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CHONDRITES, ORDINARY

The chondrites constitute about 85% of the meteorites that fall to Earth. Their chief characteristics are (1) they have essentially the same composition as the solar photosphere, (2) they are comparable in age with the solar system, and (3) they have textures which indicate little or no alteration since their formation. They therefore provide a unique opportunity to investigate processes occurring during the earliest phases of solar system history (Kerridge and Matthews, 1988). The chondrites are divided into the carbonaceous (see Carbonaceous chondrite), enstatite (see Enstatite meteorite) and ordinary chondrites (Table C2), of which the last division is much the largest (~ 79% of all meteorites).

H, L and LL classes and their significance

It has been known since the last century that iron exists in several forms in the chondrites, as metal, as silicates and as sulfides. In the carbonaceous chondrites very little iron exists as metal, while in enstatite chondrites virtually all the iron exists in metallic and sulfide forms with little in the silicates. The ordinary chondrites lie between these extremes. It was therefore assumed that the chondrites came from a common source that underwent progressive oxidation (or reduction).

After a major survey of compositional data, Urey and Craig (1952) found that the idea of a simple oxidation series was incorrect. An updated version of their plot is shown in Figure C24. Chondrites from

Table C2 Chondrite classes

		$\mathrm{Fe}^{o}/\mathrm{Fe}_t$[b]	Fe/Si	Mg/Si	Ca/Si				
Petrogic type	Fa[a] (mol%)	(atom/atom)				Co in kam[c]	$\delta^{17}O$[d]	$\delta^{18}O$[d]	
Carbonaceous chondrites									
1–6	0–35	0	~ 0.8	~1.05	0.6–0.8	–	Well dispersed, generally below terrestrial fractionation line		
Ordinary chondrites									
H3–6	16–20	0.58	0.81	0.96	0.050	~ 6.5	2.9	4.1	Above terrestrial fractionation line
L3–6	22–25	0.29	0.57	0.93	0.046	~ 10	3.5	4.6	
LL3–6	27–32	0.11	0.52	0.94	0.049	20–100	3.9	4.9	
Enstatite chondrites									
3–6	<2	0.80	0.6–1.0	0.80	0.03	–	On terrestrial fractionation line		

[a] The major mineral, olivine, is a solid solution of fayalite (Fe_2SiO_4) and forsterite (Mg_2SiO_4). The above parameter refers to the concentration of fayalite (Fa) in the olivine, expressed as mole percent.

[b] Refers to the ratio of reduced Fe (metallic Fe) to the total Fe.

[c] This parameter, the Co content of the kamacite quoted above in units of mg g^{-1}, has only been discussed as a classification parameter for the ordinary chondrites.

[d] $\delta^{18}O$ and $\delta^{17}O$ are defined by the following, using $\delta^{18}O$ as an example:

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{\mathrm{sample}}}{(^{18}O/^{16}O)_{\mathrm{SMOW}}} - 1 \right] \times 1000.$$

Where SMOW is a standard, (Standard Mean Ocean Water). 'Above', 'on' and 'below' the terrestrial fractionation line refers to measurements on fairly large bulk samples. Certain components within at least one highly unequilibrated ordinary chondrite (Allan Hills 76004) plot below the terrestrial line.

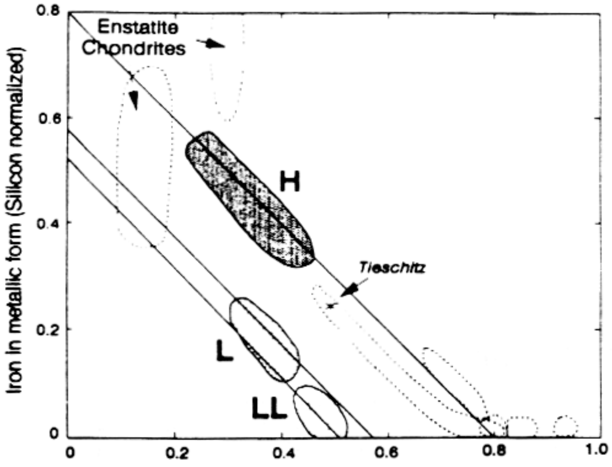

Figure C24 The ratio of Fe/Si for iron in the metallic state (Fe^0) against Fe/Si for iron in the non-metallic (i.e. oxide, silicate and sulfide forms). Many classes of chondrite can be distinguished on this plot, most notably the H, L and LL classes of ordinary chondrite. Several type 3 chondrites (like Tieschitz) plot to the lower right of their respective class fields. The unlabeled fields refer to the carbonaceous chondrite classes.

a single oxidation series would plot along a diagonal line appropriate to the bulk iron–silicate ratio for the meteorites. What Urey and Craig observed was that the ordinary chondrites plotted along two diagonals of different Fe/Si ratio. We now know that there are three. The ratios of other siderophile elements (like cobalt, nickel and iridium which tend to concentrate in the metal phase, whenever possible) to silicon show similar trends. Apparently, the oxidation (or reduction) process experienced by the chondrites was accompanied by loss (or gain) of Fe. Ordinary chondrites are thus divided into three classes, termed H, L and LL, after their high, low and very low Fe/Si ratios.

Several other measurements which relate to the trends observed in the Urey–Craig plot may be used to classify ordinary chondrites. As the amount of metal decreases along the H–L–LL series, the amount of Fe in the silicates increases. Thus the amount of FeO in the major silicates, as measured by the amount of fayalite in the olivine or ferrosilite in the pyroxene (see Table C3), is a characteristic of each class (Fredriksson, Nelen and Frederiksson, 1968; Figure C25a). Similarly, the amount of Ni in the metal also increases along the series, as Fe is removed from the metal phase. Finally, the amount of Co in the metal (to be precise, the metal phase known as kamacite) increases along the H–L–LL series (Figure C25b; Sears and Axon, 1975).

Improvement in analytical techniques yielded other differences between the classes which precluded a simple oxidation relationship. In the 1960s it became clear that the abundance of refractory elements relative to the moderately volatile elements (like silicon) varied from class to class. While carbonaceous chondrites are close to the solar value in their Mg : Si ratio (1.05), the ordinary and enstatite chondrite values are slightly but significantly below this value and H chondrites plot in the upper part of the ordinary chondrite range (Figure C26). The Ca : Si ratios show similar effects. It is as if, during their formation, a component containing refractory material (represented by Ca and Mg) and a component containing moderately volatile elements (represented in this case by Si), became physically separated so that their Ca : Si ratios were changed.

Evidence that these compositional and oxidation state differences between the classes were due to processes occurring in the primordial solar nebula, and not on a planet-like body, was provided by measurements of the relative proportions of the three isotopes of oxygen (Clayton, Grossman and Mayeda, 1973; Figure C27). On a plot of $\delta^{17}O$ against $\delta^{18}O$, terrestrial and lunar samples lie along a line of slope 0.5. Such a slope indicates the influence of processes which are mass dependent, and this is true of all of the chemical and physical processes commonly encountered. The ordinary chondrites lie slightly but significantly above the terrestrial fractionation line, with the H, L and LL classes on a line with a slope equal to 1; $\delta^{17}O$ and $\delta^{18}O$ values increase along the H–L–LL series. For data to plot off the terrestrial line, with a slope of unity, requires the mixing of components of distinctly different nucleosynthetic origin than is normally found in terrestrial and lunar samples (e.g. an ^{16}O-rich solid and a relatively ^{16}O-poor gas). The process must have occurred prior to the isotopic homogenization of the Earth and Moon, presumably in the primordial solar nebula (see Accretion; Solar nebula; Solar system: origin).

Table C3 Major minerals in ordinary chondrites and amount by weight percent (modified after Van Schmus, 1969)[a]

		H	L	LL
Olivine	Fayalite, Fa, Fe_2SiO_4 Forsterite, Fo, Mg_2SiO_4	33–37	45–49	56–60
Low-Ca pyroxene	Ferrosilite, Fs, $FeSiO_3$ Enstatite, En, $MgSiO_3$	23–27	21–25	14–18
Ca-pyroxene	Ferrosilite, Fs, $FeSiO_3$ Enstatite, En, $MgSiO_3$ Wollastonite, Wo, $CaSiO_3$	4–5	4–5	4–5
Feldspar	Albite, Ab, $NaAlSi_3O_8$ Anorthite, An, $CaAl_2Si_2O_8$ Orthoclase, Or, $KAlSi_3O_8$	9–10	9–10	9–10
Troilite	FeS	5–6	5–6	5–6
Kamacite	FeNi (BCC)	15–17	6–8	1–2
Taenite	Fe,Ni (FCC)	2–3	2–3	2–4
Chromite	$FeCr_2O_4$	0.5	0.5	0.5
Whitlockite Chlorapatite	$Ca_2(PO_4)_3$ $Ca_5(PO_4)_3Cl$	0.6	0.6	0.6

[a] Olivine, the pyroxenes and feldspar are solid solutions of the minerals listed. Whitlockite and chlorapatite are different minerals which are difficult to distinguish optically and are here listed together.

Mineralogy

The ordinary chondrites consist primarily of the silicates olivine, pyroxene and plagioclase and of metal which exists as two alloys (kamacite and taenite). There is also a sulfide unique to meteorites, termed troilite (FeS). There are also a great many minor and trace minerals found in chondrites, such as chromite, whitlockite and chlorapatite. A recent count revealed over 100 minerals recorded in chondrites. Some of the trends in metal and silicate abundance discussed above are apparent in the data in Table C3.

Texture

Chondrites are also noteworthy for their texture; indeed their name derives from *chondros* (Greek, 'a grain') which refers to ubiquitous spherical or near-spherical objects present in the meteorites, which are now known as 'chondrules'. There is agreement among petrologists that the chondrules were formed by a flash-melting event, but although it must have occurred before the rock was assembled in its present form, the details of where and how the heating occurred are unknown. Located between the chondrules and the grains of metal and sulfide is a silicate-rich material rather loosely termed the 'matrix'.

Chondrules

Chondrules range from a few micrometers to over 200 μm in size and have a variety of internal textures (Gooding and Keil, 1979), which may be due to factors such as maximum temperature, number and type of nucleation centers and cooling rate (Hewins, 1988; Lofgren, 1989). They are often surrounded by rims of matrix-like material, often rich in fine-grained metal and sulfide, which are thought to be dust accreted onto the chondrule before it became part of the meteorite.

There is considerable compositional diversity among the chondrules with some being highly refractory (free of volatiles) and reduced

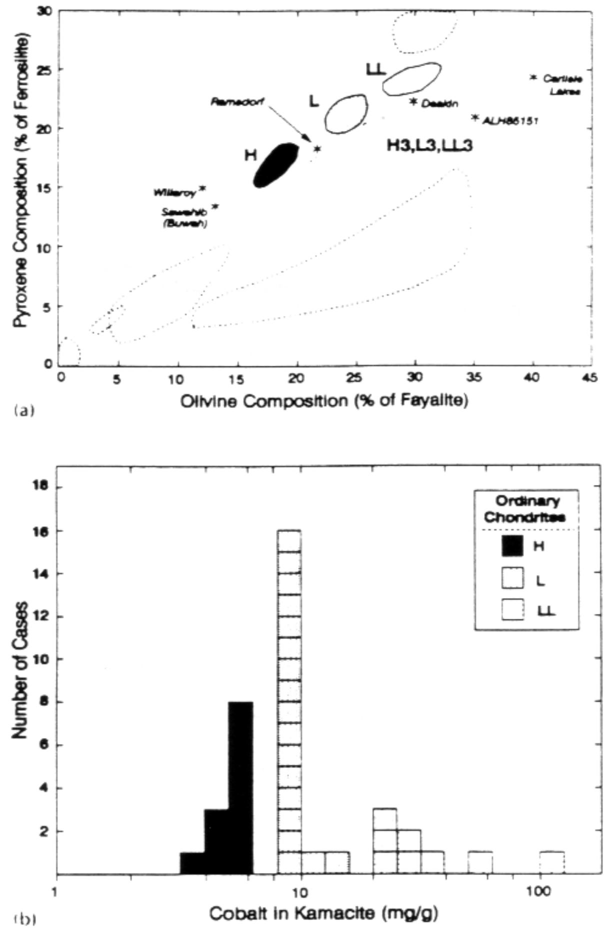

Figure C25 (a) Ferrosilite content of the pyroxene against the fayalite content of the olivine for ordinary chondrites. The three ordinary chondrite groups, corresponding to H, L and LL chondrites, are apparent in this plot. The field occupied by type 3 ordinary chondrites and data for several unusual ordinary chondrites are also plotted. The unlabeled fields refer to the carbonaceous chondrite classes. (Enstatite chondrites contain little or no olivine). (b) Cobalt content of the kamacite for ordinary chondrites. This parameter also enables the H, L and LL chondrites to be identified.

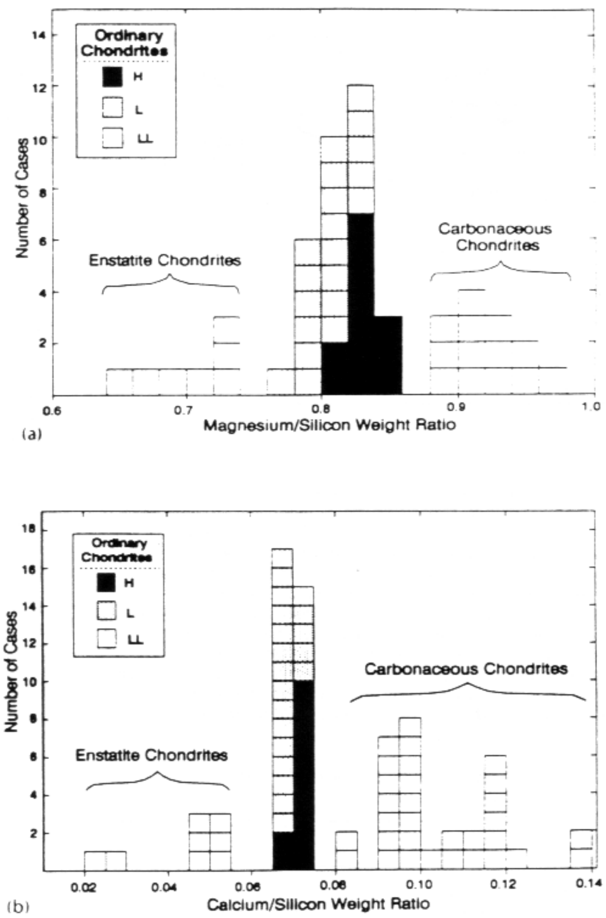

Figure C26 Histograms of (a) Mg/Si and (b) Ca/Si ratios in chondritic meteorites. These ratios permit subdivision of the chondrites into carbonaceous, ordinary and enstatite chondrite classes. Within the ordinary chondrites, H chondrites plot at the upper end of the ranges.

(their silicates are Fe free), while others contain volatile element abundances and silicates quite rich in iron (e.g. Sears *et al.*, 1992). Parent body processes (i.e. metamorphism, see below) caused these two groups to converge (in mineral composition) to average values. Significantly, there are a few chondrules of these average mineral compositions in the unmetamorphosed chondrites.

The main question concerning the origin of the chondrule groups is whether they are due to differences in the original material, or whether the differences were caused by the flash-heating event. Consistent with the latter, the amount of the volatile element Na and the amount of ^{16}O in the chondrules is related to their size. Both the loss of Na and exchange of ^{16}O would be size-dependent processes. Many chondrules contain fragments of other chondritic components such as fine-grained matrix, refractory inclusions and grains from other chondrule classes, and the narrow spread in their oxygen isotope ratios has been ascribed to multiple episodes of reheating (Clayton *et al.*, 1991).

Matrix

The matrix is a mixture of silicate minerals which may be either fine-grained or very coarse. Some authors have suggested that the matrix is primitive nebula dust (e.g. Scott *et al.*, 1984), while others have suggested that it was derived from the chondrules (e.g. Alexander, Hutchison and Barbes, 1989). The picture is complicated by brecciation, which adds fragments and chondrules to the matrix.

Sulfide and metal

These tend to be associated with each other and in the unmetamorphosed meteorites take a variety of textures, including spherules resembling chondrules. Some of the metal and sulfide exists as very finely dispersed grains in rims around chondrules. In metamorphosed meteorites these phases have increased in grain size and are intergrown with the silicates (Afiattalab and Wasson, 1981).

Metamorphism and other secondary processes

Metamorphism

After the formation of chondrites by the accretion of chondrules, matrix, sulfide and metal onto their parent bodies, most chondrites underwent a protracted period of heating which caused many solid state physical and chemical changes (metamorphism). This has lead to subdivision of the chondrites by Van Schmus and Wood (1967) into six 'petrographic types' using a variety of petrologic and compositional criteria (Table C4).

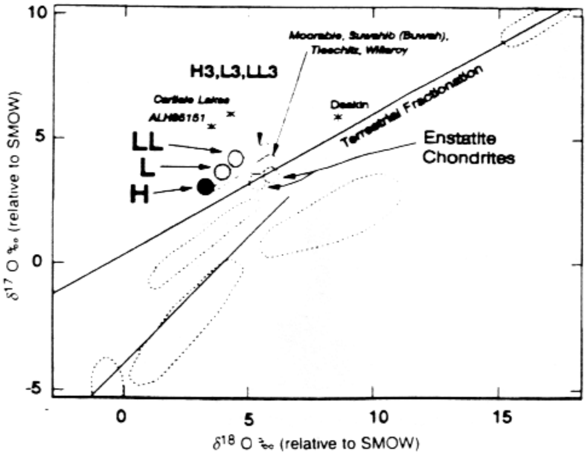

Figure C27 Plot of the oxygen isotope abundances in chondritic meteorites. The data are shown as the differences (in parts per thousand) in the ratio for ^{17}O and ^{18}O to ^{16}O compared with the laboratory standard SMOW (standard mean ocean water). The diagonal line is the terrestrial fractionation line, defined by terrestrial and lunar samples. The ordinary chondrites plot above this line, the H, L and LL chondrites occupying close but separate fields on a line with a slope of 1. For comparison, the enstatite chondrites plot on the terrestrial line while the carbonaceous chondrites (unlabeled fields) plot on or below the line and spread widely. Data for some unusual ordinary chondrites and the field occupied by type 3 ordinary chondrites are also plotted.

Types 1 and 2 are reserved for carbonaceous chondrites and largely describe the effects of aqueous alteration. The type 3 ordinary chondrites have experienced a wide range of metamorphic alteration and are subdivided into types 3.0 to 3.9 (Sears *et al.*, 1980; Table C4). Among the best studied of the ordinary chondrites is Semarkona, which is the only known 3.0 ordinary chondrite. Types 4–6 (sometimes termed 'equilibrated') represent high levels of metamorphism, so that in some even the coarsest textures are blurred.

The most unequilibrated ordinary chondrites contain isotopically heavier oxygen than the equilibrated (types 4–6) chondrites. This probably reflects the loss of CO or CO_2 during open-system metamorphism (Clayton *et al.*, 1991). Abundances of highly volatile elements, e.g. In, Tl, Bi and Pb, decrease by several orders of magnitude as petrographic type increases. Some authors also attribute this to evaporative loss during metamorphism, although others suggest that it may reflect accretion of the meteorites at different temperatures.

The lack of equilibrium between minerals makes it difficult to estimate metamorphic temperatures for type 3 chondrites, but thermoluminescence data suggest values of about 500°C for type 3.5 chondrites (Guimon, Keck and sears, 1985). For the higher petrographic types oxygen isotope data and mineral compositions suggest metamorphic temperatures of 600–700°C for type 4, 700–750°C for type 5 and 750–950°C for type 6 (McSween, Sears and Dodd, 1988). A few chondrites which underwent incipient melting during metamorphism are termed 'type 7'.

Shock heating

Some chondrites experienced short-term excursions to high temperature as a result of impact in space. Stöffler, Keil and Scott (1991) have systematized and summarized observations in a shock classification scheme. Shock causes the loss of volatile elements, especially the light rare gases; it causes feldspars and sulfides to melt and olivines and metal to assume distinctive optical properties.

Table C4 Petrographic types of chondritic meteorites (see Sears *et al.*, 1991, for references. Data on water in type 3 chondrites are from Jarosewich, 1980)

Petrologic type	Characteristic[b]							
	1	2	3	4	5	6	7	8
1	n.a.[a]	0	n.a.[a]	0	>1.9	~3.5	~6	≥65
2	≥50	0	n.a.[a]	0	>1.9	1.5–2.8	3–11	≥65
3.0	≥50	<0.0046	>26.3	<10	>1.9	≥0.60	~2	≥65
3.1	≥50	0.0046–0.01	26.3–21.3	10–20	1.9–1.7	0.60–0.50	~2	65–55
3.2	≥50	0.010–0.022	21.3–16.3	10–20	1.7–1.6	0.50–0.43	~2	55–45
3.3	≥50	0.022–0.046	16.3–12.5	10–20	1.6–1.5	0.43–0.38	≤2	45–35
3.4	≥50	0.046–0.10	12.5–10.0	~20	1.5–1.4	0.38–0.33	≤2	35–27
3.5	41–50	0.10–0.22	10.0–7.5	~50	1.4–1.3	0.33–0.30	≤2	27–18
3.6	31–40	0.22–0.46	7.5–6.3	>60	1.3–1.2	0.30–0.27	≤2	18–13
3.7	21–30	0.46–1.0	6.3–3.1	>60	1.2–1.1	0.27–0.24	<2	13–8
3.8	11–20	1.0–2.2	3.1–1.9	>60	1.1–1.0	0.24–0.21	<2	8–4
3.9	5–10	2.2–4.6	<1.9	>60	1.0	≤0.21	<2	<4
4	<5	4.6–10	<1.9	>60	1.0	<0.2	<2	<4
5	<5	>10	<1.9	100	1.0	<0.2	<2	<4
6	<5	>10	<1.9	100	1.0	<0.2	<2	<4

[a] n.a. = not applicable.

[b] Characteristics:

1. Olivine (or pyroxene) heterogeneity (standard deviations of Fa or Fs, divided by the mean, expressed as a percentage).
2. Thermoluminescence sensitivity (on a scale of Dhajala equals 1.0).
3. Heterogeneity of Co in the kamacite (standard deviation divided by the mean, expressed as a percentage).
4. Percentage of the matrix which is recrystallized.
5. FeO/(FeO+Mg0) value for the matrix divided by the same value for the bulk rock.
6. Bulk carbon content (wt%).
7. Bulk water content for observed falls (wt%).
8. Bulk ^{36}Ar content (in units of 10^{-8}cm^{-3}STPg^{-1}).

Other (mainly descriptive) characteristics:

a. The bulk Ni content of metal in type 1 and 2 chondrites is <20% so that taenite is absent or minor in these meteorites.
b. The sulfides in types 1 and 2 contain significant Ni (>0.5%).
c. The structural state of the low-Ca pyroxene in types 2 and 3 is predominantly monoclinic, in type 4 it is >20% monoclinic, in type 5 it is < 20% monoclinic while in type 6 it is orthorhombic. Pyroxene is absent in type 1 chondrites.
d. Igneous glass is clear and isotropic in types 2 and 3, turbid in type 4 and absent in types 1 and 6.
e. Secondary feldspar is absent in types 1–3, present as <2 μm grains in type 4, as <50 μm grains in type 5 and as >50 μm grains in type 6.
f. Chondrules are absent in type 1, very sharply defined in types 2 and 3, well-defined in type 4, readily delineated in type 5 and poorly defined in type 6.

Aqueous alteration

Hutchison, Alexander and Barber (1987) reported hydrous silicates and calcite with a morphology indicative of deposition from aqueous fluids in the meteorites Semarkona (LL3.0) and, subsequently, Bishunpur (LL3.1). The relative importance of aqueous alteration and dry thermal metamorphism in the history of type 3.0–3.2 chondrites is unclear (Alexander, Hutchison and Barber, 1989; Guimon, Keck and Sears, 1985; McSween, Sears and Dodd 1988).

Unusual ordinary chondrites

There are several anomalous ordinary chondrites. Tieschitz and Chainpur appear to be intermediate between H and L chondrites. Carlisle Lakes and Allan Hills A80151 are type 3.7 chondrites with especially high Fa values, high amounts of matrix and unusual oxygen isotope properties (Rubin and Kallemeyn, 1989). Pecora Escarpment 91002 may be a similar meteorite. Deakin 001 is a highly unequilibrated LL3 chondrite with heavier oxygen than observed for other type 3 chondrites (Bevan and Binns, 1989). Moorabie, Willaroy and Suwahib (Buwah) are type 3 ordinary chondrites with low Fe olivines and heavy oxygen isotopes but whose olivine heterogeneity and thermoluminescence data suggest are type 3.5–3.9 (Scott, Clayton and Mayeda, 1985). It is likely that the history of these 'unusual' ordinary chondrites, and several others that have been described in the literature, will not be well understood until more samples are available.

History and origin

Early history

A variety of radiometric dating methods indicate formation ages of 4.6 Ga for the ordinary chondrites, comparable to the ages of the Moon, Earth and Sun (e.g. Tilton, 1988) (see Chronology: meteorite). The presence of the decay products of now extinct parent nuclides provides a means of discriminating small intervals of time near the beginning of solar system history. The data indicate that the chondrites formed soon after the end of nucleosynthesis and that they formed over a small time span of less than 100 million years (Swindle and Podosek, 1988).

Many low-petrographic type meteorites also contain unusual patterns of rare gas isotopes which are thought to indicate the presence of components which predate the formation of the solar system. These exotic mixtures of isotopes are found in diamond, silicon carbide and other carbon-bearing phases (Anders, 1988; Zinner, 1988). Their abundance decreases with petrographic type, presumably indicating destruction of the carrier phases during metamorphism (Huss, 1989).

Their essentially solar composition, their age and their texture indicate that the ordinary chondrites are aggregations of dust, chondrules, metal and sulfide which were present in the primordial solar nebula during planet formation. The small but significant differences in elemental and isotopic composition from which we derive the ordinary chondrite classes may be the result of (1) chemical reactions and related physical processes in the nebula, or (2) they may be associated with the ubiquitous, but poorly understood, chondrule formation process. Detailed thermodynamic models have been developed which are successful in explaining many features of the elemental and isotopic properties of the ordinary chondrite classes (e.g. Sears, 1988), but they may be applied equally well to processes occurring in the nebula and during chondrule formation.

Recent history

Most authorities accept that chondrites are pieces of asteroids. Spectral reflectivity data for several small meteorite classes closely resemble those of certain asteroids, but the largest chondrite classes do not have close matches in the main asteroid belt (Gaffey, 1976). There are, however, several asteroids currently on Earth-crossing orbits whose spectra match those of the ordinary chondrites (see Asteroid; Reflectance spectroscopy). Orbital calculations indicate that gravitational reasonances with Jupiter provide a mechanism for transferring asteroids to Earth-crossing orbits (Wisdom, 1985).

The rates of cooling following metamorphism can be estimated from nickel profiles in the metal grains and the from the abundance of tracks of radiation damage caused by Pu fission fragments (Pellas and Storzer, 1981). The results range from 1 to 100°C per million years, which are consistent with asteroid sized parent bodies, assuming that the heating was caused by long-lived radioactive elements (Wood, 1979). If the heat source was ^{26}Al, the objects could have been much smaller. Some authors claim that the parent object of the ordinary chondrites had a simple onion skin structure with the slowly cooled, highly metamorphosed meteorites at the center (Pellas and Storzer, 1981). The inverse correlation between Pb–Pb age and petrographic type recently reported by Gopel, Manhes and Allegre (1992) is consistent with such an idea, since presumably the first solids to form in the nebula would be buried most deeply. However, others have questioned the existence of a relationship between cooling rate and metamorphism and suggest instead that the parent bodies may have been random mixtures of materials, perhaps even produced by the reassembling of previously disrupted objects (Taylor *et al.*, 1987).

A significant fraction of the L chondrites have K–Ar ages of about 500 Ma and show petrographic evidence for intense shock heating. It is widely assumed that the L chondrite parent body broke up in a very violent manner 500 Ma ago (Heymann, 1967).

More recently, ordinary and enstatite chondrites underwent further fragmentation, this time down to meter-sized objects which were small enough to undergo nuclear reactions with cosmic rays (Crabb and Schultz, 1981). The abundances of the isotopes produced by these reactions provide an estimate of the length of exposure to cosmic rays (see Cosmic ray exposure age). About one-third of the H chondrites have cosmic ray exposure ages of about 8 Ma, indicating a major impact event, or perhaps even break-up of the H chondrite parent body at that time. Others range from ≤ 1 up to about 100 Ma, consistent with the timescales for material coming from the asteroid belt to Earth via the resonance mechanisms. There is evidence that H chondrites from the 8 Ma impact have been coming to Earth over the last 1 Ma in a way that can provide new insights into parent body structure (Benoit and Sears, 1992).

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Bibliography

Afiattalab, F. and Wasson, J.T. (1981) Composition of the metal phases in ordinary chondrites: implications regarding classification and metamorphism. *Geochim. Cosmochim. Acta*, **44**, 431–46.

Alexander, C.M.O., Hutchison, R. and Barber, D.J. (1989) Origin of chondrule rims and interchondrule matrices in unequilibrated ordinary chondrites. *Earth Planet. Sci. Lett.*, **95**, 187–207.

Anders, E. (1988) Circumstellar material in meteorites: noble gases, carbon and nitrogen, in *Meteorites and the Early Solar System* (eds J.F. Kerridge and M.S. Matthews). Tucson: University of Arizona Press, pp. 927–56.

Benoit, P.H. and Sears, D.W.G. (1992) The break-up of a meteorite parent body and the delivery of meteorites to Earth. *Science*, **255**, 1685–7.

Bevan, A.W.R. and Binns, R.A. (1989) Meteorites from the Nullarbor Region, Western Australia: II. Recovery and classification of 34 new meteorite finds from the Mundrabilla, Forrest, Reid and Deakin areas. *Meteoritics*, **24**, 135–41.

Clayton, R.N., Grossman, L. and Mayeda, T.K. (1973) A component of primitive nuclear composition in carbonaceous meteorites. *Science*, **182**, 485–8.

Clayton, R.N., Mayeda, T.K., Goswami, J.N. and Olsen, E.J. (1991) Oxygen isotope studies of ordinary chondrites. *Geochim. Cosmochim. Acta*, **55**, 2317–37.

Crabb, J. and Schultz, L. (1981) Cosmic-ray exposure ages of the ordinary chondrites and their significance for parent body stratigraphy. *Geochim. Cosmochim. Acta*, **45**, 2151–60.

Fredriksson, K., Nelen, J. and Fredriksson, B.J. (1968) The LL-group chondrites, in *Origin and Distribution of the Elements* (ed. L.H. Ahrens). Pergamon, pp. 457–66.

Gaffey, M.J. (1976) Spectral reflectance characteristics of the meteorite classes. *J. Geophys. Res.*, **81**, 905–920.

Gooding, J.L. and Keil, K. (1979) Relative abundances of chondrule primary textural types in ordinary chondrites and their bearing on conditions of chondrule formation. *Meteoritics*, **16**, 17–43.

Gopel, C., Manhes, G. and Allegre, C.J. (1992) Constraints on the time of accretion and thermal evolution of chondrite parent bodies by precise U–Pb dating of phosphates. *Meteoritics*, **26**, 338.

Guimon, R.K., Keck, B.D. and Sears, D.W.G. (1985) Chemical and physical studies of type 3 chondrites – IV: annealing studies of a type 3.4 ordinary chondrite and the metamorphic history of meteorites. *Geochim. Cosmochim. Acta*, **19**, 1515–24.

Hewins, R.H. (1988) Experimental studies of chondrules, in *Meteorites and the Early Solar System* (eds J.F. Kerridge and M.S. Matthews). Tucson: University of Arizona Press, pp. 660–79.

Heymann, D. (1967) On the origin of the hypersthene chondrites: ages and shock effects of black chondrites. *Icarus*, **6**, 189–221.

Huss, G.R. (1989) Ubiquitous interstellar diamond and SiC in primitive chondrites: abundances reflect metamorphism. *Nature*, **347**, 159–162.

Hutchison, R., Alexander, C.M.O. and Barber, D.J. (1987) The Semarkona meteorite: first recorded occurrence of smectite in an ordinary chondrite, and its implications. *Geochim. Cosmochim. Acta*, **51**, 1875–82.

Jarosewich, E. (1980) Chemical analysis of meteorites: a compilation of story and iron meteorite analyses. *Meteoritics*, **25**, 323–7.

Kerridge, J.F. and Matthews, M.S. (eds) (1988) *Meteorites and the Early Solar System*. Tucson: University of Arizona Press.

Lofgren, G.E. (1989) Dynamic crystallization of chondrule melts of porphyritic olivine composition: texture experimental and natural. *Geochim. Cosmochim. Acta*, **53**, 461–70.

McSween, H.Y., Sears, D.W.G. and Dodd, R.T. (1988) Thermal metamorphism, in *Meteorites and the Early Solar System* (eds J.F. Kerridge and M.S. Matthews). Tucson: University of Arizona Press, pp. 102–13.

Pellas, P. and D. Storzer (1981) ^{244}Pu fission track thermometry and its application to stony meteorites. *Proc. Roy. Soc. London*, **A374**, 253–70.

Rubin, A.E. and Kallemeyn, G.W. (1989) Carlisle Lakes and Allan Hills 85151: members of a new chondrite grouplet. *Geochim. Cosmochim. Acta*, **53**, 3035–44.

Scott, E.R.D., Clayton, R.N. and Mayeda, T.K. (1985) Properties and genesis of two anomalous type 3 chondrites, Suwahib (Buwah) and Willaroy. *Lunar Planet. Sci.*, **16**, pp. 749–50.

Scott, E.R.D., Rubin, A.E., Taylor, G.J. and Keil, K. (1984) Matrix material in type 3 chondrites – occurrence, heterogeneity and relationship with chondrules. *Geochim. Cosmochim. Acta.*, **48**, 1741–57.

Sears, D.W.G. (1988) Chemical processes in the early solar system: A discussion of meteorites and astrophysical processes. *Vistas Astron.*, **32**, 1–21.

Sears, D.W. and H.J. Axon (1975) Ni and Co content of chondritic metal. *Nature*, **260**, 34–35.

Sears, D.W.G., Lu Jie, Keck, B.D. and Batchelor, D.J. (1991) Metamorphism of CO and CO-like chondrites and comparisons with type 3 ordinary chondrites. *Proc. NIPR Symp. Antarct. Meteorit.*, **4**, 1745–1805.

Sears, D.W., Grossman, J.N., Melcher, C.L. *et al.* (1980) Measuring metamorphic history of unequilibrated ordinary chondrites. *Nature*, **287**, 791–5.

Sears, D.W.G., Jie, L., Benoit, P.H. *et al.* (1992) A compositional classification scheme for meteoritic chondrules. *Nature*, **357**, 207–10.

Stoffler, D., Keil, K. and Scott, E.R.D. (1991) Shock metamorphism of ordinary chondrites. *Geochim. Cosmochim. Acta*, **55**, 3845–3867.

Swindle, T.D. and Podosek, F.A. (1988) Nucleo-cosmochronology, in *Meteorites and the Early Solar System* (eds J.F. Kerridge and M.S. Matthews). Tucson: University of Arizona Press, pp. 1114–26.

Taylor, G.J., Maggiore, P., Scott, E.R.D. *et al.* (1987) Original structures and fragmentation and reassembling histories of asteroids: evidence from meteorites. *Icarus*, **69**, 1–13.

Tilton, G.R. (1988) Age of the solar system, in *Meteorites and the Early Solar System* (eds J.F. Kerridge and M.S. Matthews). Tucson: University of Arizona Press, pp. 259–275.

Urey, H.C. and Craig, H. (1952) The composition of the stone meteorites and the origin of the meteorites. *Geochim. Cosmochim. Acta*, **4**, 36–82.

Van Schmus, W.R. (1969) The mineralogy and petrology of chondritic meteorites. *Earth Sci. Rev.*, **5**, 145–84.

Van Schmus, W.R. and Wood, J.A. (1967) A chemical–petrologic classification for the chondritic meteorites. *Geochim. Cosmochim. Acta*, **31**, 747–65.

Wisdom, J. (1985) Meteorites may follow a chaotic route to Earth. *Nature*, **315**, 731–3.

Wood, J.A. (1979) Review of metallographic cooling rates of meteorites and a new model for the planetesimals in which they formed, in *Asteroids* (ed. T. Gehrels). Tucson: University of Arizona Press, pp. 849–91.

Zinner, E. (1988) Interstellar cloud material in meteorites, in *Meteorites and the Early Solar System* (eds J.F. Kerridge and M.S. Matthews). Tucson: University of Arizona Press, pp. 956–83.

Cross references

Carbonaceous chondrite
Meteorite
Solar system: origin