

*Textural features of some Bushveld norites.*

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**G**EOPHYSICAL Laboratory work is especially applicable to quenched rocks, but does not lend itself to the solution of problems connected with the interpretation of structural relationships between the component minerals of deep-seated rocks. The detailed examination of a rock of simple mineral composition might be expected to yield a picture of the way in which phase-boundary adjustments are made in a rock crystallizing under such conditions. Some of the Bushveld basic rocks are of such a nature, and in the present paper an attempt is made to analyse and interpret the structural relationships between the two minerals bronzite and bytownite ( $An_{78-80}$ ), of which they are composed. The material studied was collected under the guidance of Dr. A. L. Hall during the International Geological Congress in 1929, supplemented by core specimens recently made available through the courtesy of an old student of the College.

The rocks examined are bronzite-anorthosites, leuconorites, mottled anorthosites (Hall), and melanorites. In these rocks bronzite is the dominant pyroxene, and in many, clinopyroxene has the status of a minor accessory only. The bronzite has several different modes of occurrence: it forms large, irregular crystal grains sparsely scattered through the mosaic of plagioclase in some cases; but in others it occurs as closely packed subhedral crystals, with a relatively small content of interstitial plagioclase. Round some of the isolated bronzites, clinopyroxene forms a narrow partial or complete rim, 'insulating' them from the adjacent plagioclases. In some of the norites the pyroxenes are restricted to clots within which bronzite and clinopyroxene are ophitically related to the plagioclase. Finally, in some of the mottled anorthosites similar clots consist of closely packed, rounded bronzites which, together with small plagioclase grains, are poikilitically enclosed within clinopyroxene. Each of these relationships is examined in turn.

1. *The isolated bronzites.*

The relationship between bronzite and plagioclase that is most obvious as regards interpretation is illustrated in fig. 1. The pyroxene is

interstitial to the essentially lath-shaped plagioclase, and occupies angular 'cavities' bounded by crystal-faces of the felspar. It will be noted that in the penultimate stage a little of the pyroxene substance was injected along the inter-crystal boundaries. A little late quartz at the top of the section shows the same phenomenon.

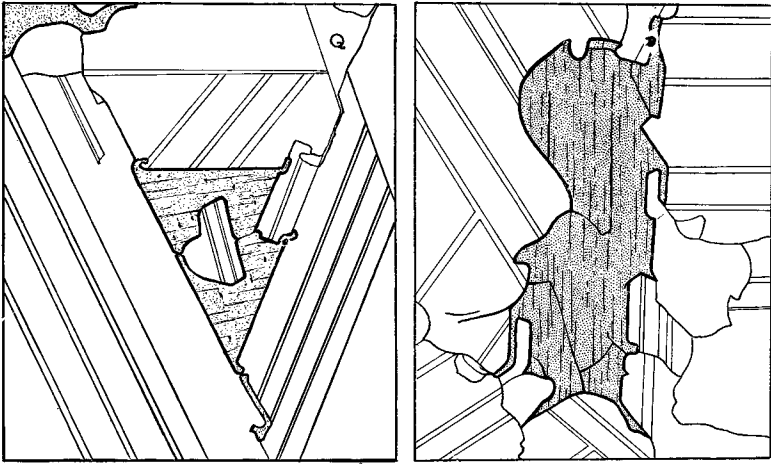


FIG. 1.

FIG. 2.

FIG. 1. Bronzite interstitial to bytownite in bronzite-anorthosite: Q = quartz. Width of section, 2 mm.

FIG. 2. Shape features of bronzite isolated in bytownite: simultaneous crystallization of the two minerals. Width of section, 1.5 mm.

Precisely the opposite relationship is encountered in melanorite approaching pyroxenite in composition, and as rich in bronzite as the previous rock is poor. The roles of the two minerals are completely reversed: the bronzites form a self-supporting mesh to which the meagre plagioclase is interstitial. Harker's explanation of a similar variation in the order of crystallization of olivine and anorthite in the allivalites of Rum<sup>1</sup> is presumably applicable to the case in point. As bytownite and bronzite are members of isomorphous series, a cotectic relationship must hold; and whichever of the two is in local excess of the cotectic ratio will crystallize first. It follows from these two extreme cases that there must be rocks in this suite in which the proportions of pyroxene and plagioclase are such as to ensure simultaneous crystallization. With this in mind we pass on to examine the shape-details of the isolated bronzites.

<sup>1</sup> A. Harker, Small Isles of Inverness. Mem. Geol. Surv., 1908, p. 86.

In the pyroxene-poor noritic rocks bronzite forms irregular grains, though sometimes with a semblance of prismatic habit, bounded by a combination of plane and strongly curved surfaces. The plane surfaces are normally crystal-faces of the adjoining plagioclases; but where the contact-surface is appreciably curved, neither mineral is euhedral towards the other. Such curved contact-surfaces are therefore characteristic of simultaneous crystallization. In confirmation of this conclusion it may be stated that in the plagioclase mosaic, which makes up the greater part of the rock, the contact-surfaces are exactly of the same types: curved surfaces predominate, but some are plane. These latter correspond in part to crystal-faces in the zone [(100) (010)] and therefore run parallel to the albite and Carlsbad twin-planes; but others cannot be correlated with actual crystal-faces. It is clear, however, that two crystals of plagioclase growing against one another will meet, other things being equal, in a plane surface. A curved surface will be developed when one crystal is so placed as to be able to exert its pressure of crystallization advantageously against its neighbour. In some grains all the contact surfaces are strongly curved, but so are the adjacent inter-plagioclase boundaries. The grain illustrated in fig. 2 is a little more complicated: the short lengths of straight-line contacts on the right-hand side are parallel to the direction of maximum growth of the bronzite, showing that it was able, within limits, to control its own shape; but on the left-hand side the strongly curved boundary against plagioclase indicates simultaneous growth. In this grain two consequences of the overlapping of the periods of crystallization may be noted for future reference: at several points the plagioclase has the appearance of growing into the pyroxene in a manner that would be interpreted by some petrologists as proving replacement; but near by exactly the opposite relationship is observable. Further, wedges, tongues, and thin veins of bronzite penetrate short distances along inter-plagioclase boundaries, again in a manner that, at first sight, suggests replacement; but, as is shown below, this also is a result of overlap of the periods of crystallization of the two minerals.

## 2. *The ophitic relationship between pyroxene and plagioclase.*

A texture approximating to the normal ophitic is seen in some of the mottled anorthosites of A. L. Hall. In these rocks the pyroxenes are virtually restricted to ill-defined dark clots irregularly scattered through the whitish anorthosite. Each clot consists of plagioclase in large excess over bronzite, or clinopyroxene, or both, associated in a manner

reminiscent of the ophitic texture, but differing from it in detail. The bronzite-plagioclase association illustrated in fig. 3 is typical. The fact that the plagioclases, of tabular habit, flattened parallel to (010), are in part welded to one another along straight-line contacts, but in part separated by narrow tongues or wedges of pyroxene, is highly significant. Again there is a strong suggestion of replacement of plagioclase by pyroxene: it *looks* at first sight as if the latter had been able to work its way along the inter-crystal boundaries, and to encroach upon the plagioclases. There is little doubt that, were other minerals involved instead of pyroxene and plagioclase in a normal igneous rock, the texture would be interpreted as indicating replacement. But again there is abundant evidence, in the details of the structure, that the appearance of replacement results from overlap of the periods of crystallization of the two minerals concerned. Because the plagioclase was in large excess over the pyroxene, it began to crystallize first, and gained a long lead. At a relatively late stage the clot consisted of a mush of plagioclase crystals, with entrapped residual liquid, consisting chiefly of potential bronzite with a small feldspathic residuum. This material was squeezed between the growing plagioclases, probably by the pressure of crystallization. At numberless points within the clots, and particularly on their outer margins, the evidence for the mobility of the residuum is conclusive: it can often be seen to have executed 'pincer-movements' round plagioclases. Where the encirclement was complete, the two 'veins', moving in from opposite directions, meet at a clearly defined point in the plane of the section, such as the points marked X in fig. 3. Where the encirclement was incomplete, due to exhaustion of material, or to freezing-in of the pyroxene, the two veins do not meet, but the gap was closed by plagioclase drawn from the small amount of still fluid residuum. Thus the two plagioclases were ultimately welded along a (usually) straight-line contact-surface, as at Z in fig. 3. It follows, of course, that many of the contact-surfaces between the two minerals are plagioclase crystal-faces, others are curved. Their significance has already been considered. Less commonly the pyroxene was able to exercise control, and the common boundary runs parallel to a plane of structural significance in the bronzite. This is usually the cleavage direction, as seen at a number of points in fig. 3.

Comparison with a really well-developed ophitic texture shows that in the present case the plagioclases are definitely less well-shaped. The perfect euhedrism of the feldspars in the ideal ophitic texture suggests that there was no appreciable overlap of the periods of crystallization.

Thus the plagioclase in the ideal case is 'pre-pyroxene'; but in the texture under consideration the bronzite crystallized simultaneously with the latter part, so to speak, of the plagioclase. In such a simple, two-mineral association, the control would appear to be relative amounts of the two minerals.

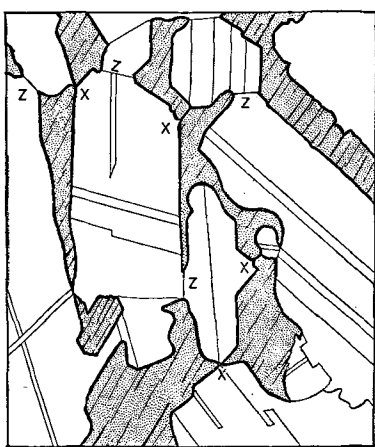


FIG. 3.



FIG. 4.

FIG. 3. Sub-ophitic clot in leuconorite. (For discussion see text.) Height of section, 2 mm.

FIG. 4. Isolated bronzite in mottled anorthosite with thin reaction rim of clinopyroxene. Pyroxene and plagioclase contemporaneous; clinopyroxene late-stage or subsequent. Pyroxene grain 2 mm. tall.

### 3. *Single bronzites with narrow rims of clinopyroxene.*

In the leuconorites and mottled anorthosites some of the isolated bronzites are mantled by a thin rim of brilliantly polarizing clinopyroxene. Such a rim may envelop the whole grain, or it may veneer part only—one end, one side, or one or two corners. It will be seen from fig. 4 that, as was the case with the similar unrimmed bronzites, the pyroxene wedges into the plagioclase mosaic, invariably *between* the component grains; and that the present boundary of the bronzite faithfully follows the outer (clinopyroxene) boundary into all these salients. In view of the evidence given above, it is clear that pyroxene and plagioclase were crystallizing at the same time, and that the fields of development of these two minerals were fully established *before* the clinopyroxene started to form. The latter occupies narrow, sinuous,

parallel-sided zones between the two minerals that, between them, were able to supply all the elements necessary for the formation of the clinopyroxene. There can be no doubt that the prior crystallization of bronzite was essential to the development of the clinopyroxene rims: in these particular rocks no clinopyroxene occurs independently of bronzite.

In seeking an explanation of the clinopyroxene rims, the several analogous structures usually attributed to ionic transfusion naturally come to mind; but there are at least three processes which may have been involved. Firstly, as bronzite and clinopyroxene are successive members of Bowen's discontinuous reaction series, it is natural that, in certain circumstances, earlier formed bronzites should be wrapped round and partially replaced by later clinopyroxene. But this is a consequence of reaction between a solid phase and a liquid, which are no longer in equilibrium on account of falling temperature. This process cannot apply to the case in point, for the two minerals concerned were sensibly solid—though only just, and still at a high temperature—*before* the clinopyroxene was formed. Secondly, ionic transfusion across the pyroxene-plagioclase boundaries, actuated by rise of temperature, and aided possibly by pore-liquids working along the inter-crystal boundaries, might be expected to give precisely the observed relationships. Indeed the conditions could scarcely be more favourable, as both minerals were at the temperature of crystallization, and their crystal lattices therefore in the right condition for ionic interchange in the atomically disordered surface-contact zone. Further, it would not be necessary to introduce ions from some unknown extraneous source, as all the required materials were at hand. Ionic transfusion of this kind would account for the approximate uniformity in width and the other observed features of the rims; but their apparently haphazard development remains a problem. In most recorded instances of this kind, metamorphism is invoked to provide the necessary impetus to bring about the atomic interchange. In this connexion it must be remembered that the particular rock showing the features under discussion is but one member of an enormous complex; and although there is no evidence of general metamorphism, re-heating of an earlier member by later ones is almost inevitable. Such re-heating, possibly to the temperature at which bronzite reacted with plagioclase to form clinopyroxene, would account for the textural relationships here described; but the fact that bronzites with well-developed rims have, as their nearest neighbours, other crystals, either rimless or with imperfect rims, would remain anomalous. The haphazard development of the

clinopyroxene cannot be accounted for by different degrees of reactivity due to varying crystallographic orientation of the two reacting minerals in this instance; but it may well be due to localization of pore-liquids which were activated by rise of temperature.

But, although ionic transfusion on these lines is the most likely means of forming the reaction rims, the writer ventures to suggest an alternative, operating during crystallization. It may well be that, as crystallization proceeded under conditions of maximum atomic mobility, the unwanted ions were expelled from the 'spheres of influence' already ear-marked as potential plagioclase and pyroxene respectively. When the remaining liquid was much reduced in amount, however, viscosity would increase and two-way ionic diffusion across the invisible boundary in the liquid still cushioning the adjacent crystals could become increasingly difficult, and after a time, might be inhibited altogether. Thus within a narrow contact zone the Ca<sup>2+</sup>, Al<sup>3+</sup> ions trying to move across into the feldspar, and the Mg<sup>2+</sup>, Fe<sup>2+</sup> ions moving in the opposite direction would be trapped, and at the temperature appropriate to the inversion of bronzite into clinopyroxene, the latter would form. This would be a late-stage phenomenon, and in no sense metamorphic. The impersistence of some rims, and their absence in other cases, then presents no difficulty. Any factor that would delay the final crystallization would allow a clean-cut separation of the pyroxenic and plagioclasic constituents: there would be no laggards among the ions, and therefore no reaction rim.

#### 4. *The coronophitic clots.*

The most interesting texture in this suite of rocks is encountered in the mottled anorthosite that contains the bronzites with reaction rims, described above. In thin section the anorthosite, apart from the clots, consists of large squarish bytownites embedded in a matrix of much smaller plagioclase grains. Apart from the clots there are no accessories. Further, the smaller grains show no evidence of cataclastic structure: they crystallized successively from a melt (fig. 7, right-hand side).

The clots contain bronzite (the most abundant mineral) associated with clinopyroxene in reaction relationship, and a small amount of plagioclase. As the clinopyroxene is vaguely ophitic towards the latter, and is related to the bronzites in a manner recalling corona structure, the texture may be called *coronophitic*.

The characters of a typical coronophitic clot are illustrated in fig. 5. It will be noted that within the clot, the poikilitic clinopyroxenes are of extraordinarily diffuse form, and, by comparison with the bronzites and

even the largest of the plagioclases, are very large. Embedded poikilitically in these clinopyroxenes are bronzites, occasionally in contact, but usually separated from one another by a more or less regular rim of clinopyroxene, and sometimes with intervening irregular tongues of plagioclase in addition. Thus the minerals are the same three as occur

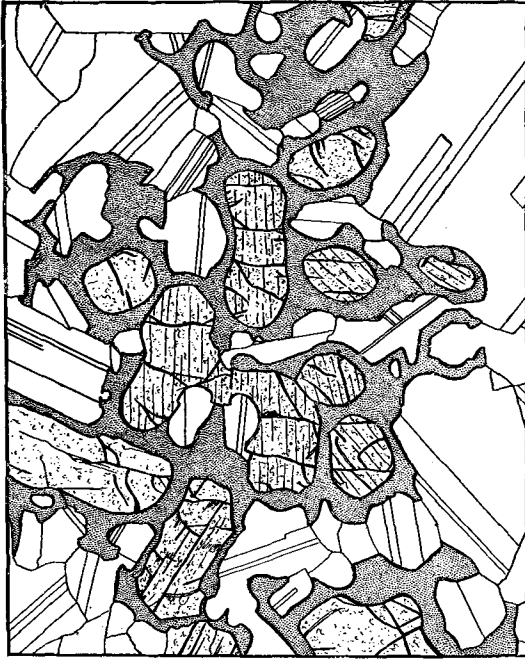


FIG. 5. Coronophitic clot in mottled anorthosite: sub-cylindrical bronzites with overgrowth of clinopyroxene (close stipple), and bytownite. Height of section, 4 mm.

elsewhere in these rocks; but the inter-relationships are strikingly different. The clinopyroxene is much more abundant relative to the bronzite; and while the anorthosite contains rather more bronzites with thin reaction rims than without them, within the clots *all* the bronzites are heavily invested with augitic material. They are also significantly different in shape, as shown by comparison of fig. 2 with figs. 5 and 6. It is clear that the clinopyroxene bears a reaction relationship to the other two minerals in both environments.

The relationship of the augitic material to the bronzites and plagioclases is reminiscent in other rocks of parallel-sided 'channels' winding



between the original crystal grains, and containing a new phase, derived at least in part from one or other of the bordering minerals. Usually such 'channels' are regarded as being of metamorphic origin, the energy needed for the reaction being supplied by a general rise of temperature. Such are the corona structures, described and accounted for on these

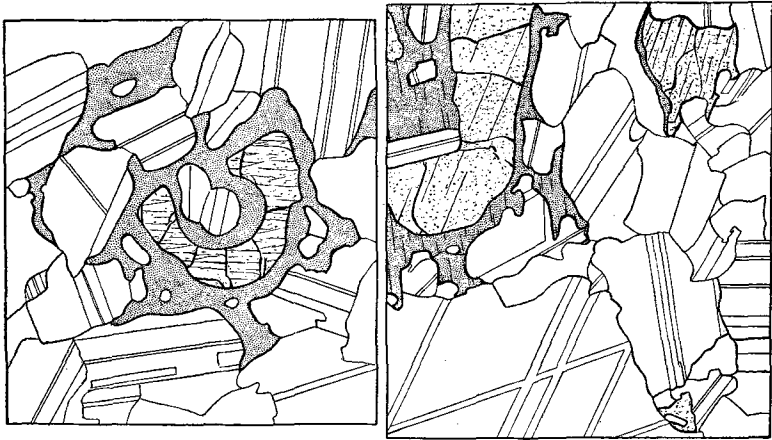


FIG. 6.

FIG. 7.

FIG. 6. Bronzite-clinopyroxene-bytownite association in mottled anorthosite, showing particularly the nature of the 'tongues' contemporaneous with surrounding plagioclase. Width of section, 3.5 mm.

FIG. 7. Part of coronitic clot showing small grains of plagioclase enmeshed in tongue-like protuberances from the clinopyroxene reaction rims.

lines by Shand,<sup>1</sup> who thought that a later intrusion supplied the necessary heat. Recently, Doris Reynolds has described 'channels' of orthoclase penetrating between grains of oligoclase and quartz in a Caledonian granodiorite, metamorphosed in Tertiary times.<sup>2</sup> Her description of the textural relationships between these three minerals would apply almost word for word to the bytownite-bronzite-clinopyroxene association here described, though there are important differences. The genuine corona structures are typically two-ply, and often involve minerals of fibrous habit containing hydroxyl and other fluxes. In the present instance the rim is never two-ply, though two minerals, anhydrous clinopyroxene and

<sup>1</sup> S. J. Shand, On coronas and coronites. *Bull. Geol. Soc. Amer.*, 1945, vol. 56, p. 247.

<sup>2</sup> D. L. Reynolds, The transformation of Caledonian granodiorite to Tertiary granophyre on Slieve Gullion, Co. Armagh, N. Ireland. *Internat. Geol. Congr.*, 18th Session, Great Britain, 1948, Report, 1950, pt. 3, p. 20.

plagioclase, are involved. In the Slieve Gullion case, the orthoclase filling the channels was demonstrably formed from, and replaces the marginal zones of, the oligoclase, for the optical orientation of the former changes at each oligoclase boundary. In the present instance, although there can be no doubt that the bronzites contributed largely to the formation of the clinopyroxene, and although the former are of haphazard orientation, there is no crystallographic relationship between the two pyroxenes: the whole of the clinopyroxene within any one clot is crystallographically continuous. One must infer, therefore, that the clinopyroxene together with the small grains of plagioclase intimately involved with it were precipitated from a liquid phase. The outer bronzites within the clots are uniformly encased in clinopyroxene, a fact that is meaningless if it does not imply essentially the same mode of origin as for the thinner imperfect rims described above. It seems impossible to escape the conclusion that the augitic material, formed by reaction, was fluxed and thus acquired, as it were, crystallographic independence.

Critical evidence bearing on the physical condition of the pyroxenic material is afforded by the many blunt wedges and finger-like processes which penetrate radially for short distances into the plagioclase-mosaic surrounding the clots (figs. 6 and 7). They were invariably inserted *along* inter-crystal boundaries; the pyroxenic material moved *between* crystals, not into them. It looks at first sight as if it had been able to thrust its way between the plagioclases, making room for itself by pushing them aside; but this possibility must be ruled out as impracticable. We must next consider the possibility of the protrusions having been formed by *replacement*, rather than displacement.

It is more difficult to assess the evidence for and against replacement of the plagioclase. If  $Mg^{2+}$  and  $Fe^{2+}$  ions were available in the reaction zones, they might, under favourable circumstances, work their way along the inter-crystal boundaries, through the contact zones of atomic disorder, producing a narrow channel of clinopyroxene at the expense of the plagioclase. This process would explain why the channels on the outside of a clot penetrate between plagioclases, as well as along bronzite-plagioclase contacts. Nevertheless, although superficial examination suggests a replacive origin, appearances in this case are deceptive. The main argument against replacement is the fact that precisely similar textural relationships are encountered repeatedly in the simpler bronzite-plagioclase association in the sub-ophitic clots, and even where isolated bronzites are embedded in plagioclase. If the clinopyroxene tongues protruding from the reaction rims within the coronophitic clots, and

illustrated in figs. 5 and 6, are replacive, then so are the similar tongues of pyroxene illustrated in figs. 2 and 3; but as we have already seen, the textural relationships in the last two cases are consistent with simultaneous crystallization rather than replacement.

Two points of detail are significant here. Many of the short tongues expand distally and cease abruptly against a plagioclase crystal-face (fig. 6). This is inconsistent with replacement, for there is no reason why replacement should be most extensive at the end of a vein, and no apparent reason why, if the clinopyroxene substance could replace plagioclase on either side, it should not be equally effective in attacking the felspar lying athwart its passage. On the other hand, a picture of a still plastic, largely augitic residuum, propelled by the pressure of the adjacent growing plagioclases and piling up behind an earlier-formed felspar, does not unduly strain the imagination. This relationship is shown repeatedly in figs. 5 and 6. The present pyroxene-plagioclase boundaries at the outer margins of the clots are not the original ones, for the *substance* of the plagioclase as well as of the bronzite was required for the formation of the clinopyroxene, though it is uncertain whether a plagioclastic residuum rather than the solid crystals made the necessary contributions. However, it is obvious from the structural details of the clots that the final residuum contained material from which both clinopyroxene and plagioclase were ultimately precipitated, for small granules of the latter lie between the projecting tongues of the former. It is clear that both minerals crystallized simultaneously (figs. 6 and 7).

Now the heterogeneity of the mottled anorthosite is apparent from the hand-specimen. In effect the dark clots considered alone could appropriately be termed 'augite-melanorite': while the rest of the rock is bronzite-bearing anorthosite. According to the current view, anorthosite represents a natural concentration of plagioclase crystals, formed from basic magma (in this case noritic), out of which the heavy silicates have been separated by gravity, and from which the late magmatic residua have been expelled by filter-press action. The dark clots, therefore, might represent either cognate xenoliths of melanorite, or pockets of residua trapped in the plagioclase crystal mush.

In support of the former hypothesis one may quote the very different mineral composition within and outside the clots, and the striking difference in shape of the bronzites in the two environments. The well-rounded, sub-cylindrical bronzites within the clots stand in striking contrast with the highly irregular isolated grains in the body of the rock. This implies differences in cooling history.

As regards the second hypothesis, it seems to the writer that a weakness lies in the composition of the clots: they are mafic, whereas late-fractions ought surely to be leucocratic. The material limitations of the present study make it impossible to dogmatize on the origin of the coronophitic clots; but crystallization within the clots appears to have proceeded under a different control from that operating in the body of the anorthosite, and therefore the writer favours a xenolithic origin. The effects of re-heating to magmatic temperatures appear self-evident. The general picture involves early-formed bronzites forming small groups, and partly in contact with one another. These were later laid under contribution, together with the adjoining plagioclases, to form a fluid reaction product containing the substance of clinopyroxene in excess of potential bytownite. Clinopyroxene was precipitated first, upon the now rounded bronzite nuclei, but was crystallographically independent of them except at the point where crystallization commenced. The clinopyroxene was quickly joined by plagioclase and the two crystallized simultaneously within the framework imposed by the external feldspar mosaic.

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