value:		1880 ± 610	
Nakhla	—	—	—	19.8	—	—	—	—	(19.8)	(1)
	—	—	—	—	—	—	—	70	(70)	(2)
	420	—	450	—	230	—	30	1140	720	(3)
	738	288	—	151	79.2	—	7.2	1264	526	(5)
	700	223	—	162	139	—	5.4	1229	529	(5)
	601	306	—	139	83	—	0	1129	527	(5)
	623	218	—	137	104	—	0	1082	459	(5)
	475	—	466	—	178	—	7.2	1127	652	(5)
							selected value:		570 ± 100	
Chassigny	—	—	—	—	—	—	—	—	(16.2)	(1)
	300	—	360	—	280	—	70	1020	720	(3)
	445	200	—	328	162	—	121	1255	810	(5)
	272	—	367	—	266	—	45	950	679	(5)
	94	—	148	—	88	—	16	346	(252)	(5)
							selected value:		740 ± 70	

— = No measurement.
Data in parenthesis are not used to compute average data. References: (1) Fallick *et al.* (1983); (2) Gooding *et al.* (1990); (3) Karlsson *et al.* (1992); (4) Kerridge (1988); (5) Leshin *et al.* (1996); (6) Yang and Epstein (1985). Other water data: McSween and Jarosewich (1983) report <1000 ppm for EET 79001 A and B; Haramura (1995) reports 2800 ppm bound water for ALH 77005.

are given. The arrangement in Table 3 is as follows: The heading lists the meteorite name and the classification as S (shergottite), N (nakhlite) or C (chassignite). Column 1 lists the element and concentration unit, and the subsequent columns give the average elemental abundances ($\pm 1\sigma$ uncertainties) and the numbers of individual analyses used to compute the mean. If only one analysis for an element is available, no standard deviation is listed. Complete lack of analytical data for an element is indicated by "—" in Table 3. Table 4 gives the major element abundances in oxide form, sulfur and water abundances, and totals.

The data in Table 3 are important for considering the question of how well we know elemental abundances in SNC meteorites. The data fall into six groups that clearly reflect which elements are difficult to analyze and which are not typically determined by routine analytical procedures, such as neutron activation analyses.

(A) Elements for which multiple analyses (>3) exist and 1σ deviations are <15% for most meteorites: Na, Mg, Al, Si, K, Ca, Sc, Ti, Cr, Mn, Fe, Co, Sm, Eu, Tb, Yb, Lu.

(B) Elements for which multiple analyses (>3) exist and 1σ deviations reach ≥15% in most meteorites: K, Ni, Zn, Ga, La, Ce, Hf, U.

(C) Elements for which 2–3 analyses per meteorite exist and the data spread <15% around the mean in most meteorites: Li, P, V, Br, Rb, Cs, Ba, Nd, Dy, Ho, Tl.

(D) Elements for which 2–3 analyses per meteorite exist and the data spread is ≥15% in most meteorites: C, S, Cu, Se, Sr, Tm, Ta, W, Ir, Au.

TABLE 3. Bulk elemental abundances in SNC meteorites.

	ALH 77005 S mean ± 1σ	#	EET 79001A S mean ± 1σ	#	EET 79001B S mean ± 1σ	#	LEW 88516 S mean ± 1σ	#	Shergotty S mean ± 1σ	#	QUE 94201 S mean ± 1σ	#	Y93605 S mean ± 1σ	#
Li ppm	1.5±0.2	2	4.5	1	2.2	1	—		4.5±0.9	7	—		—	
B ppm	—		—		—		—		—		—		—	
C ppm	140±90	2	36	1	100	2	74	1	530±130	2	—		—	
F ppm	22	1	39	1	31	1	27	1	46±6	2	40	1	—	
Na %	0.345±0.06	6	0.64±0.037	8	1.29±0.11	8	0.42±0.06	7	1.03±0.14	13	1.17±0.19	2	0.263	1
Mg %	17.0±0.8	5	9.71±0.45	6	3.96±0.66	7	15.05±0.54	4	5.58±0.11	9	3.77±0.04	2	15.8	1
Al %	1.52±0.15	5	3.13±0.32	7	5.95±0.72	7	1.75±0.23	4	3.64±0.27	9	5.81±0.58	3	1.23	1
Si %	19.8±0.4	4	23.3±0.7	4	23.1±0.2	4	21.5±0.2	2	24.0	1	22.4	1	21.2	1
P ppm	1750±150	4	2600±300	2	5580±170	2	1700	1	3230±230	3	—		—	
S ppm	510±200	2	2070±670	2	1930±20	2	950	1	1270±760	6	—		—	
Cl ppm	14	1	26	1	48	1	29	1	108	1	91	1	—	
K ppm	250±40	10	330±60	8	625±65	9	240±30	7	1440±110	17	375±80	2	204	1
Ca %	2.26±0.23	9	5.19±0.42	7	7.73±0.24	8	3.00±0.20	7	6.86±0.39	12	8.14±0.01	2	2.9	1
Sc ppm	21±1	4	36±2	7	47±4	7	25±1	7	52±7	11	48±2	2	25	1
Ti ppm	2340±440	4	4000±230	6	7100±530	6	2320±360	4	4900±430	9	11000±900	3	2100	1
V ppm	162±6	2	210±15	5	190±25	4	170±20	4	290±40	4	113±15	2	202	1
Cr ppm	6670±520	6	4240±250	8	1150±135	6	5880±430	7	1350±100	11	950±85	3	6900	1
Mn ppm	3470±80	6	3700±160	7	3300±200	7	3820±160	4	4010±130	12	3480±150	3	3700	1
Fe %	15.6±0.3	6	14.3±0.6	8	13.5±0.5	8	14.8±0.9	6	15.1±0.5	12	14.4±0.4	3	15.3	1
Co ppm	72±4	5	48±4	7	29±2	7	65±6	9	40±7	15	24±1	2	72	1
Ni ppm	290±85	8	180±70	5	28±11	5	280±30	8	79±12	10	< 20	1	28	1
Cu ppm	5.1±0.6	3	—		—		—		16±9	3	—		—	
Zn ppm	60±8	4	73±8	6	91±18	6	60±8	7	69±9	10	110	1	49	1
Ga ppm	7.3±1.2	4	13.2±0.7	4	21±6	4	9.2±0.9	4	16.0±1.3	9	27±1	2	6.8	1
Ge ppm	0.58	1	—		—		0.6	1	0.73±0.06	2	—		—	
As ppb	22	1	5	1	17±6	2	<930	2	25	1	770	1	—	
Se ppm	0.15	1	0.47±0.05	2	0.41±0.01	2	0.34±0.08	6	0.38±0.08	6	—		—	
Br ppm	0.077±0.011	2	0.141	1	0.025	1	0.05	1	0.88±0.2	5	0.35	1	—	
Rb ppm	0.70±0.08	6	1.04	1	1.78	2	1.1±0.3	12	6.4±0.6	12	—		—	
Sr ppm	14±3	6	57	1	54±19	2	17±3	4	48±8	11	70±15	2	—	
Y ppm	6.2	1	—		28	1	5.7	1	19	1	31	1	—	
Zr ppm	19.5	1	29.4	1	64.8	1	13±4	3	57±14	4	100±7	3	—	
Nb ppm	0.65±0.11	2	0.68	1	1.66	1	0.51	1	4.6	1	0.68	1	—	
Mo ppm	0.200	1	—		—		—		0.37	1	—		—	
Pd ppb	—		—		—		—		1.7	1	—		—	
Ag ppb	4.4	1	19	1	6.3	1	6.1±2.1	2	11.4±5.1	3	—		—	
Cd ppb	2.1	1	37	1	70	1	12.4±3.9	2	28±16	5	—		—	
In ppb	11	1	46	1	68	1	12.6 or 72.8		26±4	5	—		—	
Sn ppm	0.24	1	—		—		0.16	1	0.011	1	—		—	
Sb ppb	69	1	10	1	16	1	1.6±1	2	5.2±3.6	3	—		—	
Te ppb	0.5	1	5.9	1	7.4	1	25	1	3.3±0.9	3	—		—	
I ppb *	1720	1	<100		960	1	60	1	43±10	2	4600	1	—	
Cs ppb	53±26	3	73±3	3	130±1	2	55±14	8	440±50	8	—		—	
Ba ppm	4.2±1.5	6	<10		13±2	2	4.9	1	34±5	8	<15	1	—	
La ppm	0.34±0.03	6	0.40±0.045	5	0.85±0.16	9	0.33±0.06	7	2.16±0.32	10	0.40±0.06	2	0.29	1
Ce ppm	0.91±0.15	5	1.27±0.23	2	2.13±0.54	6	1.26±0.55	7	5.45±0.86	9	1.47±0.23	2	—	
Pr ppm	0.13	1	—		—		—		0.81±0.10	3	—		—	
Nd ppm	0.95±0.17	5	1.35±0.07	2	2.63±0.40	4	0.82	1	4.2±0.5	10	2.2±0.4	2	—	

	Zagami S mean ± 1σ	#	ALH 84001 S/N mean ± 1σ	#	G. Valadares N mean ± 1σ	#	Lafayette N mean ± 1σ	#	Nakhla N mean ± 1σ	#	Chassigny C mean ± 1σ	#
Li ppm	2.9±1.3	2	—		—		—		3.9	1	1.4±0.2	2
B ppm	—		—		—		—		4.6	1	6.3	1
C ppm	—		580	1	—		100	1	300±100	2	847	1
F ppm	41	1	—		—		—		57	1	15	1
Na %	0.91±0.05	5	0.10±0.022	5	0.61	1	0.30±0.04	2	0.34±0.05	7	0.092±0.012	6
Mg %	6.8±0.4	5	15.1±0.5	3	6.6	1	7.8	1	7.3±0.2	4	19.2±0.5	7
Al %	3.2±0.2	5	0.68±0.05	3	0.92	1	1.31±0.70	2	0.89±0.11	5	0.42±0.15	6
Si %	23.6±0.2	3	24.7±0.1	3	23.2	1	21.9	1	22.7±0.8	6	17.5±0.5	6
P ppm	2200±300	3	61	1	—		1960	1	500±45	3	275±35	2
S ppm	1900	1	110	1	—		410±20	2	260±80	6	260±130	7
Cl ppm	137	1	8.0±4.5	3	—		65	1	80	1	34	1
K ppm	1170±60	5	140±50	9	2400±1700	2	900±130	3	1070±190	7	300±110	7
Ca %	7.5±0.4	5	1.30±0.27	9	9.2±3.1	2	9.6±0.5	3	10.5±0.5	5	0.47±0.07	6
Sc ppm	55±0.3	2	13±1	5	—		58±13	4	51±4	7	5.3±0.4	3
Ti ppm	4720±230	6	1240±70	3	2100	1	2540±800	2	2020±250	6	480±90	4
V ppm	312	1	201±6	2	—		169	1	192	1	39±9	3
Cr ppm	2260±270	4	7760±670	5	1440	1	1280±70	2	1770±280	6	5240±1050	7
Mn ppm	3880±310	5	3560±100	4	5200	1	3880±30	2	3820±310	7	4120±840	7
Fe %	14.1±0.4	6	13.6±0.4	6	15.3	1	16.8±1.7	3	16.0±1.2	8	21.2±0.6	8
Co ppm	36±1	3	47±3	5	—		43±6	3	48±5	4	123±17	4
Ni ppm	48±21	3	5.8	1	80	1	96±15	2	90	1	500±70	4
Cu ppm	—		—		—		12	1	12±6	5	2.6	1
Zn ppm	60±4	3	92±9	5	—		78±11	3	54±11	3	72±4	2
Ga ppm	14	1	2.9±0.5	4	—		3	1	3±0.5	2	0.7	1
Ge ppm	0.78	1	1.08	1	—		2.5	1	3.0	1	0.011	1
As ppb	46	1	<30		—		<150		15	1	8	1
Se ppm	0.32±0.01	3	<0.16		—		0.07±0.03	2	0.08±0.02	2	0.037	1
Br ppm	0.83±0.06	2	—		—		0.37±0.3	2	4.5±0.2	2	0.088±0.031	2
Rb ppm	5.6±0.4	5	0.83	1	—		2.8±0.6	2	3.8±0.8	13	0.73±0.5	2
Sr ppm	45±2	3	4.5	1	—		75	1	59±10	11	7.2	1
Y ppm	—		1.6	1	—		4.4	1	3.3±1.1	3	0.64	1
Zr ppm	73±21	2	5.9	1	—		9.4	1	8.8±1.0	2	2.1±0.9	2
Nb ppm	5.5	1	0.42	1	—		1.46	1	1.57	1	0.34±0.03	2
Mo ppm	—		—		—		—		0.086	1	—	
Pd ppb	1.8	1	—		—		1.7	1	30±12	3	0.15	1
Ag ppb	27±12	3	—		—		58	1	40	1	2.6	1
Cd ppb	66±7	2	77	1	—		95±5	2	93±31	2	14	1
In ppb	24±3	3	—		—		20±1	2	20±7	2	3.9	1
Sn ppm	—		—		—		—		0.58	1	—	
Sb ppb	9±5	2	—		—		—		40±30	2	0.87	1
Te ppb	1.6±0.8	2	—		—		<5.2		<4.3		50	1
I ppb *	<5		—		—		103±24	2	180	1	<10	1
Cs ppb	360±25		43±4	2	—		320±50	2	390±90	4	37	1
Ba ppm	26±2	2	4.0	1	—		27	1	29±6	5	7.6±0.6	2
La ppm	1.51±0.60	3	0.19±0.06	8	—		1.86±0.14	2	2.06±0.33	4	0.53±0.12	3
Ce ppm	3.75	1	0.59±0.14	3	—		4.82±0.64	3	5.87±0.37	5	1.12	1
Pr ppm	—		0.06	1	—		0.80	1	0.67	1	0.13	1
Nd ppm	2.75±0.33	3	0.265	1	—		3.09±0.28	3	3.23±0.52	7	0.62±0.11	2

TABLE 3. *Continued.*

	ALH 77005 S mean ± 1σ	#	EET 79001A S mean ± 1σ	#	EET 79001B S mean ± 1σ	#	LEW 88516 S mean ± 1σ	#	Shergotty S mean ± 1σ	#	QUE 94201 S mean ± 1σ	#	Y93605 S mean ± 1σ	#	Zagami S mean ± 1σ	#	ALH 84001 S/N mean ± 1σ	#	G. Valadares N mean ± 1σ	#	Lafayette N mean ± 1σ	#	Nakhla N mean ± 1σ	#	Chassigny C mean ± 1σ	#
Sm ppm	0.49±0.07	7	0.74±0.05	5	1.66±0.23	7	0.44±0.04	7	1.47±0.14	12	2.3±0.4	2	0.45	1	1.11±0.25	5	0.12±0.03	8	—		0.84±0.02	2	0.77±0.08	6	0.14±0.03	3
Eu ppm	0.22±0.02	6	0.37±0.02	8	0.78±0.12	7	0.22±0.02	7	0.60±0.11	11	1.04±0.07	2	0.21	1	0.475±0.035	3	0.035±0.008	3	—		0.22±0.03	3	0.235±0.030	5	0.045±0.007	3
Gd ppm	0.92	1	—		2.70±0.64	3	—		2.54±0.26	8	4.3	1	—		—		0.14	1	—		0.92	1	0.86±0.08	3	0.11	1
Tb ppm	0.17±0.01	4	0.28±0.04	8	0.62±0.12	8	0.16±0.01	7	0.48±0.05	7	0.87±0.09	2	0.17	1	0.280±0.085	2	0.038±0.005	8	—		0.12±0.02	3	0.12±0.01	3	0.03±0.02	2
Dy ppm	1.08±0.08	4	1.9±0.3	2	3.76±0.79	3	1.08±0.04	2	3.50±0.64	7	5.8±0.4	2	—		2.20±0.68	2	0.28±0.03	5	—		0.95±0.08	2	0.77±0.06	2	0.20±0.11	2
Ho ppm	0.25±0.03	3	0.50	2	0.89±0.16	3	0.23±0.03	4	0.71±0.10	7	1.19	1	—		—		0.076±0.007	5	—		0.17±0.04	2	0.155±0.020	2	0.044±0.020	2
Er ppm	0.66	1	—		—		—		1.88±0.02	2	—		—		1.6	1	0.21	1	—		0.4	1	0.37±0.05	2	0.09	1
Tm ppm	0.088±0.010	3	0.18±0.06	3	0.35±0.07	3	0.10±0.02	2	0.30±0.04	7	—		—		—		0.036	1	—		0.057	1	0.047	1	—	
Yb ppm	0.59±0.03	5	1.12±0.08	6	2.02±0.18	6	0.57±0.06	7	1.63±0.15	9	3.3±0.3	2	—		1.27±0.25	3	0.29±0.03	9	—		0.33±0.03	3	0.39±0.02	4	0.11±0.01	3
Lu ppm	0.078±0.004	6	0.17±0.02	8	0.31±0.05	8	0.083±0.008	7	0.26±0.03	10	0.50±0.06	2	0.08	1	0.195±0.07	3	0.049±0.006	10	—		0.052±0.003	3	0.055±0.007	5	0.015±0.004	2
Hf ppm	0.62±0.11	4	0.95±0.03	5	1.87±0.30	9	0.52±0.05	7	2.0±0.3	7	3.41±0.02	2	0.51	1	1.7±0.2	3	0.14±0.03	6	—		0.28	1	0.27±0.03	2	<0.1	2
Ta ppb	33±7	3	30	3	80±20	6	35±7	4	250±40	6	23	1	<40	1	200±20	3	32	1	—		80	1	90	1	<20	
W ppb	84	1	83	1	140±25	2	140±40	2	460±53	3	—		—		610±270	2	79	1	—		400	1	120±80	2	46	1
Re ppb	0.102	1	—		—		<0.09	1	0.044	1	—		—		0.035	1	0.002	1	—		0.03	1	0.036±0.005	3	0.063±0.012	2
Osppb	4.4	1	—		—		3.3	1	0.4	1	—		—		0.12	1	0.010	1	—		0.6	1	0.007±0.004	2	1.58±0.31	2
Ir ppb	3.9±0.3	3	—		<3	1	3.0±0.8	6	0.057±0.025	3	<3	1	3	1	0.03	1	0.08	1	—		0.09±0.06	2	0.22±0.10	2	2.1±0.4	2
Pt ppb	—		0.67	1	0.76	1	—		0.16	1	—		—		1.4±0.4	2	—		—		—		0.5	1	—	
Au ppb	0.21±0.02	4	2.6±1.5	3	0.96±0.2	2	0.53±0.15	4	0.92±0.08	4	<0.5	1	<0.8	1	2.0±0.2	4	0.009	1	—		—		0.72±0.20	3	0.73±0.3	2
Hg ppb	—		—		—		—		—		—		—		—		—		—		—		0.7	1	—	
Tl ppb	1.7	1	6.9	1	7.9	1	4.6±0.5	2	12.8±1.3	4	—		—		11.6±0.5	3	—		—		7.0±0.3	2	3.5±0.5	2	3.7	1
Pb ppb	—		—		—		—		—		—		—		—		72		—		—		—		—	
Bi ppb	<0.7		0.67	1	0.76	1	2.4±1.2	2	1.1±0.6	3	—		—		5.1	1	—		—		5.3±0.5	2	—		0.37	1
Th ppb	57±3	3	80	1	145±5	3	37±9	3	380±75	9	<50	1	<60	1	370	1	35	1	—		150	1	198±13	3	57	1
U ppb	15±3	3	19	1	37	1	14±7	5	105±20	12	<50	1	—		120±30	4	11±2	2	—		46±5	4	52±9	6	18±4	2
H_2O ppm	—		325±70	5	—		—		280±120	5	—		—		320±50	3	550	1	750	1	1880±610	4	570±100	6	740±70	3

= Number of bulk analyses considered.
*Iodine data for antarctic meteorites are high due to contamination (see Wänke and Dreibus, 1988).

TABLE 4. Major element composition (wt%) of SNC meteorites.

Type:	ALH 77005 S	EET 79001 A S	EET 79001 B S	LEW 88516 S	Shergotty S	QUE 94201 S	Y793605 S	Zagami S	ALH 84001 S/N	G. Valadares N	Lafayette N	Nakhla N	Chassigny C
MgO	28.2±1.3	16.1±0.8	6.57±1.09	25.0±0.9	9.3±0.2	6.25±0.07	26.2	11.3±0.7	25.0±0.8	10.9	12.9	12.1±0.4	31.8±0.8
Al_2O_3	2.87±0.28	5.91±0.60	11.2±1.4	3.31±0.43	6.88±0.51	11.0±1.1	2.32	6.05±0.38	1.29±0.10	1.74	2.47±1.32	1.68±0.21	0.72±0.30
SiO_2	42.4±0.9	49.9±0.9	49.4±0.4	46.0±0.4	51.3	47.9	45.4	50.5±0.4	52.8±0.1	49.5	46.9	48.6±1.7	37.4±1.1
CaO	3.16±0.32	7.26±0.32	10.8±0.33	4.20±0.28	9.60±0.55	11.4±0.2	4.06	10.5±0.6	1.82±0.38	12.9±4.3	13.4±0.7	14.7±0.7	0.66±0.10
TiO_2	0.39±0.07	0.70±0.12	1.18±0.09	0.39±0.06	0.82±0.07	1.84±0.15	0.35	0.79±0.04	0.21±0.01	0.35	0.42±0.13	0.34±0.04	0.08±0.02
Na_2O	0.47±0.07	0.86±0.05	1.74±0.14	0.56±0.08	1.39±0.19	1.58±0.26	0.36	1.23±0.06	0.14±0.03	0.82	0.40±0.05	0.46±0.07	0.12±0.02
K_2O	0.030±0.005	0.040±0.007	0.075±0.008	0.029±0.004	0.17±0.02	0.045±0.010	0.025	0.14±0.01	0.017±0.006	0.29±0.21	0.11±0.02	0.13±0.02	0.036±0.013
Cr_2O_3	0.98±0.08	0.62±0.04	0.17±0.02	0.86±0.06	0.20±0.02	0.14±0.01	1.01	0.33±0.04	1.14±0.10	0.21	0.19±0.01	0.26±0.04	0.77±0.15
MnO	0.45±0.01	0.48±0.02	0.43±0.03	0.49±0.02	0.52±0.02	0.45±0.02	0.48	0.50±0.04	0.46±0.01	0.67	0.50±0.01	0.49±0.04	0.53±0.11
FeO	20.1±0.4	18.4±0.8	17.4±0.7	19.0±1.2	19.4±0.7	18.5±0.5	19.7	18.1±0.5	17.5±0.5	19.7	21.6±2.2	20.6±1.5	27.3±0.8
P_2O_5	0.40±0.04	0.60±0.07	1.28±0.04	0.39	0.67±0.14	—	—	0.50±0.07	0.014	—	0.45	0.13±0.04	0.071±0.03
S	0.051±0.02	0.21±0.07	0.193±0.002	0.095	0.13±0.08	—	—	0.19	0.011	—	0.041±0.002	0.026±0.008	0.026±0.013
H_2O	—	0.0325±0.007	—	—	0.028±0.012	—	—	0.032±0.005	0.055	0.075	0.188±0.061	0.057±0.010	0.07±0.01
sum	99.5±1.7	101.1±1.5	100.4±2.0	100.3±1.6	100.4±1.1	99.1±1.3	99.9	100.2±1.2	100.5±1.0	97.2	99.6±2.7	99.6±2.4	99.6±1.6

(E) Elements for which only one available analysis (if any) per meteorite exists in most meteorites: B, F, Cl, Ge, As, Y, Zr, Nb, Mo, Pd, Ag, Cd, In, Sn, Sb, Te, I, Pr, Gd, Er, Re, Os, Pt, Hg, Pb, Bi, Th.

(F) Elements for which no data are available for any SNC meteorite: Be, Ru, Rh.

Since the SNC meteorites are differentiated rocks, the groupings may reflect sample heterogeneity. In an extensive study of Shergotty's bulk composition, Laul *et al.* (1986) found that major elements are homogeneously distributed but that large ion lithophile (LIL, such as K, Ba, Sr, REE, Zr, Hf, Ta, Th, U) elements are heterogeneously distributed within ~20% of the average. They found even larger heterogeneities for elements that are very mobile (*e.g.*, Cd, Te, Tl, Bi, Au, Ag). However, the case for sample heterogeneity as a cause for significant deviations from mean values can only be made for the elements in group (B), where at least three or more analyses have been done for each element in most meteorites. For example, nine meteorites have more than three individual analyses for K. The standard deviation is ≤15% for five meteorites, and four have deviations >25%. Similarly for La, another LIL element, three out of seven meteorites that have been analyzed more than three times have standard deviations <15%. More analyses are required to establish that sample heterogeneity, and not differences in analytical procedures among different laboratories, is causing the observed data spread.

The groupings (C)-(F) show that more basic analytical data are needed for the SNC meteorites. Several elements, such as siderophile and chalcophile P, Se, Cu, Mo, W, noble metals, but also U and Th, which are often used as key elements to model planetary differentiation, are poorly known. Either no abundance data for a given SNC meteorite exist at all or only one single determination, which is the basis for modeling, is available.

Mineralogical Composition

The normative (CIPW) composition (wt% and vol%), the molar composition of pyroxene, olivine, and plagioclase, and the calculated bulk density of each SNC meteorite are given in Table 5. The normative composition was calculated from the data in Table 4. Bulk densities were calculated using density data from Robie and Hemingway (1995) for the minerals in the CIPW norm. Where a comparison is possible with observed modal compositions (*e.g.*, Banin *et al.*, 1992), good agreement with calculated data is obtained.

SUMMARY

This data survey on bulk elemental abundances in SNC meteorites is intended to provide reference compositions and an overview on how well we know our Mars rocks. This survey indicates where more basic analytical work is needed. Given the fact that future sample return missions from Mars are five to ten years away, it is highly desirable to perform more basic analyses on available Martian samples.

As so often in meteoritics, we may know the elemental and isotopic composition of a minor phase in more detail than the whole rock in which it located. There is no doubt that the understanding of composition of individual minerals in the SNC meteorites can provide a wealth of information about the host rock petrogenesis, but the whole rock compositions are the principal data used to model planetary accretion and differentiation processes.

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APPENDIX

References for Tables 2 and 3

At the end of each reference, the meteorite(s) for which bulk data are given are indicated in parenthesis. A77 = ALH 77005, A84 = ALH 84001, Ch = Chassigny, E79 = EET 79001, GV = Govenador Valadares, L88 = LEW 88516, La = Lafayette, N = Nakhla, Q = QUE 94201, Sh = Shergotty, Y =Y793605, Z = Zagami.

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TABLE 5. Calculated normative mineralogy (CIPW-norm) and density of SNC meteorites.

		ALH 77005	EET 79001A	EET 79001B	LEW 88516	Shergotty	QUE 94201	Y93605	Zagami	ALH 84001	G. Valadares	Lafayette	Nakhla	Chassigny
wt%														
px		25.8	66.7	56.7	44.5	71.4	52.2	43.8	70.0	88.0	78.1	65.7	74.3	2.7
ol		60.8	10.9	0.0	41.5	0.0	6.8	46.1	5.0	6.2	9.1	23.0	17.0	92.9
plag		9.8	19.7	37.8	11.3	24.8	36.4	7.8	21.8	4.1	8.9	8.7	6.8	2.6
il		0.7	1.3	2.2	0.7	1.6	3.5	0.7	1.5	0.4	0.7	0.8	0.6	0.2
chr		1.4	0.9	0.2	1.3	0.3	0.2	1.5	0.5	1.7	0.3	0.3	0.4	1.1
ap		0.9	1.3	2.8	0.9	1.5	—	—	1.1	0.03	—	1.0	0.3	0.2
qz		0.0	0.0	0.4	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
vol%														
px		26.4	63.7	51.0	44.5	66.5	48.8	44.6	66.9	87.5	79.7	67.0	75.5	2.8
ol		58.8	9.7	0.0	39.2	0.0	5.6	44.0	4.3	5.9	8.1	20.4	15.0	92.7
plag		12.5	23.8	44.2	14.2	29.8	43.1	9.9	26.4	5.1	11.5	10.8	8.5	3.4
il		0.5	0.9	1.5	0.5	1.1	2.3	0.5	1.0	0.3	0.5	0.6	0.5	0.1
chr		1.0	0.6	0.2	0.8	0.2	0.1	1.0	0.3	1.1	0.2	0.2	0.3	0.8
ap		0.9	1.3	2.6	0.9	1.4	—	—	1.1	0.03	—	1.0	0.3	0.2
qz		0.0	0.0	0.5	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phase composition (mol%)														
px*	en	62	54	34	62	38	28	60	41	70	33	32	31	28
	fs	24	33	47	26	42	43	24	35	26	32	29	29	13
	ws	11	12	18	11	19	28	14	23	3	34	38	39	25
ol	fo	72	62	N/A	71	N/A	40	71	54	73	50	52	52	68
	fa	28	38	N/A	29	N/A	60	29	46	27	50	48	48	32
plag	an	56	60	59	55	47	61	58	47	69	2	53	30	49
	ab	42	39	40	43	49	38	40	49	29	80	40	59	43
	or	2	1	1	2	4	1	2	4	2	18	7	11	8
Whole rock density														
ρ gcm^{-3}		3.43	3.31	3.18	3.39	3.26	3.19	3.42	3.27	3.41	3.31	3.36	3.33	3.59

N/A = not applicable.
*Pyroxene also contains normative $MnSiO_3$ (difference of 1–[en + fs + ws]).

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