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Complex synkinematic and postkinematic garnet porphyroblast growth in polymetamorphic rocks

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Abstract—Complex garnets from the Boyon Formation (Ardèche, French Massif Central) were studied from a chemical and a microstructural point of view. The history of their development is placed within the framework of the regional deformation and confirms the succession of high to medium-pressure followed by low-pressure metamorphism. Complex features, similar to those obtained by growth synkinematic to flattening are shown to be due to a static (or interkinematic) development of low-pressure garnet rims around high to medium-pressure cores. The structures preserved within the new garnet and those present in the cores were produced by pre- to synkinematic growth of the old garnet during transposition of an S_1 into an S_2 schistosity. This transposition can be described as strain-slip under metamorphic conditions.

Résumé—Quelques grenats complexes des formations du Boyon (Vivarais oriental, Massif Central français) ont été étudiés du double point de vue chimique et microstructural. Les étapes de leur développement sont replacées dans le cadre structural régional et leurs compositions chimiques confrontées aux données concernant les grenats de l'Ardèche. Ceci permet de constater, dans leur élaboration, la participation d'un métamorphisme de haute à moyenne pression suivi d'un métamorphisme de basse pression. Les structures complexes qui pourraient être interprétées comme une croissance contemporaine d'un aplatissement sont en réalité dues à la croissance statique d'un grenat de basse pression autour d'un noyau de haute pression. Les structures 'fossilisées' par le nouveau grenat et celles qui sont présentes dans le noyau sont créées pendant la croissance anté- à syncinématique de celui-ci, dans une phase de transposition. Cette phase transpose une schistosité S_1 en une schistosité S_2 au cours d'une déformation de type 'strain–slip' en ambiance metamorphique.

INTRODUCTION

The chronological relations between growth and deformation are often difficult to determine unambiguously. According to Zwart (1960, 1962) their determination is based on the comparison between the included fabrics (S_i) of porphyroblasts relative to the external fabrics (S_e). The nine cases emphasised by this author are shown in Fig. 1. Many mechanisms have been proposed to account for these various types of porphyroblast–matrix relationships which can be observed in thin sections (Ramsay 1962, Spry 1963, Rast 1965, Cox 1969, Powell & Treagus 1970, Rosenfeld 1970, de Wit 1976a, b, Schoneveld 1977, Olesen 1978). Whereas the above authors were essentially concerned with synkinematic growth (case 2, Fig. 1), Vernon (1978) reviewed the main determinative criteria for all the chronological relationships between growth and deformation.

Our purpose is to draw attention to the complex relationships between the cores and rims of garnet porphyroblasts which coexist in the same rock with garnets of simple shape. The curvature of the fabric included in the rims can be interpreted, following the model of Zwart (1960), as resulting from growth synchronous to flattening. Such an interpretation of the Zwart's type 5 relationship (Fig. 1) was followed by Rast (1965) in a review of the theory of the 'force of crystallization'. Rast concluded that the force of crystallization cannot explain

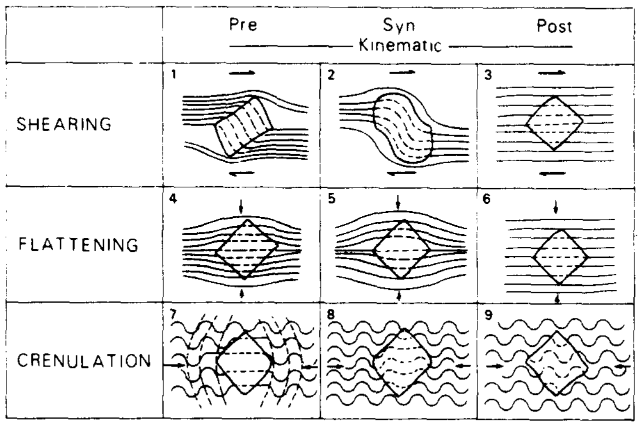

Fig. 1. The nine cases of porphyroblast–matrix relationships according to Zwart (1962).

the pushing aside of inclusions but perhaps only the idioblastic form of some minerals. Misch (1971) following Ramberg (1952) suggested that the 'force of crystallization' could in fact explain such features. This opinion led to a lively discussion (Spry 1972, Misch 1972, Shelley 1972, Ferguson & Harvey 1972). More recently, the 'force of crystallization' theory was invoked in the microstructural studies of Saggerson (1974), de Wit (1976b) and Ferguson *et al.* (1980), while interpretations of Vernon & Powell (1976) and Zwart & Calon (1977) upheld the opposite view.

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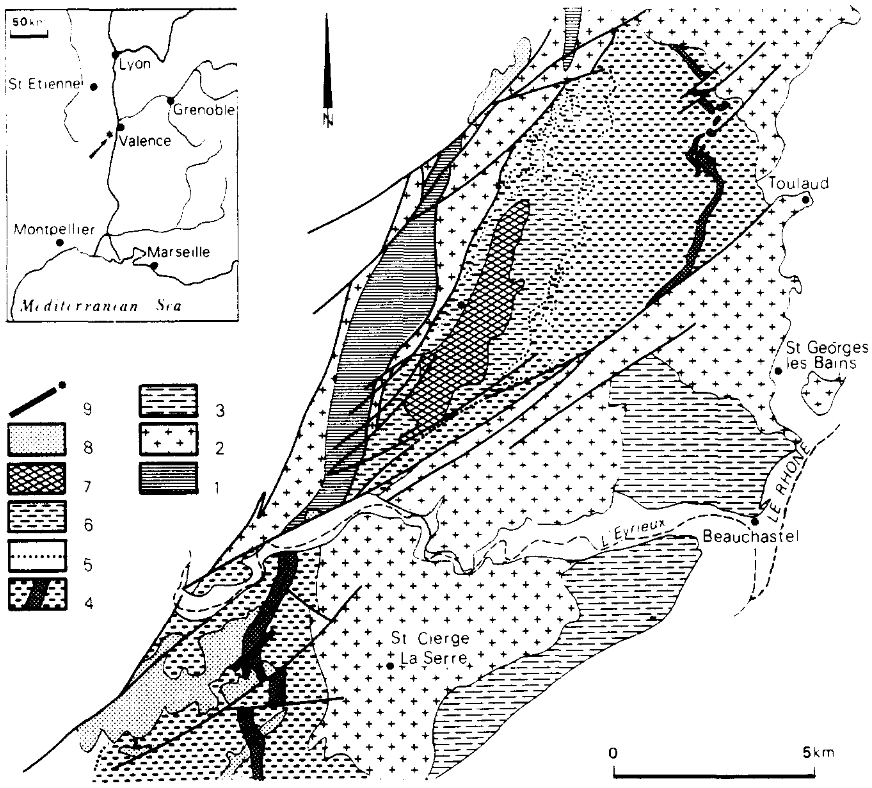

Fig. 2. Sketch map of the synform in the Boyon metamorphic series, (1) biotite–sillimanite gneisses, (2) intrusive granites, (3) Beauchastel schist Formation, (4) Boyon Formation with Al_2O_3-rich marker horizon, (5) augen schists, (6) staurolite–garnet schists, (7) Bruzac gneisses, (8) unconformable Triassic series, (9) location of garnet samples: bar, in the Boyon Formation; star, in the Bruzac Formation. Inset map shows the position of the area studied.

Garnets from this study come from the Boyon polymetamorphic series (Eyrieux valley, Ardèche, French Massif Central) which comprises pelitic and quartzopelitic to quartzitic metasedimentary rocks (Fig. 2). The most common assemblages are: muscovite–chlorite, muscovite–chlorite–garnet, andalusite–biotite–muscovite, with or without garnet, staurolite–garnet–biotite–muscovite. A few occurrences of kyanite have been observed (Chenevoy & Ravier 1968). In this study, the microstructures of the garnets are interpreted within the established framework of the growth history of the other minerals and of the chemistry and petrology of the metamorphism (Juteau *et al.* 1974, Toteu 1981). This framework allows us to determine more precisely the relationships between garnet growth and metamorphism/deformation events in such polymetamorphic series.

PHASES OF FOLDING AND THE BEHAVIOUR OF MINERALS

Structures on a megascopic scale

The region studied appears as a few kilometre-wide synform with a NNE–SSW axis (Fig. 2). It is sheared at the latitude of the Eyrieux Valley by a large dextral wrench fault striking 55°. The western part of the synform is truncated and its contact with the granites is mainly tectonic. On the east in spite of intense small-scale faulting, the contacts of the granites with the schists are intrusive. To the north, the synform is asymmetric and has a very steep western limb and a flat eastern one. Detailed studies of the megastructures have already been presented (Vigot 1963, Juteau *et al.* 1974, Toteu 1981) and the lithological succession defined. The lower (and eastern) part of the series mainly comprises homogeneous or layered albite-schists (Boyon formation) with an Al_2O_3-rich marker horizon (schistes de St-Vincent). Towards the centre (or the top) the schists are overlain by biotite–staurolite–garnet micaschists in which rare kyanite-rich lenses have been found. Between them a good lithological marker rich in microcline phenoclasts (schistes amygdalaires) can easily be traced. The core of the structure is formed of fine grained biotite–muscovite gneisses and layered leptynites (Bruzac formation).

Structures on meso- and microscopic scales

The most conspicuous schistosity (regional schistosity) is axial planar to rare intrafolial mesoscopic folds and was attributed either to a first deformation phase (P_1, S_1 of Gay *et al.* 1982, for similar series about 25 km to the north) or to a second deformation event (P_2, S_2 of Juteau *et al.* 1974). These last authors clearly recognized an earlier schistosity S_1 and an earlier set of refolded folds F_1. The layering generally seems to be parallel to S_2, but it is partly a tectonic accordance: in some places one can find less transposed domains in which S_1 turns into S_2 during strain–slip in metamorphic conditions (Fig. 3a).

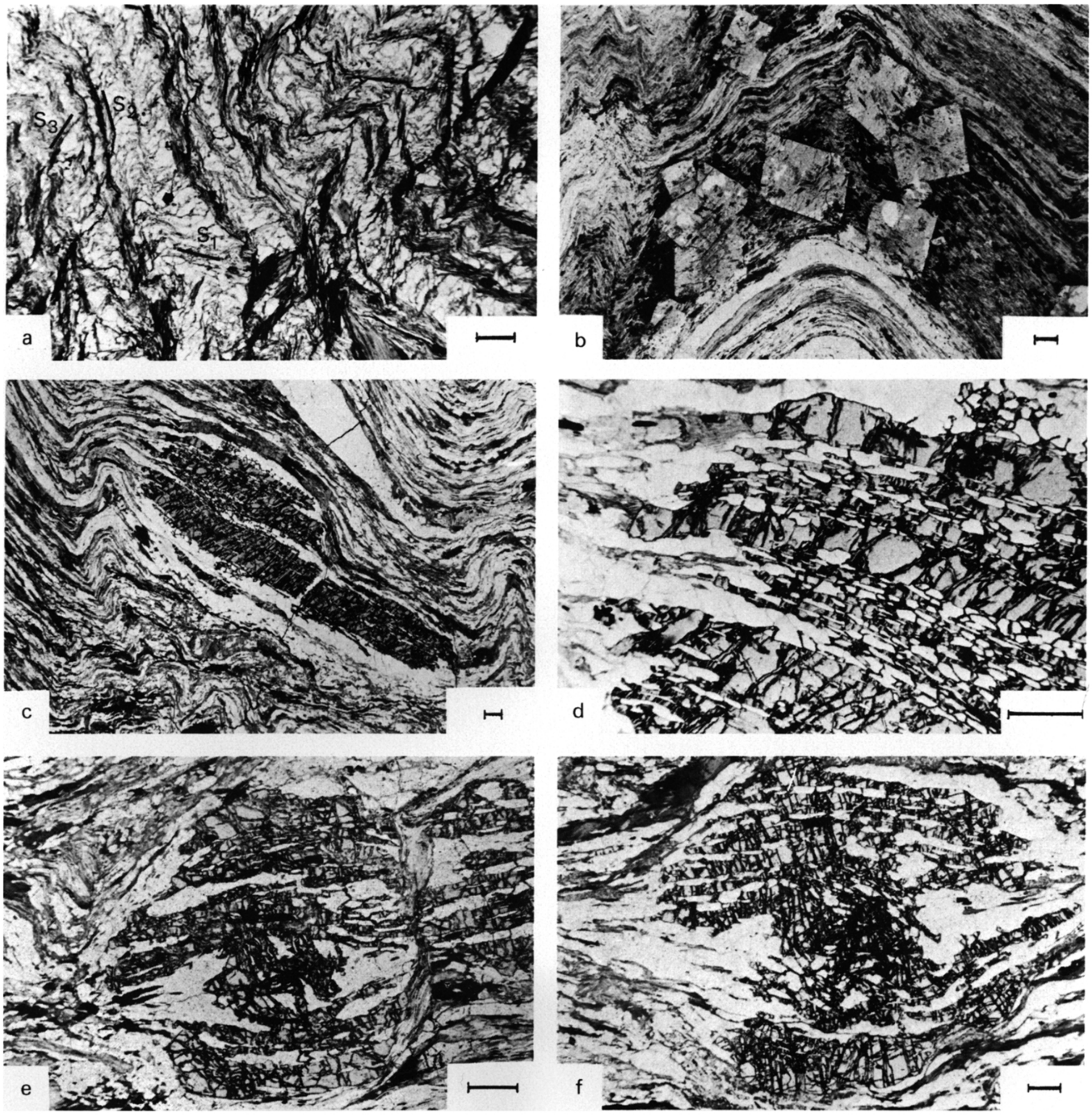

Fig. 3. Microscopic features in the Boyon Formation (Scale bar 500 μm). (a) Micaschists with three deformation fabrics, (1) relics of S_1, (2) S_2 developed by transposition of S_1 under metamorphic conditions, (3) microfolds and strain-slip cleavage S_3. (b) Post-P_3 andalusite in the granite contacts. (c) Post-S_2 garnet. The mineral develops along phyllosilicate-rich layers. Microfolding which deforms quartz (undulose extinction) and micas (kinked or bent crystals) is later than garnet crystallization. (d) Post-S_2 garnet; enlarged. Large equigranular quartz crystals in the matrix become tabular in garnet. S_i shown by quartz inclusions is here really a relic of S_e, since quartz-rich layers outside the garnet can be followed across it without any disturbance. (e) Double structure with a core and a rim. S_i in the core is nearly at right angles to S_i in the rim and to S_e. Pressure shadows of the older garnet are conspicuous. Late deformation and fracturing with chlorite development (right) and microfolding of S_2 (left) are also visible. (f) Double structure with a small old garnet.

The movement of matter (Gratier 1979, 1982) and the reorganization of a metamorphic layering (Nicholson 1966, Hobbs & Talbot 1968) or of a tectonic layering (*litage tectonique*, Soula & Debat 1976) is a well documented phenomenon. The P_1 and P_2 events may result from the same progressive deformation, as the structures are nearly coaxial and the conditions of metamorphism progressively increase. They could, however, equally well be separate tectonic events, as suggested in a general reconstruction of the tectonic evolution of the Massif Central (Autran 1980). A third event gave rise to the formation of a locally well developed crenulation and to some mesoscopic folds with rounded or acute hinges and with a weak axial plane cleavage (P_3, S_3, Fig. 3a). A NNE–SSW synform was later developed. Contrary to Gay *et al.* (1982), we do not relate this event to our phase 3 (phase 2 of these authors), as the polarity of the P_3 folds is the same on the two limbs of the synform and the angle between S_2 and S_3 nearly the same. The last events such as kink folding and several episodes of fracturing are not described in this study.

The behaviour of minerals with special regard to garnet

The regional distribution of mineral assemblages clearly indicates (Juteau *et al.* 1974, Toteu 1981) the superposition of a medium-pressure metamorphism of decreasing intensity from west to east (i.e. from the top to the bottom of the synform) and a low-pressure metamorphism decreasing in intensity from east to west. A chronological table (Fig. 4) from Juteau *et al.* (1974) with slight modifications gives the position of the main minerals in relation to the folding events. Kyanite is such a rarity and is so altered that it is impossible to be sure of its position in the deformation history. Some aspects, however, tend to indicate that it is linked to phase 2. Staurolite is abundant in the western series and especially in the lithological horizon between the Bruzac and Boyon Formations (staurolite–garnet schists). Another generation of rare staurolite crystals is also present in the low-pressure associations in the east. Andalusite seems to be mainly earlier than phase 3 events, but is sometimes also clearly later (Fig. 3b). This fact indicates that the low-pressure events (andalusite earlier than P_3) and the emplacement of granites (andalusite later than P_3), if spatially linked, are not strictly contemporaneous. In the medium grade low-pressure series to the east, the polymetamorphic history (resulting from discontinuous heat pulses under different pressure conditions) is not clearly visible, but must exist as the series in the synform are perfectly continuous. A study of the complex garnets in the Boyon Formation shows agreement between chemical and structural data and thus supports this superposition.

Garnets from layered or homogeneous metapelitic schists are of four main morphological types:

(1) *Simple type*. S_i is straight and perfectly continuous with the external schistosity S_e, which is here S_2. Later deformation clearly related to P/T conditions far from

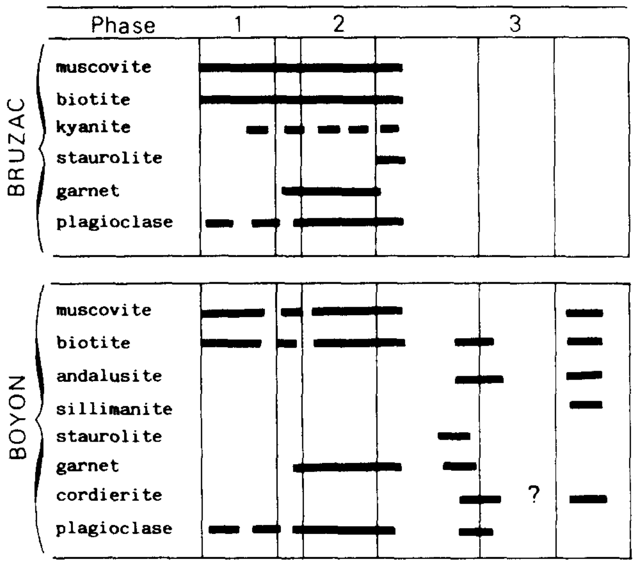

Fig. 4. Deformation phases and mineral growth for the Bruzac Formation (medium-pressure dominant) and the Boyon Formation (low-pressure dominant).

those of garnet growth sometimes modified these simple relations. (Figs. 3c & d): microfolding deformed quartz and phyllosilicates without any dynamic recrystallization or recovery; as garnet is isotropic, continuous strain is not visible in it.

(2) *Sigmoidal type*. S_1 is S-shaped but its curvature is always weak; the continuity between S_i and S_e is variable and there is sometimes a rim richer in quartz around the garnet. S_i may be planar in the centre of the crystal (Fig. 5). In spite of observations in different planes in thin sections, no characteristic ƆC or ᗡD structures were seen (Powell & Treagus 1970).

(3) *Core and rim type* (Figs. 3e & f). The internal fabric of the core is straight or undulating (smooth microfolds) or generally S-shaped. It is marked by lines of opaque minerals and small elongate quartz crystals. The angle between the most rotated part and S_2 (regional schistosity) never greatly exceeds 90°. The internal fabric of the rim is gently to strongly bent around the core. It

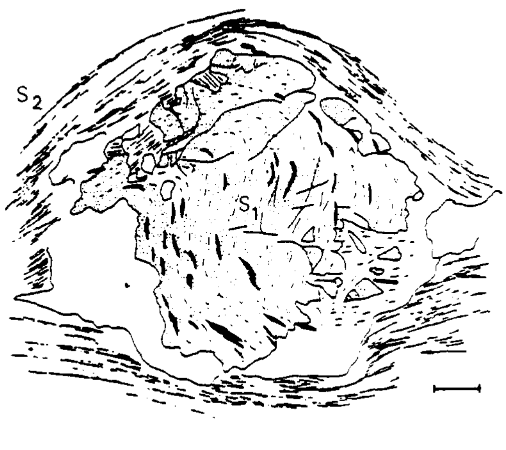

Fig. 5. S-shaped garnet. The rotated garnet includes S_0/S_1 trails with S_2 wrapped around. No young garnet developed in the lower part because of the quartz-rich rim enclosing the mineral (redrawn from colour slide; scale bar, 500 μm).

may or may not show continuity with S_i in the core. It is marked by large quartz strips which show perfect continuity with the external layering. The size of the quartz crystals is however smaller and their shape more tabular in the garnet. Some later deformations (other P/T conditions) may also be superimposed.

(4) *Idiomorphic type.* This garnet is found in homogeneous phyllosilicate-rich schists and does not display any fabric; its limits cut across the phyllosilicates of the S_2 schistosity without any disturbance.

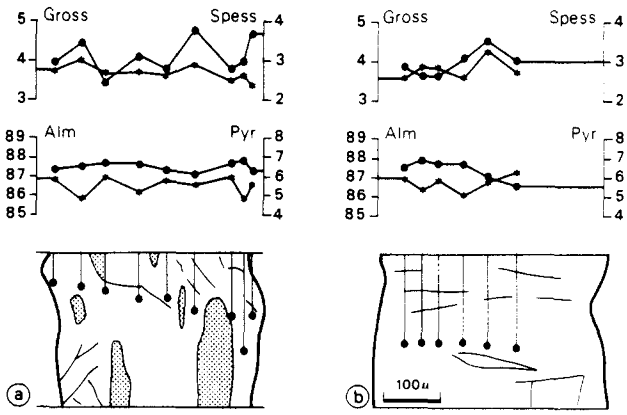

Fig. 6. Molecular compositions of low-pressure garnets (data from Toteu 1981) (a) Postkinematic type. Dotted area: quartz. (b) Euhedral type.

MICROPROBE RESULTS

A thermodynamic study of the conditions of stability of garnet was carried out by Toteu (1981) in the Ardèche region. The results on the chemical trends in zoned garnets show: (1) that grossularite-rich garnets crystallized at moderate to high pressures with a significant decrease in the grossularite and spessartite contents during prograde metamorphism towards a medium-grade facies of Barrovian type and (2) that grossularite and spessartite-poor garnets crystallized under low-pressure high-temperature conditions (2–3 kb). In the Boyon Formation, the results of microprobe analyses on the garnets show that their chemistry can often be clearly related to their structural features.

(1) The garnets of the first (Fig. 6a) and fourth types (Fig. 6b) show a nearly constant composition characterized by a high almandine content (86%) and very low grossularite (4%) and spessartite (3%) contents.

(2) The garnets of the third type (core and rim structures) show more or less smooth zoning in their cores, a nearly constant composition in their rims and a transitional zone which belongs to the inner part of the rim (Fig. 7). The compositions of their cores are very similar to those of the cores of garnets in the staurolite–garnet schists (Fig. 8). They vary within a single crystal from alm. 61%, pyr. 2.5%, gross. 18.5%, spess. 18% to alm. 69.7%, pyr. 3.5%, gross, 11.9%, spess. 14.9%. The compositions of the rims are similar to the compositions of the first and fourth type garnets. The same compositional behaviour is seen in an FeO + MgO/CaO + MnO diagram (Fig. 9).

(3) The garnets of the second type show a smooth and irregular zoning with intermediate compositions between those of the first type garnets and the cores of the third type. If we compare these results with those obtained on the Bruzac Formation (Fig. 2) and on the 'Cevennes médianes' (Toteu, 1981), they indicate that the cores are clearly related to the medium-pressure events and the rims, as well as the first and fourth type garnets, are related to the low-pressure events.

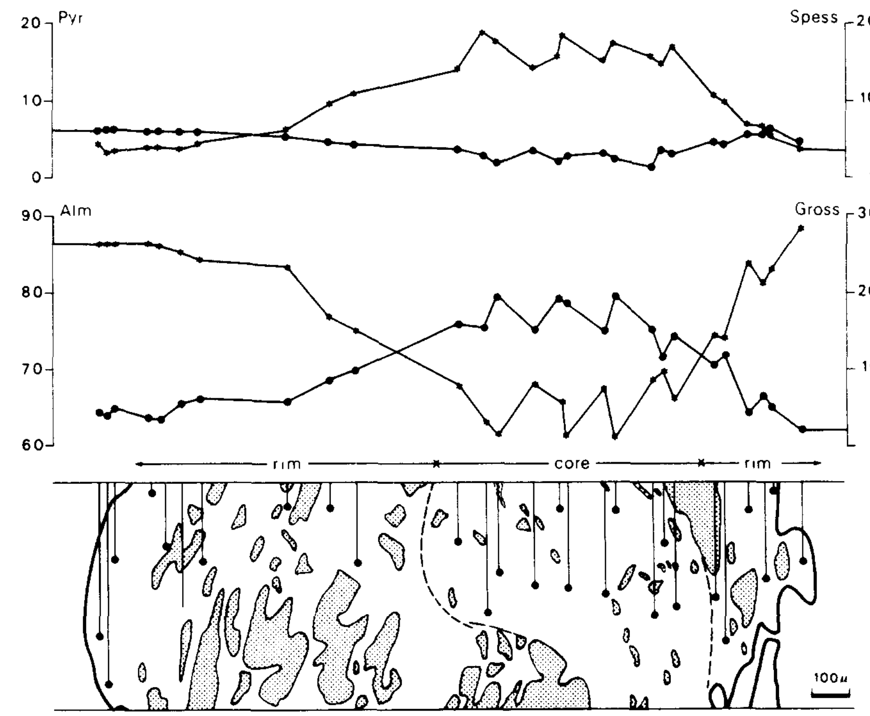

Fig. 7. Molecular compositions of core and rim garnets (data from Toteu 1981). From a structural point of view, the left-hand limit between core and rim is not as sharply defined as the right-hand limit.

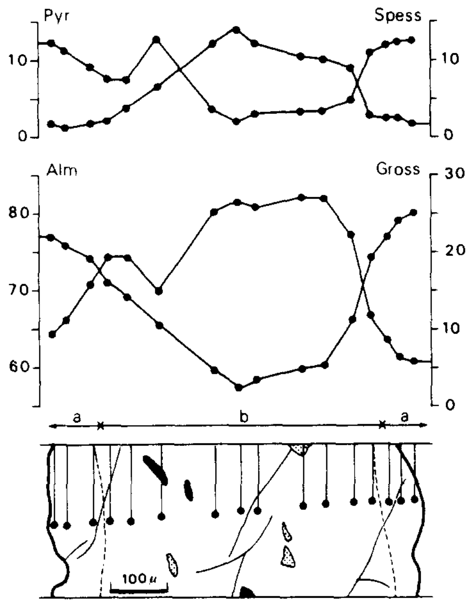

Fig. 8. Molecular compositions of the medium-pressure garnets in the staurolite–garnet schists (data from Toteu 1981).

DISCUSSION: MODEL OF GROWTH FOR THE COMPLEX GARNETS

The different structures described above can be found in the same thin section, so that their mechanisms of development cannot be simple and must reflect the complex history undergone by these rocks.

Rotational structures in the garnets of the second type and in the cores of the garnets of the third type show a moderate amount of rotation. Neither true spirals such as those described by Rosenfeld (1970) and modelled by Schoneveld (1977), nor complex structures such as those described by Powell & Vernon (1979) were found. We interpret the weak spiral structures observed as the result of pre-kinematic to synkinematic growth during the development of the main schistosity S_2 for the following reasons.

(1) The inclusion trails, S_i, clearly represent the plane of the first schistosity, S_1. There is very good continuity between S_i and S_1 in places where S_1 is locally preserved from transposition into S_2 (Fig. 10).

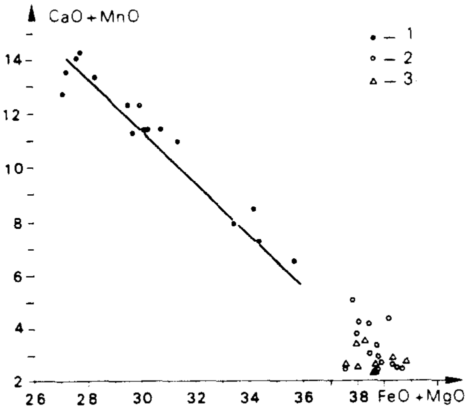

Fig. 9. CaO + MnO/FeO + MgO diagram. (1) Complex garnet cores, (2) complex garnet rims, (3) postkinematic garnets.

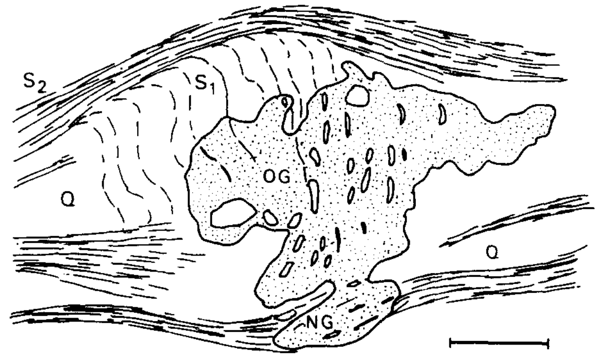

Fig. 10. Old garnet (OG) in a quartz-rich domain (Q) which locally preserves S_1. In the lower part, new garnet (NG) develops along a phyllosilicate-rich S_2 layer (redrawn from colour slide; scale bar, 500 μm).

(2) The inclusion trails may be straight in the centre of the crystal and curve progressively towards the edge; they become symmetrically parallel to S_2 (Fig. 5).

(3) The inclusion trails may sometimes be smoothly microfolded in some zones preserved from transposition.

(4) The inclusion trails are the same for quartz (minute droplets) and for other minerals which are relics of S_1.

In spite of the fact that the small number of analyses of garnets of the second type do not show compositions so typical of medium-pressure events as do the cores of the third type, we can reasonably assert that these rotational structures are synchronous. They result from interference between growth and deformation during transposition of S_1 into S_2 under metamorphic conditions of Barrovian type.

The garnets of the first and fourth types show a morphology, strongly controlled by the composition of the host rock. Alternate quartz-rich and phyllosilicate-rich layers which represent either original layering or S_1/S_2 transposition (Fig. 3a), gave rise to the particular shape of the first-type porphyroblasts.

(1) They are xenoblastic and show an elongate shape in the direction of the layering.

(2) The quartz-rich layers cut across the porphyroblast or die out into quartz-rich inclusion bands. They generally do not show any change of orientation at the limit of the crystal, but only a change in the shapes and the sizes of quartz crystals. This phenomenon has sometimes been interpreted, in the case of syntectonic recrystallization as due to progressive growth of the matrix later than trapping of quartz (Rast 1965).

(3) The garnets grew at the expense of the phyllosilicate-rich layers as shown by a mass transfer calculation (Toteu 1981) based upon microprobe analyses. As the garnet is xenoblastic, it is optically impossible to see if its crystallographic orientation is controlled by the orientation of the phyllosilicates (Powell 1966).

The fourth type garnets grew in homogeneous phyllosilicate-rich layers and hence show a euhedral shape (de Wit 1976b). They are devoid of internal structures and do not show a systematic relation between the dodecahedral plane and the phyllosilicate sheet orientation such as that described by Powell (1966).

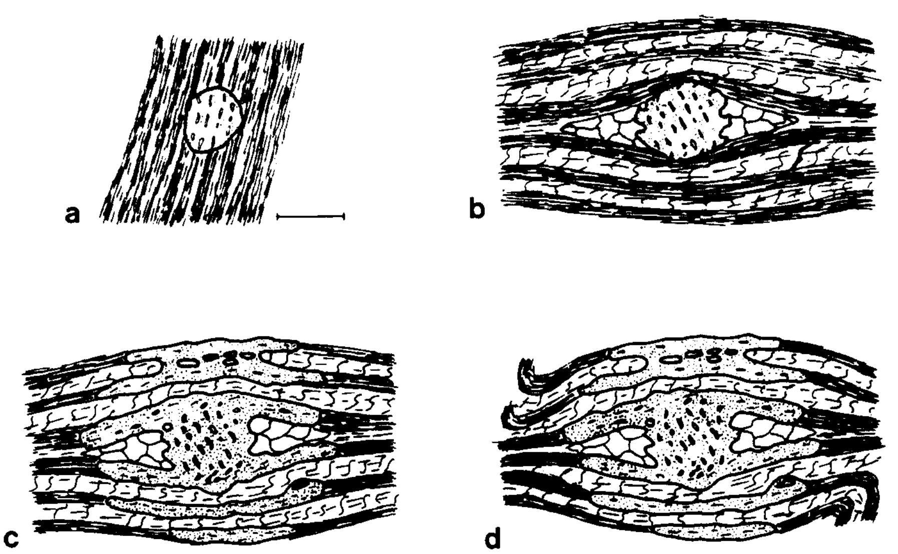

Fig. 11. Sequence of events leading to complex garnets. (Scale bar, 3 mm) (a) Old post-S_1 garnets begin to grow before S_1/S_2 transpositions. (b) S_1 is transposed into S_2 as the garnet grows. The relics of S_0/S_1 included in garnet are or are not joined to S_2: the sharpness of the transition zone is linked to the intensity of transposition and to the time of the end of garnet growth compared to the time of the end of movement. (c) The static development of younger garnet is controlled by compositional layering. The arched disposition is mimetic as resulting from D_2 deformation in the matrix prior to rim garnet growth. (d) A late post-metamorphic deformation (under other P/T conditions than garnet growth) increases the bending outside of the garnet and develops microfolding.

All the garnets of the first and fourth types show a very low CaO content, a high FeO content and have a nearly constant composition. They grew under low-pressure conditions. Petrographically they are true postkinematic porphyroblasts (Zwart 1960, Vernon 1978). Only, late postmetamorphic deformations (mainly microfolds) disturb their simple S_i/S_e relations.

Bent structures in the rims of the garnets of the third type (core and rim garnets) can be morphologically compared to case 5 of Zwart (1960) and might be interpreted as resulting from growth synkinematic with flattening. This growth could possibly have taken place during either medium or low-pressure events. The bent fabrics might equally well be interpreted by the 'force of crystallization' theory if it were possible to understand why the same sort of garnet may sometimes repel and sometimes include the same sort of matrix! We believe that the observed morphology is the result neither of growth synkinematic to flattening nor of the force of crystallization but it can be explained by static growth of garnet rims during the low-pressure event. The garnet includes bent structures thought to have been produced around the garnets during the medium-pressure events for the following reasons.

(1) The composition of the rims and of small overgrowths fringing rotational-type crystals (Fig. 10) is exactly the same as that of postkinematic garnets of types 1 or 4 and indicates low-pressure growth.

(2) The wrapping of the main schistosity S_2 around the medium-pressure garnets exists everywhere; it shows the same disposition, whether new garnet is present or not, around the rotational garnets. The deformation which gave rise to this 'augening' is generally [see (4) below] not recorded in the minerals of the low-pressure association (garnets 1 and 4, first andalusite, Fig. 4). This deformation is thus related to P_2 and not to P_3.

(3) The internal fabric of the rim is controlled by the compositional layering of the rock. The absence of new garnet around older garnets is related to the presence of a quartz-rich rim which developed around the old garnet during transposition (compare the upper and the lower part of the garnet in Fig. 5). Some symmetric or weakly asymmetric quartz pressure shadows on older garnet are preserved in the new garnet (Fig. 3f).

(4) Some rare garnets have the chemical characteristics of type 1 garnets: they show no visible core and, nevertheless, have a bent S_i. They may simply be core and rim garnets cut tangentially by the thin section. It is clear that the structures seen in the rims predate the growth of the rim garnet (Rosenfeld 1968). Nevertheless, we cannot describe this core and rim association as a tectonic unconformity (Rosenfeld 1968) for, in the neighbourhood of some rotational garnets, there is continuity between S_1 and S_2 (Figs. 5 & 10) and the rim garnet is simply superimposed on this feature.

CONCLUSION

The sequence of metamorphic and deformation events (Fig. 4) proposed for the formations of the Eastern Ardèche allows one to explain all the various morphologic features encountered in the garnets of a single thin section. This sequence can be summarized as follows.

(1) Development of old garnets under medium-pressure conditions before and during transposition of an S_1 schistosity into S_2 (Figs. 11a & b). S_1 is a metamorphic surface because it has been found as an axial plane of a first generation of folds. The S_1 and S_2 development may not be separated by a long interval of time as these two schistosities appear to develop under the same metamor-

phic conditions during prograde evolution and as P_1 and P_2 folds are mainly coaxial, but there is no radiometric evidence. The rotational garnets were produced during the transposition.

(2) Development of new garnet during a second metamorphic event earlier than the P_3 deformation event and under low-pressure conditions. This development was mainly static, as the garnet was superimposed on previously organized structures: it developed alone and gave rise to true postkinematic features (type 1 and 4 garnets); it developed as rims around older garnets (type 3 garnets) and thus included the deformation features which resulted from the presence and growth of older garnets during transposition (Fig. 11c). The resulting bent fabrics must not be confused with growth that was synkinematic to flattening (Zwart 1960).

(3) Later microfolding (under other P/T conditions than garnet growth) sometimes complicated these relationships (Fig. 11d).

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REFERENCES

Autran, A. 1980. L'évolution structurale de la France. A- L'évolution du Protérozoïque aux distensions post-hercyniennes. 26ème Congr. Géol. Intern., Paris. *Mém. Bur. Rech. geol. min. Fr.* **107**, 10–17.

Chenevoy, M. & Ravier, J. 1968. Extension des séries cristallophylliennes à andalousite-cordiérite et à disthène-staurotide dans les Cévennes septentrionales et médianes. *Bull. Soc. geol. Fr., 7 Ser.* **10**, 613–617.

Cox, F. C. 1969. Inclusions in garnet: discussion and suggested mechanism of growth for syntectonic garnets. *Geol. Mag.* **106**, 57–62.

Ferguson, C. C. & Harvey, P. K. 1972. Porphyroblasts and 'crystallisation force'. Some textural criteria: discussion. *Bull. geol. Soc. Am.* **83**, 3839–3840.

Ferguson, C. C., Harvey, P. K. & Lloyd, G. E. 1980. On the mechanical interaction between a growing porphyroblast and its surrounding matrix. *Contr. Miner. Petrol.* **75**, 339–352.

Gay, M., Briand, B., Chenevoy, M. & Piboule, M. 1982. Evolution structurale de la série métamorphique du Vivarais oriental (Massif Central). *Bull. Bur. Rech. geol. min. Fr.* (2), I, **3**, 219–232.

Gratier, J. P. 1979. Mise en évidence des relations entre changement de composition chimique et intensité de déformation dans les roches à schistosité. *Bull. Soc. geol. Fr.* 7 *Ser.* **21**, 95–104.

Gratier, J. P. 1982. Approche expérimentale et naturelle de la déformation des roches par dissolution–cristallisation avec transfert de matière. *Bull. Minéral.* **105**, 291–300.

Hobbs, B. E. & Talbot, J. L. 1968. The relationship of metamorphic differentiation to other structural features at three localities. *J. Geol.* **76**, 581–587.

Juteau, T., Leroy, J., Macaudière, J., Marignac, C. & Weisbrod, A. 1974. Etude structurale des formations polymétamorphiques et des granites du Vivarais oriental (Massif central français). *2ème Réunion annuelle des Sci. Terre, Nancy*, 232.

Misch, P. 1971. Porphyroblasts and 'crystallization force': some textural criteria. *Bull. geol. Soc. Am.* **82**, 245–252.

Misch, P. 1972. Porphyroblasts and 'crystallization force': some textural criteria: Reply. *Bull. geol. Soc. Am.* **83**, 1203–1204.

Nicholson, R. 1966. Metamorphic differentiation in crenulated schists *Nature, Lond.* **209**, 68–69.

Olesen, N. Ø. 1978. Distinguishing between inter-kinematic and synkinematic porphyroblastesis. *Geol. Rdsch.* **67**, 278–287.

Powell, D. 1966. On the preferred crystallographic orientation of garnet in some metamorphic rocks. *Min. Mag.* **35**, 1094–1109.

Powell, D. & Treagus, J. F. 1970. Rotational fabrics in metamorphic minerals. *Min. Mag.* **37**, 801–814.

Powell, D. & Vernon, R. H. 1979. Growth and rotation history of garnet porphyroblasts with inclusion spirals in a Karakoram schist. *Tectonophysics* **54**, 25–43.

Ramberg, H. 1952. *The Origin of Metamorphic and Metasomatic Rocks*. The University of Chicago Press.

Ramsay, J. G. 1962. The geometry and mechanics of formation of 'similar' folds. *J. Geol.* **70**, 309–327.

Rast, N. 1965. Nucleation and growth of metamorphic minerals. In: *Controls of Metamorphism* (edited by Pitcher, W. S. & Flinn, G. W.). Oliver & Boyd, London, 73–102.

Rosenfeld, J. L. 1968. Garnet rotations due to the major Paleozoic deformations in Southeast Vermont. In: *Studies of Appalachian Geology: Northern and Maritime* (edited by Zen, E., White, W. S. Hadley, J. B. & Thompson, J. B.). Wiley-Interscience, New York, 185–202.

Rosenfeld, J. L. 1970. Rotated garnets in metamorphic rocks. *Prof. Pap. geol. Soc. Am.* **129**, 1–105.

Saggerson, E. P. 1974. Porphyroblastesis and displacement: some new textural criteria from pelitic hornfels. *Min. Mag.* **39**, 793–797.

Schoneveld, C. 1977. A study of some typical inclusion patterns in strongly paracrystalline-rotated garnets. *Tectonophysics* **39**, 453–472.

Shelley, D. 1972. Porphyroblasts and "crystallization force": some textural criteria: Discussion. *Bull. geol. Soc. Am.* **83**, 919–920.

Soula, J. C. & Debat, P. 1976. Developpement et caractères des litages tectoniques. *Bull. Soc. geol. Fr., 7 Ser.* **18**, 1515–1537.

Spry, A. 1963. The origin and significance of snowball structure in garnet. *J. Petrol.* **4**, 211–222.

Spry, A. 1972. Porphyroblasts and "crystallization force" some textural criteria: Discussion. *Bull. geol. Soc. Am.* **83**, 1201–1202.

Toteu, S. F. 1981. Utilisation des analyses chimicominéralogiques et microstructurales dans la reconstitution des événements tectonométamorphiques des formations polycycliques: exemples du Vivarais cristallin, Ardèche (France). Thèse de 3è cycle, Nancy.

Vernon, R. H. 1978. Porphyroblast-matrix microstructural relationships in deformed metamorphic rocks. *Geol. Rdsch.* **67**, 288–305.

Vernon, R. H. & Powell, C. McA. 1976. Porphyroblastesis and displacement: some new textural criteria from pelitic hornfels—a comment. *Min. Mag.* **40**, 787–788.

Vigot, M. 1963. Etude des formations cristallophyliennes et des gîtes métallifères du socle et de la couverture de la région de Privas–St Cierge-la-Serre (Ardèche). Thèse 3è cycle, Paris.

de Wit, M. J. 1976a. A note on the origin of syntectonic porphyroblasts and their inclusion fabrics. *Geol. Mag.* **113**, 383–388.

de Wit, M. J. 1976b. Metamorphic textures and deformation: a new mechanism for the development of syntectonic porphyroblasts and its implications for interpreting timing relationships in metamorphic rocks. *Geol. J.* **11**, 71–100.

Zwart, H. J. 1960. The chronological succession of folding and metamorphism in the central Pyrenees. *Geol. Rdsch.* **50**, 203–218.

Zwart, H. J. 1962. On the determination of polymetamorphic associations and its application to the Bosost area (central Pyrenees). *Geol. Rdsch.* **52**, 38–65.

Zwart, H. J. & Calon, T. T. 1977. Chloritoid crystals from Curaglia: growth during flattening or pushing aside? *Tectonophysics* **39**, 477–486.