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The textures and genesis of metamorphic pyroxene in the Freetown Intrusion

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ABSTRACT. The Freetown Intrusion, Sierra Leone, evolved by recurrent injection of olivine-bearing magma producing an aggregate thickness greater than 6000 m of rhythmically layered rocks. Sedimentation and constrained viscous flow of crystallizing magma concentrated olivine crystals during initial formation whilst concentration of volatiles locally lowered residual melt temperatures. This affected the crystallization of pyroxenes especially in pyroxene-troctolites where abundance of olivine caused deferred pyroxene growth. Three examples are described: (1) Flattened and elongated schlieren of augite enclosing plagioclase in ophitic intergrowths show preferred orientation cutting across primary layering defined by olivine, proving that pyroxene growth was secondary and influenced by stress directions in a relatively rigid rock. (2) In some pyroxene-troctolites, augite is segregated into coarse ophitic nodules which are widely and evenly spaced in a troctolitic host rock. Successful pyroxene nucleation and extensive diffusion caused development of domains of equilibration within a 'cotectic' pyroxene-plagioclase-volatile system. Crystallization within this was deferred compared with the surrounding olivine-plagioclase assemblage in which effects of granulitization are conspicuous. (3) Occasionally the pyroxenes are segregated in dispersed lenticular bodies of noritic pegmatite in troctolite. As in the previous cases, growth of pyroxene involved resorption and regrowth of olivine. This reflects the highest temperatures of crystallization in equilibrium with volatile-enriched pegmatite fluids. Temperatures decreased inwards giving a zonal structure and late growth of biotite, orthoclase, and apatite.

The formation of late crystalline pyroxenes and pegmatites thus involved extensive diffusion of volatile and other components accompanying the establishment of domains of reduced pressure in hot and slowly cooled rocks subjected to gradual deformation due to progressive subsidence of the central parts of the intrusion. The final fabric is therefore metamorphic resulting from annealing rather than crystal accumulation.

THIS paper is part of a research programme concerned with two basic layered intrusions, the hypersthene-gabbro of Ardnamurchan (Wells, 1954) and the troctolites and gabbros of the Freetown intrusion (Wells, 1962). In both intrusions the dip of the funnel-shaped layering surfaces steepens towards the inferred centre (fig. 1). Although cumulus conditions have influenced the formation of some of the layering, on the whole other processes are seen to be more important. Cryptic layering appears to be absent in the Freetown body and careful textural and geochemical studies are necessary to delineate and distinguish the properties of the intrusive and crystallizing stages of its formation (Wells, 1962; Bowles, 1976, 1977, 1978).

From gravity results (Baker and Bott, 1961) and sparse core sampling the layering of the Freetown intrusion is probably approximately concordant with a funnel-shaped floor comprising high-grade gneisses and schists of the Precambrian Kasila Series. The intrusion has been given an age of 193 ± 3 Ma (Beckinsale *et al.*, 1977). Two magnetometer traverses at sea (Krause, 1963) agree with the view that the complete intrusion is roughly circular with a radius of about 30 km.

Differential erosion of the stratified rocks produced four parallel ranges of hills corresponding to four zones into which the exposed sequence was divided by Wells (1962). An additional distinct basal sequence is known only in boreholes (fig. 1). In the lower part of each exposed zone, troctolites are dominant, forming high ground whilst olivine-gabbros, leucogabbros, and occasional anorthosites form the middle to upper parts of each zone and occupy the intervening valleys. This sequence in each zone is repeated in small-scale cyclic units which are 50–150 m thick and, to a lesser extent, in fine banding on the scale of a few cm (Wells and Baker, 1956; Wells, 1962; Hatch *et al.*, 1972 fig. 136).

The 6000 m of layered rocks was probably emplaced by a series of pulses with pauses indicated by cognate xenolithic pyroxene-granulites formed from material consolidated at earlier stages. Such rocks are now widely distributed although chiefly concentrated near zone boundaries. Shearing and high-temperature metamorphism accompanied the multiple intrusion and gradual deformation of the evolving complex, with amphibolitization of pyroxenes confined to zones of shearing in the basal rocks. Rare xenoliths with contorted banding (e.g. near Fourah Bay College, Freetown) are probably metasediments. Other evidence of thermal metamorphism of earlier crystalline rocks by later magma is shown by clouding of feldspar and the development of symplectic textures, particularly in the vicinity of Kent.

The evidence appears to be strong, therefore, that each of the main zones corresponds to a separate and major episode of intrusion. Probably the second-order cyclic units reflect alterations in the rate of magma injection if not distinctly separated events as accepted by Umeji (1975). If this is correct and the intrusion is sheeted, the temperature distribution and opportunity for convective circulation of magma would have been vitally different from that originally envisaged for Skaergaard (Wager and Deer, 1939).

A lengthy period of emplacement and cooling is indicated by a reversal in the polarity of the remnant magnetism within 1 km of the base of the intrusion (Briden *et al.*, 1971). The intrusion may have occurred at considerable depth and high crustal temperature because there appears to be no marginal chilled facies. Drill cores (Baker and Marmo, 1956; Wells, 1962) indicate concordance between the lowest banded troctolites, the basal rocks and the country rocks. Beckinsale *et al.* (1977) suggest that the intrusion was associated with crustal deformation linked with preliminary stages in the opening of the Atlantic (Jones and Mgbatogu, 1977; Culver and Williams, 1979; Morel, 1979; McConnell, 1974).

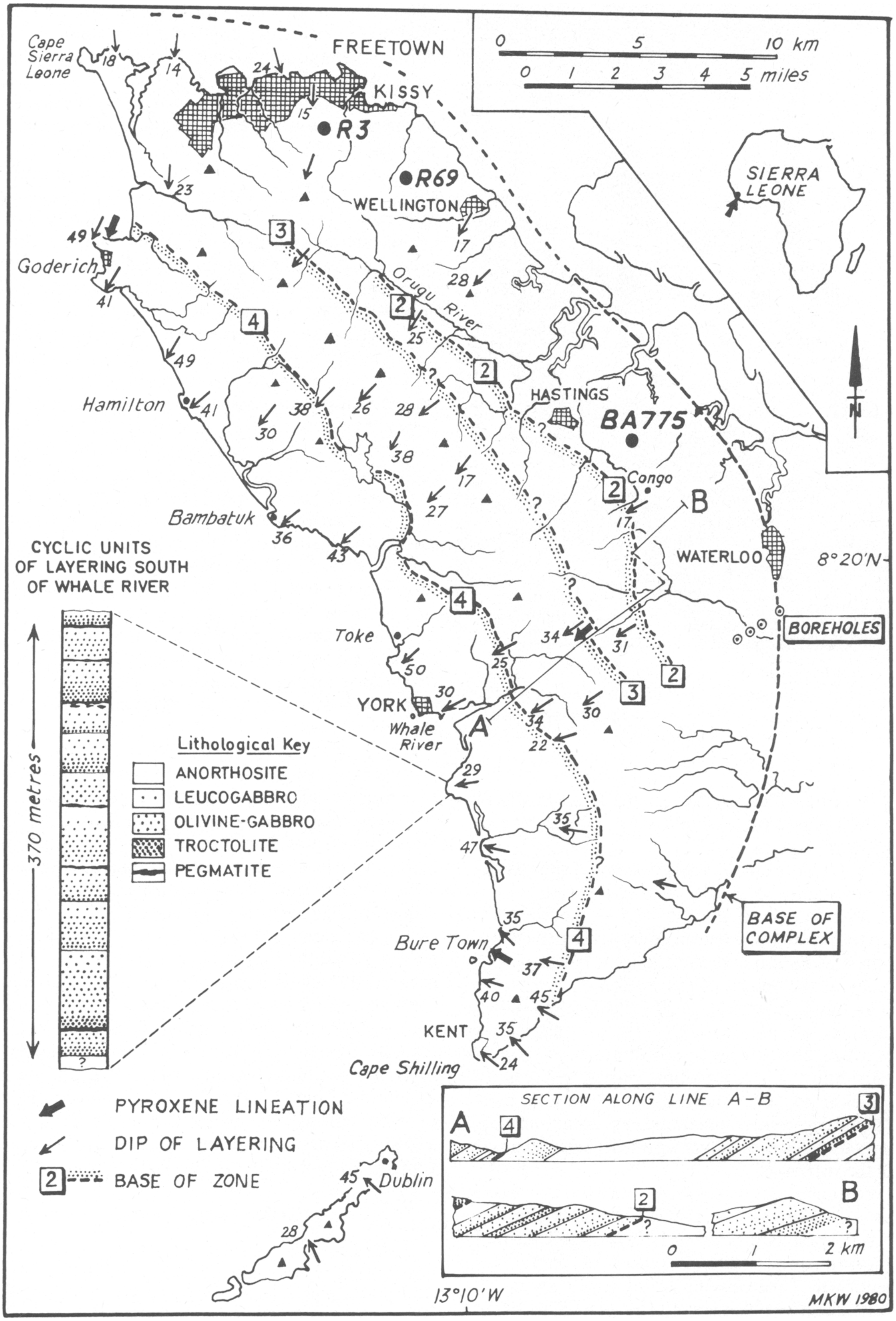
Layering in the complex is a combination of modal and textural variation with practically no cryptic layering. The plagioclases range only from An_{57-62}, largely from optical measurements (Wells, 1962) whilst olivines (determined optically and by XRD) vary from Fo_{65-8}.

Late crystalline pyroxene. Textural variations between plagioclase, olivine, and the pyroxenes are closely linked to modal variations. The gabbroic and anorthositic rocks are generally coarser grained than the troctolites, so the textures within each rhythmic unit tend to coarsen upwards. This tendency climaxes in layers of pyroxene-rich, olivine-free pegmatites. Many pyroxene-troctolites show late pyroxene growth as: (1) elongated and flattened growths of augite which cut obliquely across layering defined by olivine-concentrations in the host troctolite; or (2) evenly spaced nodule-like growths of ophitic augite; or (3) irregular shaped and lenticular bodies (averaging a few centimeters in thickness) of coarse gabbro or gabbro-pegmatite that are relatively sharply demarcated from the enclosing troctolite. With the possible exception of (1), all three types of pyroxene growth, together with other less well-defined examples, may be found widely distributed in the troctolites of the complex. The examples described in detail below are, however, all from zone 1, where primary layering structures defined by olivine distributions are well preserved.

Cross-cutting pyroxene schlieren

The phenomenon of elongated pyroxenes oriented oblique to banding was first reported by Wells (1962, fig. 24). *In situ* examples were later found near the engine shed of Kissy Spur Quarry (fig. 2), where the lineation marked by the pyroxene growth is conspicuous and interrupts rather than displaces the primary layering. Here troctolites show well defined 'inch-scale' banding, false bedding with only minor angular variations, and graded bedding marked by modal variations of olivine and plagioclase. Pyroxene growth-planes

FIG. 1 (*opposite*). Map of the Freetown Intrusion, Sierra Leone indicating the dip of the layering and limits of three of the zones defined by Wells (1962). The base of zone 1 is not shown since it occurs in low ground and, like the base of the intrusion, is obscured by young sediments. The position of the base is located mainly on geophysical and borehole data. The locations of the three critical specimens examined in this work are shown and the layering is indicated on the large scale by means of a section across the intrusion and on the small scale by a continuous succession of cyclic units from a coastal exposure.


FREETOWN
KISSY
Cape Sierra Leone
R3
R69
WELLINGTON
Goderich
Orugu River
Hamilton
HASTINGS
BA775
Congo
Bambatuk
WATERLOO
8°20'N
BOREHOLES
Toke
YORK
Whale River
Bure Town
KENT
Cape Shilling
BASE OF COMPLEX
SIERRA LEONE
0 5 10 km
0 1 2 3 4 5 miles
CYCLIC UNITS OF LAYERING SOUTH OF WHALE RIVER
370 metres
Lithological Key
ANORTHOSITE
LEUCOGABBRO
OLIVINE-GABBRO
TROCTOLITE
PEGMATITE
PYROXENE LINEATION
DIP OF LAYERING
BASE OF ZONE
Dublin
SECTION ALONG LINE A-B
0 1 2 km
13°10'W
MKW 1980

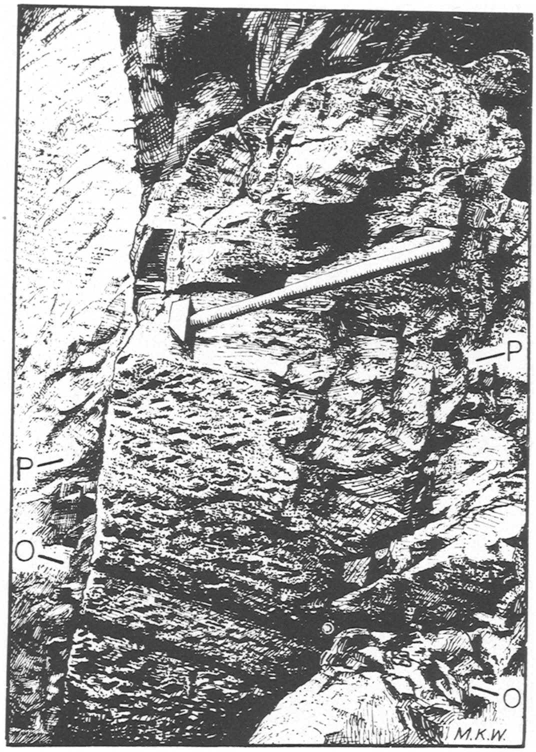


FIG. 2. Elongated pyroxene schlieren (P—P) cutting across the primary layering (O—O) defined by olivine concentration in a rock face in Kissy Spur Quarry. Drawn from a photograph.

(P—P in figs. 2 and 3) dip about 20° more steeply than the planes (O—O) defined by olivine concentration.

Fig. 3 is taken from a large oriented thin section cut perpendicular to the olivine layering (O—O) and showing the maximum dip of the elongated pyroxene growths. Clear primary layering is shown by the alternation of mafic and felsic bands perpendicular to the length of the section.

The host troctolite in the section shows an irregular lamination with tabular plagioclases separating thin, impersistent laminae of granular olivine (fig. 5). Mutual boundaries between the olivine grains are relatively straight and metamorphic triple-junction textures are common. These characteristics are shared with troctolites throughout the intrusion.

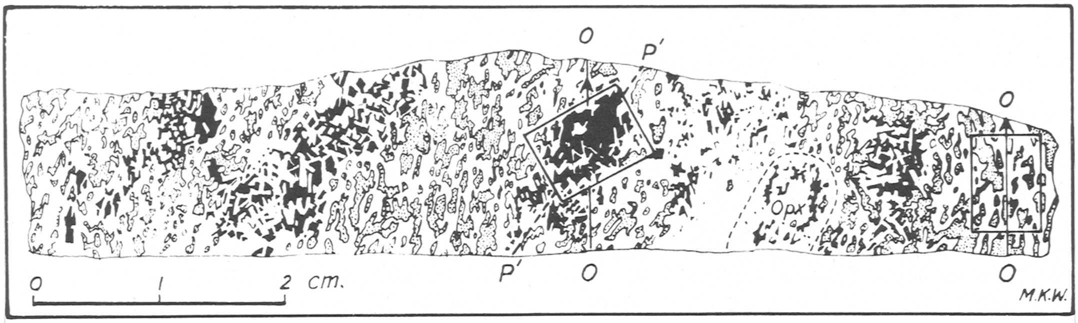
The augite segregation (figs. 3 and 4) is irregular although elongate in shape with optically continuous crystals extending between, and partially enclosing small rounded grains of olivine and plagioclase. Those olivine grains which occur close to the margins of the segregation are serpentinized ('S' in fig. 4), in complete contrast to the fresh olivine of the surrounding rock. This phenomenon appears commonly in the intrusion and is thought to be a low-temperature reaction with late-stage volatiles associated with the pyroxenes. The nucleus of the segregation consists of parts of two augite crystals in which no inclusions occur and which may be inherited from a primary pyroxene phase. Plagioclase crystals within the augite segregation are about 2 mm × 0.25 mm, comparable with those of the surrounding troctolite, and sometimes comprise aggregates of roughly aligned crystals which must be regarded as fragments of pre-existing rock engulfed by later growth of the augite.

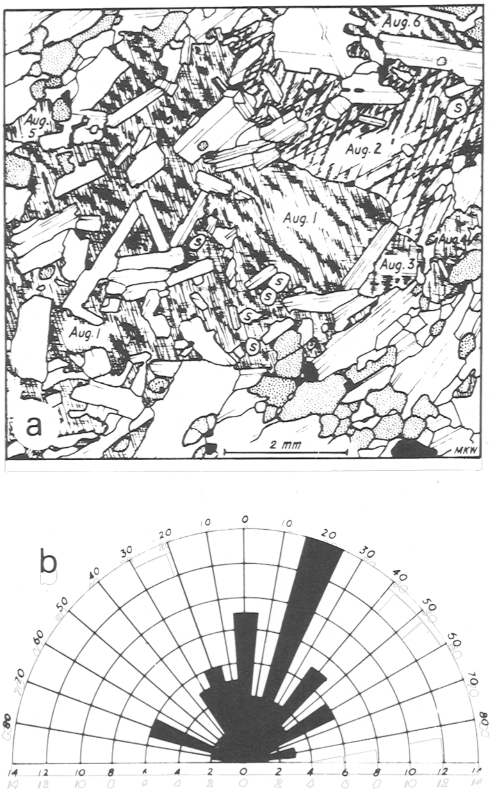
Traces of the (010) planes, indicated by the twin lamellae, of the plagioclase crystals in the schlieren and shown in fig. 4*a* are represented in the rose diagram of fig. 4*b*. A significant proportion of the larger plagioclases show a marked degree of preferred orientation coincident with the direction of elongation of the pyroxene growth. The relation of the smaller tabular plagioclases to the pyroxene in the schlieren indicates a simultaneous, ophitic intergrowth, allowing the formation of numerous, generally randomly oriented, small euhedral crystals, some of which have developed perpendicular to the (010) faces of the larger, earlier formed crystals. A similar exercise conducted on the troctolitic host rock (fig. 5*a* and 5*b*) reveals that the orientation of the plagioclases is parallel to the elongation of the pyroxene growths rather than the olivine layering.

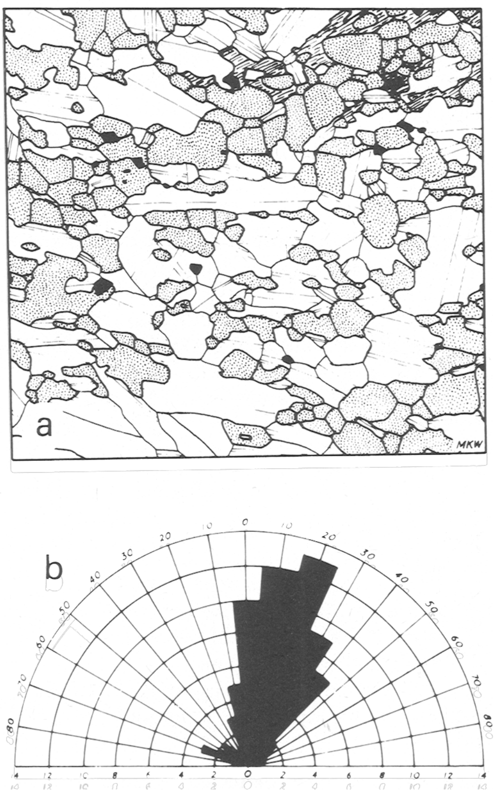
Origin of the pyroxene schlieren. It is therefore clear that although the bands of layering of olivine and intervening plagioclase in the troctolitic host are preserved, the original plagioclases in the layering and in the schlieren have been recrystallized and aligned in a new direction, coincident with the direction of elongation of the pyroxene schlierèn. The textural evidence shows that much of the pyroxene growth is metamorphic and occurred whilst the host rock was undergoing deformation. The prevalent stress direction controlled both the direction of elongation of the pyroxene growth and the realignment of the plagioclase crystals throughout the rock. Some plagioclase crystallized simultaneously with the pyroxene in an ophitic intergrowth. These schlieren therefore provide compelling evidence for an origin by sub-solidus crystallization under shearing conditions in an essentially hot crystalline rock.

Ophitic augite nodules

Roughly spherical nodules of ophitic augite occur in the pyroxene troctolite from the lower half of the layered succession of zone 1. Specimen







FIGS. 3, 4, and 5. FIG. 3 (*top*). Large oriented thin section of specimen R3 taken from the outcrop of fig. 2. The primary layering (O—O) is defined by mafic and felsic bands perpendicular to the length of the section. The direction (P′—P′) corresponds to the longest dimension of the pyroxene growths shown in fig. 4*a* and approximates to the preferred orientation of the schliere generally. Drawn from a photograph. Olivine is shown stippled, feldspar white and pyroxene black. FIG. 4 (*lower left*) (*a*) The pyroxene segregation outlined in the centre of the section of fig. 3 consists of two major units of augite (Aug. 1, 2) and several minor units (Aug. 3-6). Olivine is shown stippled and feldspar white with an indication of the traces of the twin lamellae. Diallagic features of augite are shown. Oxides are black. Drawn from a photograph. (*b*) Rose diagram showing the number and direction of the traces of the (010) planes of the plagioclase crystals in the schlieren of fig. 4*a*, as indicated by the twin lamellae. The reference direction (0°) is parallel to the olivine layering (O—O) but a high proportion of the plagioclase crystals are oriented at about 20° to that direction. FIG. 5 (*lower right*). (*a*) The troctolite host rock in an area corresponding to that outlined to the right of fig. 3. Olivine stippled, feldspar white with traces of the lamellae indicated, minor pyroxene shaded and oxides black. Drawn from a photograph. (*b*) Rose diagram corresponding to fig. 4*b* of plagioclase orientation in fig. 5*a* showing again the predominate angle of about 20° to the primary layering.

BA 775 from near Congo (fig. 1) is used here as an example. The greater part of the nodule (fig. 6) is a single crystal (A) of diallagic augite which is narrowly separated in the plane of the section from part of a second crystal (B). Around most of the margin of the nodule a thin zone of coarsely crystalline plagioclase separates the black nodule from the pale brown host rock. The ophitic areas contain no olivine whereas the surrounding rock is mainly olivine and plagioclase and is almost devoid of pyroxene. There is thus an almost perfect segregation of the mafic components to form pockets of gabbro evenly spaced in troctolite.

The texture is more ideally ophitic than in the lenticular pyroxene segregations described above. Individual plagioclases are distributed uniformly throughout the augite and vary widely in orientation. They occupy about 65% of the main part of the intergrowth suggesting that both minerals crystallized simultaneously in a eutectic relationship in the presence of local concentrations of residual fluids.

Towards the margin the proportion of plagioclase increases rapidly to form an encircling shell of feldspar. In this and in a septum of plagioclase which crosses the main augite growth, the crystals tend to be larger and to occur in aggregates which show a similar degree of parallelism to that in the lenticular pyroxene segregations described above.

Perfect optical parallelism of the augite extends to the outer limits of the intergrowth where the pyroxene is restricted to very thin septa enclosing and penetrating between plagioclase crystals (fig. 6, area G). It is possible that optically parallel growth of augite once extended beyond the boundary of the nodule since eight small patches of augite scattered through the troctolite near the nodule in fig. 6 all share a closely similar orientation, although subsequent deformation of the enclosing troctolite has slightly displaced them.

The surrounding troctolite is relatively fine-grained, with impersistent laminae of granular olivine separated by strongly fluxioned plagioclase. The lamination is deflected around the ophitic nodule similar to the foliation which surrounds a porphyroblast. Both the larger, prismatic plagioclases and the smaller equidimensional grains show preferred orientation of twin lamellae, comparable with that seen in the host of the pyroxene schlieren.

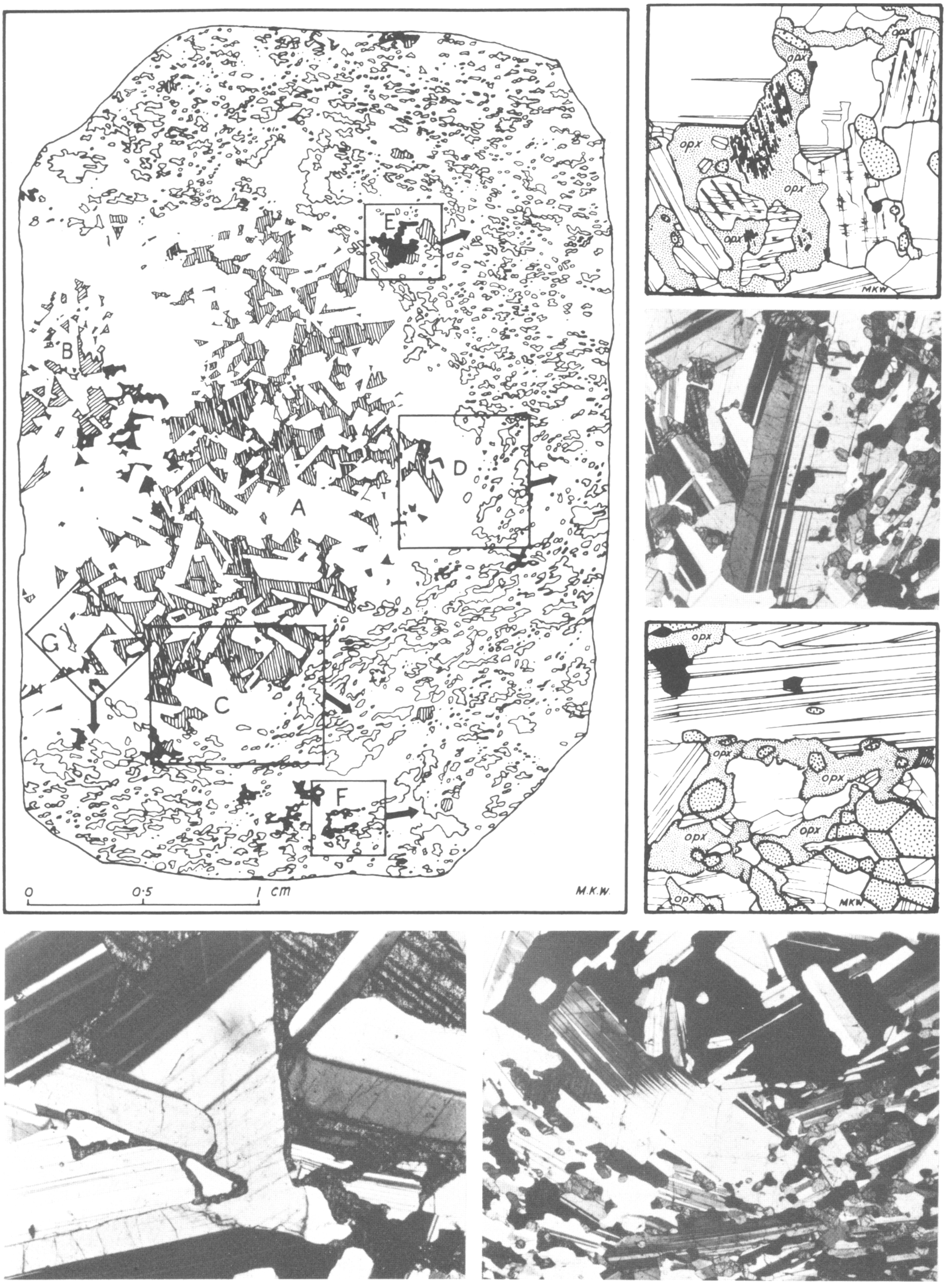
The influence of shearing is shown by bending and tapering of twin lamellae in several large plagioclase crystals and occasionally it is possible to trace twin lamellae across the boundaries of adjacent small equidimensional grains formed by recrystallization of an original larger grain. Pericline twinning, developed in many of the larger crystals in the troctolite but absent from the interior of the ophitic nodule, probably originated as a means of accommodating stresses in the crystals.

Several features of these rocks are more characteristic of granoblastic than primary magmatic rocks. The two largest plagioclase crystals (fig. 6, areas C and D) for instance are subhedral and of normal ophitic appearance within the augite environment, but develop lobate margins and enclose minute grains of olivine in the manner of porphyroblasts in the troctolitic environment. In area C the effects of stress near the margin of the nodule are shown by the tapered twin lamellae and bending of the crystal, whilst the plagioclase at D shows contrasting styles of crystal growth in the two halves of a Carlsbad twin.

Distribution of orthopyroxene associated with the nodules. Orthopyroxene is present only sparingly and the main occurrences are shown in black in fig. 6, lying close to the nodule and forming, in effect, a transitional zone of leuconorite between the olivine-rich rocks and the augite-rich nodule.

Four types of occurrence can be recognized. (1) As unusually robust lamellae exsolved from the compact augite grains that occur in the troctolite. In contrast to the ophitic nodules these diallagic augites may have accompanied original olivines as primocrysts. (2) Inverted pigeonite as seen in the core of the orthopyroxene growth in fig. 6, area E, and characterized by blebs and lamellae of clinopyroxene. This may also be a relict primocryst phase, initially formed prior to inversion and at a temperature just above 1000 °C (Brown, 1968,

FIG. 6 (*opposite*). The ophitic nodule of augite in specimen BA 775 from near Congo consists of two units of augite (A and B) shaded parallel to cleavage, with feldspar (white). In the troctolitic host the olivines are outlined and orthopyroxene is shown black. Five areas of particular interest (C—G) discussed in the text illustrating effects of stress imposed on the nodule, and involving recrystallization of the feldspar and late-stage crystallization of pyroxene are shown in greater detail by means of marginal photographs and drawings. All parts of the orthopyroxene (opx-fine stipple) in areas E and F are optically parallel, in contrast with separately oriented olivine grains (coarse stipple). Diallagic features of augite are shown. Oxides are black. Plagioclase twinning ruled. Note minute amounts of biotite (closed ruled).


A
B
C
D
E
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G
0
0·5
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1972; Bowen and Schairer, 1935; Wells, 1962). (3) As exsolved lamellae in the ophitic augite. Other examples in the intrusion contain lamellae that are known to be monoclinic, sharing the (010) optic axial plane with the host augite and differing from this chiefly in possessing lower birefringence and a smaller 2V. This phase may be the clinohypersthene of Binns *et al.* (1963) which is described in similar circumstances. Unfortunately these lamellae are too thin for microprobe analysis due to the fluorescence considerations discussed by those authors. (4) Most of the orthopyroxene shown has crystallized at a late stage as primary orthopyroxene as in the case illustrated in fig. 6, area F, forming an optically continuous growth between grains of the other minerals and enclosing numerous olivines which show the effects of earlier granulation.

Origin of the ophitic augite nodules. Because the nodules have behaved to some extent as rigid units in a more plastic medium it is natural to consider that they may have crystallized early, co-existing with early-formed olivines and subjected to the same processes of crystal accumulation. This is unlikely to have been so since early precipitates of calcic pyroxene are more likely to be in the form of discrete crystals than ophitic intergrowths.

Given that the magma was saturated in the relevant components, the chances of establishing and sustaining stable crystal growth would be greater for olivine than for augite. Olivine would crystallize around close-spaced nuclei while crystallization of augite would be deferred with its components dispersed in solution until a critical degree of supersaturation was reached in the remaining fluid, when rapid growth would occur at widely spaced centres of nucleation.

Similar explanations have been offered for various kinds of poikilitic growth of pyroxene in rocks of a cumulate character (Brown, 1956, Wager *et al.*, 1960). How far similar explanations can be extended to the present rocks is difficult to judge because of the effectiveness of subsolidus equilibration in eliminating chemical characteristics which might have distinguished primary precipitate phases. Virtually all trace of early pyroxenes has been lost and their substance has been incorporated in later poikilitic or ophitic growths. The evidence strongly suggests that the latter developed *in situ* after precipitation of initial olivine and, to some extent, at the expense of the olivine.

Preferred orientation of equidimensional grains is often seen in pyroxene granulites and other granoblastic rocks and seems to require recrystallization under conditions of directed stress for its formation. It is difficult to see how this texture could arise through settling from a melt or by alignment in a flowing magma. Although mechanical sorting of primary crystals suspended in a melt was certainly significant in the early stages of development of the layering, textural evidence of recrystallization is very strong and the question arises as to whether any primary igneous textures have survived to which the term cumulate and its relatives could be applied.

Lenticular segregation of pegmatitic gabbro

This kind of segregation is shown by sample R69 from a quarry near the Kissy Methodist School to the east of Freetown. The host troctolite is relatively homogeneous with little evidence of layering. Parallelism of feldspars is well developed. Microscopic examination shows that small amounts of both clino- and ortho-pyroxene are present in the troctolite, poikilitically enclosing olivines. The predominant pyroxenes appear in irregular lenticles often elongated parallel to the feldspar lamination of the host rock. Their margins are sharply defined. Petrography suggests segregation of late-crystallizing components derived by diffusion from the surrounding rock rather than injection from some external source, although that alternative interpretation could be placed on these segregations as seen in the rock face because of their varied size, wide spacing and irregular shape and distribution.

Gradual changes of mineral association and texture occur from margin to centre of the segregation as shown in fig. 7. The host troctolite contains some pyroxene but is otherwise similar to those already described. The outermost zone of the segregation is marked by particularly large olivines which cut across the lamination of the troctolite. These olivines enclose sparse plagioclase crystals like those in the host troctolite and have generally lobate margins, but are occasionally bounded by plane surfaces which may be growth faces. It seems unlikely that these olivines are relict, and the evidence suggests that they developed during the last stages of formation of the troctolitic fabric in response to the highest tremperature pegmatitic condition.

In the inner parts of the zone of large olivines much of the intervening space is occupied by poikilitic pyroxene growths in relatively coarse, irregular patches of optically parallel orthopyroxene in a host crystal of clinopyroxene or vice versa. Close to the troctolite these are crowded with rounded, separate olivine grains represented as black dots in fig. 7 and generally somewhat smaller than those in the troctolite. Since the spacing of the centres of the separated grains in pyroxenes is comparable with that of the grains that are in mutual contact in the host troctolite, it seems likely

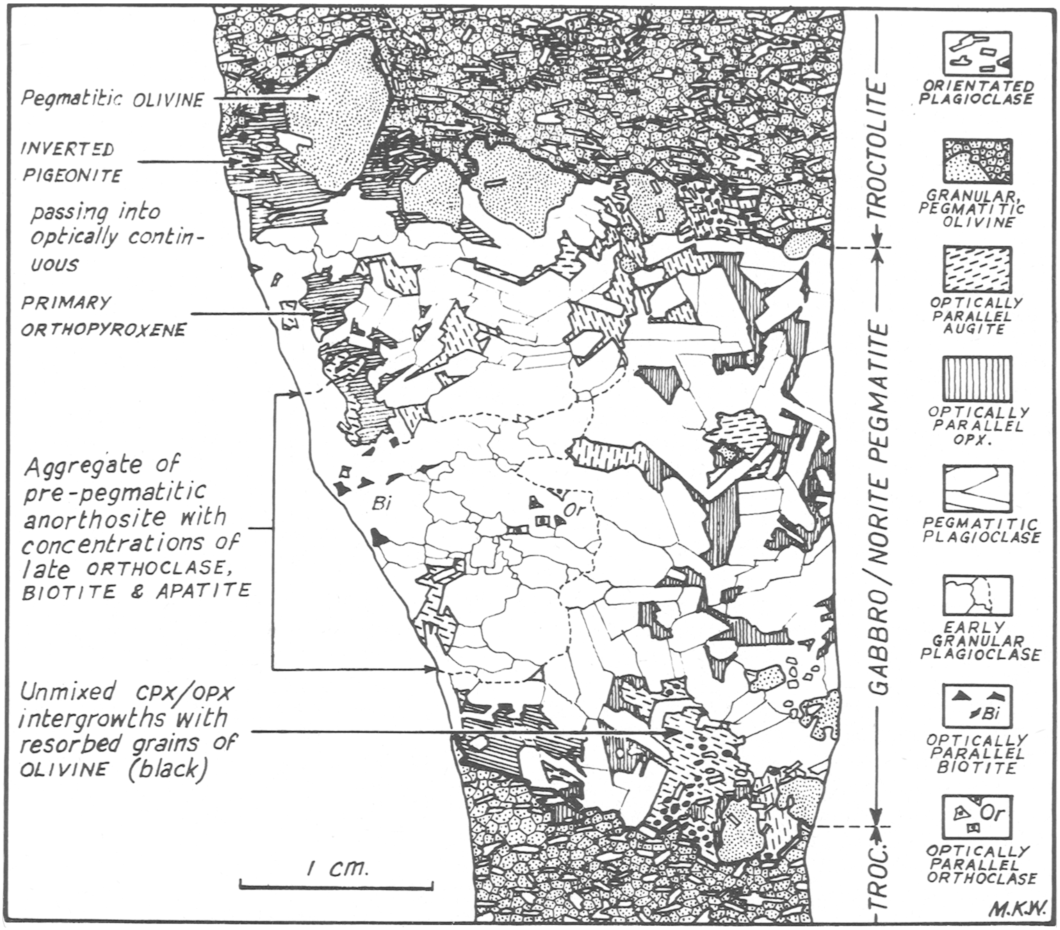

FIG. 7. Zoned gabbroic and noritic segregation in the troctolite of sample R 69; for explanation see text.

that growth of the pyroxene has followed resorption of the olivine. The large olivines, however, were apparently unaffected by this reaction, thus helping to confirm their stable growth simultaneously with the marginal pyroxenes. Where orthopyroxene is the host phase it shows the characteristics of inverted pigeonite providing evidence of high temperature during this stage of growth of the segregation.

The main part of the segregation has a uniformly coarse texture of large and randomly orientated plagioclases accompanying growths of schillerized augite and growths of bronzite in equal abundance (fig. 7). The feldspars display an equally high degree of euhedrism towards both pyroxenes and are devoid of zoning or evidence of post-crystallization strain. Absence of shearing stress during crystal growth is also indicated by perfect optical parallelism throughout each pyroxene unit. Several of the units in the interior of the segregation are optically continuous with the host phase in the pyroxene intergrowths of the marginal zones. The latter appear to have provided the roots from which outgrowth of pyroxenes extended towards the heart of the evolving segregation. This phenomenon represents a passage during crystal growth through the relevant clinopyroxene to orthopyroxene inversion temperature. In contrast to the marginal pyroxenes, the major augite and bronzite units in this zone are free of inclusions of the one phase in the other except near their mutual contacts. Here the host phase is in optical continuity with enclosed fragments of the same phase in the other host.

During the period of rapid growth of the pyroxenes, conditions in the heart of the segregation were therefore essentially those of a 'cotectic' system involving plagioclase, pyroxene, and volatile constituents.

Neither the distribution of plagioclase nor the shape and size of individual crystals seems in any way dependent on the species of pyroxene which is its nearest neighbour. It seems therefore that conditions towards the centre of the developing segregation led to formation of a pegmatitic fluid phase which interacted with previously formed minerals, enabling perfect equilibrium to be established.

The central zone contains two contrasting mineral associations. One is composed largely of aggregates of plagioclase showing marked effects of strain, seen as varied and shadowy extinction, oblique twin lamellae additional to those of the usual Carlsbad and Albite laws, and sutured grain boundaries with sparsely distributed, corroded olivine grains rimmed with late-formed orthopyroxene. These are regarded as xenolithic relics of anorthosite which have survived recrystallization. The other association comprises late orthopyroxene in a close relationship with magnetite, ilmenite, biotite, apatite, and orthoclase indicating an environment in which free growth was permitted. Orthoclase and biotite occur in unstrained, optically parallel growths occupying spaces between the cognate plagioclase 'xenoliths' described above and the main pegmatite crystals of pyroxene and plagioclase. Some calcite is present.

Origin of the pegmatitic segregations. Dixey (1922) regarded the substantial sheets of pegmatite, which are abundant in the upper zone of the intrusion, as introduced distinctly later than the finer grained, olivine-rich rocks. However, the evidence suggests otherwise. Pegmatitic layers, as seen in the continuously exposed section of cyclic units (fig. 1), are mostly perfectly concordant and occur consistently at the top of one differentiated unit and immediately adjacent to the basal olivine-rich rocks of the unit above.

During gravity-controlled crystal sorting, leading to concentration of olivine towards the base of each evolving unit, there must have been a complementary upward diffusion of volatile components through the inter-precipitate liquid. This, combined in its effects with mechanical concentration of plagioclase, helped in the formation of coarse anorthositic layers (Wells and Baker, 1956), but also segregated to form discrete pegmatitic layers rich in pyroxene, and oxide minerals which sometimes appear as veins or vugs.

Little is known about the structure of fluxed silicate melts just prior to crystallization, but from the textural evidence it seems that during initial crystallization within the evolving segregation, the pyroxenes behaved chemically as a unified mafic phase in cotectic relationship with plagioclase. If this is correct and the cations were somewhat randomly dispersed in initial hot solidus pyroxene lattices, it follows that while crystallization was in progress, and immediately afterwards, extensive diffusion must have occurred to give the present distribution of separated augite and bronzite. Compared with this essentially pegmatitic stage of crystallization subsequent diffusion was restricted, resulting in the formation of exsolved pyroxene lamellae and deuteric rims of lamella-free orthopyroxene.

The composition of the last-formed minerals (biotite, titanomagnetite, orthoclase, apatite, and calcite) suggests the existence of a final hydrothermal fluid enriched in K, P, and CO_2 which migrated to domains of reduced pressure and probably merged with the fluids which promoted the formation of pneumatolitic granite veins developed during incipient jointing (Beckinsale *et al.*, 1977).

Conclusions

The structural evidence from flattened and lineated crystal growths, well illustrated by the pyroxenes, combined with indications of shearing stress from cross-cutting structures and the granulation of olivine and plagioclase, leave little doubt that the layered rocks of the Freetown Complex have been subjected to metamorphism. This occurred at near-magmatic temperatures during an extended cooling history under conditions of gradual deformation.

The intrusion was formed from repeated injection of small volumes of magma from depth with a low initial $^{87}Sr/^{86}Sr$ ratio (0.70389, Beckinsale *et al.*, 1977). Each pulse carried suspended crystals of olivine with some pyroxene (Wells, 1962) and was depleted in oxide minerals (Bowles, 1978). Relatively short time intervals between successive pulses of magma affected the thermal history of the intrusion, delaying or even reversing the cooling trend locally and allowing varied degrees of consolidation, crystallization, and bulk viscosity to coexist at a given time within a considerable thickness of the layered sequence. Varied concentration of volatile components in different parts of the intrusive body depressed crystallizing temperatures in the manner indicated by Yoder (1954) and subsequently illustrated in relation to the Freetown intrusion by Wells (1962) and by Bowles (1976, 1977).

Regimes of flow differentiation similar to those described by Irvine and Smith (1967), McBirney and Noyes (1979), and Irvine (1980), and volatile-dependent crystallization therefore predominated over those of fractionation and crystal accumulation. This calls for reassessment of the petrological problems involved, and of the criteria to be sought in solving them. Analytical and geothermometric considerations which help to define the conditions of mineral growth and equilibration are to be discussed in a second, related paper.

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