POLYMETAMORPHIC GARNET ZONING FROM SOUTHEASTERN VERMONT

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ABSTRACT. Textural unconformities involving garnet inclusion trails indicate garnet grew in two stages in an aluminous schist within the late Proterozoic to Cambrian Hoosac Formation on the east flank of the Green Mountains massif in southern Vermont. Textures record a pervasive retrogression which partially chloritized first stage garnet and preceded second stage garnet. The retrogression resulted in garnet zoning anomalies in an outer first stage garnet shell up to 0.5 mm thick. Normal growth zoning patterns resume in the second stage garnet rim. The zoning anomalies probably reflect diffusion within garnet during retrogressive alteration. The rate of diffusion, however, is likely enhanced by grain boundary diffusion along inclusion-garnet boundaries. The first prograde metamorphism is probably Ordovician, and the second Devonian. The retrogression and a period of thrust faulting are both approximately bracketed by two sets of folds, thus the retrogression may reflect thrusting of the rocks from garnet grade to colder temperatures, followed by later reburial and a second prograde metamorphism.

INTRODUCTION

Textural and chemical evidence indicates that the Late Precambrian to Ordovician cover rocks east of the Grenville I by old basement rocks of the Green Mountains massif in southern Vermont had complex metamorphic histories. Rosenfeld (1968) described garnet inclusion textures produced during two distinct growth stages resulting in a "tectonometamorphic" unconformity from the Cambrian Pinney Hollow Formation near the Athens dome in southeastern Vermont (see Doll and others, 1961). Rosenfeld suggested that these rocks record both Ordovician and Devonian metamorphism, because similar textures are not found in Silurian and Devonian rocks. Laird and Albee (1981a,b) presented textural and chemical evidence for polymetamorphism from Cambrian and Ordovician mafic schists in Vermont and also proposed that they experienced Ordovician and Devonian metamorphism, supporting Albee's (1968) evidence for polymetamorphism in northern Vermont based on superimposed metamorphic belts. Cheney (1980) cited evidence for polymetamorphism in highly aluminous schists of the Late Precambrian to Cambrian Hoosac Formation in western Massachusetts. Recent radiometric dating accords with the textural and chemical evidence for polymetamorphism. Ordovician and Devonian thermal events have been documented by Sutter, Ratcliffe, and Mukasa (1984) in the Berkshire and southern Green Mountains massifs and by Lanphere and Albee (1974) and Laird, Lanphere, and Albee (1984) in northern and central Vermont.

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Karabinos (1984) reported textures and garnet zoning patterns in chlorite–chloritoid bearing schists near Jamaica, Vt. that record a prograde-retrograde-prograde metamorphic history and discussed possible tectonic implications of this metamorphic pattern. This paper describes in detail the textural and chemical evidence for polymetamorphism in these rocks and presents a model to explain garnet zoning anomalies produced during the intermediate retrogression. These garnets are especially valuable because the textures independently record a detailed metamorphic history which can then be compared with the garnet zoning profiles.

STRUCTURAL SETTING

The chlorite–chloritoid schists described here are from a highly aluminous unit in the Hoosac Formation which is Proterozoic Z to Cambrian in age (Doll and others, 1961; Norton, 1976; Zen and others, 1983). This belt of the Hoosac Formation was thrust westward along with an unconformably underlying wedge of Proterozoic Y basement onto the east flank of the Green Mountains massif (Karabinos, 1984; fig. 1). The Proterozoic Z to Middle Ordovician metamorphosed sedimentary and volcanic rocks east of the Berkshire and Green Mountains massifs were deformed during the Taconic orogeny with significant crustal shortening due to thrust faulting (Norton, 1975; Ratcliffe and Mose, 1978; Stanley, 1978; Knapp and Stanley, 1978; Stanley and Ratcliffe, 1980; Zen and others, 1983). Devonian deformation and metamorphism were intense east of the Green Mountains massif in southern Vermont (Rosenfeld, 1968; Thompson and Norton, 1968; Skehan, 1972; Hepburn, 1975) and made recognition of Ordovician structures difficult.

In the Jamaica area (fig. 1) an early deformation produced km-scale, westward overturned F₁ folds with an axial-planar S₁ fabric (fig. 2). Thrusting occurred late in or after this period of folding, and the Cobb Brook thrust is not folded by the F₁ Jamaica anticline (fig. 1). The thrust faults are deformed by later F₃ folds which have half-wavelengths of about 200 m and an east-dipping, axial-planar crenulation cleavage, S₃ (fig. 1). F₃ folding gently warped S₂ into open, upright, east-trending folds with wavelengths less than 2 m and no new crystallization parallel to the axial planes defining S₃.

TEXTURAL EVIDENCE FOR POLYMETAMORPHISM

Description of the chlorite–chloritoid schist.—The chlorite–chloritoid schist is made up of, in approximate order of abundance, white mica (muscovite and paragonite), chloritoid, quartz, chlorite, garnet, ilmenite, epidote, apatite, and tourmaline. Magnetite is present in some samples, and rutile is found as inclusions in garnet cores but is absent from the matrix. Staurolite occurs as an additional phase in some samples from the southeastern part of the area, and one outcrop has the assemblage kyanite–staurolite–garnet–chlorite (Karabinos, ms). Garnet porphyroblasts are up to 2 cm in diameter; all other minerals are less than 2 mm in longest dimension. This lithology is very similar to the Gassetts schist in the Chester dome in southeastern Vermont studied by Thompson, Lyttle, and Thompson (1977) and Thompson and others (1977).
Textural unconformities in garnet.—Textural unconformities are present in virtually all the 65 garnet bearing samples from the Hoosac Formation (fig. 1) studied in thin section. They occur in the assemblages garnet–chlorite–biotite–albite and garnet–chlorite–chloritoid–paragonite. Garnets from the latter assemblage, however, are consistently larger and have clearer inclusion trails defining the textural unconformities than garnets from the chlorite–biotite–albite assemblage. The inclusions pattern in the garnet from sample 120 (fig. 3) is typical of all the garnet bearing samples studied. Aligned grains of chloritoid, quartz, white mica, rutile, and ilmenite in the inner garnet shell preserve an early fabric. This inclusion trail is abruptly truncated along an irregular boundary marked by a high concentration of ilmenite. The outer garnet shell overgrew minerals conformable with the well developed crenulation cleavage, $S_2$, in the matrix. Rutile needles are abundant in most of the inner shell but are absent from the matrix, the outer shell, and the inner shell within about 0.5 mm of the textural unconformity and along irregular embayments.

Fig. 1. (A) Geologic map of the Jamaica, Vt. area. Mapping was done at a scale of 1:20,000 using enlargements of the Londonderry and Saxtons River 15’ Quadrangles, 1957. Numbers refer to sample localities mentioned in text. WS, CS, ES—western, central, and eastern sequences, respectively; JT—Jamaica thrust; CBT—Cobb Brook thrust; g—granodiorite near CBT; tr—terra rosa.
(B) Structure section, no vertical exaggeration.
The textural unconformity between the inner and outer inclusion trails indicates that the garnet grew in two stages separated by a deformation. Inclusion trails in the inner garnet shell are straight or gently sigmoidal in contrast with the crenulated matrix fabric. The inner inclusion trails are, therefore, assumed to be relict \( S_1 \) and the crenulation cleavage in the matrix is \( S_2 \). The first garnet stage, \( G_1 \), grew late in or after \( S_1 \) development, and the second garnet stage, \( G_2 \), grew late in or after \( S_2 \) development (fig. 2). These textural unconformities are very similar to those described by Rosenfeld (1968) from the Pinney Hollow Formation on the west limb of the Athens dome about 6 km to the east.

**Intermediate retrogression.**—In more than 90 percent of the samples garnet is embayed and/or rimmed by clots of randomly oriented chlorite grains. Figure 4 shows an unusually extensive chloritization of garnet from sample 111 (see fig. 1). These chlorite clots are texturally distinct from fine-grained, elongate chlorite flakes that parallel folded \( S_1 \) in the matrix. There are rutile inclusions (not shown in fig. 4) in the core of the garnet suggesting that some of it was produced during the first growth stage. Second stage growth in this partially pseudomorphed garnet cannot be clearly recognized, however, due to the absence of well defined inclusion trails. Such textures clearly record retrogressive replacement of garnet by chlorite but do not tightly constrain the timing of retrogression.

In figure 5 the irregular boundary between the inner and outer garnet shells is marked by a high concentration of ilmenite, and rutile is abundant in the inner shell but absent from the outer. \( G_1 \) overgrew min-
erals defining S₂, and G₂ overgrew S₂. A large clot of randomly oriented chlorite grains showing the characteristic retrograde texture is in contact with sharp, clear, euohedral G₂. Importantly, chlorite clots outside garnet pressure shadows were deformed by S₂ and therefore predated that deformation, but G₂ grew late in or after S₂ development. These textures record partial chloritization of first stage garnet followed by second stage garnet growth at the expense of retrograde chlorite.

The amount of second stage garnet growth is generally higher in the eastern part of the area, near and above the staurolite isograd (fig. 1). Therefore, textures recording the partial chloritization of first stage garnet are variable and best preserved in the western part of the area (sample 111), while textures indicating second stage garnet overgrew the crenulation cleavage, S₂, are clearer in rocks from the eastern part of the area (sample 120).

**COMPOSITIONAL ZONING IN GARNETS**

*Methods.*—I performed all analyses on the automated MAC electron microprobe at the Geophysical Laboratory of the Carnegie Institute of Washington. The data reduction program uses a Bence-Albee correction scheme. Natural mineral and synthetic glass standards provided by the laboratory were chosen such that correction factors were minimized. Accelerating voltage was 15 KV, and counting intervals were 50 sec or 30,000 counts. The beam current was approx 0.1 microamp, and the beam diameter was 5 to 6 micrometers.

*Results.*—The garnet zoning profile from sample 120 (fig. 6) is typical of all the 25 samples studied with the electron microprobe. From core to rim there are three segments: (1) rutile-bearing, first stage garnet with increasing Mg/Fe and decreasing Mn/Fe ratios, (2) rutile-free, first stage garnet adjacent to the textural unconformity with anomalously low Mg/Fe and high Mn/Fe ratios, and (3) rutile-free, second stage garnet with in-
Fig. 3. Drawing from photomicrograph of garnet porphyroblast with early garnet growth (G₁) separated from later garnet growth (G₂) by a textural unconformity (TU). The line C-R shows location of probe traverse in figure 6. Sample 120. The inner inclusion trail is assumed to represent the early schistosity, S₁, and the outer inclusion trail is conformable with the matrix crenulation cleavage, S₂. The opaque inclusions are ilmenite and magnetite, the elongate grains are white mica, chlorite, and chloritoid.

creasing Mg/Fe and decreasing Mn/Fe ratios. Less detailed zoning profiles from other garnets show similar anomalies (fig. 7).

The compositional variation of chloritoid inclusions in garnet from sample 120 is strikingly similar to that of garnet (fig. 8). To increase the number of data points the chloritoid inclusion compositions are taken from grains throughout the three garnet zones and not just along the garnet zoning profile. Within zones 1 and 3 of the garnet the Mg/Fe ratio of chloritoid increases and the Mn/Fe ratio decreases regularly with increasing radial distance from the garnet center. Within zone 2, the chloritoid inclusions show anomalously high Mn/Fe and low Mg/Fe ratios, similar to the garnet zoning profile. There are no chlorite inclusions, so its compositional variation is unknown. The garnet and chloritoid compositions are compatible with these phases having been in equilibrium with respect to exchange reactions Albee (1972). Table 1 gives representative garnet and chloritoid microprobe analyses from this sample. Importantly, garnet rim compositions in these samples are extremely consistent regard-
less of the local mineral assemblage in contact with the garnet, including the clots of randomly oriented chlorite grains.

Interpretation.—The Fe, Mg, and Mn endmember components of garnet are produced by the continuous reaction (Karabinos, ms):

\[
\text{Chlorite + chloritoid + quartz} \rightarrow \text{garnet} + \text{H}_2\text{O.} \quad (1)
\]

This reaction is trivariant in the SiO$_2$-Al$_2$O$_3$-FeO-MgO-MnO-H$_2$O system; assuming fixed a$_{\text{H}_2\text{O}}$, the phase compositions should depend upon pressure, temperature, and bulk composition at equilibrium. The relative Mg/Fe ratios are: garnet < chloritoid < chlorite, and the relative Mn/Fe ratios are: garnet > chloritoid > chlorite. The relative equilibrium temperatures of reaction 1 in the Fe, Mg, and Mn endmember systems are: T-Mn < T-Fe < T-Mg, and with increasing temperature and extent of reaction the phase compositions should trend toward higher Mg/Fe and lower Mn/Fe ratios (fig. 9; Thompson, 1976).

A simple way of interpreting the compositional zoning pattern in these garnets (figs. 6 and 7) is that the normal chemical growth trends in segments 1 and 3 reflect prograde garnet growth by reaction 1, and the

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Fig. 4. Drawing from photograph of garnet (G) rimmed and embayed by clots of randomly oriented chlorite (Ch). Sample 111. Opaques are ilmenite and magnetite; elongate grains are muscovite.
anomalies in zone 2 record partial resorption of first stage garnet during retrogression preceding second state garnet growth. This interpretation is consistent with the metamorphic history deduced from textural evidence. De Bethune and others (1968) and Blackburn and Navarro (1977) described garnets with similar zoning patterns and also attributed them to retrogression separating two garnet growth stages.

Inverse zoning, outwardly increasing Mn content from garnet core to rim, and Mn zoning reversals near garnet rims have been attributed to retrogressive effects by Evans and Guidotti (1966), Grant and Weiblen (1971), Birk (1973), de Bethune, Laduron, and Bacquet (1975), Amit (1976), Tracy, Robinson, and Thompson (1976), and Yardley (1977). However, Hollister (1969) suggested that marginal zoning reversals in garnets from the Kwoiek area of British Columbia were produced during garnet growth by the breakdown of ilmenite, which provided a new source of Mn for garnet (p. 2478). This proposal does not help explain the zoning reversals in the Jamaica area where textural evidence suggests ilmenite grew at the expense of rutile during development of the anomalies. Additionally, the Mn/Fe ratio of ilmenite is smaller than that of garnet in these rocks (Karabinos, ms); therefore, the breakdown of ilmenite would not increase the Mn/Fe ratio of garnet.
Thompson and others (1977) pointed out that textural unconformities and, by extension of their arguments, zoning reversals, could develop during a continuous prograde metamorphism. Garnet may participate in a series of prograde reactions; therefore, if an intermediate reaction partially consumes garnet and a later reaction produces garnet, textural unconformities could develop accompanied by zoning reversals. The example Thompson and others (1977) used for the intermediate, garnet consuming reaction is:

$$\text{Garnet} + \text{chlorite} + \text{muscovite} \rightarrow \text{staurolite} + \text{biotite.}$$  \hspace{1cm} (2)

Thompson and others (1977) also note that textural unconformities may reflect tectonic events and/or polymetamorphism. There is no evidence for garnet consuming prograde reactions in the Jamaica area (Karabinos, ms); therefore, retrograde garnet consuming reactions are presumed responsible for the textural unconformities.

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**Fig. 6.** Electron microprobe garnet zoning profile from sample 120 shown in figure 3. C – core; TU – textural unconformity; R – rim.
Other mechanisms for producing Mn zoning reversals near garnet rims have been proposed: (1) changing rates of garnet growth relative to chemical diffusion in the matrix (Edmunds and Atherton, 1971); (2) limited zoning in chlorite leading to Mn-enrichment of the last chlorite to be consumed (Kretz, 1973); (3) post-growth diffusion in garnet (Anderson and Buckley, 1973), and (4) changing values of $f_{O_2}$ (Tewhey and Hess, 1976). It is difficult to evaluate the applicability of these models to the garnets from the Jamaica area, because the effects of second stage garnet growth would probably remove any subtle chemical evidence supporting one of these mechanisms for the zoning reversals.

The zoning anomalies clearly developed either during first stage garnet growth or during the hiatus between first and second stage garnet growth. If they developed during first stage garnet growth, by some growth zoning model, the actual or effective bulk Mn content must have increased dramatically to produce them, or a garnet-producing reaction which enriches both garnet and chloritoid in Mn must have occurred (fig. 8). Such a reaction, however, does not appear possible in this assemblage (see fig. 9), and there is no clear evidence for bulk Mn enrichment. If the anomalies developed during the hiatus between first and second stage garnet
Fig. 8. Log Mn/Fe versus log Mg/Fe plot of garnet zoning and chloritoid inclusion data from unaltered first stage, altered first stage, and second stage garnet zones from sample 120. Arrows indicate increasing radial distance from the garnet center to the beginning of the altered first stage rim and from the textural unconformity to the outer rim.
growth some diffusive alteration of a preexisting zoning profile is involved. The location of the zoning anomalies in the outer shell of first stage garnet, adjacent to the textural unconformities and the textural evidence for partial resorption of first stage garnet, when taken together, strongly suggest that the zoning anomalies reflect limited diffusive alteration of garnet during retrogression. Although there are no chlorite inclusions, the nearly parallel chemical trends of garnet zoning and chloritoid inclusions (fig. 8) suggest the garnet–chloritoid–chlorite tie triangle moved systematically through compositional space (fig. 9), presumably in response to changing metamorphic conditions, during growth, partial resorption, and later growth of garnet.

The lack of chemical zoning in garnets near or above the sillimanite–potassium feldspar isograd has been attributed to diffusive homogenization of originally zoned garnets (Blackburn, 1969; Grant and Weiblen, 1971; de Bethune, Laduron, and Bacquet, 1975; Tracy, Robinson, and Thompson, 1976; Woodsworth, 1977; Yardley, 1977) at temperatures near 650°C (Chatterjee and Johannes, 1974). A significant feature of the garnet zoning profiles from the Jamaica area is that they appear to record considerable diffusion within garnet at temperatures on the low grade side of reaction 2.

### Table 1

Representative garnet (Gt) and chloritoid (Ct) microprobe analyses from sample 120. All Fe reported as FeO

<table>
<thead>
<tr>
<th></th>
<th>Altered 1st stage garnet next to textural unconformity</th>
<th>Unaltered 1st stage garnet near textural unconformity</th>
<th>Near garnet center</th>
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<tr>
<td></td>
<td>Gt rim</td>
<td>Ct matrix</td>
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<td>Weight percent</td>
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<tr>
<td>SiO₂</td>
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<td>0.05</td>
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<td>Al₂O₃</td>
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### Atomic proportions

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Figure 10 illustrates the proposed evolution of the zoning profiles using the Mn/Fe ratio. The normal growth zoning profile at the end of the first garnet growth stage is altered during retrogression. Mn is concentrated in the garnet rim, and the resulting steep compositional gradient induces diffusion in a thin layer adjacent to the receding garnet boundary (see also, Tracy, 1982). During the later prograde event some Mn diffuses out from the altered rim into second stage garnet growth, so the presently observed maximum Mn/Fe ratio anomaly may be smaller than just after retrogression, and the present maximum value is located a small distance interior from the textural unconformity (fig. 6).

Assuming this interpretation is correct a fundamental question is why the zoning anomalies develop during retrogression. If chloritoid and chlorite grew at the expense of garnet during retrogression much faster than material could diffuse out of garnet all three minerals could have followed compositional paths opposite their prograde reaction paths. Thus garnet could have been partially resorbed without producing the Mn/Fe and Mg/Fe zoning anomalies. The presence of these zoning anomalies suggests that the rate of the retrograde reactions could not keep pace with the changing metamorphic conditions and the rate of diffusion in garnet. According to this model the mineral assemblage tried to reequilibrate after a relatively rapid change in metamorphic conditions by diffusive exchange and reaction with an outer garnet shell of finite thickness. Possibly, the rate of influx of H₂O necessary for the retrograde hydration reactions was the rate-controlling process.

Typically, there is a one to one correspondence between chemically altered first stage garnet and the rutile-free zone adjacent to the textural unconformities. In this zone ilmenite is abundant. This suggests that during retrogression garnet and rutile were consumed by the reaction:

\[
\text{Garnet} + \text{rutile} + \text{H}_2\text{O} \rightarrow \text{chloritoid} + \text{ilmenite} + \text{quartz}.
\]

(3)

Garnet was probably also consumed by reaction 1 operating in a retrograde sense.

**DIFFUSION RATES IN GARNET**

The zoning anomalies commonly penetrate about 0.5 mm of the first stage garnet (fig. 6), and textural and chemical evidence strongly suggests
that diffusion within garnet took place during their development. Intracrystalline diffusive transfer in garnet of this magnitude may be unusually great considering the estimated metamorphic conditions and time available for alteration.

In most pelitic rocks from the Jamaica area the reaction:

\[
\text{Chloritoid + quartz} \rightarrow \text{garnet + chlorite + staurolite + H}_2\text{O}
\]  \hspace{1cm} (4)

did not occur, and where it did in southeastern outcrops not all the chloritoid was consumed (fig. 1). I found no staurolite inclusions in first stage garnet, so there is no evidence that reaction 4 occurred during the first prograde metamorphism. The second prograde metamorphism was on the low grade side of reaction 2 or about 580°C (Thompson, 1976). Temperature estimates of higher grade metamorphism in the Chester dome area range widely from 360° to 740°C (Thompson, Lyttle, and Thompson, 1977) based on a variety of geothermometric techniques. In particular, calc-silicate assemblages suggest temperatures of 520° to 570°C for pressures of 5 to 6 kb (Thompson, 1975); calcite-dolomite geothermometry indicates temperatures of 560° to 575°C (Sheppard and Schwarz, 1970); and quartz-muscovite oxygen isotope fractionation gives temperatures near 530°C (Epstein and Taylor, 1967). A reasonable estimate of peak metamorphic temperatures in the Jamaica area, therefore, is below about 550°C, and the retrogressive, diffusive alteration of garnet occurred at lower temperatures.
The first and second prograde metamorphisms are probably Taconic and Acadian events, respectively (Rosenfeld, 1968; Laird and Albee, 1981; Karabinos, 1984), but both could be Acadian. Therefore, the maximum time available for the retrogressive alteration of the garnet zoning profile is about 90 to 110 my based on Ar$^{40}$/Ar$^{39}$ and K/Ar ages (Sutter, Ratcliffe, and Mukasa, 1984; Laird, Lanphere, and Albee, 1984). The length scale (L) of diffusion depends upon the diffusion coefficient (D) and time scale (t) in the form: $L = (4DT)^{3/2}$ (Crank, 1956, p. 36). Using the observed value of $L = 0.05$ cm and the maximum t available $\approx 100$ my, D must be greater than $2 \times 10^{-19}$ cm$^2$/sec at temperatures near 500°C. Lasaga, Richardson, and Holland (1977) estimated the minimum Fe–Mg interdiffusion coefficient for garnet at approx 650°C is $1.5 \times 10^{-18}$ cm$^2$/sec. Using this value and their minimum estimate for the activation energy of interdiffusion (Q) of 69 Kcalories/mol, the minimum interdiffusion coefficient at 500°C is $1.1 \times 10^{-21}$ cm$^2$/sec using the formula:

$$\frac{D(T_1)}{D(T_2)} = \exp \left( \frac{Q}{RT_2} - \frac{Q}{RT_1} \right).$$

The actual coefficient must be around 200 times greater to account for the intracrystalline diffusion in garnets from the Jamaica area.

The diffusive transfer within these garnets, however, may not be strictly intracrystalline. The first stage garnet growth contains abundant inclusions of muscovite, paragonite, chloritoid, ilmenite, epidote, and rutile. Grain boundary diffusion along the inclusion boundaries is probably much faster than lattice diffusion in garnet under these metamorphic conditions (Fisher, 1978) and may have greatly increased the penetration distance in garnet during retrogressive alteration. The effective interdiffusion coefficient in these garnets is probably some intermediate value of the pertinent grain boundary coefficient and the garnet lattice coefficient. It seems likely that grain boundary diffusion along inclusions may be important in retrogressive alteration of garnet and the development of Mn zoning reversals near garnet rims.

CONCLUSIONS

Textures and garnet zoning patterns record a polymetamorphic history in rocks from Jamaica, Vt. in accord with evidence presented by Rosenfeld (1968) and Laird and Albee (1981). A pervasive retrogression separated two prograde stages of garnet growth in rocks from the hanging-wall of one thrust fault (fig. 1). There is no textural evidence for retrogression in the foot-wall rocks of this thrust, and the relative timing of metamorphism and deformation suggests that the retrogression may reflect thrusting of the hanging-wall rocks to a higher, colder environment where they were retrogressively altered (Karabinos, 1984). Prograde, dehydration reactions in the foot-wall rocks may have supplied the necessary H$_2$O for the retrograde reactions in the hanging-wall.

There is radiometric evidence for Ordovician and Devonian metamorphism in western New England (Lanphere and Albee, 1974; Laird, Lanphere, and Albee, 1984; Sutter, Ratcliffe, and Mukasa, 1984) and
the first and second garnet growth stages may be Taconic and Acadian in age, respectively. Both prograde stages, however, may be Acadian. This allows a maximum time of about 100 my for the retrogressive alteration to have occurred, but it may have taken place in much less time.

The garnet zoning profiles are dominated by the normal growth patterns predicted from reaction 1. The zoning anomalies (figs. 6 and 7) occur within the retrogressively altered rims of first stage garnet and appear to record limited diffusion within garnet. The rate of cation diffusion in garnet may be significantly enhanced by grain boundary diffusion along inclusion boundaries. Lattice diffusion coefficient estimates based on these rocks may, therefore, be misleadingly large.

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REFERENCES


Cheney, J. T., 1980, Chloritoid through sillimanite zone metamorphism of high-alumina pelites from the Hoosac Formation, western Massachusetts: Geol. Soc. America, Abs. with Programs, v. 12, no. 7, p. 401.


Polymetamorphic garnet zoning from southeastern Vermont


Tewhey, J. D., and Hess, P. C., 1976, Reverse manganese-zoning in garnet as a result of high fO2 conditions during metamorphism: Geol. Soc. America, Abs. with Programs, v. 8, no. 6, p. 1135.


