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21ST KECK RESEARCH SYMPOSIUM IN GEOLOGY SHORT CONTRIBUTIONS

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Origin of big garnets in amphibolites during high-grade metamorphism, Adirondacks, NY
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Students: Monica Arienzo, Ashley Burkett, Alexander Burpee, Sarah Chamlee, Timmons Erickson
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Sedimentary Environments and Paleoecology of Proterozoic and Cambrian "Avalonian" Strata in the United States
Mark McMenamin (Mount Holyoke College) and Jack Beuthin (U of Pittsburgh, Johnstown)
Students: Evan Anderson, Anna Lavarreda, Ken O'Donnell, Walter Persons, Jessica Williams

Development and Analysis of Millennial-Scale Tree Ring Records from Glacier Bay National Park and Preserve, Alaska (Glacier Bay)
Greg Wiles (The College of Wooster)
Students: Erica Erlanger, Alex Trutko, Adam Plourde

The Biogeochemistry and Environmental History of Bioluminescent Bays, Vieques, Puerto Rico
Tim Ku (Wesleyan University) Suzanne O'Connell (Wesleyan University), Anna Martini (Amherst College)
Students: Erin Algeo, Jennifer Bourdeau, Justin Clark, Margaret Selzer, Ulyanna Sorokopoud, Sarah Tracy

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Keck Geology Consortium: Projects 2007-2008
Short Contributions – Adirondacks

ORIGIN OF BIG GARNETS IN AMPHIBOLITES DURING HIGH-GRADE METAMORPHISM, ADIRONDACKS, NY: p129-134
Project faculty:
KURT HOLLOCHER: Union College

DETERMINATION OF THE DURATION OF RETROGRADE METAMORPHISM AT GORE MOUNTAIN AND RUBY MOUNTAIN, NY: p135-139
ALDEN DENNY: Western Washington University
Research Advisor: David Hirsch

ANALYSIS OF IRON OXIDATION IN GARNETS: p 140-144
ERICA EMERSON: Mount Holyoke College
Research Advisor: Darby Dyar

COMPARISON OF THE WARRENSBURG AND GORE MOUNTAIN BIG-GARNET AMPHIBOLITES, ADIRONDACK MOUNTAINS, NY: p145-150
KATHRYN M. STACK: Williams College
Research Advisor: Reinhard A. Wobus

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ORIGIN OF BIG GARNETS IN AMPHIBOLITES DURING HIGH-GRADE METAMORPHISM, ADIRONDACKS, NY

KURT HOLLOCHER: Union College

INTRODUCTION

For this project we examined some well-known and lesser-known big garnet amphibolites in the North River area of the Adirondacks in northern New York State. Despite the abundance of garnet throughout the Adirondack highlands, this is the only region in the Adirondacks with large garnets in economic quantities (Bartholomé, 1960). The project goal was to apply modern analytical and modeling methods to better understand the origin of these remarkable rocks.

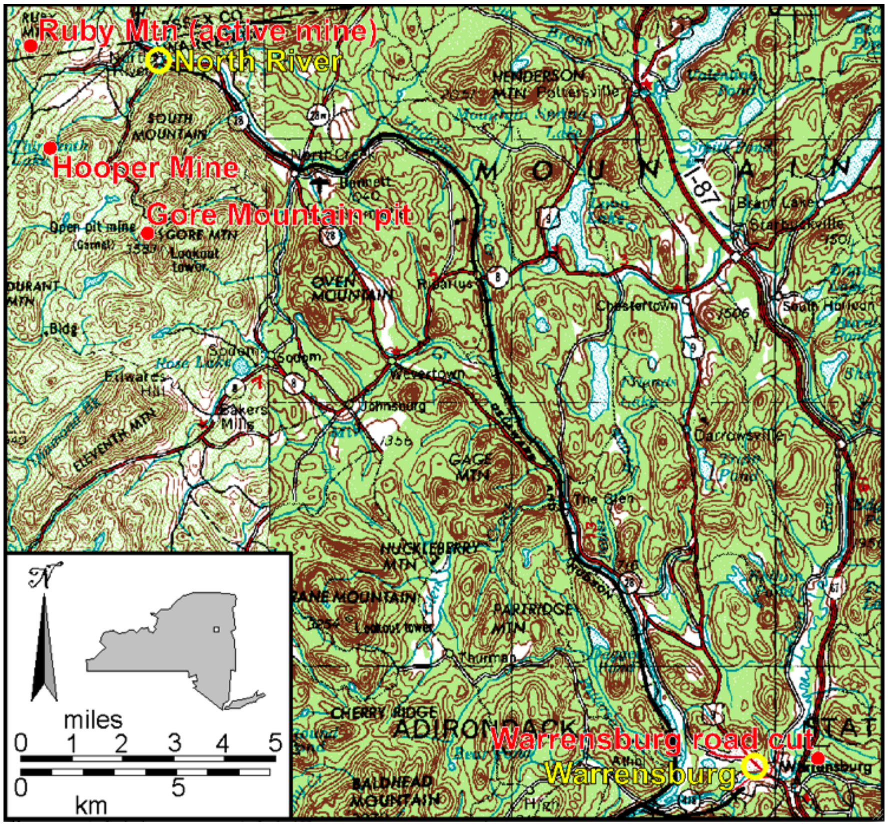

Figure 1. Location map showing the sites from which big garnet amphibolites were taken for study.

During an initial field trip we collected rocks from four different localities (Fig. 1): the old Barton Mines ore pits on Gore Mountain (pits 1, 4, 9), now a rock shop and tourist attraction; Ruby Mountain, the current active mining operation of Barton Mines in New York; the Hooper Mine, an abandoned garnet mine pit; and a big garnet outcrop in Warrensburg. Work is concentrating on the rocks from Warrensburg and Gore Mountain, which have similar mineralogy and textures: large garnets in a dark hornblende-plagioclase-orthopyroxene-biotite matrix, and garnets that are usually associated with coarse areas of the same mineralogy that resemble pegmatitic melt segregations. In contrast to these two sites, garnet ore at Ruby Mountain is a gabbroic anorthosite gneiss with garnets typically 1-5 cm. The Hooper Mine rocks are similar in appearance to those at Ruby Mtn., but are less homogeneous.

Of the collected samples, 50 whole rocks and rock parts and an additional 25 mineral separates were analyzed for major and trace element composition. 60 thin sections were made and all polished. Thin sections and grains collected from the sand on mine pit floors were examined and analyzed using an SEM and energy dispersive X-ray spectrometer. Samples, polished sections, and data were shared among the project group.

FIELD SITES AND ROCKS

The four field sites (Fig. 1), Gore Mountain, Ruby Mountain, Horton Mine, and Warrensburg, represent a range of broadly amphibolitic lithologies hosting large garnets. The most abundant minerals are hornblende, plagioclase, garnet, orthopyroxene, and biotite, with clinopyroxene also being abundant at Ruby Mountain.

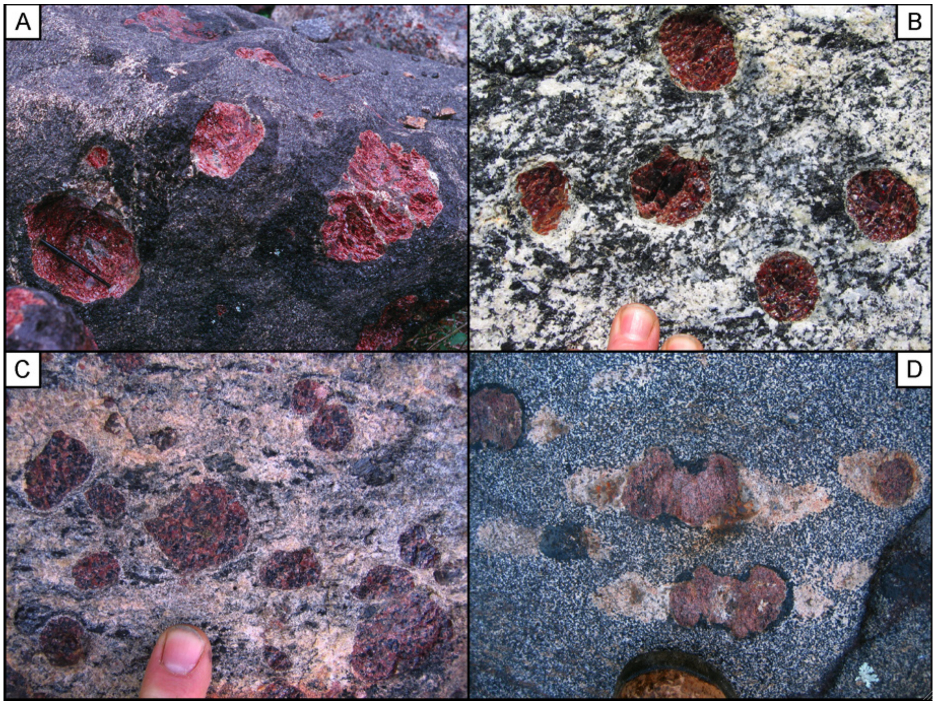

Figure 2. Field photographs from the four big garnet amphibolite localities. A) Gore Mountain, pit 1, showing typical large garnets, hornblendite rims, and host amphibolite matrix. Note coarse, plagioclase-rich pegmatitic zones to the upper left. B) Ruby Mountain, upper pit. C) Hooper Mine, northwest wall. D) Warrensburg outcrop, showing garnet-free amphibolite that is host to coarse, elongate pegmatitic zones with the assemblage garnet – plagioclase – hornblende – orthopyroxene – biotite. Note that some of the garnets have discontinuous hornblendite rims, somewhat like those at Gore Mountain (A).

The Gore Mountain site (Fig. 1A) was the original Barton Mines ore body, mined from 1887 to 1983 (Kelly and Darling, 2002). The garnet ore (Fig. 2A) is the hydrated margin of a much less hydrous olivine-bearing corona gabbro. The granulite facies corona gabbro mineralogy (Fig. 3A-B) has been reconstituted into the hornblende-garnet-plagioclase-orthopyroxene-biotite assemblage of the garnet ore (Fig. 3C-D). Cumulate layering extending from the corona gabbro into the garnet ore leaves no doubt that the garnet amphibolite ore is derived from the corona gabbro. Immediately south of the ore body, forming the south wall of the mine pit, is a shear zone against syenite. It has been suggested that water found its way into the corona gabbro via this fault (Bartholomé, 1960; Luther, 1976; Goldblum, 1988; Goldblum and Hill, 1992). The famous ore in Pit 1 has garnets commonly up to 20 cm in diameter, usually surrounded by thick hornblendite rims, and are set in an orthopyroxene-amphibolite matrix. The garnets are commonly associated with irregularly shaped, comparatively small, coarse-grained zones that have been informally interpreted to be crystallized partial melts (Peter Robinson, oral communication 1998). The mineralogy of the coarse zones is identical to the rest of the rock. Most garnets are surrounded by obvious 0.5-3 mm thick plagioclase-rich rims which, on close inspection, are seen to be plagioclase – OPX ± hornblende ± biotite symplectites (Fig. 3C, 4A). Some samples contain second order symplectite rims on hornblende only 30 μm thick (Fig. 4B, C).

The garnet ore on Ruby Mountain, the currently active Barton Mines operation in the Adirondacks, is quite different (Fig. 2B). It is a deformed anorthositic gabbro, and does not appear to be associated with corona gabbro or otherwise derived by reaction of fluids with some dramatically different protolith rock. Garnets do not have hornblendite rims as do many at Gore Mountain, but instead are commonly associated with plagioclase-rich rims and with coarse, nebulous, leucocratic patches that are

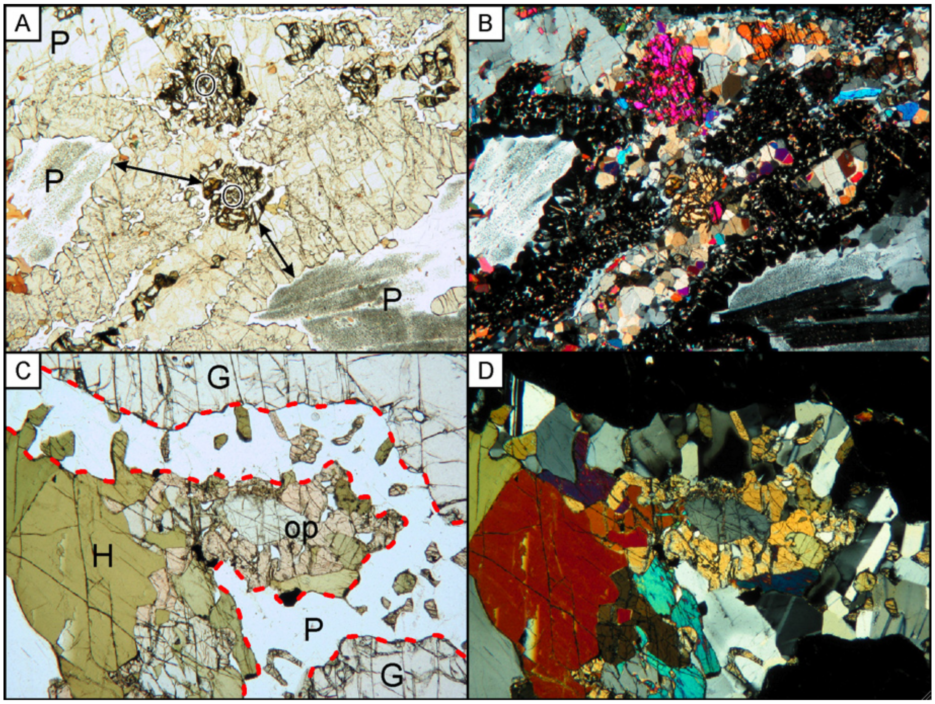

Figure 3. Photomicrographs of thin sections from pit 1, Gore Mountain locality. A and B are of the corona gabbro exposed on the north side of the pit. Dark, partly altered olivines (O) are surrounded by layers (arrows) with the approximate sequence: orthopyroxene – clinopyroxene –garnet + plagioclase – garnet – exterior plagioclase (P). The exterior plagioclase is composed of relic igneous crystals, compositionally modified and containing clouds of tiny green spinel inclusions. C and D are from a garnet amphibolite, containing the assemblage garnet (G) – hornblende (H) – plagioclase (P) – orthopyroxene (op). A narrow plagioclase – hornblende – orthopyroxene symplectite can be seen between the garnet and matrix minerals (between the red dashed lines). A and C are in plane polarized light, B and D in cross polarized light. Field width is 6 mm for all photos.

suggestive of crystallized partial melts. Numerous garnet-rich, deformed mafic dikes cut the ore body.

The Hooper Mine is an abandoned pit active from 1908 to 1928 (Krieger, 1937; Fig. 2C). This rock resembles that on Ruby Mountain, but is considerably less homogeneous. Garnets vary widely in size, and the proportions of hornblende, garnet, biotite, and plagioclase also vary widely. Biotite-rich rocks with small garnets are common, and thin layers and small boudins of amphibolite and hornblendite are widely distributed.

The Warrensburg site is much like that at Gore Mountain (Fig. 2D). This rock is relatively rich in biotite and ilmenite compared to the other sites, and garnets are less abundant and range only up to ~8 cm across. The garnets are all hosted in elongate, coarse-grained, pegmatitic patches containing garnet, plagioclase, hornblende, biotite, and orthopyroxene. The matrix has the same mineralogy, excepting garnet, and is much finer grained.

GEOCHEMISTRY

We have only preliminary results from the extensive geochemical data. Many previous workers have noted that the gore Mountain ore rock is essentially identical in chemical composition to the parent corona gabbro, save for higher Fe3+ and H2O content in the ore (Levin, 1950; Bartholomé, 1960). Our results largely agree with these findings, but find that the average garnet ore differs markedly from the corona gabbro for some trace elements. Compared to the corona gabbro, the average ore is richer in Li (factor of 5), poorer in S (4), Cu (6), Mo (2), Cs (10), Th (7), and U (3), and has lower Lan/Cen ratios. This indicates that there was considerable fluid flux through the ore, capable of depositing and removing substantial amounts of some minor chemical components.

The enrichment and depletion factors above were calculated from bulk chemical analyses of average matrix amphibolite, garnet, and hornblendite rims in the proportions 74:11:15 (Levin, 1950). About half of the matrix amphibolites have particularly extreme depletion and enrichment factors. Bulk ore calculated from this subset of matrix amphibolites, compared to the corona gabbro, is even richer in Li (factor of 6), and poorer in S (11), Cu (70), Mo (7), Cs (8), Th (22), and U (6).

In contrast, a set of rocks from the 2 meter contact

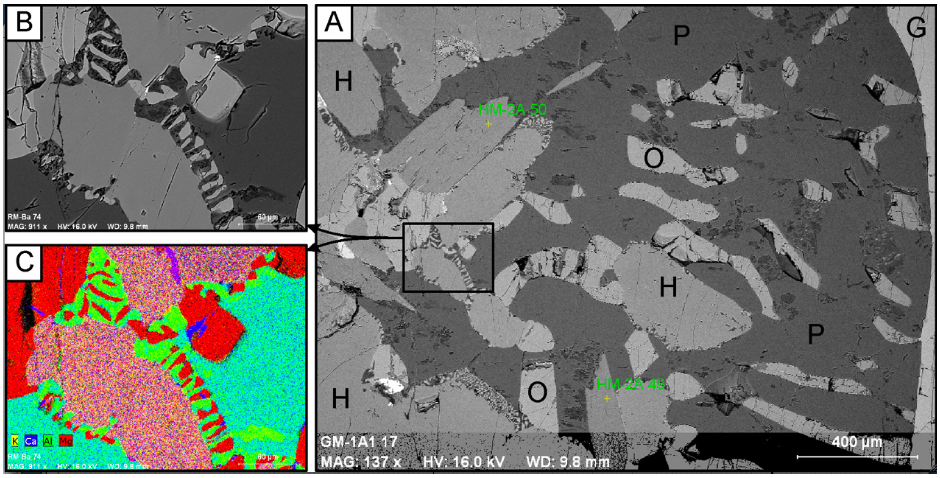

Figure 4. Photomicrographs of a symplectite rim on garnet from Gore Mountain, pit 1. A) Backscattered electron micrograph of the 1.5 mm thick plagioclase – orthopyroxene – hornblende symplectite rim on a small garnet (garnet, G; orthopyroxene, O; plagioclase, P; hornblende, H). B) Backscattered electron image of a small area on the outer margin of the symplectite in A, showing a 30 μm thick, second generation orthopyroxene – plagioclase symplectite bordering hornblende. C) X-ray emission map of the same area as B (plagioclase, light blue; orthopyroxene, red; hornblende, pink; white mica, yellow-green; calcite, dark blue; dolomite, purple). The calcite, dolomite, and white mica are presumably unrelated to the symplectite-forming reactions. I speculate that the white mica is located here because of K-rich plagioclase, or even K-feldspar, that grew during hornblende breakdown.

zone in pit 4, between big garnet amphibolite ore and the parent gabbro, have no trace element enrichments or depletions. The variable enrichment and depletion of trace elements in the garnet ore matrix amphibolite, and the lack of depletion or enrichment in contact zone rocks, indicate that the fluid flow was strongly channelized. Some ore rocks interacted with considerably more fluid than others. Rocks in the contact zone reacted with some fluid to produce hornblende and permit partial recrystallization, but experienced insufficient net flow to modify rock trace element compositions.

THERMODYNAMIC CALCULATIONS

Thermodynamic modeling using the Perple-X software (Connoly, 1990) was begun, constrained by using petrographic, bulk chemical, and mineral analysis data. The ultimate goal of this work is to better constrain the P, T, fH_2O, and fO_2 values during development of the big garnet rocks. The software has a steep learning curve, which I am still on. Figure 5 shows some preliminary results calculated using anhydrous Gore Mountain (Fig. 5A, B) or Warrensburg (Fig. 5C, D) bulk rock compositions, with 2 weight percent water. Perple-X was run with a set of mineral solution models over the P-T ranges of 4000-9000 bars and 600-900°C.

The calculated phase stability fields in Figures 5A and C are color coded for H_2O fluid, melt, garnet, olivine, orthopyroxene, clinopyroxene, rutile, and chlorite. Figures 5 C and D show isopleths for calculated plagioclase An% and garnet Mg/(Mg+Fe) ratio. Compositional contours for hornblende, clinopyroxene, orthopyroxene, and silica in melt have also been calculated. Ideally, analyzed mineral compositions for these rocks would identify two crossing isopleths, the crossing point being an estimate of the P-T conditions during garnet growth. Thus far, this method has not yielded consistent P-T estimates.

The failure to yield consistent P-T estimates could stem from a number of different problems. Some possibilities are: the thermodynamic solution models are sufficiently incorrect to yield quantitatively incorrect phase compositions even though the phase relations are qualitatively reasonable; the analyzed mineral compositions are inconsistent with the bulk chemical analysis; local mineral disequilibrium that is inconsistent with the equilibrium thermodynamic calculations; unrealistic starting conditions, and badly incorrect mineral analyses (unlikely). Work is continuing to resolve these problems.

One thing that is clear from the modeling, with results that are nicely in accord with melting experiments (see summary in Hollocher, 1993): the coarse patches at Gore Mountain and Warrensburg are too mafic to have been bulk partial melts at metamorphic temperatures up to 900°C. Model and experimental partial melts in such systems are tonalitic to dioritic. Small amounts of tonalitic partial melt could, however, have permitted fast material diffusion and suppressed nucleation, allowing coarse, pegmatitic patches to form in dilatational spaces.

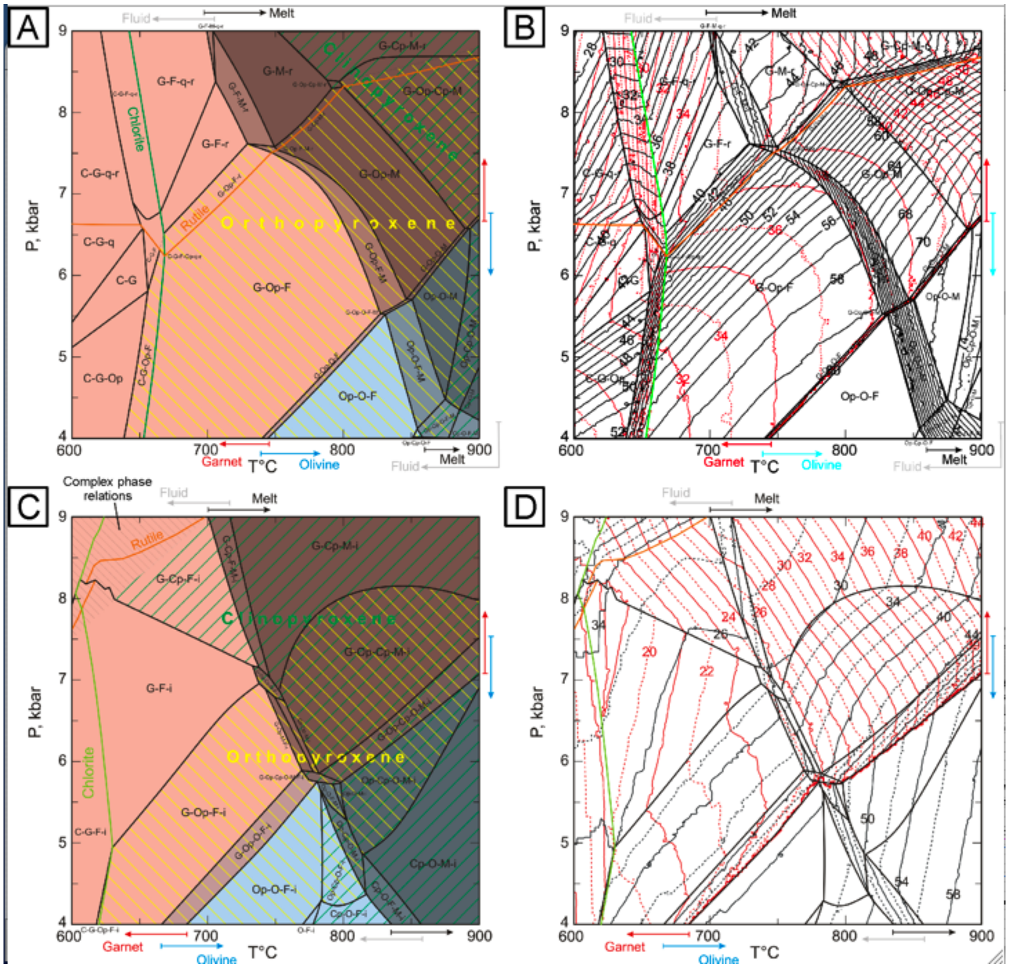

Figure 5. Phase diagrams (pseudosections) calculated using Perple-X thermodynamic modeling software. A and B are for Gore Mountain, using calculated average ore composition. C and D are for the Warrensburg rock, using a calculated whole rock composition. A constant 2% (weight) water was assumed in both cases. A and C are shaded to illustrate phase compositions: light (left) and dark (right) areas for fluid and melt-bearing assemblages, respectively; pink (upper left) and blue (lower right) areas for garnet and olivine-bearing assemblages, respectively. Orthopyroxene occupies the yellow-striped region, clinopyroxene the green-striped. B and D are like the others, but model plagioclase (An content, black) and garnet (Mg/(Fe+Mg), red) isopleths are shown. Rutile is stable to the upper left of the orange line, chlorite is stable to the left of the green line. All model assemblages contain hornblende, plagioclase, biotite, and magnetite. Model ilmenite is stable in all fields except those in the extreme upper left. Model melts are tonalitic at low temperature to dioritic at high temperature.

STUDENT PROJECTS

Alden Denny is looking at trace element zoning profiles in the big garnets to better understand garnet growth and subsequent reequilibration and resorption during cooling. He is using the RESORB reaction and diffusion modeling software, constrained by electron probe and laser ablation ICP-MS analyses. His preliminary results suggest that garnets grew under conditions of disequilibrium with respect to the elements Ti, Zr, Y, Dy and Yb, and underwent variable amounts of resorption during cooling. His best results so far suggest a temperature path of 700-800-650°C, with resorption and diffusion taking place over a 6 Ma time scale.

Erica Emerson is using Mössbauer and XANES spectrometry to analyze the proportions of Fe2+ and Fe3+ in a variety of garnets, including those collected in this study. Among her initial conclusions are that the garnets in the rocks we are studying do not have significant amounts of Fe3+. This result contradicts older reported wet chemical analyses of the garnets, but is consistent with calculations based on modern electron probe analyses and on some wet chemical analyses of my own, done 25 years ago.

Katie Stack has been concentrating on the petrology of Gore Mountain and Warrensburg sites, studying both garnet growth and symplectite rim formation. Her work is constrained using thin sections, mineral analyses, and Perple_X thermodynamic modeling. She has also been using the major and trace element bulk chemical analyses to help understand development of the large garnets and associated textural and mineralogic features. For example, do the coarse zones at Warrensburg represent partial melts or something else?

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