Rhythmic amphibole overgrowths in appinites associated with explosion-breccias in Argyll

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[Read 25 September 1963]

Summary. Tremolite and actinolite form rhythmic overgrowths over hornblende in appinites associated with pipes of explosion-breccia and represent growth under alternating physical conditions arising from increase of gas pressure and its explosive release. The number of overgrowths present in each appinite mass is related to the number of explosions required to breach the particular structural trap that hindered the upward movement of the volatiles.

THE geographical and genetic association of appinite intrusions with pipes of explosion-breccia has been recorded in Argyll, at Back Settlement near Kentallen (Bowes and Wright, 1961), and at Gleann Chàrnan between Glen Coe and Glen Etive (Bowes and others, 1963). A similar association has been noted on Ardsheal Hill, near Kentallen (Bowes and Wright, 1961, p. 294), and subsequent investigations have shown that all of the major appinite, diorite, and kentallenite intrusions of the Kentallen and Ardsheal Peninsula district are associated with pipes of explosion-breccia.

The formation of explosion-breccia has been explained as the result of a series of explosions of volatiles, which rose ahead of a volatile-rich magma and accumulated below a structural trap, such as an anticline of massive quartzite (Bowes and Wright, 1961, p. 309). The rapid increase of pressure that caused the explosions was a product of the crystallization of the magma (Morey, 1922, p. 230). The high volatile content is indicated by the abundance of hydrous minerals in the igneous masses, the evidence of post-crystallization carbonation (Bowes and Wright, 1961, pp. 303, 306), and the relative abundance of apatite and pyrite (Bowes and others, 1963).

Another mineralogical feature common to these rock types is the rhythmic amphibole overgrowths over large amphibole crystals. These overgrowths have been recorded at Back Settlement and Gleann Chàrnan, and similar overgrowths have been described from the hornblendite and appinite at Kiloran Bay, Colonsay (Reynolds, 1936, pp. 377, 379), which are associated with breccias considered by Bowes and Wright (1961, p. 307) to be explosion-breccias.

Description of overgrowths

Back Settlement—main pipe. The amphibole overgrowths are both common and well developed in the appinite (9084, table I)[1] that is exposed near the centre of the Back Settlement explosion-breccia complex (Bowes and Wright, 1961, fig. 2). The abundant large hornblende phenocrysts have α straw-green, β straw, γ dull green, γ:[001] 21° and $2V_{\alpha}$ 71°; some have a core of colourless augite, others enclose several small randomly oriented augite, sphene, or plagioclase crystals. Many are terminated by outgrowths or surrounded by overgrowths consisting of alternating rims of light and dark green amphibole of tremolite–actinolite composition (fig. 2). The tremolite rims, which are colourless with γ:[001] 21° and $2V_{\alpha}$ 80°, show both sharp junctions and rapid gradations with the actinolite rims, which have the pleochroic scheme α pale straw-green, β light straw, γ clear green. A few crystals show a complete or near complete overgrowth that is very narrow in the prismatic zone, but of considerable extent on the terminal faces (fig. 1*a*, centre). The most common form of overgrowth is that of an irregular saw-tooth on the terminal faces, with a thin discontinuous rim on the prism faces (fig. 1*e*). In most cases, the outgrowth on the terminal faces is better developed at one end of the crystal than at the other. The core itself grades into a narrow rim of very dark green hornblende (fig. 2) along margins that have been overgrown without previous resorption.

The overgrowths are almost invariably crystallographically continuous with the large hornblende core, as shown by the common cleavage planes and the correspondence of the various bands with the faces of the crystal on which they have grown (figs. 1 and 2), but in rare instances this is not so (fig. 1*b*, top). In many cases the complete crystal outline of the hornblende is shown (fig. 1*e*) and the rhythmic tremolite–actinolite bands are parallel to the crystal faces on which they have grown. In some cases, some of the crystal faces of the hornblende crystals are

[1] Numbers refer to specimens in the rock collections of the Hunterian Museum, Glasgow University.

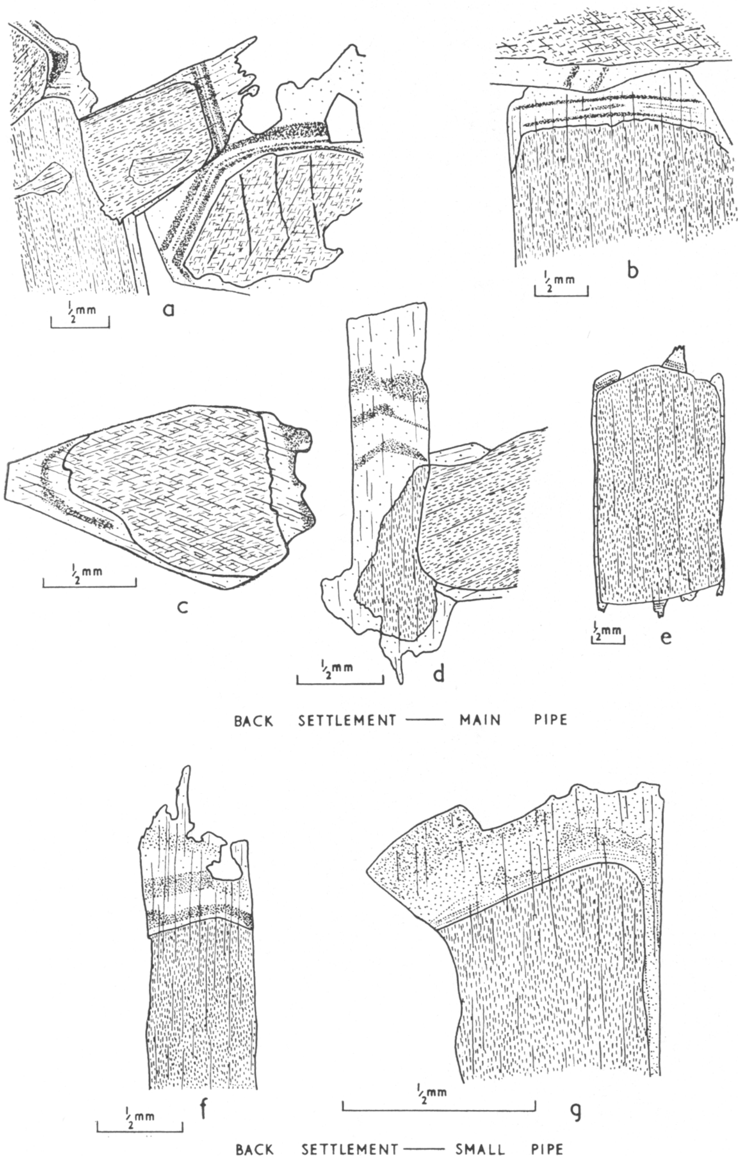

FIG. 1. Rhythmic amphibole overgrowths over amphibole in appinites from the main pipe, Back Settlement (9084) and the small pipe, Back Settlement (9085). (Hornblende, short dashes parallel to cleavage; tremolite, widely spaced dots; actinolite, closely spaced dots; cleavage planes, long dashes.)

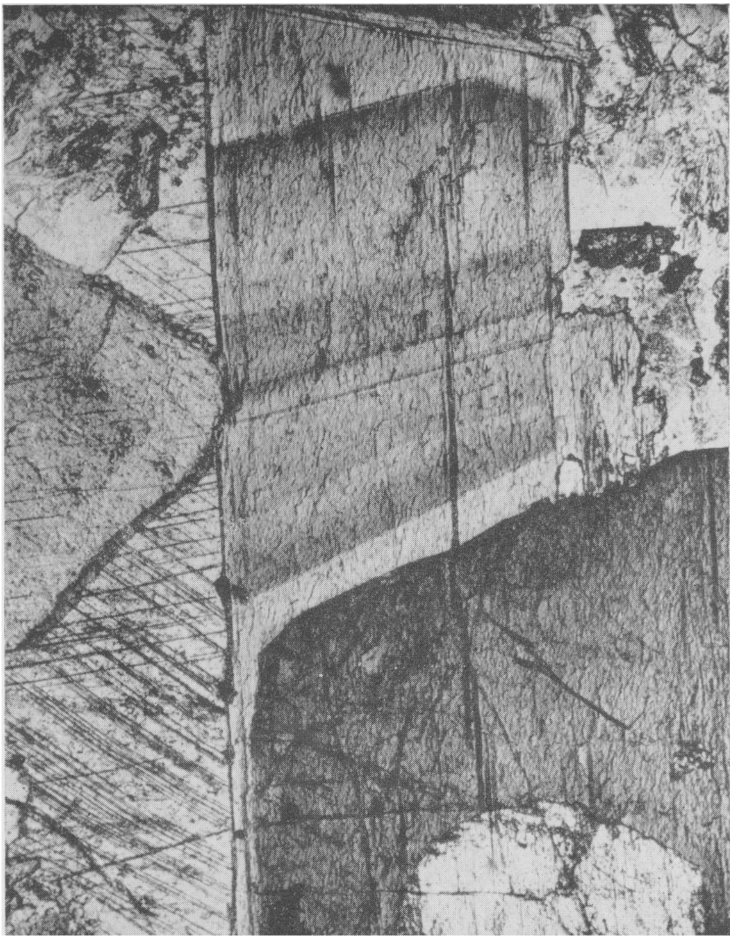

FIG. 2. Rhythmic overgrowths of tremolite and actinolite on a hornblende crystal, with a core of augite, in the appinite (9084) exposed near the centre of the Back Settlement explosion-breccia complex (Bowes and Wright, 1961, fig. 2). Three major bands of actinolite and four major bands of tremolite are shown on the terminal faces, with minor alternations within the major bands. A single overgrowth band of tremolite is developed on the prism face with calcite adjacent. Ordinary light. ×65.

perfectly shown, while other faces show evidence of slight or considerable reaction (figs. 1*a*, right; 1*b*, centre; 2). Rarely the hornblende core shows evidence of extensive reaction with no external crystal form remaining (fig. 1*d*) and in a few cases only the general shape of the host crystal is preserved while the overgrowths show almost perfect amphibole crystal outline (figs. 1*c*; 3).

Seven main overgrowth bands are shown by most of the crystals (figs. 1 *a*, *b*, *d*, *e*; 2; 3); three actinolite bands alternate with four tremolite

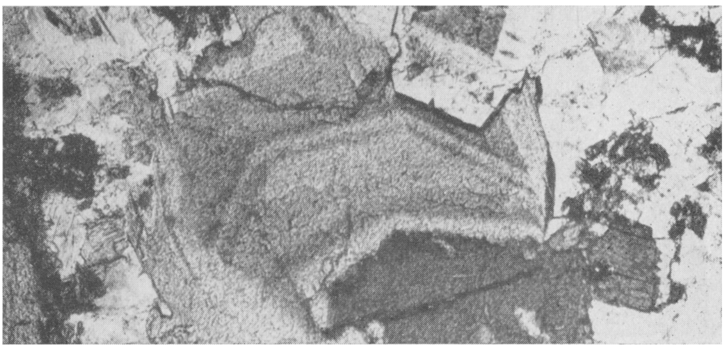

FIG. 3. Rhythmic overgrowths of tremolite and actinolite on a hornblende crystal, showing evidence of reaction, in the appinite (9084) exposed near the centre of the Back Settlement explosion-breccia complex (Bowes and Wright, 1961, fig. 2). Ordinary light. ×50.

bands, particularly on the terminal faces. Up to seven overgrowth rims have been observed on the prism faces (figs. 1*a*, right; 1*c*; 3) but only one tremolitic overgrowth is usual (figs. 1*e*; 2). In exceptionally well-developed overgrowths it is possible to observe that, in addition to the seven major overgrowth bands, there are rhythmic alternations of slightly lighter and slightly darker coloured amphibole within both the tremolite and the actinolite bands (fig. 2); at least eleven minor bands are present in the middle actinolite band on a few crystals (fig. 2).

The width of the individual overgrowth bands varies from crystal to crystal but there are certain characters that are common to the crystals showing well developed overgrowths. The outer tremolite band is commonly strongly developed (fig. 1*a*, centre; 1*d*) while the middle actinolite band is generally the palest green, the thinnest, and the least persistent of the three actinolite bands (figs. 1*a*, *b*, and *d*). There is generally a gradation from the tremolitic to the actinolitic varieties, but the junction between the inner tremolite and actinolite bands is usually sharp (figs. 1*d*; 2). In some instances there is also a sharp boundary between the outer actinolite and tremolite bands (fig. 2), but elsewhere this junction is gradational (fig. 1*d*).

Back Settlement—small pipe. The overgrowths in the appinite (9085; cf. 9086—table I) of the small pipe at Back Settlement (Bowes and Wright, 1961, fig. 3) are generally similar in character to those in the appinite intruding the main pipe, but not as abundant or as prominent.

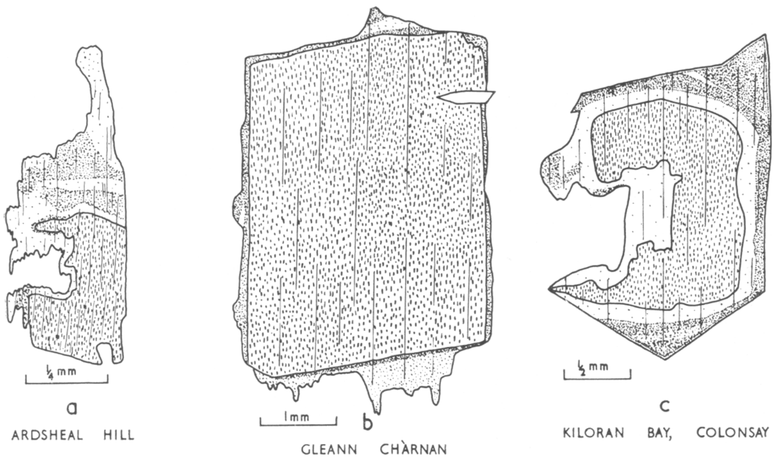

FIG. 4. Rhythmic amphibole overgrowths over amphibole in appinites from Ardsheal Hill (9087), Gleann Chàrnan (9089), and Kiloran Bay, Colonsay. (Ornament as in fig. 1.)

Seven overgrowth bands, four of tremolite and three of actinolite, are shown (fig. 1*f*), of which the inner two show the clearest separation because of the sharp junction and the marked colour difference. In a few cases there is an inner zone consisting of seven bands, three of tremolite, three of actinolite, and an outer band of variable tremolite–actinolite with an irregular sawtooth outline similar to that shown by other overgrowths. This is succeeded by a further, and much larger, outer rim of actinolite of a variable green colour (fig. 1*g*).

Other masses. Five overgrowth bands, three of tremolite and two of actinolite, are present around some of the hornblende crystals in the appinite mass (9087; cf. 9088—table I) of Ardsheal Hill, near Kentallen (fig. 4*a*). The overgrowths are not as common as in the main pipe at Back Settlement but the characters are similar; the central crystals often show effects of reaction and the overgrowths are in crystallographic continuity with the hornblende core.

Amphibole overgrowths also surround hornblende crystals in the appinite mass (9089) of Gleann Chàrnan (Bowes and others, 1963). The hornblende crystals show little evidence of reaction but the overgrowths are unusual in that the inner band is actinolitic, as is the outer band in part. The general form and nature of the overgrowths is, however, similar to that seen in the other masses described, with thin rims in the prismatic zone and sawtooth overgrowths in the terminal faces (fig. 4*b*).

The presence of 'outgrowths of tremolite, or pale actinolite followed outwards by tremolite' has been recorded for the hornblendite of Kiloran Bay, Colonsay (Reynolds, 1936, p. 377) and five overgrowth bands are present around hornblende crystals in the associated appinite (fig. 4*c*). The inner tremolite band is strong and persistent as are the two actinolite bands, but the middle tremolite band is poorly developed and discontinuous. The outer tremolite band is distinct but very thin.

Discussion

The appinites from both the main and small pipes at Back Settlement and from Ardsheal Hill are essentially basaltic in composition (table I), only varying markedly from the composition of normal alkali basalts and dolerites in their greater proportion of potassium and volatile constituents. The affinity of these appinites to basalts is also shown by the abundance of modal augite and plagioclase. However, both the growth of the large hornblende phenocrysts, which typify appinites (cf. Bailey and Maufe, 1960, p. 214), and the development of rhythmic amphibole overgrowths indicate the unusual conditions under which the appinites crystallized.

The high volatile content of the appinitic magma is indicated by the very coarse grain of much of the amphibole in intrusions of relatively small size, the abundance of hydrous minerals, the relative abundance of apatite and pyrite (Bowes and others, 1963), and the highly carbonated nature of some of the appinites due to post-crystallization gas streaming (Bowes and Wright, 1961, pp. 303, 306). Calcite is also present as a significant accessory, of apparently primary origin, in many of the appinites (cf. fig. 2).

The conditions under which the amphibole of the appinites crystallized can be deduced from the results of the experimental studies of Yoder and Tilley (1962, pp. 430–470) concerning the crystallization of basic magma under conditions of high water-vapour pressure. In this environment, amphibole crystallizes in place of pyroxene, the basaltic composition being represented at relatively low temperatures, in the presence of excess water, by hornblende and plagioclase. Where the water-vapour pressure is greater than 5300 bars, amphibole appears earlier than

TABLE I. Chemical analyses of appinites

(D. R. Bowes and A. E. Wright, anal.)

	9084	9086 Coarse	9086 Fine	9088	A
SiO_2	47·0	47·3	45·3	44·8	45·78
TiO_2	0·99	1·0	1·1	1·4	2·63
Al_2O_3	12·7	14·9	13·3	14·6	14·64
Fe_2O_3	2·6	3·1	2·4	5·0	3·16
FeO	5·8	7·3	8·7	7·2	8·73
MnO	0·12	0·13	0·15	0·14	0·20
MgO	10·8	9·6	11·4	9·8	9·39
CaO	11·0	7·7	8·3	8·1	10·74
Na_2O	2·6	2·7	2·3	3·0	2·63
K_2O	3·0	2·2	1·4	1·9	0·95
P_2O_5	0·20	0·63	0·55	0·43	0·39
H_2O^+	1·0	2·2	2·9	1·9	0·76
CO_2, etc.*	2·7	1·4	2·7	1·2	—
	100·5	100·2	100·5	99·5	

* From loss on ignition.

9084. Appinite; from mass in centre of main pipe, Back Settlement (Bowes and Wright, 1961, fig. 2).

9086. Appinite; coarse and fine grained varieties, small pipe, Back Settlement (Bowes and Wright, 1961, fig. 3).

9088. Appinite; summit of Ardsheal Hill (cf. Walker, 1927, analysis II, p. 154).

A. Average of 96 normal alkali basalts and dolerites (Nockolds, 1954, p. 1021).

pyroxene in alkali basalt and may be the first crystallizing mineral above about 11 100 bars. In addition, the silicate liquidus in natural olivine–tholeiite–water system is lowered significantly with increasing water-vapour pressure and the upper stability temperature of amphibole is increased. Thus the presence of abundant amphibole in the appinites is explained by crystallization of a volatile-rich basic magma, at high water-vapour pressure, with amphibole replacing pyroxene as the crystallizing phase. Increase in vapour pressure will cause both a lowering of the liquidus temperature and an increase in the temperature of the magma. These effects will result in the growth of amphibole over a much extended range with the development of large phenocrysts, and, in favourable circumstances, will result in the resorption of the existing crystal phases prior to crystallization under the new conditions.

Subsequent rhythmic variations in vapour pressure in the magma, causing corresponding variations in both magma temperature and the silicate liquidus temperature, resulted in the rhythmic crystallization of amphibole overgrowths as seen, with minor rhythmic alternations occurring within the major rhythms. An appropriate and adequate controlling mechanism is the build-up and release of gas pressure associated with the explosive uprise of gases in a magma chamber similar to that observed in volcanic activity. The nature of the crystallizing phase is dependent upon the decrease in temperature of the magma due to the gradual cooling of the intrusion and the increase or decrease of vapour pressure resultant upon explosive activity with the associated increase or decrease of magma temperature and the lowering or raising of the liquidus temperature. The interplay of conditions dependent upon variations in vapour pressure and conditions dependent upon the cooling of the intrusion, which varies from centre to margin of the intrusion, accounts for the variations in sharpness of both specific and different tremolite–actinolite band boundaries.

The appinite masses at Back Settlement, Ardsheal Hill, Gleann Chàrnan, and Kiloran Bay, in which the rhythmic amphibole overgrowths occur, are associated with breccia pipes, the formation of which has been explained by Bowes and Wright (1961, pp. 307–310) as the result of explosions (gas rushes) of volatile constituents rising ahead of a volatile-rich magma. On the basis of field evidence it was suggested that the volatiles were trapped below structures in the country rock and that a series of explosions took place, with the rhythmic build up and release of pressure, until the trap was breached. These conditions correspond with those deduced from a study of the rhythmic overgrowths.

In the Back Settlement mass there are seven major overgrowth rims and in both the Ardsheal Hill and Kiloran Bay masses, there are five major overgrowth rims. The number of rims is taken to be related to the number of major explosions, occurring during the period of amphibole growth, required to breach a particular structural trap. The tremolite bands represent crystallization under very high water-vapour pressure, and the actinolite bands represent crystallization under conditions of somewhat lower pressure brought about by an explosion which shattered part of the trap but did not release the gas from the confinement of the remaining part of the trap. The increase of vapour pressure resultant upon the crystallization of the tremolite (cf. Morey, 1922) triggered off the explosions, the outer, and usually larger, tremolite overgrowth (cf. fig. 1) preceding the final breaching of the trap.

Resulting from this final explosion large volumes of gas escaped, probably in association with an upward intrusive surge of magma, and, in most cases, amphibole ceased to be the crystallizing phase. However, the outer actinolitic overgrowths over the inner zone of seven bands in the small pipe at Back Settlement (fig. 1*g*) appear to represent crystallization during the period of gas escape. The occurrence of this phenomenon in the small pipe but not the large pipe at Back Settlement is in accord with the field evidence, which suggests an intrusive nature for the small pipe and an explosive, *in situ*, nature for the main pipe (cf. Bowes and Wright, 1961, p. 305). The overgrowth rims in the Gleann Chàrnan appinite (fig. 4*b*) and the hornblendite at Colonsay (Reynolds, 1936, p. 377) also vary from the otherwise regular pattern in showing either inner or inner and outer rims of actinolite. Both of these masses are similar to the small pipe at Back Settlement, showing evidence of considerable gas-streaming in a breccia pipe with intrusive relations.

The presence, in some of the appinites, of augite crystals, often of considerable size and without evidence of reaction or a rim of hornblende, suggests that the crystallizing phase reverted to pyroxene. Such a reversion from amphibole to pyroxene indicates a great decrease in water content due to the escape of a large proportion of the gases corresponding with the final escape of the gases through the structural trap.

The preferential growth of the overgrowths on one termination of a crystal is very common as is the preferential growth on the terminal rather than the prism faces (fig. 1). This, and the preferential resorption of hornblende on one side of a crystal (fig. 4 *a* and *c*), may be related to the movement of magma or to the flow of gases through the magma, the preferential growth taking place on the 'leeward' side of the crystals. Any directional alignment of crystals during this stage of crystallization would be destroyed during the intrusion of the magma subsequent to the breaking of the structural trap.

Conclusions

The rhythmic amphibole overgrowths represent deep-seated crystallization in a volatile-rich appinitic magma under conditions of high but varying gas pressure. Water was an abundant volatile constituent and the water-vapour pressure in the magma during the crystallization of the overgrowths is considered to have been above 5300 bars and possibly of the order of 11 000 bars. The influence of other volatiles or the effects of other constituents in the magma in lowering the pressure at which hornblende would crystallize may make this an overestimate.

The alternation in physical conditions was the result of build up and explosive release of gas pressure.

The number of overgrowths is related to the number of explosions that took place before the breaching of the structural trap hindering the upward movement of the volatiles, and is characteristic of the particular intrusion.

The tremolite rims grew under conditions of greater gas pressure and temperature than the actinolite rims.

A rim of actinolite, of variable composition, may develop over the rhythmic overgrowths during the gas-streaming phase immediately following the breaching of the structural trap.

The development of rhythmic overgrowths adds support to the mechanism of formation of explosion-breccias suggested by Bowes and Wright (1961, pp. 309–310).

Acknowledgements. Thanks are due to Prof. T. Neville George who kindly read the manuscript and made many helpful suggestions, to Dr. N. Holgate for providing thin sections from Colonsay, to Mr. A. R. Ferguson who took the photographs, and to Mr. C. Armit and Mr. D. L. Skinner who assisted with the chemical analysis.

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Electron-probe analysis by Dr. J. V. P. Long of the Department of Mineralogy and Petrology, University of Cambridge, has shown that the colour changes in the amphibole overgrowths in the appinite exposed near the centre of the Black Settlement complex are directly related to the iron content. The maximum recorded Fe concentration in the darkest zones was $14{\cdot}3 \pm 1\%$ Fe and in the lightest zones the minimum was $7{\cdot}7 \pm 1\%$ Fe.