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TEXTURAL AND TWIN SECTOR-ZONING AND DISPLACEMENT OF GRAPHITE IN CHIASTOLITE AND PYRALSPITE AND GRANDITE GARNETS IN THE VARISCIDES OF SOUTH-WEST ENGLAND

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Porphyroblasts of contact metamorphic chiastolite from Okehampton, Ramsley Mine, Aish Tor and Rinsey Cove and regional metamorphic pyralspite garnet from Trewethet Gut, Treworld and Trevilla all show textural sector-zoning, with matrix-derived inclusions (type 1 inclusions) along growth pyramid interfaces and usually quartz intergrowths (type 2 intergrowths) normal to the pyramid base. Alteration of chiastolite to white mica has obscured the evidence in some cases. Where present in large amounts, graphite in the matrix is displaced at crystal faces. Some anisotropic twin-sectored hydrothermal grandite garnets from Greenhill, Ramsley Mine and Haytor Iron Mine show evidence of textural sector-zoning, generally in the presence of displaced matrix graphite. Similar garnets in graphite-free samples from the same localities and Botallack and Meldon show no evidence of textural sector-zoning. These textural relations support the hypothesis that there is a link between the development of textural sector-zoning, matrix graphite and matrix displacement.

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INTRODUCTION

Previous work has proposed a link between the development of textural sector-zoning, in which inclusions are regularly distributed within crystals, the development of textures indicating that matrix material had been displaced by a growing porphyroblast and the presence of modal graphite (Burton, 1986; Rice and Mitchell, 1991).

This paper documents a test of the hypothesised textural relationships described above, using samples collected from three distinct geological environments within the Variscides of south-west England (regional and contact metamorphism and hydrothermal mineralisation). However, emphasis must be made here that not all potential sites where the relationships might be tested in south-west England have been examined; this is particularly the case for chiastolite and grandite garnets. A detailed description of some of the textures observed has been given to show the considerable variations possible.

Sector-Zoning

Sector-zoning has been found in a wide range of minerals, including silicates, carbonates, phosphates, sulphates, sulphides, fluorides, halides and oxides. A sector-zoned crystal consists of a set of growth pyramids, the apices of which lie together at the centre of the crystal and the bases of which comprise the faces (Figure 1). In thin-section the sector boundaries observed are the interfaces between adjacent growth pyramids; differently oriented sections through a sector-zoned crystal will produce widely differing sectoral patterns.

Within each pyramid growth occurs in discrete units, termed lineages, slightly misoriented relative to each other but all aligned essentially normal to the crystal faces (Petreus, 1978). The mechanism of growth within each lineage is unclear; although not discussing lineages specifically, Burton (1986) proposed that either a screw dislocation, or a symplectite growth model (or both since they are not mutually incompatible), was responsible for textural sector-zoning in garnet.

Three types of sector-zoning have been identified (see references below); textural, chemical and twin sector-zoning.

Textural sector-zoning is recognised by the regular distribution of inclusions, of which two types have been distinguished (Andersen, 1984; Burton, 1986). Type 1 inclusions, which are concentrated along the pyramid interfaces, are derived by overgrowth of the matrix and may preserve any grain shape fabric present in the matrix before overgrowth. Generally the amount of material included at the interfaces varies during crystal growth, creating a ‘eather edge’ appearance. In some instances matrix inclusions continue to be overgrown further from the interface, forming 'inclusion bands' normal to the crystal face. Type 2 inclusions, or intergrowths, are rod-shaped single crystals of quartz, a few microns to 0.1 mm diameter. These rods grew at the same time as, and parallel to the growth direction in, the host crystal. Normally the intergrowths are straight, but they may alternately curve towards and away from alternate pyramid interfaces, with the direction of curvature the same for all intergrowths in any given pyramid.

In chemical sector-zoning, which occurs with textural sector-zoning (e.g. Hollister, 1970), crystal faces of different form have different chemical compositions (Kouchi *et al.*, 1983). Cubic minerals, in which all faces can have the same form, cannot exhibit chemical sector-zoning, but may show twin sector-zoning, in which the optical orientation of different pyramids varies. (e.g. Lessing and Standish, 1973).

Displacement Growth

Whether a growing crystal can displace matrix material was a contentious issue in the 1970s (see summary in Rice and Mitchell, 1991). Yardley (1974), who noted that displacement growth should occur in all directions, proposed that stresses exerted by crystal growth would dissolve material out of the way of the crystal, or, if a grain is insoluble, the stress would be transmitted to a more distant soluble grain. Insoluble material is thus accumulated at, or in the vicinity of, the growing faces. Ferguson *et al.* (1980) demonstrated that stresses caused by a crystal growing under a bulk hydrostatic stress will produce a small dome-shaped cleavage at its faces, composed of displaced insoluble grains. The presence of 'cleavage domes' appears to be diagnostic of displacement growth and reflects the stress condition noted above.

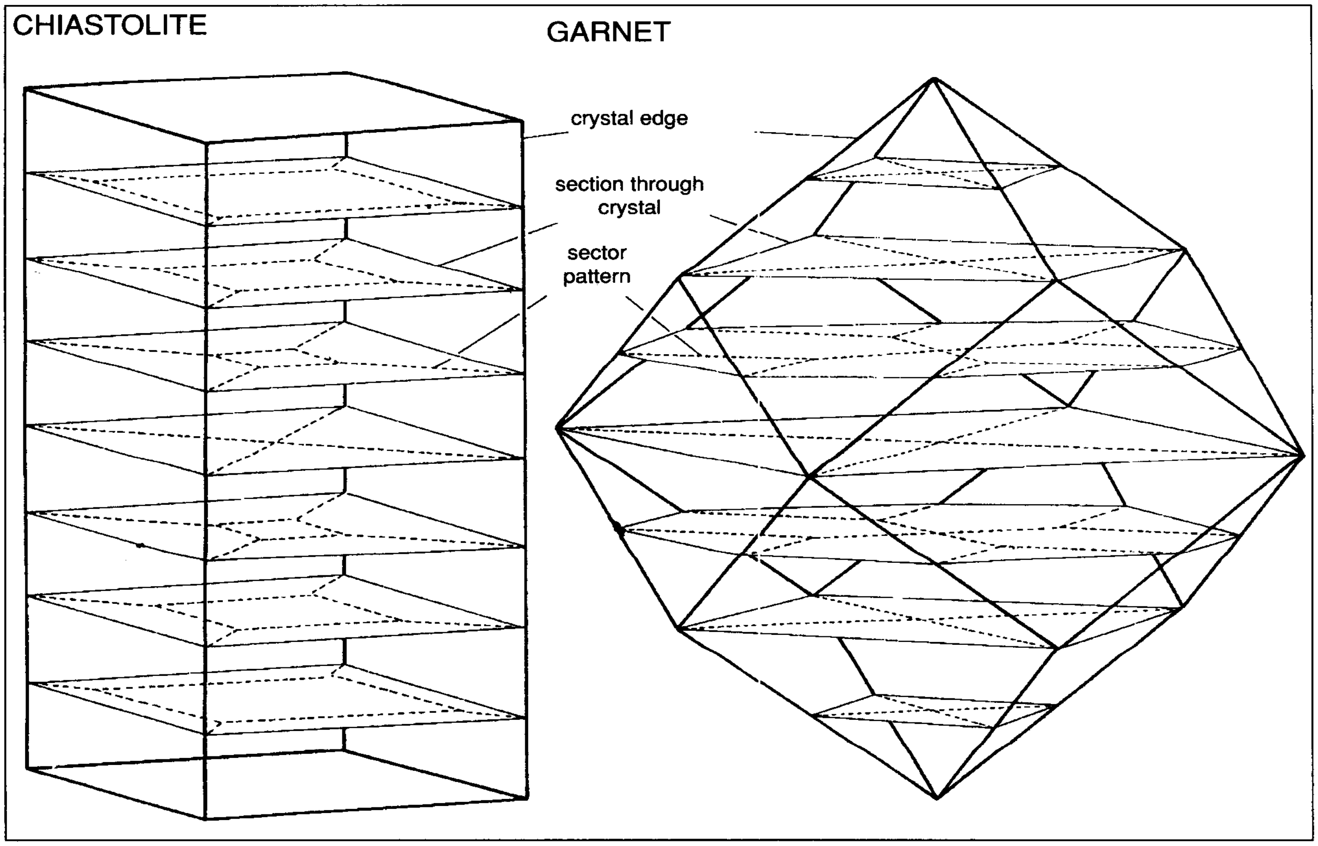

Figure 1: Three-dimensional views of chiastolite and rhombdodecahedral garnet showing the sector patterns developed on a series of sections through the porphyroblasts.

Burton (1986) noted an association between textural sector-zoning and the presence of graphite. Subsequently, Rice and Mitchell (1991) extended this by documenting a common association between the development of graphite, displacement textures and textural sector-zoning. Of the 32 localities which Rice and Mitchell (1991) documented, from contact and regional metamorphic, as well as diagenetic and hydrothermal, conditions, most showed the textural relationships described above (see summary of Rice and Mitchell's data in Table 1). The exceptions were largely related to either a low graphite mode in the rock or a lack of published data in the examples taken from the literature.

MINERAL SECTOR-ZONING IN SOUTH-WEST ENGLAND

Sector-zoned minerals have been found in a number of localities and tectonometamorphic environments in south-west England. Chiastolite has been found in the contact metamorphic aureole of both the Cornubian batholith (e.g. Ussher, 1912; 1913; Reid *et al.* ,1911; 1912) and mafic dykes (Reid *et al.,* 1910). Sector-zoned garnets have been found in regionally metamorphosed pelites (Reid *et al.,* 1910; Andrews and Power 1984, Primmer, 1985) and in hydrothermal deposits around the Dartmoor Granite (Scrivener *et al.,* 1987) and in calc-flintas and skarns (Barrow and Thomas, 1908; Reid *et al.,* 1911; Floyd *et al.,* 1992).

Chiastolite

With one exception, all the chiastolites described here come from graphitic rocks in the aureole of the Dartmoor Granite. They have been found in relatively soft grey Carboniferous pelites at the site of the former railway station at Okehampton [SX 5880 9425], the waste dumps of Ramsley Mine [SX 6500 9305] and in loose blocks at Aish Tor [SX 7066 7131] and also in hard grey Devonian semi-pelitic hornfels in a small quarry north of Ivybridge Station [SX 636 562].

Chiastolite occurs as small (<7 mm by <2 mm^2) idioblastic to sub-idioblastic porphyroblasts (Figure 2A, 2B); all porphyroblasts have re-entrants. Different corners of the same crystal may have varying re-entrant depths, with aspect ratios of 1:1.5 to 4:1 when observed parallel to the basal section (pyramid width:re-entrant depth). Detailed inclusion patterns are generally not well preserved, due to extensive alteration of the chiastolite to white mica, although all porphyroblasts show a relic of the characteristic cross inclusion pattern picked out by graphite type 1 inclusions. In some samples type 1 inclusions show a fabric parallel to that in the matrix. Type 2 intergrowths are rare but have been seen in the Okehampton samples. At all localities except Ivybridge, graphite in the matrix has been obviously displaced, forming either cleavage domes or solid accumulations at growth faces. S2 crenulation cleavage planes adjacent to the chiastolites in the Aish Tor samples have also been zones of preferential solution and graphite concentration (Figure 2A). At Ivybridge the graphite mode is lower and the matrix coarser and less cleaved than elsewhere; evidence of displacement stresses are seen in the increase in the graphite mode adjacent to the faces as well as in a general homogenisation of rock fabric (Figure 2B).

At Aish Tor porphyroblasts cut across an S1 penetrative and S2 crenulation fabric and in the other samples described an S1 cleavage is overgrown. Except at Ivybridge, both the S1 and the S2 fabrics are slightly wrapped around the chiastolite, forming an augen texture (Figure 2A); justification for ascribing a tectonic origin to this augening in most cases is given in the discussion. The absence of such deformation at Ivybridge may be ascribed to the considerably greater hardness of the hornfels in that area.

A sample of chiastolite-cordierite hornfels from rocks of the Middle Devonian Mylor Slate Formation in the metamorphic aureole of the

TABLE 1: Textural data from south-west England with the data from Rice and Mitchell 1991 numerically summarised.

LOCALITY	ALTER -ED	CLEAV DOME	GRAPH -ITE	TEXTUR SECT	TYPE 2	FIG
CHIASTOLITE						
R&M91	3	9	9	9	4	-
Okehampton	Y	Y	Y	Y	Y	-
Ramsley Mine	Y	Y	Y	Y	/	-
Aish Tor	Y	Y	Y	Y	/	2A
Ivybridge	Y	?	Y	Y	/	2B
Rinsey	N	Y	Y	Y	Y	-
PYRALSPITE GARNET						
R&M91	13	9	13	12	9	-
Trewethet Gut	N	Y	Y	Y	Y	2C
Trevilla	N	N	Y	?	N	2D
Treworld	N	Y	Y	Y	Y	3A-D
GRANDITE GARNET						
R&M91	1	Y	?	Y	Y	-
Meldon	N	N	N	N	N	-
Greenhill	N	?	Y	Y	?	4C
Ramsley	N	Y	Y	Y	Y	4D
Haytor	N	N	N	N	?	4A-B
Botallack	N	N	N	N	N	-

R&M91 – data of Rice & Mitchell 1991
Y- observed; N – not observed;
? – uncertain or similar texture seen
/ - not determinable due to alteration

Tregonning Granite, at Rinsey Cove SW 5925 2695 has also been briefly examined. The chiastolite is unaltered, idioblastic with re-entrants, of similar size to that in the Dartmoor Granite aureole and has displaced graphite during growth. Type 1 inclusion patterns are ubiquitous, preserving the S1 fabric seen in the matrix, but type 2 intergrowths are less common. In some cases the external fabric is weakly deflected around the porphyroblasts. The xenoblastic cordierite is fresh, with a poikiloblastic texture preserving the S1 fabric and has not displaced graphite, although possible displacement textures associated with idioblastic cordierite have been recorded elsewhere (Rice and Mitchell, 1991). The irregular sector trilling observed is a result of inversion of high temperature hexagonal cordierite to low temperature orthorhombic cordierite during cooling (Barker 1989, pp. 42-43).

Pyralspite Garnet

Pyralspite garnets from regionally metamorphosed rocks are rare in south-west England. Reid *et al.* (1910) figured texturally sector-zoned garnets in graphitic Slaughterbridge Beds at Villa Park, now called Trevilla [SX 1123 8615]. Loose samples of medium grey coloured pelite, collected from recently dug pits, have <0.75 mm diameter idioblastic garnets with a planar Si inclusion fabric of quartz and rare opaques (Figure 2D). The S2 external fabric is inclined to the internal fabric (by 24° +/-8°, N=53, in sample 201/D/92/HR). Chlorite porphyroblasts are typically found in the strain shadows of these garnets, with an inclusion fabric parallel to that in the garnets. Evidence of textural sector-zoning is very poor, with slight localisation of inclusions, but no type 2 intergrowths have been observed, although they are present in the sample figured by Reid *et al.* (1910).

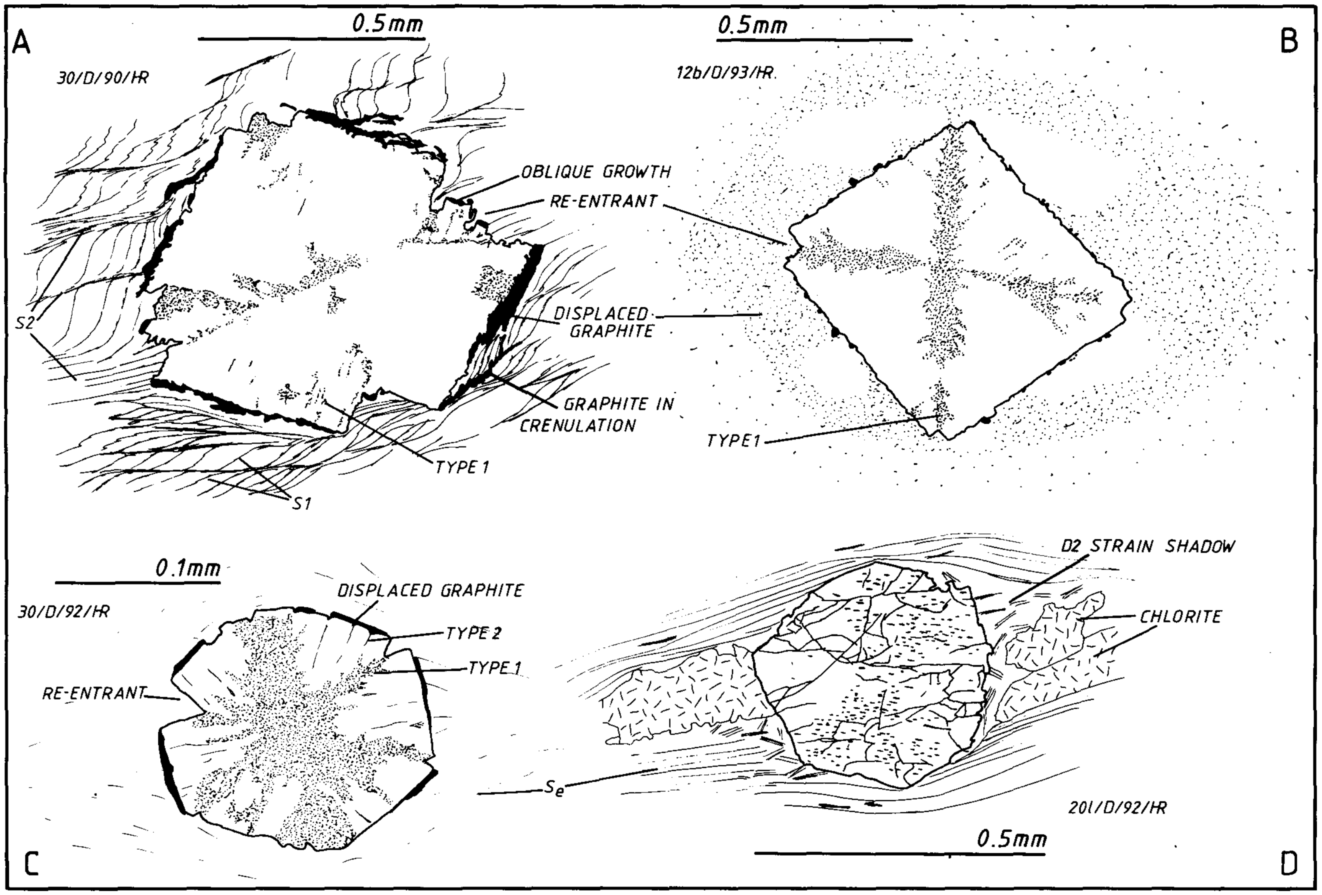

Figure 2: A. Chiastolite porphyroblast from Aish Tor, cutting across the S1 and S2 (crenulation) cleavages. Note that the latter are slightly deflected around the porphyroblast and that where close to the porphyroblast have become zones of intense solution, with resultant graphite accumulation. B. Chiastolite porphyroblast from unfoliated rock at Ivybridge. Note the general increase in graphite mode near the porphyroblast rather than the more usual massive graphite accumulations. C. Garnet porphyroblast from Trewethet Gut, showing sharp re-entrants and linear type 2 intergrowths. D. Garnet porphyroblast from Trevilla Park. This shows only very slight evidence of sector-growth, with the inclusions concentrated into two parts of the crystal.

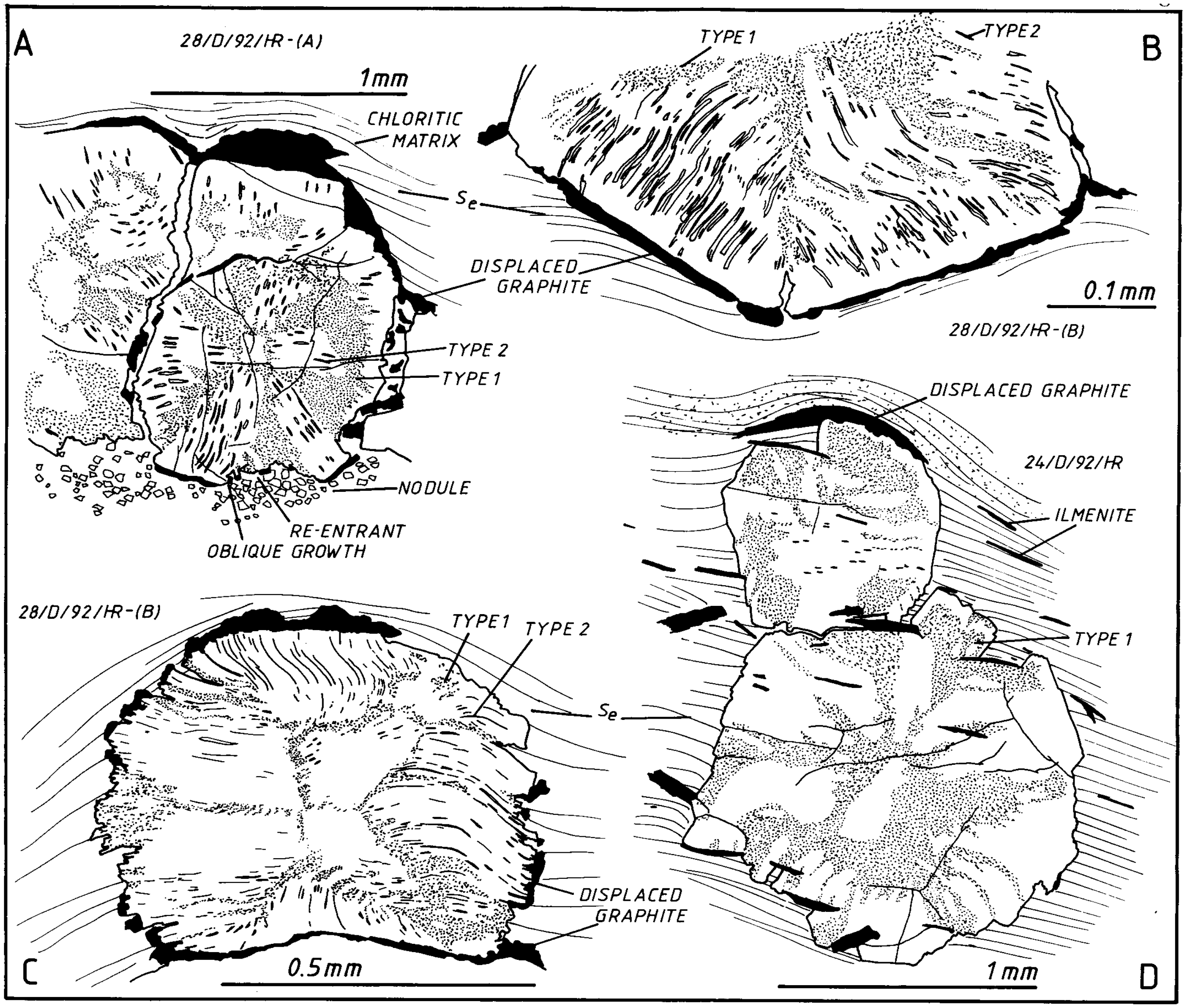

Figure 3. Garnet porphyroblasts from Treworld. A. Garnets from adjacent to a nodule rim, where re-entrant growth has occurred. B. Part of garnet porphyroblast showing two textural zones - inner with type 2 intergrowths and outer without. Note how the type 2 intergrowths are curved in the same growth period and with the same sense of displacement. C. Garnet porphyroblast from graphite rich zone, with no outer textural zone. The abundant type 2 intergrowths show symmetrical curvature about pyramid interfaces. Of particular interest, note how the intergrowths define different growth segments which have grown to different lengths at the porphyroblast rim. D. Two garnet porphyroblasts - the upper one has grown into graphitic matrix, forming a large accumulation of material. The remaining parts have grown into graphite-free or graphite-poor matrix, developing good type 1 sector patterns, but neither type 2 intergrowths nor displacement textures. The large ilmenite blades show progressive envelopment by the garnet.

Evidence of displacement growth, either as cleavage domes or as more massive accumulations at the porphyroblast margins, is also lacking; note, however, that the graphite mode is very low in the samples sectioned.

Texturally sector-zoned garnets have been found south of Trewethet Gut [SX 0728 8975], in a dark, very friable semi-pelitic graphitic schist of the Upper Devonian Tintagel Slates, lying immediately under the Tintagel Volcanic Formation (Primmer, 1985). The garnets are idioblastic to xenoblastic and between 0.25 and 1.5 mm in diameter (Figure 2C). At microscopic level they are sometimes concentrated into particularly graphitic bands. The more idioblastic crystals show good sector-zoning features, often with abundant type 1 inclusions, which sometimes encompass large parts of the section seen through the crystal, possibly reflecting a section cut parallel to the pyramid interface. The orientation of inclusions remains the same as in the matrix, demonstrating growth after the formation of the S1 penetrative fabric. Later deformation has wrapped the matrix foliation around the garnets.

Type 2 intergrowths are common in some thin sections -each sample sectioned has slight textural differences, whilst retaining the fundamental features of textural sector-zoning. Primmer (Fig. 2C, 1985) noted "...evidence of flattening and deflection of inclusion trails within the porphyroblast..." but these are almost certainly curved type 2 intergrowths, the curvature of which is a primary feature (cf Burton, 1986); no consistent orientation of curvature has been found to support the inference that it is deformation-related. Graphite has been displaced in all rocks thin sectioned.

Andrews and Power (1984) found garnet-phosphate nodules in graphitic rocks of the Upper Devonian-Carboniferous Transition Group at Forrabury [SX 0961 9089] and Treworld [SX 1180 9056]. At the latter outcrop, eight nodules were found on the north side of the road and one on the south, all as described by Andrews and Power (1984). In thin section three zones of garnets can be defined in the nodules; the core contains many small sub-idioblastic garnets with abundant type 1 inclusions showing poor textural sector-zoning. The rim, which is marked

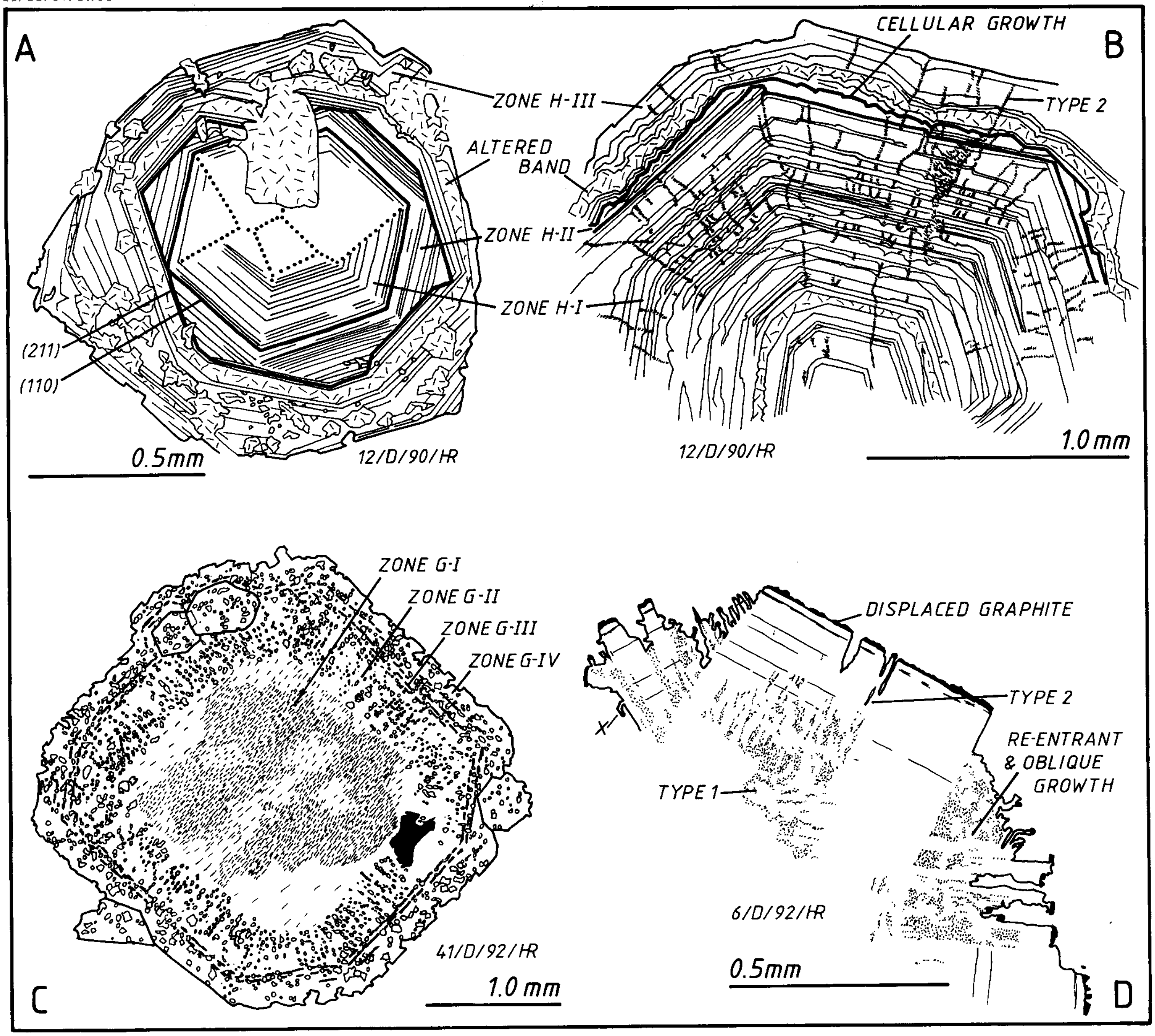

Figure 4: Birefringent grandite garnets from hydrothermal veins. A and B from Haytor Iron Mine; the lines show the oscillatory zoning pattern. In both note the three compositional zones and the prominent layer altered to hornblende just outside the zone H-III boundary. The dotted lines are sector boundaries in areas where oscillatory banding is not obviously developed. In B note the obvious 'type 2 intergrowths' roughly normal to the base of each growth pyramid. Note further how the boundaries of many of the cellular andradite growths are in line with the type 2 intergrowths. C. Garnet from Greenhill, showing four textural zones; fine oscillatory zoning not shown, but is present. Note the poor orientation of inclusions normal to the crystal faces in zone B-II (?type 2 intergrowths) and the small graphite inclusions in zone B-III (?displaced material). D. Garnet from Ramsley mine showing displaced graphite; this has only poor oscillatory zoning. Large re-entrants have formed and are filled by oblique growths which have different growth directions and optical orientations; growth at point X is back towards the crystal centre.

by a major increase in graphite, has large sub-idioblastic texturally sector-zoned garnets (<1.5 mm). Outside the graphitic zone, in a chlorite-dominated matrix, smaller idioblastic garnets (<1 mm), generally without sector textures, are present in a narrow zone. Only the garnets in the two outer zones are discussed further.

As noted by Andrews and Power (1984) many of the garnets have two growth zones; an inner zone, with classic textural sector-zoning features and a thin outer zone, with neither type 1 inclusions nor type 2 intergrowths (Figure 3B). In such cases the boundary of the two zones is only rarely marked by a thin layer of graphite, indicative of a change in growth conditions, and even in these cases the rim of the porphyroblast is marked by either a solid accumulation, or a narrow zone of cleavage development parallel to the porphyroblast face, or both textures. The presence of the displaced material at the rim implies that displacement growth continued after sector-zoning ceased. In areas with a high graphite mode, the outer growth zone is absent and textural sector-zoning patterns continue to the crystal edge (Figures 3A, 3C).

Type 1 inclusions are locally common, and may form broader zones towards the edge of the crystal. In sections through or near the garnet centre complex sector patterns can be identified from the type 1 inclusion patterns. Where the growth direction was sub-parallel to the external fabric, the inclusions retain the same fabric orientation, but where growth was across the external fabric, the type 1 inclusions frequently display no preferred orientation. The external fabric is in all cases wrapped around the porphyroblasts (Figure 3).

Type 2 intergrowths are both abundant and relatively thick and in most samples are essentially straight, although in porphyroblasts from volumes with a high graphite mode the type 2 intergrowths may be symmetrically curved across the pyramid interfaces (Figure 3C). In other porphyroblasts the intergrowths in adjacent pyramids are curved the same way, first away from and then back towards the crystal face (Figure 3B). As this double curvature occurs in a narrow band at the same distance from the porphyroblast rim in adjacent growth pyramids, it almost certainly occurred during the same period of growth; its cause is unknown.

Large ilmenite porphyroblasts in the chloritic schist around the lens clearly interfered with garnet growth, since they are too large to be displaced or to be dissolved away (Figure 3D). Despite this, ilmenite inclusions occur in garnets. Ilmenites at or close to the garnet rim have in some instances been partially overgrown at their ends by garnet, suggesting that inclusion was by lateral growth after the porphyroblast had grown past the ilmenite. The depth of the indentations in the porphyroblast rim outline over some ilmenites suggests that lateral growth was slow compared to outward growth.

Grandite Garnet

Loose blocks containing twin-sectored orange-green anisotropic andraditic garnets have been collected from hydrothermal deposits within Upper Carboniferous rocks around the Dartmoor Granite; from Meldon [near SX 56 92], Greenhill [SX 6395 9430] and Ramsley Mine [SX 6500 9305] to the north and from Haytor Iron Mine [SX 773 772] to the east. In most cases the garnet rock is massive, but small vugs show idioblastic rhombdodecahedral crystals <0.75 cm across. The garnets are largely composed of oscillating anisotropic and (near) isotropic idioblastic growth bands, representing Fe^{3+}/Al^{3+} variations (Lessing and Standish, 1973). Microprobe analyses of garnets from Haytor Iron Mine showed that the cores are pure andradite and the outer parts $And^{90}Gro^{10}$, both parts being anisotropic (Scrivener et al., 1987), although one cannot be certain that this chemical zonation applies to other samples, since markedly different textural zonations are found in different samples.

In the following section a detailed textural description of some of the material thin-sectioned is given. Note, however, that there is a wide variation in textures seen in samples from a single locality and that the material described is that which shows textural sector-zoning. The many samples that do not show textural sector-zoning are not illustrated.

Under plane polarised light, the garnets in sample 12/D/90/HR from Haytor Iron Mine show superb planar oscillatory zoning, with alternating very pale pink and orange-buff layers (Figure 4A, 4B). The latter are presumed to be more andraditic (Deer, Howie and Zussman, 1973) and under crossed polarisers show only slight birefringence. The more grossularrich bands show marked birefringence in first order greys. The almost isotropic behaviour of the andraditic layers suggests a near end-member composition (0.2>XGro>0.8; Jamtveit, 1991); this conforms with the chemical data of Scrivener et al. (1987).

In this sample three growth zones have been identified in the garnets (H-I/H-III in Figures 4A, 4B). Zone H-I is comprised of oscillating zones of varying andradite composition as described above. The orange colour is more pronounced in the central growth bands. At the corners of some porphyroblasts (Figure 4B) it can be seen that the pure andradite layers show a modification to the icositetrahedral form, with (211) faces. At the same time growth along faces may show a breakdown to cellular growth (Jamtveit and Andersen, in press), in which growth is concentrated into a series of discrete growth centres along the main crystal face, rather than being evenly distributed, giving an irregular profile. However, these irregularities disappear during subsequent grossular-enriched growth, reforming an idioblastic rhombdodecahedral outline, unless extensive cellular growth had previously occurred. Icositetrahedra faces occur at the same time on all edges of a particular rhombdodecahedron, or not at all, and their development is presumed to be compositionally induced.

Zone H-I is surrounded by a zone of very weakly birefringent pale orange andraditic garnet of variable thickness (zone H-II). The zone boundary is sharp and planar and, where thick, zone H-II shows complete modification to the icositetrahedral form (Figure 4A), with a doubling in the number of faces in most, but not all section orientations through porphyroblasts. In many instances this zone shows pronounced cellular growth, with distinct idioblastic crystals forming. Zone H-II is surrounded by zone H-III, in which both oscillatory zoning is apparent and a return to an idioblastic rhombdodecahedral form may occur. The zone boundary is sharp but may be planar or irregular, the latter reflecting the cellular growth in zone H-II. Due to impingment of adjacent crystals during earlier growth, zone H-III has frequently developed as a continuous zone around more than one garnet nucleus.

In zone H-I many garnets have irregularly developed `fractures' essentially normal to the faces, similar to type 2 intergrowths; rarely, thin rod-like inclusions are present. These fractures are frequently coincident with boundaries of cellular andradite growth, indicating that they are a primary feature and not tectonic fractures; similar depressions associated with type 2 intergrowths have been seen in pyralspite garnet and other minerals (Rice and Mitchell, 1991). In several instances there are slight offsets in the oscillatory zones across the fractures, again similar to the offset of growth across some type 2 intergrowths.

Alteration of the garnets to a blue-green amphibole has occurred selectively, with garnet layers of appropriate composition selectively replaced, often leaving the adjacent growth zones completely unaffected. This has occurred particularly prominently at one layer close to the inner boundary of zone H-III, irrespective of the thickness of the earlier growth zones (compare Figures 4A and 4B). This selective alteration is presumed to reflect bulk mineral composition control on the alteration, in which case the altered zone provides a distinctive time marker throughout the thin section. Patchy alteration to amphibole also occurred.

Figure 4C shows a idioblastic garnet from Greenhill, with eight sides, indicating development of icositetrahedral faces. Four textural zones have been recognised (zones G-I/G-IV in Figure 4C), but these are entirely different from those seen at Haytor Iron Mine. Zone G-I is an idioblastic growth, forming slightly over half the diameter of the crystal. Most of zone G-I is finely poikiloblastic with a planar inclusion fabric. The boundary between zones G-I and G-II is sharp, as defined by the oscillatory zoning, even where G-I is not poikiloblastic and thus not distinguishable in plane polarised light. Zone G-II is coarsely poikiloblastic, with inclusions tending to form trails lying normal to the crystal face. The inference that these reflect lineage growth, as do the type 2 intergrowths, seems not unreasonable; similar, but finer-grained, trails of spherical inclusions forming 'type 2 intergrowths' have been found in other texturally sector-zoned garnets (see Fig. 8A in Rice and Mitchell, 1991).

Zone G-III is marked by a series of thin graphite layers between oscillatory compositional zones. Two bands are essentially continuous around the porphyroblast, although divided into short lengths by numerous inclusions, whilst two other bands are more sparsely developed. The development of inclusion zones reflecting earlier growth forms was interpreted by Harvey and Ferguson (1973) as evidence of displacement growth and such may be the case here, although no distinct domal structure has been seen in the graphite. Neither the inclusions in this zone, nor the somewhat larger and more irregularly shaped inclusions in zone G-IV, form bands normal to the porphyroblast faces. The G-II to G-III boundary can be interpreted as a cessation of displacement growth, contemporaneous with a cessation of lineage growth.

Garnets in sample 6/D/92, from Ramsley Mine are xenoblastic, with particularly large re-entrants (Figure 4D), and have formed separately within a finer-grained texturally isotropic matrix. The centre of the porphyroblasts is poikiloblastic (zone R-I) and merges with the outer zone, which is essentially inclusion free (zone R-II), although there are rare type 2 intergrowths and inclusion bands oriented normal to the growth face. The important feature of these garnets is that matrix graphite has clearly been displaced, forming planar and arcuate solid accumulations at the faces (Figure 4D).

Brown-orange grossular garnetite veins cutting the contact aureole of the Lands End Granite at the Crowns, Botallack [SW 362 337, Floyd *et at,* 1992], are also anisotropic. In the single sample examined porphyroblasts are <1 mm diameter, idioblastic in vugs, and predominantly inclusion-free. No evidence of textural sector-zoning has been found in these garnets and the matrix is without graphite.

DISCUSSION

Re-entrant growth features

A feature of the porphyroblasts from most of the localities described is the development of re-entrants, formed as a result of inhibited lateral growth during continuing growth normal to the crystal faces. Whilst almost ubiquitous for chiastolite, this habit is uncommon in garnet. Where developed, re-entrants typically have formed on all edges, although if the matrix varies around the porphyroblast, as is the case for garnets growing on the edge of the nodules at Treworld, re-entrants may form selectively in different matrix types. In most cases the sides of the major growth prongs defining the re-entrants have acted as nucleation loci for subsequent minor oblique growths into the re-entrant volume (Figures 2A, 3A, 4D), and these may in turn act as host for further oblique growths.

In the plane of a thin-section the first recognisable oblique growths develop parallel to the lineages in the adjacent growth pyramid. Since this is the case in two-dimensional sections it seems probable that this is also the case in three dimensions, which implies that in chiastolite and garnet the observed initial oblique growths form at 90° and 60° respectively to their host growth pyramid, this being the angle between the lineages in adjacent pyramids, assuming a rhombdodecahedral garnet. Quite probably initial oblique growths form parallel to lineages in other growth pyramids, but these will cut directly through the plane of the section and will not necessarily be recognisable.

Subsequent oblique growths form at 90° and 60°, for chiastolite and garnet respectively, to previous oblique growths, and thus may also cut through or lie parallel to the plane of the thin-section. In one case three successive oblique growths have been sectioned in a grandite garnet, resulting in growth back towards the porphyroblast centre (X in Figure 4C).

In the grandite garnets the oblique growths have the same optical orientation as that part of the main crystal parallel to which they grew, despite the fact that there is no physical continuity. This confirms that the change in extinction angle, and thus the angle of twinning, between twin sectors (and thus between sucessive oblique growths) is not random, but is controlled by the crystal lattice. The oblique growths have chemical zonation patterns equivalent to their time of growth compared to zoning patterns in the main porphyroblast.

Displacement growth

The conditions required for displacement growth are thought to be a tendency towards an idioblastic shape, a large activation energy, slow porphyroblast growth and an insoluble material in the matrix (Yardley 1974). Displacement under bulk hydrostatic stress conditions may result in the formation of cleavage domes (Ferguson *et al.,* 1980). In the examples presented here a dome-shaped graphite accumulation at the prophyroblast rims is not evident on all crystal faces - frequently the graphite mass has an irregular or planar form (e.g. Figure 2A). However, in all thin sections, even if not in all porphyroblasts, dome-shaped accumulations have been found, suggesting displacement during a bulk hydrostatic stress.

Since the development of cleavage domes requires a bulk hydrostatic stress during crystal growth (Ferguson *et al.,* 1980), their presence in the samples described suggests that deformation had effectively ceased when porphyroblast growth occurred. However, in most cases the tectonic fabrics are wrapped around the chiastolites and pyralspite garnets, forming an augen texture. In theory, this may have been due to either the stresses exerted by crystal growth or tectonic deformation after growth. Although the asymmetry of the augen and the deposition of quartz in a strain shadow (e.g. Figure 2D) seem to indicate a deviatoric stress, whilst the stresses caused by a growing crystal should be equal in all directions, these textures are not unambiguous; Yardley (1974) argues that where the matrix is strongly anisotropic (as in these cases) "...a pressure shadow may be created by the lifting apart of parallel mineral plates...". In some cases, particularly the pyralspite garnets, (Figures 2C, 2D) it is clear that tectonism occurred after porphyroblast growth, since the size of the augen is greater than might be expected from crystal growth stresses and the external fabric is oblique to the internal fabric, indicating fabric rotation after porphyroblast growth.

In other cases, however, particularly with the chiastolites, the augening mechanism remains uncertain, since the deformation is very local to the porphyroblasts. In Figure 2A, for example, solution along cleavage planes has occurred close to three sides of the crystal. In two of these cases the graphite accumulations in the cleavage planes is coincident with a markedly less than normal accumulation on the crystal faces. These features indicate both a symmetrical strain and that solutional removal of material was not restricted to the crystal faces, and thus that crystal growth stresses propagated into the matrix. Thus from a microstructural viewpoint the augen texture could have been caused by the crystal growth. From a regional viewpoint, however, Warr *et al.* (1991) suggested that large-scale regional updoming occurred during granite emplacement, to account for the correlation of the regional epizone isocryst and the sub-surface limit of the Cornubian batholith. Such deformation could have continued after contact metamorphic porphyroblastesis had finished, forming weak augen textures.

Growth of pyralspite garnets

The pyralspite garnets, which all lie within the area of epizone metamorphism (Warr *et al.,* 1991), are presumed to represent the peak metamorphic assemblage; no higher grade assemblages have been reported. The presence of garnet in a region of typically very-low to low grade metamorphism -although Primmer (1985) estimated surprisingly high temperatures of 450° to 500°C at Trewethet Gut - may be accounted for by two not incompatible processes. First, the stability of spessartine is lower than that of almandine; consequently in Mn-rich rocks, garnet will nucleate at lower than usual temperatures. Reid *et al.* (1910), Andrews and Power (1984) and Primmer (1985) all allude to the high MnO concentrations in the rocks. An alternative, or complimentary, reason may lie in the presence of graphite; both Burton (1986) and Selverstone and Munoz (1987) noted that garnets in graphite-rich bands grew at lower temperatures than in adjacent graphite-free bands (in both examples the garnets in the graphitic rocks are sector-zoned), as a consequence of carbon species (CO_2, CH_4) in the fluid changing P_2 and aH_2O, and thus reducing the stability of the garnet-forming reactants.

CONCLUSIONS

Nearly all the chiastolite and pyralspite garnets examined support the model proposed by Rice and Mitchell (1991) that there is a link between textural sector-zoning, modal graphite and displacement growth. This is reflected in Table 1, which shows that at all localities at which textural sector-zoning has been found, graphite is present, although matrix displacement textures are not always present. Note, however, that not all rocks with modal graphite will necessarily have texturally sector-zoned porphyroblasts with displacement textures. In the samples from Trevilla Park, where the graphite mode is low, only poor textural sector-zoning has developed and no displacement textures have been found.

The development of textural sector-zoning in some of the grandite garnets is particularly interesting; the author knows of only one other example (Atherton and Brenchley, 1972). As stated earlier, however, most of the grandite garnets showed no evidence of textural sector-zoning; these samples all lacked modal graphite.

The possibility that rocks *without* modal graphite may have porphyroblasts that show textural sector-zoning and/or displacement of other insoluble matrix grains has not been tested. Indeed, the only entirely reliable test would involve thin sectioning every rock that has a porphyroblast.

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