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Petrofabric analysis of a large microporphyritic chondrule in the Parnallee meteorite

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SUMMARY. Olivine microphenocrysts in a large microporphyritic chondrule in the Parnallee chondrite show a linear preferred orientation of the long ($\beta = c$) axes, which is thought to reflect flowage of a partly crystalline parent magma. The orientation pattern is somewhat disturbed by post-crystallization fracturing.

THE origin of chondrules and chondrites remains in dispute in spite of intensive petrographic and chemical study during the last century. At one extreme, chondrules are currently interpreted as quenched droplets formed in the solar nebula either by condensation of gas (Wood, 1963; Anders, 1964; Blander and Katz, 1967) or by fusion of dust (Whipple, 1966). At the other, they are regarded as products of volcanic or impact processes on planetary bodies (Fredriksson, 1963; Fredriksson and Ringwood, 1963; Ringwood, 1966; Urey, 1961). There is general agreement that most or all chondrules crystallized from molten material: at issue is whether they were always independent droplets of roughly their present sizes or were drawn from larger masses of magma or solid rock.

A decision on this point requires detailed study of many individual chondrules in an attempt to reconstruct their histories. This task, which seems endless in light of the great profusion of chondrules in any chondrite, is simplified by the fact that the great majority of chondrules are of three types: *excentroradial*, consisting of fan-like arrays of low-Ca pyroxene; *barred-olivine*, consisting of one or more sets of optically parallel plates of olivine separated by glassy or microcrystalline material; and *microporphyritic*, consisting of subhedral to euhedral microphenocrysts of olivine or, less commonly, low-Ca pyroxene in a fine-grained to glassy groundmass. As Dodd and Teleky (1967) observed, the last of these types may be further divided according to the abundance or paucity of nickel-iron into metal-rich and metal-poor subtypes. The abundances of these four types of chondrules in nine ordinary chondrites are given in table I, which shows clearly the overwhelming predominance of the porphyritic types and, in particular, the metal-poor porphyritic type.

Studies to date of individual chondrules indicate that these bodies experienced a variety of histories prior to their accumulation in the meteorite parent bodies. Although some (notably the excentroradial and glassy types) are approximately spherical and appear to represent quenched droplets that underwent little change before they were agglomerated, others show various degrees and types of alteration in the solid state, which include: recrystallization and attendant homogenization of olivine and pyroxene (Van Schmus, 1967; Dodd, 1968 and in press); fracturing (Dodd and Teleky, 1967); and chemical modification, either at the margin (Binns, 1967) or throughout (Dodd, Van Schmus, and Marvin, 1966). It is no longer possible to assume a single—and simple—line of evolution for all chondrules.

Of the major chondrule types, microporphyritic chondrules are of particular interest, both because of their great abundance (table I) and because they most closely resemble terrestrial magmatic rocks in their textures and phase relationships. Dodd and Teleky (1967) suggested that preferred orientation of microphenocrysts in these chondrules might be used as evidence that they were drawn from larger magma bodies and not formed as individual droplets in space. Of ten chondrules they studied in Hallingeberg and Krymka, nine were found to possess modest preferred orientations (both planar and linear) of elongate olivine crystals, which Dodd and Teleky interpreted as due to flowage in extended bodies of partly crystalline magma.

TABLE I. *Abundances of major chondrule types in nine unequilibrated ordinary chondrites, determined by point counting (100 points per sample). 'Others' includes unusual types and, in many cases, common types cut in unusual orientations*

Chondrite	Microporphyritic, metal-poor	Microporphyritic, metal-rich	Excentro-radial	Barred olivine	Others
Krymka (I)	66	1	10	12	11
Parnallee (LL)	82	5	3	5	5
Hallingeberg (L)	65	4	15	6	10
Mezö-Madaras (L)	68	—	9	10	13
Khohar (L)	77	3	8	8	4
Sharps (H)	69	9	16	0	6
Bremervörde (H)	69	8	9	7	7
Sindhri (?) (H)	75	11	5	2	7
Prairie Dog Creek (H)	76	10	7	3	4

The chondrules studied by Dodd and Teleky (1967) are small (0·5–2·5 mm diameter), in no case could they study more than 150 crystals, and the preferred orientations observed were typically weak. The opportunity to check their results on a larger sample has been provided by the discovery of an exceptionally large chondrule (4·0×3·6×1·6 cm) in the Parnallee chondrite (Binns, 1967).

Parnallee is one of a small group of ordinary chondrites (the 'unequilibrated ordinary chondrites' of Dodd and Van Schmus, 1965) that contain homogeneous olivine and pyroxene and which, on this basis and on textural grounds, appear to have experienced little metamorphism. It is classified as type LL-3 by Van Schmus and Wood (1967).

Binns (1967) has adequately described and illustrated the giant chondrule in Parnallee. His description is repeated here only to the extent necessary to trace the pre-accumulation history of the chondrule, an understanding of which is essential for interpretation of the petrofabric data.

As Binns notes, the texture of the chondrule (euhedral and subhedral olivine crystals in a microcrystalline and glassy matrix) and the compositional variations of its minerals (e.g. normal zoning of olivine) are consistent with crystallization from a melt. There is no tendency toward a zonal arrangement of either mineral assemblages or grain sizes within the chondrule such as would suggest different cooling rates for the rim and interior. Furthermore, the chondrule is irregularly shaped rather than drop-like, and olivine microphenocrysts are abruptly broken off at the rim. It thus appears that the chondrule was originally somewhat larger than it is now and has been reduced to its present size by attrition.

The presence of a partial rim of glass and spongy troilite (Binns, 1967) suggests some degree of thermal (and perhaps chemical) alteration after solidification of the chondrule. That this alteration preceded the accumulation of Parnallee is indicated by the fact that nearby chondrules are not affected by it. That it was mild is indicated by the survival of zoned olivine crystals in the chondrule.

It is unlikely that reheating significantly changed the orientation of olivine crystals. However, fracturing, on two scales and apparently representative of two episodes, did affect olivine orientation and the effects of this fracturing must be considered in evaluating the petrofabric data.

Individual olivine crystals commonly display irregular extinction and contain both healed and open fractures. Inasmuch as these fractures do not extend into the microcrystalline groundmass, it is likely that the deformation implied by them preceded final solidification of the chondrule.

The chondrule as a whole is also cut by a profusion of irregular but subparallel fractures, along some of which differential movement can be demonstrated. These fractures clearly post-date solidification, and they certainly altered the primary disposition of olivine crystals.

From the foregoing discussion we can conclude that the giant chondrule experienced a pre-accumulation history that included: crystallization from a melt, with concomitant deformation; mild thermal alteration; and a second episode of deformation represented by fractures that cut the entire chondrule. This résumé provides a framework within which to consider the petrofabric data.

All petrofabric data were acquired with a Leitz 5-axis universal stage, using low-index hemispheres (1·516) to simplify corrections (Munro, 1963). The data were corrected according to methods described by Emmons (1943) and were plotted on a Schmidt equal-area net.

Two sets of data were collected. One includes 250 crystals and represents the entire chondrule; the other includes 66 crystals from a small portion (a few square mm) that appears to be free of continuous fractures. Both sets were taken at random, on a grid, to avoid possible bias in the selection of the grains. The data recorded for each crystal are its longest dimension, its apparent shape (sketched), and the attitudes of α, β, and γ.

The method of contouring the plots is somewhat unorthodox and worth brief explanation. Where data are few and preferred orientation is weak, the conventional method in which points are counted in 1 % areas of the net commonly produces a very complex diagram. Dodd and Teleky (1967) circumvented this problem by counting in 5 % areas. The present paper employs both 1 % and 5 % counting conventions, the former to facilitate comparison with other petrographic data and the latter to eliminate spurious concentrations and emphasize dominant patterns. Regardless of the counting convention used, the data are contoured in per cent per 1 % area of the net.

Seventy-five of the 250 olivine crystals examined in this study have one of the crystal axes (*a*, *b*, and *c*, parallel respectively to γ, α, and β) less than 20° away from the normal to the plane of the thin section. Sketches of these crystals (fig. 1) can be used to infer the habit, and in particular the elongation scheme, for crystals in this chondrule.

Fig. 1 suggests that the most prominent forms are {110}, {021}, {101}, and {100}. The side pinacoid, {010}, is weakly developed, with the result that the olivine crystals typically show the least elongation in the *a* direction (in this respect, they differ from olivines in many terrestrial magmatic rocks, which tend to be tabular with minimum elongation parallel to the *b* crystal axis (Drever and Johnston, 1957; Brothers, 1959). The typical elongation scheme is $(c \| \beta) > (b \| \alpha) > (a \| \gamma)$. Elongation is modest: c/a rarely exceeds 3 and is typically approximately 2. There is some evidence (fig. 1) that *a* and *b* are somewhat interchangeable as the shortest axis, a point of some importance in interpreting the petrofabric diagrams.

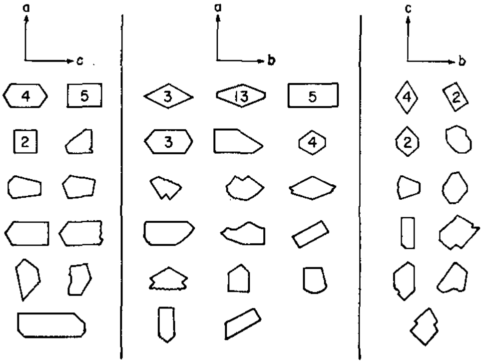
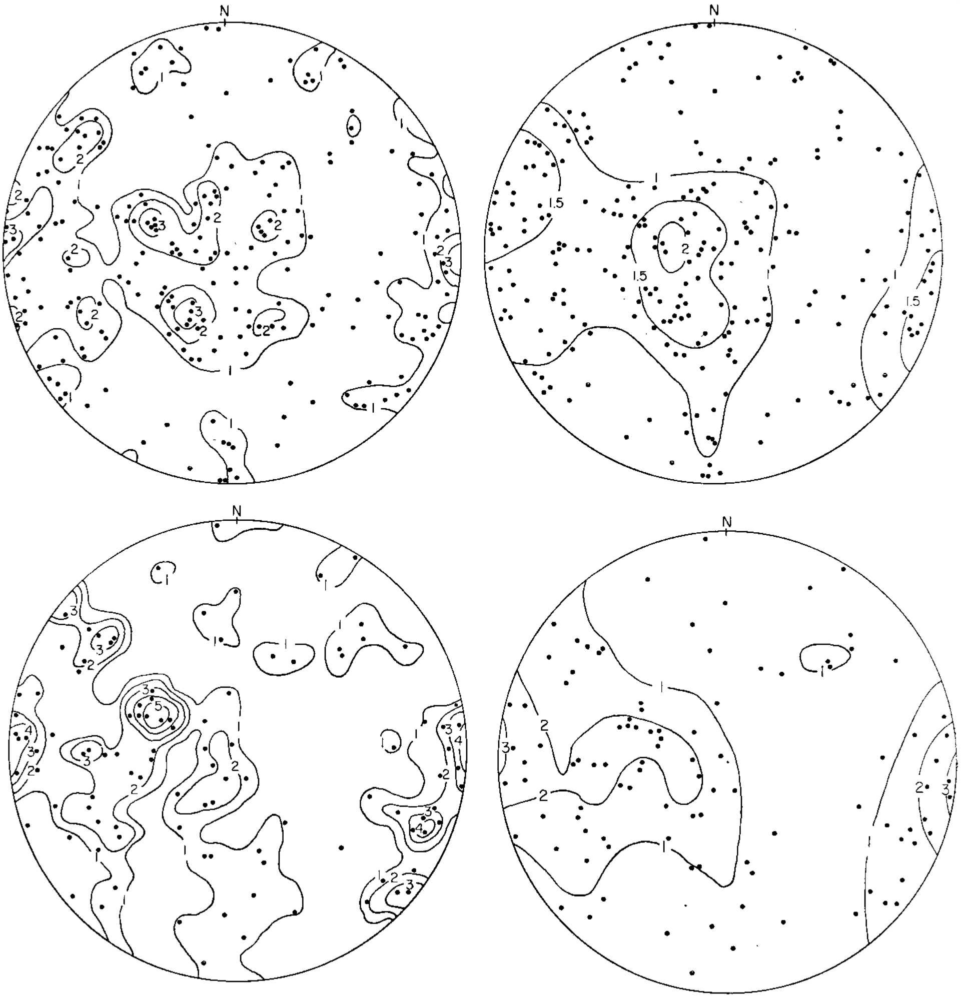


Fig. 1. Drawings of olivine crystals (cut 90±20° to $\alpha = b, \beta = c$, or $\gamma = a$) in a large microporphyritic chondrule in the Parnallee meteorite. Scale variable. Numbers on sketches refer to the number of crystals found to have the indicated shape.

Orientation data for the giant chondrule are summarized in figs. 2–4. Fig. 2 shows the disposition of 250 β-axes for crystals distributed throughout the chondrule. Fig. 2*a* employs the 1 % counting technique and 2*b* the 5 % technique. The main features of fig. 2*a* are two broad maxima about 70–80° apart, each of which includes several minor maxima. The pattern is complex but suggests a crude linear alignment of the β-axes of the olivines, with some spread toward a girdle. The general pattern is shown more clearly in fig. 2*b*, where the minor modes are suppressed; the two diagrams are otherwise similar.

Dodd and Teleky (1967) observed that the larger crystals in microporphyritic chondrules commonly show a stronger preferred orientation than do the smaller crystals. All crystals from the giant chondrule with maximum intercepts greater than 0·1 mm are plotted in fig. 3. Fig. 3*a* (1 % counting areas) resembles fig. 2*a*, but the subordinate maxima are slightly more prominent. Likewise fig. 3*b* resembles fig. 2*b*. The influence of crystal size on degree of preferred orientation is evidently slight in this chondrule.

It is likely that some or all of the complexity of figs. 2 and 3 results from disturbance of the primary disposition of olivine crystals by fracturing. Fig. 4 summarizes data



FIGS. 2 and 3: Fig. 2. Equal-area projections (lower hemisphere) of the β-axes of 250 olivine crystals in a large chondrule in the Parnallee chondrite. *a* (top left) data points counted in 1 % areas of the net; *b* (top right) points counted in 5 % areas. Fig. 3. Equal-area projections (lower hemisphere) of the β-axes of 104 olivine crystals (sizes greater than 0·1 mm) in a large chondrule in the Parnallee chondrite. *a* (bottom left) 1 % counting areas; *b* (bottom right) 5 % counting areas.

for a small area within which such fracturing seems to have had little effect. This area is comparable to the largest areas studied by Dodd and Teleky (1967). The α-, β-, and γ-axes are plotted separately, and the 5 % counting convention is used in view of the small sample population (66 crystals).

All three axes show preferred orientations in this area, with β showing the clearest pattern. The β-axes fall in a broad point maximum; the α- and γ-axes are concentrated within a girdle normal to β. There is considerable overlap of the diagrams for

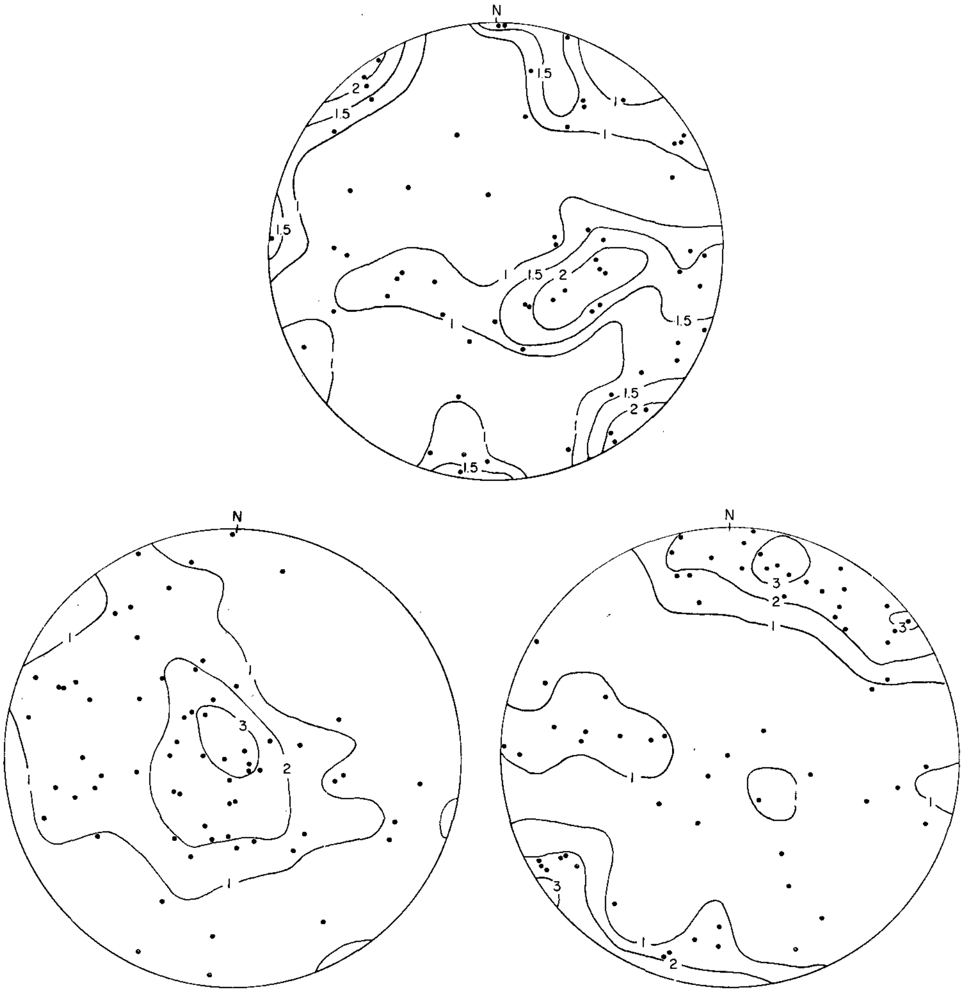


FIG. 4. Equal-area projections (lower hemisphere) of 66 olivine crystals in a small, unfractured area of a large chondrule in the Parnallee chondrite. *a* (top), α-axes; *b* (bottom left), β-axes; *c* (bottom right), γ-axes. All diagrams employ 5 % counting areas and are contoured in per cent per 1 % area of the net.

α and γ, which may be due to occasional interchange of α and γ as the shortest crystallographic axis (see also fig. 1).

These diagrams suggest that the preferred orientation in this chondrule is dominantly linear and is complicated both by fracturing and by occasional variations in the relative elongations of the α- and γ-axes. It may also be complicated by inhomogeneity of the primary fabric, but this possibility cannot be checked with the data at hand.

With due regard for the differences in form between chondritic and most terrestrial olivines, we may compare the type and intensity of preferred orientation in the chondrules with that found in terrestrial magmatic rocks. The most suitable rock data are those reported by Brothers (1959) for basaltic dykes and lavas.

In dykes, olivine phenocrysts show varying degrees of preferred orientation. The α-axes (parallel to the shortest crystal dimension) are perpendicular to a β–γ girdle, suggesting that the dominant structure is a planar arrangement of tabular crystals. In some cases, the β–γ girdle contains point concentrations of β-axes (parallel to the longest crystal dimension), indicating a linear component in the orientation pattern. The strongest orientations of α-axes found in dyke rocks are of the order of 8–12 %. The data for basalt flows resemble those for dykes, but tend to show more numerous subordinate maxima. Brothers attributes these to the alternating effects of flow and crystal settling during episodic lava movement.

The preferred orientations found in chondrules are weaker than those reported for basaltic rocks: maxima are typically of the order of 3 % and are not known to exceed 6 % (Dodd and Teleky, 1967). The difference in intensity may be due to modest elongation of the chondritic olivines, to a high proportion of crystals in the chondritic melt, which would impede rotation of individual crystals to preferred orientations, to differences in the types and rates of flow in the chondritic and basaltic liquids, or to some combination of these factors. There is no basis at present for a choice among these alternatives.

The present study and the data of Dodd and Teleky (1967) suggest that linear alignment is more common in chondrules than in basaltic rocks. This in turn suggests flow rather than crystal settling as the orienting mechanism in chondrules. The absence of a well-defined planar preferred orientation from chondrules may, however, be due less to the orienting mechanism than to the habit of the olivine crystals: one would expect the prismatic crystals described in this paper to be less prone to planar orientation than the tabular crystals found in basalts.

The establishment of preferred orientation of olivine in the giant chondrule described by Binns (1967) strengthens the conclusion of Dodd and Teleky (1967) that such preferred orientation is common in microporphyritic chondrules. Dodd and Teleky attempted to reconcile the fabrics of these chondrules with crystallization from droplets in space, and found this mode of origin unlikely. The writer concurs with the conclusion of Binns (1967) that the giant chondrule in Parnallee (and perhaps all microporphyritic chondrules) represents a fragment of an extended body of partly crystalline magma or solid rock. Whether this body was disrupted while still semi-molten (e.g. by explosive ejection from a volcanic vent), or by shattering of solid rock (during explosive volcanism or by impact, as suggested by Urey (1961) and Ringwood (1966)) is a moot point. The commonness of fractures in chondrules of this type indicates at the very least that the process of disruption was violent.

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