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Primitive meteorites: an attempt towards unification

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[Plates 1–4]

A model is developed that recognizes genetic links between almost all meteorites. The model is based on processes that were active in the solar nebula. The most important processes identified are: (1) early part to total evaporation of presolar matter; (2) recondensation beginning with olivine followed by other phases; (3) aggregation of the condensates to millimetre-sized objects during condensation; (4) partial or total compaction of early aggregates by continuing condensation preferentially utilizing the aggregate's pore space; (5) a second heating event leading to sintering and partial melting of the aggregates (chondrule formation) and mild vapour fractionation; (6) vapour–solid exchange reactions introducing Fe^{2+} (and other elements) into the silicates ('equilibration' via metasomatism) and forming FeS via S-metasomatism; (7) depending on conditions, centimetre-sized aggregates of early aggregates form either before or while processes (4)–(7) are active, or later. This process can continue to form decimetre-sized aggregates; (8) accretion takes place at very low temperatures with condensation of volatile elements still continuing; (9) some matter experienced H_2O- and CO_2-metasomatism (formation of phyllosilicates and carbonates) and almost total oxidation before accretion (C1, C2).

The typical early condensate is olivine, which displays different growth features depending on physical conditions. Common are 'barred' olivines (greater than 200 μm), huge (100 μm) subparallel stacks of olivine platelets and small stacks (10–50 μm) of similar platelets. These olivines have highly defective lattices and contain large amounts of minor elements (including refractory lithophile elements). Depending on growth rate and particle abundance, primitive olivines aggregate to millimetre-sized objects (the protoliths of chondrite constituents) or centimetre-sized aggregates. Formation of large aggregates apparently takes place when the condensation rate is high. This quickly leads to compaction of the aggregates and highly reduced pore space. These aggregates will ultimately end up in ureilites and pallasites. Slower growth rates produce smaller aggregates (millimetre-sized) with abundant pore space which serves as a cold trap for the condensation of the volatile elements. Olivine is partly converted into pyroxene by reaction with the vapour (formation of poikilitic pyroxenes). Pyroxene and olivine abundances will vary depending on reaction time and other parameters. The pore space will also be highly variable. Moderately volatile elements condense into this pore space with their abundance governed by the space available. In this manner, the protoliths for chondrules formed.

The chemical fractionations observed in meteoritic constituents can be accounted for mostly by physical parameters: (1) the main condensing phase and the pore space provided by the aggregates; (2) the timing of formation of aggregates of aggregates and of the closure of pore space (physical isolation of aggregate interiors); (3) reprocessing of aggregates in a high temperature event; (4) metasomatic exchange reactions between solid aggregates and vapour; (5) isolation of aggregates from vapour via shielding by condensates (e.g. metal) or physical removal; (6) timing and rate of final accretion; (7) degree of mixing with solar and presolar dust.

Introduction

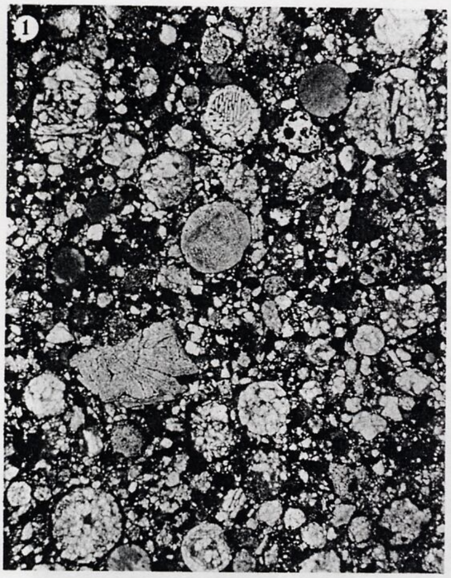
Chondrites are the most common meteorites. Their chemical compositions are fairly similar to that of the condensable portion of the solar matter (see, for example, Anders 1964, 1968), a fact which clearly indicates that they are primitive. However, the most common chondrites, the ordinary chondrites (OCs) have highly fractionated (depleted) volatile element abundances (see, for example, Larimer & Anders 1967; Larimer 1973; Laul *et al.* 1973). Their oxidation state is high (FeO is dissolved in silicates) which is incompatible with a direct derivation of OCs from an unfractionated solar nebular gas (Wood 1962; Grossman 1972). In addition, the major silicate phases of OCs, olivine and orthopyroxene, have homogeneous chemical compositions (Keil & Fredriksson 1964). All these facts led to the very popular belief that the OCs are metamorphic rocks which acquired some of their properties by remodelling in a parent body (Van Schmus & Wood 1967). Thus, the overwhelming majority of chondrites are commonly considered to be not primitive. Ironically, the clearly more complex carbonaceous chondrites (CCs), which represent a mixture of at least two components of high-temperature and low-temperature origin (Anders 1964) are believed to be 'more' primitive than the OCs. The rarest of all types of chondrites, the carbonaceous chondrites of type I (Wiik 1956), (now called CI), are believed to be the 'least altered samples of primitive solar matter accessible to man' (Anders & Ebihara 1982). This belief, which relates principally to bulk chemistry, overlooks the petrographic evidence that CI chondrites are chaotic mixtures of the most heavily 'altered' meteoritic matter (mostly phyllosilicates), containing olivines with solar-flare tracks and veins of apparently remobilized sulphates (Du Fresne & Anders 1962; Bostrom & Fredriksson 1966; Kerridge 1968; Kerridge & Macdougall 1976). However, CI chondrites have the highest abundances of volatile elements of all chondrites and closely approach the solar abundances (Anders & Ebihara 1982). This is the rationale for their use as a standard in cosmochemistry but does not necessarily imply that they are 'the primitive', planetologically unprocessed matter.

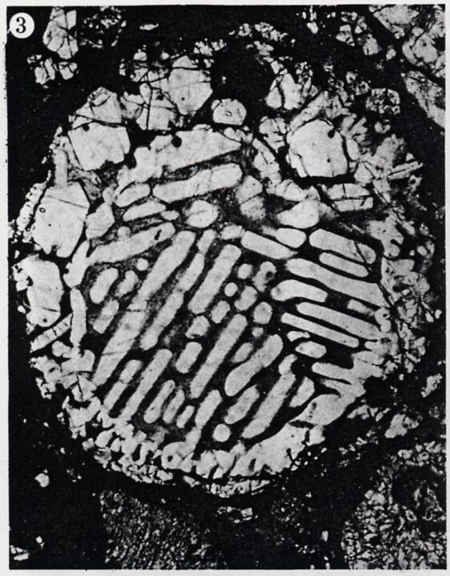
The 'differentiated' meteorites (achondrites, stony irons, and irons) are generally believed to be the products of planetary differentiation processes (Anders 1964; Wasson 1974). There exists some evidence for igneous fractionation for many members of the 'differentiated' meteorite clan. However, there is also increasing evidence for some members to be of primitive parentage.

In this paper, I will make an attempt to develop a new model for solar nebula processes which will attempt to explain both why most meteorites are probably primitive, and what processes provide the links between the different meteorites. The term 'primitive' will be restricted to presolar and solar nebula processes and their products. Naturally, several properties of meteorites can also be explained by planetary processes which might be difficult to distinguish from primitive ones. However, the main purpose of this paper is to provoke some re-thinking and stimulate meteorite research free of preconceived or traditional ideas.

Chondrules and the aggregation of matter

Chondrites are truly chaotic microbreccias (figure 1, plate 1), consisting of a variety of objects (chondrules, lithic and mineral fragments, mineral aggregates, and sometimes a chondrite matrix). In spite of the rather monotonous bulk chemical compositions of chondrites,





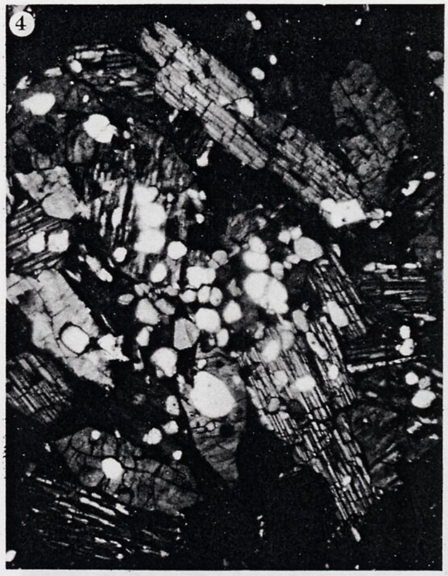


FIGURE 1. The Sharps (H3) chondrite. Chaotic mixture of objects of different sizes, shapes, and mineralogical compositions. Most objects are covered by a thin rind of very fine-grained pre-accretionary 'matrix' matter, typical for type-3 ocs. Transmitted light; length of picture is 6 mm.

FIGURE 2. Recrystallized stacks of olivine platelets from a partly molten aggregate in the Sharps (H3) chondrite. Part of the original pore space is preserved and filled mainly by pyroxene. Transmitted light, *x* nicols; length of picture is 0.78 mm.

FIGURE 3. Barred olivine (bo) chondrule in the Sharps (H3) chondrite. Three staples of bo are intergrown and covered by a dense olivine shell of intergrown bars. On top of these are recrystallized small stacks of olivine platelets (now subhedral crystals) with different orientations (aggregate texture). Note that on top of the well-crystallized shell olivines there is a layer of smaller, less-well-crystallized olivines. The pore space of the inner bars is completely filled by dusty glass. Transmitted light; length of picture is 0.78 mm.

FIGURE 4. Clinopyroxenes with abundant poikilitically enclosed olivines (remnants of pyroxenization) forming an aggregate in the Sharps (H3) chondrite. This is a typical texture for all chondrites, the pyroxene of which, however, is mostly orthopyroxene. Transmitted light, *x* nicols; length of picture is 0.78 mm.

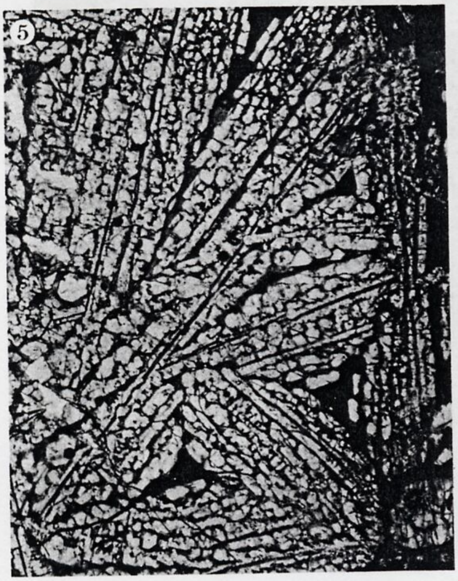
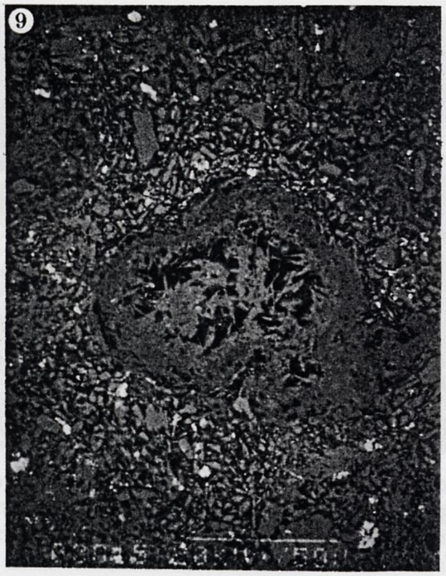


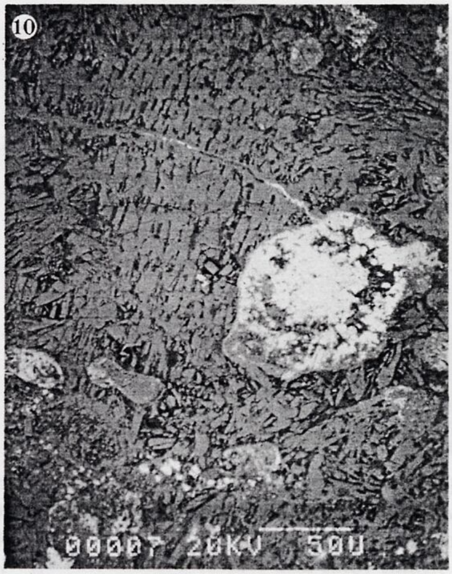
FIGURE 5. Aggregate of stacks of pyroxene platelets of different orientation but intergrown with each other. Pyroxene is badly crystallized and full of inclusions and pore space that is only partly filled by other phases. This type of crystallization strongly suggests growth from vapour. Transmitted light; length of picture is 0.78 mm.

FIGURE 6. Aggregate of staples of olivine bars in McKinney (L4). Part melting was not sufficient to reshape the object. Note the abundant cracks perpendicular to the elongation of the bars – a well preserved relict growth feature indicating the orientation of the original platelets which formed the thick plates ('bars'). Transmitted light; length of picture is 3.6 mm.

FIGURE 7. Recrystallized olivine aggregate and chondrite matrix of Allende (C3). The olivine and metal-rich globules are well recrystallized and sintered to a densely packed texture. Metasomatic addition of Fe^{2+} proceeded from the surface (light grey) and followed the grain boundaries. The dark interior of olivines have the original, low-Fe composition preserved. The original metal has been sulphurized and oxidized. The matrix consists of loosely aggregated olivine platelets. BSE image; length of picture is 0.38 mm.

FIGURE 8. Fine-grained dark inclusion Allende DF. Stacks of olivine platelets and aggregates of intergrown stacks are suspended in a fine-grained matrix also consisting of platelets of olivine and stacks thereof. Note the enormous pore space which is only to a very low degree filled by nepheline and sodalite (dark grey). BSE image; length of picture is 0.44 mm.





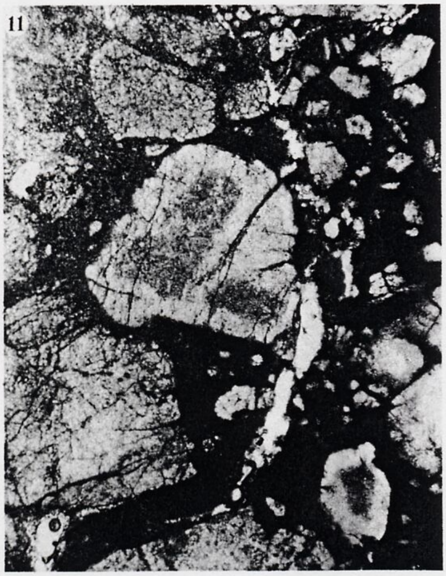


FIGURE 9. Aggregate of intergrown stacks of olivine platelets rimmed by a dense shell of clinopyroxene in Allende dark inclusion DF. Note the growth of olivine spines into the enormous pore space. The matrix contains single and oriented intergrown stacks of olivine platelets. BSE image; length of picture is 0.18 mm.

FIGURE 10. Huge intergrown stacks of olivine platelets in a aggregate in Allende dark inclusion AF. The separate stacks are intergrown with each other and the originally metal-rich objects are tightly packed into that structure. The lower end rich in bright grains is the 'matrix' of inclusion AF. The pore space is mostly filled by nepheline and sodalite (dark grey). BSE image; length of picture is 0.3 mm.

FIGURE 11. The Mayo Belwa aubrite. Badly crystallized and inclusion-rich enstatite in dark matrix. Many enstatites have a zonal structure which suggests reaction relation with an external source before accretion. Note the large elongated voids (white). Transmitted light; length of picture is 3.6 mm.

FIGURE 12. The Haverö ureilite. Large recrystallized aggregates of olivine and badly crystallized and inclusion-rich pyroxenes (dark grey) in a matrix rich in carbon (black). Some of the olivines display subparallel orientations. In the lower left corner two of such intergrowths are intergrown with each other. Note the very large elongated voids (white). Transmitted light; length of picture is 5.5 mm.

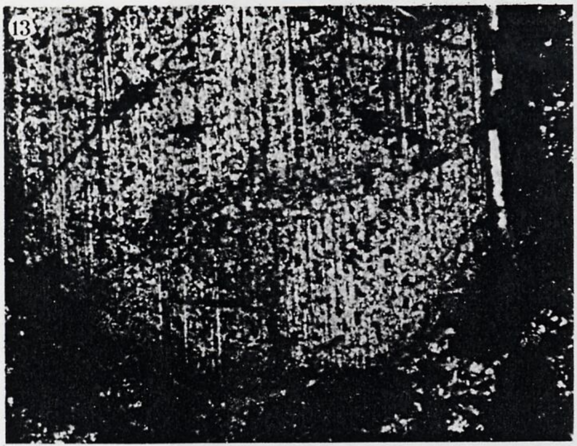


FIGURE 13. Pyroxene in the Haverö ureilite. The large grain consists of thin pyroxene plates which are intergrown with each other. The plates appear to be well crystallized. Interplate pyroxene is badly crystallized and does not fill the total space available (rich in voids and 'glassy' inclusions). Note the deposition of carbon rich matter (black) within voids and cracks. Transmitted light; length of picture is 0.78 mm.

FIGURE 14. Recrystallized olivine 'bars' in the Haverö ureilite. Transmitted light; crossed polarizers; length of picture is 0.78 mm.

their constituents are highly fractionated. The most prominent objects, the commonly spherical apparently solidified droplets called chondrules have been intensively studied ever since their recognition (see, for example, Howard 1802). Their origin has been a major puzzle for a long time, as is so for all other constituents of chondrites. As a result of detailed mineralogical, petrological, geochemical and isotope geochemical studies we are now able to model the processes that led to the formation of chondrules and related objects fairly accurately. The following summary is based on the recent review by Kurat (1984). Chondrules were formed from mineral aggregates which subsequently were at least partly melted to form drops, which in turn solidified before incorporation into the chondritic rock (Nagahara 1983). Most chondrules are deficient in siderophile elements. This could indicate preferred aggregation of non-metallic phases before chondrule formation. This metal–silicate fractionation was very effective. Fractionations among the lithophile elements are very common. They show wide variations, and consequently indicate a variety of processes such as incomplete sampling of available phases (sampling fractionation), vapour fractionation (loss of volatile and medium volatile elements) and metasomatism (addition of some elements from the vapour into the liquid or solid (Kurat *et al.* 1984, 1985)). Melting must have taken place in a dense, volatile-rich atmosphere to allow most chondrules to retain volatile elements. The melting event must have taken place early in the history of the Solar System because chondrules are rich in radiogenic gases and contain radiogenic ^{129}Xe (derived from short-lived ^{129}I). The nature of the prechondrule minerals can sometimes be identified from trace element patterns. The major minerals must have been olivine and pyroxene. Fractionations among Na and K and halogens indicate variable proportions of nepheline and sodalite in Allende chondrules. Alkali fractionation and uncorrelated fractionations among the rare earth elements (REEs) have been interpreted as due to admixture of different sulphide phases (Kurat *et al.* 1984). Thus, although most chondrule data indicate aggregation of common mineral phases, which can be derived directly from the solar nebula, some provide evidence for aggregation of preprocessed (e.g. sulphurized) matter. It is worth noting that the latter case indicates a link between the most reduced and sulphurized enstatite chondrite (EC) chondrules and the strongly oxidized LL chondrite chondrules. Redox conditions must have been highly variable in the early solar nebula because indications of changing conditions are very common. Thus reduced chondrules contain oxidized relics and vice versa. If the primordial matter was derived from the solar nebula gas (with high H/O ratio) it must have been highly reduced. Thus the presence of oxidized (FeO-bearing) relics in chondrules also indicates prechondrule processing in an oxidizing environment. Several cycles appear to be possible in the processing of prechondritic matter.

The presence or absence of sampling fractionation in chondrules also allows some estimation of the grain-size of prechonditic matter. Such fractionation can be expected if the grain size of the components is comparable to the size of the aggregate. Because chondrules and other constituents of chondrites have typical diameters of about 1 mm, the sizes of prechondritic phases should range downwards from approximately 1 mm. The lower limit cannot be estimated, but could be in the submicrometre range. The major components, however, can be expected to have been of a grain size comparable to that of the major minerals now present in chondrites.

In conclusion, chondrules and related constituents of chondrites formed by aggregation and subsequent sintering and partial melting of prechondritic unprocessed or processed solid phases. Another important point is that each aggregate apparently had an individual history. From the available data it appears that there do not exist within a given chondrite two objects that can be matched in all their properties. Yet the total mixtures – the chondrites themselves – match one another very closely in composition. However, most constituents of chondrites have features in common and these can provide a clue to the nature of prechondritic matter and the process of agglomeration.

The most common objects in chondrites are sintered aggregates of olivine, olivine and pyroxene, or pyroxene, and chondrules of similar compositions and texture (Gooding & Keil 1981). Olivines have commonly prismatic habits with a distinct tendency towards hollow forms with one or more elongated, parallel oriented voids filled by other phases (figure 2, plate 1). Common extreme examples of this type are the barred olivines (figure 3, plate 1), which can either be part of or form an entire object (barred olivine chondrules, BO). In mixed olivine–pyroxene objects, pyroxenes fill interstices between olivines, occur as isolated crystals or form overgrowths on olivines. The most common type of pyroxenes are large crystals which poikilitically include olivine (figure 4, plate 1). This indicates that olivine was incompletely converted into pyroxene. Quite commonly pyroxenes are concentrated at the surface, which implies that olivine was converted to pyroxene by interaction with an external source. There is a gradual trend towards objects containing only pyroxene with diminishing amounts of poikilitically enclosed olivine. The second most common pyroxene-rich objects are radiating pyroxene (RP) chondrules, which apparently represent chilled pyroxene-rich liquids. Less common are aggregates of pyroxene dendrites with irregular outlines and abundant pore space and incomplete filling of interstitial space (figure 5, plate 2). Compared with rocks of igneous origin, chondritic rocks show a high proportion of feathery to barred olivine habits, pyroxenes with poikilitically enclosed olivines, and relict aggregate structures of their constituents (figure 6, plate 2). Relict structures are generally better preserved in carbonaceous chondrites as compared with ordinary chondrites (figure 7, plate 2). Apparently the high-temperature event which led to sintering and partial melting of the original aggregates differed in intensity in different locations of the Solar System or the primary mixture of phases was different. The small amount of matter that appears to have escaped the high-temperature event is probably preserved in the fine-grained chondrite matrices, especially those of carbonaceous chondrites (figure 7), and the so-called dark inclusions of carbonaceous chondrites (figure 8, plate 2).

In considering H_2O-free assemblages, the matrices of C3 chondrites should be the best candidates for containing relict primitive features. Indeed, these matrices (figure 7) are highly porous aggregates of olivines, clinopyroxene, sulphides, magnetite, metal, sodalite, nepheline and carbonaceous matter (Wark 1979; Peck 1983; Kornacki & Wood 1984). Olivine is by far the most common phase and forms a highly porous framework. The crystals are predominantly subhedral plates which vary in thickness from about 1–10 μm. Plates that in cross section display highly elongated spindle-like shapes are also common. Some plates are oriented in a subparallel manner, and some are intergrown with each other. All other phases partly fill the intersticies between olivine grains (feldspathoids), or envelop other phases (clinopyroxene) or form separate grains (sulphides, metal). The highly anisotropic nature of olivines in C3 matrices could indicate an origin by growth from a vapour phase. However, their chemical compositions partly conflict with such a model because they are very rich in FeO (Fo 50–65 in Allende for example (Kornacki & Wood 1984)). As we shall see later this fact does not pose a real problem because the FeO was very likely added later by an exchange reaction with the cooler vapour phase (metasomatism). This explanation finds support in the highly unequilibrated olivine compositions of many C3 meteorite matrices (Peck 1983), in relict low FeO clinopyroxenes and enstatites, and by the omnipresent metasomatic alteration rims of large olivine crystals and aggregates in C3 chondrites (figure 7). The high minor element contents of platy matrix olivines with up to 0.7 % Al_2O_3, 0.4 % CaO and 0.2 % TiO_2 (by mass) (Kornacki & Wood 1984) and high Cr_2O_3 (Peck 1983) are in favour of a condensation origin. Such high minor element contents of olivines are incompatible with olivine–liquid distribution coefficients (McKay 1986) and constitute an additional indication of growth from a vapour phase (Steele 1986; Kurat *et al.* 1987*b*).

In conclusion it can be stated that C3 matrices contain abundant olivines which exhibit highly anisotropic growth forms and consequently are likely to have been formed by growth from a vapour phase. The most primitive form of these olivines is isolated plates of small sizes (1–10 μm thick).

The fine-grained dark inclusions in C3 chondrites are generally devoid of recrystallized aggregates and chondrules (Fruland *et al.* 1978) and are rich in trapped noble gases (Ott *et al.* 1979). They consist mainly of olivines of similar shape and size (or smaller) like those of the chondrite matrices but in addition contain aggregates of olivine and other phases (figure 8). Although the matrix olivines are in general very similar to those of the normal chondrite matrix there is a distinct tendency for them to form small clusters consisting of intergrown subparallel plates which ultimately form stacks of plates, thick plates or blocky crystals with feathery or subhedral outlines. Some fine-grained dark inclusions do not contain any aggregates but most do. These aggregates mainly comprise coarser-grained olivines mostly of the feathery and blocky type. Olivines of different orientations are loosely stuck together, intergrown in places but have enormous pore space in between. Most of this is empty, with only a very small proportion filled by nepheline and sodalite. Occasionally thin spines of olivine protrude into the empty space. Olivine aggregates which are rimmed by clinopyroxene are also common (figure 9, plate 3). Clinopyroxene forms a rather compact shell which contrasts to the mostly extremely porous interior. Olivine compositions in fine-grained dark inclusions are also generally rich in Fa (20–40 mol %) and rich in minor elements such as Al, Cr, Ca and Ti.

In conclusion, the average dark inclusion of C3 chondrites is a chondritic rock consisting of olivine aggregates suspended in a matrix consisting also mainly of olivines. The olivines have growth features and chemical compositions that suggest that they were grown from a vapour phase. Growth apparently continued during aggregation of the aggregates and the aggregation of the rock. The typical primitive shapes of olivine are plates, stacks of plates and feathery intergrowths of plates.

One dark inclusion (Allende AF) was encountered in the Allende C3 chondrite which is an aggregate of aggregates basically of olivine (Palme *et al.* 1985; Kurat *et al.* 1987*b*). The olivine is mostly of the advanced type similar to the larger olivines in the fine-grained dark inclusions as discussed above. The average olivine grain size of the whole rock is considerably larger than that of normal Allende matrix (about 5 times) and there is no difference in average grain size between olivines in aggregates and in the matrix. Exceptions are huge stacks of subparallel olivine plates (up to 200 μm in diameter) and barred olivines (figure 10, plate 3). The latter consist of subparallel bars of olivine, about 30 μm thick, which apparently evolved from large stacks of platy olivine intergrown in a direction perpendicular to the original plate elongation. Aggregates contain all types of olivines which are partly intergrown with each other and silicate–sulphide–metal objects with commonly lobate, oval or round shapes. The latter are concentrated mostly close to the surfaces of aggregates and surprisingly do not disturb the growth pattern of the olivines. That fact allows only one conclusion to be drawn, namely, that olivines continued to grow during aggregation. The aggregates are intergrown with the matrix in a manner which is scarcely discernible in the scanning electron microscope. In transmitted light, however, the matrix is opaque due to a high abundance of minute sulphide, metal and probably other inclusions.

The aggregates and the matrix have abundant pore space which is partly filled with nepheline and sodalite. All olivines are rich in Fa (about 25–50 mol %) and rich in minor elements such as Al, Cr, Ca and Ti. The Allende AF rock does not contain any low-Ca pyroxenes. Relict clinopyroxenes with low FeO contents could indicate that the rock was formerly FeO-poor and that FeO was supplied during a metasomatic event. The bulk composition (Palme *et al.* 1985) is, however, close to bulk Allende, except for the Fe content, which is lower and some moderately volatile, and volatile element contents, which are higher than in bulk Allende.

In conclusion, olivines in the dark fragment Allende AF display advanced growth forms that appear to be completely compatible with growth from a vapour phase. From the succession of growth types in aggregates it can be deduced that the intergrowth of olivine plates to form thick plates (barred olivine) is the earliest type, followed by large stacks of subparallel olivine plates, smaller stacks grading into feathery olivines and almost euhedral crystals. The aggregates are well intergrown but still very porous and the way other objects are incorporated indicates that aggregation took place while condensation was still continuing. The sizes of the aggregates are directly comparable to aggregates and chondrules in most chondrites. We, therefore, very probably see in Allende AF the protoliths for chondrules and recrystallized aggregates of chondrites. The fact that Allende AF does not contain any low-Ca pyroxene does not weaken this conclusion. Similar, but recrystallized aggregates in normal Allende clearly show that pyroxenes were commonly formed from olivines probably by an exchange reaction with the vapour phase. Allende AF simply escaped that process as it also escaped the high-temperature event experienced by the constituents of the majority of chondrites.

On the basis of the findings outlined above a rather simple model can be developed for the origin of chondrules and other constituents of chondrites.

(1) Condensed grains aggregate while condensation continues. Grains therefore continue to grow inside the aggregates, leading to grain intergrowths and compaction.

(2) Pore space of the vapour-grown crystals is still high when compounds of more volatile elements condense. Because the pores provide the best cold traps (Arrhenius & Alfvén 1971; Arrhenius & De 1973) these phases fill part of the pore space provided rather than condense at aggregate surfaces. Depending on pore space provided, accessibility to vapour and exposure time, individual aggregates will collect different amounts of moderately volatile and volatile elements.

(3) These aggregates then experienced a high-temperature event which led to recrystallization of the porous and poorly crystallized vapour-grown phases, to sintering of the grains, and partial melting to different degrees. A low degree of melting will partly preserve the aggregate structure and part of the original growth features of the phases. A high degree of melting will enable the aggregates to be reshaped into spheres, *the chondrules*. The degree of part melting will depend on the temperature the aggregate is exposed to and the amount of low-melting-point compounds present.

(4) After solidification the processed aggregates aggregate to form larger bodies. Depending on the physical conditions this aggregation may or may not include fine-grained processed or unprocessed matter (matrix).

A fairly similar model for the formation of chondrules and aggregates has been developed previously by Mueller (1969). In his model 'microchondules', 5–50 μm in diameter, represent the primary condensation products which aggregated. The aggregates then experienced different degrees of heating, so forming the textural spectrum observed ranging from sintered aggregates to chondrules. It is surprising that Mueller's model which is based on accurate petrographic observation has not been accepted by the scientific community. In general I confirm his findings and conclusions (see below).

ORDINARY CHONDRITES

Ordinary chondrites (OCS) are widely believed to be metamorphic rocks of primitive composition that were processed in planetesimal-sized parent bodies (see Dodd 1981). As I have briefly mentioned in the introduction this belief stems mainly from four major characteristics of OCS: (1) the high oxidation state (presence of FeO in silicates); (2) the homogeneous chemical composition of the major (Mg, Fe)-phases, (3) the lack of a fine-grained matrix, and (4) the well-crystallized nature of many OCS.

The high oxidation state is incompatible with a formation in equilibrium with a gas of solar composition (Wood 1962; Suess 1964; Grossman 1972; Herndon & Suess 1977) at equilibration temperatures indicated by coexisting minerals (800–1000 °C; Bunch & Olsen 1974; Colucci & Hewins 1984; Olsen & Bunch 1984). It can be achieved by a metamorphic equilibration of a reduced and an oxidized component as they are present in most carbonaceous chondrites. Such a metamorphism taking place inside a planetesimal body could also account for the equilibration of the (Mg, Fe)-phases which is typical for OCS (Keil & Fredriksson 1964). Van Schmus & Wood (1967) developed a scheme which roughly links the 'equilibration' of the major silicates to a sort of 'degree of recrystallization'. This petrographic classification grid became very popular and is certainly very useful. Its tight relation to the concept of metamorphism, however, has misled the direction of meteorite research. This happened in spite of the criticism the concept received from the very beginning (see, for example, Fredriksson 1963; Suess & Wänke 1967; Kurat 1967*a*, *b*, 1971; Kurat & Kurzweil 1965). Although observations and data incompatible with the concept of metamorphism existed before the hypothesis was developed, their number has grown tremendously over the years. Some important facts, all in conflict with the concept of metamorphism of OCS, can be summarized (somewhat incompletely) as follows (Kurat 1987).

Bulk chemistry of OCS

Ordinary chondrites of all types and C3 chondrites have very similar contents of refractory and moderately volatile elements. They differ from each other in the degree of oxidation, in total Fe (and siderophile element) content, and in their contents of volatile elements (see Wasson 1974). They are linked to each other by metal–silicate fractionation (Larimer & Anders 1970) and a vapour–solid fractionation (Larimer & Anders 1967). The abundances of highly volatile elements are clearly lower in OCS as compared to C3 abundances. If OCS experienced a metamorphic event one would expect to find a correlation between the degree of metamorphism and the abundance of highly volatile elements. This is clearly not so. As has been shown by Larimer (1973) for L chondrites, all metamorphic classes fit a Tl/In against Tl correlation and all show the same accretion temperature at about 458 ± 5 K. Volatile element contents of some highly 'metamorphosed' chondrites are incompatible with the concept of metamorphism (Takahashi *et al.* 1978) and there are some 'recrystallized' chondrites which are enriched in volatile elements even compared with the most 'primitive' members of the same group (Higuchi *et al.* 1977). Volatile-rich components have been identified in high-grade 'metamorphic' chondrites (Higuchi *et al.* 1977; Rambaldi *et al.* 1981) and the retention of Hg in chondrites (Jovanovic & Reed 1985) is totally incompatible with metamorphism.

All chondrites (and several other meteorites) contain trapped planetary type noble gases (Zähringer 1968; Heymann & Mazor 1968; Alaerts *et al.* 1977). Because chondrites are highly porous rocks (Yomogida & Matsui 1983; Sugiura *et al.* 1984) with high permeabilities (Sugiura *et al.* 1986), properties which themselves are incompatible with 'metamorphism', the retention of noble gases and other highly volatile elements during a metamorphic event appears to be highly unlikely. We, therefore, have to conclude that the presence of volatile elements in chondrites is a primordial property which excludes any large-scale processing after accretion.

Non-equilibrium phase compositions in OCS

The so called 'equilibrated' OCS should by definition consist of chemically homogeneous major (and also minor) phases. This would be appropriate for metamorphic rocks of high equilibration temperatures as is apparently indicated by coexisting mineral pairs in OCS (Bunch & Olsen 1974; Olsen & Bunch 1984). In reality, however, major and minor phases of equilibrated OCS are very often not in equilibrium with each other in their major, minor, and trace element contents. Careful studies of individual chondrites commonly reveal the presence of olivines out of equilibrium with most other olivines (Kurat *et al.* 1974; Mason 1974; Nagahara 1980; Christophe Michel-Levy 1981; Fredriksson & Wlotzka 1985; Pellas & Bourot-Denise 1985; Scott *et al.* 1985) regardless of the 'degree of metamorphism'. Trace element studies of olivines from L-6 chondrites (Curtis & Schmitt 1979) showed that the rare earth elements (REES) are too abundant to have been in equilibrium with a melt of chondritic composition. Pyroxenes are not only commonly compositionally heterogeneous (Kurat *et al.* 1969; Scott *et al.* 1985) but also structurally. Relict clinobronzites have been found in several equilibrated chondrites (Binns 1967; Ashworth 1980; Yasuda *et al.* 1983; Shima *et al.* 1986; Watanabe *et al.* 1985) demonstrating that they have never seen a metamorphic event (Ashworth *et al.* 1984). Beside inhomogeneities in phases like plagioclase (Dodd 1969; Kurat *et al.* 1969; Bischoff & Keil 1984) and phosphates (Reed & Smith 1985) there exists a variety of relict phases clearly out of equilibrium with the host chondrite. Most common are Al-spinels (Kurat 1967*a*, *b*, 1971; Hoinkes & Kurat 1974; Kracher & Kurat 1980; Bischoff & Keil 1984) and SiO_2-phases (Christophe Michel-Levy & Curien 1965; Binns 1967; Wlotzka & Fredriksson 1980; Olsen *et al.* 1981; Brandstätter & Kurat 1984).

Metal is the phase which should be easier to equilibrate than all other phases but it is very commonly not equilibrated in chondrites. Equilibration at metamorphic temperatures above 800 °C should have homogenized all metal grains in their Ni and Co contents. Consequently, precipitation of kamacite from taenite should produce composite grains with equal amounts of kamacite and taenite. This is actually never the case in chondrites as has been already pointed out by Urey & Mayeda (1959). Metallographic cooling rates are rarely unique in a given chondrite (Wood 1967; Scott & Rajan 1981; Willis & Goldstein 1981, 1983) and apparently unrelated to the degree of metamorphism. Compositional differences between individual grains in major element contents (Semenenko *et al.* 1986; Kurat *et al.* 1987*a*) as well as in trace element contents (Widom *et al.* 1986) exclude the possibility of a metamorphic event, as do the high volatile element contents (Dodd 1974).

One of the major minerals of chondrites, troilite, should not be present at all. The precursor of troilite can form in the solar nebula by a reaction of gaseous H_2S with solid metal at $T \lesssim 680$ K (Larimer 1967). Heating to $T > 1100$ K in an open system such as the chondritic one with its high porosity and permeability must lead to a total loss of S. Consequently no sulphides should be present with the possible exception of some refractory sulphides (niningerite, oldhamite?) most of which, however, will not be stable in the oxidizing environment provided by ordinary chondrites. A recent evaluation of the textural metal–sulphide relations in 32 OCs (Matsueda & Sanga 1985) showed that all of them contained non-equilibrium paragenetic textures.

Turning to the unequilibrated ordinary chondrites, which are believed to be the parents of the equilibrated ones, we can find in almost all of them some constituents which are partly or perfectly equilibrated (Kurat 1967*a*, *b*; Binns 1968; Dodd 1968, 1978). If equilibrium is due to a metamorphic event then the unequilibrated OCs must be reworked rocks that incorporated some constituents from previously metamorphosed rocks. Why do they then contain more highly volatile elements than the equilibrated OCs?

The constituents of equilibrated OCs have highly diverse textures and chemical composition. Chondrule compositions show undisturbed sampling effects (see, for example, Fredriksson 1963; Walter 1969; Walter *et al.* 1973; Dodd & Walter 1972) and rock fragments retained their compositional and textural peculiarities (Fodor *et al.* 1972; Fredriksson *et al.* 1974; Fodor & Keil 1976; Fredriksson 1983; Wlotzka *et al.* 1983; Nakamura *et al.* 1984). The constituents are also not in isotopic equilibrium with each other regardless the degree of metamorphism. Oxygen and nitrogen isotopes are not equilibrated between different constituents (Olsen *et al.* 1981; Clayton *et al.* 1983; Fredriksson *et al.* 1985) and radiogenic gases are not depleted (Merrihue 1963; Podosek 1970; Caffee *et al.* 1982).

In conclusion it can be safely stated that ordinary chondrites cannot have been reprocessed in a metamorphic event. The survival of non-metamorphic textural features, the ubiquitous presence of unequilibrated phase compositions, the presence of troilite, of highly volatile elements, and of planetary noble gases make it necessary to abandon the concept of metamorphism. A model has to be found which can account for the apparent high temperature history of the major chondritic minerals, their subsequent near 'equilibration', and their accretion together with phases and elements which are stable only at very low temperatures.

The model

Here I make an attempt to construct a model to account for most of the observational constraints outlined above. The most important to be covered are:

(1) formation and nature of prechondritic matter;
(2) formation of aggregates and chondrules;
(3) oxidation and Fe/Mg equilibration of major silicates;
(4) formation of sulphides;
(5) collection and fractionation of volatile elements;
(6) retention of volatile elements.

Prechondritic matter

We shall not discuss the nature of the presolar matter (the matter present before the collapse of the solar nebula) because too little is known at present. Presolar matter is being identified in increasing amounts in meteorites (see, for example, Swart *et al.* 1983; Pillinger 1984; Lewis *et al.* 1987; Anders 1988). Some information about it is carried into the constituents of chondrites by the chemical memory mechanism (Clayton 1982) and some grains apparently survived the chondrite-forming event. The latter can be mixed with the processed matter and can end up as parts of meteorites.

Our main concern is the nature of particles that aggregated to form the protoliths for chondrules and recrystallized aggregates. The best candidates are apparently the grains that we have identified as probably being primitive: barred olivines (intergrown olivine platelets), large stacks of olivine platelets, small stacks of olivines platelets, and single olivine platelets (figures 7–10). These objects are all highly anisotropic in shape and badly crystallized (low birefringence and mosaic extinction) which makes it very likely that they grew from a vapour phase. Thus, probably the major portion of presolar matter was vaporized in the early solar nebula. From primitive aggregates in dark Allende inclusions we can learn that the larger subparallel stacks of platelets aggregate to objects of the size of chondrules.

During and after aggregation, condensation of olivine continues leading to a compaction of the aggregates. Metal condenses separately (mostly on and inside small olivine aggregates) and a small portion of it takes part in the formation of aggregates (figure 10). Some of the aggregates are exposed to a vapour with high Si activity. Olivines react with the vapour to form low-Ca pyroxene. This way aggregates with poikilitic pyroxenes (figure 4) of varying amounts and the protoliths of porphyritic pyroxene objects are formed. Parts of the already fractionated solar nebula became oversaturated in pyroxene leading to direct condensation of pyroxenes either as close-packed stacks of platelets (very much like the olivines) or dendrites (figure 5). At this stage the temperature must have been close to the solidus of pyroxene-rich systems because (probably supercooled) liquid drops condensed and quickly crystallized: the radiating pyroxene chondrules. All aggregates are still highly porous and provide the ideal sites for the moderately volatile phases (nepheline, sodalite and feldspar) to condense and fill part of the pore space. The condensate can also be amorphous (glass; Arrhenius & Alfvén 1971).

The high-temperature event

If such an object is subjected to high temperatures it will partly melt. The primitive, badly crystallized olivines and pyroxenes will recrystallize and form subhedral crystals (figure 7). In this way porphyritic olivine or olivine–pyroxene aggregates or chondrules will form, depending on the degree of melting. Part of the original olivine and pyroxene shapes will survive (barred and feathery olivines, feathery, dendritic, and poikilitic pyroxenes), the intersticies, however, will now be filled by glass or finely crystalline igneous matrix (figures 2–4, 6).

The products of the high-temperature event will be aggregates and chondrules consisting of various proportions of olivine and pyroxene and will contain variable amounts of moderately volatile elements. The moderately volatile elements may be vapour fractionated depending on the degree of heating. Because the refractory elements condense into the olivine (the only host available at the time of condensation) they will be unfractionated in most aggregates and chondrules. During the recrystallization event they will partly redistribute into the low melting portion and the vapour phase because most of them are incompatible elements with respect to the olivine lattice. However, redistribution commonly is not complete, resulting in high trace element contents in the olivine.

In this way, most of the fractionations observed in chondritic constituents can be explained. The end products of the processes outlined above will be recrystallized aggregates and chondrules consisting of forsterite, enstatite, glass or fine-grained matrix, and variable, but mostly few globules of low-Ni metal. The major, minor and trace element contents will be almost as we observe now. The constituents are degassed and have variable proportions of radioactive elements. The missing factors are essentially oxidized Fe (FeO) and volatile elements such as S, Se and Zn.

The metasomatic events

Metasomatism is the key process in chondrite (and meteorite) genesis. It is an exchange reaction which replaces certain elements in the solid by others from the vapour. Such a reaction is not easily identified if it runs to completion. However, there are a growing number of observations of incomplete metasomatic 'alterations' which affect all constituents, for example, of carbonaceous chondrites. Metasomatism has involved many elements, the most important of which are O^{2-}, S^{2-}, Fe^{2+}, Mn^{2+}, Zn^{2+}, the alkalis and H_2O. For the genesis of ordinary chondrites the most important elements are O^{2-}, S^{2-}, Fe^{2+}, Mn^{2+} and Zn^{2+}.

Oxygen isotope data on chondrules (Clayton *et al.* 1983) clearly show that chondrules of all chondrite types are not in isotopic equilibrium with each other and that individual chondrules to different degrees exchanged oxygen with an ambient vapour phase. This probably happened during the high-temperature event because oxygen diffusion rates are low in densely packed silicate structures. Also, during the Fe^{2+} metasomatism event we can expect some oxygen exchange to take place. Oxygen will also be added to the aggregates at lower temperatures but will involve mainly metal. Oxidation of elements with a tendency towards lithophile behaviour dissolved in metal (P, Cr, Si) leads to the formation of phosphates, chromites, and silicates (Kurat 1975; Brandstätter & Kurat 1984; Rubin & Grossman 1985; Yabuki & El Goresy 1986). Oxidation apparently continued at still lower temperatures leading to the formation of iron oxides (Nelen *et al.* 1975) but this event mainly affected constituents of carbonaceous chondrites.

The almost homogeneous Fe–Mg distribution in silicates of the equilibrated ordinary chondrites is most easily explained by metasomatic exchange reaction of Fe^{2+} with the ambient vapour. This is a process that can be easily identified in carbonaceous chondrites because there it did not proceed to completion (figure 7). All Mg silicates are affected, the pyroxenes commonly less so than the olivines because of the very low diffusion rates for Fe^{2+} and Mg^{2+} in pyroxenes (Kurat 1975; Kurat & Kracher 1980; Wark 1981; Housley & Cirlin 1983; Kring 1985; Kurat *et al.* 1985; Peck 1986; Peck & Wood 1987). For the constituents of ordinary chondrites the Fe^{2+} metasomatic event took place at higher temperatures and led to an almost complete 'equilibration' of Fe–Mg in the major silicate phases. Because each individual object apparently had its own history during all stages up to accretion, some probably did not receive the full amount of Fe^{2+} and others received more than the average (the FeO-rich silicate assemblages (Dodd *et al.* 1966)). Iron metasomatism was probably accompanied by Zn^{2+} metasomatism of the major silicates. Manganese could have been present in the silicates before Fe^{2+} metasomatism started (Kurat *et al.* 1984) but could also have been added, at least in part, during the Fe^{2+} metasomatism event. The exchange reaction Mg^{2+} (solid)–Fe^{2+} (vapour) should liberate large amounts of Mg^{2+} (and probably also other elements). Because this liberation takes place at temperatures far below the condensation temperature of Mg silicates the mobilized Mg will tend to recondense at the first possible site. These sites will preferentially be the still available pore spaces but also include rough surfaces. At this stage Mg^{2+} will naturally co-condense with Fe^{2+} and form silicates that will reduce the pore space and facilitate compaction. It is possible that at this stage of development the constituents of chondrites have already aggregated to form centimetre to decimetre sized chunks. The earlier this aggregation to the next hierarchical order of sizes takes place the larger is the degree of recrystallization and compaction to be expected.

The presence of troilite (FeS) as the major sulphide in ordinary chondrites requires a metasomatic exchange reaction between solid metal and the ambient gas at fairly low temperatures (Larimer 1967; Grossman 1972). Sulphurization of metal can be observed in many places (Kurat 1975; Cirlin 1984) and extreme sulphurization is probably the process which played a major role in the formation of enstatite chondrites (although at different *p–T* conditions). For the sulphurization process to be as effective as is observed in the ordinary chondrites the average size of the agglomerated constituents must not be large. Because of the low temperature at which sulphurization can be expected to take place, volatile elements with some chalcophilic tendency will follow S. The most likely are Cu, Se, Sb, Te, Hg, Tl and Bi. Fractionations between these elements can be expected depending on the temperature range during which sulphurization takes place. Sulphurization and addition of volatile elements will cease when the pore space is shielded by the increasing size of a particular aggregate chunk. Thus it can be expected that the volatile elements will be inhomogenously distributed both within individual ordinary chondrites and between different ordinary chondrites. This is indeed so (see, for example, Huston & Lipschutz 1984; Laul *et al.* 1973; Morgan *et al.* 1985; Ligner *et al.* 1987).

Metasomatic 'alterations' involving a variety of other elements can be observed in carbonaceous chondrites. Of these the common alkali metasomatism (Kurat & Kracher 1980) could have been of some importance in the genesis of ordinary chondrites. Hydration (H_2O metasomatism) was obviously not important.

In conclusion the equilibrated Fe–Mg distribution between the major silicates in ordinary chondrites and other meteorites and the presence of troilite as the major sulphide can best be explained by metasomatic processes (exchange reactions) which took place continuously in a cooling gas phase. For these processes to be effective the average size of the agglomerates of condensed matter must have been small (of the order of centimetres to decimetres). Consequently, these characteristic features of ordinary chondrites must have been established before accretion. The different chemical chondrite groups (E, H, L, LL) therefore probably represent accretionary chunks from different nebula regions rather than from distinct parent bodies. Chunks from a part of the nebula will be similar but not equal because each chunk and its constituents will have its own history. It is therefore not necessary to postulate parent bodies. In such bodies, internal heating by short-lived radioisotopes would lead to destruction of the primitive record (planetary gases, highly mobile elements, sulphides, primitive textures) which, however, is still preserved in ordinary chondrites.

Primitive meteorites

Ordinary chondrites

The equilibrated ordinary chondrites are by far the most common meteorites. As outlined above they preserve records of a variety of solar nebula processes from high temperatures to very low temperatures. All their properties are compatible with solar nebula processes but many are incompatible with planetary reprocessing (such as 'metamorphism'). The model presented here allows for the formation of the most common meteorites during normal processing in the solar nebula. Indeed, the most common meteorites should represent the products of the most common succession of events. It is my opinion that they do and therefore the ordinary chondrites are the representative primitive matter of the solar nebula and the processes having taken place in the region of meteorite formation. In this view all other chondrites owe their existence to less common variations of basically the same processes (provided the statistic of meteorite falls is representative of their abundances).

The unequilibrated ordinary chondrites (figure 1), widely believed to be the primitive precursors of the equilibrated ordinary chondrites, appear to represent a sort of border facies of the normal development of chondrites. The two major differences between the unequilibrated and equilibrated ordinary chondrites are the non-equilibrated compositions of the major phases and the presence of a fine-grained chondrite matrix. The different degrees of non-equilibrium of different constituents of such chondrites indicate that these constituents experienced the Fe^{2+} metasomatism event to different degrees. The presence of a fine-grained matrix indicates that accretion of the high temperature agglomerates occurred late as compared to most equilibrated chondrites, collecting volatiles before and during accretion. Unequilibrated ordinary chondrites therefore represent a mixture of constituents which have been processed in many different ways. Although they are also primitive, they are not the representative products of chondrite forming processes in the solar nebula. However, they provide a convenient record of most of the processes having taken place in the early Solar System.

Carbonaceous chondrites

The carbonaceous chondrites are a very heterogeneous group of meteorites which have experienced some processes which did not affect the ordinary chondrites. Type 3 carbonaceous chondrites (figure 7) in many respects resemble unequilibrated ordinary chondrites. They also consist of aggregates and chondrules which have seen a high temperature event as well as a fine-grained matrix. The aggregates and chondrules abundantly display examples of incomplete Fe^{2+}-metasomatism, oxidation and sulphurization of metal, and commonly also alkali-metasomatism. The matrix olivines are strongly affected by the metasomatic event. They retained their primitive shapes but their chemical compositions were changed, apparently because of their small grain-sizes. Like the unequilibrated ordinary chondrites, type 3 carbonaceous chondrites accreted late and collected processed aggregates, metasomatized primitive condensates (matrix olivine and other phases), organic matter and unprocessed presolar matter (e.g. diamonds). Type 3 carbonaceous chondrites are certainly primitive, but not 'more primitive' than ordinary chondrites. They just record a somewhat different succession of events from a different region of the solar nebula.

The constituents of C1 and C2 chondrites have experienced an additional metasomatic event compared to all other chondrites: H_2O-metasomatism. Although there is clear evidence in places that H_2O-metasomatism occurred (serpentinization) this evidence should not be over-emphasized. There are abundant observations that indicate that phyllosilicates (and carbonates, etc.) could have been formed by direct condensation (from remobilized vapour?). Most C2 chondrites are rich in primitive textural features but C1s are not (except for the platy magnetite stacks which somewhat resemble primitive stacks of olivine platelets in C3s). Both chondrite types are dominated by 'matrix', a fact which could be interpreted to indicate very late accretion and insufficient formation of aggregates. Although they are certainly primitive, the highly mobile nature of some phases of C1 chondrites (e.g. sulphates) make them more likely to be inhomogeneous in major elements than other chondrites. Such properties, however, do not necessarily imply planetary processing.

Enstatite meteorites

Enstatite chondrites comprise an inhomogeneous group with highly variable Fe and S (and related elements) contents (Anders 1964). They are conveniently classified into two types. The EH group is rich in Fe and S and is generally of the low-grade metamorphic type. The EL group is lower in Fe and S than EHs and comprises highly recrystallized types only (Baedecker & Wasson 1975; Sears *et al.* 1982; Hertogen *et al.* 1983; Kallemeyn & Wasson 1986). They are generally rich in volatile elements but extremely heterogeneous with volatile element abundances ranging from over CI abundances to below OC abundances. The high abundances are found mainly in EHs (Hertogen *et al.* 1983). This difference in volatile element contents has been attributed to thermal metamorphism on the E chondrite parent body which partly mobilized the volatile elements (Biswas *et al.* 1980). Enstatite chondrites have the most reduced and sulphurized mineral assemblages known from meteorites (Keil 1968; Keil & Anderson 1965; Leitch & Smith 1982; McKinley *et al.* 1984). Many lithophile elements became partially siderophile (P, Si, Cr) or chalcophile (Ca, Mg, Na, K, Cr, Mn, REE, U, etc.) under the conditions prevailing during E chondrite formation. Mineral compositions, however, and mineral associations present in different constituents (clasts) of E chondrites are not equilibrated (Leitch & Smith 1981; Rambaldi *et al.* 1983, 1986; Rubin & Keil 1983; Sears *et al.* 1983; McKinley *et al.* 1984; Frazier & Boynton 1985; Petaev *et al.* 1985; Nagahara 1985; Lusby *et al.* 1986; Fogel *et al.* 1987). This had led to the construction of complex models and the classification of many E chondrites as breccias which formed by impact on the E chondrite parent body. This model faces severe problems because of the high abundances of volatile elements, the absence of solar-wind noble gases (Rubin 1983), the presence of 'subsolar' gases in enstatites, the retention of ^{129}Xe (Crabb & Anders 1982), and the abundant presence of planetary noble gases (Crabb & Anders 1981).

The E chondrites can be derived from the model for chondrite genesis in very much the same way as the ordinary chondrites. The only major difference lies in the redox conditions under which the early aggregates were processed. Olivine is an abundant relict phase in E-chondrites (Rambaldi *et al.* 1984; Nagahara 1985) which makes it possible that the original aggregates consisted mainly of olivine, like those of the ordinary chondrites. However, relict olivines of E-chondrites contain FeO, which implies that they had experienced a Fe^{2+} metasomatism before they were strongly reduced and sulphurized although not necessarily before pyroxene was formed. The inhomogeneous minor element compositions of enstatites indicate a heating event. This would lead to recrystallization of some of the enstatites, and expulsion of most of their minor elements. Sulphurization (S^{2-} metasomatism) could also influence the minor element compositions of enstatites. However, it mainly led to the formation of sulphides from silicates and metal. The high trace-element contents of oldhamite and niningerite could indicate that these refractory sulphides might be condensates or recondensates if the heating event took place under high p_{S_2}. The variable mineralogical and bulk chemical compositions of different clasts of E-chondrites could indicate differing degrees of processing during the S^{2-} metasomatic event.

Early formation of larger chunks of aggregates will lead to less-pronounced sulphurization, a higher degree of recrystallization (via a vapour phase), hence a reduced pore space and consequently lower contents of volatile elements (EL). Late accretion will have the opposite effect – similar to the ordinary and carbonaceous chondrites – and will allow the collection of exotic components (Crabb & Anders 1981; Grady *et al.* 1986).

Enstatite achondrites (aubrites) appear to be closely related to the E-chondrites with respect to the exotic mineralogy (see, for example, Wasson & Wai 1970; Graham *et al.* 1977; Watters & Prinz 1979), oxygen isotopic composition (Clayton *et al.* 1976), ^{129}I-^{129}Xe formation interval (Podosek 1970), and many other properties. They differ, however, in mineral abundances and bulk chemistry. The major mineral is enstatite, which has much larger grain sizes than in E-chondrites (figure 11). The bulk compositions are highly variable and fractionated (Wolf *et al.* 1983). Refractory lithophile elements are slightly depleted (0.1–0.6 times that of CI), refractory siderophile elements are strongly depleted (*ca.* 10^{-3} to 10^{-5} times that of CI). Surprisingly, moderately volatile elements and even highly volatile elements are much less depleted. These trace element characteristics have been interpreted to be due to igneous differentiation (see Wolf *et al.* 1983). Thus, the aubrites are currently considered to be cumulate pyroxenite rocks derived from a planetary differentiation process. If this were so, we could expect the highly siderophile, chalcophile, and incompatible lithophile elements to be highly depleted. This is clearly not so. Of the highly siderophile elements Au (and also Ni under the highly reducing conditions) are on average almost 100 times more abundant than Ir and Os. The chalcophile element Se is on average more than 100 times as abundant as Ir and the highly incompatible element K has abundances between 1 and 2×10^{-2} times that of CI. Thus it is very likely that a melt never was in contact with aubrites. This view is also strongly supported by the trace element distributions between minerals of the Mayo Belwa aubrite (Graham & Henderson 1985) where the plagioclase is strongly enriched in REES. In applying experimentally derived distribution coefficients (Drake & Weill 1975) the liquid which could have precipitated such a plagioclase must have had concentrations of REES of about 50 times that of CI. Furthermore, the heavy REES should be about equally abundant in enstatite and plagioclase (Weill & McKay 1975). Instead they differ by a factor of five.

Without going into more details here it appears likely that the aubrites are collections of fairly large enstatite clasts (processed in a similar way to E-chondrites) rather than igneous cumulate rocks. The clasts could have originally been aggregates of olivine (very large stacks of platelets) which became converted to low-Ca pyroxene, or they could have consisted of similar large stacks of enstatite directly condensed from the gas phase. The disordered structural state of enstatite (Graham *et al.* 1977) is compatible with both possibilities as are the bulk contents of refractory lithophile elements (which are high) and siderophile elements (which are low). During the olivine–pyroxene conversion or during part recrystallization of the enstatite, the more mobile incompatible elements were expelled from the enstatite lattice (probably together with Al) and were only partly retained by other phases (mainly plagioclase and/or oldhamite).

Accretion of the large aggregates and single enstatite crystals occurred early and therefore phases containing highly siderophile elements could not be sampled and moderately volatile and volatile elements were sampled insufficiently despite the high porosities of aubrites. The channels in Mayo Belwa (figure 11) are decorated by condensed enstatite crystals and do not contain any intercumulus melt (Graham *et al.* 1977). All elemental depletions observed in aubrites could be due to the possibility that aggregates of early phases grew and agglomerated too fast. The, probably finer-grained, refractory siderophile component was excluded from the agglomeration process and the more volatile elements could not enter the large chunks in appropriate proportions. Thus, aubrites (and other achondrites, see below) are primitive meteorites and could represent a special case of the normal processing of matter in the solar nebula.

Ureilites

The genesis of ureilites has been controversial for a long time. Currently two models are *en vogue*, both of which use igneous events. The more popular model sees the ureilites as cumulate rocks derived from a liquid which was rich in C and which probably was derived from a carbonaceous chondrite-like parent (Berkley *et al.* 1980; Goodrich *et al.* 1987; Janssens *et al.* 1987). The second model sees the ureilites as residues of a part melting event which affected a parent of carbonaceous chondrite-like composition (Binz *et al.* 1975; Boynton *et al.* 1976; Higuchi *et al.* 1976; Wasson *et al.* 1976; Takeda 1987). The ultimate goal of both models is to offer an explanation for the depletion of incompatible elements in ureilites as compared with chondrites. However, both models face difficulties in explaining the most typical features of ureilites: The presence of a matrix (commonly called 'veins') rich in graphite, diamonds, planetary noble gases, siderophile elements and incompatible lithophile elements. I cannot envisage any mechanism that will retain highly volatile elements and noble gases during a melting event (Begemann & Ott 1983). Furthermore, the existence of a diamond-free ureilite – ALHA 78019 (Berkley & Jones 1982) – containing noble gases in comparable amounts to diamond-bearing ureilites (Wacker 1986) considerably weakens the models that tried to explain the high noble gas contents by shock implantation from an 'atmosphere' into the diamonds. In addition, the recent discovery of diamonds of interstellar origin (Lewis *et al.* 1987) in the Allende carbonaceous chondrite make shock events unnecessary as a means for diamond genesis. Recent experiments (Fukunaga *et al.* 1987) conclusively showed that vapour-grown diamonds take up and retain large amounts of noble gases from the environment. It therefore appears very likely that the gas-rich diamonds of ureilites (Göbel *et al.* 1978) are primordial and probably formed in the early solar nebula.

Mineralogically, ureilites are a rather heterogeneous group consisting of olivine and low-Ca pyroxene (mostly pigeonite, but also clino-bronzite and sub-calcic augite) in highly variable proportions (figure 12) ranging from about 1:1 (Y74659 and Dingo Pup Donga) to more than 5:1 (Haverö; Berkeley *et al.* 1980; Takeda 1987). This heterogeneity makes the residua model unlikely.

The original core compositions of silicates were apparently almost 'equilibrated' before partial reduction took place on contact with the carbon-rich matter. These core compositions, however, vary over a wide range from FaO to Fa25 (Takeda 1987). This covers the total range from enstatite chondrites to ordinary chondrites. Thus, ureilites apparently record the total range of redox conditions experienced by the non-carbonaceous chondrites. Highly reduced relict phases are common in ureilites: Cr-, Si-, and P- bearing metal, suessite, cohenite, Ca-bearing sulphides, diopside, NaCl, KCl (Berkley *et al.* 1978, 1980; Jaques & Fitzgerald 1982; Delaney & Prinz 1987; Prinz *et al.* 1987; Takeda 1987). These phases demonstrate that ureilites were originally highly reduced – comparable with the enstatite chondrites – and later acquired different amounts of FeO.

The minor element contents of olivines and pyroxenes are high. Olivines are always rich in Cr_2O_3 (0.4–0.8% (by mass)) and CaO (0.2–0.4% (by mass)); similar to the primitive olivines of dark inclusions in C3 chondrites. Contents of Al_2O_3, however, are generally below 0.05% (by mass) and TiO_2 below 0.03% (by mass). MnO contents are between 0.25 and 0.45% (by mass) and are independent of the FeO content (Mittlefehldt 1986). Takeda (1987) even finds a weak negative correlation between MnO and FeO. Both findings are incompatible with fractional crystallization as also is the fact that the distribution of Mn between olivine and pigeonite is not in equilibrium (despite the 'equilibrated' Fe/Mg of the cores).

Olivines display two types of textures in ureilites. They either form large single crystals or granular integrowths of similar size. This has been used to establish a petrographic classification (Vdovykin 1970): type I ureilites contain large single olivine crystals (less than 4 mm), type II ureilites (figure 12, plate 3) contain granoblastic intergrowth of small olivine crystals (0.1–2 mm). The second type texture has been interpreted to represent the recrystallized version of type I with the recrystallization having been induced by heavy shock loading (Lipschutz 1964; Vdovykin 1970; Berkley *et al.* 1980). This interpretation appears to be incorrect. Haverö, for example is a type II ureilite with well developed 'mosaicism' of olivine but it contains abundant large voids (Neuvonen *et al.* 1972; Marvin & Wood 1972) which should not have survived a shock event in excess of 600 kbar (Vdovykin 1970). It is worth mentioning here that very similar interconnected voids are also common in some aubrites (Graham *et al.* 1977) figure 11.

Pyroxenes are mostly very cloudy (rich in inclusions) and badly crystallized, exhibiting mosaic or lamellar extinctions (figure 13, plate 4). X-ray data show mosaic spreading and lattice rotation about the *b*-axis (Berkley *et al.* 1980) and no twinning as suggested by the optical behaviour (Takeda 1987). These features have all been interpreted as being due to shock alteration. However, pyroxene pairs indicate formation temperatures in excess of 1200 °C and fast cooling. If such a shock event caused the olivines to recrystallize into a granulite-like texture, why were the distorted pyroxenes, which show no sign of recrystallization or unmixing preserved? The pyroxenes appear to have features typical of vapour-grown crystals and must be expected to be highly defective if grown at temperatures well below the solidus.

Bulk compositions of ureilites are highly heterogeneous (Wänke *et al.* 1972; Wiik 1972; Boynton *et al.* 1976; Higuchi *et al.* 1976; Wasson *et al.* 1976; Jaques & Fitzgerald 1982; Janssens *et al.* 1987) and fractionated. The refractory lithophile elements are slightly to strongly depleted with respect to CI, except for Sc and V. The REE contents of individual ureilites are very different but mostly have a common pattern: the heavy REES (HREE) and the light REES (LREE) are enriched over the intermediate REES. This V-shaped pattern is certainly not a pattern that can be expected from igneous fractionation processes but rather documents mixing of two components, one rich in HREE and poor in LREE and the other with a reciprocal pattern. These patterns are very common in terrestrial upper mantle peridotites which after having been depleted in LREEs by extraction of partial melts became enriched in LREE by metasomatic processes (migrating fluid phases). However, HREE contents of peridotites vary widely depending on the degree of extraction of partial melts (for example, Kurat *et al.* 1980). This is not so with ureilites which have fairly uniform HREE contents. Analyses of acid-cleaned samples showed (Boynton *et al.* 1976; Spitz & Boynton 1986) that the HREEs reside in the major silicates whereas the LREEs are in matrix phases. The Lu content of one of the most olivine-rich ureilites, Haverö, is the same as that of all others. Consequently, the HREEs probably reside in the olivine. The abundances, however, are much too high for those olivines having ever attained equilibrium with a coexisting melt (McKay 1986) of chondritic composition. The slope of the depletion patterns from Lu to Eu, however, fairly closely follows the slope for the distribution coefficients.

The moderately volatile lithophile elements (Mg, Si, Cr, Li, Mn) are all enriched when compared with CI and only slightly fractionated. Elements more volatile than Mn are increasingly depleted with increasing volatility and highly variable. This is similar to chondritic constituents and reflects probably similar processes: vapour fractionation and mixing. The abundances of lithophile elements appear to be governed by the acceptance of ions by the olivine lattice (all compatible elements like Mg, Li, Cr, V, Mn and Sc are abundant) and a component, presumably residing in the matrix, which contains high amounts of highly incompatible elements (La, Ce, K, Na).

The siderophile and chalcophile elements are highly fractionated in ureilites. The refractory siderophile elements (Re, W, Ir) are quite abundant (0.1–2 times that of CI) and abundances decrease with decreasing condensation temperature (in the order Pt–Ni–Pd). The low Ni/Co ratio and the high Fe content indicate a metasomatic event under oxidizing conditions. Because the highly siderophile elements are more abundant than Ni and Co, a conventional silicate–metal fractionation is impossible. The highly refractory siderophile elements reside in the matrix (Wänke *et al.* 1972) and are clearly a primitive component which must have been added from a primitive reservoir (and not from a differentiated planetary body) before ureilites accreted.

The moderately volatile and volatile siderophile and chalcophile elements are highly fractionated and also enriched in the matrix except for Zn which probably resides in the olivine into which it presumably was introduced together with Fe.

Ureilites are very rich in C which is present mainly as graphite and diamond (Vdovykin 1970). Carbon isotope compositions of ureilites are comparable to those of CI and C2 chondrites (Smith & Kaplan 1970; Belsky & Kaplan 1970; Grady *et al.* 1985) nodular graphite from IAB irons (Deines & Wickman 1973, 1975) and graphite from E chondrites (Carr *et al.* 1983). Oxygen isotopes are related to C3 chondrites insofar as they occupy a position directly on the C3 mixing line (Clayton *et al.* 1976) thus making them an endmember with the heaviest oxygen.

Ureilites are also rich in noble gases which predominately reside in carbon phases and preferentially in diamond (Weber *et al.* 1971, 1976; Göbel *et al.* 1978). Silicates are gas-poor and as such demonstrate separate processing and subsequent mixing of silicates and carbon (Begemann & Ott 1983). The trapped gases are also extremely poor in ^{40}Ar which makes them very likely to be of primitive heritage. The diamonds therefore acquired the noble gases in a primitive environment and were then attached to the silicate phases either before or during accretion, as has been pointed out by Ramdohr (1972). The pronounced crystallographic orientation of diamonds observed by Lipschutz (1964) could indicate that they condensed *in situ*.

The many primitive features displayed by ureilites make it highly unlikely that they are igneous rocks. In applying my model for the genesis of chondrites and aubrites, ureilites can easily be placed among the primitive meteorites (see also Mueller 1969). They formed as olivine aggregates very much like the constituents of chondrites. Because of probably higher-than-average growth rates of olivine from vapour the aggregates consisted either of huge stacks of olivine platelets or of densely intergrown large stacks and 'bars'. This primary orientation is still preserved in many ureilites (figure 14, plate 4) and has been attributed to cumulate processes (Berkley *et al.* 1976). The low pore space prohibited the collection of condensates of moderately volatile and volatile elements. Subsequently the aggregates experienced a heating event which led to part recrystallization, formation of fairly well crystallized single crystals (from huge stacks) or granular intergrowth. The heating event caused remobilizations of some elements like Al, LREES, Ca and Ti originally in the olivines but left the more compatible ones like Sc, Lu, and possibly Li. This probably took place under highly reducing conditions. Pyroxenes formed either before or during this heating event partially by a reaction of the vapour with olivine (there are some poikilitic pyroxenes in ureilites) and partially by direct precipitation from the vapour (highly cloudy and striated stacks of pyroxene plates). Subsequently the aggregates were subjected to a metasomatic event under oxidizing conditions which resulted in different FeO contents (plus MnO) of the silicates in different regions of the solar nebula. The aggregates then collected dust containing refractory siderophile elements, and carbon. During accretion, precipitation of carbon and subsequently volatile elements continued until the interiors of the growing chunks became isolated from the gas phase.

Other meteorites

The meteorites identified above to be probably of primitive origin have many relatives. If we add to the major processes already identified, the condensation of metallic iron during accretion of aggregates almost all meteorites could be found to belong to the family of primitive Solar System objects. These relations need further study. A brief compilation of possible links should suffice for the time being.

Directly related to chondrites appear to be the silicate-bearing iron meteorites, winonaites, lodranites, mesosiderites, pallasites, Steinbach, diogenites, Angra dos Reis, and maybe a few more. Each of these cases needs careful study and evaluation to be fitted within the framework of a unified theory on meteorites.

CONCLUSIONS

Most meteorites are very likely to be primitive, which means that they were formed in the solar nebula by solar nebula processes. The most important processes which can be identified by studying meteorites and their constituents are the following (in approximate chronological order). (1) An early heating event causing part to total evaporation of presolar matter. (2) Recondensation beginning with olivine, followed by other phases with falling temperature. (3) Aggregation of condensates to form millimetre-sized objects during condensation.

(4) Compaction of early aggregates by continuing condensation which preferentially uses the pore space of early aggregates. (5) A second heating event causes sintering and partial melting of the aggregates (chondrule formation) and mild vapour fractionation. (6) During subsequent cooling the recrystallized objects are metasomatized and experience exchange reactions with the solar nebula. Oxidized Fe is exchanged for Mg in the silicates ('equilibration'). (7) At lower temperature, exchange of Fe/Mg ceases, but sulphurization of metal forms FeS. (8) Accretion takes place at very low temperatures with condensation of volatile elements still continuing. (9) Carbonaceous chondrites accreted at lower temperature than all other meteorites. Before they accreted, some (C1, C2) experienced H_2O, and CO_2, metasomatism (formation of phyllosilicates and carbonates) and almost total oxidation.

The typical early condensate appears to be olivine. This olivine displays different growth features depending on growth rate, oversaturation of the vapour, and other parameters. Early and probably fast-growing olivine consists of subparallel thick plates ('barred olivine') or huge (larger than 100 μm) stacks of subparallel platelets (1–5 μm thick) or smaller stacks. These olivines have highly defective lattices and contain large amounts of minor elements including refractory lithophile elements. Depending on growth rate and aggregate abundance these olivine aggregates can accrete to centimetre-sized objects which quickly loose porosity by continuing condensation of olivine into the pore space and thus their interiors can become isolated from the vapour. These aggregates of early aggregates could ultimately end up in ureilites or pallasites.

Slower condensation and accretion will result in aggregates of different but fairly high porosity. Olivine will partly react with the vapour to form low-Ca pyroxene which typically will include some relict olivine. The different amounts of pore space will allow different amounts of more volatile phases to condense. In such a manner the protoliths for chondrules and other constituents of chondrites could acquire their variable chemical compositions. Not all of the pyroxenes apparently formed by reaction of the vapour with olivine. There is ample evidence that some pyroxenes directly condensed from the vapour in a similar way to olivine. The very large stacks of pyroxene platelets could ultimately end up in aubrites, diogenites, and siderophyres but also be mixed into ureilites and E-chondrites. Similarly, large clinopyroxene stacks could ultimately form angrites.

The second heating event was experienced by most small (of the order of millimetres) and large (of the order of centimetres) aggregates, but not all. The same holds for the Fe-metasomatism event. In addition, there are indications that some matter experienced at least two cycles of reprocessing before final accretion took place. The major fractionation mechanisms appear to be the following. (1) The composition of major condensing phase and the pore space provided by aggregates. (2) The timing of formation of aggregates of aggregates and the timing of the closure of pore space. (3) Reprocessing of aggregates in a high-temperature event with part remobilization and loss of incompatible and volatile elements. (4) Oxidation and metasomatic exchange reactions between solid aggregates and vapour, its intensity and duration. (5) Isolation of aggregates from vapour through shielding by condensates (e.g. metal) or physical removal from a particular nebula gas region. (6) Rate and temperature of final accretion. (7) Degree of mixing with solar and presolar dust during accretion.

Theoretical and empirical explorations of these processes should eventually allow us to track the history of each individual meteorite or even of each individual constituent of a meteorite.

However, the sequence of events so deduced can be expected to be comparable to the chaotic nature of those common products of processing in the solar nebula: the chondrites.

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