Porphyroblast textural sector-zoning and matrix displacement

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Abstract

There is an association between the development of cleavage domes, a texture reflecting the displacement of insoluble matrix grains by porphyroblasts growing under a bulk hydrostatic stress, and textural sector-zoning. This has been found in garnet, staurolite, chiastolite, pyrite and possibly emerald porphyroblasts. Sector-zoned porphyroblasts form by lineage growth normal to the crystal faces. This causes several distinctive textures (type 1 inclusions and type 2 intergrowths, inclusion bands, growth prongs), all of which are directly or indirectly related to displacement growth. Graphite or other carbonaceous material is ubiquitous in samples showing textural sector-zoning.

KEYWORDS: graphite, cleavage dome, matrix displacement, porphyroblasts, sector-zoning, textures, garnet, staurolite, chiastolite, pyrite, emerald.

Introduction

THIS article outlines an association between the development of textural sector-zoning in porphyroblasts and the displacement of matrix grains by porphyroblasts as they grow. Since these two textures have not been frequently discussed in the literature, the first part of the paper reviews the published material and describes several unpublished examples, whilst the second part links the two textures into a single growth model.

Matrix displacement

Previous literature. The notion that a growing porphyroblast may displace matrix grains was commonly held (cf. Harker, 1950, Ch. XIV). This notion was rejected by Zwart (1962) in a classic paper on the interpretation of porphyroblast–matrix textural relationships, although Schuiling and Wensink (1962) showed that copper sulphate crystals grown within sand and glass-pearls displaced the matrix during growth, to produce an 'augen' texture. Despite the work of Zwart (1962), Misch (1971) argued that some textures can be *unequivocally* interpreted to reflect matrix displacement. Specifically Misch (1971) asserted that where a fabric is both wrapped around and overgrown by a porphyroblast, often such that the degree of curvature of S_i increases outwards (i.e. with growth and time), then displacement of the matrix occurred.

Although subsequent discussions rejected this criterion (Ferguson and Harvey, 1972; Shelley, 1972; Spry, 1972; and replies by Misch, 1972*a*, *b*) in favour of the syn- or post-tectonic non-rotational flattening strain model of Zwart (1962), the topic received a considerable stimulus. Harvey and Ferguson (1973) suggested that 'spherically arranged' inclusion patterns, representing relic idioblastic porphyroblast shapes, reflected displaced matrix grains subsequently overgrown as the metamorphic conditions changed, although Spry (1974) disputed this interpretation. Saggerson (1974), using the criteria proposed by Misch (1971), attempted to show that porphyroblasts in the thermal aureole of the Bushveld Complex had displaced matrix grains. Crucial to Saggerson's (1974) argument was the supposition that no deformation had occurred during the metamorphism; Vernon and Powell (1976) rejected this idea, citing several possible sources of small-scale localised strain that might occur in a thermal aureole as a consequence of the metamorphism. Some of these proposed strains resulted indirectly from the presence of the porphyroblasts.

From an entirely theoretical viewpoint, Yardley (1974) suggested that insoluble grains were most likely to be displaced and that displacement was more likely to occur with high fluid pressures and slow growth. These features were combined into a model in which insoluble grains were carried in an intercrystalline pore fluid. Stresses induced by the growing phase were transmitted through insoluble grains to more soluble grains further from the porphyroblast. A stated corollary of this model was that a porphyroblast would not displace insoluble grains whilst overgrowing soluble grains.

Yardley (1974) also stated that displacement should occur in all growth directions of the porphyroblast, echoing the 'spherically arranged' inclusion patterns described by Harvey and Ferguson (1973), and not in a single direction normal to a pre-existing foliation, as implied in the model of Misch (1971). Deviations from equal displacement might occur if growth was inhibited in a particular direction, either by large insoluble grains or by large volumes of insoluble material accumulating at a face of a porphyroblast, due to displacement growth.

Harvey *et al.* (1977) and Ferguson *et al.* (1980) described a localised small-scale arcuate cleavage developed at the faces of idioblastic garnets in an isotropic pelitic hornfels from the Black Hills of Dakota, U.S.A. In three dimensions this cleavage, which consists of muscovite and graphite with a low quartz mode compared to the undisturbed matrix, has a dome shape. Finite element analysis showed that these '*cleavage domes*' (Fig. 1A, B) developed by the displacement of matrix graphite and muscovite during garnet growth, as a result of the stresses caused by the growing porphyroblast. A requirement for the development of cleavage domes is a bulk hydrostatic stress field; any deviatoric stress would both overwhelm the small stresses related to mineral growth and destroy existing textures by flattening and extending previously accumulated material. At present the cleavage dome texture is the only reliable evidence of displacement growth.

Ferguson (1980) developed a '*volume balance*' constraint, whereby the volume of material displaced is compared to the volume it was displaced from. The resulting modal composition should be the same as that in the undisturbed matrix. Using this criterion, Ferguson (1980) rejected the claim that feldspars in Precambrian granitic gneisses from Colorado, U.S.A., had displaced zircons (Harris, 1977).

More recently, Carstens (1986) presented the constraints on displacement growth from a chemical viewpoint. Crystal growth will only occur in an oversaturated solution; the crystallisation pressure, ΔP, created by a growing crystal is dependant on the degree of oversaturation (Correns and Steinborn, 1939):

$$\Delta P = (RT/V_s).\ln(C/C_s)$$

where R is the gas constant, T the temperature in K, V_s the molar volume of the solid phase and C/C_s the saturation ratio, with C being the actual solute concentration and C_s the saturation concentration. The crystallisation pressure is, therefore, directly proportional to the natural log of the degree of oversaturation.

Carstens (1986) also expressed the ease with which displacement can occur in terms of the effective pressure, p_e:

$$p_e = p_t - p_w$$

where p_t is the lithostatic pressure (overburden) and p_w is the pore fluid pressure (hydrostatic pressure). Note that deviatoric stresses are not considered. Increasing the pore fluid pressure reduces p_e, enhancing displacement growth (cf. Yardley, 1974, and Ferguson *et al.*, 1980), although it may also facilitate diffusion, tending to reduce the degree of oversaturation. An example of displacement growth at very low p_t and high saturation conditions is given by Saigal and Walton (1988).

Published examples of displacement growth. Cleavage domes, taken as the only reliable indicator of displacement growth, have been reported from only five areas. The textural features seen at four of these localities are listed in Table 1.

As stated, Harvey *et al.* (1977) and Ferguson *et al.* (1980) described the 'type material' from Dakota, U.S.A. In this instance the cleavage domes were formed by muscovite and graphite at the faces of idioblastic garnets which contain few inclusions. Ferguson *et al.* (1980) also reported the presence of cleavage domes on chiastolite porphyroblasts in slates from the metamorphic aureole of the Skiddaw Granite, N.E. England, although no details were given. In both instances the cleavage domes formed in a non-deviatoric stress environment during medium- to high-grade contact metamorphism.

Rubenach and Bell (1988) described graphite accumulations at the margins of sector-zoned andalusite from the Tinaroo Batholith aureole, Queensland, Australia. In most cases the dis-

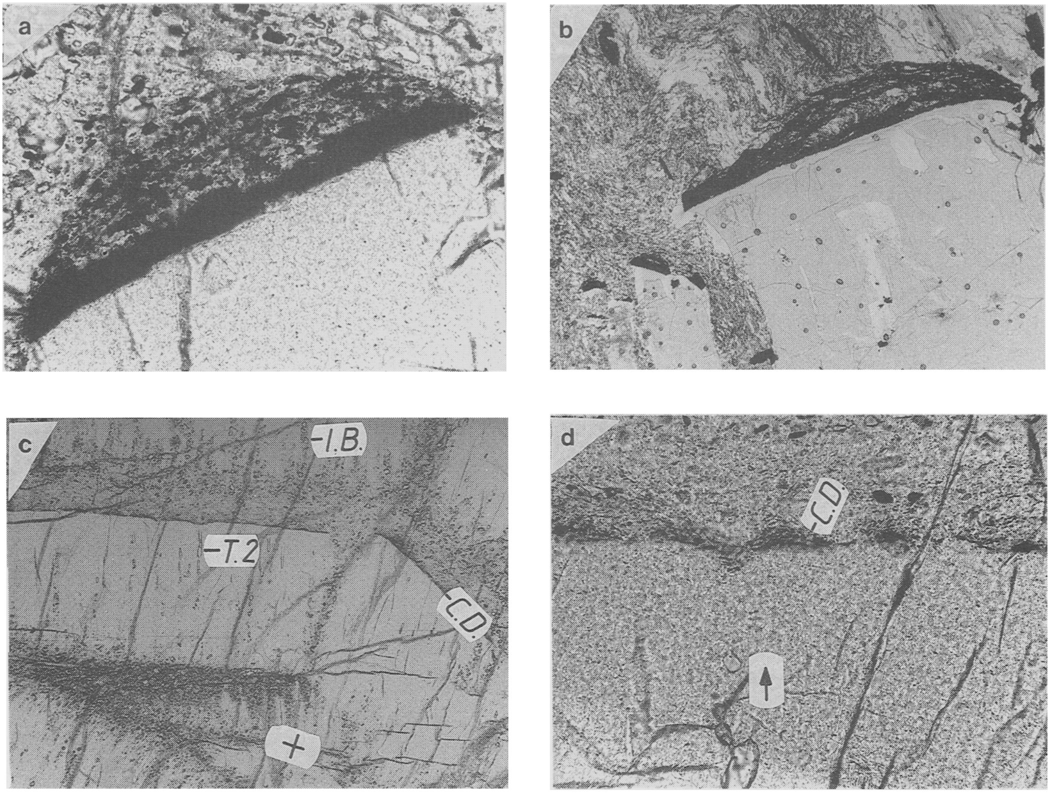

FIG. 1. (A) Well developed cleavage dome preserved *within* staurolite porphyroblast from the Caledonides of Finnmark, N. Norway. Note the narrow zone of solid graphite next to the inclusion-free zone, and the arcuate fabric in the adjacent graphite-rich zone. Field of view 0.67 × 0.43 mm. PPL. Sample 2/84/HR. (B) Graphite accumulations at the ends of several growth prongs of a single chiastolite porphyroblast from the Tinaroo Batholith aureole, Australia. The arcuate graphite-rich zone may be a crenulation fabric tightened by the displacement growth. Note the thin muscovite zone (mz) between the graphite and andalusite. Black circles are air bubbles. Field of view 4.25 × 2.7 mm. PPL. Sample DO3.11N. (C) View of large staurolite porphyroblast, the centre of which is marked by a cross. Growth outwards during variable stress/fluid conditions resulted in varying quartz inclusion densities. The outer rim of the low quartz inclusion zone is marked by a thin graphite rich zone (CD), composed of a series of small-scale cleavage domes. From the N. Norwegian Caledonides. Note inclusion bands (IB) and type 2 intergrowths (T2). Field of view 4.25 × 2.7 mm. PPL. Sample 16/84/HR. (D) Enlargement of Fig. 1C showing small scale cleavage domes (CD). Arrow gives growth direction. Field of view 0.67 × 0.43 mm. PPL.

placed material, graphite, forms one or more solid dome-shaped accumulations at the porphyroblast face (Fig. 1B) although often no arcuate *fabric* can be seen. Since crenulation axial surfaces are weakly deformed around andalusite porphyroblasts, the age of metamorphism is

TABLE 1 TEXTURES ASSOCIATED WITH PUBLISHED EXAMPLES OF DISPLACEMENT GROWTH

LOCALITY	MINERAL	META TYPE	CLEAV. DOME	GRAPH ITE	BANDS/ TYPE 2	SECTOR ZONED	FIG.
Dakota 1*	garnet	C	Y	Y	N/N	N	------
Tinaroo 2	andalusite	C	Y	Y	Y/Y	Y	1B,5C
Finnmark 3	staurolite	R	Y	Y	Y/Y	Y	1A,C,D
Yorkshire 4*	pyrite	D	Y	Y	Y/N	Y	------

C - contact, R - regional, D - diagenetic
* - indicates material seen only in publication.
Y - observed, N - not observed
band/type 2 - inclusion bands seen/type 2 intergrowths seen

1* Ferguson et al. 1980; 2 Rubenach & Bell 1988; 3 Rice 1987; 4* Carstens 1986.

thought to have been during the very last part of D2 crenulation (Rubenach and Bell, 1988). However, it seems possible that this late deformation could be indirectly related to the contact metamorphism, as proposed by Vernon and Powell (1976) for augen textures around porphyroblasts in the aureole of the Bushveld Complex.

Carstens (1986) described cleavage domes developed around sector-zoned authigenic idioblastic pyrite crystals in carbonaceous Liassic shales from Yorkshire, England. Although this seems an unlikely occurrence, the growth conditions were probably relatively ideal, with high fluid pressures trapped by clay minerals, a relatively low lithostatic pressure (and thus a low effective pressure) and, intuitively, probably a slow growth rate.

Graphite cleavage domes associated with idioblastic staurolite porphyroblasts in regionally metamorphosed rocks of the Caledonides of N. Norway have been described by Rice (1987). Displacement growth was ascribed to a period of high fluid pressures developed during prograde dehydration reactions at the same time as the emplacement of overlying thrust sheets.

Although previously described, some further details of the material from N. Norway are given here. In most instances only partial displacement of graphite occurred; where displacement occurred no quartz inclusions are present and the displaced graphite forms a cleavage dome (Fig. 1A). This localised displacement has resulted in alternating inclusion-free and poikiloblastic zones of matrix inclusions (here termed '*inclusion bands*') aligned normal to the staurolite porphyroblast margin, reflecting growth normal to the margin in a series of discrete growth units. Further evidence in support of the hypothesis that a mineral will not displace insoluble grains whilst overgrowing soluble phases is shown in Fig. 1C and D. In this example the metamorphic/fluid conditions gradually changed during staurolite growth and quartz and graphite inclusions gradually become less abundant (Fig. 1C). A sudden change in growth conditions, however, led to the overgrowth of quartz; the boundary of the quartz-free and quartz-rich zones is marked by a thin band of small-scale graphite cleavage domes (Fig. 1D). In many instances, each cleavage dome is separated by a small inclusion band, although this may have died out before the change in growth conditions resulted in the overgrowth of the cleavage domes.

Unpublished examples of displacement growth. With relatively little effort several further examples of displacement growth have been found. Since contact metamorphic processes seemed the most likely to produce suitable stress and metamorphic conditions for displacement growth, chiastolite slates were examined. Textural details are summarised in Table 2.

Although there is some variation in textural style in the chiastolite porphyroblasts studied (compare Figs. 2A–D, 3A–B), there are a considerable number of similarities. Particularly, all examples bar one exhibit evidence of displacement growth in the form of cleavage domes or graphitic accumulations at the porphyroblast margin. The exception, from Urungwe, Zimbabwe, has not been seen in thin section and the figured material only shows the porphyroblast, not the matrix (Workman and Cowperthwaite, 1963).

In the sample from Brittany (Fig. 2B) the evidence for displacement is poor. However, applying the model of Yardley (1974), it may be that the relatively low quartz mode in these rocks made it impossible for the interlocking mica grains to be moved by the crystallisation stresses; effectively the mica formed a rigid mosaic within which the chiastolite grew.

In most cases graphite has been found in the

TABLE 2 TEXTURES ASSOCIATED WITH CHIASTOLITE PORPHYROBLASTS

LOCALITY	CLEAV. DOME	GRAPH ITE	BANDS/ TYPE 2	SECTOR ZONED	FIG.
Riu Molas, Sardinia 1	Y	Y	Y/Y	Y	2D
Dartmoor, England 2	Y	Y	Y/a	Y	2C
Fichtelgebirge, Germany 3,4	Y	Y	N/a	Y	3A
Guerphales, Brittany 4	Y	Y	Y/Y	Y	2B
Skiddaw, England 4,5*,6*	Y	Y	Y/Y	Y	--
Balfour Hill, Nigeria 4	Y	Y	Y/Y	Y	--
California, USA 4	Y	Y	Y/a	Y	2A
Urungwe, Zimbabwe 7*	x	Y	Y/a	Y	--
Evans Lake, Wa, USA 6*,8*	Y	Y	Y/x	Y	3B
Dusky Sound, New Zealand 6*	Y	Y	Y/x	Y	--

* - indicates material seen only in publication.
Y - observed, N - not observed, a - pseudomorphed, x - not reported
band/type 2 - inclusion bands seen/type 2 intergrowths seen

1 Greiling 1977; 2 Reid et al. 1912; 3 Williams et al. 1954; 4 National Museum Wales, samples FJN unregistered, 86.2G.T1, 85.57G.T1, 83.41G.T7, 83.41G.T9; 5* Ferguson et al. 1980; 6* Yardley et al. 1990; 7* Workman & Cowperthwaite 1963; 8* Misch 1971.

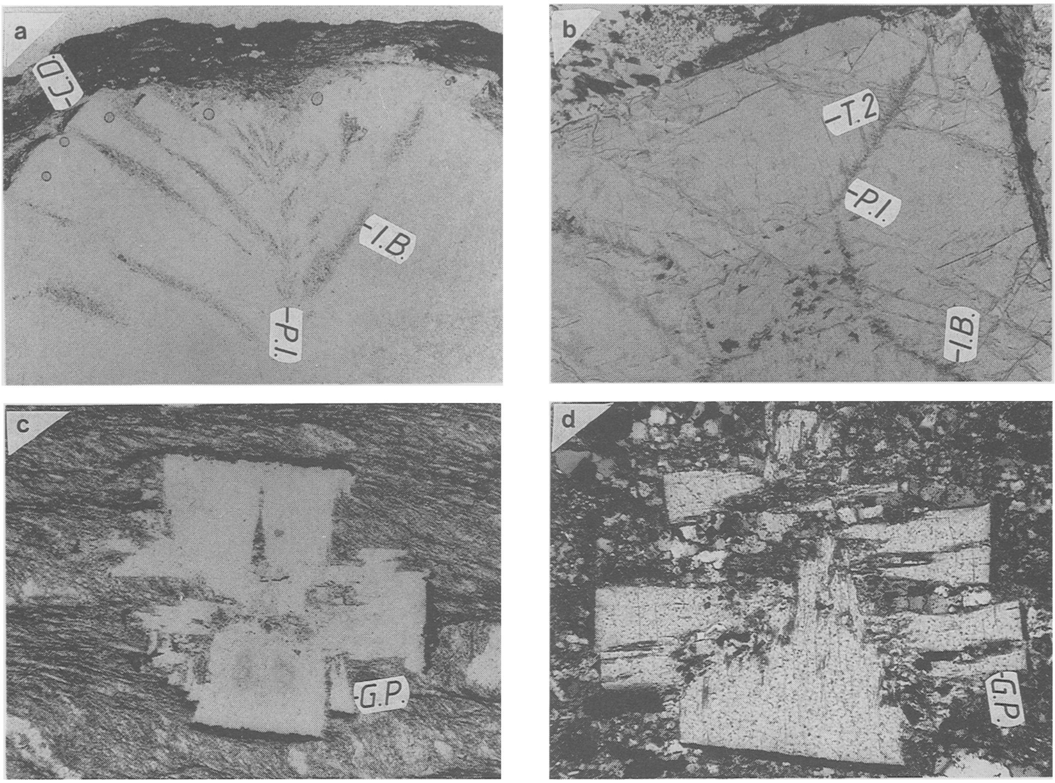

FIG. 2. (A) Corner (re-entrant) of chiastolite porphyroblast altered to muscovite, from California, U.S.A., showing a series of inclusion bands (IB) developing from pyramid interface (PI). Note the small arcuate graphite cleavage domes (CD) towards the outer margin of the left side of the porphyroblast and set between the inclusion bands. Circular 'inclusions' are air bubbles. Field of view 4.25 × 2.7 mm. PPL. Sample 83.41G.T9.NMW. (B) Corner of idioblastic chiastolite from Guerphales, Brittany, France. Note the feathered texture developed along the pyramid interface (PI) with inclusion bands (IB) and type 2 (T2) intergrowths. Some graphite accumulation has occurred at the margin of the porphyroblast. Field of view 4.25 × 2.7 mm. PPL. Sample 86.2G.T1.NMW. (C) Chiastolite porphyroblast altered to muscovite, from Aish Tor, Dartmoor, England. This cuts across two cleavages, in several growth prongs (GP), displacing matrix graphite. Note the complex growth/displacement patterns in the bottom left re-entrant zone. Field of view 1.7 × 1.1 mm. PPL. Sample 3/AT/90/HR. (D) Chiastolite porphyroblast from Riu Molas, Sardinia, showing multiple growth prongs (GP) all of which have displaced matrix graphite. Field of view 0.67 × 0.43 mm. Sample TS-N3/ROG.

rock and displaced by the porphyroblast; in some cases muscovite has been deflected also. Inclusion bands aligned normal to the porphyroblast faces occur in many of the studied porphyroblasts (Table 2; Figs. 1C, 2A–B).

No evidence of displacement has been found associated with the commonly recorded poikiloblastic/skeletal xenoblastic porphyroblasts of andalusite.

Sector-zoning

Previous literature. Harker (1950) identified garnet, chiastolite and staurolite as having chemical or textural sector-zoning and cordierite as having a regular inclusion pattern. Subsequently, analcime, halite, pyrite, ankerite, calcite, corundum, dolomite, quartz, tourmaline, melilite, vesuvianite, apatite, beryl, amphiboles, gypsum, micas, pyroxenes, anorthoclase, microcline and plagioclase have been found with sector-zoning (see references in Kwak, 1981; Kouchi *et al.*, 1983; Petreus, 1978; Reeder and Prosky, 1986; Searl, 1990; Vaniman, 1978; and references below).

In sector-zoned minerals the crystal is divided into a series of pyramids, the bases of which form the crystal faces; in thin-section these give the crystal its sectoral form (Sahama, 1966). Rela-

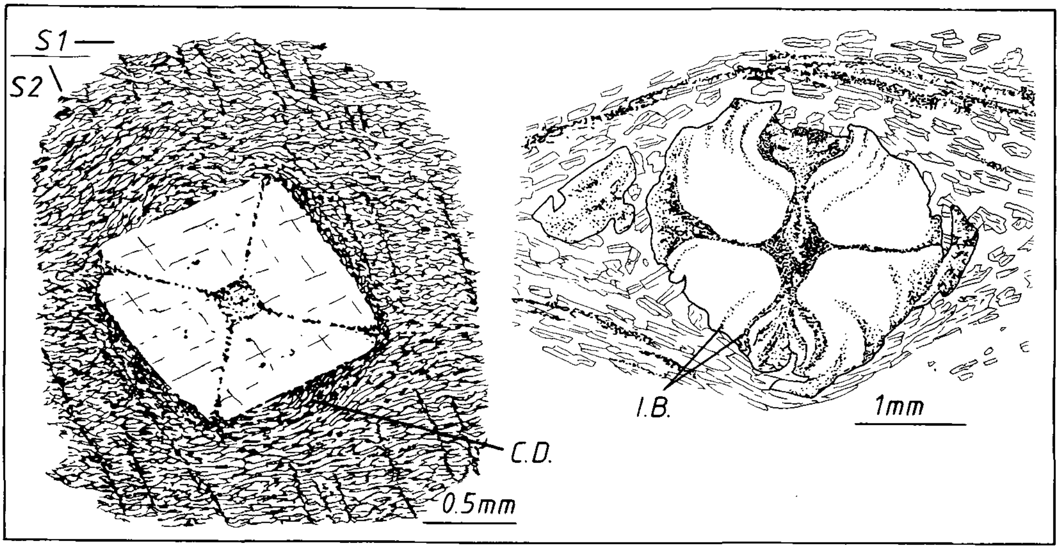

FIG. 3. (A) Chiastolite porphyroblast from Fichtelgebirge, Bavaria, Germany. Note the cleavage domes (CD) which have destroyed S1 and an S2 crenulation fabric. Redrawn from Williams *et al.*, 1954. (B) Chiastolite porphyroblast from Okanogan Co., Washington, U.S.A. Note how the inclusion bands (IB) curve symmetrically in towards two of the pyramid interfaces and away from the others. Redrawn from Misch (1971).

tively complex sector patterns can be seen in thin sections, depending on the orientation of the section through the crystal. Within each pyramid the crystal structure is divided into a series of slightly misorientated units aligned normal (or nearly normal; Carstens, 1986) to the crystal face; this structure has been referred to as lineage or block structure (Buerger, 1932, 1934; Petreus, 1978) and mosaic structure (Zwicky, 1929); the first term is used here. The lineage structures develop close to the sector (pyramid) boundaries and between adjacent lineages a lattice mismatch of 1–3° may develop (Ignatov, 1971).

Although Carstens (1986) reviewed possible mechanisms for the development of lineage structure, no firm conclusion was drawn for its development in authigenic pyrite from Yorkshire, England.

Sector-zoning is revealed in minerals in three different manners; as textural sectoring, chemical sectoring and twin sectoring. This article is primarily concerned with features associated with the first type, although it is believed that all three are related.

In chemical sector-zoning, growth pyramids of different crystal habit have marginally different chemical compositions. These variations are most commonly reported from pyroxenes (Ferguson, 1973; Hollister and Gancarz, 1971; Kouchi *et al.*, 1983; Wass, 1973) but have been described also in mica (Kwak, 1981). Similar variations are known in staurolite porphyroblasts (Hollister, 1970; Smellie, 1974) and in dolomite (Reeder and Prosky, 1986). Kouchi *et al.* (1983) list four mechanisms proposed to account for chemical sectoring, based on: (1) properties relating to the ion exchange taking place at the crystal face; (2) variations in the atomic configuration of the crystal structure or adsorption layer at different faces; (3) systematic variations in growth rates at different faces and relative diffusion rates of cations in melts; (4) element partition coefficients and the roughness of crystal faces.

Since the chemical variations develop between faces of different form, cubic minerals with a habit in which all the faces have the same form will not display chemical sector-zoning. However, Ca-rich birefringent garnet frequently displays twin sector-zoning (e.g. Lessing and Standish, 1973; Fig. 4).

Textural sector-zoning. Anderson (1984) described texturally sector-zoned garnets from the Caledonides on Magerøy, North Norway. The country rocks is a weakly schistose graphitic kyanite–staurolite–garnet–biotite rock. Garnet growth occurred during the metamorphic peak (inter D1–D2) within the contact metamorphic aureole zone of syn-orogenic mafic and ultramafic intrusions which significantly affected the regional isograd pattern (Andersen, 1984).

Within the garnets two types of inclusions were identified by Andersen (1984). Type 1 inclusions of quartz, Fe–Ti oxides and graphite are found preferentially along the pyramid interfaces and

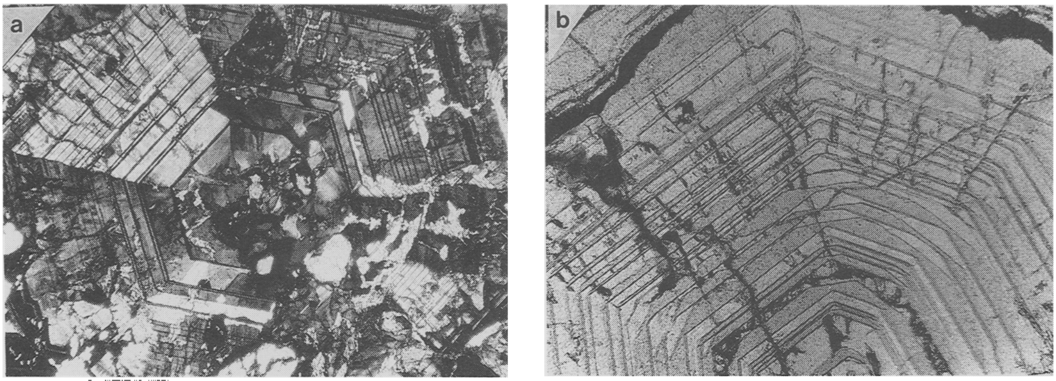

FIG. 4. Twin-sectored birefringent Ca-garnet from Hay Tor, Dartmoor, England. Sample 1/HT/90/HR. (A) Note that the composition of any particular pyramid base appears to be homogeneous between sector boundaries. XPL. Field of view 1.55 × 1.15 mm. (B) Inclusion and/or alteration trails oriented normal to the base of the growth pyramid within which they lie, possibly reflecting lineage growth controlling inclusion/alteration zones. PPL. Field of view 1.55 × 1.15 mm.

were derived from the matrix (Fig. 5B). Anderson (1984) stated that a weak S1 fabric is preserved by matrix biotite grains and that the type 1 inclusions are equidimensional. In the thin section observed (Section TBA-7840-II) the type 1 inclusions preserve a fabric which is parallel in garnet and staurolite porphyroblasts (orientation of type 1 inclusions in garnet normalised to 000° ± 10°, $n = 21$; staurolite inclusion fabric 001° ± 14°, $n = 54$), although no preferred orientation is discernible in the matrix biotite.

Type 2 inclusions (or, more properly 'intergrowths'; Burton, 1986) consist of '. . . slender inclusions of quartz which are not relics of the matrix, but have formed simultaneously with garnet growth' (Andersen, 1984). These inclusions (Fig. 5A) have a tubular cross-section and form an angle of 30° with the pyramid interfaces and of *c.* 90° with the base of the pyramid within which they formed, although they may be somewhat curved (Figs. 2*a* and 3 in Andersen, 1984). Each tubular quartz intergrowth has uniform extinction, but different intergrowths have different extinction orientations. Rarely, two adjacent quartz crystals may develop in a single type 2 intergrowth. Andersen (1984) interpreted the intergrowths to reflect non-coherent lattice bonding between quartz and garnet, with quartz added continuously during garnet growth. Possibly type 2 intergrowths nucleated from type 1 inclusions, developing with the crystal orientation of the parent grain.

Andersen (1984) attributed the development of these textures to relatively rapid growth at high levels of supersaturation, but below that needed for dendritic growth. The type 2 intergrowths were thought to have developed along lattice defects within the garnets which grew as cellular layerites.

Burton (1986) examined garnets in graphitic and non-graphitic schists interbanded on a <1 cm scale, from the Sulitjelma area of the Scandinavian Caledonides. The garnets in the graphitic rocks have textural sector-zoning and contain type 1 inclusions and type 2 intergrowths (1–5 μm diameter, sometimes widening to 40 microns towards the pyramid base). In the graphite-free rocks garnets do not exhibit textural sector-zoning. Estimates of the *P–T* conditions of growth indicate that the garnets in the graphite-free rocks grew at higher *P–T* conditions, and thus probably later, than the garnet which contains type 2 intergrowths.

Burton (1986) rejected Andersen's (1984) model of cellular solidification for the development of type 2 intergrowths, arguing that this would not produce *circular* quartz intergrowths. Instead, Burton (1986) suggested that either a symplectite growth model (Spry, 1969) or a dislocation growth model (Frank, 1951), or a combination of both, operated. Burton (1986) suggested that the difference in garnet inclusion fabrics between the graphite-rich and -free bands was essentially a result of the lowering of the solubility of quartz in CO_2-rich fluids. As a result quartz moves only a relatively short distance during garnet growth before being precipitated continuously between growing garnet lineages.

Other examples of textural sector-zoning. Textural sector-zoning has been found in a number of minerals (Tables 2 and 3); most commonly, however, it has been found in chiastolite and garnet. Examination of the chiastolite porphyroblasts showing displacement textures revealed that

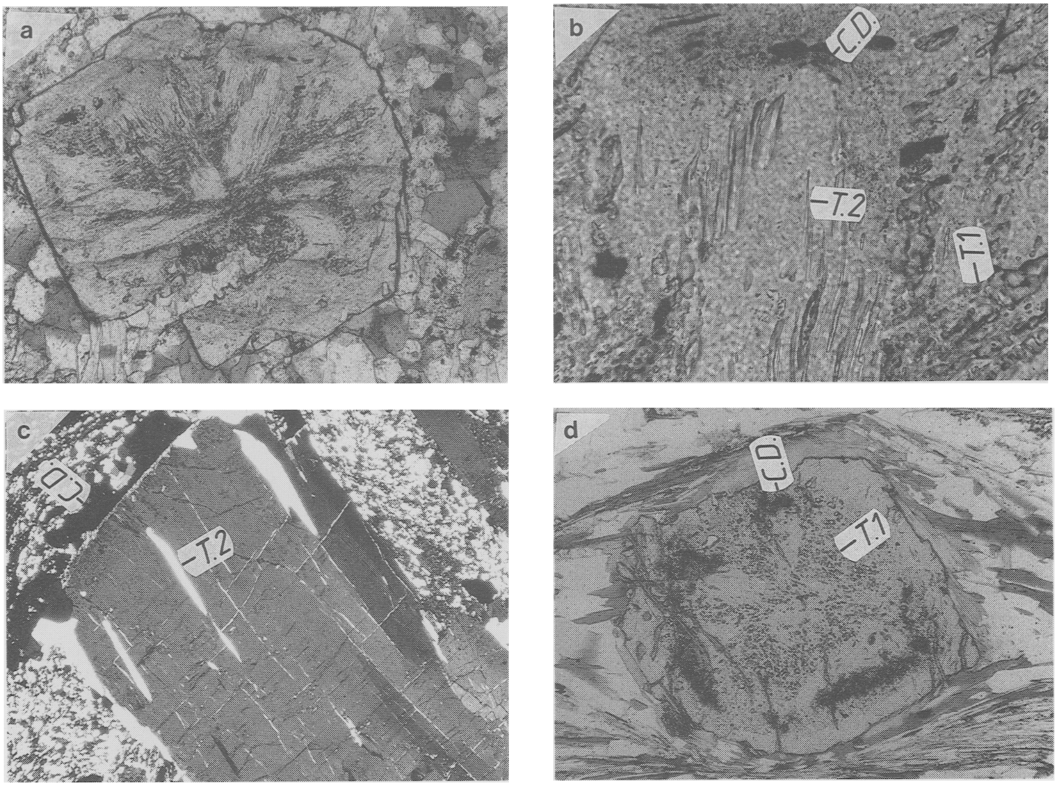

FIG. 5. (A) Texturally sector-zoned garnet from Magerøy, N. Norway. The clear areas are where displacement has occurred; type 2 intergrowths lie within this area. Field of view 4.25 × 2.7 mm. PPL. Sample 7840-II/TBA. (B) Enlargement of top of A, showing type 2 (T2) intergrowths and type 1 (T1) inclusions. Note the graphite cleavage dome (CD) at the end of the type 2 intergrowths. Field of view 0.67 × 0.43 mm. PPL. (C) Single growth prong of chiastolite from Tinaroo, Australia. Note how the massive graphite accumulations (CD) are separated by the very large type 2 (T2) intergrowths, even though the latter do not reach the rim of the chiastolite. Field of view 4.25 × 2.7 mm. XPL. Sample DO. (D) Texturally sector-zoned garent from the Cheyenne Belt, U.S.A., showing three textural zones (compare with Fig. 6A). The type 1 (T1) quartz inclusions form sectors which pass between the cleavage domes (CD) of zone 2. Field of view 1.7 × 1.1 mm. PPL. Sample M084.2.

type 2 intergrowths are present in most samples except where alteration of the chiastolite has occurred. In chiastolites from Tinaroo Batholith aureole single type 2 quartz intergrowths 0.1 mm thick are present (Fig. 5C).

Texturally sector-zoned garnets have been described by several authors from the Moine rocks of N.W. Scotland (Howkins, 1961; Powell, 1966; MacQueen and Powell, 1977; Olimpio and Anderson, 1978; Finlay and Kerr, 1979). Powell (1966) studied the textural development of such garnets from the Morar area in detail. The garnets have three textural zones (Fig. 6A); only the inner one exhibits sector-zoning, with type 2 intergrowths. The outer zone comprises an inner part rich in graphite and a graphite-free outer part. The outermost part ('third zone' of Powell) is not significant here. Between the inner and outer zones are small curved 'inclusions' of graphite. Large quartz and opaque type 1 inclusions cut across both zones.

Garnets similar to those in the Morar region have been found on Porsangerhalvøya, Kvaløy and Sørøy in the Scandinavian Caledonides (Hayes, 1980; Rice, unpubl. data—samples 148 and 149/83/HR; Fig. 63 in Roberts, 1968).

Harker (1950) illustrated a superb texturally sector-zoned garnet from Glen Lyon, Perthshire, Scotland (Fig. 6B). Within the garnet opaque inclusions, tentatively identified as graphite by Harker (1950), are concentrated along the pyramid interfaces and at the porphyroblast faces. Within the pyramids abundant thin type 2 quartz intergrowths are present.

TABLE 3 TEXTURES IN OTHER SECTOR ZONED PORPHYROBLASTS

LOCALITY	META TYPE	CLEAV. DOME	GRAPH ITE	BANDS/ TYPE 2	SECTOR ZONED	FIG.
Garnet						
Sulitjelma, Norway 1*	R	N	Y	N/Y	Y	----
Narvik, Norway 2	R	Y	Y	N/N	Y	6D
Kvaløy, Norway 3	R	Y	Y	Y/Y	Y	----
Porsanger, Norway 4	R	Y	Y	Y/Y	Y	7B
Sørøy, Norway 5*	R	Y	Y	N/Y	Y	----
Andorfjell, Norway 6	R	N	Y	Y/Y	Y	8A
Cheyenne, USA 7	R	Y	Y	N/N	Y	5D,7A
Morar, Scotland 8	R	Y	Y	Y/Y	Y	6A
Glen Lyon, Scotland 9	R	N	Y	N/Y	Y	6B
Tauern, Austria 10*	R	Y	Y	x/x	Y	----
Magerøy, Norway 11	C	Y	Y	Y/Y	Y	5A,B
Ardennes, Belgium 12*	C	x	Y	x/x	Y	----
Andes, Peru 13*	C	Y	x	N/Y	Y	6C
Tinaroo, Australia 14	C	Y	Y	N/Y	N	8B
Staurolite						
Tinaroo, Australia 14	C	Y	Y	N/Y	N	----
Kwoeik, Canada 15*	C	x	Y	Y/Y	Y	----
Emerald						
Chivor, Columbia 16*	H	x	Y	Y/x	Y	----
Muzo, Columbia 16*	H	x	Y	Y/x	Y	----

C - contact, R - regional, H - hydrothermal
* - indicates material seen only in publication.
Y - observed, N - not observed, x - not reported
band/type 2 - inclusion bands seen/type 2 intergrowths seen

1* Burton 1986; 2 Barker 1986; 3 Rice unpubl. data.; 4 Hayes 1980; 5* Roberts 1968; 6 Andréasson & Johansson 1983; 7 Duebendorfer & Frost 1988; 8 Powell 1966; 9 Harker 1950; 10* Selverstone & Munoz 1983; 11 Andersen 1984; 12* Raisin 1901; 13* Atherton & Brenchley 1972; 14 Rubenach & Bell 1988; 15* Hollister & Bence 1967; 16* Nassau & Jackson 1970.

Atherton and Brenchley (1972) described garnets from calc-silicate rocks within a contact metamorphic aureole in the Peruvian Andes (Fig. 6C). Birefringent sector-zoned garnet porphyroblasts from one locality occur in a '. . . calcite groundmass with a dark very fine grained dust of unknown mineralogy' (Atherton and Brenchley, 1972). These garnets contain two zones—a core and a surrounding corona. Well developed textural sector-zoning, with both type 1 inclusions and type 2 intergrowths, is present in the core and may persist somewhat into the corona, although no type 2 intergrowths are found there. Type 1 inclusions are of coarse calcite and an unidentified fine opaque which, for reasons given later, may be graphite. No mineralogy was given for the type 2 intergrowths. Fine opaque and ore inclusions are concentrated at the interface of the core and corona (which may be irregular or idioblastic) and at the outer rim of the garnet.

Garnet porphyroblasts in graphitic schists from the Cheyenne belt, Wyoming, U.S.A., have three main textural zones (Duebendorfer and Frost, 1988; Figs. 5D, 7A); a core (zone 1) which sometimes has an inclusion fabric of occasionally elongate quartz grains (oriented at 007° ± 32°, n = 12, relative to the external fabric) and a rim (zone 3) which is generally inclusion free. Zone 2 consists of fine grained inclusions thought to be of biotite and perhaps hematite (Duebendorfer, pers. comm.); the concentration of inclusions is considerably greater closer to the zone 1 margin. In the thin section examined, textural sector-zoning is present in only nine of twenty garnets showing all three zones (in several other cases extensive retrogression has made textural interpretation difficult), although it is clearly seen in only five cases (Figs. 5D, 7A). The inclusions in zone 2 tend to be concentrated in regions between the pyramid interfaces, along which quartz type 1 inclusions are concentrated. No type 2 intergrowths have been found. In many instances the zone 2 inclusions form curved masses, concave towards the garnet core and meeting at the pyramid interfaces (Fig. 7A). As is typical in many examples of poorly developed sector-zoning, the type 1 inclusions often fill a large part of the porphyroblast, leaving only relatively small inclusion-free areas which are often lensoid (Fig. 5D).

Fig. 6D shows a garnet from pelitic schists with a very low graphite mode, from the Narvik area of the Scandinavian Caledonides (Barker, 1986). This has a complex pattern of quartz type 1 inclusions which form large and relatively ill-defined areas within the porphyroblast. By comparison, garnets from biotite schists containing high graphite modes in the Gula Group near Andorfjell, Central Scandinavia (Fig. 8A; Andréasson and Johansson, 1983) have comparatively few type 1 inclusions. However, they have abundant fine trails of equidimensional grains of graphite and probably quartz. The quartz grains are thought to have the same origin as the type 2

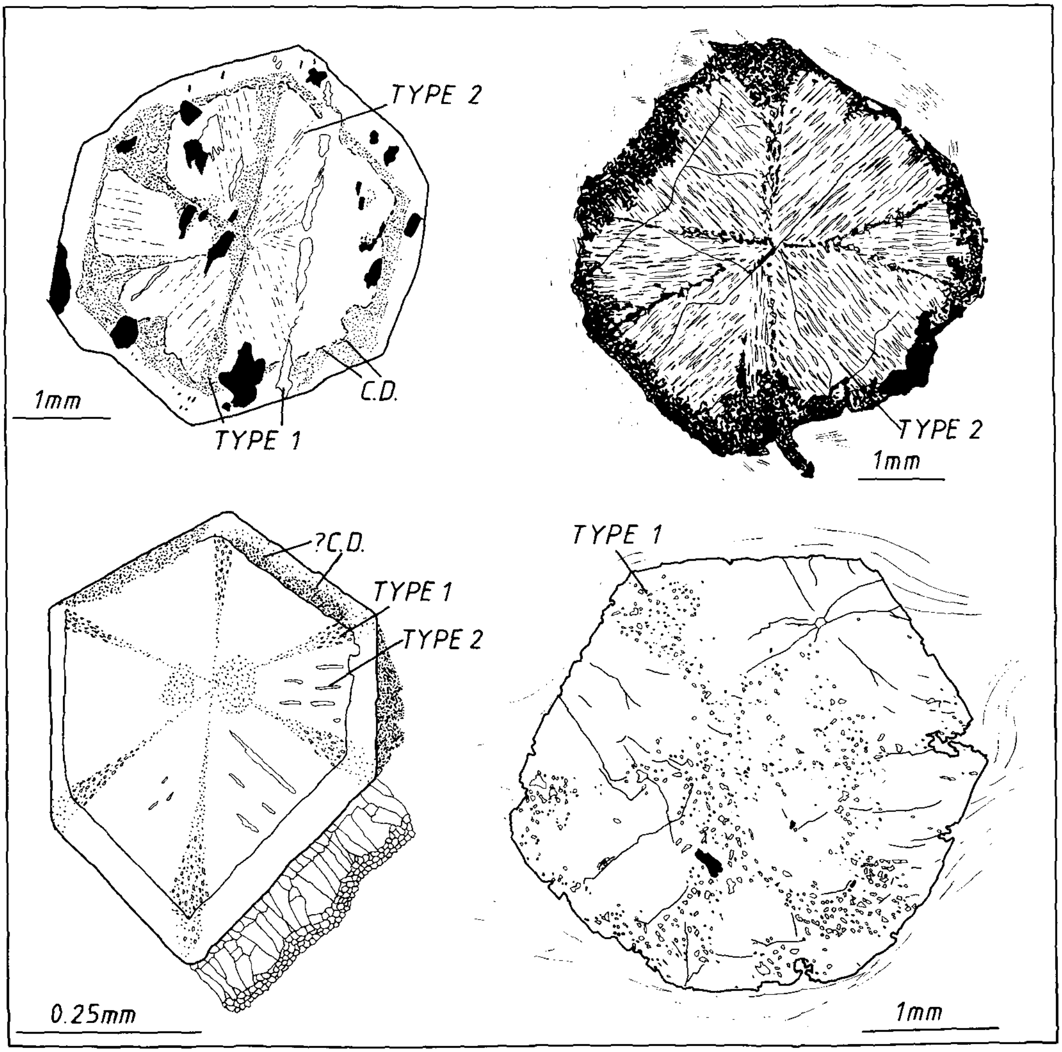

FIG. 6. Texturally sector-zoned garnets. Type 1 and Type 2 refers to quartz inclusion and quartz intergrowths respectively; C.D. indicates cleavage domes. (A) From the Morar region of Scotland. Redrawn from Powell (1966, Fig. 2a). (B) From Glen Lyon, Scotland. Redrawn from Harker (1950, Fig. 100A). (C) From Peru. Redrawn from Atherton and Brenchley (1972, Fig. 2). (D) From the Narvik area, Norway. Note the poorly developed sectoring in this sample which has a very low graphite mode. Sample 444/81/AJB.

intergrowths of Anderson (1984) and are treated as such below.

Garnets within graphitic amphibole schists in the Tauern Window also appear to display sector zoning (cf. Fig. 2*d* in Selverstone and Munoz, 1987), although this is not described by the authors. Each garnet has two main zones—a graphite-free core and a graphite-rich rim.

In graphitic andalusite hornfelses from the Tinaroo batholith metamorphic aureole (Rubenach and Bell, 1988) idioblastic garnets are generally inclusion-free except for occasional type 1 inclusions and type 2 quartz intergrowths (Fig. 8B). No direct evidence of textural sector zoning (i.e. the sector boundaries) can be seen in the porphyroblasts but sector growth can be inferred from the radial orientation of the type 2 intergrowths. From a contact aureole in the Ardennes area, Raisin (1901) described idioblastic textural sector-zoned garnets which grew in nodules containing a carbonaceous groundmass; in carbon-free rocks no garnets have grown.

A common feature in many of the garnets showing textural sector-zoning is the presence of

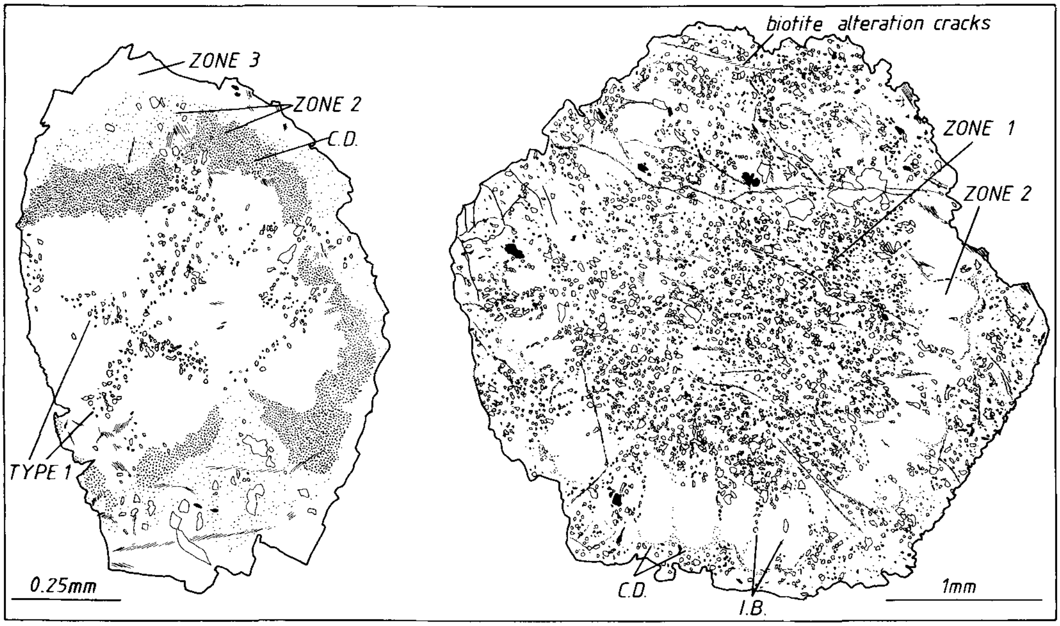

FIG. 7. (A) Garnet from the Cheyenne Belt, U.S.A., partially resorbed, especially along the left side. Note the arcuate shape and higher density of fine inclusions on the inner side of zone 2. Note also the four pyramid apices, outlined by the type 1 inclusions form the porphyroblast centre. Sample M084.2. (B) Garnet from the Caledonides of Porsangerhalvøya, North Norway. This is unusual in that the evidence for displacement growth lies in zone 2 (cleavage domes—CD; inclusion bands—IB) outside the poikiloblastic zone 1 core. Sector zone growth, therefore, began at some time after garnet growth. Sample 11.12SJH-(HR).

arcuate concentrations of graphite (or rarely other minerals) in a textural zone (often very thin) lying immediately outside the sector-zoned region. These were illustrated in Powell (1966; Fig. 7A), who interpreted them as bodily rotated matrix grains, by Andersen (1986; Fig. 5B) and by Atherton and Brenchley (1972; Fig. 6C). Similar features have been seen in garnets from the Cheyenne Belt (Figs. 5D, 7A) and from several parts of the Norwegian Caledonides. These accumulations, which lie along the margin of the inclusion-free areas between the pyramid interfaces and a graphite-rich zone outside the sector-zoned part of the garnet, are here interpreted as cleavage domes. Where the cleavage domes are relatively small they may be separated by either narrow inclusion bands or more rarely, by type 2 intergrowths (Fig. 6A). Anderson (1984) noted that graphite inclusions fill depressions at the ends of narrowly spaced type 2 intergrowths (Fig. 2D of Anderson, 1984), thus implying an arcuate graphite boundary between each type 2 intergrowth. The arcuate boundary between the two growth zones in the garnets from the Tauern Window appears to be marked by a thin graphite concentration (Fig. 2*d* and *f* in Selverstone and Munoz, 1987) and this has tentatively been interpreted to reflect the formation of cleavage domes.

Hydrothermal emeralds from two localities in Colombia also exhibit textural sector-zoning although at neither locality were the examined emeralds set within matrix material (Nassau and Jackson, 1970). Samples from Chevor came from sediments which contain lenses of carbonaceous shales. The emeralds comprise a tapering hexagonal core surrounded by an outer growth of six sectors, all crystallographically continuous with the *c*-axis along the hexagonal symmetry axis of the core. The sectors are separated from each other and the core by '. . . a white to grey material which may be appreciably softer than the emerald . . .'. This material, which is an intergrowth of emerald and albite, may form a thin layer, with feather edges into the sectors (type 1 inclusions), or it may broaden outwards such that the sectors take on a rectangular section as growth prongs, rather than a trapezoid section. The emerald within the intergrowth is crystallographically continuous with the main crystal whilst the albite is polycrystalline.

Emerald from Muzo, Colombia, formed in carbon-rich black shales and associated carbonate layers. In this instance the emerald core, which is

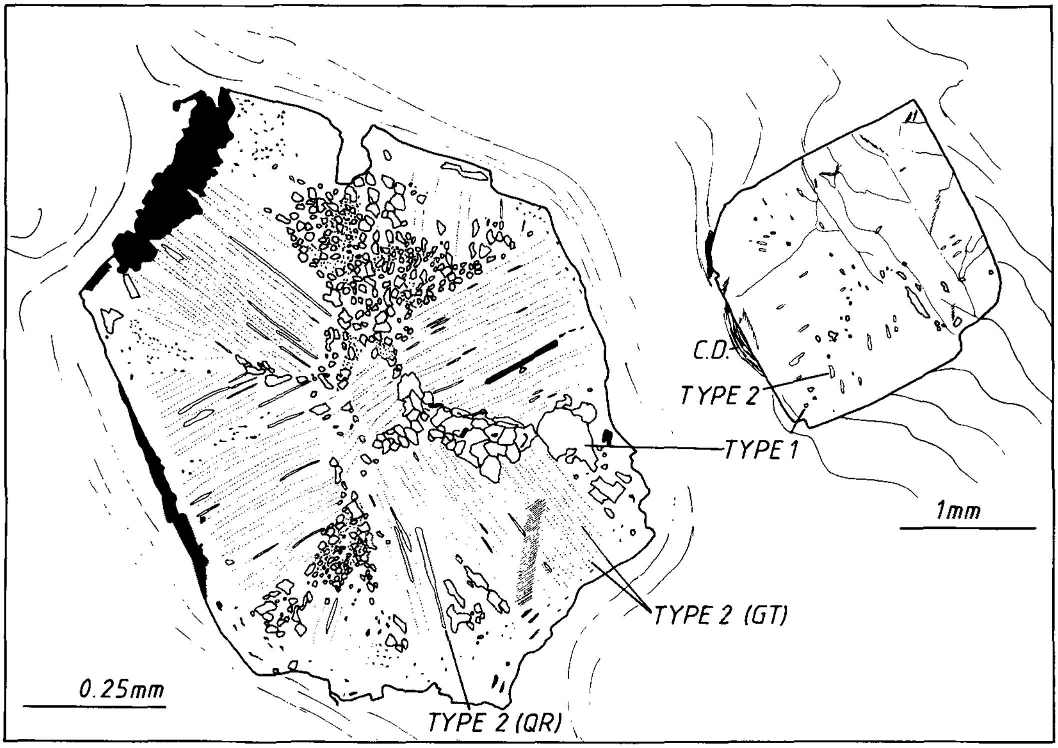

FIG. 8. (A) Texturally sector-zoned garnet from the Gula Group, Central Norwegian Caledonides. The abundant type 2 intergrowths comprise fine trails of graphite and rounded quartz inclusions (GT), with only occasional quartz rods (QR). Sample A75-15-PGA. (B) Garnet from the Tinaroo area, Australia. Although the matrix is graphite-rich, no sector-zoning as such can be seen except by noting the radial distribution of type 2 quartz intergrowths. Scattered type 1 inclusions also suggest a radial distribution on the sector boundaries. On one face there may be a poorly developed cleavage dome (CD). Sample DO.

again tapered, is dark, probably due to abundant carbonaceous inclusions. The outer sectors are separated by fine feather edges of carbon material (type 1 inclusions) but are still crystallographically continuous with the core (Nassau and Jackson, 1970).

Discussion

Textural interrelationships. Table 4 shows the correlation between the development of textural sector-zoning and the presence of displacement textures. Of the twenty-nine samples in which textural sector-zoning has been observed, cleavage domes or similar graphite accumulations have been found in twenty-one cases. Of the eight exceptions, six come from material taken from the literature and have not been directly observed in thin section, and so can be provisionally set aside from this part of the discussion. The two remaining exceptions come from garnets found in regionally metamorphosed terranes where post-displacement stresses may have destroyed any cleavage domes which formed (but see later for an alternative reason). In nearly all cases where cleavage domes have been found in regionally metamorphosed terranes, the porphyroblast has overgrown the cleavage domes prior to any recorded subsequent shearing. The only exception is around large staurolite porphyroblasts from north Norway (Fig. 2B in Rice, 1987).

Conversely, in the twenty-four samples in which cleavage domes have been observed (or, in the case of literature material, inferred) all except three exhibit sector-zoning. Garnets from the Black Hills of Dakota, U.S.A., have few inclusions (Lloyd, pers. comm.) indicating that solution processes were operating very efficiently. The garnets from the Tinaroo area also fail to show textural sector-zoning but the radial distribution of type 2 intergrowths indicates sector growth (Fig. 8B). Similarly, in the relics of staurolite porphyroblast from Tinaroo, which

TABLE 4 SUMMARY TABLE

	N	SZ+ CD	CLEAV. DOME	GRAPH ITE.	BANDS/ TYPE 2	SECTOR ZONED
Mineral						
GARNET	15	9	11	14	5/10	13
CHIASTOLITE	11	10	10	11	10/ 5	11
STAUROLITE	3	1	2	3	2/ 3	2
PYRITE	1	1	1	1	1/ 0	1
EMERALD	2	0	0	1	2/ 0	2
Type of Metamorphism						
REGIONAL	11	8	8	11	5/ 8	11
CONTACT *	18	12	15	17	12/10	15
DIAGENETIC	1	1	1	1	1/ 0	1
HYDROTHERMAL	2	0	0	1	2/ 0	2
Totals						
SEEN *	19	15	17	19	13/14	17
FROM PUBLICATIONS	13	6	7	11	7/ 4	12
TOTAL *	32	21	24	30	20/18	29

* - note that in these cases chiastolite, garnet and staurolite, all from Tinaroo, Australia, are included separately, since not all three phases have the same textural features; sector zoning and inclusion bands have been found only in the chiastolite.

N - total number of examples
sz+cd - sector zoning & cleavage domes seen together
band/type 2 - inclusion bands seen/type 2 intergrowths seen

have been largely altered to biotite and muscovite (Rubenach and Bell, 1988), no unambiguous evidence of sector-zoning has been found in the material available, although rare type 2 quartz intergrowths are present.

In both the formation of cleavage domes and textural sector-zoning it is apparent that growth occurred normal to the porphyroblast crystal faces. The only exceptions to this are where the inclusion bands and type 2 intergrowths indicate that symmetrically disposed curved growth occurred (Fig. 3B, cf. Burton, 1986). In the description of cleavage domes it was emphasised that displacement was often seen to have occurred in discrete zones, separated by inclusion bands. In most garnet and staurolite porphyroblasts with cleavage domes, type 2 intergrowths are also present (Figs. 1C, 5A, 6A–C, 8, Table 4). Equally, inclusion bands oriented normal to the porphyroblast face are commonly seen in chiastolite porphyroblasts (Fig. 2A–B, Table 2), in which type 2 intergrowths are common. In some chiastolite, staurolite and emerald porphyroblasts growth occurred as a series of discrete *growth prongs*, the orientation of which indicated growth normal to the porphyroblast crystal faces (Figs. 1B, 2C–D). All three of these textures (inclusion bands, type 2 intergrowths and growth prongs) are interpreted to reflect the presence of lineage structures.

Another striking feature brought out by Table 4 is that graphite or carbonaceous material is usually present within the rock and is, in most cases, one of the displaced minerals. One exception is the garnets from Andes (Atherton and Brenchley, 1972), in which an unidentified fine opaque mineral was present in the position where graphite has been reported in other texturally sector-zoned garnets; it seems probable that this unidentified material is graphite. Another exception is the emeralds from Chevor, Colombia, which were not examined in the country rock, although this did contain pockets of carbonaceous material (Nassau and Jackson, 1979). Carbonaceous material is also present in carbonate rocks containing texturally sector-zoned authigenic albite (Kastner and Waldbaum, 1968).

An observational conclusion, then, is that there is a link between the presence of graphite within rocks, the formation of textural sector-zoning in porphyroblasts of garnet, staurolite and chiastolite, the development of lineage structures and/or type 2 intergrowths and the displacement of insoluble matrix grains (typically the graphite). This may also be the case for pyrite and emerald, but insufficient data are available to be certain.

Although textural, chemical and twin sector zoning are all thought to be related, they have not commonly been found in conjunction. Hollister and Bence (1967) described textural and chemical sector-zoning together in staurolite, and Atherton and Brenchley (1972) described textural and twin zoning together in birefringent garnets. Another example, also from birefringent garnet is shown in Fig. 4.

Growth model. Fabrics typical of texturally sector-zoned minerals are illustrated in Fig. 9; although this is based on a chiastolite porphyroblast, the textures are found in staurolite and garnet porphyroblasts.

Spry (1969) reviewed three mechanisms for the growth of textural sector-zoning: Harker (1950) suggested that material in the pyramid interfaces was an overgrowth of material brushed aside

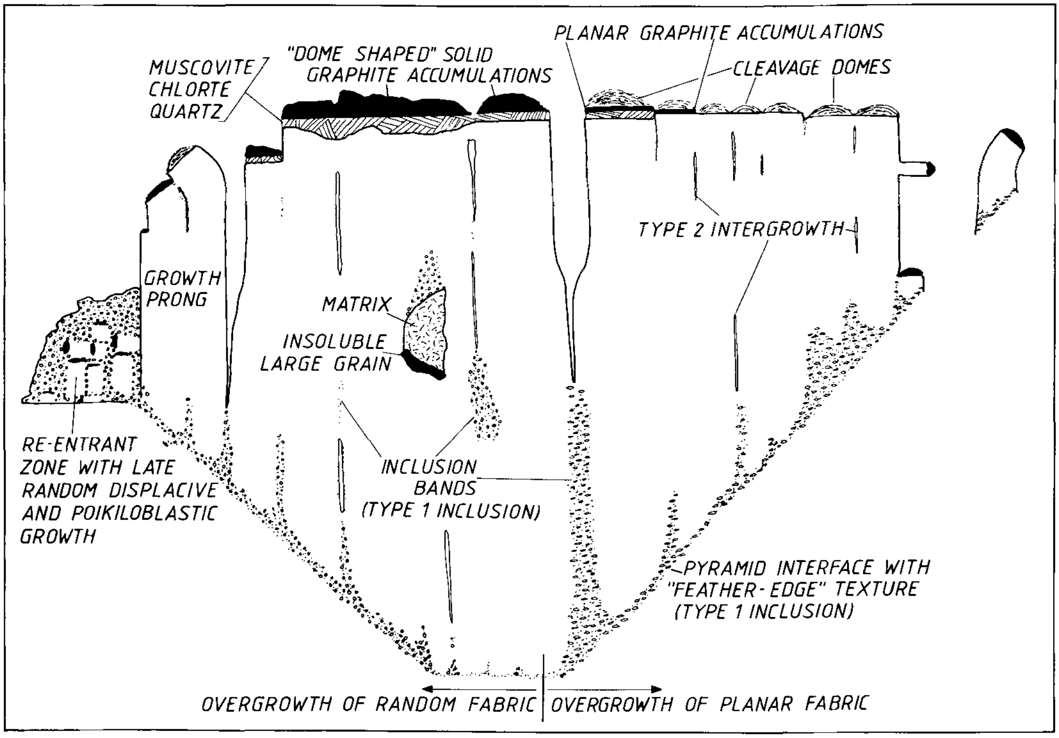

FIG. 9. Schematic drawing showing the typical textures developed during the growth of a texturally sector-zoned chiastolite porphyroblast that has displaced its matrix.

laterally during growth, although no evidence was given to support this notion. Serendipitously Harker (1950) stated that 'The streaming out of trains of inclusions away from the centre presents almost a visible picture of the operation of the forces of crystallisation'.

Rast (1965) preferred a model of dendritic (rapid) growth at the sector boundaries of porphyroblasts growing in an oversaturated solution. A decrease in the oversaturation resulted in a cessation of growth at the corners and an enlargement of growth on existing faces, filling in the region between the sector boundaries. However, if this model were correct then the corners of at least some porphyroblasts should preserve dendritic growth in advance of that of the main crystal faces, a texture not described for the minerals under discussion, although Carstens (1986) has described hopper growth in sector-zoned pyrite. Further, if the central parts of sector pyramids were the result of later growth infilling between the sector boundaries, one might expect a gradual change in mineral composition from the sector boundaries along a particular sector pyramid base, since it seems unlikely that such infilling would occur evenly from the core outwards rather than equally from all parts of the dendritic growth. However, optical evidence of chemical and twin sector-zoning suggests that growth was synchronous across the base of individual growth pyramids, rather than being a two-stage process (Fig. 4A; cf. also Hollister and Gancarz, 1971; Kwak, 1981; Lessing and Standish, 1973; Reeder and Prosky, 1985; Vaniman, 1978; Wass, 1973; Figs. 101 and 102 in Mackenzie *et al.*, 1982).

Spry's (1969) model is based on the adsorbtion of carbonaceous material at prism faces, particularly at prism edges in the re-entrant zones. This inhibits growth in the corners and prevents an idioblastic habit from developing, ultimately leading to the development of growth prongs. However, for such a model to work, growth within a re-entrant must be fast, once started, otherwise the re-entrant zone would continuously lag behind the main face and an idioblastic form would not occur. The fast growth could account for the poikiloblastic nature of the material at the sector boundaries.

Neither Andersen (1984) nor Burton (1986) considered the development of textural sector-zoning *per se* to be of importance in their models; both authors were more concerned with the origin of the type 2 intergrowths and the growth mechanism of the intervening garnet lineages. However, although type 2 intergrowths have been found in fourteen of the eighteen samples in which textural sector-zoning has been observed in thin-section, in most cases they are not significant and can often be seen to have formed after the textural sector-zoning began to develop (Figs. 1C, 5C, 6A, 8B).

The presence of graphite or carbonaceous material in nearly all rocks containing texturally sector-zoned porphyroblasts appears to be more significant and has been mentioned by previous authors (Burton, 1986; Hollister, 1970; Spray, 1969). The role of graphite is not simply that of a passive marker of the development of sector growth; the distribution of quartz type 1 inclusions in garnets from the Narvik region clearly shows sector growth (Fig. 6D), as does the pattern of type 2 intergrowths in some garnets from Tinaroo (Fig. 8A); in neither is graphite an inclusion. Burton (1986) stated 'Graphite, by controlling the composition of the fluid effectively dictates the mechanism and timing of garnet growth'. However, the significance of graphite should be treated with some caution; syntectonic spiral garnets have been reported from graphitic schists in many areas, some of them adjacent to areas with texturally sector-zoned garnets (MacQueen and Powell, 1977; Rice, unpubl. data; Wilson, 1971), reflecting the dependence of the development of all these textures on the presence of a hydrostatic stress field.

In the model proposed here, single lineages develop from the initial point of nucleation, one in the direction of each crystal face. These lineages displace graphite material as they propagate away from the nucleus. Between each lineage a re-entrant forms. Growth into this volume must take place laterally, normal to the preferred direction of growth within that sector. As noted by Andersen (1984) lateral growth must be faster than outward growth by a factor of 1.2 and this increased growth rate may account for the poikiloblastic nature of this zone.

Where lateral growth keeps pace with outward growth then it seems probable that idioblastic porphyroblasts will form with relatively few type 1 inclusions, although clearly other factors will be of significance. In particular the rates of dissolution and transport of material away from the growth faces will be significant and thus so will the fluid conditions within the rock. Where lateral growth lags behind, such that a major re-entrant forms, lateral growth will be poikiloblastic. Within this poikiloblastic region lineage structures will begin to develop, as growth occurs normal to the crystal face, and the inclusion density decrease, leaving inclusion bands. With continued growth the inclusion bands die away, sometimes changing into a type 2 intergrowth.

The alternation of periods in which lateral growth lags and keeps pace with outward growth results in alternating poikiloblastic (type 1 inclusions) and inclusion-free zones; these give sector-zoned minerals their distinctive feather-edge appearance along pyramid interfaces.

Segments between type 2 intergrowths displace the matrix as a single unit (as described indirectly by Andersen, 1984). Often these coincide with the spacing of earlier inclusion bands. Where many type 2 intergrowths are present it may not be possible to see a curved fabric in the displaced material between the ends of the inclusions; this could account for the absence of observed cleavage domes in the samples from Sulitjelma and Andorfjell in Norway and Glen Lyon in Scotland (Table 3), all of which have abundant type 2 intergrowths.

In most cases the pyramid apices lie at the centre of the porphyroblast, indicating sector zoning began with nucleation. In the garnet shown in Fig. 7B, however, conditions suitable for sector-zoning and displacement growth occurred after nucleation such that a poikiloblastic core of rounded and randomly oriented quartz grains and finely disseminated graphite (zone 1) passes into an essentially inclusion-free region (zone 2) within which inclusion bands reflect growth normal to the porphyroblast faces. The outer margin of zone 2 is marked by a series of graphite cleavage domes.

Carstens (1986, p. 255) stated that the cleavage formed by the displacement stresses was curved because growth, and thus displacement, had been greatest in the middle of porphyroblasts. The presence of several (or very many) cleavage domes along a single porphyroblast face, all having essentially congruent geometry but resulting from variable displacements, suggests that curvature is a feature of the stress field itself and how it is accommodated in nearby rock, and not of the amount of displacement. With continued displacement growth and matrix removal, either by solution or reaction, insoluble grains will gradually be accumulated as a solid band adjacent to the porphyroblast (Fig. 1A). Where no cleavage dome formed, but graphite has accumulated directly at the porphyroblast margin, rapid solution processes can be inferred, with the applied stress relieved by solution/reaction in the matrix immediately adjacent to the porphyroblast face. Even in these cases, however, the graphite accumulations are broken into segments where type 2 intergrowths are present in the porphyroblast (Fig. 5C). The presence of a fluid zone *between* the porphyroblast and the graphite accumulations may be reflected in the common occurrence of a thin muscovite, quartz or chlorite zone between the two phase (Figs. 1B, 5C).

Conclusions

1. There is a common association between the presence of textural sector-zoning and the displacement of insoluble matrix grains by porphyroblasts. This has been seen in garnet, chiastolite, staurolite and pyrite. Inclusion bands have also been found in cordierite, in a sample with regularly arranged inclusion patterns (thin-section 75.7G.T1 in the National Museum of Wales; this is similar to Fig. 11a in Harker, 1950), but no type 2 intergrowths or cleavage domes were observed, possibly due to the complete alteration of the cordierite.

2. In all sections examined in thin section which contained textural sector-zoning and/or displacement textures, graphite was present.

3. Both textural sector-zoning and matrix displacement require growth normal to the porphyroblast crystal faces. Evidence for this is seen in the type 2 intergrowths, inclusion bands and growth prongs.

4. Although cleavage domes remain the best indication that displacement growth has occurred, the development of inclusion bands, type 2 intergrowths and sector-zoning in graphitic metamorphic rocks are indicators that displacement may have occurred and evidence for it should be sought. In this vein it is ironic that Misch (1971) figured a chiastolite porphyroblast (Fig. 3B) with inclusion bands but failed to realise its significance.

5. A bulk hydrostatic stress field is required for displacement growth (Ferguson *et al.*, 1980) and thus, from conclusion 1, it is required for textural sector-zoning. These textures can be used to infer a pre- or interkinematic growth of porphyroblasts, a useful criterion in porphyroblast-matrix-deformation studies.

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