# A compositional classification scheme for meteoritic chondrules

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**A taxonomic scheme is proposed for the main component of the primitive chondrite meteorites—the chondrules. The scheme provides insight into the variety of chondrules originally produced in the primordial solar nebula, and the effects on them of secondary processes on meteorite parent bodies. It may also contribute to understanding the origin of compositional diversity in the chondrites.**

THE nine classes of meteorites known as the chondrites are the most primitive known rocks in the Solar System[1]. The main constituents of these rocks are chondrules, roughly spherical aggregates of silicate minerals unlike anything found in lunar and terrestrial rocks[2,3]. Chondrules have therefore attracted considerable attention throughout the history of meteorite studies. Not only are they crucial to understanding their host meteorites, but they also afford unique insights into processes that occurred in the dusty, turbulent and apparently energetic nebula in which the Sun and planets formed.

The compositional trends displayed by the nine chondrite groups reflect processes occurring in the pre-planetary nebula, and therefore may be relevant to planet formation, but the details are contentious. Some authors argue[4,5] that the compositional trends reflect the proportion of chondrules to matrix, so that chondrule formation is the principal process affecting the composition of dust in the nebula. Other authors have argued[6,7] that the chondrite groups reflect compositional trends caused by the separation of nebular gas and dust before chondrule formation. Part of the reason for the lack of agreement is the variety and complexity of chondrules and, in our opinion, the lack of a systematic approach to chondrule study.

Whatever the processes that were responsible for the formation of chondrules, they produced a wide variety of textures and compositions. To complicate matters further, once on their parent bodies the meteorites were altered, mainly by thermal metamorphism but also by the passage of aqueous fluids. A comprehensive classification scheme for chondrules is clearly needed, but none of those so far suggested[3,8-11] has proved entirely satisfactory.

Existing schemes depend on texture[3,8,9] or a combination of texture and mineral chemistry[10,11]. Texture is important in deducing certain aspects of chondrule formation (such as post-formation cooling rates), but depends on many apparently random factors such as the type and abundance of nucleation sites. The schemes that combine mineral chemistry and texture have also proved helpful, but are confusing when applied to metamorphosed meteorites. They also concerned fairly homogeneous subsets of the chondrule population, so that arguments were inevitably based on an incomplete data base, and satisfactory discussions of mass balance, and the relevance of chondrule compositions to whole rock compositions, were impossible.

We now propose a compositionally based classification scheme that will help in systematizing the wealth of data available and in disentangling the effects of nebular and subsequent processes. The scheme builds on the strengths of earlier work, using fundamental properties of the chondrules, is applicable to >95% of the chondrules and is easily applied by anyone with an electron microprobe. Most important, the new scheme stresses the original diversity of the chondrules and the complex yet facile way in which chondrules respond to parent-body metamorphism. Our results suggest that arguments against an important role for chondrules in determining the compositional trends of the chondrites were premature.

## Chondrules: diverse and altered

The earliest workers described the chondrules as 'globules'[12], and in the mid-nineteenth century they were referred to 'drops of fiery rain'[13]. In the present century they were thought to be silicate liquids which had condensed in the primordial solar nebula[14], or impact-produced melts[15]. None of these ideas is currently popular, and other suggestions abound[16]. There is agreement, however, that the chondrules have been flash-heated. Some chondrules are pure glass, whereas some have textures indicative of once having been wholly melted but subsequently crystallized into a variety of textures depending on composition, nucleation processes, temperature and cooling rate[17]. Others have textures which are 'igneous', but surprisingly coarse-grained, and some part of these may never have been totally melted[18]. Kieffer refers to the former as 'droplet' chondrules[8], and Dodd and others refer to the latter as 'clastic' or 'lithic' chondrules. Dodd even suggests that the lithic chondrules are abraded fragments of previously existing igneous rocks[3]. Gooding and Keil developed a successful scheme for classifying chondrule textures[9], sorting the chondrules into nonporphyritic (uniform fine-grained textures known as cryptocrystalline, radial pyroxene, barred olivine and granular) and porphyritic (coarse-grained with phenocrysts of olivine and pyroxene located in a mesostasis of highly variable composition).

Other workers have stressed the importance of mineral compositions and identified two contrasting extremes, the type IA chondrules with FeO-poor olivine and the type II chondrules in which the olivine is FeO-rich[10]. Type IB chondrules have also been identified in which olivine, slightly higher in FeO than is type IA, is enclosed in pyroxene[11].

A complication in studying the early history of any meteoritic material is the alteration processes they have suffered, most notably metamorphism. The 'petrologic types' of Van Schmus and Wood[19] and Sears *et al.*[20], which rely on physical and mineralogical measurements, have been developed to assess the amount of metamorphism.

## Cathodoluminescence and composition

We became interested in the diversity of chondrule compositions during studies of their cathodoluminescence (CL)[21-23]. We first sorted the chondrules into those with bright CL (group A) and those with little or no CL (group B) and then further subdivided them according to the colour and intensity of the CL in the chondrule grains and the mesostasis that encloses the grains (Table 1). It became apparent that the CL properties were correlated with differences in composition. Thus we can take as our starting point for the classification scheme the composition of the chondrule mesostasis. As this is of ill-defined mineralogy (it is often a glass) its composition can best be expressed in

TABLE 1 Chondrule groups defined in terms of cathodoluminescence and mesostasis composition

| | Mesostasis* | Chondrule grains |
|---|---|---|
| A1 | yellow | red |
| A2 | yellow | none/dull-red |
| A3 | blue | red |
| A4 | blue (An ≥ 50) | none/dull-red |
| A5 | blue (An ≤ 50) | none |
| B1 | none/dull-blue (Qz ≥ 50) | none/dull-red |
| B2 | dull-blue (Qz 30–50) | none/dull-red |
| B3 | purple (Qz 15–30) | none |

* An and Qz refer to normative anorthite and quartz (mol %) calculated from defocused electron-beam microprobe analysis.

terms of the 'CIPW norm', which refers to mineral abundances calculated from the bulk composition of the mesostasis. To a good approximation, chondrule mesostases are quartz-, albite- and anorthite-normative, and in the meteorites of lowest petrologic type the chondrules are uniformly spread across the quartz–anorthite–albite ternary (Fig. 1*a*). With increasing petrologic type, the proportion of quartz- and anorthite-rich chondrule mesostases decreases, and the data migrate to the albite-rich corner of the diagram. Clearly, parent-body metamorphism is homogenizing the mesostasis composition, and in the most metamorphosed chondrites (type 5 or 6) the quartz component is missing and the feldspar is fairly albitic ($An_{10}Or_6Ab_{84}$)[24].

As with the earlier work, the CL properties emphasize the importance of olivine composition. Unlike terrestrial and lunar olivines, some chondritic olivines contain high abundances of refractory elements, such as Ca, Ti and Al (ref. 25). The amount depends on the levels of parent-body metamorphism suffered by the meteorite, and on the individual chondrule. Figure 2 compares the CaO content of chondrule olivines with the FeO content for meteorites of four petrologic types. Like the mesostasis, chondrules in the type 3.0 chondrite contain olivines with a wide range of compositions, whereas chondrites of type ≥3.8 are fairly homogeneous. Chondrites at intermediate petrologic type may contain olivines with a greater range of CaO; presumably olivines in group B chondrules lose their Ca faster than the olivines in group A chondrules. This difference in the behaviour of olivines in the two groups of chondrule probably reflects the differences in Ca diffusion in Fe-rich and Fe-poor olivines. The plots for Al and Ti are almost identical to that of Ca, although Ti lags slightly behind Ca and Al, and only olivines of type 4 or higher are uniform in Ti. There are a few chondrules in which olivine is absent but pyroxene behaves in a similar way, although at a slower rate because of lower diffusion rate.

## Compositional classification scheme

We can use olivine and mesostasis compositions to divide the chondrules into eight groups, most of which have unique CL properties. Those whose mesostasis compositions are migrating down the quartz–albite axis constitute three 'B' groups; those moving along the feldspar axis constitute four 'A' groups. The compositions towards which both groups migrate correspond to those of group A5. Similarly, we can define fields on plots of the refractory element against iron to characterize the groups further. The A series, for example, shows systematic decreases in Ca and increases in Fe along the A1,2–A3–A4–A5 sequence (A1 and A2 are genetically related, so really A1 goes to A3, then A4 and then A5, while A2 goes to A4 then A5); Ca, in contrast, decreases along the B1–B2–B3–A5 series, although there is some overlap. These series are gradational and subdivision sometimes involves arbitrary values, but the discrimination plots shown in Figs 1 and 2 constitute a straightforward and workable means of defining the groups. In cases where olivine is absent, we can use the FeO content of the pyroxene and the FeO axis in Fig. 2. The A1 and A2 groups are closely related, showing many shared trends and similar bulk compositions involving major volatile element depletions and strong positive Eu anomalies[21].

Inevitably this classification scheme preserves some of the features of earlier schemes. The Semarkona type IA chondrules of refs 10 and 11 are all members of the present group A1, and group A2 includes low-FeO porphyritic pyroxene chondrules that did not have a place in the previous mineral-chemical scheme. Group B1 includes the type II chondrules of previous workers. To a good approximation, the A groups consist of the 'droplet' chondrules, whereas the B groups constitute the 'clastic' chondrules. Unlike earlier schemes, the scheme proposed here does not depend on texture, nor is it restricted to a fairly homogeneous subset of chondrules. The textural terms of Gooding and Keil[9] can be used with the present group definitions, describing for example a group A1 barred olivine chondrule or a group A5 porphyritic olivine–pyroxene chondrule.

With two exceptions, we can use the CL properties in Table 2 to determine the relative proportions of the chondrule groups in other chondrites without the need for analytical data. The

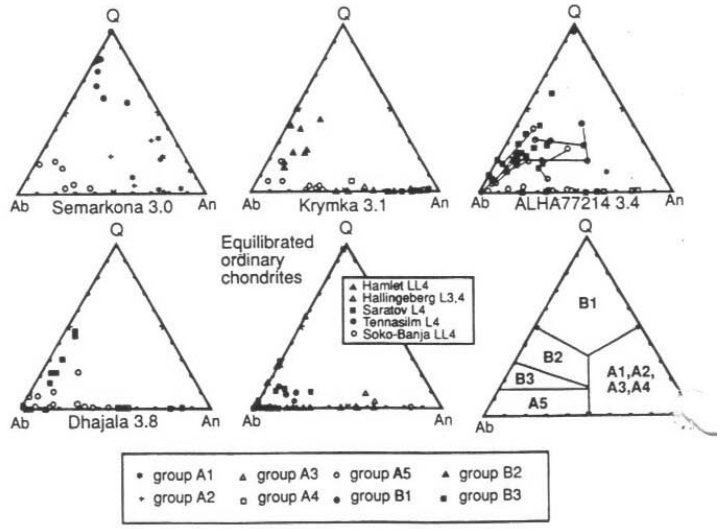


FIG. 1 Ternary plots for the calculated major mineral abundances in the chondrule mesostases of the Semarkona, Krymka, Allan Hills A77214, and Dhajala meteorites and a group of 'equilibrated' (essentially type 4) chondrites. The symbols for the minerals are: Q, quartz; Ab, albite; An, anorthite. The degree of parent-body metamorphism is reflected in the 'petrologic type' 3.0–4, which is assigned on the basis of physical, mineralogical and petrological criteria[19,20]. The chondrules in the virtually unmetamorphosed Semarkona have a wide range of composition, but this decreases with increasing petrologic type as the data migrate to the albite corner of the diagram. The chondrule group assignments are purely on the basis of cathodoluminescence and are shown for comparison with the compositional definitions which are shown in the sixth ternary. Tie-lines connect data for chondrules in which the mesostases have outer zones and interiors with differing CL, and whose CL classification is sometimes difficult. This mainly applies to Allan Hills A77214. The data are from the present study except those for the equilibrated meteorites which are from ref. 35.

TABLE 2 Sections used here with frequency of chondrule groups as a function of petrologic type

| Meteorite | Section number source* | Petrologic type | Number of chondrules | CL groups | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 |
| Semarkona | USNM 1805 | 3.0 | 76 | 10.5 | 25.0 | 0.0 | 0.0 | 5.0 | 56.9 | 0.0 | 2.6 |
| Bishunpur | BM 80399 | 3.1 | 98 | 7.1 | 0.0 | 12.2 | 12.8 | 12.8 | 0.0 | 51.0 | 1.0 |
| Krymka | USNM L729-7 | 3.1 | 134 | 5.2 | 0.0 | 20.9 | 17.8 | 17.8 | 0.0 | 29.9 | 1.5 |
| Chainpur | BM 1915,86 | 3.4 | 90 | 0.0 | 0.0 | 10.0 | 11.7 | 27.2 | 0.0 | 38.8 | 6.7 |
| ALHA77214 | MWG PTS#8 | 3.5 | 124 | 1.6 | 0.0 | 2.4 | 15.5 | 36.1 | 1.6 | 0.0 | 41.9 |
| Hedjaz | BM 1925,13 | 3.7 | 69 | 0.0 | 0.0 | 0.0 | 21.3 | 49.7 | 0.0 | 0.0 | 29.0 |
| Dhajala | PRL | 3.8 | 62 | 0.0 | 0.0 | 0.0 | 18.4 | 42.9 | 0.0 | 0.0 | 38.7 |
| Bremervörde | BM 33910 | 3.9 | 60 | 0.0 | 0.0 | 5.0 | 19.0 | 44.3 | 0.0 | 0.0 | 31.7 |
| Barwell | BM 1966 | 5 | 63 | 0.0 | 0.0 | 0.0 | 0.0 | 100.0 | 0.0 | 0.0 | 0.0 |

Data obtained by assigning all the chondrules in these sections to the chondrule groups using their CL. Frequencies are per cent by numbers. Groups A4 and A5 cannot readily be distinguished by CL and the above statistics assume the following (based on the four analysed chondrites in bold type): **Semarkona**, 100% A5; **Krymka**, Bishunpur, 50% A5; Chainpur, **ALHA77214**, Hedjaz, **Dhajala**, 70% A5. We assume Barwell chondrules are entirely A5 because many studies show that the mesostases of equilibrated chondrites are sodic feldspar[24].

* USNM: R. Clark and T. Thomas, National Museum of Natural History, Smithsonian Institution (Semarkona polished thick section made at University of California, Los Angeles). BM: R. Hutchison, British Museum (Natural History). MWG: Meteorite Working Group of the NSF/NASA. PRL: D. Lal, Physical Research Laboratory, Ahmedabad (polished thin section made at Johnson Space Center).

exceptions concern the distinctions between the A4 and A5 chondrules and between the B1 and B2 chondrules. For the moment, we assume the B1 chondrules are unique to Semarkona. The A4 and A5 chondrules have similar CL properties and we have assumed an A4 : A5 ratio for chondrules in the unanalysed chondrites based on analysed chondrites of similar petrologic type. We find that the proportion of group A to group B chondrules covers a small range within which the ratio of group A to group B chondrules increases steadily with petrologic type. Presumably the group A to group B ratio for the Semarkona chondrite is an original, pre-metamorphic quantity characteristic of all ordinary chondrites. On closer inspection, it seems that with increasing petrologic type, chondrules of group A1,2 disappear to be replaced by A3 and then A4, which ultimately merge into group A5. Similarly, group B1 evolves into group B2, then group B3 and ultimately A5. Evolution along the A series is much more rapid than evolution along the B series; that is, greater levels of metamorphism are required to homogenize the B series. This is shown schematically in Fig. 3.

## Deciphering meteorite history

The groups and the relationships described in Fig. 3 have many implications. The chondrule-forming process apparently produced four types of chondrule, of which two are strongly related, one of which resembles the chondrules in metamorphosed meteorites in the bulk compositions of its major components. (Note, however, that mineral compositions in the A5 chondrules become more homogeneous with increasing petrologic type, showing a range of 5–25 wt% FeO in the type 3.0, 3.1 and 3.4 chondrites but only a 17–20 wt% range in the type 3.8.) Metamorphism increased the diversity of the chondrule population, but in a complicated way, as some chondrules respond to metamorphism faster than others. Individual chondrules may actually increase in mineral heterogeneity during metamorphism, because the smaller grains react faster than larger grains and secondary pyroxene is formed as the quartz component of the mesostasis is destroyed by reaction with olivine. The properties of the chondrules in a given chondrite therefore depend on the variety originally present, the range in their responsiveness to metamorphism and the metamorphism suffered by the meteorite as a whole. There is no reason to assume, because chondrules vary in their internal heterogeneity, that certain chondrules were metamorphosed before emplacement in the meteorite[26,27].

It has been suggested that chondrules as a whole do not show a relationship between calculated liquidus temperature and Na content, and that chondrules therefore did not suffer volatile loss during formation[6]. The group A1,A2 does show the expected trend, and group B1 is clearly genetically unrelated to group A1,2 (ref. 28), so it is possible that volatiles were lost during

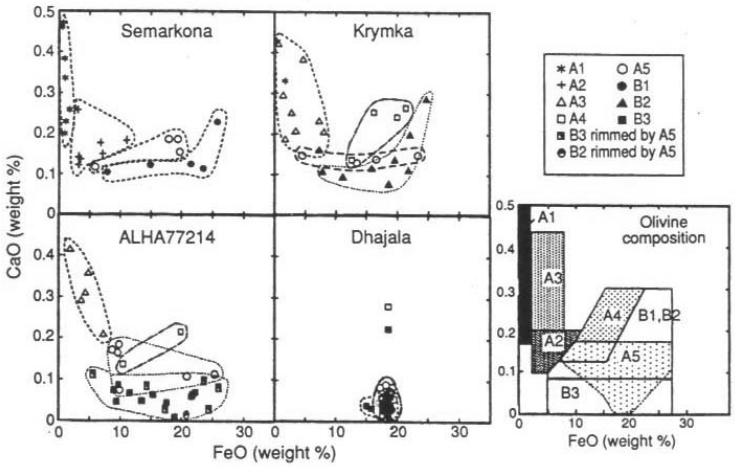


FIG. 2 Compositions of chondrule olivines, the major silicate mineral in chondrules. Again chondrules in the least-metamorphosed meteorites have a wide range of compositions which disappears with increasing petrologic type. B2/A5 and B3/A5 refer to chondrules whose mesostases are zoned in their CL and compositional properties, B2 or B3 in the central regions and A5 in the outer regions. Aluminium and Ti show very similar patterns to Ca, the only important difference being that the olivines in A4,5 chondrules in Dhajala are significantly higher in Ti than the olivines in B3 chondrules in Dhajala. The volatile elements Mn, Cr and P behave very differently from the refractory elements and from each other, but the chondrule groups are still resolvable, albeit with some overlap. Assignments to groups has also been made on the basis of CL for comparison with the compositional definitions. Each chondrule can uniquely be assigned to a group using the composition of the two main chondrule components and compositional fields shown here and in Fig. 1. In a few chondrules in which olivine is absent, pyroxene composition can be used.

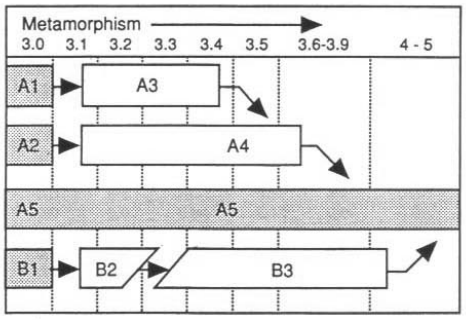


FIG. 3 Schematic representation of the proposed metamorphic relationship between the chondrule groups. Group A1, and the genetically related group A2, group A5 and group B1 are 'primary' (pre-metamorphic) and compositionally distinct. Metamorphism causes chondrules in the A and B series to undergo major compositional changes in their olivine and mesostasis and ultimately to converge on group A5 (Figs 1 and 2). Homogenization is easier, however, for group A, and considerable parent-body metamorphism is necessary to homogenize group B chondrules. An estimate of the level of parent-body metamorphism, as reflected in the petrologic type, is indicated by the type alongside each step. The mean olivine and mesostasis compositions of group A5 do not change during metamorphism, although the degree of composition heterogeneity of these phases decreases.

chondrule formation. It is also possible, however, that volatile content was a factor controlling liquidus temperature.

## Processes in the early Solar System

The similarity of some compositional trends in the chondrites and the planets has often led to the suggestion that similar physical and chemical processes may have been responsible[29]; that is, that the composition of the planets was controlled by the composition of their 'building blocks'. Both the planets and the chondrite groups show variations in their redox states, lithophile element abundance patterns, oxygen isotope systematics and siderophile element abundances. The cause of the compositional differences between the nine chondrite classes is controversial, the two main viewpoints being (1) that they reflect a nebula-wide process so that compositions are related to solar distance and the composition of the chondrules depends on their precursor[1,7], and (2) that they reflect the proportion of chondrules and matrix[4,5,7,30]. There is an implicit assumption in the second model that chondrules are isochemical, but this is now known to be untrue.

As chondrules constitute the main fraction of the silicate portion of these meteorites, it is possible that the ratio of group A to group B chondrules in the original accreted material played an important part in determining the bulk compositions of the chondrites and thereby their class. The differences between group A and group B chondrules involve two, and perhaps three, of the relevant chemical trends. Group A chondrules are more reduced, have higher abundances of refractory lithophiles than group B chondrules and probably have different proportions of oxygen isotopes. Because of their small size and friability[31], we have not yet obtained oxygen isotope data for group A chondrules, but data for the Allende carbonaceous chondrite are at least suggestive of a systematic difference[32,33], and there seems to be a size dependency in the oxygen isotope for chondrules from the Dhajala meteorite[34].

In short, it seems possible that the differences between the chondrite classes reflect the proportion of group A to group B chondrules, rather than the proportion of chondrules to matrix. We think that the existence of such diverse groups of chondrules in the same rock, whose bulk composition is remarkably close to cosmic, may indicate that the chondrule groups were formed by the same processes acting with differing degrees of intensity on the same or very similar precursor material. Other arguments that the group A chondrules obtained their unusual compositions during chondrule formation have been summarized elsewhere[21]. It is therefore possible that the compositional variations in the meteorites, and planets, reflect differences in the intensity of chondrule-forming process at different points of the Solar System, rather than nebula-wide chemical processes.

## Conclusions

We suggest that chondrules should not be classified by texture or the composition of a single phase, or by some mixture of the two, but in a comprehensive, systematic manner using the composition of the two main chondrule components. We believe that this will focus attention on the most meaningful meteorites, stress the range of materials present and provide a means of sorting them out by both pre-metamorphic composition and metamorphic alteration. We also argue that the recognition of these chondrule groups, and their various abundances in different types, has interesting implications for early Solar System studies. □

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