Evidence for differences in growth rate among garnets in pelitic schists from northern Sutherland, Scotland

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Abstract

MnO zoning profiles for various sizes of garnets from two pelitic schists were examined. The data from garnets of specimen A are consistent with a constant growth law, while the compositional–crystal size relationships of garnets from specimen B are best explained by heterogeneous growth rates.

KEYWORDS: garnet, growth rate, pelitic schists, Sutherland, Scotland.

Introduction

DETAILED work by various authors (Galwey and Jones, 1963, 1966; Jones and Galwey, 1964, 1966; Kretz, 1966, 1973, 1974 and Jones et al., 1972) have shown that information on nucleation and growth rates in metamorphic rocks can be obtained from studies of the crystal size distribution within a rock. Galwey and Jones (1963) offered two models to explain the size distribution data. According to the 'instantaneous random nucleation model', the final size of any crystal is a measure of the dimensions of the diffusion domain supplying reactant material to the growing nucleus. In the alternative 'nucleation and growth model' nucleation is considered to be progressive with the crystal size distribution being a direct reflection of nucleation rate so that the ultimate size of any crystal is a function of the time span in which it grew (Anderson and Olimpio, 1977). Studies on regionally metamorphosed rocks have supported the latter model. (Atherton and Edmunds, 1966; Kretz, 1973; Raheim, 1975; McAteer, 1976; Finlay and Kerr, 1979). Such data

appear to indicate that all crystals could not have nucleated simultaneously but that progressively smaller garnets nucleated at progressively later points in time (Atherton, 1976).

Implicit in the nucleation and growth model is the assumption that growth rate is constant for all garnets in a rock. Thus the crystal size distribution would be a direct reflection of the nucleation rate. Kretz (1973) examined the form of the growth rate equation and considered three possible models in which the respective rates of increase of radius (r), surface area (a) and volume (v) were assumed to be constant. He concluded that the compositional data for the specimen studied indicated a growth rate lying between that expressed by model 1 and that for model 2 (Kretz, 1974).

In the decade since this work was published few additional data on nucleation and growth in metamorphic rocks have been forthcoming (Tracy, 1982). Furthermore, the assumption of a constant growth rate for crystals from a single sample has not been rigorously tested. This paper is an attempt to provide some additional data.

Specimen A

Finlay and Kerr (1979) described compositional zoning profiles of garnets extracted from a typical Moinian garnet–mica schist from the Port Vasgo area, northern Sutherland, Scotland. Data from this sample, particularly the virtually direct correlation between crystal size and MnO core composition (Fig. 1) and the matching of points on
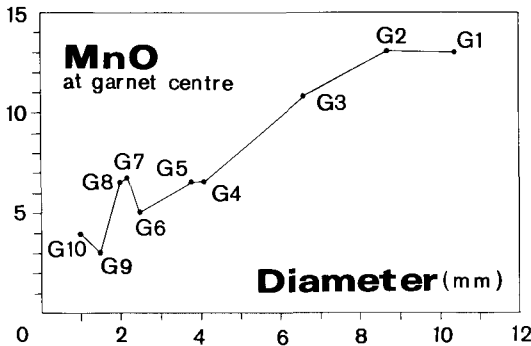

FIG. 1. Plot of MnO concentration (wt. %) at garnet centre against crystal size for grains from specimen A. Note the generally positive correlation.

profiles of differently sized crystals (Fig. 2) suggested a model of continuous nucleation and growth.

These data can now be re-examined to test the assumption of a constant growth rate. That this might be so is supported by the following data.

Firstly, a characteristic feature of some of the larger garnets is the presence of fine, opaque, needle-like inclusions of ilmenite which occur either as a cluster at the garnet core or are arranged as one or two discrete rings within a crystal. These zones of inclusions occur at similar MnO concentration levels and, where arranged in two rings, they *always* have a linear separation of 2 mm. This remarkable constancy suggests that the inclusions may act as time markers within the crystal and that growth rate for all crystals was equal at least for the period of growth covering ilmenite incorporation.

Secondly, apart from the two smallest crystals (which according to the model had not yet nucleated) all garnets display a distinctive 'shoulder' in the CaO profiles; this occurs at 8% CaO and is of equal width in all crystals regardless of diameter.

These data could therefore be offered in support of a constant growth rate for most of the garnets in specimen A. To test this further an attempt was made to define the form of the growth rate equation using the method of Kretz (1974). Several plots of different compositional-contour pairs were produced for the range of garnet sizes, with two data point obtained from measurements on opposite sides of the same zoning profile. A slight scatter was found for some plots although the best-fit line appeared to be approximately similar in all cases. A composite diagram (Fig. 3) incorporating all the measurements emphasised this, and the data define a narrow zone bounded by the empirical line of Kretz (*op. cit.*) and that for theoretical growth model 1. The results would thus appear to be consistent with a constant growth rate for garnets in specimen A.

Specimen B

A second specimen of garnet–mica schist from the same area (Finlay, 1976) was subjected to similar analysis. MnO profiles from different sizes of garnet are given (Fig. 4) as well as a plot of crystal size against MnO core composition (Fig. 5).

Apart from generally simpler compositional profiles, the most obvious difference from the results obtained from the garnets of specimen A is that the largest crystal does not contain the highest MnO core composition, a requirement of the progressive nucleation of garnet (Hsu, 1968; Miyashiro and Shido, 1973; Anderson and Olimpio, 1977). This suggests that crystal diameter may not be used as a measure of the relative time of nucleation. Therefore, several alternative models to explain these data were considered for this specimen.

Model 1: Instantaneous nucleation

This is characteristic of porphyroblasts in thermal regimes (Atherton, 1976) and requires that all crystals should have the same crystal : matrix distribution coefficient and therefore similar MnO core compositions (Ono, 1975a, b). This is not so for the present data. Furthermore, instantaneous nucleation would result in a relationship between the ultimate size of a crystal and the distance to its nearest neighbour (Kretz, 1973; Atherton, 1976; Loomis, 1983). Such a relationship is not present in specimen B nor has it been established by detailed investigation of a variety of other regionally metamorphosed rocks (Jones and Galwey, 1964; Galwey and Jones, 1966; Kretz, 1966, 1973).

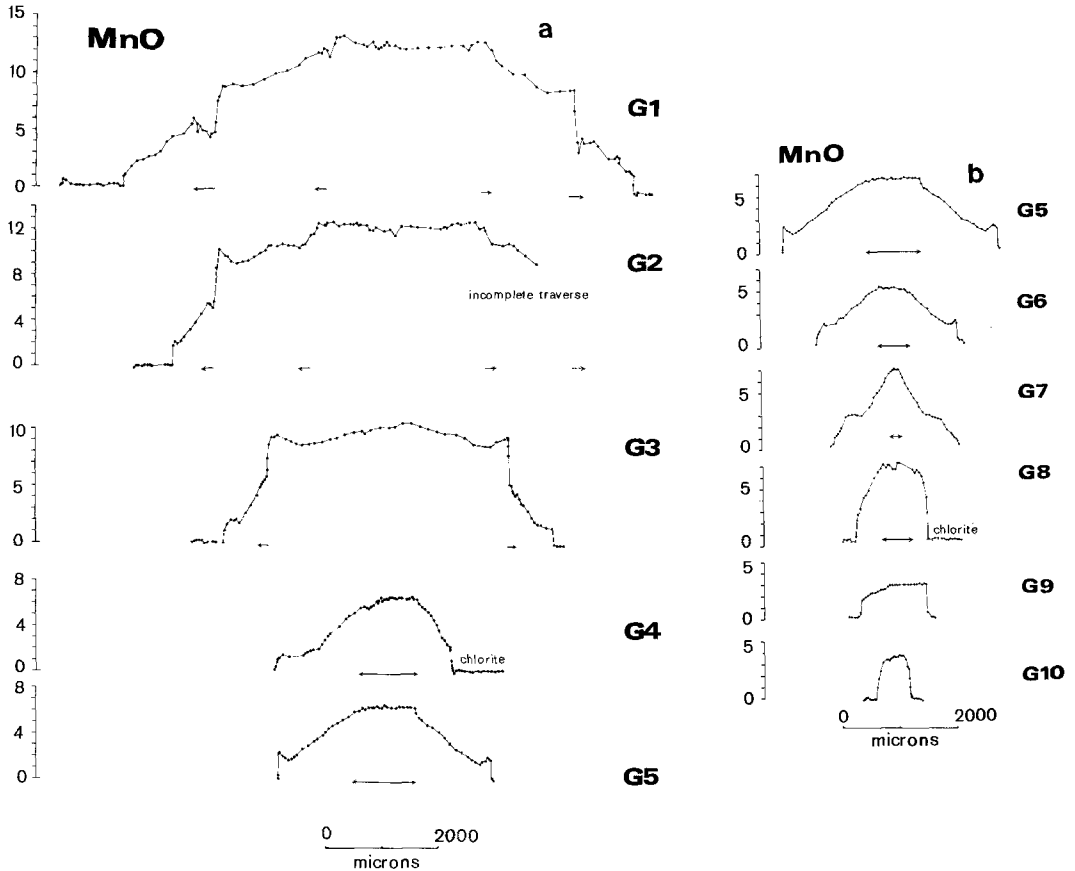Various non-instantaneous nucleation models were then considered.

FIG. 2(a) MnO compositional profiles across garnets G1 and G5 from specimen A. Arrows indicate the extent and position of ore inclusion zones. (b) MnO compositional profiles for smaller (later) garnets G5 to G10.

Model 2: Domainal equilibrium

Each crystal nucleated and grew in an isolated domain with little or no intergranular diffusion between domains. Such a local equilibrium model might explain the overall lack of correlation between MnO core concentration values and crystal size but is rejected for the following reasons.

(a) Lack of interdomainal diffusion might be expected to result in the development of leached zones (diffusion haloes) round some crystals (Woodland, 1963; Rast, 1965; Hess, 1971; Atherton, 1976). Such depletion aureoles around garnets are not seen in specimen B (Finlay, 1976). Each crystal is surrounded by the same minerals in approximately the same proportions implying that diffusion through the matrix was possible for certain major components at least.

(b) All crystals have compositional profiles consistent with (? prograde) growth in a fractionating system (Cygan and Lasaga, 1982; Loomis, 1983). This process requires that diffusion in the matrix is rapid compared to growth rate in order to produce smooth zoning profiles (Hollister, 1969). It is difficult to accept that diffusion in any system can be rapid within domains but restricted between them in the absence of any obvious microstructural or lithological controls (cf. Olimpio, 1979).

(c) The model requires gross heterogeneity in MnO distribution in the rock prior to garnet formation in order to explain the variation in garnet core compositions. Given a process of continuous nucleation and the existence of such Mn-rich domains, it would be expected that the crystal containing the highest MnO core value would nucleate first in such domains (Trzcienski, 1977; Loomis and Nimick, 1982; Loomis, 1982) and subsequently grow to the largest size (Hsu, 1968; Anderson and Olimpio, 1977; Finlay and Kerr,
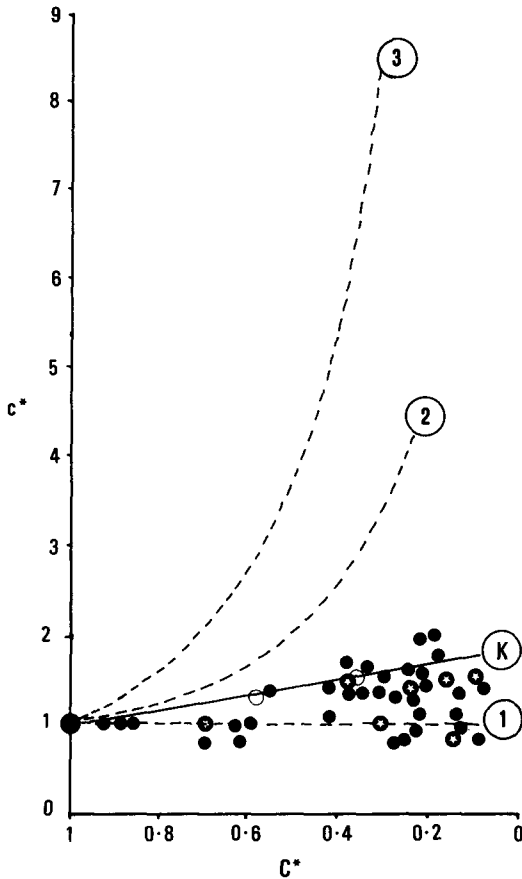
FIG. 3. Composite diagram of C^* and c^*. C^* is the distance from a crystal centre to the mid-point between two chosen compositional contours relative to the equivalent point in the zoning profile of the largest crystal. c^* is the linear separation of these two chosen compositional contours relative to the distance between the same contours on the largest crystal. The dashed lines, numbered 1, 2 and 3 represent the theoretical growth laws defined by Kretz while the solid line, with data points and marked by 'K', is the empirical line found by Kretz (1974). The data points for the 2.5–3.5% compositional contour pair are indicated by solid dots with central star.

1979). This is not so and the isolated domain theory is rejected.

Model 3: Influx of MnO

The largest crystal was the first to nucleate with a core value of 5.5% MnO. At a later stage, release of, or metasomatic introduction of MnO

into the sytem, or a change in the distribution coefficient, allowed crystals with core values of almost 14% MnO to nucleate. Such addition of MnO into the system should be reflected in the compositional profiles of all crystals existing *at that time*, and hence should be present in the profiles of the earlier (now larger) crystals. Since the MnO profiles of all analysed crystals decrease continuously from core to rim with no inflexions, this model is rejected. Similarly the above argument would also militate against two distinct generations of garnet being present in specimen B.

Model 4: Volume diffusion

Nucleation occurred in the order given by crystal sizes but the compositional profiles of the larger garnets have been modified and flattened by subsequent volume diffusion (Atherton, 1968; Blackburn, 1969; Anderson and Buckley, 1973; Woodsworth, 1977; Yardley, 1977; Tracy, 1982; Loomis, 1983). Indeed, this model has been utilized to explain data from a study of garnet zoning in Moinian rocks of similar grades from the Moray area, Scotland (Anderson and Olimpio, 1977). Certainly, intracrystalline diffusion of varying extent in different garnets would explain the present data but is considered unlikely to have occurred in the garnets from specimen B because:

(*a*) The MnO compositional profiles and those for Ca, Mg, Fe (Finlay, 1976) are reasonably typical of 'normal' zoning profiles widely accepted as originating through fractionation processes operating during crystal growth (Cygan and Lasaga, 1982; Dietvorst, 1982). Such zoning behaviour is common in garnets from low- and medium-grade pelitic rocks (Tracy, 1982) and probably represents a primary formation during crystal growth without interference by chemical diffusion (Dempster, 1985).

(*b*) Specimen B has undergone metamorphism of relatively low temperatures of garnet grade (Finlay, 1976; Winchester, 1974) whereas homogenization or modification of MnO compositional profiles of garnets by thermally-activated diffusion process is usually reported from rocks which have been metamorphosed at considerably higher temperatures (Blackburn, 1968; Hollister, 1969; Tracey *et al.*, 1976; Woodsworth, 1977; Yardley, 1977; Cygan and Lasaga, 1982; Dempster, 1985).

(*c*) The MnO profiles from specimen A garnets show no evidence of the effects of intracrystalline diffusion. They have thus remained refractory despite being metamorphosed to higher temperatures close to staurolite grade (Finlay, 1976).
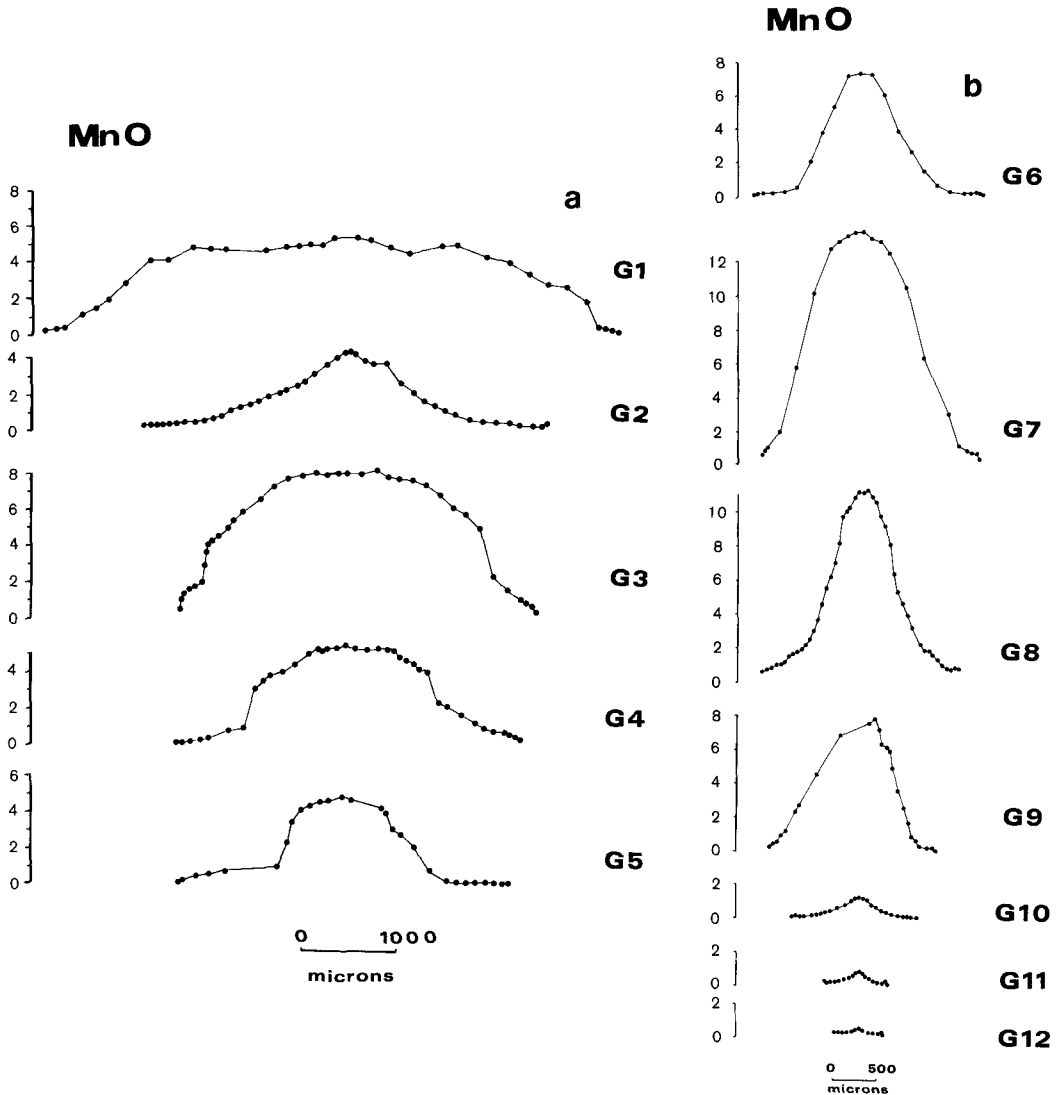
FIG. 4(a) MnO compositional profiles across garnets G1 to G5 from specimen B. (b) MnO compositional profiles across garnets G6 to G12 from specimen B.

Model 5: Heterogeneous growth rates

The largest garnet did not nucleate first. Rather nucleation occurred as for specimen A in a sequence indicated by MnO core composition values. This seems a reasonable assumption given the strong affinity of garnet for Mn (Hollister, 1969; Miyashiro and Shido, 1973) which forms the basis of many models for garnet zoning (Hollister, 1969; Atherton 1968, 1976; Harte and Henley, 1966; Grant and Weiblen, 1971; Miyashiro

and Shido, 1973; Tracy et al., 1976). In addition it is compatible with the finding that garnet commonly nucleates first in MnO-rich domains (Loomis and Nimick, 1982) and hence would be expected to grow ultimately to the largest size. However, if this is so, then some crystals which nucleated later grew significantly larger than expected. A consequence of this is that growth rate was heterogeneous i.e. varied *between* crystals. To test this hypothesis the data were subjected to the Kretz method of growth-rate analysis
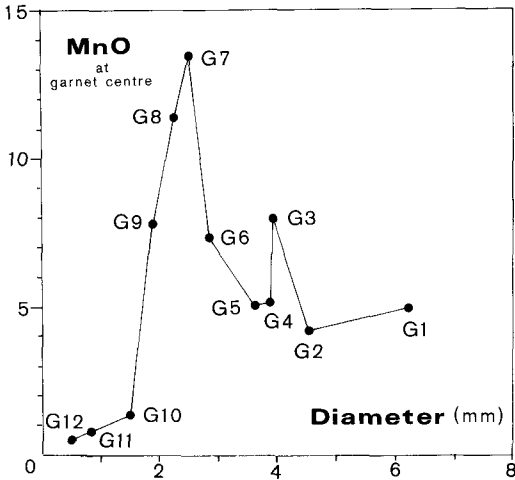
FIG. 5. Plot of MnO concentration (wt. %) at garnet centre against crystal size grains from Specimen B. Note the irregular pattern.

FIG. 6. Composite diagram showing the relationship between C* and c* for specimen B. (Parameters as for Fig. 3).

(Fig. 6). The points do not lie on any one theoretical curve and indeed there is a concentration below the line for $dr/dt = k$. The possibility that points should lie below this line lies outside the models considered by Kretz suggesting that data from this specimen are not amenable to this type of analysis. There is however a tendency for the spacing of compositional contours to become smaller with decreasing crystal size. This indicates that crystal growth varied with larger crystals growing faster than smaller ones. This is compatible with model 5, where some garnets have diameters larger than predicted by their MnO core contents.

Factors that might cause such a variation in growth rate are complex and might include changes in the rate of decomposition of reactants, variations in intergranular diffusion rates, differences in the dissipation of latent heat, or the rate of incorporation of reactants. Any one or combination of these would determine the rate at which individual crystals would increase their size (Loomis, 1982).

Whatever the reason, the fact that growth rate varied between garnets in specimen B suggests some heterogeneity in their growth environment. The nature of this heterogeneity is problematical as the matrix is apparently homogeneous.

Petrographic analysis of the time of garnet growth relative to the rock fabric gives ambivalent results. Some crystals show curved inclusion trails of quartz grains and slight bowing of the matrix aroun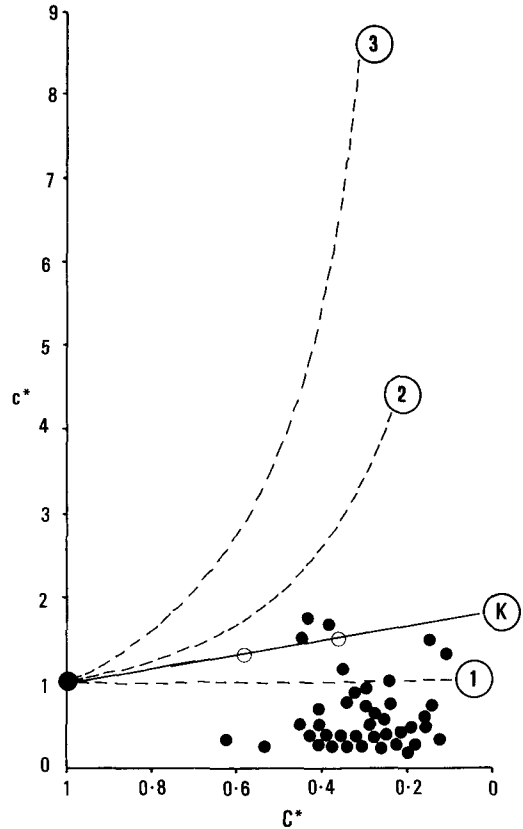d the crystals. These features are normally interpreted as indicative of syntectonic growth. Other garnets however have euhedral shapes and textural relationships which suggest growth in a post-tectonic period (Finlay, 1976).

If garnet growth was largely syntectonic, the possibility exists that, as deformation proceeded, certain growth sites became particularly favourable. The development of microfractures, possibly resulting from incompatibilities of strain rate between adjacent grains or groups of grains, could create an increased number of diffusional pathways around the growing crystals (Etheridge et al., 1983).

Alternatively, if garnet growth was largely post-tectonic, it is possible that the growth environment contained residual strain energy of deformation (Rast, 1965). If this was not homogeneously distributed nucleation of garnet in strained areas would effectively release such stored energy

resulting in slight flow, and grain boundary reorganisation of contiguous matrix minerals. Such localised readjustments could create more diffusion channelways.

As the garnets examined in this work were extracted from the rock it is impossible to study the nature and position of the growth sites of various sized crystals relative to the tectonic fabric. Indeed, whether such microfractures could still be identified in the rock is problematical, since it is commonly believed that such cracks would be annealed subsequently during the metamorphic process. Therefore, both of the above speculations seem equally feasible with the accelerated growth of the larger crystals attributable to the creation of additional channelways along which garnet-forming reactants could migrate. The diffusion rate of reactants could remain constant, thus maintaining chemical equilibrium throughout the rock, yet in those regions where such additional channelways existed garnet growth per unit time was enhanced. This might account for some crystals having a larger size than predicted from their core composition.

While it is not possible to isolate the exact mechanism controlling the rate of garnet growth in specimen B, the data do suggest that interfacial processes of some kind were a major factor. The homogeneity of the groundmass, the lack of diffusion haloes, the euhedral shape of many garnets and the lack of correlation between crystal size and position in the rock (Kretz, 1973) indicate that growth was probably not diffusion controlled (Loomis, 1982, 1983).

Conclusions

While the above results for specimen B are not unequivocal, the data do indicate the probability of variable growth rate between crystals from a single rock. That growth rate might vary is sometimes suggested in the literature. However, these variations are usually utilized to explain anomalies or marked inflexions in the compositional profile of a single crystal which is *assumed* to be representative of all crystals in the rock (Dowty, 1980). The implication is that all garnets responded in a similar manner at the same time.

If the present interpretation is correct then the possibility that crystals grew at the same time but with different growth rates will be an additional complication in unravelling the metamorphic history of a particular rock. This possibility obviously needs further study.

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