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CORRESPONDENCE

On the beerbachites from Freetown, Sierra Leone

SIR – The origin of a finely equigranular plagioclase–hypersthene–clinopyroxene–magnetite/ilmenite rock suite found within the layered basic (gabbroic) intrusion of Freetown, Sierra Leone (Fig. 1) has long been discussed. This peculiar rock type with mosaic or saccharoidal texture has been given various names which depend on views of the origin of beerbachite (Chelius, 1892) from the gabbro massif in Odenwald, Germany. The early view was that the Odenwald beerbachite is igneous (Chelius, 1892; Rosenbusch, 1901). More recently, however, it has been shown that the beerbachite is a highly metamorphosed xenolithic country rock enclosed within the Odenwald gabbroic intrusion (Klemm, 1927; Trochim, unpub. thesis, Univ, Freiburg, 1960; Matthes & Schubert, 1971). By this a recognition is made of the much wider significance of distinguishing igneous from metamorphic textures in high grade basic rocks.

Shand (1918) identified 'a fine-grained melanocratic suite with equigranular crystals' in the Freetown intrusion, which he named ('micro norite or trap granulite'. This rock suite was later named beerbachite by Dixey (1922) who considered that it was of intrusive igneous origin, emplaced into the layered gabbro. Both Junner (1929) and Pollett (1951) held the same view.

Wells (1962) first recognized that the granular suite is xenolithic and that its texture is granoblastic. He identified it as a hornfels, and named it a granulite, restricting the term beerbachite to pseudo-dyke forms. He thought that earlier layered gabbro became recrystallized during subsequent magma pulses of the multiple intrusion and that the 'granulite' was concentrated near the contact horizons of the main zones (Wells, 1962, p. 83).

In this report the gross features that bear on the origin of this peculiar granular suite of rocks are shown and its name is given.

1. Association and description of the participating rocks

1.a. The basement complex

The country rocks are metasediments and metavolcanics with a late Precambrian Pan-African (600 ± 150 Ma) history (Kennedy, 1964; Hurley *et al.* 1971). Amphibolites and hornblende gneisses predominate, and attained amphibolite

KEY
- Beerbachite
- Layered gabbro
- Boundary of Mega-Units
- Magnetite & ilmenite
- Dip of layering
- Fault
- Wells(1962) line of section
- Peak of hills (m)
- Sediment
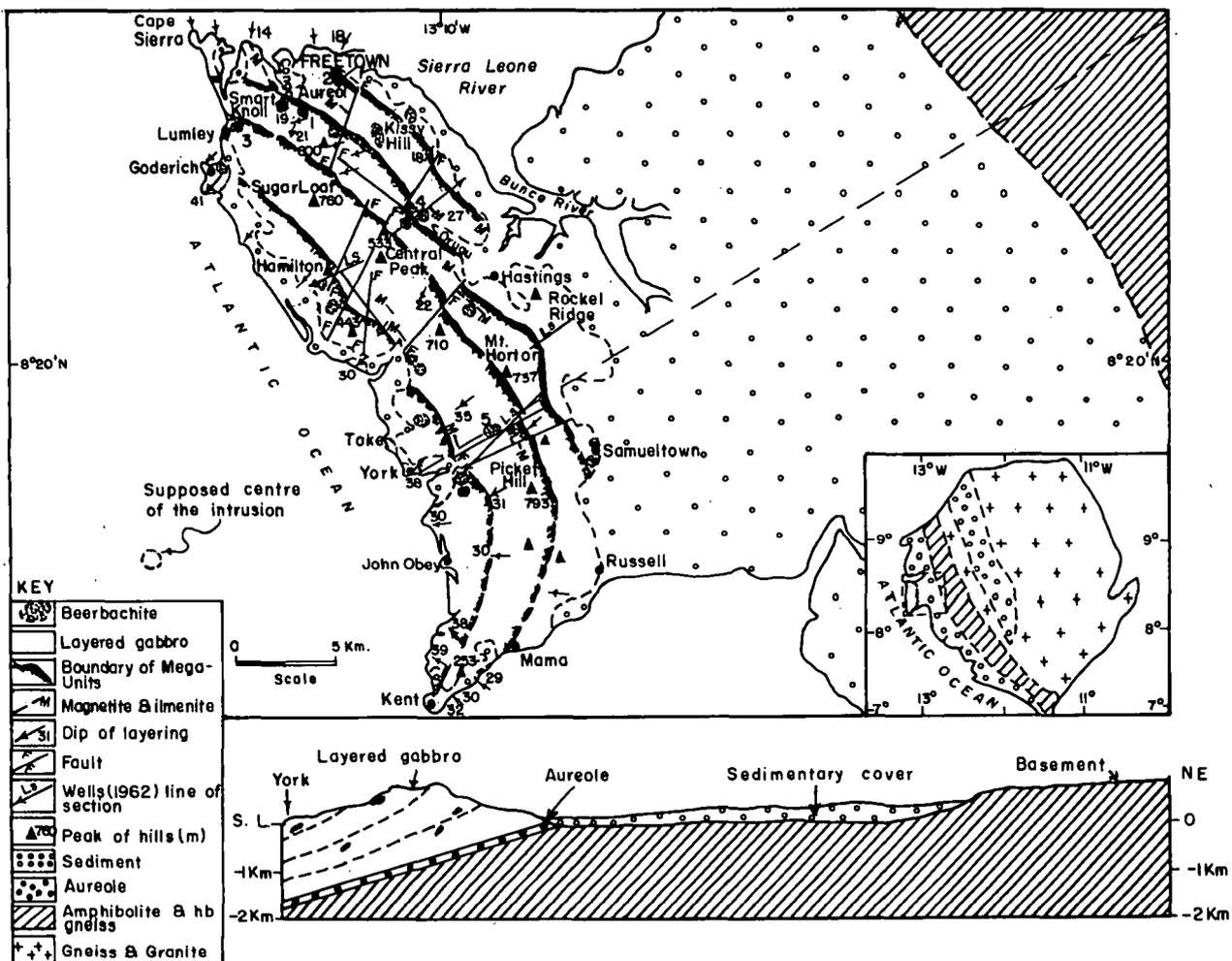- Aureole
- Amphibolite & hb gneiss
- Gneiss & Granite

Figure 1. Geological map of and section across the peninsula area of Freetown.

Table 1. Modal analysis of some of the beerbachites

Serial No....	1	2	3	4	5	6	7	8	9
Sample No....	166	309	393	903	523	635	670	269	962
Plagioclase	51.4	58.0	55.8	62.5	58.2	48.0	45.6	57.0	54.0
Hypersthene	28.6	18.2	26.3	14.9	19.2	10.0	15.4	22.0	23.0
Clinopyroxene	17.3	21.5	15.0	16.5	17.5	30.0	24.5	18.5	19.5
Ilmenomagnetite	2.4	2.3	2.8	6.0	4.8	12.0	14.0	2.5	3.5
Others	0.3	—	0.1	0.1	0.3	—	0.5	—	—
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1. Smart Knoll; 2. Mount Aureol; 3. Lumley Road Station; 4. W of Orugu River; 5. Big Water; 6. Big Water; 7. Banana Island; 8. Kissy Spur; 9. Spike Hill.

facies metamorphism. They are composed of plagioclase (An_{27-30}), green hornblende, biotite, quartz and, occasionally, garnet with zircon, sphene and epidote as accessory minerals.

1.b. Layered gabbro

The Freetown basic magma was emplaced in the basement complex of Sierra Leone (Fig. 1) during the Triassic (Briden, Henthorn & Rex, 1971) as repetitive magma pulses (Wells, 1962). Olivine and ilmenomagnetite-rich layers (dunite, troctolite and olivine gabbro) occur in the lower part, and plagioclase-rich layers (leuco-gabbro and anorthosite) in the upper part (Umeji, 1975, 1983). Five fully developed layered successions have been recognized as mega-units (Fig. 1) but several miniature units have been mapped within each of them (Wells, 1962; Umeji, 1983). The intrusion is circular or elliptical in outline and the dips are towards the centre which is located to the west of York (Junner, 1929; Baker & Bott, 1961; Wells, 1962; Krause, 1963). The dips of the layered rocks vary from 14°–22° near the outer margin to 30°–45° near the centre (Fig. 1), and the thickness of the sequence is about 6 km.

1.c. Contact aureole: hornblende hornfelses

The boundary between the intrusion and the host basement complex is concealed beneath a thick cover of younger sediments (Fig. 1). Samples of the aureole have, however, been obtained from borings through the sediments and the supposed contact (Geological Survey of Sierra Leone Annual Reports, 1956, 1957). The borehole near Rokel passed through about 500 m of hornblende hornfels into unrecrystallized country rock.

In the outer part of the aureole, the hornfels consists of plagioclase An_{35-42}, green hornblende, clinopyroxene, biotite and poikiloblastic hypersthene whilst magnetite, apatite and sphene occur as accessory minerals. Adjacent to the layered gabbro, the hornfels becomes more granoblastic and is composed of plagioclase An_{48-50}, clinopyroxene, hypersthene and greenish-brown hornblende with magnetite/ilmenite, apatite and sometimes biotite in accessory amounts. In this inner aureole, plagioclase is finely mosaic and hypersthene is granoblastic and poikiloblastic, enclosing flakes of green biotite, and grains of hornblende.

1.d. Beerbachites: hypersthene hornfels xenoliths

Nowhere is the roof of the Freetown intrusion preserved but xenoliths occur sporadically throughout. The locations of xenoliths shown in Figure 1 are concentrated in parts of the
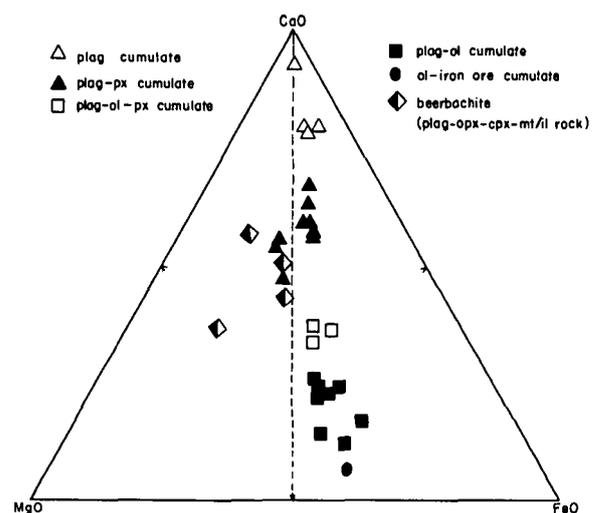

Figure 2. CaO-MgO-FeO diagram for Freetown layered gabbro and enclosed beerbachites. Broken line separates beerbachites and contaminated gabbro from the trend of the layered igneous rocks. (Data from Umeji, 1983).

central and the northern portions of the intrusions but this may reflect the fact that only these areas were well mapped. The xenoliths range from lenses a few centimetres long and about a centimetre thick to large masses up to 300 m long, 150 m wide and 5 m thick. Of over sixty outcrops visited, there are only two areas in which the outcrops are steeply inclined and apparently wedge across the layered gabbro. The rest are flat-lying, more or less paralleling the layering of the host gabbro. In all cases, the xenoliths have sharp and irregular contacts with the gabbros and no chilled margin has been observed. Occasionally a porphyroblastic or pegmatitic texture is developed at the margin of the xenoliths.

The xenoliths are distinctively dark with a fine-grained granoblastic texture, usually equigranular. They are composed of plagioclase An_{55-64}, hypersthene, clinopyroxene and some magnetite and/or ilmenite. The modes of xenoliths are given in Table 1. Magnetite and ilmenite are often more abundant in these rocks than in the host layered rocks. Olivine and hornblende are invariably absent, but retrogressive biotite may occur. A case in which biotite originating from layered gabbro grew across the contact into beerbachite was reported by Wells (1962, p. 94 and fig. 34a). Normally the size of mineral grains depends on the size of the xenolithic body. For very small bodies the mineral grain size can be as little as 0.05 mm across, but the larger masses are composed of minerals whose average diameter is about
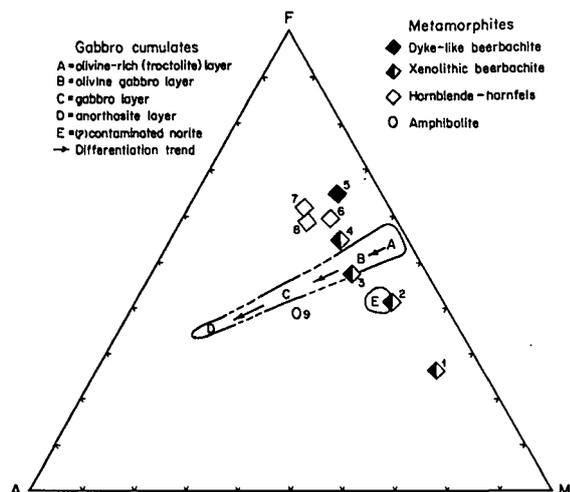
Figure 3. Plot of the Freetown beerbachites and hornblende hornfels in the AFM diagram of the Freetown layered gabbro (cf. Umeji, 1983, fig. 6). Locations for 1–5 are shown in Figure 1; 6–9 are borehole samples of the aureole. Data for 1 and 2 are from Umeji (1983) and for 3–9 from Wells (1962).
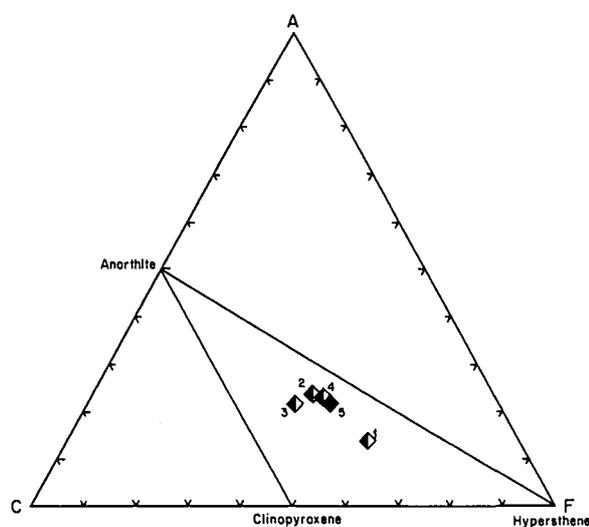

Figure 4. Plot of the Freetown beerbachites on an ACF diagram (after Winkler, 1979). Symbols and numbers are as in Figure 3.

0.5 mm. The marginal pegmatites around equigranular xenoliths are rich in porphyroblastic pyroxenes, and magnetite and/or ilmenite which approach the size of the minerals in the layered gabbro (1–2.5 mm). In the gabbro, fine-grained layers have plagioclase 1.5 mm long and 0.5 mm across and in the coarse-grained layers it reaches 4.5 mm by 1.5 mm. The opaque phases, and to a lesser extent the pyroxenes, in the marginal pegmatites of the xenoliths are characterized by sieve or skeletal texture. All the xenolithic rocks found may be assigned to the pyroxene hornfels facies.

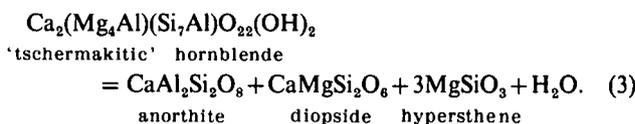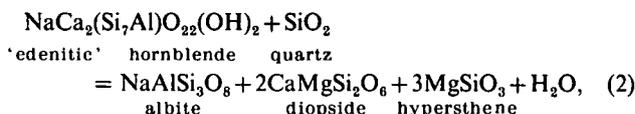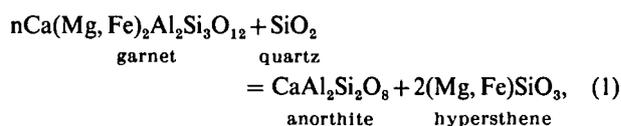## 2. Chemical, genetic and phase relations

2.a. Chemical characteristics and genetic relations

Published analytical data (Junner, 1929, p. 426; Wells, 1962, tables 7, 8 and 9; Umeji, 1983 table 1) are used in the present paper. It will be seen from the CaO–MgO–Feo diagram (Fig. 2) that beerbachites and a few hybrid gabbroic rocks

plot away from the trend of differentiation shown by normal gabbro cumulates. Similarly the beerbachites and hornblende hornfelses of the contact zone do not plot within the area of the cumulate rocks in the AFM triangular diagram (Fig. 3). Some of the coarse-grained noritic rocks within the layered rocks seem to be contaminated by the country rock. Sr is lower in the beerbachites (169.8–192.6 ppm) than in norites and gabbros of the layered sequence (381.6–605.7 ppm). It had been shown that in the layered gabbro intrusion the abundances of Sr and Ni are related to the amounts of Al-silicate (plagioclase) and Mg-silicates (olivine/pyroxenes) respectively, and the positive correlation of Ni vs. MgO and Sr vs. Al_2O_3 shows that the layered rocks are cumulates from the same parent magma (Umeji, 1983). The indication is that these beerbachites are not genetically related to the layered rocks. The bulk of hornfelsic rocks (beerbachites and hornblende hornfelses) are seen (Figs. 2 and 3) to be derived from the country rocks rather than from the gabbros. It is also observed that the hornblende hornfelses plot with beerbachite on Figure 3.

2.b. Mineral reactions

In the aureole surrounding the intrusion garnet is no longer stable and according to Krogh (1982, p. 313) garnet breaks down to green hornblende + magnetite or to plagioclase + biotite + magnetite while rutile breaks down to ilmenite at temperatures in excess of about 700 °C. With increasing dehydration and metamorphic grade, quartz and hornblende disappeared and hypersthene and the anorthite content of plagioclase increased in the beerbachites. The latter (see Fig. 4) attained the pyroxene-hornfels facies (Eskola, in Barth, Correns & Eskola, 1939, p. 344; Turner, 1981). The mineral reactions may also be explained by some of the following:

$$nCa(Mg, Fe)_2Al_2Si_3O_{12} + SiO_2$$
$$\text{garnet} \qquad \text{quartz}$$
$$= CaAl_2Si_2O_8 + 2(Mg, Fe)SiO_3, \quad (1)$$
$$\text{anorthite} \qquad \text{hypersthene}$$

$$NaCa_2(Si_7Al)O_{22}(OH)_2 + SiO_2$$
$$\text{'edenitic' hornblende} \quad \text{quartz}$$
$$= NaAlSi_3O_8 + 2CaMgSi_2O_6 + 3MgSiO_3 + H_2O, \quad (2)$$
$$\text{albite} \qquad \text{diopside} \qquad \text{hypersthene}$$

$$Ca_2(Mg_4Al)(Si_7Al)O_{22}(OH)_2$$
$$\text{'tschermakitic' hornblende}$$
$$= CaAl_2Si_2O_8 + CaMgSi_2O_6 + 3MgSiO_3 + H_2O. \quad (3)$$
$$\text{anorthite} \qquad \text{diopside} \qquad \text{hypersthene}$$

The amphibole substitutions involved here are the 'edenite' substitution $\Box Si = NaAl$; and the 'tschermakite' substitution $MgSi = AlAl$.

3. Causes of metamorphism and temperature–pressure distribution

The regionally metamorphosed country rocks of western Sierra Leone (Rollinson, 1982) were essentially cool before they were intruded by gabbro about 350 Ma after the climax of the Pan-African thermotectonism; hence the presence of a distinct hornfelsic aureole around the intrusion. The intrusion is believed to be associated with the opening of the North Atlantic which began its latest cycle about 200 Ma (Klein, 1969; Kaye, 1983). Transform fault/fracture zones intersecting with the Sierra Leone coastline (Williams & Williams, 1977) must have been developed during the Trassic

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rifting apart of North America from Africa/South America whose onset created fault-bounded late Triassic volcano-sedimentary basins of the eastern coast of the U.S.A. (Klein, 1969). Similar fault-controlled magmatism of late Triassic age has been identified in this part of West Africa. One example is the coast-parallel dykes of Liberia (Dalrymple, Gromme & White, 1975), and the Freetown layered gabbro on the coast of Sierra Leone is regarded as another (cf. Williams & Williams, 1977). The Freetown gabbro was therefore emplaced anorogenically. The original depth of burial is thought to be shallower than 9 km corresponding to a pressure of around 2.5 kbar.

A gabbroic magma intruding at a temperature of 1200 °C (liquidus) would possess a maximum possible contact temperature of 1000 °C (solidus), above which remelting could begin. The estimated contact metamorphic conditions for the country rock hornfelses of Freetown are comparable with those of the contact aureoles around the Newer intrusions of the southern Scottish Highlands (Ashworth & Chinner, 1978) and of the Nain anorthosite body, Labrador (Bohlen & Boettcher, 1981) whose respective estimates are temperatures of 690 °C and 750–800 °C and pressures of 3.8 kbar and 3.2 kbar. Greater depths of equilibruim with pressures of 4–15 kbar estimated from granulite facies metamorphism (e.g. Miyashiro 1961; Grew, 1980; Perkins & Newton, 1981) may not be applicable; this is because contact metamorphic rocks, as considered here, are products of low pressures.

The thickness of the aureole (500 m) is in reasonable agreement with that of an intrusion about 1500 m thick judging from Jaeger's (1957) estimate. A much thicker aureole could have emerged were the 6000 m thick gabbro a product of a single batch of magma. The size of the hornfelsic aureole will serve as further evidence for emplacement of discrete batches of magma into Freetown crust. Using equations 9 and 10 of Jaeger (1968) and numerical values given in his tables I and II it can be shown that the cooling or solidification time for the initial intrusion, assumed to be 1500 m thick, would be about 3600 years. This assumes a sheetlike body, without convection, cooling against the country rock whose initial temperature is taken as zero. Jaeger (1968) also made calculations to simulate convection (formulae 58–62) and showed that convection in a sheetlike body 1000 m thick intruded at a temperature of 1225 °C would have the value of 1000 °C after a time of 4000 years. At the contacts of the Freetown magma, in which evidence for convection abounds (Wells, 1962; Umeji, 1975), a temperature of 1000 °C would be retained for a period of well over 4000 years for, at least, the first magma pulse. The large quantity of heat conducted into the country rock for this long period of time would be adequate for contact metamorphic recrystallization.

In the hornfelsed country rocks, the temperature did not exceed the stability limit for hornblende. This confirms the low temperature of the country rocks prior to intrusion. However, small bodies of country rock that stoped off, and became entirely immersed in Freetown magma, became raised to magmatic temperatures and hence produced a higher temperature assemblage than the surrounding hornfelses. In xenoliths, therefore, the temperature exceeded the stability limit for hornblende. Convection in the magma and an intermittent or pulsating intrusive mechanism would help in the production and redistribution of xenoliths. It is significant that no sign of contact metamorphic overprinting has been observed within the layered sequence due to fresh magma intruding.

4. Conclusions

The following conclusions are drawn:

(1) A prograde thermal metamorphism is recognized at the contact of the Freetown basic intrusion with the basement, and hornblende hornfelses occur at the inner aureole.

(2) The fine-grained plagioclase–hypersthene–clinopyroxene–magnetite/ilmenite rocks characterized by mosaic texture are rafts or blocks torn off the surrounding country rocks. They are xenoliths which were thermally recrystalized to pyroxene hornfels facies by the hot gabbroic magma. No transition from the gabbros to the xenoliths has been observed and the xenoliths are not restricted to the boundary between two layered units; therefore the xenoliths are not cognate masses derived from the gabbroic host as suspected by Wells (1962, p. 81). This conclusion is supported by geochemical considerations.

(3) It is now known that the beerbachites of Odenwald, Germany are highly metamorphosed rock older than the gabbro in that area (Klemm, 1927; Trochim, 1960), that they are xenoliths from surrounding amphibolite series and that they are high grade hornfelses (Matthes & Schubert, 1971). The observed conditions under which the Freetown granular rocks were formed are similar to those of Odenwald. The plot of the Freetown beerbachite suite on an ACF diagram (Fig. 4) compares well with the high grade of Odenwald (Matthes & Schubert, 1971, fig. 13), which reached the pyroxene hornfels facies. The name beerbachite given to this suite of rock from Freetown (Dixey, 1922) should therefore be retained because it is similar in texture, mineralogy, facies grade and origin to the Odenwald beerbachite suite.

(4) Metamorphosed basic rocks recrystallized at magmatic temperatures can be distinguished from primary gabbros by granoblastic texture in the former. The beerbachite consists of a mosaic of xenoblastic mineral grains, commonly equigranular. The interpretation of such relations thus differs fundamentally from that of grabbros in which euhedral character is determined by order of crystallization.

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