4.3.3 Meteorites

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4.3.3.1 Definition and nomenclature

A meteorite is an extraterrestrial solid object (observed masses are from < 1 g up to 60 metric tons) which survived passage through the Earth's atmosphere and reached the Earth's surface as a recoverable object. Meteorites recovered following observed falls are called falls, those that cannot be associated with observed falls are called finds [85Was]. Meteorites are generally named according to the location where they are recovered. Names of meteorites found in Antarctica are composed of the find location, the year of discovery, and a specimen number, those of meteorites found in deserts consist of the find location and a specimen number [98Lod]. Before a meteorite enters the Earth's atmosphere it is called a meteoroid. Meteoroids made incandescent by friction during atmospheric entry are called meteors [85Was].

4.3.3.2 Significance of meteorite study

In contrast to terrestrial rocks, most meteorites have preserved records of early solar system processes. The most primitive meteorites even contain presolar matter that formed in the interstellar medium (see section 4.3.3.6) and around evolved stars (see section 4.3.3.7). The laboratory study of meteorites provides information on the history and origin of the Solar System. The study of presolar matter provides detailed information on stellar nucleosynthesis and evolution, dust formation around evolved stars, chemical reactions in the interstellar medium, and the types of stars that contributed dust to the molecular cloud from which our Solar System formed 4.57 Gy ago. Meteorites also serve as interplanetary space probes to record cosmic-rays.

4.3.3.3 Classification

A number of variations on classification have been used. In a popular classification scheme meteorites are divided into chondrites and nonchondrites based on bulk composition and texture [03Kro] (Table 1). Nonchondrites include primitive achondrites and differentiated meteorites (achondrites, stony-irons, and irons). The differentiated meteorites have experienced strong post-accretionary thermal alteration and their elemental abundances are not representative of the bulk compositions of their parent bodies. The primitive achondrites experienced only partial melting and retained a primitive chemical affinity to their chondritic precursors [06Wei]. The chondrites have preserved the bulk elemental and isotopic compositions of their parent bodies [00Pal]. They are called chondrites because they contain chondrules, round objects with sizes of up to about 1 cm which consist mostly of olivine and low-Ca pyroxene (Px). Based on chemical and isotopic composition, degree of oxidation, abundance ratio of chondrules to matrix, and degree of chemical and textural equilibration, the chondrites are further subdivided into carbonaceous, ordinary, and enstatite chondrites and their subgroups as well as the rare Rumuruti- and Kakangari-like chondrites. The second letter in the name of the carbonaceous chondrite group represents the name of a prominent group member (e.g., the "I" in the CI group stands for the meteorite Ivuna). CI chondrites do not contain chondrules, but based on chemical and mineralogical arguments they are classified as chondrites. A second dimension, the petrologic type ranging from 1 to 6, is used to discern metamorphosed meteorites (type 3 to 6) from very weakly or non-metamorphosed but aqueously altered meteorites (type 1 to 3) [67Van, 88Sea].

Table 1. Meteorite classification and typical minerals (see Table 2) [98Lod, 03Kro].

Class/Group	Typical minerals	Fall abundance
Chondrites		
Carbonaceous chondrites:		3.9 %
CI	Hydrated phyllosilicates (serpentine)	
CM	Hydrated silicates, low- and high-Ca Px[1], olivine	
CV	Olivine, sulfides	
CO	Olivine, sulfides, hydrated silicates	
CK	Olivine, low- and high-Ca Px	
CR	Olivine, low- and high-Ca Px, metal	
CH (high iron)	Metal, low- and high-Ca Px, olivine	
CB	Metal	
Ordinary chondrites:		79.7 %
H (high iron)	Low-Ca Px, olivine, metal	
L (low iron)	Low-Ca Px, olivine, metal	
LL (low iron, low metal)	Low-Ca Px, olivine, metal	
Enstatite chondrites:		1.6 %
EH (high iron)	Low-Ca Px (enstatite), metal, sulfides	
EL (low iron)	Low-Ca Px (enstatite), metal, sulfides	
Others:		0.2 %
K (Kakangari-like)	Low-Ca Px, olivine, sulfide, metal	
R (Rumuruti-like)	Olivine, feldspar, low- and high-Ca Px	
Nonchondrites		
Primitive Achondrites:		0.3 %
Acapulcoites	Low- and high-Ca Px, olivine, plagioclase, sulfide, metal	
Lodranites	Low-Ca Px, olivine, metal	
Winonaites	Olivine, low-Ca Px	
Silicate incl. in IAB, IIICD	Low- and high-Ca Px, olivine, plagioclase, sulfide, metal	
Achondrites:		8.4 %
HED[2] (Vesta?)	Low- and high-Ca Px, plagioclase	
Martian[3] (SNC)	High-Ca Px, maskelynite, olivine	
Lunar	Plagioclase (anorthite)	
Angrites	High-Ca Px	
Aubrites	Low-Ca Px (enstatite)	
Brachinites	Olivine	
Ureilites	Olivine, high-Ca Px, graphite/diamond	
Stony-irons:		1.3 %
Mesosiderites	Low- and high-Ca Px, olivine, plagioclase, metal	
Pallasites	Metal, olivine	
Irons:		4.5 %
Many groups[4]	Metal	

[1]) Pyroxene.
[2]) HED: Howardites, Eucrites, Diogenites; probably from the asteroid Vesta [70McC, 93Bin].
[3]) SNC: Shergottites, Nakhlites, Chassignites, Orthopyroxenite.
[4]) IAB, IC, IIAB, IIC-E, IIIAB, IIICD, IIIE-F, IVA, IVB.

Table 2. Common meteoritic minerals. Modified from [85Was, 07Lip].

Mineral name	Chemical formula	Mineral name	Chemical formula
Alkali feldspars[1]		Olivine[1]	
Albite	$NaAlSi_3O_8$	Fayalite	Fe_2SiO_4
Orthoclase	$KAlSi_3O_8$	Forsterite	Mg_2SiO_4
Cohenite	$(Fe_xNi_{1-x})_3C$, $x \approx 0.9$	Plagioclase[1]	
High-Ca pyroxene[1]		Albite	$NaAlSi_3O_8$
(high-Ca Px)		Anorthite	$CaAl_2Si_2O_8$
Diopside	$CaMgSi_2O_6$	Schreibersite	$(Fe_xNi_{1-x})_3P$, $x \approx 0.7$
Hedenbergite	$CaFeSi_2O_6$	Serpentine	$(Mg, Fe)_6Si_4O_{10}(OH)_8$
Low-Ca pyroxene[1] (low-		Sulfide	
Ca Px)		Alabandite	MnS
Enstatite	$MgSiO_3$	Niningerite	MgS
Ferrosilite	$FeSiO_3$	Oldhamite	CaS
Maskelynite	isotropic, glassy plagiocl.	Troilite	FeS
Metal			
Kamacite	Fe_x-Ni_{1-x}, $0.93 \le x \le 0.96$		
Taenite	Fe_x-Ni_{1-x}, $0.5 \le x \le 0.8$		

[1]) Solid solution series; mineral compositions are intermediate between those of the listed endmembers (e.g., olivine contains both Mg and Fe and compositions are commonly expressed as molar percentages of forsterite and fayalite).

4.3.3.4 Chemical composition of chondrites

The most abundant elements in chondrites are O, Fe, Si, and Mg. Variations in elemental abundances among chondrites are generally small for refractory and moderately volatile elements. These variations are typically within a factor of two (Fig. 1 and Table 3). Highest refractory element abundances are observed in the carbonaceous chondrites and lowest in the enstatite chondrites. Larger variations are seen in the abundances of the volatile elements H, C, N, and the noble gases.

The Si-normalized elemental pattern of CI chondrites is remarkably similar to that observed in the solar photosphere. The abundances of most elements agree within a factor of 1.5 and for many elements the agreement is even within a few percent (Fig. 2). Noticeable exceptions are the volatile elements H, C, N, O, and the noble gases which are incompletely condensed in chondrites, and Li which is depleted in the solar photosphere due to nuclear reactions at the bottom of the Sun's convection zone. Except for the volatile elements, the CI chondrites are taken as chemical reference for bulk solar system matter.

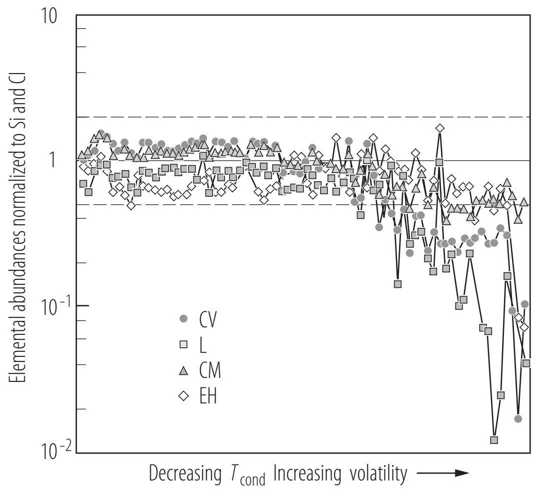

Fig. 1. Si- and CI-normalized elemental abundances of CM, CV, L, and EH chondrites. Elements are ordered according to decreasing condensation temperature (increasing volatility). For a pressure of 10^{-4} bar the condensation temperature on the left-hand side of this figure is 1800 K, on the right-hand side 80 K. Data from [98Lod]. The dashed lines indicate a difference of a factor of 2 from CI abundances. Figure adapted from [01Hop].

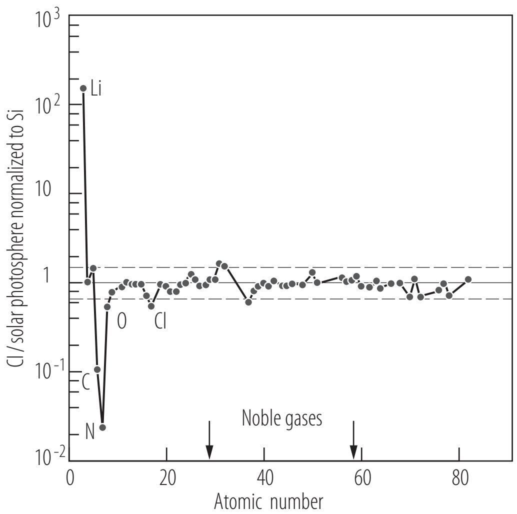

Fig. 2. Elemental abundances in CI chondrites [98Lod] (compilation of data in [81Pal, 82And, 88Was, 89And, 93Pal, 95McD]), normalized to Si and solar photospheric abundances [03Pal] (compilation of data in [93Pal, 98Gre, 99Cun, 00Bié, 01All, 01Hol, 02All]. The dashed lines represent a difference of a factor of 1.5 between CI and solar photospheric abundances. Figure adapted from [01Hop].

Table 3. Average chemical composition of chondrites. Element abundances are given in ppm weight if not otherwise indicated (light grey background shading). Data source: [98Lod].

Element	CI	CM	CV	CO	CK	CR	CH	H	L	LL	EH	EL
H [wt%]	2.02	1.40	0.28	0.07								
Li	1.5	1.5	1.7	1.8	1.4			1.7	1.85	1.8	1.9	0.7
Be	0.025	0.040	0.050					0.030	0.040	0.045	0.021	
B	0.87	0.48	0.30					0.40	0.40	0.70	1.0	
C [wt%]	3.45	2.20	0.53	0.44	0.22	2.0	0.78	0.21	0.25	0.31	0.39	0.43
N	3180	1520	80	90		620	190	48	43	70	420	240
O [wt%]	46.4	43.2	37.0	37.0				35.7	37.7	40.0	28.0	31.0
F	60	38	24	30	20			125	100	70	155	140
Na	5000	3900	3400	4200	3100	3300	1800	6110	6900	6840	6880	5770
Mg [wt%]	9.70	11.50	14.30	14.50	14.70	13.70	11.30	14.10	14.90	15.30	10.73	13.75
Al [wt%]	0.865	1.13	1.68	1.40	1.47	1.15	1.05	1.06	1.16	1.18	0.82	1.00
Si [wt%]	10.64	12.7	15.7	15.8	15.8	15.0	13.5	17.1	18.6	18.9	16.6	18.8
P	950	1030	1120	1210	1100	1030		1200	1030	910	2130	1250
S [wt%]	5.41	2.7	2.2	2.2	1.7	1.9	0.35	2.0	2.2	2.1	5.6	3.1
Cl	700	430	250	280	260			140	270	200	570	230
K	550	370	360	360	290	315	200	780	920	880	840	700
Ca [wt%]	0.926	1.29	1.84	1.58	1.70	1.29	1.30	1.22	1.33	1.32	0.85	1.02
Sc	5.9	8.2	10.2	9.5	11	7.8	7.5	7.8	8.1	8.0	6.1	7.7
Ti	440	550	870	730	940	540	650	630	670	680	460	550
V	55	75	97	95	96	74	63	73	75	76	56	64
Cr	2650	3050	3480	3520	3530	3415	3100	3500	3690	3680	3300	3030
Mn	1940	1650	1520	1620	1440	1660	1020	2340	2590	2600	2120	1580
Fe [wt%]	18.20	21.3	23.5	25.0	23.0	23.8	38.0	27.2	21.75	19.8	30.5	24.8
Co	505	560	640	680	620	640	1100	830	580	480	870	720
Ni [wt%]	1.10	1.23	1.32	1.42	1.31	1.31	2.57	1.71	1.24	1.06	1.84	1.47
Cu	125	130	104	130	90	100	120	94	90	85	215	120
Zn	315	180	110	110	80	100	40	47	57	56	290	18
Ga	9.8	7.6	6.1	7.1	5.2	6.0	4.8	6.0	5.4	5.3	16.7	11
Ge	33	26	16	20	14	18		10	10	10	38	30
As	1.85	1.8	1.5	2.0	1.4	1.5	2.3	2.2	1.36	1.3	3.5	2.2
Se	21	12	8.7	8.0	8.0	8.2	3.9	8.0	8.5	9.0	25	15

Element	CI	CM	CV	CO	CK	CR	CH	H	L	LL	EH	EL
Br	3.5	3.0	1.6	1.4	0.6	1.0	1.4	0.5	1.0	1.0	2.7	0.8
Rb	2.3	1.6	1.2	1.3		1.1		2.3	2.8	2.2	3.1	2.3
Sr	7.3	10	14.8	13.0	15	10		8.8	11	13	7	9.4
Y	1.56	2.0	2.6	2.4	2.7			2.0	1.8	2.0	1.2	
Zr	3.9	7.0	8.9	9.0	8.0	5.4		7.3	6.4	7.4	6.6	7.2
Nb	0.25	0.4	0.5		0.4	0.5		0.4	0.4			
Mo	0.92	1.4	1.8	1.7	0.38	1.4	2.0	1.4	1.2	1.1		
Ru	0.71	0.87	1.2	1.08	1.1	0.97	1.6	1.1	0.75		0.93	0.77
Rh	0.14	0.16	0.17		0.18			0.21	0.155			
Pd	0.56	0.63	0.71	0.71	0.58	0.69		0.845	0.62	0.56	0.82	0.73
Ag	0.20	0.16	0.10	0.10		0.095		0.045	0.05	0.075	0.28	0.085
Cd	0.69	0.42	0.35	0.008		0.30		0.005	0.03	0.04	0.705	0.035
In	0.08	0.05	0.032	0.025		0.03		0.085	0.01	0.01	0.085	0.004
Sn	1.7	0.79	0.68	0.89	0.49	0.73		0.35	0.54		1.36	
Sb	0.135	0.13	0.085	0.11	0.06	0.08	0.09	0.066	0.078	0.075	0.19	0.09
Te	2.3	1.3	1	0.95	0.8	1.0		0.52	0.46	0.38	2.4	0.93
I	0.43	0.27	0.16	0.20	0.20			0.06	0.07		0.21	0.08
Cs	0.19	0.11	0.09	0.08		0.084		0.105	0.26	0.15	0.21	0.125
Ba	2.35	3.1	4.55	4.3	4.7	3.4	3.0	4.4	4.1	4	2.4	2.8
La	0.235	0.32	0.47	0.38	0.46	0.31	0.29	0.301	0.318	0.33	0.24	0.196
Ce	0.62	0.94	1.19	1.14	1.27	0.75	0.87	0.763	0.97	0.88	0.65	0.58
Pr	0.094	0.137	0.174	0.14				0.12	0.14	0.13	0.10	0.07
Nd	0.46	0.626	0.919	0.85	0.99	0.79		0.581	0.70	0.65	0.44	0.37
Sm	0.15	0.204	0.294	0.25	0.29	0.23	0.185	0.194	0.203	0.205	0.14	0.149
Eu	0.057	0.078	0.105	0.096	0.11	0.080	0.076	0.074	0.080	0.078	0.052	0.054
Gd	0.20	0.29	0.405	0.39	0.44	0.32	0.29	0.275	0.317	0.29	0.21	0.196
Tb	0.037	0.051	0.071	0.060		0.050	0.050	0.049	0.059	0.054	0.034	0.032
Dy	0.25	0.332	0.454	0.42	0.49	0.28	0.31	0.305	0.372	0.36	0.23	0.245
Ho	0.056	0.077	0.097	0.096	0.10	0.10	0.070	0.074	0.089	0.082	0.050	0.051
Er	0.16	0.221	0.277	0.305	0.35			0.213	0.252	0.24	0.16	0.16
Tm	0.025	0.035	0.048	0.040			0.040	0.033	0.038	0.035	0.024	0.023
Yb	0.16	0.215	0.312	0.27	0.32	0.22	0.21	0.203	0.226	0.23	0.154	0.157
Lu	0.025	0.033	0.046	0.039	0.046	0.032	0.030	0.033	0.034	0.034	0.025	0.025
Hf	0.105	0.18	0.23	0.22	0.25	0.15	0.14	0.15	0.170	0.17	0.14	0.21
Ta	0.014	0.019						0.021	0.021			
W	0.093	0.16	0.16	0.15	0.18	0.11	0.15	0.164	0.138	0.115	0.14	0.14
Re	0.038	0.05	0.057	0.058	0.060	0.050	0.073	0.078	0.047	0.032	0.055	0.057
Os	0.49	0.67	0.80	0.805	0.815	0.71	1.15	0.835	0.53	0.41	0.66	0.67
Ir	0.465	0.58	0.73	0.740	0.76	0.67	1.07	0.77	0.49	0.38	0.57	0.56
Pt	1.0	1.1	1.25	1.24	1.3	0.98	1.7	1.58	1.09	0.88	1.29	1.25
Au	0.145	0.15	0.153	0.190	0.12	0.16	0.25	0.220	0.156	0.146	0.33	0.24
Hg	0.31								0.030	0.022	0.06	
Tl	0.142	0.092	0.058	0.040		0.06		0.001	0.003	0.015	0.10	0.007
Pb	2.5	1.6	1.1	2.15	0.80			0.240	0.040		1.50	0.24
Bi	0.11	0.071	0.054	0.035	0.020	0.04		0.005	0.014	0.017	0.090	0.013
Th	0.029	0.041	0.058	0.080	0.058	0.042		0.038	0.042	0.047	0.030	0.038
U	0.008	0.012	0.017	0.018	0.015	0.013		0.013	0.015	0.015	0.0092	0.007

4.3.3.5 Isotopic compositions

The isotopic compositions of meteorites provide unique information about the origin of the matter in the solar nebula and its evolution during the following ~4.6 Gyr of solar system history. Isotopic heterogeneity is found on the macroscopic (whole-rock) and microscopic scale. The latter is linked to organic matter (see section 4.3.3.6) and presolar grains (see section 4.3.3.7).

The O-isotopic composition of whole-rock material is a characteristic signature of the different meteorite classes (Fig. 3). Chemical processing is expected to proceed along lines with slope 0.52 in an O-three-isotope-representation [03Cla] (line labeled "TFL" in Fig. 3). The spread in O-isotopic composition among the different chondrite classes is thus indicative of O-isotopic heterogeneity in the solar nebula. Calcium-aluminum-rich inclusions (CAIs), μm to cm-sized objects found in primitive chondrites, which may represent the earliest condensates in the solar nebula, show enrichments in ^{16}O (relative to SMOW) of up to 5 %, with different mineral grains falling along a line with slope 0.94 (line labeled "CCAM" in Fig. 4) [03Cla]. Similar isotopic signatures are observed in amoeboid olivine aggregates [02Fag, 02Ito]. The ^{16}O-rich endmember has been considered to represent the O-isotopic composition of the primordial solar nebula [03Cla].

Whole-rock chondrites have C concentrations of up to 3.5 % and N concentrations of up to 0.3 % (Table 3). C- and N-bearing components are present in both organic and inorganic form. Whole-rock C-isotopic compositions vary by about 4 % (Fig. 5). Variations in the whole-rock N-isotopic compositions are much larger (Fig. 5), and are probably controlled by the presence of an organic ^{15}N-rich host [06Pea].

Meteorites preserve records of short-lived radionuclides which are now extinct but which were present when our solar system formed (Table 4) [00Gos, 03McK]. Their former presence can be inferred from overabundances of their respective daughter isotopes which linearly correlate with the parent/daughter elemental ratios. The short-lived radionuclides may have served as heat sources for planetary melting and differentiation (^{26}Al, ^{60}Fe) and they can be used as chronometers to date events in the early solar system history. They may have been produced locally by irradiation of solids with energetic particles from the young Sun (e.g., ^{10}Be) and/or may have been synthesized in external stellar sources and injected into the solar nebula (e.g., ^{60}Fe).

Table 4. Extinct short-lived radioactive nuclides in meteorites [03McK].

Radioactive nuclide ^{i}X	Half-life [Myr]	Stable reference isotope ^{ref}X	Daughter nuclide	Initial solar system abundance ($^{i}X/^{ref}X$)	References
^{10}Be	1.5	^{9}Be	^{10}B	$\sim 6 \times 10^{-4}$	[00McK]
^{26}Al	0.7	^{27}Al	^{26}Mg	5×10^{-5}	[77Lee, 95Mac]
^{41}Ca	0.1	^{40}Ca	^{41}K	1×10^{-8}	[94Sri, 96Sri]]
^{53}Mn	3.7	^{55}Mn	^{53}Cr	$\sim 2\text{-}4 \times 10^{-5}$	[85Bir, 98Lug]
^{60}Fe	1.5	^{56}Fe	^{60}Ni	$\sim 3\text{-}10 \times 10^{-7}$	[03Tac, 05Mos]
^{92}Nb	36	^{93}Nb	^{92}Zr	1×10^{-4}	[02Sch]
^{107}Pd	6.5	^{108}Pd	^{107}Ag	$\sim 5 \times 10^{-5}$	[90Che]
^{129}I	15.7	^{127}I	^{129}Xe	1×10^{-4}	[61Jef]
^{146}Sm	103	^{144}Sm	^{142}Nd	$\sim 8 \times 10^{-3}$	[94Nyq]
^{182}Hf	9	^{180}Hf	^{182}W	1×10^{-4}	[02Kle, 02Yin]
^{244}Pu	82	^{238}U	Fission products	7×10^{-3}	[88Hud]

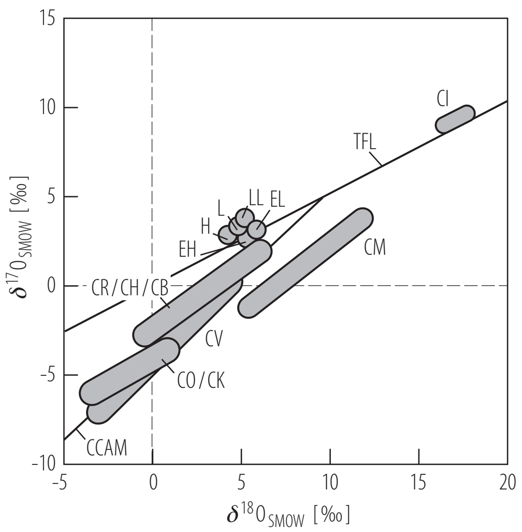

Fig. 3. O-isotopic compositions of whole-rock chondrites given as per mil deviation from the terrestrial SMOW (Standard Mean Ocean Water, $(^{17}O/^{16}O)_{SMOW}$ = 0.0003799, $(^{18}O/^{16}O)_{SMOW}$ = 0.0020052) standard. $\delta^{i}O = [(^{i}O/^{16}O)/(^{i}O/^{16}O)_{SMOW} - 1] \times 1000$. TFL: Terrestrial fractionation line. CCAM: Carbonaceous chondrite anhydrous mineral line. Data sources: [98Lod, 03Cla].

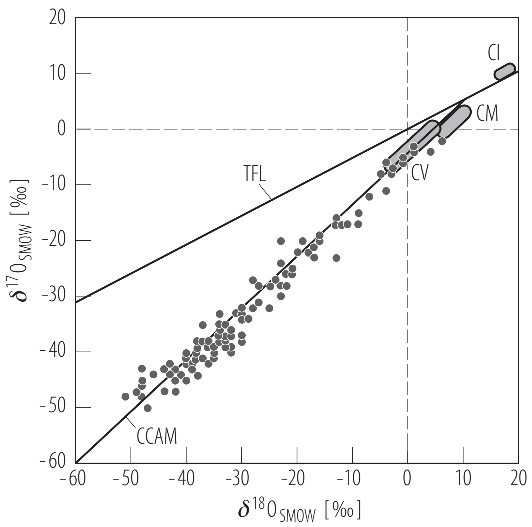

Fig. 4. O-isotopic compositions of individual minerals in CAIs given as per mil deviation from the terrestrial SMOW standard. Whole-rock CI, CM, and CV ranges are shown for comparison. TFL: Terrestrial fractionation line. CCAM: Carbonaceous chondrite anhydrous mineral line. Data sources: [02Alé, 02Fag, 02Kro].

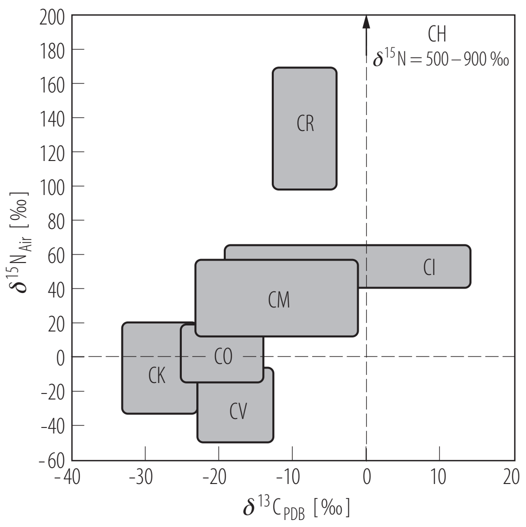

Fig. 5. Whole-rock C- and N-isotopic compositions of carbonaceous chondrites given in per mil deviation from the terrestrial PDB (Peedee Belemnite, $(^{13}C/^{12}C)_{PDB}$ = 0.011237) and air ($(^{15}N/^{14}N)_{Air}$ = 0.0036765) standards. The $\delta^{15}N$ values of CH chondrites are off-scale. Data sources: [85Ker, 91Gra, 06Pea].

4.3.3.6 Organic matter

Carbonaceous chondrites contain organic molecules that are the product of ancient chemical evolution [03Gil]. Among the proposed formation sites are the interstellar space, the solar nebula, and meteorite parent bodies. The organic matter may represent an important source of pre-biotic molecules that were essential for the origin of life on Earth. Less than 25 % of organic matter in chondrites is present as low-molecular-weight compounds which can be extracted with common organic solvents. Most abundant among these compounds are carbon dioxide, aliphatic and aromatic hydrocarbons, mono-, di-, and hydroxycarboxylic acids, amino acids, alcohols, aldehydes, ketones, sugars and related compounds, ammonia, urea, dicarboximides, and sulfonic acids [03Gil]. Most organic matter is found as high-molecular-weight macromolecular materials (insoluble organic matter, "IOM"). Isotope anomalies in H and N (Table 5) suggest that at least some fraction of the organic matter is interstellar material or material that formed in the cold outer regions of the protoplanetary disk. Viable mechanisms to produce large D and ^{15}N enrichments in either environment are low-temperature (10 K) ion-molecule reactions in the gas phase and catalytic processes on dust grains [06Bus].

Table 5. Ranges of H-, C-, and N-isotopic compositions of organic matter (OM) from chondrites.

Type of OM	δD_{SMOW} [1] [‰]	$\delta^{13}C_{PDB}$ [‰]	$\delta^{15}N_{Air}$ [‰]	References
Extractable OM	+70 to +1600	–32 to +30	+40 to +180	[78Cha, 82Bec, 84Yue, 87Eps, 90Eng, 91Piz, 91Sil, 92Kri, 93Cro, 94Gil, 94Piz, 97Co, 97Eng, 98Sep, 00Nar, 00Sep, 01Coo, 02Piz]
IOM				
Bulk	+190 to +5600	–25 to +4	–12 to +420	[98Ale, 98Sep, 00Sep, 01Sep, 05Ale]
Hotspots [2]	~ +19000		~ +3000	[06Bus]

[1]) $(D/H)_{SMOW} = 1.558 \times 10^{-4}$.
[2]) Observed maximum enrichments on a micrometer-scale by high-resolution imaging mass spectrometry.

4.3.3.7 Presolar grains

Chondrites (and interplanetary dust particles (IDPs)) contain small quantities (ppb to ppm, see Table 6) of presolar dust grains that formed around evolved stars and in the ejecta of supernova and nova explosions [93And, 93Ott, 97Ber, 98Zin, 00Hop1, 03Nit1, 03Zin1, 05Lod]. These grains carry large isotopic anomalies (with respect to average solar system matter) which are characteristic fingerprints of their stellar sources. Among the presolar minerals identified to date (Table 6) are diamond, silicon carbide (SiC), graphite, silicon nitride (Si_3N_4), spinel ($MgAl_2O_4$), corundum and other forms of Al_2O_3, hibonite ($CaAl_{12}O_{19}$), titanium oxide (TiO_2), and silicates (olivine; GEMS: 'Glass with embedded metal and sulfides' [94Bra]; amorphous Mg- and Fe-rich silicates; $MgSiO_3$-perovskite).

Presolar diamond, SiC, and graphite can be isolated from meteorites in almost pure form because they are tagged with isotopically anomalous Ne and Xe components (Xe-HL in diamonds [87Lew], Ne-E(H) and s-process Xe in SiC [87Ber, 88Tan], Ne-E(L) in graphite [90Ama]). What fraction of the presolar diamonds represents true stardust is still a matter of debate. The reason for this is their small size of only 2-3 nm which excludes isotopic measurements of individual grains. All other types of presolar grains are larger (Table 6) and information on the istopic compositions of a large number of elements was obtained for individual grains by secondary ion mass spectrometry (SIMS), resonance ionization mass spectrometry (RIMS), and laser heating and gas mass spectrometry.

The best studied presolar mineral type is SiC. Isotopic information exists for C, N, Mg, Si, Ca, Ti, Fe, Sr, Zr, Mo, Ru, Ba, Nd, Sm, and the noble gases [89Zin, 90Lew, 90Ott, 91Zin, 92Ama, 92Nic, 93Ale, 93Pro, 94Hop, 94Lew, 95Nit, 96Hop1, 96Nit, 97Hop1, 97Hus, 97Nic, 98Nic1, 98Nic2, 99Pel, 00Ama, 00Hop2, 01Ama1, 01Ama2, 01Ama3, 02Hop, 03Bes, 03Nit2, 03Sav, 04Sav, 05Nit, 07Hec, 07Zin].

Based on the isotopic compositions of C, N, and Si (Figs. 6 and 7), SiC was divided into 7 distinct populations which originate from different types of stellar sources (Table 7). Presolar Si_3N_4 grains are related to the supernova SiC type X grains, as indicated by the isotopic signatures of N and Si and the abundance of now extinct ^{26}Al [95Nit]. For presolar graphite, isotope data are available for C, N, O, Mg, Si, K, Ca, Ti, Zr, Mo, and the noble gases [90Ama, 92Nic, 94Nic, 95Ama1, 95Ama2, 95Hop, 95Zin, 96Ama, 96Nit, 98Nic3, 99Tra, 05Sta1]. For most graphite grains the ^{12}C/^{13}C ratios are higher than those of typical SiC grains (Fig. 8). Presolar graphite grains contain small subgrains of Ti-, Zr-, and Mo-rich carbides, kamacite, and cohenite [91Ber, 96Ber, 99Ber, 03Cro, 05Cro]. Based on their O-isotopic compositions, presolar oxide grains are divided into 4 distinct groups (Fig. 9) [97Nit]. Isotope data exist for O, Mg, Ca, and Ti [94Hus, 94Hut, 94Nit, 97Nit, 98Cho, 98Nit, 99Cho, 03Zin2, 05Zin]. Presolar silicates have been studied for O-, Mg-, and Si-isotopic compositions [03Mes, 04Mos, 04Nag, 04Ngu, 05Mes, 07Ngu, 07Vol]; their O-isotopic ratios are compatible with those of oxide grains (Fig. 9). Short-lived radioactive nuclides have left imprints in most types of presolar grains (Table 8).

Table 6: Presolar minerals found in primitive meteorites.

Mineral	Size [μm]	Abund. [ppm][1]	Most important isotopic signatures	Stellar Source	Relative Contr.[2]
Diamond	~0.0026	1500	Xe-HL, Te-H[3]	Supernovae	?
SiC	0.1-10	30	Enhanced ^{13}C, ^{14}N; Ne-E(H)[4]; s-process elements	AGB stars	>90%
			Low ^{12}C/^{13}C, often enhanced ^{15}N	J-type C stars ?	<5%
			Enhanced ^{15}N, ^{28}Si; extinct ^{26}Al, ^{44}Ti, ^{49}V	Supernovae	1%
			Low ^{12}C/^{13}C, ^{14}N/^{15}N; enhanced ^{30}Si	Novae	0.1%
Graphite	1-10	10	Enh. ^{15}N, ^{18}O, ^{28}Si; extinct ^{26}Al, ^{41}Ca, ^{44}Ti, ^{49}V	Supernovae	<80%
			s-process elements	AGB stars	>10%
			Low ^{12}C/^{13}C	J-type C stars ?	<10%
			Low ^{12}C/^{13}C; enhanced ^{30}Si; Ne-E(L)[4]	Novae	2%
Si_3N_4	~1	0.002	Enhanced ^{15}N, ^{28}Si; extinct ^{26}Al	Supernovae	100%
Oxides[5]	0.1-5	50	Enhanced ^{17}O, depleted ^{18}O	RGB/AGB stars	>90%
			Enhanced ^{16}O or ^{18}O	Supernovae	1%
Silicates	0.1-1	200[6]	Enhanced ^{17}O, depleted ^{18}O	RGB/AGB stars	>90%
			Enhanced ^{18}O	Supernovae	<10%

[1]) Reported maximum values from different meteorites are given.
[2]) Note uncertainty about actual fraction of diamonds that are presolar and about the relative fractions of graphite grains that are attributed to AGB stars and supernovae.
[3]) Xe-HL: enhanced abundances of the heavy and light Xe istopes [87Lew]; Te-H: enhanced abundances of the heavy Te isotopes [98Ric].
[4]) Ne-E: Almost monoisotopic ^{22}Ne that is released at low (L) and high (H) temperatures, respectively; Ne-E(L) is probably from the decay of short-lived ^{22}Na (half-life 2.6 yr) [75Cla].
[5]) $MgAl_2O_4$, Al_2O_3, $CaAl_{12}O_{19}$, and TiO_2.
[6]) Higher abundances are observed in IDPs.

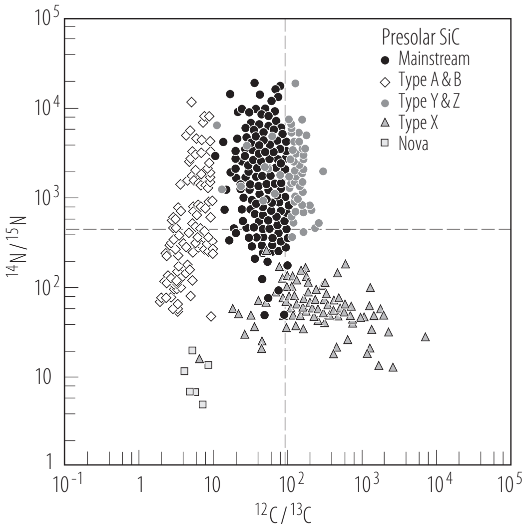

Fig. 6. C- and N-isotopic compositions of presolar SiC. The dashed lines represent the solar ratios. For the solar $^{14}N/^{15}N$ ratio the value inferred for Jupiter [01Owe] was taken. Data sources: [94Hop, 95Nit, 96Hop1, 96Hop2, 97Gao, 97Hop1, 97Hus, 00Hop2, 01Ama1, 01Ama2, 01Ama3, 05Nit].

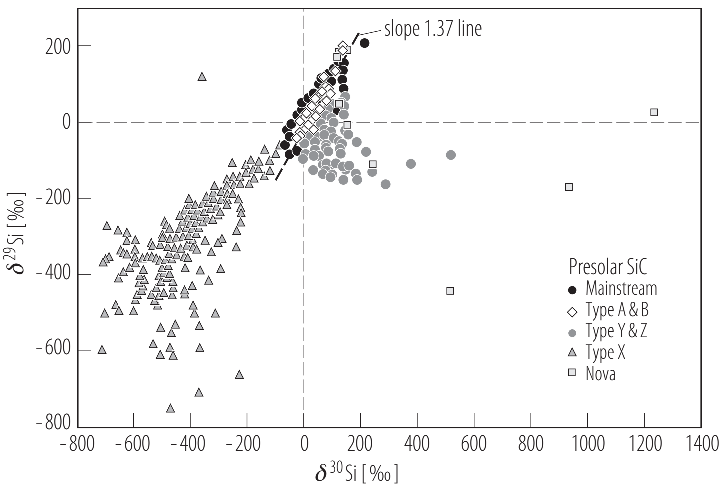

Fig. 7. Si-isotopic compositions of presolar SiC given as per mil deviation from the solar $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ ratios. Data sources: [93Ale, 94Hop, 95Nit, 96Hop1, 97Gao, 97Hop1, 97Hus, 00Hop2, 01Bes, 03Bes, 03Nit2, 05Nit].

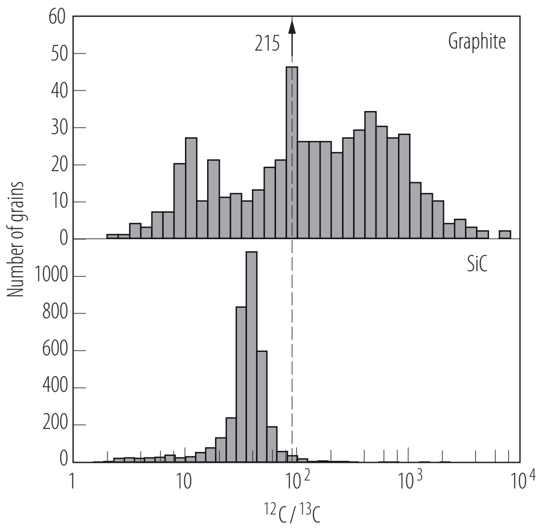

Fig. 8. Histograms of $^{12}C/^{13}C$ ratios of presolar graphite and SiC grains. The solar ratio is indicated by the dashed line. Data sources: [95Hop, 99Tra] for graphite; [94Hop, 96Hop1, 03Nit2] for SiC.

Table 7. Presolar SiC populations: Abundances, isotopic signatures of major elements, and stellar sources (modified version of [97Hop2]).

Population	Abund. [%]	$^{12}C/^{13}C$-ratio	$^{14}N/^{15}N$-ratio	Si	Stellar sources
Mainstream	80-90[1]	10-100	50-20000	Mainstream line[2]	1-3 $M_\odot$ AGB stars, ~solar metallicity
Type A	~2	<3.5	50-1500	Mainstream line	J-type C stars, Born-again AGB stars[3]
Type B	~4	3.5-10	50-10000	Mainstream line	J-type C stars, Born-again AGB stars[3]
Type X	~1	6-7000	10-250	Enhanced ^{28}Si	Supernovae
Type Y	2-6[1]	>100	300-20000	^{30}Si-rich side of mainstream line	1-3 $M_\odot$ AGB stars, ~1/2 solar metallicity
Type Z	0-7[1]	10-100	900-7000	^{30}Si-rich side of mainstream line; $\delta^{29}Si < 0$	1-3 $M_\odot$ AGB stars, ~1/3 solar metallicity
Nova	~0.1	4-10	5-20	Enhanced ^{30}Si	Novae
Solar System		89	272 (air) 435 (Jupiter)	$^{29}Si/^{28}Si = 0.050633$ $^{30}Si/^{28}Si = 0.033621$	

[1]) Depending on grain size.
[2]) $\delta^{29}Si = -20 + 1.37 \times \delta^{30}Si$ [07Zin]; cf. Fig. 7.
[3]) Stellar sources are uncertain.

4.3.3.8 Origin of meteorites

Meteorites are fragments of asteroids, small planets with sizes between < 1 km and 1000 km, most of which are concentrated in a belt between 1.8 and 4 AU (i.e., between the orbits of Mars and Jupiter) [07Bri]. This is evidenced by (i) network observations of meteorite falls from which orbits with aphelion in the asteroid belt are inferred, (ii) the similarity of reflectance spectra of meteorites to several classes of asteroids, and (iii) the mineralogical diversity of meteorites. Their initial orbits in the asteroid belt are eventually disturbed by the gravitational forces of Jupiter and Saturn and meteoroids may finally reach the Earth at entry velocities of 11-70 km/s [07Lip]. The dynamic processes that deliver the meteoroids from the asteroid belt to Earth are likely biased toward sampling matter from just two resonances in the asteroid belt, the so-called 3:1 Kirkwood gap and ν_6 [07Bri]. While traveling in space meteoroids are exposed to cosmic rays. This leads to the production of cosmogenic nuclides by nuclear reactions from which the residential times in space can be inferred. Specifically the noble gases have been used to calculate cosmic ray exposure ages [03Her].

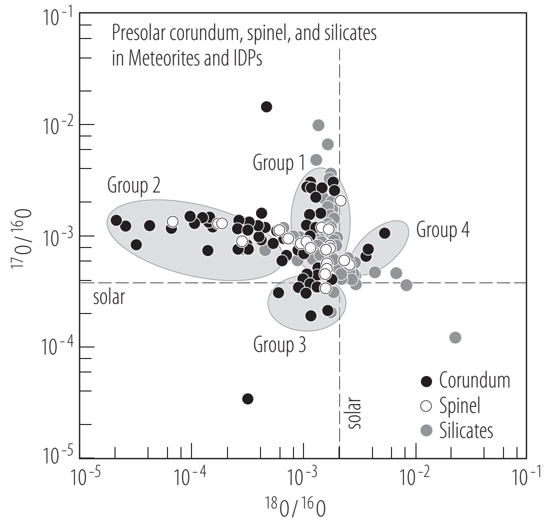

Fig. 9. O-isotopic ratios of presolar corundum, spinel, and silicate grains. The solar ratios are indicated by the dashed lines. The four O-isotope groups defined by [97Nit] are shown as grey ellipses. For the silicates, data for grains from meteorites, IDPs, and Antarctic micrometeorites (AMM) are shown. Data sources: [04Mos, 04Ngu, 05Hop, 05Sta2, 06Mar, 07Ngu, 07Vol] for silicates from meteorites; [03Mes, 05Mes, 06Flo] for silicates from IDPs; [06Yad] for silicates from AMMs; [94Hut, 97Nit, 98Cho, 98Nit, 99Cho] for corundum; [05Zin] for spinel.

Table 8. Extinct short-lived radionuclides in presolar grains.

Radioactive nuclide ^{i}X	Half-life [yr]	Stable reference isotope ^{ref}X	Daughter nuclide	Abundance at time of grain formation ($^{i}X/^{ref}X$)	Grain type	References
^{22}Na	2.6	^{23}Na	^{22}Ne	?	Graphite	[75Cla, 94Nic, 95Ama1]
^{26}Al	700000	^{27}Al	^{26}Mg	up to 0.60	All (except diamond)	[94Hop, 95Hop, 95Nit, 97Nit, 04Ngu, 05Zin]
^{41}Ca	105000	^{40}Ca	^{41}K	up to 0.01	Graphite, hibonite	[96Ama, 99Cho]
^{44}Ti	60	^{48}Ti	^{44}Ca	up to 0.50	SiC-X, graphite	[96Nit, 00Hop2]
^{49}V	0.9	^{51}V	^{49}Ti	up to 0.25	SiC-X, graphite	[99Tra, 02Hop]
^{99}Tc	210000	none	^{99}Ru		SiC mainstream	[04Sav]

4.3.3.9 References for 4.3.3

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