1 Introduction

Solar System history started some 4567 million years ago with the collapse of an interstellar molecular cloud to a protoplanetary disk (the solar nebula) surrounding a central star (the Sun). Evolution of the Solar System continued through a complex process of accretion, coagulation, agglomeration, melting, differentiation and solidification, followed by bombardment, collision, break-up, brecciation and re-formation, then to varying extents by heating, metamorphism, aqueous alteration and impact shock. One of the key goals of planetary science is to understand the primary materials from which the Solar System formed, and how they have been modified as the Solar System evolved. The last two decades have seen a greater understanding of the processes that led to the formation of the Sun and Solar System. Advances have resulted from astronomical observations of star-formation regions in molecular clouds, the recognition and observation of protoplanetary disks and planetary systems around other stars, and also from advances in laboratory instrumentation that have led to more precise measurements on specific components within meteorites, e.g., refinement of chronologies based on short-lived radionuclides. Results from meteorites are important because meteorites are the only physical materials available on Earth that give direct access to the dust from which the Solar System formed. Study of meteorites allows a more complete understanding of the processes experienced by the material that resulted in the Earth of today.

1.1 Naming of meteorites

Meteorites are pieces of rock and metal, almost all of which are fragments broken from asteroids during collisions. They fall at random over the Earth's surface, and have also been identified as components within lunar soils [1.1, 1.2] and on Mars' surface [1.3]. Meteorites are named from their place of find or fall, traditionally after a local geographic feature or centre of population. However, where large numbers of meteorites are found within a limited area, this convention is not possible to follow. The recovery of meteorites from desert regions has resulted in a name–number nomenclature that combines geographic and date information. Antarctic specimens collected by government-funded expeditions are given a year–number combination with a prefix recording the icefield from which they were retrieved (e.g., Allan Hills 84001), whereas meteorites collected in hot deserts are simply numbered incrementally by region (e.g., Dar al Gani 262). The rules for naming newly recovered meteorites have been standardized by the Nomenclature Committee of the Meteoritical Society, which also assigns names to meteorites and keeps track of the total number of reported specimens. This information is available at http://www./pi.usra.edu/meteor/metbull.php.

Newly recovered meteorites are also reported in the *Meteoritical Bulletin* (published in the journal *Meteoritics and Planetary Sciences*, and updated regularly on the website as above). The *Catalogue of Meteorites*, last published in book form in 2000, is a database of all meteorites [1.4], and is also available through a searchable interface at http://www.nhm.ac.uk/jdsml/research-curation/research/projects/metcat/.

1.2 Classification of meteorites

Classifying meteorites enables similarities and differences between specimens to be recognized. This, in turn, allows inferences to be drawn about relationships between groups, their origins and the common processes that they have experienced. Over the years, meteorite classification has become a more precise science, partly as a result of the increasing sophistication of the instrumentation available for meteorite analysis, and partly owing to the increasing numbers of meteorites recovered from desert locations. Many schemes for classification have been devised, some with more utility than others, but all schemes, right from the very first descriptions of meteorites, recognized a basic division between stone and iron meteorites. Meteorites can be divided into two main types, according to the processes they have experienced: unmelted (unfractionated, undifferentiated) and melted (fractionated, differentiated). The unmelted meteorites, or chondrites, are all stones, and in all but the most volatile of elements, have compositions that are close to that of the solar photosphere. Melted meteorites

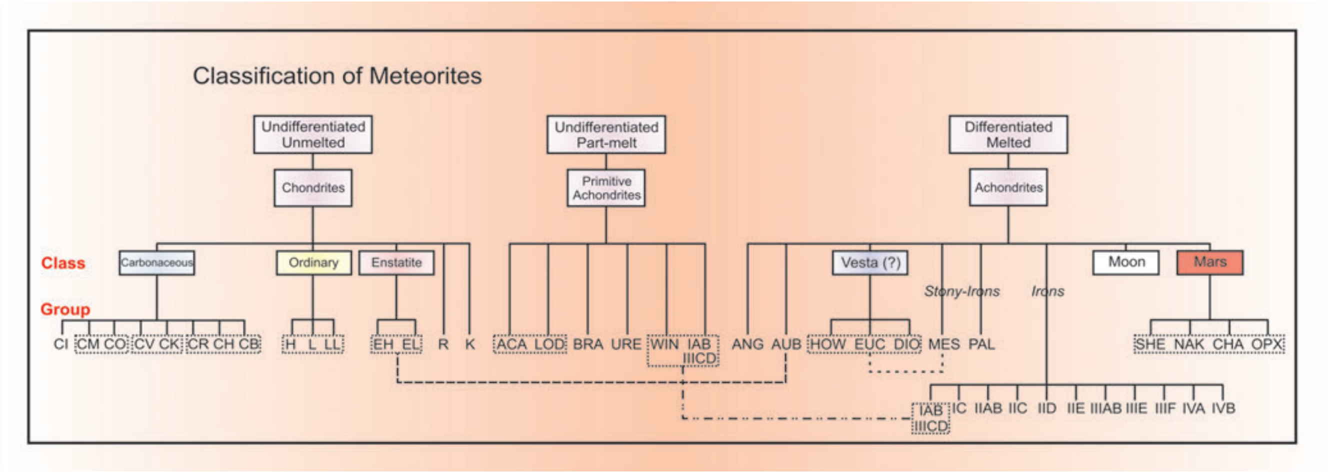

Figure 1.1: Schematic classification of meteorites, showing the main groups of each class. The dashed boxes and lines indicate clans (or supergroups) of meteorites that might have formed in closely neighbouring nebular or parent body locations [1.7]. ACA – Acapulcoites; ANG – Angrites; AUB – Aubrites; BRA – Brachinites; CHA – Chassignites; DIO – Diogenites; EUC – Eucrites; HOW – Howardites; LOD – Lodranites; MES – Mesosiderites; NAK – Nakhlites; OPX – Orthopyroxenite; PAL – Pallasites; SHE – Shergottites; URE – Ureilites; WIN – Winonaites. After [1.6, 1.7].

(achondrites) cover a range of compositions from stone, through stony-iron to iron. Bridging between these two major divisions are the primitive achondrites: meteorites that have an unfractionated composition, but textures that indicate they have been strongly heated, if not melted. Both unmelted and melted meteorites are further subdivided into classes and groups; their interrelationships are shown in the 'family tree' in Figure 1.1. Classification of meteorites is one way of identifying materials that might be associated in space and time, e.g., through accretion in closely neighbouring regions of the solar nebula, or having suffered similar processes of heating, melting, differentiation and/or hydrothermal alteration. Despite enormous progress brought about by increasing numbers of meteorites and advances in analytical instrumentation, the classification scheme is incomplete, and there are many meteorites that do not fit comfortably into the framework. There is not always a clear-cut distinction between types: e.g., there are many iron meteorites that contain silicate inclusions related to chondritic meteorites. Clasts and inclusions within meteorites also frequently defy ready assignation to recognized meteorite groups.

1.2.1 Historical background

One of the most detailed classification schemes was proposed in 1863 by the curator of the meteorite collection at the Mineralogical Museum in Berlin, Gustav Rose [1.5]. He subdivided meteorites according to their mineralogy, into three groups of iron meteorites (pure nickel–iron, pallasites and mesosiderites) and seven groups of stones. It was Rose who first introduced the term *chondrule* (from the Greek *chondros*, meaning grain or seed) to describe the spherical globules present in many of the stony meteorites. He also named the chondrule-bearing meteorites *chondrites*, and recognized separate classes of *carbonaceous chondrites*, *eucrites*, *howardites* and *chassignites*, terms that all survive today.

Rose's scheme was later expanded in 1883 by the custodian of the Vienna mineral and meteorite collection, Gustav Tschermak [1.8], who subdivided Rose's iron meteorites into irons and stony-irons. Tschermak also attempted the first classification of iron meteorites on the basis of the width of the kamacite lamellae in the Widmanstätten pattern revealed by etching. Tschermak renamed Rose's class of shalkites to *diogenites*. Tschermak's successor at Vienna, Aristides Brezina, continued to modify and expand the classification system, to include divisions by structure and colour [1.9]. It was he who introduced the term *achondrite* to distinguish non-chondrule-bearing stones from chondrites. By the end of the nineteenth century, the combined Rose–Tschermak–Brezina system (RTB) of meteorite classification was the most widely used and accepted scheme throughout the international meteorite community. Although the RTB classification system, based on structure and mineralogy, was widely used, it was mostly a qualitative system, reliant on subjective judgements such as colour. Between 1916 and 1920, George T. Prior, Keeper of the Mineralogy Department at the (then) British Museum (Natural History) proposed a revised and simplified meteorite classification scheme based on reliable chemical analyses [1.10, 1.11]. He formulated 'Prior's Rules', which noted the relationship between the amount of iron metal in a chondrite, and the iron content of its silicate: the less the amount of nickel–iron metal, the richer in iron are the silicates. The scheme subdivided the chondrites according to the iron content of their pyroxenes, into enstatite, olivine–bronzite and hypersthene–bronzite chondrites, and the achondrites into calcium-rich and calcium-poor groups. The Prior classification for chondrites is the basis of that in use today.

In 1953, Urey and Craig [1.12], using only what they termed 'superior' chemical analysis of chondrites, demonstrated that the chondrites were distinguishable on the basis of their total iron content, in addition to the extent of oxidation of this iron (Figure 1.2). The olivine–bronzite chondrites corresponded to a group which they termed H-group (for high total iron content, approximately 28%) and the hypersthene–bronzite chondrites to a group termed L-group (low total iron content, 22%). Prior [1.10, 1.11] had also noted that the hypersthene–bronzite chondrites could be further subdivided into two types, chemically and mineralogically distinct, the Baroti and Soko–Banja types. Mason and Wiik [1.13] found that the Soko–Banja-type meteorites were very similar to another, minor, group of meteorites, the amphoterites. Up until this time, analysis of mineral chemistry had relied on the painstaking separation of minerals from meteorites, followed by measurement using either wet chemistry or X-ray diffraction techniques. Keil and Fredriksson [1.14] were among the first analysts to apply the electron microprobe to meteorite samples, using thin sections of ordinary chondrites. They studied meteorites from Prior's Soko–Banja subgroup, and noted that they had the same total iron content as the L-group chondrites, but a lower iron metal (as opposed to oxidized iron in the silicates) content. On these grounds, the Soko–Banja-type meteorites and amphoterites were renamed the LL-group (for low total iron, low metallic iron). The three groups, H, L and LL chondrites, are now collectively known as **ordinary chondrites** (Chapter 3), and, without accounting for pairing, in total comprise some 87% of all known meteorites, around 95% of all chondrites [1.4].

The **carbonaceous chondrite** (Chapter 2) class of meteorites exhibits considerable variation in mineralogy. The term 'carbonaceous chondrite' is a misnomer on two counts: there are other meteorite groups (e.g., the ureilite achondrites, Chapter 9) that contain comparable amounts of carbon, and one of the carbonaceous chondrite groups (CI) does not contain chondrules. Notwithstanding this, the name has remained since Gustav Rose first introduced it in 1863. Carbonaceous chondrites may also be subdivided into chemically and structurally distinct types. The first such distinction was made by Wiik [1.15], who based the divisions on volatile element content (C, H_2O and S), as well as on the specific gravity of the meteorites. Using mean values of these criteria, he distinguished three types (I, II and III). Mason [1.16] redefined these types, following which they became the C1, C2 and C3 types according to mineralogy [1.17]. The C3 chondrites were further subdivided [1.18, 1.19] into the Ornans and Vigarano subtypes (C3(O) and C3(V), respectively).

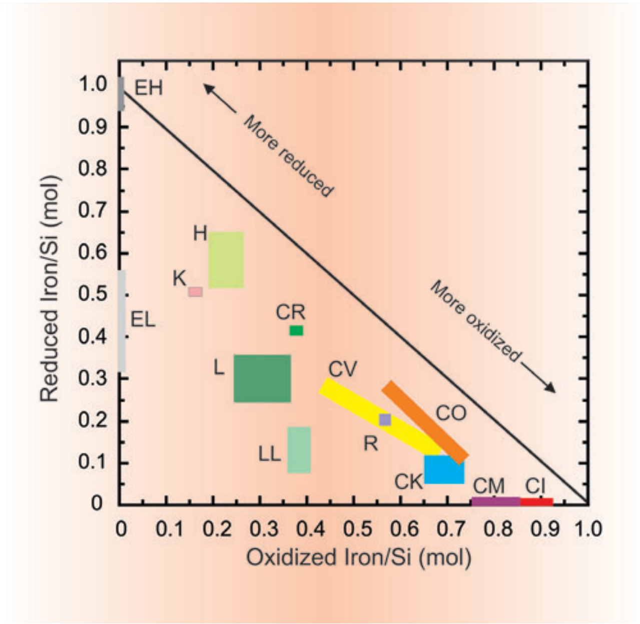

Figure 1.2: Urey–Craig plot, modified from [1.24], showing how the ratio of reduced iron (metal and sulphides) varies with oxidized iron (silicates and oxides) among the different chondrite groups. The line (slope −1) is that along which meteorites with the same total iron content but different oxidation states would fall [1.24].

The remaining class of chondrites, the **enstatite chondrites** (Chapter 4), named by Prior [1.10, 1.11] after their dominant mineral composition, show extreme variation in iron and sulphur contents [1.20]. These changes in composition also correlate with their degree of metamorphism [1.21, 1.22] and so the group was subdivided into two types [1.20]: EI (high iron and sulphur, little recrystallization) and EII (low iron and sulphur, highly recrystallized). The groups were renamed as EH and EL, respectively [1.23], by analogy with the high- and low-iron groups (H and L) of the ordinary chondrites.

Figure 1.2 is a modified version of the Urey–Craig plot (after ref. 1.24), showing the relative positions of the enstatite, carbonaceous and LL-group ordinary chondrites, in addition to the original H- and L-group ordinary chondrites. Other major element ratios (e.g., Mg, Ca and Al) have been used to separate the chondrites into various

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Table 1.1: Criteria for assigning petrologic type to chondrites (after refs. 1.18, 1.24, 1.37)

Criterion	1	2	3	4	5	6
Homogeneity of olivine and low Ca-pyroxene	–	> 5% mean deviations		≤ 5%	Homogeneous	
Structural state of low Ca-pyroxene	–	Predominantly monoclinic		> 20% monoclinic	< 20% monoclinic	Orthorhombic
Feldspar	–	Minor primary grains only		Secondary < 2 μm grains	Secondary 2–50 μm grains	Secondary > 50 μm grains
Chondrule glass	–	Altered, mostly absent	Clear, isotropic, variable abundance	Devitrified, absent		
Metal: maximum bulk Ni content		< 20%; taenite minor or absent	> 20%; kamacite and taenite in exsolution relationship			
Sulphides: mean Ni content	–	> 0.5 wt.%		< 0.5 wt.%		
Matrix	Fine-grained, opaque	Mostly fine, opaque	Clastic and minor opaque	Transparent, recrystallized, coarsening from 4 to 6		
Chondrule–Matrix integration	No chondrules	Chondrules very sharply defined		Chondrules well defined	Chondrules readily delineated	Chondrules poorly defined
Carbon (wt.%)	3–5	0.8–2.6	0.2–1	< 0.2		
Water (wt.%)	18–22	2–16	0.3–3	< 1.5		

groups [1.17, 1.25–1.27]. Figure 1.3 illustrates these groups, distinguished by varying Ca/Si and Al/Si atomic ratios.

By the mid- to late-1960s, it had been recognized that not only were there variations in the chemistry and mineralogy of distinct meteorite groups, but there were very significant changes in texture that seemed to cut across the chemical differences. This led to a comprehensive chemical and petrological classification scheme for chondrites [1.18].

Mineralogical and structural criteria were used to define a two-dimensional grid (Table 1.1), into which fit both chemical and textural variations. This is the basis of the classification system used in meteorite work today. Van Schmus and Wood [1.18] recognized a variation in petrologic character among the ordinary chondrites, across a spectrum from unaltered (disequilibrium of iron in silicates, presence of glass, sharply defined chondrules) to altered (homogenous silicates, no glass, recrystallized matrix, containing only relict chondrules). This gradation of properties was numerated, to allow ready classification of ordinary chondrites, and is reproduced in Table 1.1.

Petrologic type was originally defined for, and applied to, ordinary chondrites. The definitions have subsequently been expanded and applied to all chondrite classes (Table 1.2). The increase in petrologic type of a meteorite, from type 3 to type 6, implies an increasing extent of thermal metamorphism, from practically unaltered (type 3) to metamorphosed and recrystallized (type 6). Petrologic types 3 to 6 are found in carbonaceous, ordinary and enstatite chondrites, whilst types 1 and 2 are confined to carbonaceous chondrites.

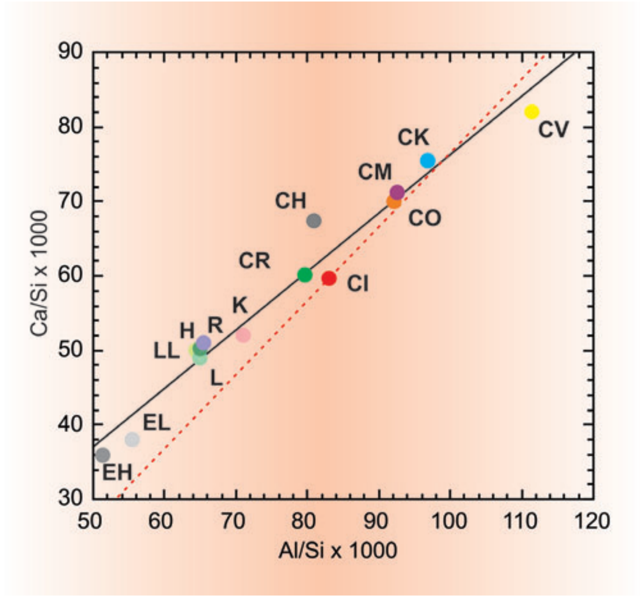

Figure 1.3: Plot of mean Ca/Si and Al/Si ratios for the different chondrite groups. The solid black line is the line of best fit to the data. The dashed red line is a line of slope 1 fit to the CI values. Data from [1.28–1.30].

Electron microprobe analysis of meteorites showed not only the very narrow range of olivine and pyroxene compositions exhibited by the H, L and LL groups of ordinary chondrites [1.14], but that mineralogy varies with petrologic

Table 1.2: Distribution of petrologic types by chondrite class

Total by number (June 2014)	1	2	3	4	5	6	7	Other*	Total
Carbonaceous									
CI	9	–	–	–	–	–	–	–	**9**
CM	37	422	–	–	–	–	–	8	**467**
CO	–	–	432	–	–	–	–	–	**432**
CV	–	1	298	–	–	–	–	–	**299**
CK	–	–	24	98	107	21	–	3	**253**
CR	2	149	–	–	–	2	1	9	**163**
CH	–	–	23	–	–	–	–	–	**23**
CB	–	–	–	–	–	–	–	19	**19**
Ungr§	2	16	17	6	1	2	–	8	**52**
Total	*50*	*588*	*794*	*104*	*108*	*25*	*1*	*47*	***1717***
Ordinary									
H	–	–	900	5224	8079	4741	16	143	**19103**
H/L	–	–	17	18	7	12	–	–	**54**
L	–	–	912	1450	5261	8919	22	125	**16689**
L/LL	–	–	50	24	25	33	–	1	**133**
LL	–	–	358	335	3038	2486	32	292	**6541**
Ungr§	–	–	–	–	–	–	–	156	**156**
Total	–	–	*2237*	*7051*	*16410*	*16191*	*70*	*717*	***42676***
Enstatite									
EH	–	–	122	27	6	7	2	8	**172**
EL	–	–	20	14	7	81	1	3	**126**
Ungr§	–	–	212	5	8	10	–	14	**249**
Total	–	–	*354*	*46*	*21*	*98*	*3*	*25*	***547***
Rumurutiite			66	49	24	10	–	3	***152***
Kakangari-type			2	–	–	–	–	1	***3***
Ungrouped Chondrites								15	***15***

Total by percentage (June 2014)	1	2	3	4	5	6	7	Other*	% by Group
Carbonaceous									
CI	100	–	–	–	–	–	–	–	**0.5**
CM	7.9	90.4	–	–	–	–	–	1.7	**27.2**
CO	–	–	100	–	–	–	–	–	**25.2**
CV	–	0.3	99.7	–	–	–	–	–	**17.4**
CK	–	–	9.5	38.7	42.3	8.3	–	1.2	**14.7**
CR	1.2	91.4	–	–	–	1.2	0.6	5.5	**9.5**
CH	–	–	100	–	–	–	–	–	**1.3**
CB	–	–	–	–	–	–	–	100	**1.1**
Ungr§	3.8	30.8	32.7	11.5	1.9	3.8	–	15.4	**3.0**
% by Type	*2.9*	*34.2*	*46.2*	*6.1*	*6.3*	*1.5*	*0.1*	*2.7*	***100***
Ordinary									
H	–	–	4.7	27.3	42.3	24.8	0.1	0.7	**44.8**
H/L	–	–	31.5	33.3	13.0	22.2	–	–	**0.1**
L	–	–	5.5	8.7	31.5	53.4	0.1	0.7	**39.1**
L/LL	–	–	37.6	18.0	18.8	24.8	–	0.8	**0.3**
LL	–	–	5.5	5.1	46.4	38.0	0.5	4.5	**15.3**
Ungr§	–	–	–	–	–	–	–	100	**0.4**
% by Type	–	–	*5.2*	*16.5*	*38.5*	*37.9*	*0.2*	*1.7*	***100***
Enstatite									
EH	–	–	70.9	15.7	3.5	4.1	1.2	4.7	***31.4***
EL	–	–	15.9	11.1	5.6	64.3	0.8	2.4	***23.0***
Ungr§	–	–	85.1	2.0	3.2	4.0	–	5.6	***45.5***
% by Type	–	–	*64.7*	*8.4*	*3.8*	*16.8*	*0.5*	*4.6*	***100***
Rumurutiite			43.4	32.2	15.8	6.6	–	2.0	***100***
Kakangari-type			66.7	–	–	–	–	33.3	***100***
Ungr. Chondrites			–	–	–	–	–	100	***100***

For simplicity, anything labelled transitional (e.g., 3/4) or inclusive (e.g., 4–6), was binned into the lower type; this assumption has little effect on the overall percentages. More significantly, no account was taken of pairing, which does have a big effect on the absolute numbers of a category, but by and large not on the totals expressed by percentage. The table includes both falls and finds. If only meteorites that had been observed to fall were selected, pairing would not be an issue, but many of the more rare meteorite types would not show up (e.g., there would be no entry for CH chondrites, or for CK 5 and CK6).

* The columns labelled 'Other' include impact melt breccias and unclassified meteorites; it also includes the CB meteorites, none of which has a designated petrologic type.

§ The rows labelled 'Ungr' include meteorites that have been assigned a petrologic type but not a chemical group. Data from the Meteoritical Bulletin website (www.lpi.usra.edu/meteor/metbull.php; accessed June 2014).

grade [1.31, 1.32]. The dominant mineral phases present in all three ordinary chondrite chemical groups are olivine, pyroxene, feldspar, metal and sulphides. For the most part, in petrologic types 4–6, in all chemical groups, the olivines and low-calcium pyroxenes are homogenous with respect to their iron contents, whereas in the type 3 chondrites, the iron content of the silicates is highly variable, more so in the pyroxenes than in the olivines [1.31]. The differences in silicate mineral composition led Dodd and Van Schmus [1.33] to coin the phrase 'unequilibrated' for those ordinary chondrites in which the olivine and pyroxene iron content was inhomogeneous. The extent of this inhomogeneity also correlated with the degree of recrystallization of the mineral matrix. Hence type 3 ordinary chondrites are unequilibrated and higher petrologic types are equilibrated.

Up until the beginning of the 1970s, there was a slow but steady increase in the number of meteorites available for study, allowing progressive refinement of classification schemes. Meteorite taxonomy, however, suffered from a lack of specimens: frequently only unique examples of an apparent subdivision might be known, a problem that was particularly acute for the achondrites. The situation changed with the recovery of large numbers of meteorites from cold and hot deserts. In 1969, a team of Japanese glaciologists discovered nine meteorites in a restricted area of the Yamato Mountains in Antarctica [1.34]. The nine fragments were found to represent at least six different meteorites; subsequently, it has been recognized that vast numbers of meteorites accumulate in blue ice regions over the continent [1.35]. Since 1969, Antarctica has become the region from which the highest number of meteorites has been retrieved, over 35,000 by spring 2009. This is not because meteorites fall over Antarctica any more frequently than they do elsewhere over the globe, but a result of the unique mechanism that acts to preserve and concentrate meteorites in specific areas of the continent. The meteorites are also readily visible on the blue ice.

Hot deserts (e.g., the Sahara in Northern Africa and the Nullarbor Region of Western Australia), where the dry conditions prevent chemical degradation of metal, have also yielded several thousand meteorites [1.36]. The rapid increase in the numbers of meteorites available for analysis has led to developments in meteorite classification. There are now much greater numbers of ordinary chondrites, allowing subtle refinements of the petrological subclassification. But, perhaps more importantly, there are many more unusual and rare meteorites that have populated previously under-represented classes, extended the range of compositional variations shown by the major meteorite groups and expanded the number of recognized subdivisions. Over the last 30 years, meteorites from desert collections together with advances in scientific instrumentation have allowed revision and modification of the meteorite classification scheme that is now accepted and used internationally.

1.2.2 Chondrites

The increasing number of desert meteorites showed the limitations of the Van Schmus and Wood classification when applied to type 3 ordinary chondrites: there is almost as much variation in chemical composition occurring in this class alone, as across the rest of the spectrum. The amount of unequilibration within the type 3 chondrites is also variable, some samples being recognizably more recrystallized than others. The need for further subdivision of the unequilibrated ordinary chondrites was recognized, and several workers proposed independent parameters for this division, including the distribution of cobalt in kamacite [1.38] and the extent of matrix recrystallization [1.39]. However, these parameters, based as they were on only a few measurements, distinguished only four subtypes. Sears and colleagues, using a much greater database, recognized 10 subtypes, distinguishable by their thermoluminescence (TL) sensitivity, which trended in the same manner as the parameters mentioned above [1.40]. The new groups were numbered from 0 to 9. Hence Semarkona, a highly unequilibrated ordinary chondrite, is classified as a type LL3.0, whereas Bremervörde, a more equilibrated type 3, is type H3.9. Classification into petrologic subtype is not linear, and is regarded as accurate to ± 1 subgroup [1.23, 1.40].

The Van Schmus and Wood classification system also required modification for application to carbonaceous chondrites. Their classification as C1, C2, C3(O) and C3(V) implied some type of genetic interrelationship, which was not necessarily the case. Wasson rechristened the groups CI, CM, CO and CV (corresponding to C1, C2, C3(O) and C3(V), respectively), the letters being the initials of the type specimens of each class: Ivuna, Mighei, Ornans and Vigarano [1.37]. A few years later, the CR class was added, after its type specimen, Renazzo [1.41].

Another significant advance in the history of meteorite classification was made in the late 1970s, by R. N. Clayton of the University of Chicago. Clayton measured the oxygen isotopic composition of silicates separated from individual meteorites, and found that different groups had different isotopic compositions [1.42–1.45]. Figure 1.4 shows the oxygen isotopic composition of the major chondrite groups. The variations in composition are generally taken to be a reflection of primordial nebular heterogeneity, modified in some groups as a result of widespread fluid–solid exchange processes.

It is two hundred years since the first paper was published on the chemical composition of meteorites [1.46]. We now recognize 15 different chondrite groups. There are eight carbonaceous chondrite groups: CI, CM, CO, CV, CR, CK [1.47], CB [1.48] and CH [1.49]. The type specimens for the CK and CB chondrites are Karoonda and Bencubbin, respectively. The CH chondrites are not named for a type specimen, but their relatively iron-rich composition is recognized with a

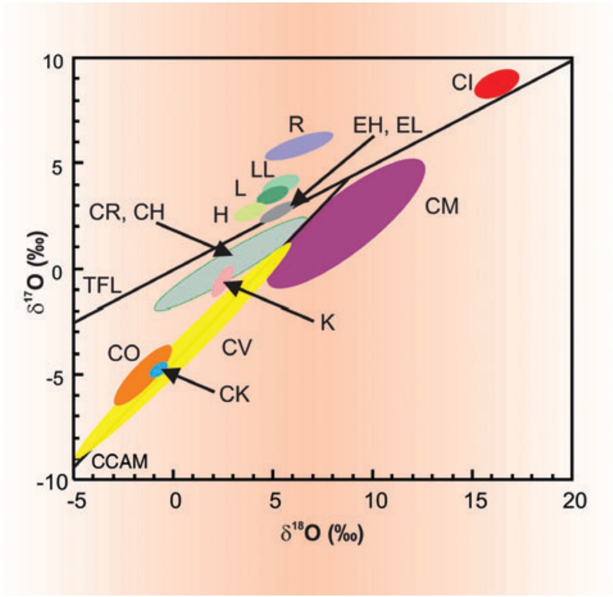

Figure 1.4: The oxygen isotopic composition of the different chondrite groups. TFL – Terrestrial Fractionation Line; CCAM – Carbonaceous Chondrite Anhydrous Mineral line. Data from [1.42–1.45] and references therein.

label analogous to that of the high-iron groups of the ordinary and enstatite chondrites [1.49]. As well as eight groups of carbonaceous chondrites, there are three groups of ordinary chondrites (H, L and LL), plus the EH and EL enstatite chondrites, and the rumurutiite (R) [1.50, 1.51] and Kakangari-type (K) chondrites [1.30] (treated together in Chapter 5). The groups are distinguished on the basis of elemental and isotopic chemistry, matrix, metal and chondrule contents and chondrule properties (size, type, etc.). The differences between the groups are primary, i.e., were established as the parent bodies accreted in different regions of the solar nebula. Subsequent to accretion, most meteorites have experienced varying extents of thermal metamorphism or aqueous alteration. These secondary processes occurred on the meteorites' parent bodies, and did not affect the overall composition of the chondrites. Mobilization and redistribution of elements such as Fe, Mg and Ca occurred as primary silicates either became homogeneous in composition through heating, or through formation of secondary mineral phases (e.g., clay minerals, carbonates) during aqueous alteration. The petrologic subclassification of chondrites, into H5, CM2, LL4, etc., is a reflection of secondary processes acting on a parent body, quantifying the extent of dry thermal or aqueous alteration experienced after the parent asteroid aggregated. The various meteorite classes have experienced secondary processes to different extents, demonstrated by variety in the range of petrologic types exhibited by the groups (Table 1.2). It is also recognized that modification does not cease, even after metamorphism or metasomatism ends: collisions between asteroids lead to brecciation, and the production of shock veins and melt glass. These tertiary effects can be recognized as textural changes within mineral grains. There is a semi-quantitative scale for shock classification of ordinary chondrites [1.52] that has subsequently been applied to carbonaceous and enstatite chondrites [1.53, 1.54]. The scale is based on characterization of defects in silicate grains (mainly olivine), and ranges from S1 (unshocked) to S6 (highly shocked, to about 75–90 GPa) (Table 1.3).

The final parameter required to classify fully a chondrite is applied to meteorites that have been found, rather than those observed to fall, as it is a measure of the amount of weathering experienced by the meteorite during its terrestrial lifetime. Weathering rusts metal, and breaks down primary silicates to clay minerals; a semi-quantitative scale to assess the weathering grade of chondrites was proposed by Wlotzka [1.55]. Thus, a full classification of a shocked ordinary chondrite might be H5 (S4, W2). This designation gives an outline of the primary, secondary and tertiary pre-terrestrial history of the rock, as well as an indication of its terrestrial history. The texture of a chondrite results from a combination of two factors: its constituents (i.e., the relative abundances of different components, including matrix, chondrules, metal, etc.) and the processes that the chondrite (or its parent body) has experienced (thermal metamorphism, fluid alteration).

1.2.3 Primitive achondrites

The distinction between chondrites and achondrites is no longer as clear as was the case when Mason [1.56] described five separate achondrite groups on the basis of their calcium content [1.56]. Four groups (the **acapulcoite–lodranite** clan (Chapter 6), **brachinites** (Chapter 7), **winonaites** (Chapter 8) and **ureilites** (Chapter 9); type specimens Acapulco, Lodran, Brachina, Winona and Novo Urei, respectively) are regarded as primitive achondrites (Figure 1.1). They have almost chondritic compositions (i.e., they are very little fractionated relative to the Sun), but their textures indicate that they have experienced some degree of heating and partial melting. Winonaites are closely related to the silicate inclusions in IAB irons, and may derive from the same parent body, bridging between iron meteorites and chondrites. The characteristics of primitive achondrites may help in the understanding of early differentiation processes in asteroidal bodies. Figure 1.5 shows the oxygen isotopic compositions of the primitive achondrite groups.

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Table 1.3: Shock classification of meteorites [1.52–1.54]

	Effects resulting from equilibration peak shock pressure				
Shock stage	**Olivine**	**Orthopyroxene**	**Plagioclase**	**Local effects**	**Shock pressure (GPa)**
S1 Unshocked	Sharp optical extinction; irregular fractures			None	< 4–5
S2 Very weakly shocked	Undulose extinction; irregular fractures			None	5–10
S3 Weakly shocked	Planar fractures; undulose extinction; irregular fractures	Clinoenstatite lamellae on {100}; undulose extinction; planar fractures; irregular fractures	Undulose extinction	Opaque shock veins; incipient formation of melt pockets, sometimes interconnected	15–20
S4 Moderately shocked	Weak mosaicism; planar fractures	Weak mosaicism; twinning on {100}; planar fractures	Undulose extinction; partially isotropic; planar deformation features	Melt pockets; interconnecting melt veins; opaque shock veins	30–35
S5 Strongly shocked	Strong mosaicism; planar fractures and planar deformation features	Strong mosaicism; planar fractures	Maskelynite	Pervasive formation of melt pockets, veins and dikes; opaque shock veins	45–55
S6 Very strongly shocked	Restricted to local regions in or near melt zones			As for S5	75–90
	Solid state recrystallization and staining; ringwoodite; melting	Majorite; melting	Shock melted (normal glass)		
Shock melted	Whole rock melting (impact melt rock and melt breccias)				

1.2.4 Achondrites

Achondrites are meteorites that formed from melts, and thus have differentiated compositions. Achondrites traditionally only comprised stony meteorites that had lost a large fraction of their primordial metal content, their name emanating from the observation that such meteorites generally do not contain chondrules. However, the current convention is to regard all differentiated meteorites (stone, iron and stony-iron) as achondrites (Figure 1.1).

1.2.4.1 Asteroidal stone achondrites

Stony achondrites differ from chondrites in their major element content, especially calcium and similar elements. They have almost no metal or sulphides, and neither do they contain chondrules. They are mainly composed of crystals that appear to have grown from a melt. There are many different groups of achondrites, some of which can be linked together to form associations allied with specific parents. The separate associations have little, if any, genetic relationship to each other. Figure 1.5 shows the oxygen isotopic compositions of the different achondrite groups.

Angrites (Chapter 10; type specimen Angra dos Reis) are medium- to coarse-grained basaltic igneous rocks. Although the angrites have similar oxygen isotopic compositions to the HEDs (Figure 1.5), they are unrelated. **Aubrites** (or enstatite achondrites (Chapter 11), type specimen Aubres) are highly reduced meteorites with mineralogies and oxygen isotopic compositions similar to those of enstatite chondrites, leading to the suggestion that aubrites might have formed by partial melting of an enstatite chondrite precursor.

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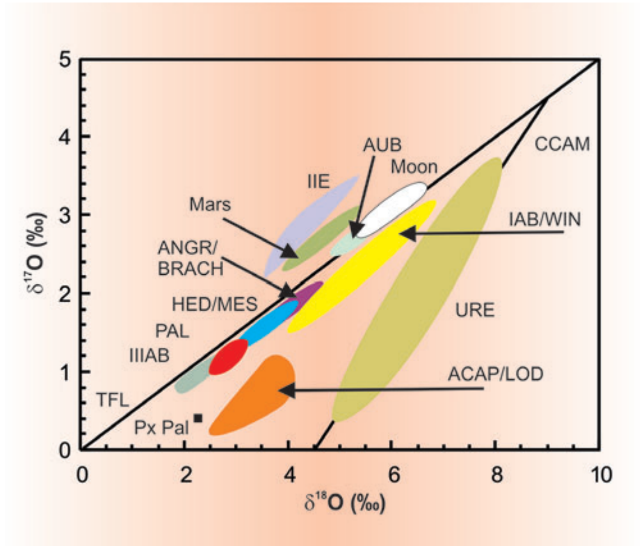

Figure 1.5: The oxygen isotopic composition of different achondrite groups. TFL – Terrestrial Fractionation Line; CCAM – Carbonaceous Chondrite Anhydrous Mineral line. Data from [1.41, 1.45].

The **howardite–eucrite–diogenite** (HED) clan (Chapter 12) is a suite of generally brecciated igneous rocks ranging from coarse-grained orthopyroxenites (**diogenites**) to cumulates and fine-grained basalts (**eucrites**). The **howardites** are regolith breccias, rich in both solar wind gases and clasts of carbonaceous material. The HEDs all have similar oxygen isotopic compositions (Figure 1.5); a strong candidate for the HED parent body is asteroid 4 Vesta.

1.2.4.2 Stony-irons

The stony-irons are divided into two groups: **mesosiderites** (Chapter 13) and **pallasites** (Chapter 14), similar only in their approximately equal proportions of silicate and metal. The two groups have very different origins and histories. Mesosiderites are a much more heterogeneous class of meteorites than the pallasites. They are a mixture of varying amounts of iron–nickel metal with differentiated silicates, the whole assemblage of which seems to have been brecciated (Figure 1.6).

Pallasites are perhaps the most strikingly beautiful of all meteorites. They are an approximately equal mixture of iron–nickel metal and silicates (predominantly olivine), and the metal forms a continuous network, into which the olivine grains are set (Figure 1.7). Pallasites are presumed to represent material from the core–mantle boundary of their parent bodies.

1.2.4.3 Iron meteorites

Iron meteorites (Chapter 15) are highly differentiated materials, presumed to be products of extensive melting processes on their parents. They are composed of iron metal, generally with 5–15 wt.% nickel, and account for approximately 5% of all observed meteorite falls. The mineralogy of iron meteorites is dominantly an intergrowth of two phases, the iron–nickel metals kamacite and taenite. Kamacite, or α-Fe-Ni, has a body-centred cubic structure and a Ni content

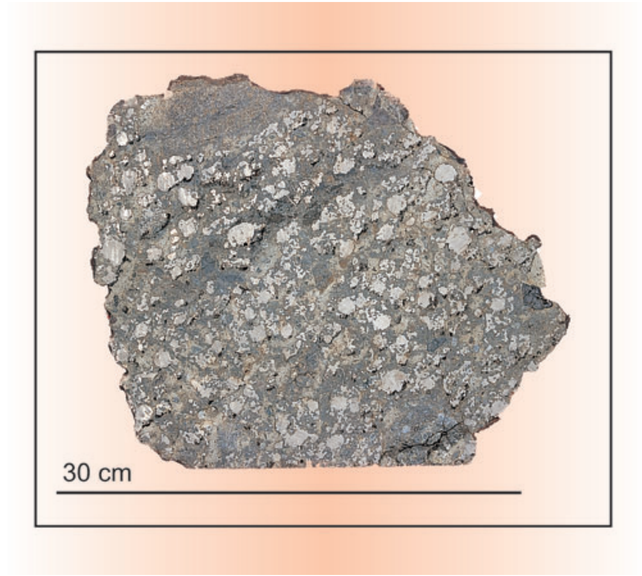

Figure 1.6: A cut slice from the Estherville mesosiderite, showing a range of different clast types.

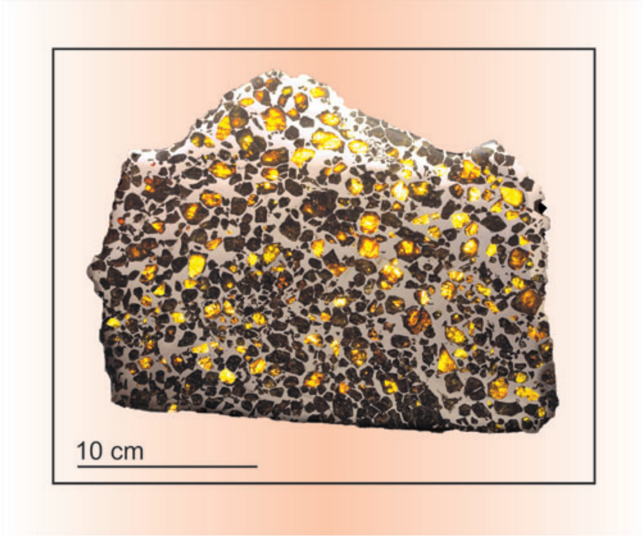

Figure 1.7: A cut and polished slice of the Esquel pallasite. The slice is sufficiently thin that the olivine grains appear transparent.

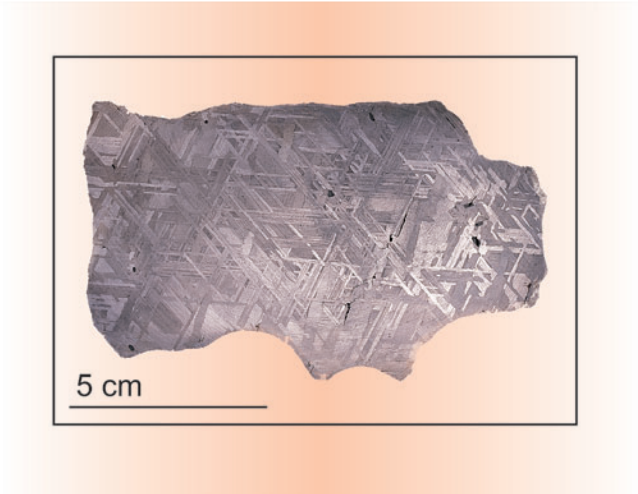

Figure 1.8: A polished and etched slab of the Henbury iron meteorite, illustrating the Widmanstätten pattern.

$<$ 7 wt.%, whilst taenite, or γ-Fe-Ni, is face-centred cubic and approximately 15–50 wt.% Ni. When polished and etched in dilute mineral acid, irons reveal a distinctive structure, known as a Widmanstätten pattern (Figure 1.8). This consists of plates of kamacite in an octahedral orientation with interstices between the platelets filled with taenite and plessite (a very fine-grained, submicron, intergrowth of kamacite and taenite). The width of the kamacite lamellae is related to the cooling history of the parent bodies. The pattern is named for Aloys J. B. von Widmanstätten, who, at the start of the nineteenth century, observed the pattern on several iron meteorites, although he probably was not the first to describe the structure [1.57].

The coarseness of the Widmanstätten pattern is expressed as the width of the kamacite lamellae (or bandwidth), and iron meteorites were originally classified by Tschermak [1.8] into five structural groups: the coarse, medium and fine octahedrites, ataxites and hexahedrites. The structural classification of iron meteorites was redefined and made systematic by V.F. Buchwald [1.58].

Structural classification of iron meteorites has been succeeded by classification based on metal composition [1.59]. The irons are subdivided into 12 different groups on the basis of nickel and trace element chemistries (Ga, Ge and Ir contents); see Figure 15.2. The relatively tight coupling between Ni and Ga and Ge for 10 of the individual groups (Figure 1.1) indicates that the groups represent discrete parents that had completely melted and then solidified by fractional crystallization [1.59]. These groups were previously known as the magmatic iron meteorites, although this term is no longer in favour [1.6].

Two groups, the IAB and IIICD irons, have a wide range in Ga and Ge abundance with Ni content. They were thought to derive from parent bodies that had not completely melted, and were coupled together as non-magmatic iron meteorites that possibly formed during impact processes on their parent asteroids. It is now recognized that silicate inclusions in the IABs are very closely linked to the winonaite group of primitive achondrites. Winonaites and IABs, if not coming from the same parent body, must at least have formed in closely located regions of the solar nebula [1.60, 1.61].

Many irons defy chemical classification, and simply remain ungrouped. The chemical classification of iron meteorites has mainly been undertaken by J.T. Wasson and coworkers at UCLA. On the basis of trace-element compositions, it is estimated that iron meteorites might represent samples of at least 70 individual asteroids.

1.2.4.4 Non-asteroidal stone achondrites

All the meteorites that have been considered so far originated from asteroids. In the early 1980s, it was recognized that there were two groups of meteorites derived from planetary rather than asteroidal sources. **Lunar meteorites** (Chapter 16) are mostly anorthositic regolith breccias. The lunar origin of the meteorites is certain: the mineralogy and chemistry of the samples is indistinguishable from that of the samples returned directly by the Apollo astronauts. **Martian meteorites** (Chapter 17) almost certainly originate on Mars. There have been many missions to Mars since the first successful fly-by of Mariner 4 in 1965. Imagery and other data from orbiting satellites and landed craft have increased our knowledge of Mars and our understanding of its formation, the relative chronology of the major events that shaped its surface, and the mineralogy of the surface materials. A valuable source of information about Mars, complementary with data returned from space missions, is the class of meteorites that were ejected from Mars' surface by impact. Although we do not (yet) have rocks returned directly from Mars by spacecraft with which these rocks can be compared, the Martian origin of the meteorites is fairly secure, and is based on the age, composition and noble gas inventory of the meteorites.

1.3 Components of chondrites

Chondrites are mechanical mixtures of a variety of components that originated at different times in different regions of the protosolar nebula. They also contain, to a greater or lesser extent, grains that originated prior to the formation of the solar nebula (presolar grains). The relative abundances and sizes of