Petrology and Monazite Geochronology of the Scarboro Formation, Jefferson, Maine

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The eastern metamorphic lobe of Maine records Acadian and post-Acadian deformation and metamorphism. Thermodyanmic modeling is used to constrain a P-T path from 6-7 kbars to high T, low P conditions. Monazite geochronology suggests that heating and exhumation were rapid.

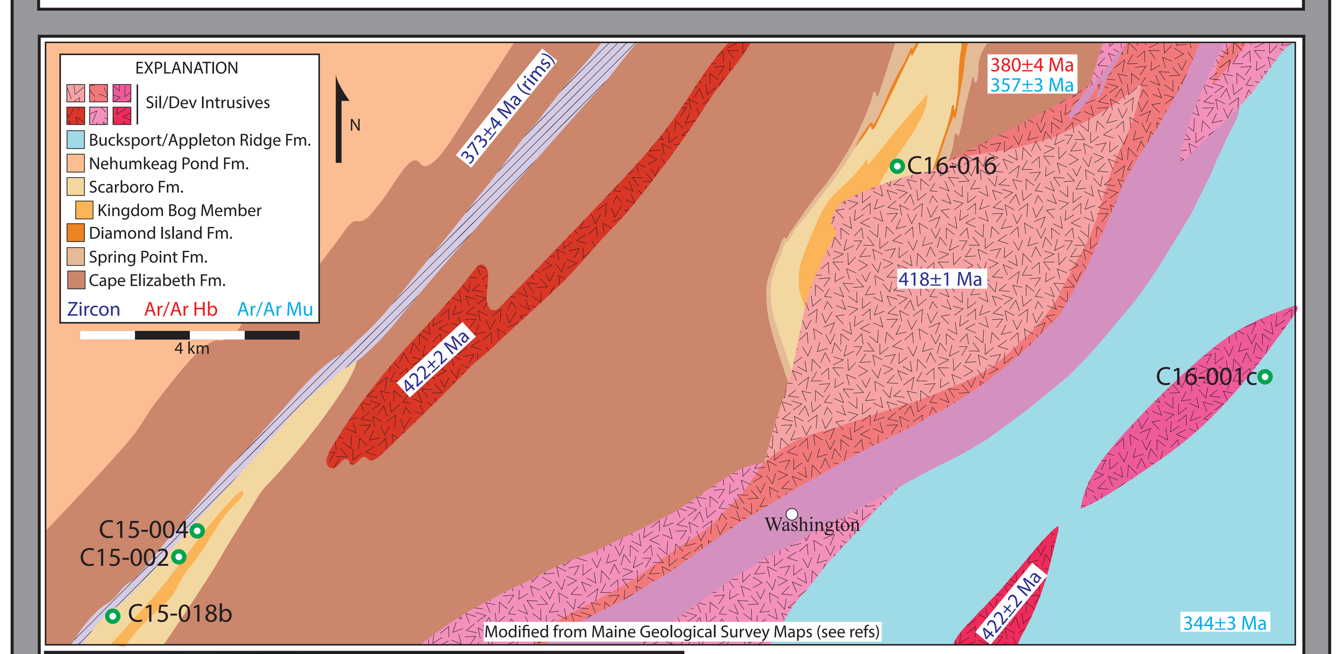
Overview

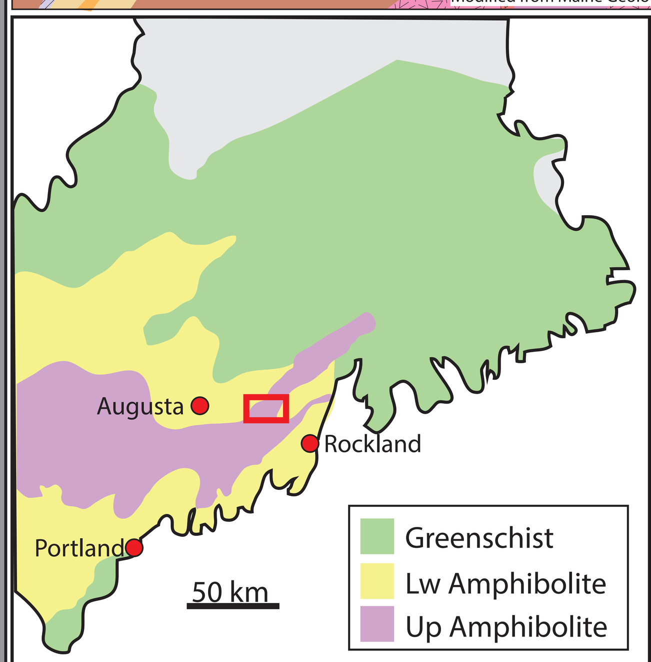
Two samples from the Scarboro Formation show polyphase garnet growth broadly associated with Acadian metamorphism. Garnet cores correspond to a higher pressure prograde history at 6-7 kbar, while garnet rims record regrow at or close to migmatite grade at pressures of ~3.5 kbar.

LA-ICPMS monazite geochronology suggests deformation and prograde metamorphism was occurring at 375-370 Ma. Textural relationships indicate that monazite growth was concurrent with staurolite growth. This is affirmed by monazite-xenotime thermometry, which gives temperatures of ~600°C.

Garnet zonation is minimally modified by diffusion. Smaller garnet crystals have core compositions that suggest apparent overstepping of garnet-in, while the largest crystal has compositions that match the thermodynamically predicted beginning of garnet growth.

Existing local geochronology indicates zircon rim growth (migmatization?) at 373±4 Ma (Gerbi and West, 2007) and Ar/Ar closure of hornblende at 380±4 Ma (West et al., 1995). The prograde peak and retrograde parts of this metamorphic evolution are temporally indistinguishable by these methods, indicating relatively rapid heating and exhumation.





Geologic Background

Sediments that comprise the Casco Bay Group (Scarboro Fm) were likely deposited during Ordovician time.

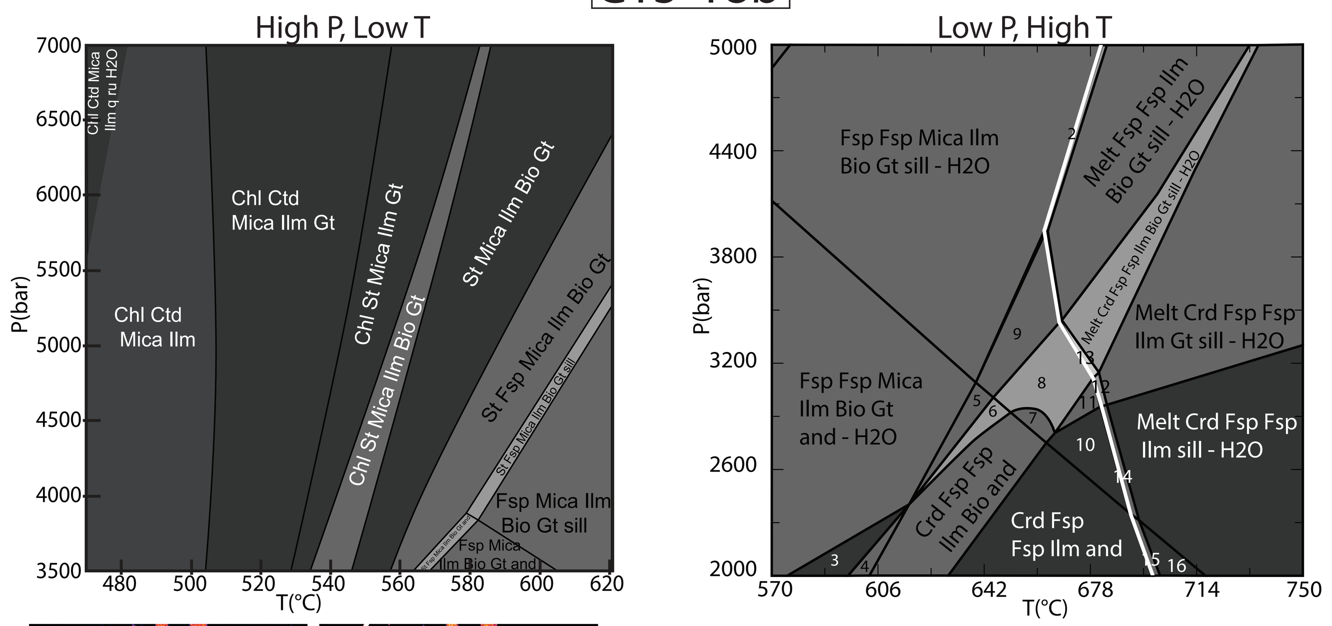
Early bedding parallel foliations may have accompanied thrust faulting. Large upright folds (D2) deform this earlier fabric.

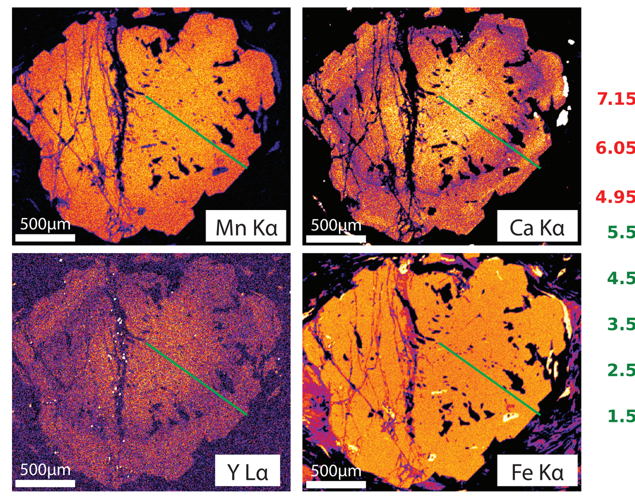
Strike-slip to transpressive deformation produced the dominant vertical foliation with shallowly plunging lineations.

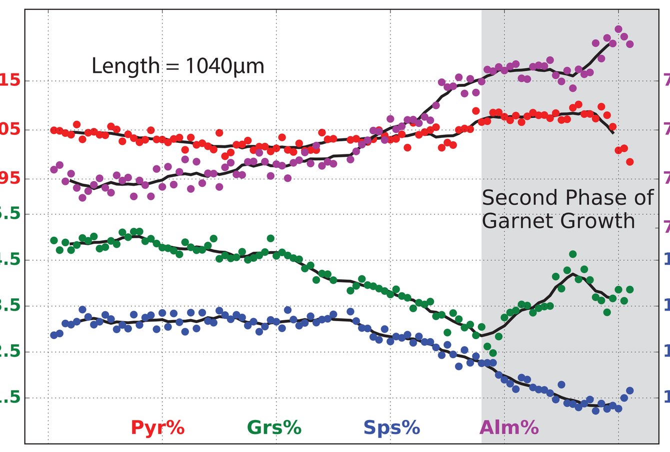
Strike-Slip deformation was initially broad and later focused into the mylonite zones of the Norumbega Fault System.

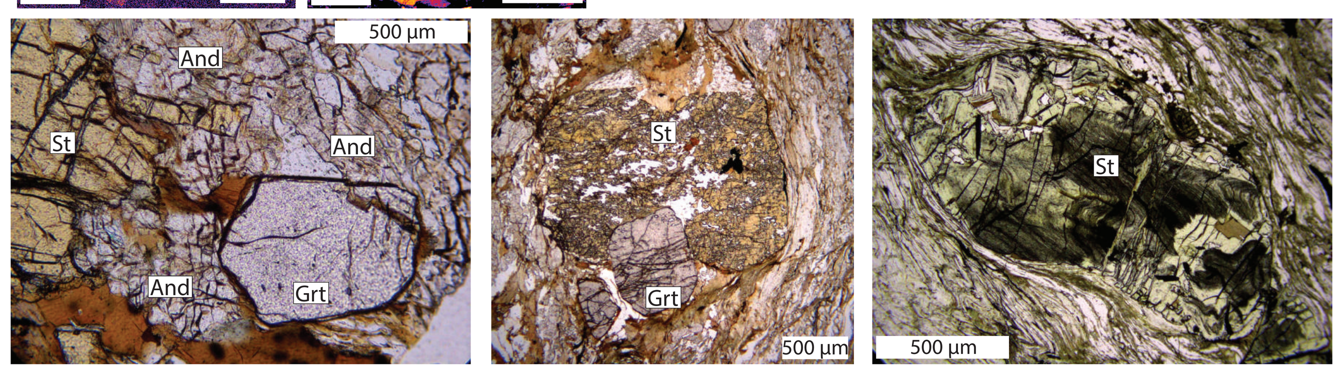
Metamorphism is associated with the Acadian Orogen and post-orogenic magmatism. Many studies have shown that a low P, high T metamorphic signature dominates.

C15-18b



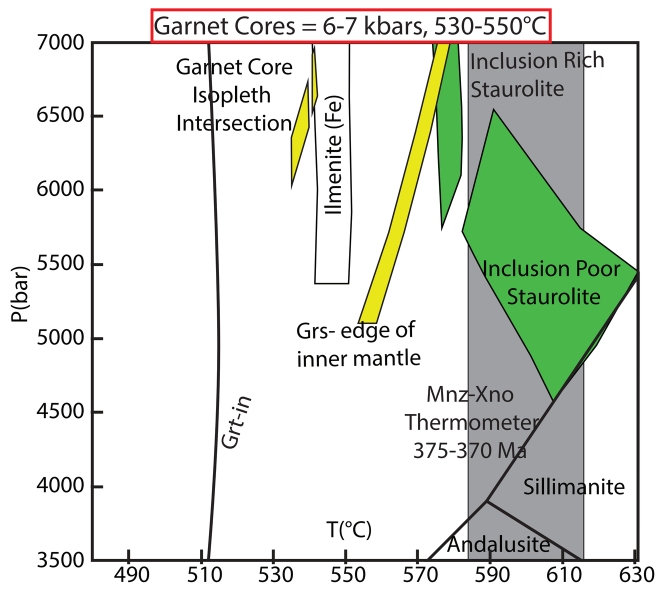


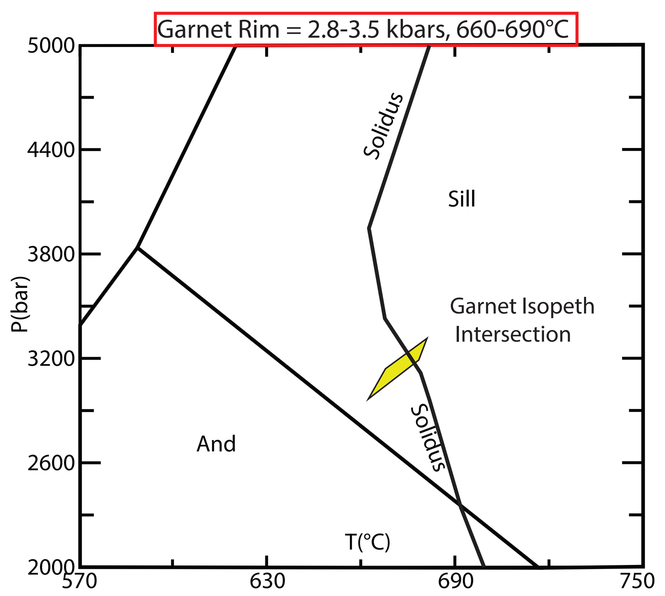




Garnet is consistently overgrown by staurolite and biotite predates staurolite growth, a typical Barrovian sequence. There are clear examples of staurolite being consumed by andalusite.

The clear increase in Ca at the rim of garnet is reflected in Mg and Fe and not Mn. The relatively sharp zoning pattern, especially in Ca content suggests minimal diffusional modification in the rim.

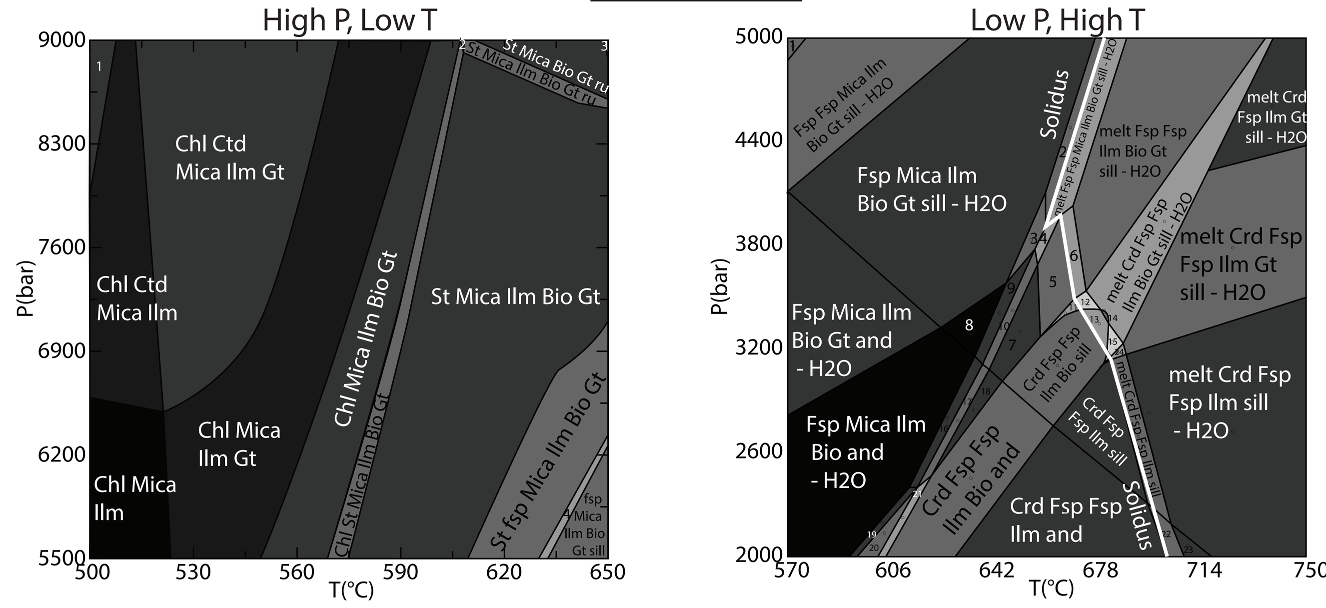


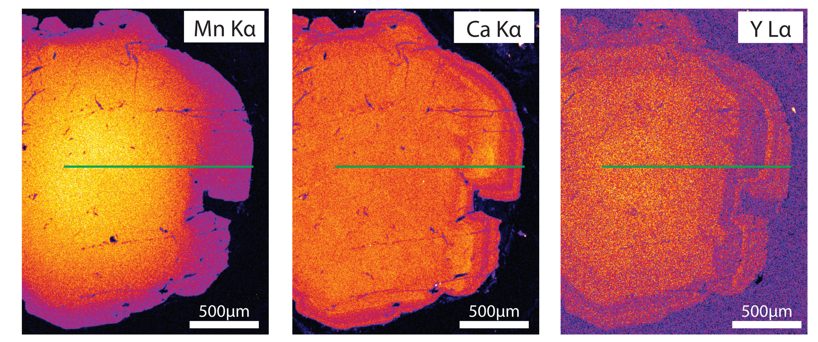


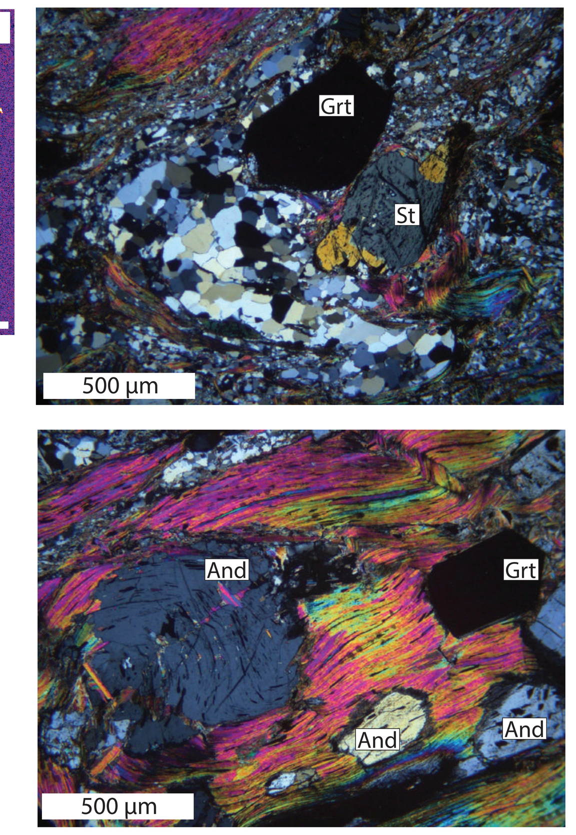
Garnet-in is apparently overstepped by ~25°C. If diffusion was important the original core composition would be closer to garnet-in. Of the two garnet cores shown, the smaller garnet has more apparent overstepping. It is possible that apparent overstepping is due solely to diffusion.

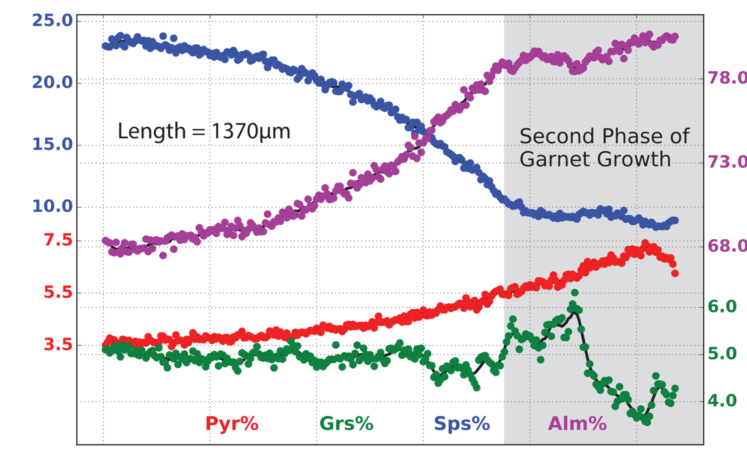
Garnet compositions suggest that the second phase of garnet growth occurred along with or very close to partial melting. There are no other textures in this sample that suggest partial retrogression and deformation after garnet growth.

C16-016



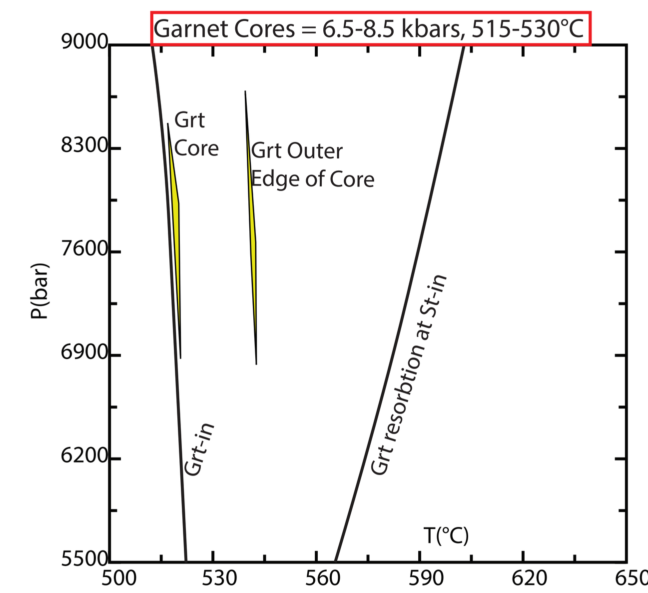


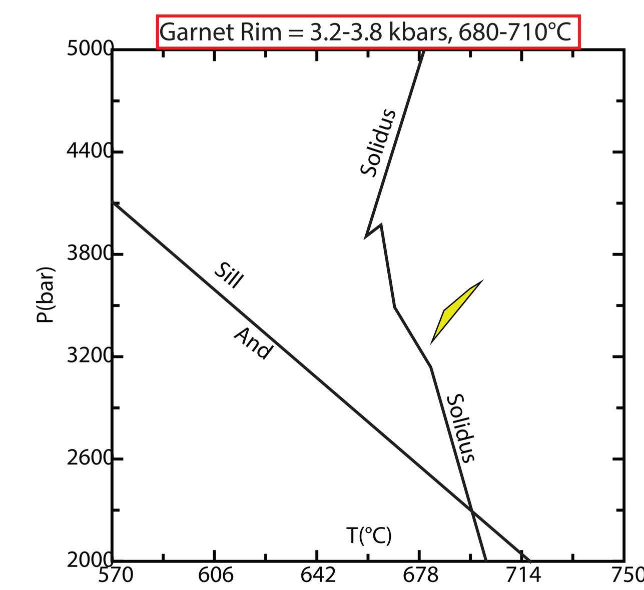




Garnet in this sample shows patchy Ca zonation in the core and oscillatory zoning in the rim. Zoning is sharp and well preserved, with even the fast diffusing Mn showing a distinct break.

Textures in this sample as compatible with a biotite-garnet-staurolite sequence. Andalusite is abundant and occasionally preserves curving inclusion trails, primarily of ilmenite.

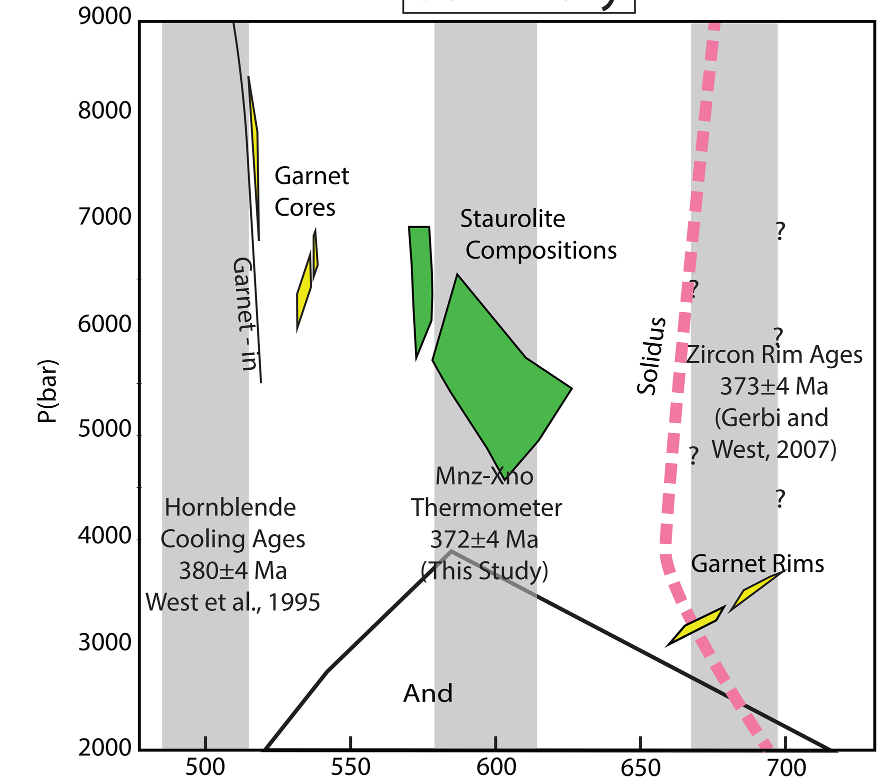


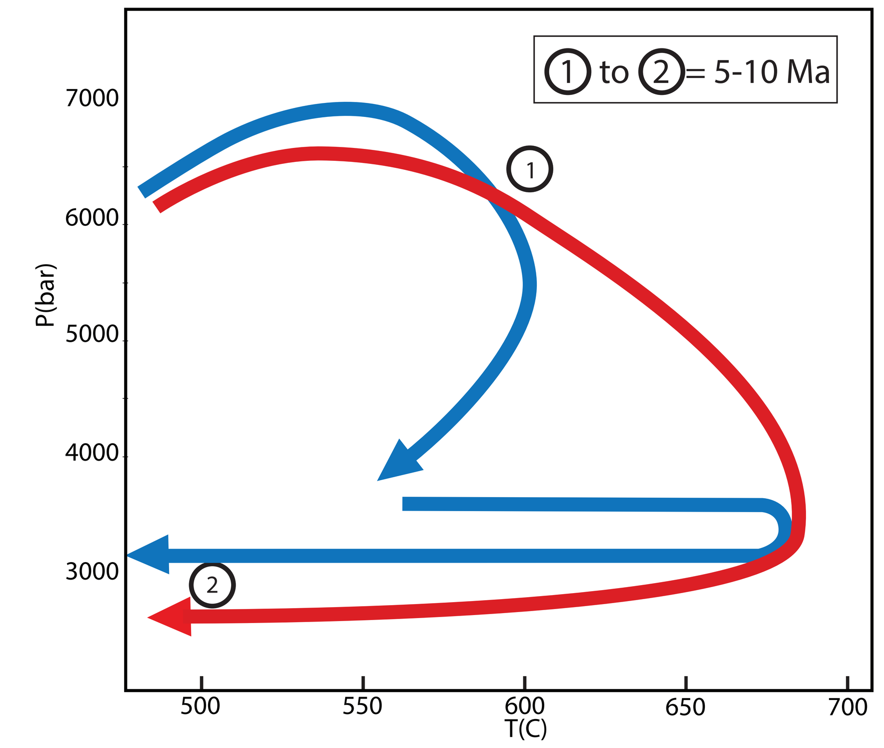


Garnet core compositions suggest growth at the thermodynamically predicted position. Isopeth intersections are drawn from Fe, Mg and Mn, while Ca does not line up with other components. Patchy Ca zoning suggests that its addition to the growing crystal was diffusion limited.

Like C15-18b, garnet rims suggest regrowth during partial melting. Again, there are no other textures in this sample that suggest partial melting, likely due to retrogression and deformation after garnet growth.

Summary





It is possible that garnet rim growth (migmatization) was part of a short lived thermal pulse. This would result in andalusite growth on a prograde path. Large porphyroblasts are less likely to growth during cooling for energetic reasons. The data can also be explained by a single path to higher temperatures. This might correspond to a longer duration of high T, which would probably have resulted in more garnet diffusion than is observed.

Conclusions

Garnet-Staurolite-andulasite assemblages may represent two phases of metamorphism at ~375 Ma.

Garnet core and Staurolite compositions suggest a 6-7 kbar Barrovian P-T path, while andalusite and garnet rims grew during low P and partial melting conditions.

Is this an example of very short duration metamorphism?

Methods

Electron Microprobe
Mineral compositional data and images were collected via EPMA. Standard operating conditions of 20nA and 15kV were used. Analyses were conducted at Virginia Tech. For garnet analyses, weight percent totals of 98-102% were considered acceptible. Staurolite totals of 97-100% were considered acceptible.

Perple_X
The program Perple_X was used to construct thermodynamic models of predicted mineral assemblages and compositions across P-T space. The Holland and Powell (2004) database was used with the following solution models: Gt(WPPH), St(HP), TiBio(HP), Mica(CHA1), Chl(HP), Ctd(HP), hCrd, feldspar, melt(HP), IlGkPy. The water content in the high T, low P phase diagrams was estimated by calculating the amount of mineral-bound water at 650°C, 3500 bar. This effectively fractionates the free fluid phase and produces a more realistic melt proportion above the solidus. Note all phase diagram assemblages contain H2O and quartz. Calculated isopleth intersections reflect only the variability in microprobe measurements and do not reflect thermodynamic and analytical uncertainties. The absolute uncertainties on the calculations are probably much larger than shown.

LA-ICPMS Monazite and Xenotime
Monazite and xenotime geochronology was conducted at the University of California, Santa Barbara. Isotopic and trace element data were collected simultaneously. The Stern and 44069 standards were used and the data was reduced in Iolite.

Monazite-Xenotime Thermometry
The Heinrich et al. (1997) calibration was used for monazite-xenotime thermometry. The presence of xenotime of the same age as monazite is taken to reflect YPO_4 saturation during monazite growth. Laser ablation measurements of Y + LREE contents of monazite were used after being renormalized to 100%. The Heinrich et al. (1997) calibration is preferred to the Pyle et al. (2001) calibration as it often more closely matches silicate phase P-T estimates, as is exemplified in this study.

References

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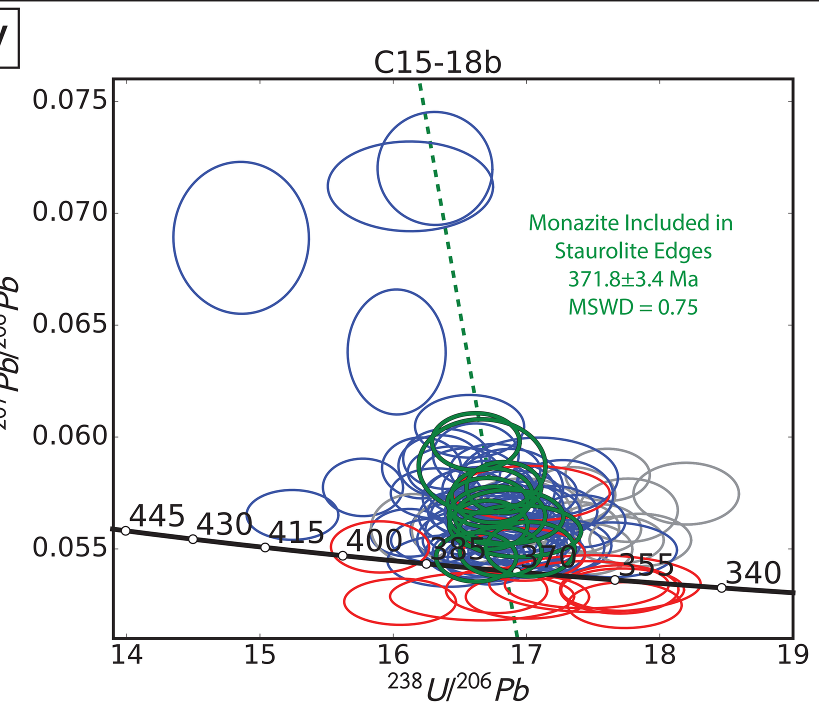
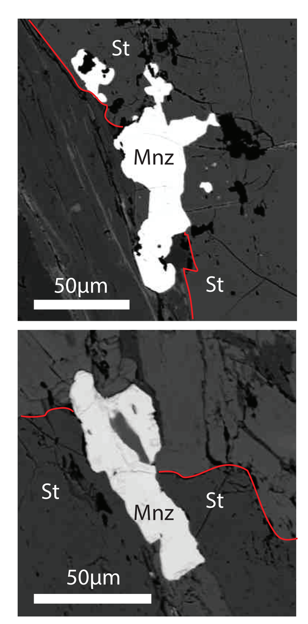
Geochronology

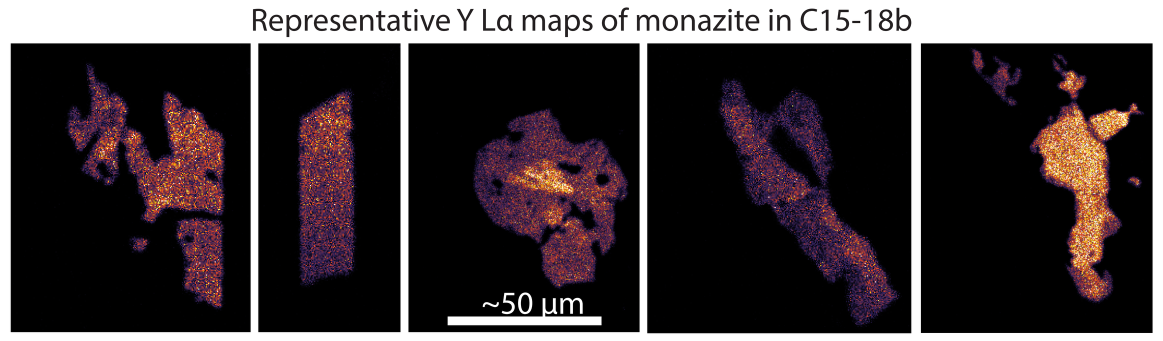
Explanation
All Monazite
All Xenotime
Mnz Included in Staurolite
Mnz excluded from isochron

Monazite and xenotime data were plotted using a python code. Weighted averages and isochrons were calculated in Isoplot. All data are plotted showing 2σ uncertainty. Only analyses with 90-110% concordance were included in weighted averages.



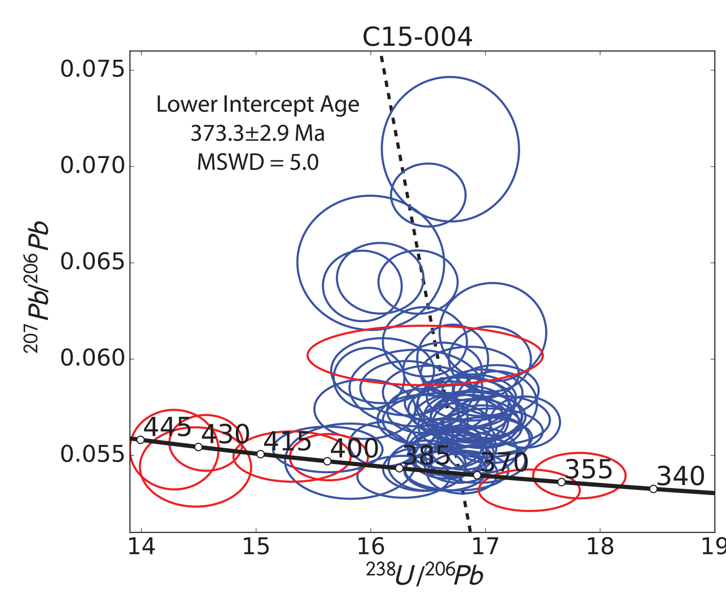


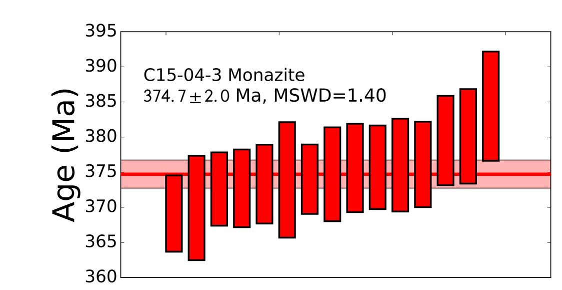
Representative Y Lα maps of monazite in C15-18b



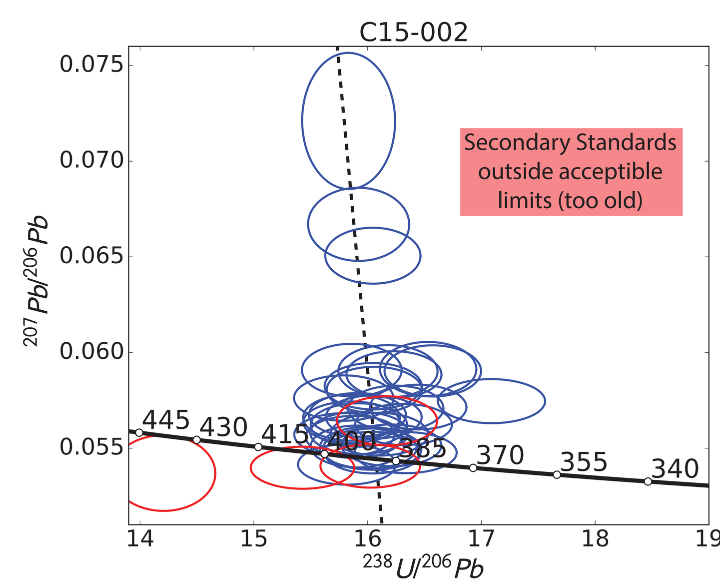
Monazite-Xenotime Thermometry

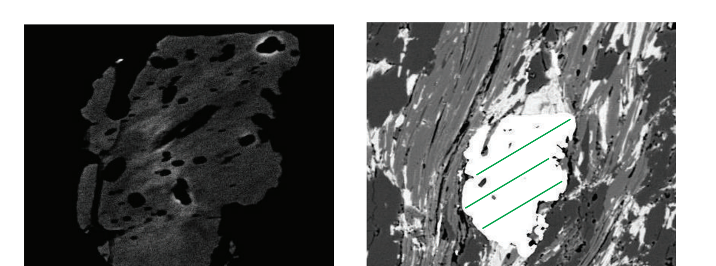
An average of 14 analyses of monazite that are included in the rims of staurolite yields a molar Y+HREE proportion of 0.0695. Using the Heinrich et al. (1997) calibration, this composition yields a temperature of ~600°C. There are probably at least a 30-50°C total uncertainty associated with this calculation.





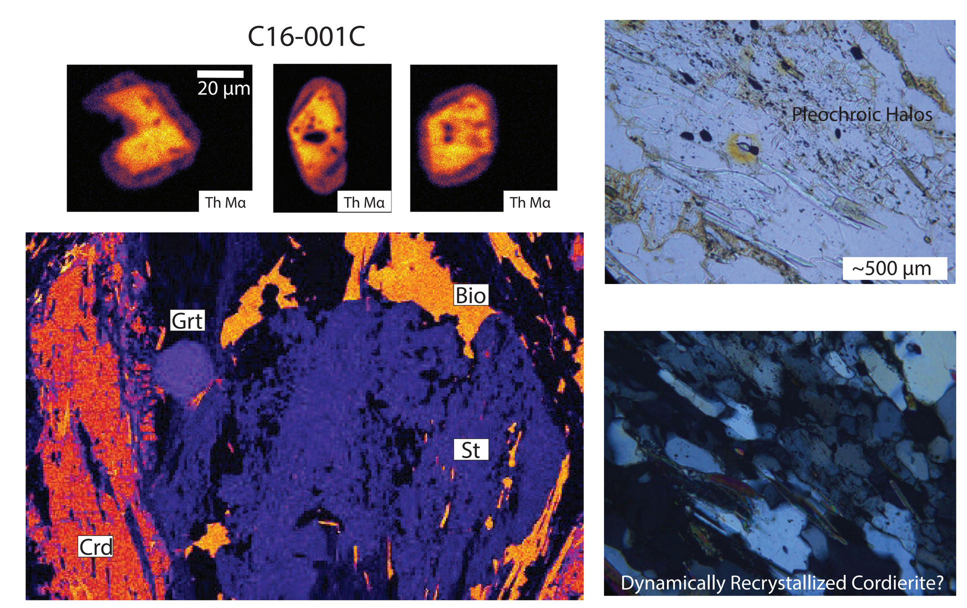
Monazite geochronology general indicates crystallization at 375-370 Ma. Sample C15-002 has a lower intercept age of ~390 Ma, however given that the secondary standard was not reproduced, this is probably not a true age. Monazite growth occurred on a prograde path during staurolite growth.





Monazite in sample C15-02-1 appears to overgrow a biotite-muscovite fabric that is oblique to the enveloping foliation, which suggests that it is a kinematic indicator. Stirke-slip deformation must have been ongoing at 375-370 Ma.

Future Work



Phase Diagram Labels

C15-18b: Low P
1 = Fsp Fsp Mica Ilm Bio Gt ky - H2O
2 = Melt Fsp Fsp Mica Ilm Bio Gt sill - H2O
3 = Fsp Fsp Mica Ilm Bio and - H2O
4 = Crd Fsp Fsp Mica Ilm Bio and - H2O
5 = Fsp Fsp Ilm Bio Gt and
6 = Crd Fsp Fsp Ilm Bio Gt and
7 = Crd Fsp Fsp Ilm Bio sill
8 = Crd Fsp Fsp Ilm Bio Gt sill
9 = Fsp Fsp Ilm Bio Gt sill
10 = Crd Fsp Fsp Ilm sill
11 = Crd Fsp Fsp Ilm Gt sill
12 = Melt Crd Fsp Fsp Ilm Gt sill
13 = Melt Crd Fsp Fsp Ilm Bio Gt sill
14 = Melt Crd Fsp Fsp Ilm sill
15 = Melt Crd Fsp Fsp Ilm and
16 = Melt Crd Fsp Fsp Ilm and - H2O

C16-016: High P
1 = Chl Ctd Mica Ilm q ru H2O
2 = Chl St Mica Ilm Bio Gt q ru H2O
3 = St Mica Bio Gt ky q ru H2O
4 = St fsp Mica Ilm Bio Gt sill q H2O

C16-016: Low P
1 = Fsp Fsp Mica Ilm Bio Gt ky - H2O
2 = melt Fsp Mica Ilm Bio Gt sill - H2O
3 = Fsp Mica Ilm Bio Gt sill
4 = Fsp Fsp Mica Ilm Bio Gt sill
5 = Fsp Fsp Ilm Bio Gt sill
6 = melt Fsp Fsp Ilm Bio Gt sill
7 = Fsp Fsp Ilm Bio sill
8 = Fsp Mica Ilm Bio sill - H2O
9 = Fsp Mica Ilm Bio sill
10 = Fsp Fsp Mica Ilm Bio sill
11 = Crd Fsp Fsp Ilm Bio Gt sill
12 = melt Crd Fsp Fsp Ilm Bio Gt sill
13 = melt Crd Fsp Fsp Ilm Bio sill
14 = melt Crd Fsp Fsp Ilm Bio sill - H2O
15 = melt Crd Fsp Fsp Ilm Bio Gt sill
16 = Fsp Mica Ilm Bio and
17 = Fsp Fsp Mica Ilm Bio and
18 = Fsp Fsp Ilm Bio and
19 = Crd Fsp Mica Ilm Bio and - H2O
20 = Crd Fsp Fsp Mica Ilm Bio and - H2O
21 = Crd Fsp Fsp Mica Ilm Bio and
22 = melt Crd Fsp Fsp Ilm and
23 = melt Crd Fsp Fsp Ilm and - H2O
24 = melt Crd Fsp Fsp Ilm Gt sill