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1.1. OVERVIEW AND CLASSIFICATION OF METEORITES

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Before interpreting properties of meteorites in terms of putative processes and conditions in the early solar system, it is necessary to understand just what sort of objects meteorites are. Such understanding begins with classification. In this chapter, we summarize the current taxonomy of meteorites, and show how certain stone meteorites, the chondrites, possess chemical and petrographic features that make them potentially attractive as probes of the early solar system. The prevalence of secondary alteration effects, often capable of perturbing the primitive record even in chondrites, is also emphasized.

1.1.1. METEORITE CLASSIFICATION

The purpose of classification is to sort the meteorites into broadly similar types of object, so that their origins and relationships can be better understood. Meteorites are a unique source of information about the materials present and conditions prevailing in the solar system during the earliest phases of its history: that is the central tenet of this book. It is clear that not all meteorites are the same; there are various compositional and physical differences between one meteorite and another, sometimes quantitatively minor, and sometimes major. One has to distinguish fundamental, primary properties, attributable to the starting material from which the meteorite was made, from

TABLE 1.1.1
Meteorite Classes and Numbers[a]

Class	Falls[b]	Fall frequency (%)[c]	Finds[d] Non-Antarctic[b]	Finds[d] Antarctic[e]
Chondrites				
CI	5	0.60	0	0
CM	18	2.2	5	34
CO	5	0.60	2	6
CV	7	0.84	4	5
H	276	33.2	347	671
L	319	38.3	286	224
LL	66	7.9	21	42
EH	7	0.84	3	6
EL	6	0.72	4	1
Other	3	0.36	3	3
Achondrites				
Eucrites	25	3.0	8	13
Howardites	18	2.2	3	4
Diogenites	9	1.1	0	9
Ureilites	4	0.48	6	9
Aubrites	9	1.1	1	17
Shergottites	2	0.24	0	2
Nakhlites	1	0.12	2	0
Chassignites	1	0.12	0	0
Anorthositic breccias	0	0	0	1
Stony-irons				
Mesosiderites	6	0.72	22	2
Pallasites	3	0.36	34	1
Irons				
IAB	6	0.73	97	4
IC	0	0.08	11	0
IIAB	5	0.45	60	6
IIC	0	0.05	7	0
IID	3	0.09	12	0
IIE	1	0.10	13	0
IIF	1	0.03	4	0
IIIAB	8	1.42	189	0
IIICD	2	0.14	19	0
IIIE	0	0.10	13	0
IIIF	0	0.05	6	0
IVA	3	0.39	52	1
IVB	0	0.09	12	0
Other irons	13	1.32	175	0

[a] Groups within a classification scheme conventionally contain 5 or more members; meteorites not falling into a group are generally termed "anomalous." In cases where it is useful to identify associations of less than 5 meteorites, the term "grouplet" is occasionally used; for example, Al Rais and Renazzo are normally considered CM chondrites, but they are more reduced than the others and may be referred to as the CR grouplet.

[b] Graham et al. (1985), with minor modification.

[c] Iron-meteorite fall statistics calculated from finds, scaled to percentage of total iron meteorite falls.

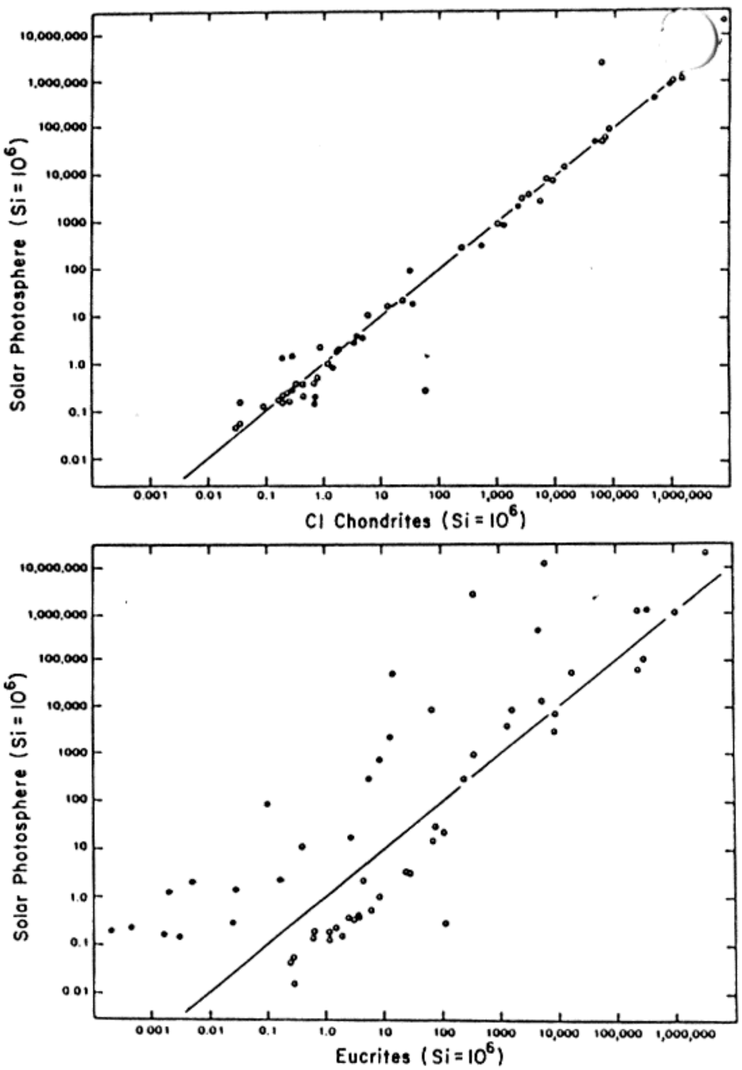

Fig. 1.1.1. Plots of element abundance in the solar photosphere against element abundance in the CI chondrites (a) and the eucrite achondrites (b). Siderophile and chalcophile elements are represented by filled symbols, others by open symbols. With the exception of several highly volatile elements and Li (which is underabundant in the Sun as a result of destructive nuclear reactions), the elements are present in similar proportions in the CI chondrites and the solar photosphere. On the other hand, in the eucrites (b), siderophiles and chalcophiles are 100-fold depleted and lithophiles are 10-fold enriched, relative to the solar photosphere (Sears 1987).

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[d] Data for finds are given to provide an indication of available material. The unusual conditions in the Antarctic favor the recovery of large numbers of meteorites without the selection biases of non-Antarctic regions (e.g., in non-Antarctic regions, stony meteorites, especially achondrites, are more easily confused with terrestrial rocks than iron meteorites). The statistics for Antarctic finds, therefore, more closely resemble those of falls than non-Antarctic finds. In fact, several rarer classes are overrepresented in the Antarctic collections.

[e] US finds in the Antarctic (Antarctic Meteorite Working Group 1986); probable pairings have been taken into account, but more may still be present. In addition, >6000 meteorites have been recovered from the Antarctic by Japanese teams.

TABLE 1.1.2

The An[illegible] and Ebihara Table of Cosmic Abundances of the Elements Based on Analyses for CI Chondrites[a]

Element	Atomic Abundance (atoms/10^6 Si)	Orgueil[c] Concentration
1 H	2.72×10^{10}	20.2 mg/g
2 He	2.18×10^{9}	56 nL/g
3 Li	59.7	1.59 μg/g
4 Be	0.78	26.7 ng/g
5 B	24	1.25 μg/g
6 C	1.21×10^{7}	34.5 mg/g
7 N	2.48×10^{6}	3180 μg/g
8 O	2.01×10^{7}	464 mg/g
9 F	843	58.2 μg/g
10 Ne	3.76×10^{6}	203 pL/g
11 Na	5.70×10^{4}	4830 μg/g
12 Mg	1.075×10^{6} [b]	95.5 mg/g
13 Al	8.49×10^{4}	8620 μg/g
14 Si	1.00×10^{6}	106.7 mg/g
15 P	1.04×10^{4}	1180 μg/g
16 S	5.15×10^{5} [b]	52.5 mg/g
17 Cl	5240	698 μg/g
18 Ar	1.04×10^{5}	751 pL/g
19 K	3770	569 μg/g
20 Ca	6.11×10^{4}	9020 μg/g
21 Sc	33.8	5.76 μg/g
22 Ti	2400	436 μg/g
23 V	295	56.7 μg/g
24 Cr	1.34×10^{4}	2650 μg/g
25 Mn	9510	1960 μg/g
26 Fe	9.00×10^{5} [b]	185.1 mg/g
27 Co	2250	509 μg/g
28 Ni	4.93×10^{4}	11.0 mg/g
29 Cu	514	112 μg/g
30 Zn	1260	308 μg/g
31 Ga	37.8	10.1 μg/g
32 Ge	118	32.2 μg/g
33 As	6.79	1.91 μg/g
34 Se	62.1	18.2 μg/g
35 Br	11.8	3.56 μg/g
36 Kr	45.3	8.7 pL/g
37 Rb	7.09	2.30 μg/g
38 Sr	23.8	7.91 μg/g
39 Y	4.64	1.50 μg/g
40 Zr	10.7	3.69 μg/g
41 Nb	0.71	250 ng/g
42 Mo	2.52	920 ng/g
44 Ru	1.86	714 ng/g
45 Rh	0.344	134 ng/g
46 Pd	1.39	557 ng/g
47 Ag	0.529	220 ng/g
48 Cd	1.69	673 ng/g

TABLE 1.1.2 *(continued)*

Element	Atomic Abundance (atoms/10^6 Si)	Orgueil[c] Concentration
49 In	0.184	77.8 ng/g
50 Sn	3.82	1680 ng/g
51 Sb	0.352	155 ng/g
52 Te	4.91	2280 ng/g
53 I	0.90	430 ng/g
54 Xe	4.35	8.6 pL/g
55 Cs	0.372	186 ng/g
56 Ba	4.36	2270 ng/g
57 La	0.448	236 ng/g
58 Ce	1.16	619 ng/g
59 Pr	0.174	90 ng/g
60 Nd	0.836	462 ng/g
62 Sm	0.261	142 ng/g
63 Eu	0.0972	54.3 ng/g
64 Gd	0.331	196 ng/g
65 Tb	0.0589	35.3 ng/g
66 Dy	0.398	242 ng/g
67 Ho	0.0875	54 ng/g
68 Er	0.253	160 ng/g
69 Tm	0.0386	22 ng/g
70 Yb	0.243	166 ng/g
71 Lu	0.0369	24.3 ng/g
72 Hf	0.176	119 ng/g
73 Ta	0.0226	17 ng/g
74 W	0.137	89 ng/g
75 Re	0.0507	36.9 ng/g
76 Os	0.717	590 ng/g[d]
77 Ir	0.660	473 ng/g
78 Pt	1.37	953 ng/g
79 Au	0.186	145 ng/g
80 Hg	0.52	390 ng/g
81 Tl	0.184	143 ng/g
82 Pb	3.15	2430 ng/g
83 Bi	0.144	111 ng/g
90 Th	0.0335	28.6 ng/g
92 U	0.0090	8.1 ng/g

[a] See Anders and Ebihara (1982) for details and sources.

[b] Average of mean values for individual meteorites. For the remaining elements, a straight average of all acceptable analyses was used.

[c] Abundances in Orgueil, the "typical," i.e., most widely studied, CI chondrite, are adequately close to the CI chondrite mean, except for REE, where the values given in Table 6 of Anders and Ebihara (1982) are preferable. For maximum accuracy, a CI chondrite mean, for elements other than H, C, N, O and the noble gases, may be calculated from the atomic abundances in column 2, using the relation $C = 3.788 \times 10^{-3}\ HA$, where C = weight concentration (μg/g), H = atomic abundance, and A = atomic weight.

[d] The Os value is a correction to that of Anders and Ebihara (1982), based on a personal communication from E. Anders.

properties which were produced by later events and which may overlay the original properties; sometimes later events may totally destroy primary properties. Several of the details of classification and interpretation are therefore intertwined, and while some interpretations are simple and well understood, and classifications based on them are secure, others may be more controversial. The route to the present meteorite classification schemes was therefore long and tortuous, and some abortive early efforts still permeate the literature (see Sears 1978, p. 60, for a review). The meteorite classes commonly recognized today are briefly described in this chapter and are listed in Table 1.1.1, along with some statistics of falls and finds. Brief definitions of the classes and other terms commonly used in meteorite studies, which might not be familiar to readers, are listed in the Glossary at the back of the book.

The simplest classification of meteorites is into stones, irons and stony-irons. However, further subdivision is essential because there is considerable diversity within these divisions; in fact, these three divisions unite objects of dissimilar character and history, and separate objects that we now know to be closely related. The irons are pieces of metal (essentially Fe-Ni alloys) while the stony-irons are mixtures of stony material and metal. Among the stones there is enormous diversity in chemical and physical properties. The most fundamental distinction is that some, termed chondrites (since they usually contain distinctive features known as chondrules), have a composition which is remarkably similar to that of the solar photosphere for all but the most volatile elements (Fig. 1.1.1a), while others, the achondrites (and other differentiated meteorites) differ considerably from the Sun in composition (Fig. 1.1.1b). While the details may differ from one class of meteorite to another, chondrites are approximately solar in composition while achondrites are enriched in lithophile elements, and depleted in siderophile and chalcophile elements, by about an order of magnitude or more.

The compositional similarity between chondrites and the photosphere, two very different types of extraterrestrial material, has profound implications for the study of both. The Sun is a fairly normal star, and astrophysical observations indicate that much of the cosmos has a composition similar to it. The concept of "cosmic abundances" is not without its flaws, but the idea that there is a mean starting composition from which solar-system objects were formed, has become important in modeling meteorite and solar histories. Table 1.1.2 is a compilation of current best estimates of cosmic abundances.

On the basis of subtle differences in the proportions of major, nonvolatile elements, and differences in mineralogy and mineral composition, the chondrites are divided into 9 classes: the CI, CM, CO and CV chondrites, many of which are characterized by relatively high C contents and which are collectively termed the "carbonaceous chondrites"; the H, L and LL classes, which are qualitatively similar to each other, constitute the most abundant meteorite type and are collectively termed the "ordinary chondrites" and the EH and

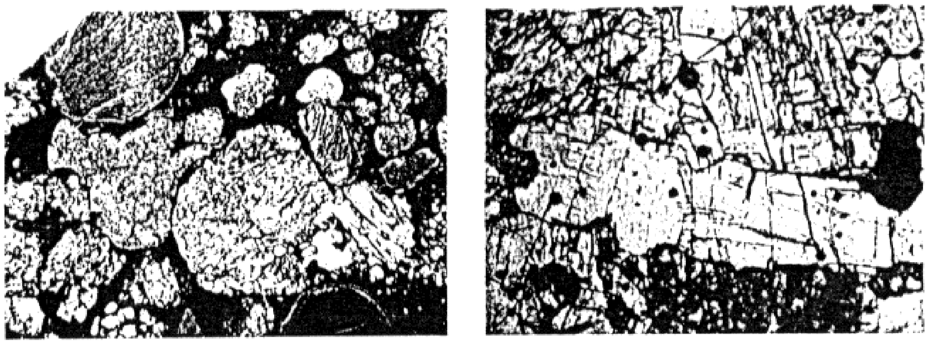


Fig. 1.1.2. The internal structure of (a) a chondrite and (b) an achondrite are clearly apparent when the samples are prepared as thin (30 μm) sections and viewed through a microscope using transmitted light. In the Semarkona chondrite, the fine-grained opaque matrix and chondrules, with a variety of internal structures, are readily apparent. The section is about 1.2 mm across. In the achondrite (Serra de Magé), large well-formed crystals of feldspar with occasional small grains of pyroxene and troilite are visible. The width of field is about 2.6 mm. (Both photographs kindly provided by R. Hutchison.)

EL chondrites, which are collectively termed the "enstatite chondrites" after their dominant mineral. Significantly, isotopic properties can also be used to identify most of these classes. The details of the classification of chondrites are discussed further below. There are also considerable petrological differences between the chondrites and the others; the chondrites are aggregates of different sorts of material ("cosmic sediments") while the achondrites are either igneous rocks or derived from igneous rocks. The major lithic components in chondrites are the chondrules, matrix, metal and sulfide and, in certain classes, inclusions rich in Ca, Al and similar refractory elements. Chondrules are an especially important component, both in terms of their high abundance and their scarcity in other rocks. They are essentially silicate mineral assemblages, typically 0.1 to 1.0 mm in size, which had an independent existence prior to the formation of the meteorite. They have a wide variety of internal structures, but generally consist of silicate grains enclosed either in glass or in crystals which formed from a glass (Gooding and Keil 1981; see also Chapter 9.1). Chondrules have been partially or totally melted (Chapter 9.2) and many owe their droplet form to their liquid origin. The origin of chondrules is discussed in Chapters 9.3 and 9.4. Figure 1.1.2 compares the overall structure of a chondrite and an achondrite, as seen in transmitted light under a low-powered microscope. Figure 1.1.3 shows some hand specimens of various meteorites.

The achondrites and stony-iron meteorites are relatively few in number but very diverse in their properties and histories. Brief descriptions of their major mineralogy are given in the Glossary. All have experienced major planetary processing, typically including melting, which has virtually obscured the nebular phases of their history, but they sometimes provide an

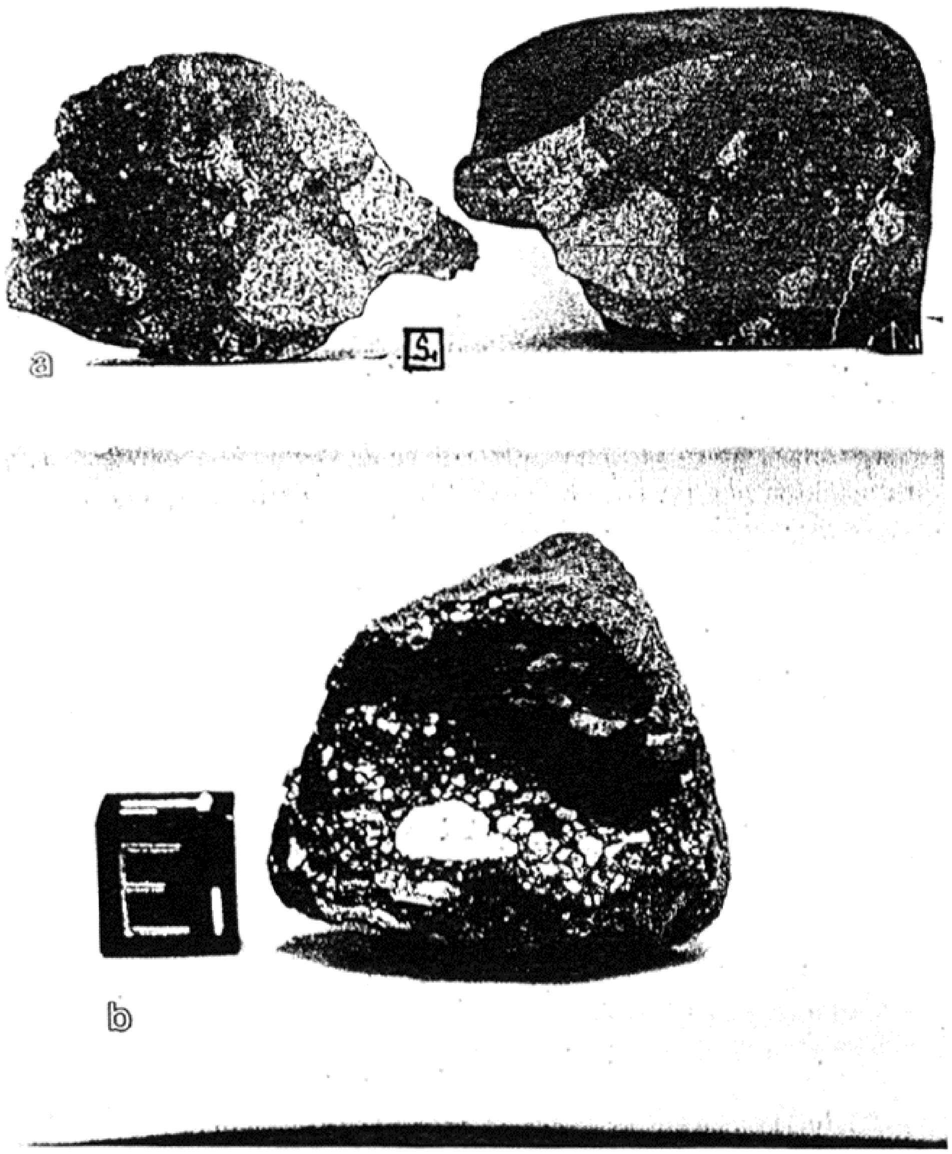
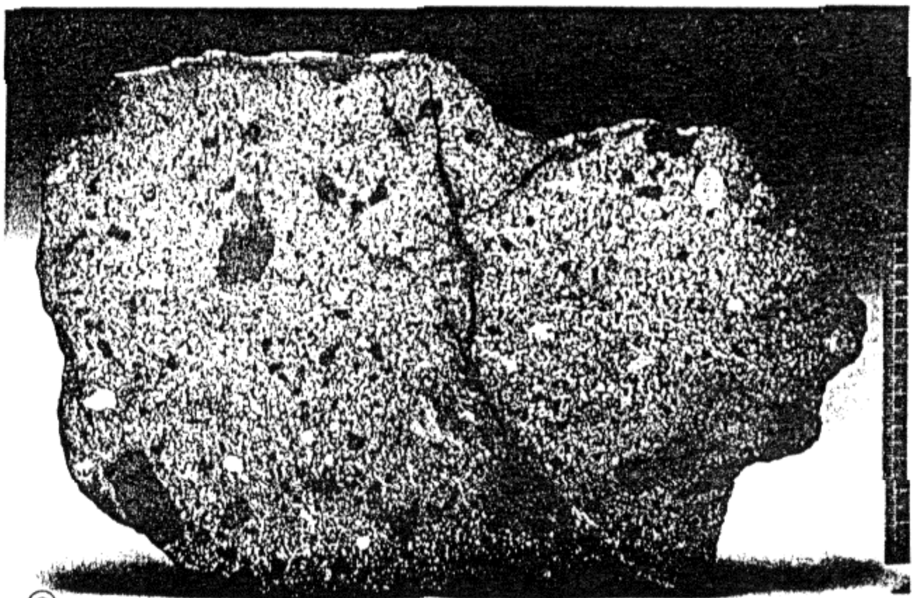


Fig. 1.1.3. Some hand specimens of meteorites. (a) The Fayetteville regolith breccia showing the light-dark structure of the interior and the black fusion crust produced by the heat of atmospheric passage. Scale cube is 1 cm. (b) The Allan Hills A81005 achondrite which is from the Moon. Scale cube is 1 cm. (c) The Crab Orchard stony-iron meteorite (mesosiderite). (d) The Edmonton, Kentucky, III C,D iron meteorite showing an etched, polished face exhibiting the Widmanstätten structure. (Photographs were kindly provided by (a) C. Schwarz, (b) J. Annexstad, (c) R. Hutchison, (d) J. T. Wasson.)

c



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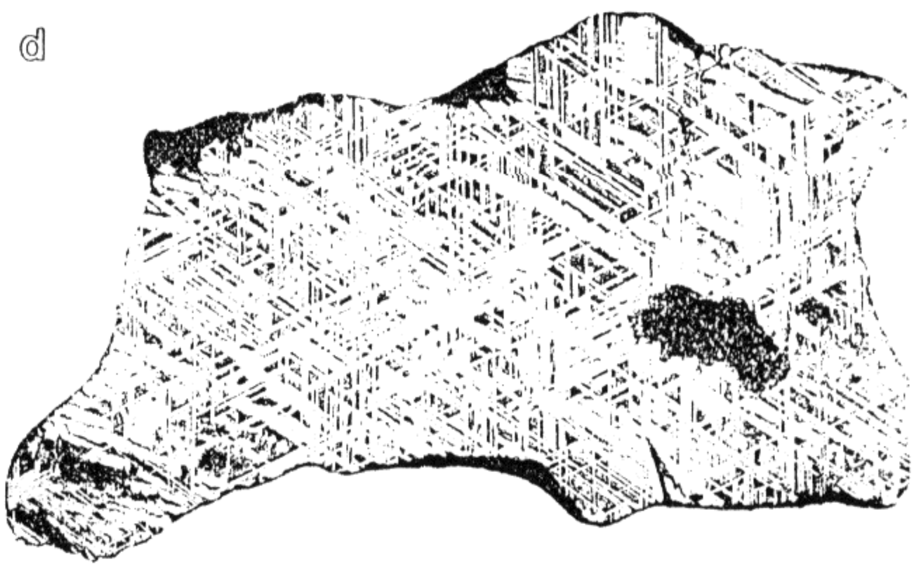

indication of the scale and type of igneous processes that occurred in the early solar system (Chapter 3.2). These, in turn, sometimes provide insights into available heat sources, sizes of parent objects and time of accretion.

Pallasites consist of networks of Fe-Ni alloy containing angular or rounded nodules of olivine (typically 4 to 5 mm in size). They are clearly of igneous origin, and probably formed at the interface between a large molten metal body (such as a core or large metal nugget) and a large magma chamber in which olivine could form and sink to the bottom.

Three groups of achondrite (eucrites, diogenites and howardites) and the pyroxene-plagioclase stony-irons, or mesosiderites, are closely related. The eucrites and diogenites are magmatic rocks, while the others are breccias of these two classes. In the case of the mesosiderites, a large metallic component is also present, while howardites may contain fragments of more extreme composition than normally seen in eucrites and diogenites. Most authors agree that the parent material for these classes was chondritic, and that their varied textures and compositions reflect differences in cooling history, complicated considerably in some cases by metamorphism and shock.

The shergottites, nakhlites and Chassigny, collectively termed the SNC meteorites, are also closely related achondrites. Their bulk compositions, trapped noble gases and relatively young formation ages (around 1.25 Gyr) suggest that they came from Mars (Chapters 5.3, 7.8 and 7.10). The four anorthositic breccia achondrites found in the Antarctic have no established class name, though a wide variety of compositional, chronological and petrographic data indicate that they are of lunar origin. The other major achondrite classes are aubrites and the ureilites. The aubrites may be partially melted EL chondrites, but the matter is disputed. The ureilites are magmatic rocks to which significant amounts of C and volatile-rich material have been added.

There are many unusual achondrites and stony-irons, some of which may be related to established classes. A unique achondrite is Angra dos Reis that was formed by magmatic processes 4.55 Gyr ago, very close to the time of formation of the solar system at 4.56 Gyr (Chapter 5.2). Lodran is a unique stony-iron meteorite of uncertain origin, possibly related to the IAB irons, see below, and several unusual chondrites like Winona. It has been suggested that these meteorites may constitute an additional class of meteorite. Bencubbin and Weatherford are unclassified breccias that contain chondritic and achondritic clasts.

The study of iron meteorites illustrates the strong influence of taxonomy on interpretation, and the effect of advancing technology on both. Iron meteorites are essentially Fe-Ni alloys with minor amounts of C, S and P. The alloy segregates into two phases, a low-Ni body-centered-cubic phase known as the α phase or "kamacite," and a high-Ni face-centered-cubic phase known as the γ phase or "taenite." Iron-meteorite structures may range from pure kamacite, with shock-twins (Chapter 3.6) as their only structural feature (these are structurally termed "hexahedrites"), to meteorites which are structureless to the naked eye but consist of taenite with microscopic grains of kamacite ("ataxites"). In between these extremes are the majority of irons, which consist of plates of kamacite, in an octahedral arrangement, with taenite filling the interstices; an example appears in Fig. 1.1.3d. Irons with this structure are termed "octahedrites," and their characteristic structure is called the "Widmanstätten structure" after one of its discoverers. The structure of an iron meteorite, and its coarseness, depend on the bulk Ni content and the cooling rate of the meteorite. Until recently, irons were classified almost en-

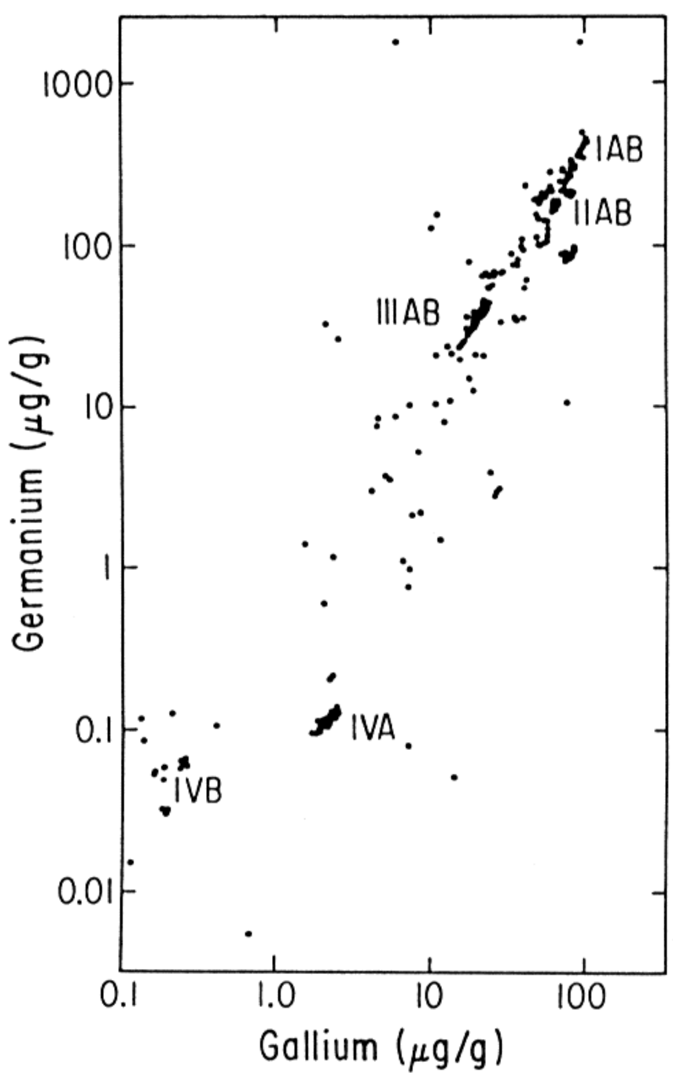

Fig. 1.1.4. Plot of Ge content against that of Ga for iron meteorites. Some of the larger classes are indicated (figure from Sears 1978).

tirely in terms of their structure and, although this scheme has largely given way to one based on composition, structure is clearly relevant to major questions concerning starting composition and subsequent history.

The structures and Ni contents of iron meteorites do not produce well-defined groups. The structural types grade into each other and, while there are some peaks in the histogram of Ni contents, there are no gaps. This is not true for the volatile trace elements Ga and Ge (Fig. 1.1.4), which show a 10^4- and 10^6-fold range in abundance, respectively, throughout the irons as a whole, but produce many tight clusters within which these elements vary by less than a factor of 2. It seems that these elements are unique because (1) their volatility made them especially sensitive to small differences in the pressure and temperature in the region of the solar nebula in which the irons formed, and (2) their distributions were relatively insensitive to subsequent igneous processes. Irons are therefore commonly classified on the basis of Ga, Ge and Ni content, qualified occasionally by structural and mineralogical factors. The most populous classes are known as IAB, IIAB, IIIAB, IVA and IVB, and there are a great many smaller classes (the nomenclature originally reflected Ga and Ge abundance, but has become somewhat arbitrary). The classification of iron meteorites has been reviewed by Scott and Wasson (1975).

It should be stressed that while classification sorts meteorites which differ from each other in a manner which can help us identify origins and formation mechanisms, it does not preclude genetic relationships between classes. In Fig. 1.1.5, an attempt has been made to indicate the relationships, or lack thereof, between the various classes. For example, the two types of

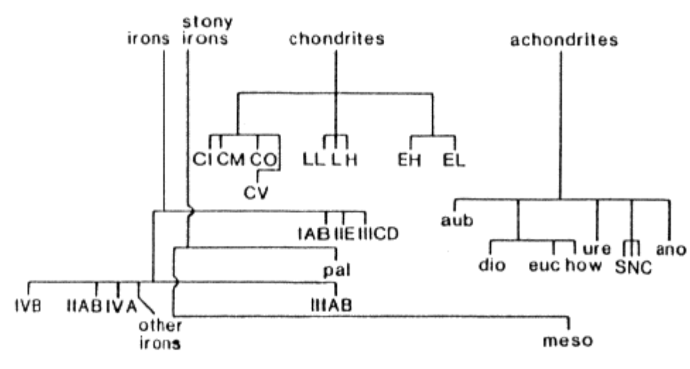

Fig. 1.1.5. A "family tree" of meteorite classes and an indication of possible interclass relationships; for example, the IAB, IIE and IIIAB iron meteorites and the pallasites (pal) may be related to the ordinary chondrites, although it is clear that the relationship is closest for the IAB and IIE irons (which contain silicates of approximately chondritic composition); the mesosiderites (meso) may be related to the howardite and eucrite achondrites, and the aubrites have been related to the enstatite chondrites. Abbreviations for the achondrites are as follows: aubrites, aub; diogenites, dio; eucrites, euc; howardites, how; ureilites, ure; shergottites, nahklites and chassignites, SNC; the anorthositic breccias, ano.

stony-iron meteorites discussed above share the relatively trivial characteristic of being about half metal and half silicate, but the pallasites are much more closely related to iron meteorites than they are to the mesosiderites. The mesosiderites are, in turn, more closely related to eucrites and howardites than they are to the pallasites. The CI, CM and CO chondrites are, likewise, more closely related to each other than any are to the CV chondrites.

1.1.2. THE CHONDRITES: PRIMARY CLASSIFICATION

After many decades of having been considered to be almost identical in composition, small systematic differences in composition among the chondrites were discovered in the early 1950s. These differences led, ultimately, to the definition of the 9 chondrite classes (Table 1.1.3). There appear to have been a number of processes which caused elemental abundances to depart from their mean cosmic values. In terms of the kinds of elements involved, and how they are used in classification, the taxonomic discriminants are as follows:

1. Nonvolatile lithophile elements cause the cleanest separations; for example, Mg/Si is 1.05 for carbonaceous chondrites, 0.95 for ordinary chondrites and 0.83 for enstatite chondrites (Fig. 1.1.6) (Ahrens et al. 1968). If refractory elements (e.g., Ca/Si), are taken into account, the CV class separates from the others (Van Schmus and Hayes 1974);
2. The siderophile elements lead to further subdivision of these classes; the

TABLE 1.1.3
Chondrite Classes and Mean Properties[a]

Group	Mg/Si (a/a)	Ca/Si (a/a)	Fe/Si (a/a)	Fa (mol%)	Co in Kamacite (mg/g)	Fe_{met}/Fe_{tot}	$\delta^{18}O$ (‰)[c]	$\delta^{17}O$ (‰)[c]
CI	1.05	0.064	0.86	—	—	0	~16.4	~8.8
CM	1.05	0.068	0.80	—	—	0	~12.2	~4.0
CO	1.05	0.067	0.77	—	—	0–0.2	~−1.1	~−5.1
CV	1.07	0.084	0.76	—	—	0–0.3	~0	~−4.0
H	0.96	0.050	0.81	16–20	5.2	0.58	4.1	2.9
L	0.93	0.046	0.57	23–26	10.6	0.29	4.6	3.5
LL	0.94	0.049	0.52	27–32	22.9[b]	0.11	4.9	3.9
EH	0.77	0.035	0.95	—	—	0.76	5.6	3.0
EL	0.83	0.038	0.62	—	—	0.83	5.3	2.7

[a] Data from Von Michaelis et al. (1969); Anders and Ebihara (1982); Sears and Axon (1976); Sears and Weeks (1986); Wiik (1969); Mason (1966); Van Schmus and Hayes (1974); R. N. Clayton 1981 and other sources.
[b] While many of the LL chondrites cluster around the value indicated, they show a "tail" up to 110.0 mg/g (see Fig. 1.1.9).
[c] Relative to SMOW.

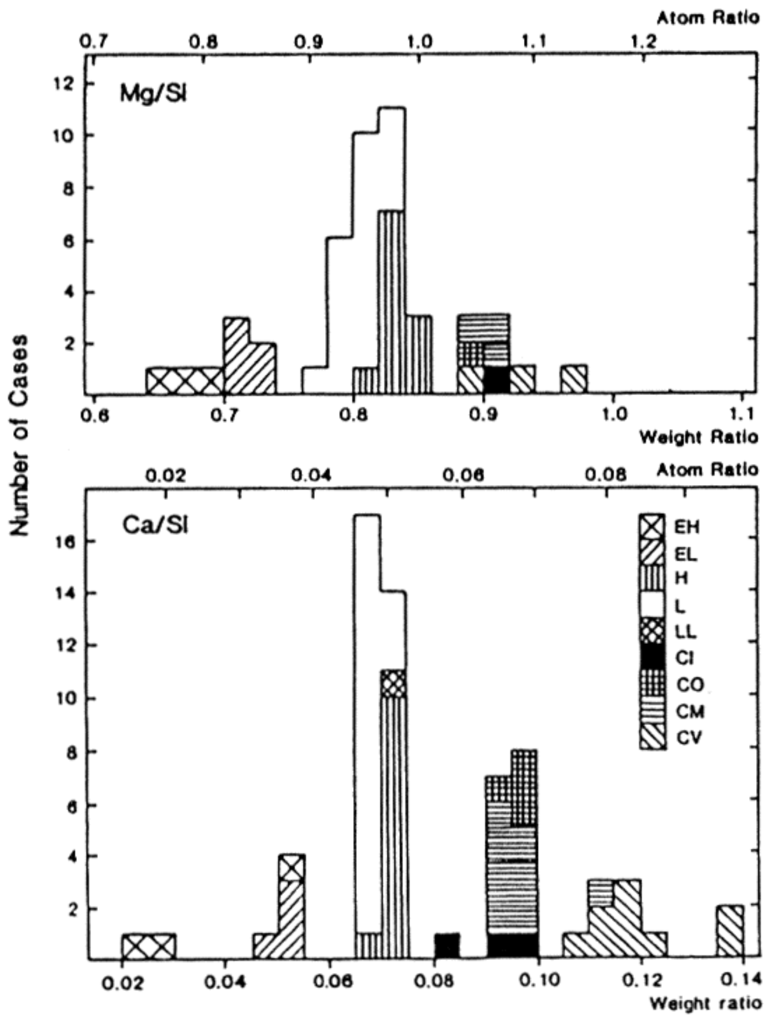

Fig. 1.1.6. Histograms of the Mg/Si and Ca/Si contents of chondrites. These elemental ratios are the basis of classification into enstatite (EH and EL), ordinary (H, L and LL) and carbonaceous (CI, CM, CO and CV) chondrites. Further resolution into individual classes is sometimes possible; for example, the CV chondrites are clearly resolved from the other carbonaceous chondrites on the basis of Ca/Si (figure after Von Michaglis et al. 1969; Van Schmus and Hayes 1974).

ordinary chondrites into the H, L and LL classes (Urey and Craig 1953; Craig 1964) (for high Fe, low Fe and low Fe-low metal) and the enstatite chondrites into the EH and EL classes (Sears et al. 1982). Carbonaceous chondrites can also be subdivided to some degree on the basis of Fe/Si, but the same subdivisions are more readily made on the basis of other criteria;

3. Oxidation state, or, more precisely, the proportion of Fe in the silicates and sulfides as compared to that in metal, varies throughout the classes defined by lithophile and siderophile elements (Keil 1968; Fredriksson

and Keil 1964; Fredriksson et al. 1969; McSween 1979). To discuss oxidation-state-related parameters further, it is necessary to look briefly into the relevant mineralogy.

As of 1975, more than 100 minerals had been identified in meteorites, many of them unknown elsewhere (a list of the better documented minerals may be found in Appendix 1). However, most of them are present in trace amounts. The important minerals for the classification of ordinary chondrites are olivine, Ca-poor pyroxene (commonly orthopyroxene), feldspar, sulfide and metal. Olivine and pyroxene are solid solutions of Fe-, Mg- and Ca-silicates. Olivine is a solid solution of two main components, fayalite (Fe_2SiO_4, symbol Fa) and forsterite (Mg_2SiO_4, Fo). Pyroxenes are solid solutions of ferrosilite ($FeSiO_3$, Fs), enstatite ($MgSiO_3$, En) and Wollastonite ($CaSiO_3$, Wo). Other components are more abundant in pyroxene than olivine, and the structure of pyroxene allows for large amounts of "impurities." Feldspar is a solid solution of three Al-silicate end members, albite ($NaAlSi_3O_8$, symbol Ab), anorthite ($CaAl_2Si_2O_8$, An) and orthoclase ($KAlSi_3O_8$, Or). Various names are given to feldspars of intermediate compositions; for example, feldspar in ordinary chondrites is typically oligoclase ($Ab_{84}An_{10}Or_6$). The sulfide in ordinary chondrites is almost always pure FeS, known as troilite after an eighteenth century monk who observed the mineral with the naked eye in a newly fallen meteorite. The metal occurs as two phases (kamacite and taenite), as in iron meteorites; they exist as small, widely dispersed grains surrounded by silicates.

The enstatite and the carbonaceous chondrites generally have a distinctly different mineralogy from that of the ordinary chondrites. The enstatite chondrites are predominantly metal, enstatite and various sulfides (Mason 1966; Keil 1968). In addition to troilite, which is unusual for its large content of Ti, the enstatite chondrites contain a number of remarkable sulfide, phosphide and carbide minerals (see Appendix 1). There is also an oxynitride of Si, not observed elsewhere, called sinoite (Si_2N_2O).

The carbonaceous chondrites, likewise, have varied mineralogy (McSween 1979). The CI and CM chondrites consist mainly of a variety of clay-like hydrous sheet silicates often identifiable with terrestrial phyllosilicates such as serpentine (see Chapter 3.4). They also contain hydrous Mg- and Ca-sulphates (sometimes in veins that suggest deposition from aqueous solutions), magnetite in a variety of morphologies, and considerable quantities of C, as carbonate or complex organic compounds (Chapter 10.5). Unlike the CM chondrites, the CI chondrites do not contain chondrules. The CO and CV chondrites are similar to the ordinary chondrites in their major mineralogy, but contain olivines with a mean composition that is richer in Fe. The CO chondrites are noteworthy for the smallness of their chondrules.

The CV chondrites are especially known for the presence of mm-sized white or pinkish inclusions of Ca- and Al-rich minerals (Ca-Al-rich inclusions or CAI, see Chapter 10.3). CAIs are also frequently observed in other carbonaceous classes, and occasionally in ordinary chondrites. They may be either fine grained (< 1 μm) and composed essentially of spinel and pyroxene, with sodalite, nepheline and grossularite, or coarse grained (100 μm to 1 mm) and composed predominantly of spinel and melilite (type A) or spinel, anorthite and pyroxene (type B). Both types of CAI occasionally contain sulfide-metal assemblages, referred to as "Fremdlinge," whose metal is rich in rare refractory elements like Re, Os and Ir. High-temperature mineral assemblages similar to those observed in the CAIs sometimes occur as chondrules (Grossman 1980).

We now return to the question of the classification of chondrites and, in particular, the relevance of parameters that involve the degree of oxidation of Fe. Figure 1.1.7 compares the amount of Fe in the "reduced" form, i.e., as metal, with the amount in the "oxidized" and "sulfurized" form, usually as

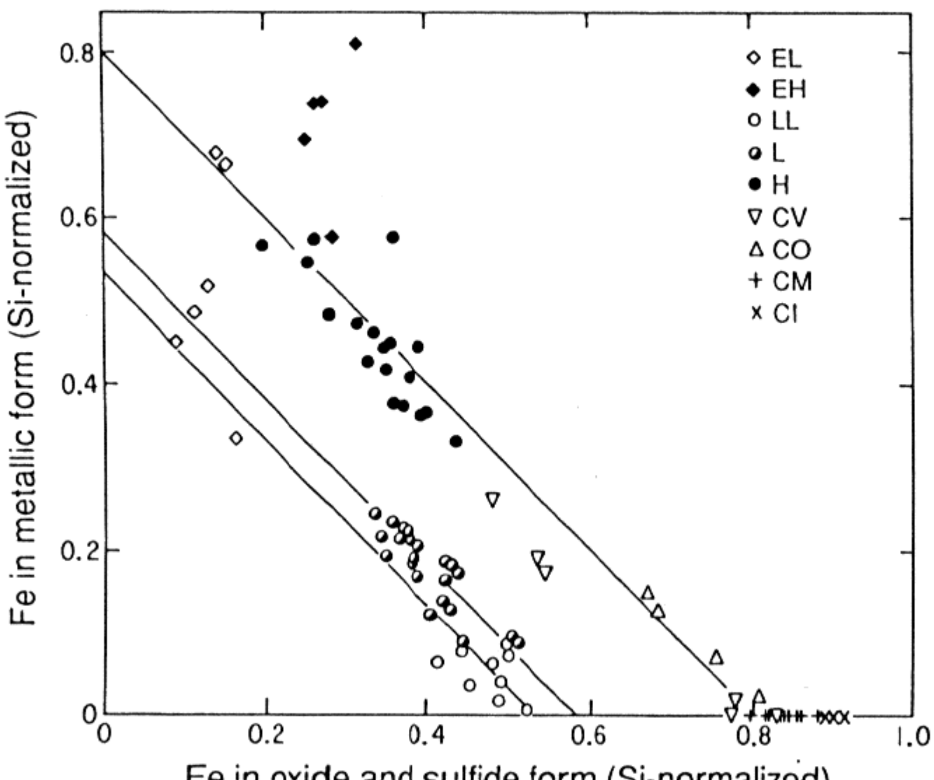

Fig. 1.1.7. Plot of the Fe/Si ratio for the sulfides and metal against Fe/Si in the oxidized phases (mainly silicates) for the chondritic meteorites. The bulk Fe/Si for the meteorites determines the position of the diagonal, while the oxidation state of the Fe determines the location of a given data point on the diagonal. The enstatite, ordinary and carbonaceous chondrites are clearly resolved, but resolution on a finer scale is also possible, especially for EH and EL chondrites and H, L and LL chondrites. See also Fig. 7.4.1.

silicates and sulfides. A meteorite with a specific Fe/Si ratio, but with all the Fe in the reduced form, would plot at the top-left end of one of the diagonal lines. A meteorite with the same bulk Fe/Si ratio, but with a high level of oxidation, would plot on the same diagonal but at the lower-right end of the line. Intermediate degrees of oxidation or reduction would cause meteorites to plot at intermediate locations on the diagonal. Different bulk Fe/Si ratios would correspond to different diagonals. Thus the plot reveals two trends in the data, (1) variations in Fe oxidation (see also Chapter 7.7) and (2) variations in bulk Fe/Si (see also Chapter 7.4). On the basis of such data, the enstatite, ordinary and carbonaceous chondrites are resolved, since the enstatite chondrites are highly reduced, the carbonaceous chondrites are highly oxidized and the ordinary chondrites are intermediate. These data enable the ordinary chondrites to be resolved further into the H, L and LL classes (Urey and Craig 1953; Craig 1964).

These differences in Fe oxidation within the ordinary chondrites are also reflected in their mineralogy. A plot of the fayalite content of olivine against the ferrosilite content of pyroxene, for instance, clearly resolves the H, L and LL classes (Fig. 1.1.8). Although other factors are involved, the Co content of the kamacite is also in large part determined by the degree of Fe oxidation

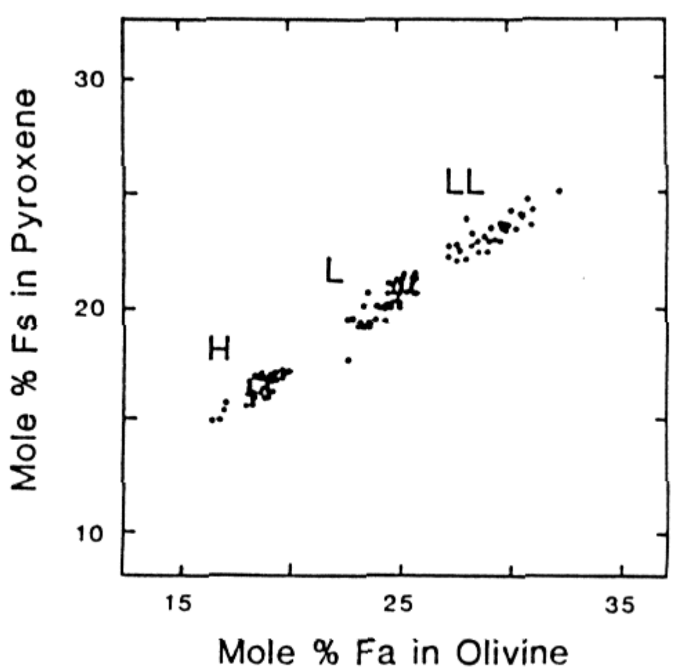

Fig. 1.1.8. Plot of the ferrosilite in the low-Ca pyroxene against the fayalite content of the olivine for the equilibrated (types 4–6) ordinary chondrites. This measure of the oxidation state of the Fe sorts the ordinary chondrites into the H, L and LL classes (figure after Fredricksson and Keil 1964; Fredricksson et al. 1969).

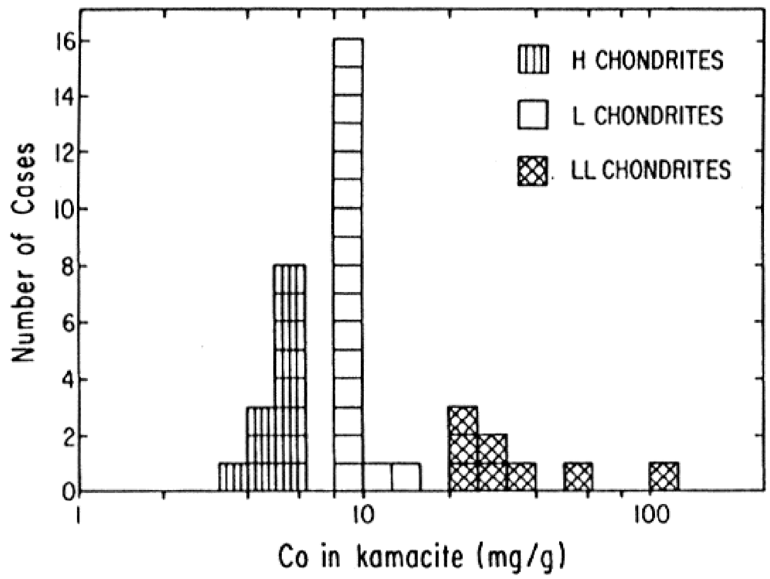

Fig. 1.1.9. Histogram showing the amount of cobalt in the kamacite of equilibrated ordinary chondrites. This measurement is acutely sensitive to the extent to which Fe has been oxidized, the H and L chondrites having 4–6 and 8–14 mg/g of Co in the kamacite, respectively. The LL chondrites show much larger amounts of Co in the kamacite and show a wide range of values (Sears and Weeks 1986).

and can be used to resolve the groups (Fig. 1.1.9). These data indicate that the LL chondrites are not only more oxidized than the others, but they also show a much greater spread in the degree of Fe oxidation.

It should be stressed that although certain elemental ratios (e.g., Mg/Si, Ca/Si) were singled out for discussion above, the elements chosen are representative rather than unique; for example, one can generally substitute any refractory lithophile element and produce a histogram like that of Ca/Si (see Chapter 7.3). Nevertheless, elements that are geochemically similar may vary systematically in volatility and this may also help with classification. Thus, plots of elemental abundance, with elements ranked according to their volatility in a gas of solar composition, can also be meaningful for distinguishing the classes from each other as they constitute a "finger-print." Figure 1.1.10 shows schematic diagrams for the element abundances as a function of volatility for the 9 chondrite classes (see also Chapters 7.5 and 7.6). When both lithophile and siderophile/chalcophile element trends are taken into account, each chondrite class has a unique abundance pattern.

The relative abundances of the 3 isotopes of O have provided an independent means of classification (Clayton et al. 1976; Fig. 1.1.11). A convenient way to examine the data is to plot differences in the $^{17}O/^{16}O$ ratio between the sample and a standard, such as standard mean ocean water (SMOW), against the corresponding differences in $^{18}O/^{16}O$. The differences

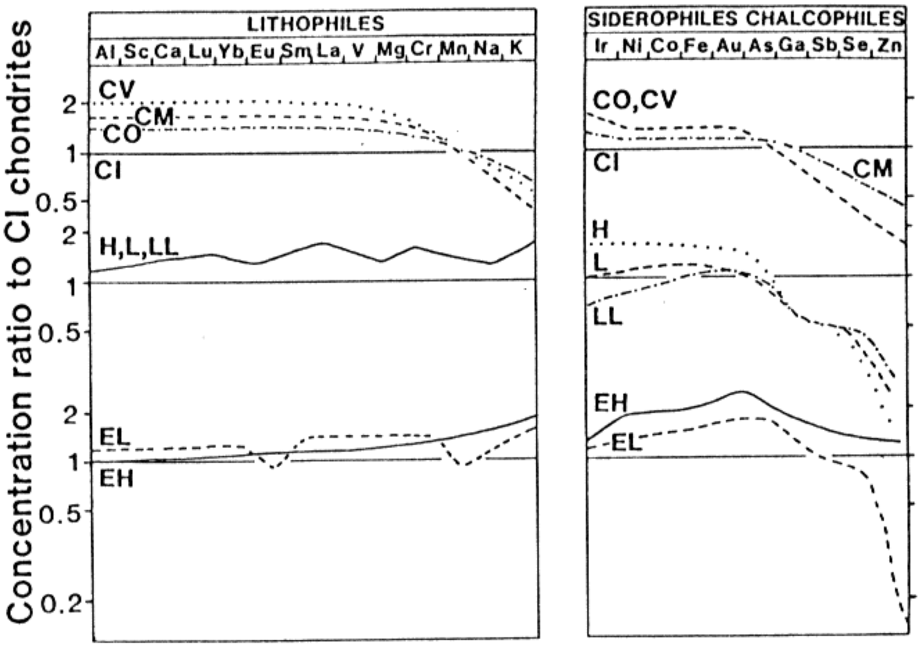

Fig. 1.1.10. Schematic diagrams showing elemental abundance patterns in the chondritic meteorite classes. The concentration of each element in each class is expressed as a ratio to its concentration in CI chondrites. Taking this ratio removes the effects of differences in elemental abundances produced during nucleosynthesis and enables us to examine small differences from CI patterns. Each class has a unique elemental abundance pattern (see also Chapters 7.3, 7.4, 7.5 and 7.6).

are expressed as parts per thousand, or per mil (‰). Two processes seem to have determined the isotopic proportions of O in a given meteorite or part of a meteorite: (1) mixing of two or more components with different isotopic proportions and, (2) mass fractionation. An unusual component of O is enriched in ^{16}O, and mixtures of this with more "normal" O (i.e., containing greater amounts of ^{17}O and ^{18}O) result in lines of slope very near unity in a plot such as Fig. 1.1.11. Mass fractionation is the adjustment of isotopic proportions by physical and chemical processes which are mass dependent (see also Chapter 12.1). Most processes (e.g., volatilization, crystallization, chemical reactions) are of this kind and tend to distribute samples along a line of slope close to 0.5 on a 3-isotope plot. The H, L and LL classes of ordinary chondrites plot in similar regions of the plot, with the H chondrites clearly resolved from the others and the L chondrites weakly resolved from the LL chondrites. The carbonaceous-chondrite classes plot in very widely dispersed regions of the diagram, and it was the distribution of data for minerals in CAIs from the Allende CV chondrite along a slope-1 line which first indicated the presence of exotic ^{16}O-rich material, probably of extrasolar-system origin, in meteorites. The enstatite chondrites plot on the line occupied by terrestrial

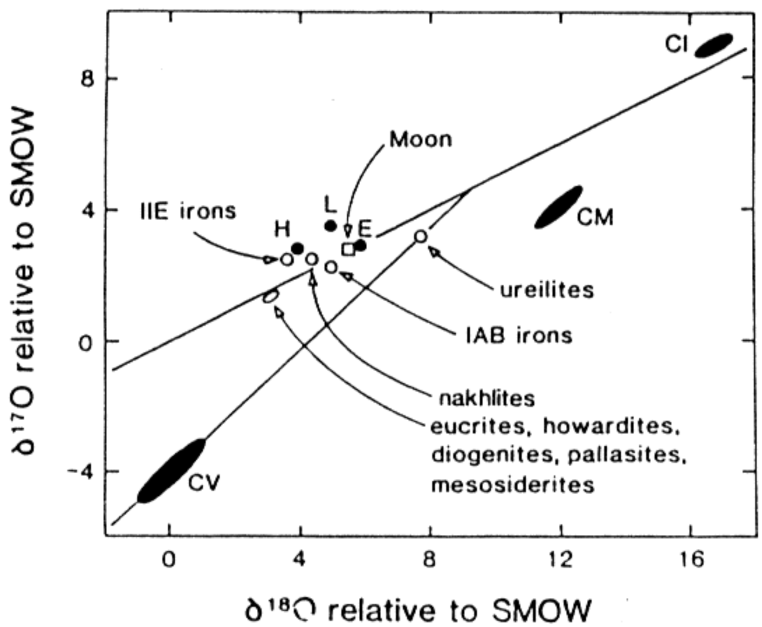

Fig. 1.1.11. Plot showing the distribution of the three isotopes of O in meteorites. The δ parameter refers to the difference in the ratio ^{17}O or ^{18}O to ^{16}O (in parts per thousand, or per mil) between the sample and standard mean ocean water (SMOW). Terrestrial and lunar samples plot along the line with slope ~0.5 which is referred to as the "terrestrial mass-fractionation" line. The line with slope ~1.0 is produced by components from Allende and other meteorites and reflects mixing of an ^{16}O-enriched component and a more "normal" component (figure after Clayton 1981).

samples and, while the EH and EL chondrites differ slightly in their O-isotope systematics, the two groups are not well resolved.

1.1.3. THE CHONDRITES: SECONDARY PROPERTIES

During or after the accretion of chondritic material in the solar nebula, this material underwent several processes that modified its original nebular properties. As discussed above, the classification of meteorites often involves judgment concerning these primary (nebular) and secondary properties. Over the last several decades, schemes have been devised which attempt to describe the nature and extent of the secondary processes and they are often regarded as part of the meteorite's classification in as much as they can be reported, in a routine way, along with the meteorite's class. The processes which have received most attention are metamorphism, shock, aqueous alteration and brecciation. These are described in some detail in Part 3 of this book and are dealt with only briefly here as they relate to classification.

The few chondrites that escaped significant levels of metamorphism (up to 1200°C) on their parent bodies are particularly helpful for identifying pro-

TABLE 1.1.4
Definitions of Petrographic Types[a]

	Petrographic Types					
	1	2	3	4	5	6
(i) Homogeneity of olivine and pyroxene compositions	—	>5% mean deviations		<5% mean deviations to uniform	Uniform	
(ii) Structural state of low-Ca pyroxene	—	Predominantly monoclinic		monoclinic: >20%	monoclinic: <20%	orthorhombic
(iii) Degree of development of secondary feldspar	—	Absent		<2 μm grains	<50 μm grains	>50 μm grains
(iv) Igneous glass	—	Clear and isotropic primary glass; variable abundance		Turbid if present	Absent	

(v) Metallic minerals (maximum Ni content)	—	(<20%) Taenite absent or very minor	kamacite and taenite present (>20%)			
(vi) Sulfide minerals (average Ni content)	—	>0.5%	<0.5%			
(vii) Overall texture	no chondrules	very sharply defined chondrules		well-defined chondrules	chondrules readily delineated	poorly defined chondrules
(viii) Texture of matrix	all fine-grained, opaque	much opaque matrix	opaque matrix	transparent micro-crystalline matrix	recrystallized matrix	
(ix) Bulk carbon content	~3.5%	1.5–2.8%	0.1–1.1%	<0.2%		
(x) Bulk water content	~6%	3–11%	<2%			

[a] Table modified after Van Schmus and Wood (1967). The strength of the vertical line is intended to reflect the sharpness of the type boundaries. A few ordinary chondrites which show signs of partial melting, in response to higher metamorphic temperatures than those associated with type 6, are described as petrographic type 7. Water contents do not include loosely bound, i.e., terrestrial water.

cesses that occurred before accretion, especially at the level of individual grains. Van Schmus and Wood (1967) have devised a widely used scheme in which chondrites are assigned to one of six petrographic types on the basis of a variety of petrographic and mineralogic properties (Table 1.1.4). [Editor's Note: Traditionally, the term "petrologic" has been used in connection with these types, but in fact "petrographic" is the correct term for use within a taxonomic context. The latter is therefore used throughout this book, even in chapters where the authors' versions used "petrologic." Of course, the relevant observations have also a petrologic significance.] As petrographic type increases, minerals that were initially inhomogeneous become more homogeneous, the dominant form of Ca-poor pyroxene changes from monoclinic to orthorhombic, volatile inventories decrease and primary textures become obliterated and chondrules less well defined. The glassy material in the chondrules, which is characteristic of the lower petrographic types, becomes turbid in type 4 and disappears in the higher types, to be replaced by feldspar which increases in grain size at the highest types. In recent years, meteorites and meteorite clasts have been identified in which metamorphism seems to have caused partial melting; these are sometimes referred to as type 7.

The type 3 ordinary chondrites have experienced a considerable range of metamorphic intensity which is evident in several of the parameters discussed above (Dodd et al. 1967), but especially in thermoluminescence (TL) sensitivity (Sears et al. 1980). TL sensitivity is acutely dependent on the extent of crystallization of the chondrule glass and, while it displays a 10^5-fold range

TABLE 1.1.5
Definition of Subtypes of Type 3 Ordinary Chondrites[a]

Type	TL Sensitivity (Dhajala = 1)	C.V.(Fa) in Olivine[b]	C.V.(Co) in Kamacite[c]	Matrix Recrystallization (%)	F/FM Ratio[d]
3.9	2.2–4.6	5–10	<1.5–1.9	>60	<1.0
3.8	1.0–2.2	11–20	1.9–3.1	>60	1.0–1.1
3.7	0.46–1.0	21–30	3.1–6.3	>60	1.1–1.2
3.6	0.22–0.46	31–40	6.3–7.5	>60	1.2–1.3
3.5	0.10–0.22	41–50	7.5–10.0	~50	1.3–1.4
3.4	0.046–0.10	>50	10.0–12.5	~20	1.4–1.5
3.3	0.022–0.046	>50	12.5–16.3	10–20	1.5–1.6
3.2	0.010–0.022	>50	16.3–21.3	10–20	1.6–1.7
3.1	0.0046–0.010	>50	21.3–26.3	10–20	1.7–1.9
3.0	<0.0046	>50	>26.3	<10	>1.9

[a] Table from Sears et al. (1980).
[b] Coefficient of variation of Fa in olivine. Standard deviation expressed as a percentage of the mean.
[c] Coefficient of variation of Co in kamacite.
[d] FeO/(FeO+MgO) in the matrix normalized to the same quantity for the whole rock.

over the ordinary chondrites as a whole, within the type 3 ordinary chondrites there is a 10^3-fold range. Thus the type 3 ordinary chondrites can be subdivided into types 3.0–3.9 (Table 1.1.5). There are also significant changes in the way in which TL is emitted as petrographic type increases; these reflect the state of the feldspar and can be used to provide unique insights into palaeotemperatures (Chapter 3.3). CO chondrites share many mineralogical properties with type 3 ordinary chondrites, and like them constitute a metamorphic sequence. Using petrographic criteria similar to those used for type 3 ordinary chondrites, McSween (1979) identified three subdivisions which he labeled I, II and III. One of the parameters identified by McSween was the disappearance of glass and the formation of feldspar; as expected, TL sensitivity also increases along the metamorphic sequence (Keck and Sears 1987). However, the emission characteristics differ from the ordinary chondrite case, implying different cooling histories for the two classes.

As noted above, and discussed in Chapter 3.4, CI1 and CM2 chondrites show evidence of considerable aqueous alteration, so that type 3 chondrites may better represent original nebular material. Recently, hydrous silicates, calcite and magnetite have been found in two type 3.0–3.1 ordinary chondrites, so it seems possible that several of their unusual properties, once thought due to weak thermal metamorphism, are actually aqueous-alteration effects (Hutchison et al. 1987). A cartoon, which summarizes the probable relative roles of metamorphism and aqueous alteration in carbonaceous and ordinary chondrites, is shown in Fig. 1.1.12.

Brecciation and shock are common features of meteorites of all classes; however, the effects vary more randomly from group to group than the sec-

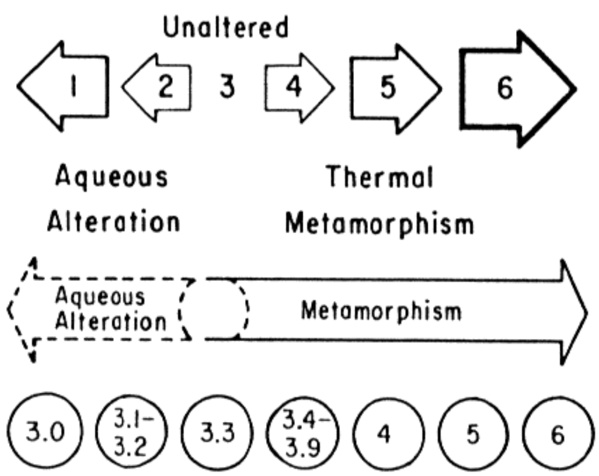

Fig. 1.1.12. Sketches suggesting possible relationships between aqueous alteration, metamorphism and petrographic type for all chondrites (*above*, from McSween [1979]) and for ordinary chondrites (*below*, based on Guimon et al. [1987]). These meteorites have apparently experienced aqueous alteration, but its importance relative to metamorphism is unclear.

TABLE 1.1.6
Classification of Chondritic Breccias*

Breccia Type	Description
Lithic fragments in breccias	— xenolithic—clasts of different chemical class to host
	— cognate—impact-melt fragments
Regolith breccias	— fragmental debris on surface of body (contain solar-wind gases, solar-flare tracks, agglutinates, etc.), usually have light-dark structure
Fragmental breccias	— fragmental debris with no regolith properties
Impact melt breccias	— unmelted debris in igneous matrices
Granulitic breccias	— metamorphosed fragmental breccias
Primitive breccias	— type 3 ordinary chondrite breccias

* Table after Keil (1982).

ondary properties summarized by Van Schmus and Wood (1967), and lesser significance is usually given to them in modern classification schemes. The terms polymict, monomict and genomict are often used to describe breccias. Polymict breccias are those in which the fragments differ from each other compositionally, while monomict means that the fragments of the breccia are similar compositionally. Genomict means that the fragments differ from each other petrographically but not compositionally. However, this scheme is less precise and comprehensive than that recently suggested by Keil (1982), which is described in Table 1.1.6; but, there is again a complex interplay between classification and interpretation. Brecciation is discussed in detail in Chapter 3.5.

Shock played a major part in disrupting the parent objects of the meteorites and perhaps in sending the fragments to Earth. Systematic studies of shock effects have resulted in several classification schemes, some based on metal structures and others based on silicate properties. The widely used scheme of Dodd and Jarosewich (1979) is summarized in Table 1.1.7, with some additional data. Identified are six shock "facies" labeled a–f which represent increasing levels of shock. Laboratory calibration experiments provide rough estimates of the shock level described by each facies and these are given in Table 1.1.7. However, it should be stressed that chondrites, which are complex mixtures of minerals with highly diverse physical properties, behave very differently from pure minerals during the passage of shock waves so that the classification is essentially qualitative. Shock effects on meteorites, and minerals which are relevant to meteorite studies, are discussed in Chapter 3.6.

TABLE 1.1.7

Definition and Properties of 6 Shock Facies in Ordinary Chondrites[a]

Shock Facies	Pressure[b] (GPa)	Olivine	Plagioclase	Melt Pockets	^{40}Ar	TL Sensitivity	Trace Elements
a	<5	fractured	<50% deformed	None	normal	normal	normal
b	5–20	fractured & undulose extinction	<50% deformed	None	normal	normal	normal
c	20–22	fractured & undulose extinction	>50% deformed	None	~0.7 × normal	0.15–0.4	Bi,Ag,Zn <0.8
d	22–35	fractured & mosaic extinction	100% deformed or maskelynite	Present	~0.7 × normal	0.0025–0.15	In,Tl,Cd <0.5
e	35–57	fractured, mosaicked & marginal granulation	>50% maskelynite	Present	~0.1 × normal	0.025–0.15	Bi,Ag,Zn <0.5
f	>57	recrystallized	100% maskelynite	Present	~0.1 × normal	0.025–0.15	In,Tl,Cd <0.1

[a] Table after Dodd and Jarosewich (1979); Walsh and Lipschutz (1982); Sears et al. (1984); Dennison and Lipschutz (1986).

[b] 1 Gigapascal (GPa) equals 10 kbar. A recalibrated scale of shock effects can be found in Table 3.6.2.

1.1.4. SIGNIFICANCE OF THE CHONDRITE CLASSES

It is clear from four lines of evidence that the 9 chondrite classes offer unique insights into conditions in the early solar system. First, as described in detail above, they are compositionally very similar to the Sun and quite unlike other known samples of solid material in the solar system. This suggests a relatively simple origin from a common pool of starting material. Second, they have formation ages similar to those inferred for the Earth, Moon and Sun, and presumably that of the solar system as a whole, namely about 4.55 Gyr (Chapter 5.2). Radiometric systems which can readily be disturbed, such as those dependent on the retention of gases, sometimes yield lower ages, but in these cases there is usually evidence that the ages refer to a subsequent event such as shock heating. Third, virtually all chondrites, especially some of the low type 3 ordinary chondrites, contain highly non-equilibrium assemblages which have been altered very little, if at all, since the components came together. An example is the coexistence of Si-bearing metal and silicates (see Chapter 7.7). Fourth, chondrites contain isotopic evidence for accumulation quite soon after the end of element synthesis (Chapter 15.1). Also some elements are present with isotopic proportions that are not encountered in any other known solar-system material; apparently this material escaped the isotopic homogenization experienced by most solids (Chapter 12.1). In some instances, there is a resemblance between these unusual isotopic ratios and those in interstellar molecules (Chapters 13.1 and 13.2).

Given this background, the existence of 9 distinct classes of chondrite is significant because it leads to the conclusion that those classes were established in the solar nebula. This means that the properties that distinguish one class from another—the variations in Mg/Si, Fe/Si, oxidation state and O-isotope ratios, for instance—in some way reflect nebular processes. For example, there was apparently a nebular process for separating metal and silicate to produce the Fe/Si variations (Chapter 7.4). Another process caused mixing of reservoirs with different O-isotope properties. Some of these properties seem to be paralleled in the different planets to some extent (Fe/Si and oxidation state variations, for example) which may mean that the chondrite classes sampled different regions of the nebula. Thus each of the classes, and any unusual property each displays, may be providing a snap-shot view of conditions ~ 4.55 Gyr ago at a particular nebular location. The major challenge of modern meteorite studies is to take these complex, ancient samples from the earliest days of solar-system history, disentangle the diverse properties which have resulted from their great age and the various processes that they have experienced, and thus learn something about a unique time and place in the history of our planetary system.

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