KECK GEOLOGY CONSORTIUM

21ST KECK RESEARCH SYMPOSIUM IN GEOLOGY SHORT CONTRIBUTIONS

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Keck Director
Franklin & Marshall College

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DETERMINATION OF THE DURATION OF RETROGRADE METAMORPHISM AT GORE MOUNTAIN AND RUBY MOUNTAIN, NY

ALDEN DENNY: Western Washington University
Research Advisor: David Hirsch

INTRODUCTION

This project focuses on secondary growth structures and late-stage resorption reactions, namely the formation of symplectites (Hollocher , this volume, Fig. 4a) surrounding numerous garnets from both Gore Mountain and Ruby Mountain (Hollocher, this volume, Fig. 1). The secondary growth structures are late-stage growth features that are preserved in trace element profiles. The formation of symplectite is here interpreted to be a disequilibrium reaction of Grt → Hbl + Pl ± Opx. The level of spatial ordering within the symplectite indicates the likely absence of a dominant fluid phase (Fischer 1977). This suggests that the resorption reaction was likely limited by intergranular and intracrystalline diffusion, and thus can be modeled quantitatively (Carlson 2002).

BACKGROUND: DISEQUILIBRIUM

Carlson (2002) argues that under most metamorphic conditions some elements within a growing porphyroblast (specifically garnet in this study) are not in equilibrium with the surrounding matrix. At upper greenschist conditions, garnet zoning patterns for Mn are irregular (disequilibrium) and those for Mg and Fe are concentric (equilibrium) (Hirsch 2003). At higher temperatures more and more elements equilibrate, but even at temperatures approaching the solidus, evidence of disequilibrium in rare earth and tetravalent elements may be present (Yang and Rivers 2002).
This model is only appropriate for hydrous but non-fluid saturated systems without partial melt, in a fluid saturated system the transport of elements may be via convective fluid flow rather than diffusion. Convective fluid flow is orders of magnitude more efficient at element transmission. Any system involving a fluid component would likely have little or no disequilibrium texture preserved in the bulk chemical profile, though such textures may be preserved by REEs. For the Gore Mountain garnets several lines of evidence point to the addition of a fluid phase at high temperature, which allowed for the formation of metamorphic minerals (Bartholome 1960; Luther 1976; Goldblum and Hill 1992) and homogenized the bulk chemistry of the garnets.

METHODS

Sample Analysis

Samples from Gore Mountain and Ruby Mountain were prepared as polished thin sections during the project's summer phase. One sample from Ruby Mountain (RM-Bb) with symplectite (Fig. 1) and two samples from Gore Mountain (GM-32-6C and GM-9a), without and with symplectite respectively (Figs. 2, 3) (Insert Figures 1-3 here), were used for

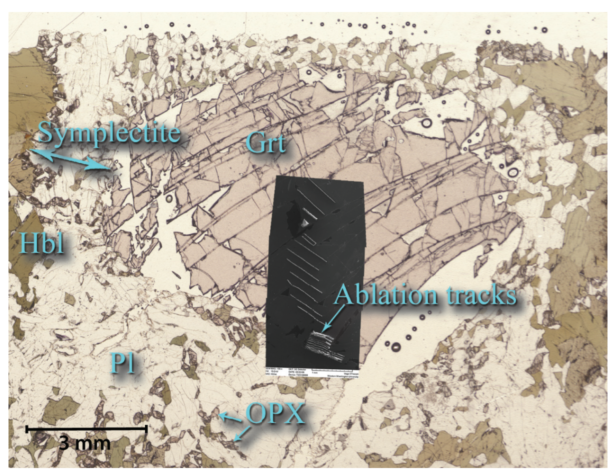

Figure 1. SEM backscatter composite image of ICP-MS analysis tracks overlaid on a plane-polarized thin section image of RM-Bb. Note the high density of ablation tracks at the rim progressing to a lower density in the core.

Figure 2. SEM backscatter composite image of ICP-MS analysis tracks overlaid on a plane-polarized thin section image of GM-32-6C. Note the two regions analyzed were combined to create a full profile. For the purposes of this study this garnet was considered concentrically homogenous, which allowed the two transects to be combined. The main set of ablation tracks do not run perpendicular to the garnet rim, and may cut across growth zoning regions.

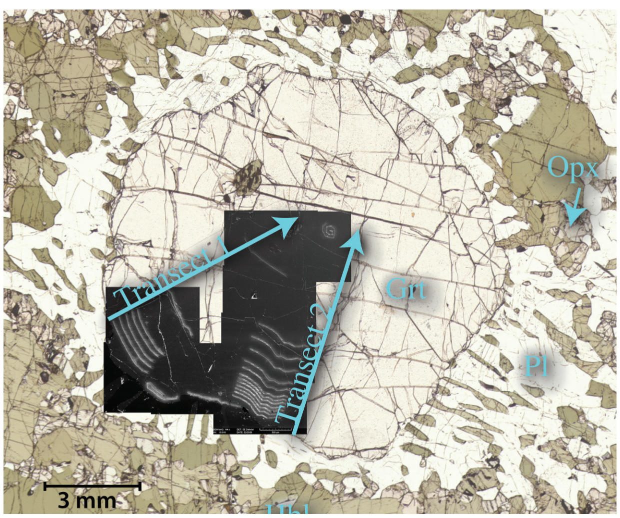

Figure 3. SEM backscatter composite image of ICP-MS analysis tracks overlaid on a plane-polarized thin section image of GM-9a. Two transects were done on this garnet, note that transect 1 may not run parallel to concentric zoning regions.

analysis. In the preparation of these sections a good faith effort was made to cut through the morphologic center of the garnet.

Trace element analysis of these samples was done by electron microprobe using a JOEL 733 superprobe and LA-ICP-MS using a Finnigan Element2 ICP-MS with a New Wave UP-213 laser ablation system. The microprobe analysis proved largely unsuccessful; with probe conditions at 15Kv, 500nA, and a 500s count time all REEs except Yb were below the detection limit, and Yb showed no consistent pattern. The LA-ICP-MS analysis was done using a 30 µm laser beam and ablation of a 1mm line. The lines were ablated parallel to the rim of the garnet so as to run parallel to any concentric zoning profiles. Analysis lines were chosen arbitrarily, with the highest spatial resolution at the rim of the garnet (Fig. 1-3). This analysis proved successful, with a set of 5 trace elements (Ti, Y, Zr, Dy, and Yb) in high enough abundance to show distinct variation in a core-rim profile (Fig. 4, 5).

Modeling

Modeling of the resorption phase was done using RESORB (Carlson 2002). This program models a garnet as a set of equal-volume spherical shells and models resorption from the initial radius to the final radius over a series of time steps, partitioning elements between the garnet rim and the matrix at each step. A thermal history links temperatures to each time step. Elements that are partitioned into the garnet will build up in the rim and diffuse inwards via intracrystalline diffusion; elements partitioned into the matrix will be depleted in the rim. An initial profile and radius was estimated by extrapolating core concentrations to an initial garnet radius equal to that of the garnet + symplectite. The measured element profiles (Fe, Mg, Mn, Ca, and Y) are the target of the simulation.

RESULTS

Trace Element Profiles

The trace element profile of RM-Bb suggests two phases of growth and one possible resorptive phase (Fig. 4). The initial growth phase appears to be homogenized either by a two step process of growth followed by post-growth heating and homogenization or by growth in an externally buffered system. Regardless of the method of growth the garnet would have had to achieve at least upper amphibolite - lower granulite conditions in order to homog-

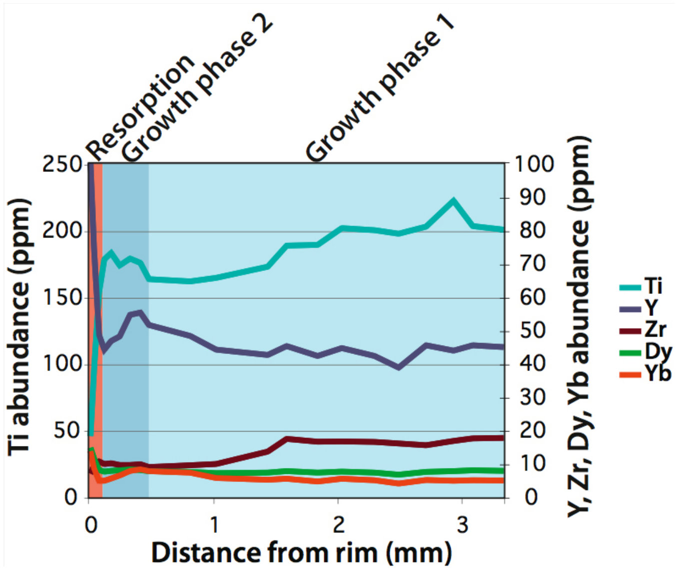

Figure 4. Trace element profile of RM-Bb. RM-Bb has a relatively flat interior profile with enrichment in Y and Ti marking the end of the largely homogenous growth phase one. The second growth phase demonstrates a bell-shaped pattern for Y and Ti, with little change in the other elements. The resorption profile is distinguished by enrichment in Y, Yb, and Dy and depletion in Ti and Zr.

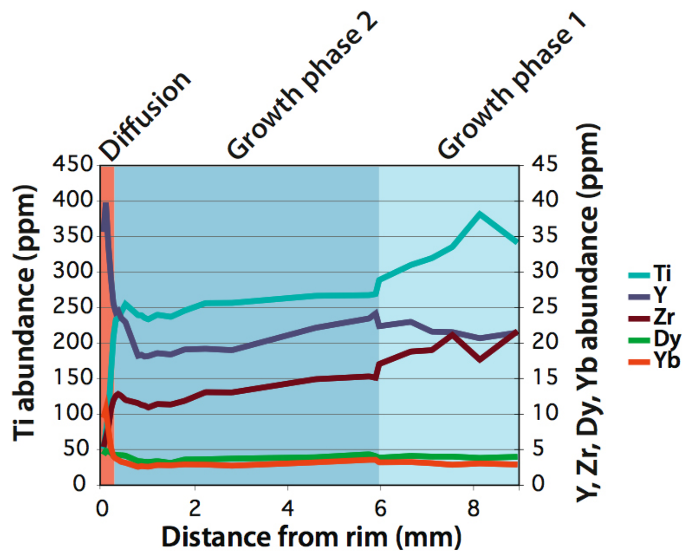

Figure 5. Trace element profile of GM-32-6C. The first growth zone is homogenous in Y, Yb, Dy and Zr, with a roughly constant depletion in Ti. The break between zone one and zone two is defined by perturbations in all the measured trace elements. The diffusion profile is marked by enrichment in Y, Dy, Yb and depletion in Ti and Zr.

enize all bulk and trace element profiles (Carlson 2002), though the role of a fluid phase in reducing the threshold temperature for homogenization is poorly constrained. The change in element abundances that defines growth phase two represents growth into an environment enriched in Y and Ti, both of which are preferentially partitioned into the garnet. This second phase of growth shows a preservation of trace element profiles, which is indicative of either the decreased activity of a fluid phase or a cooling to upper- amphibolite conditions. The third phase is interpreted to be resorption of the garnet. Here the garnet preferentially partitions in Y, Dy, and Yb and is depleted in Ti and Zr.

The GM-32-6C trace element profile indicates that this garnet underwent two growth phases followed by a poorly constrained diffusion-controlled phase (Fig. 5). The initial growth phase is separated by perturbations in all the trace elements from the second growth phase. This change represents growth after either a temporal break or in a new chemical environment. Lastly, the rimward diffusion profile is poorly understood. Due to the lack of a symplectite this cannot be a resorption texture, unless the symplectite was destroyed by later fluid flow, of which there is no direct evidence. This profile then must be interpreted as a diffusive profile, which is surprisingly similar to the resorption profile seen in Rm-Bb including the anomalous Ti interior preferential partitioning and rimward depletion.

The two transects of GM-9a (Fig. 3) show marked differences in their trace element profiles. This may be due to sectored zoning within the garnet or some other non-homogeneity in concentric trace element abundance. Without a trace element map of the garnet determination of the reason of the non-homogeneity is not possible, and to date efforts at interpretation have proven fruitless. This sample was consequently excluded from further study.

Modeling

RESORB modeling for RM-Bb indicates a range of possible thermal histories with the best fit a progression from 700-800-650 oC (in steps of 1 Ma and 50 °C) with resorption from 1-3 Ma and diffusion only from 3-6 Ma. A variation of peak temperature by ±50°C, resorption cutoff by ±2 Ma and total modeled duration by ±3 Ma all yielded possible Y profiles with the cooler and shorter model runs underestimating rimward Y and the longer and hotter runs overestimating. The issue with the estimations is that the main variance is in the outer ~30 μm of the garnet, which is beyond the spatial resolution of the target dataset. The one consistent element is that the thermal histories that yield a good fit to the target profile involve an increase and then decrease in temperature within the range of 600-850 °C. An attempt was made to model a diffusion only thermal history for RM-Bb, which yielded inconclusive results.

Modeling of GM-32-6C has proven more challenging, as without a symplectite this garnet must be modeled using diffusion only. A trial thermal history at 800 °C over 5 Ma produced a poor fit to the Y profile, with the rimward concentration gradient far too steep, suggesting a longer or hotter thermal history was required for intracrystalline diffusion to allow the Y gradient to penetrate into the garnet. Unfortunately RESORB cannot run a longer thermal history in a reasonable time frame. The best constraint on the thermal history is that both the duration and temperature of diffusion were likely markedly higher than that of RM-Bb.

DISCUSSION

In the second phase of growth RM-Bb appears to preferentially partition Y and Ti, but in the resorption phase garnet partitions in Y only and is depleted in Ti. This suggests a change in either the partitioning coefficient for Ti in garnet / the matrix mineral assemblage, or the amount of available Ti. Because the former would have to be a dramatic change in the partitioning coefficient, for which there is no evidence, the latter is most likely. The preferred interpretation for the Ti profile is the loss of ilmenite in the matrix; a change in the amount of Ti available in the fluid is a viable alternative.
The RESORB modeling results indicate that Ruby Mountain and Gore Mountain underwent different post-growth thermal histories. While RESORB modeling of the Rm-Bb sample produced a reasonable set of possible thermal histories, the modeling only represents a set of possible thermal histories, not a unique history. Modeling of GM-32-6C can only be used to constrain a minimum set of conditions and predict that the true thermal history was longer than 5 Ma, though the possible inclusion of a post-growth fluid phase would question this assertion.

One hypothesis that cannot be excluded is that these textures do not represent resorption, but rather are formed somehow during growth. The fact that both RM-Bb (with a symplectite) and GM-32-6C (without a symplectite) both show similar rimward changes suggests this possibility. If correct, then these zoning patterns must be explained by some combination of: (1) changes in fluid composition; (2) changes in matrix mineralogy; (3) changes in extensive variables (P, T, etc.) during growth, all of which must have occurred at high enough temperatures to erase any zoning in major elements.

REFERENCES

Bartholome, P., 1960. Genesis of the Gore Mountain garnet deposit, New York. Economic Geology, v. 55, p. 255-277.

Carlson, WD, 2002. Scale of disequilibrium and rates of equilibration during metamorphism. American Mineralogist, v. 87, p. 185-204.

Carlson, WD, 2006. Rates of Fe, Mg, Mn, and Ca diffusion in garnet. American Mineralogist, v. 91, p. 1-11.

Chernoff, CB and Carlson, WD, 1999. Trace Element Zoning as a record of Chemical Disequilibrium During Garnet Growth. Geology, v. 27, p. 555-558.

Fischer, GW, 1977. Non-equilibrium thermodynamics in metamorphism. Thermodynamics in Geology (ed. Fraser, DG), p. 381-403. D. Reidel Publishing Co., Boston.

Goldblum, D.R. and Hill, M.L., 1992. Enhanced fluid flow resulting from competency contrast within a shear zone; the garnet ore zone at Gore Mountain, NY. Journal of Geology, v. 100, p. 776-782.

Hirsch, D et al, 2003. An overgrowth model to explain multiple, dispersed high-Mn regions in the cores of garnet porphyroblasts. American Mineralogist, v. 88, p. 131-141.

Johnson, CD; Carlson WD, 1990. The origin of Olivine-plagioclase coronas in metagabbros from the Adirondack Mountains, New York. Journal of Metamorphic Geol., v. 8, p. 697-717.

Luther, F., 1976. A chemical reaction for the formation of the Gore Mountain garnet deposit, Warren County, New York. Unpub. Ph.D. Thesis, Lehigh University, Pennsylvania.

Yang, P and Rivers, T, 2002. The origin of Mn and Y annuli in garnet and the thermal dependence of P in garnet and Y in apatite in calc-pelite and pelite, Gagnon terrane, western Labrador. Geological Materials Research, v. 4.