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When Earth's Tectonic Plates Collide: Reevaluation of the Pressure and Temperature History of Metamorphic Rocks in the Eastern Alps

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Metamorphic rocks form and evolve in response to changes in Pressure (P) and Temperature (T). Application of thermodynamics to mineral compositions is commonly used to calculate P-T histories of metamorphic rocks. Geologists use this information to interpret Earth's processes. Here, we test the accuracy of the P-T paths for the eastern Alps constructed 35 years ago (Selverstone et al., 1984, Journal of Petrology, v25 501-531) using improved thermodynamic calculations.

We first used optical petrography to identify of minerals, textures, and metamorphic facies. We then used Boise State's Electron Probe Microanalyzer, with back-scattered electron imaging to verify mineral identifications and guided where to collect chemical analyses. Lastly, we used thermodynamic calculation software applied to these chemical data to constrain bounds on P-T conditions. Whereas Selverstone et al. (1984) report P-T conditions of 7±1 kilobars (25 km depth) and 550±25 degrees °C, our calculations show an indistinguishable pressure of 7±1 kilobars, but a higher temperature of 635±25°C. The higher temperature implies that tectonic plates were warmer than once inferred. Because rocks become less brittle with increasing temperature, brittle phenomena such as earthquakes in the past would have occurred at shallower depths.

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Metamorphic rocks form and evolve in response to changes in Pressure (P) and Temperature (T). Application of thermodynamics to mineral compositions is commonly used to calculate P-T histories of metamorphic rocks. Geologists use this information to interpret Earth's processes. Here, we test the accuracy of the P-T paths for the eastern Alps constructed 35 years ago (Selverstone et al., 1984, Journal of Petrology, v25, 501-531) using improved thermodynamic calculations.

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Geologic Background

- Sample FH1M is exposed in the Tauern Window Series located in the Eastern Alps of western Austria (Figure 1 and 2).
- This hornblende garbenschist unit was developed within Austroalpine thrust sheets (Figure 3).
- The maximum pressure and temperature previously determined for this region are 10.5 kbar (c. 35 km depth) and 550 °C (Selverstone et al. 1984).

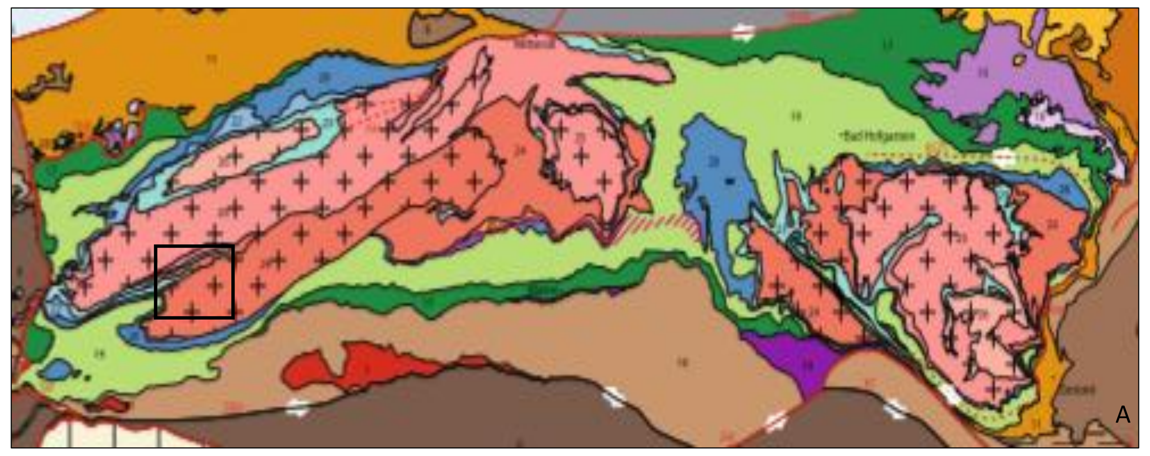


Figure 1: Geologic map of Tauern Window (Reference). Colors denote different geologic units. Blue units are the subject of this study. Box shows study area (Schmid et al., 2013).

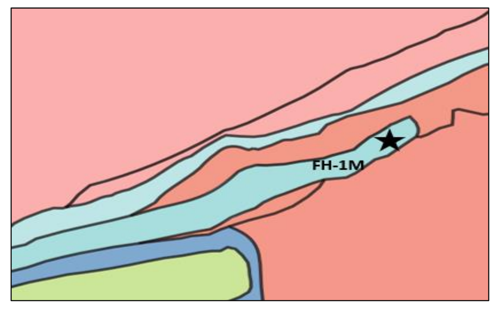


Figure 2: Zoomed in image of Figure 1. Sample location site (star indicates FH-1M) from Selverstone et al. (1984) overlaid onto Schmid et al. (2013). Colors correspond to colors in Figure 1.

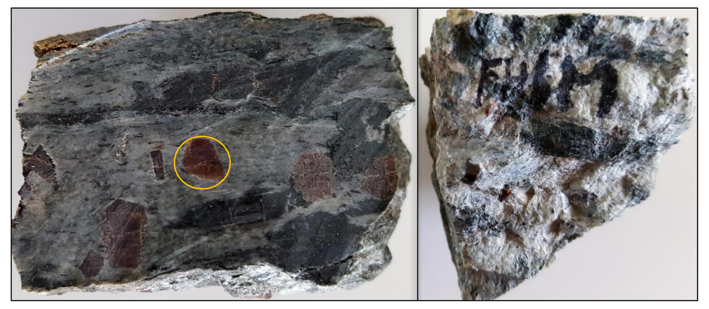


Figure 3: Hand sample of FH-1M depicting slight foliation with randomly dispersed subhedral to (black circle) euhedral garnet grains and elongated porphyroblastic hornblende.

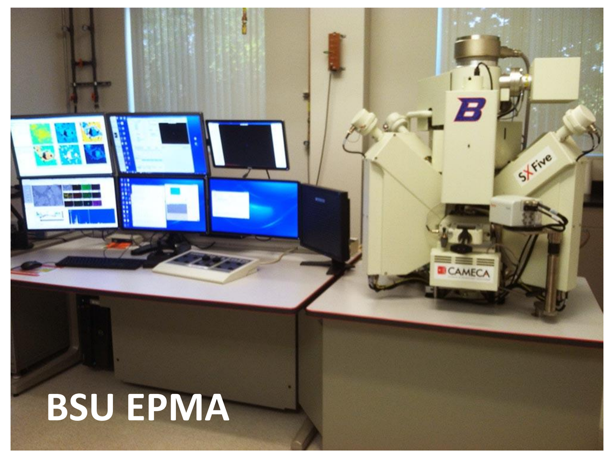
Objectives

To complete an independent analysis of PT conditions for the Eastern Alps and to compare with Selverstone et al. (1984).

Methods

Mineral Identification:
- Light microscopy using a petrographic microscope
- Back-scattered electron imaging using Electron Probe Microanalyzer (EPMA)
- Energy dispersive analysis using EPMA

Defined mineral compositions and zoning:
- X-ray mapped thin section (EPMA)
- c. 1 µm spot analysis (EPMA)



Data analysis:
- Pressure-temperature conditions: Geothermobarometry (GTB)
  - Uses only well-calibrated thermometers and barometers

  Thermocalc
  - Solves for a best-fit P-T condition based on multiple equilibria

  TWQ
  - Calculates all possible thermometers and barometers
- P-T growth history of chemically zoned garnets: Gibbs
  - Uses differential thermodynamics to calculate ΔP and ΔT

Key Results

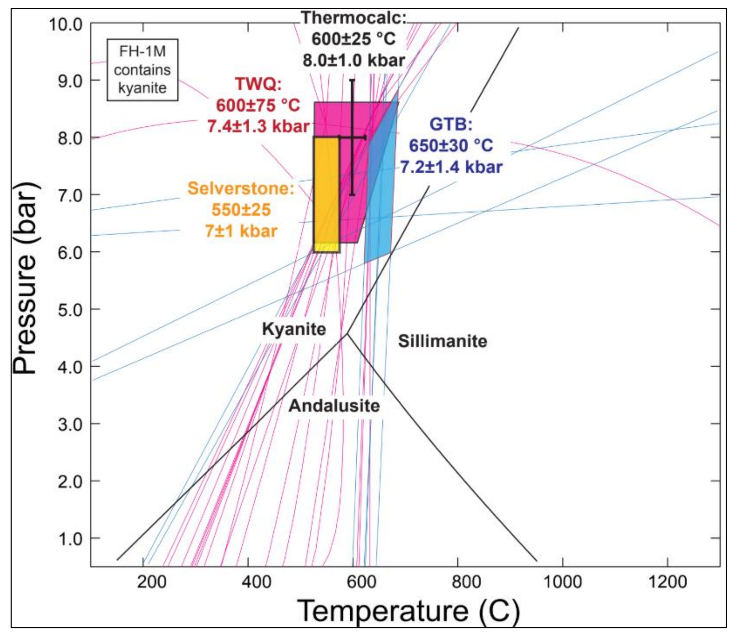


Figure 3: Results constraining pressure-temperature conditions. Pink shaded region is TWQ, blue shaded region is GTB, and black box is Thermocalc. Corresponding colored lines are bounds given by programs. Yellow shaded region is Selverstone et al. (1984) pressure-temperature constraint for comparison.

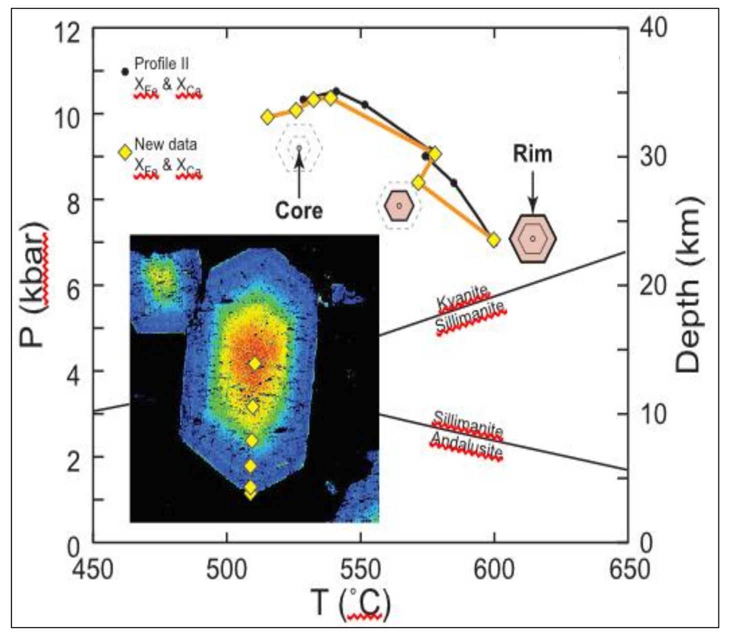


Figure 4: Pressure-Temperature paths as determined from zoned garnet in FH-1M, using original data from Selverstone et al. (1984; black path) and new data (orange path). Yellow dots correspond to locations within chemically zoned garnet from core to rim.

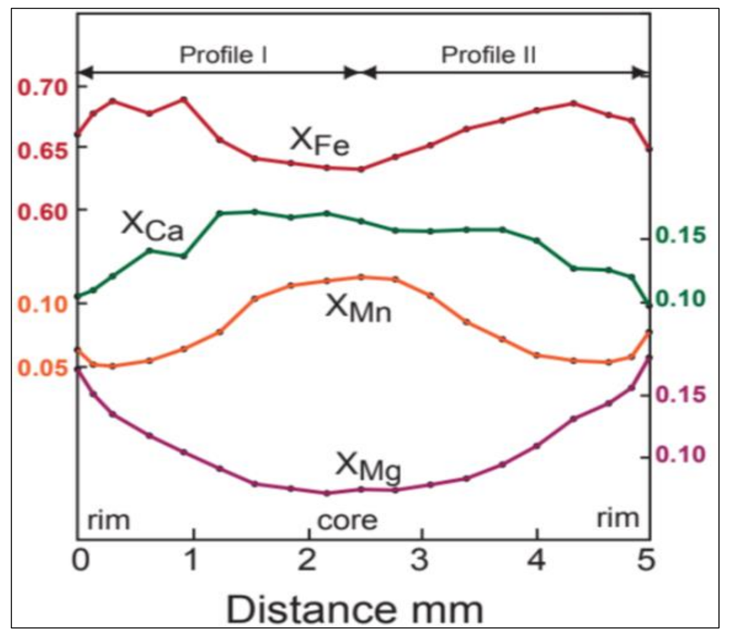


Figure 5: Chemical zoning profile of four main endmembers.

- Garnets preserve growth zoning in their chemistry (Figure 4 and 5).
- Calculations of garnet rim pressure-temperature conditions are similar using different methods (Figure 3).
  GTB: 650±30 °C and 7.2±1.4 kbar
  Thermocalc: 600±25 °C and 8.0±1.0 kbar
  TWQ: 600±75 °C and 7.4±1.3 kbar

Conclusions

- Calculated peak temperatures(c. 600 °C) are higher than Selverstone et al.'s (550±25 °C) (Figure 3).
- Calculated peak pressures are Indistinguishable from Selverstone et al.'s estimates (within ±1 kbar) (Figure 3).
- Using new chemical measurements and models yields a similar P-T path as older data and models.
- Future analysis will determine P-T paths using a different thermodynamically based method (PerpleX).
- We will also use a physics-based method (rather than thermodynamics) to calculate maximum pressures at which garnet nucleated.

Implications

- The decrease in pressure recorded in the garnet zoning reflects uplift and erosion after thickening of the crust (Figure 6).
- The increase in temperature recorded in the garnet zoning reflects a response of the thermal structure of the crust after thickening (Figure 7).

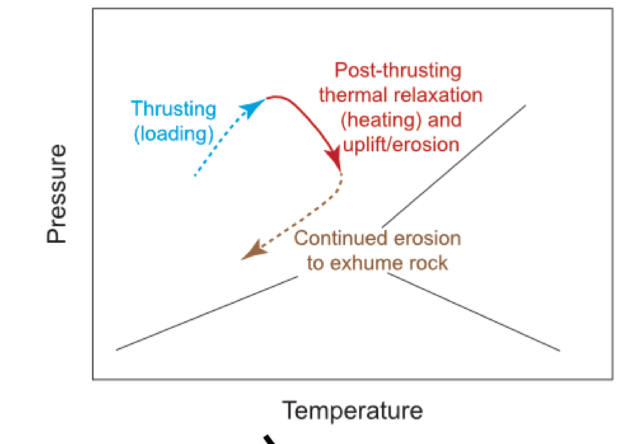


Figure 6: Typical pressure-temperature progression of thrust sheets showing an increase in pressure in temperature, followed by a decrease in pressure, and finally, a decrease in both pressure and temperature.

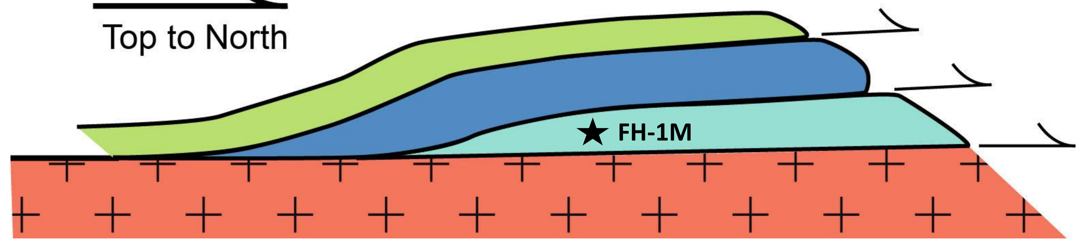


Figure 7: Schematic representation of the thickening of thrust sheets on top of collected sample, FH-1M. This overlaying of sheets caused the increase of temperature.

Details

- Pressure and temperature data are consistent with Selverstone et al. (1984) which shows an increase in pressure followed by a decrease in pressure with a increasing temperature (Figure 4).
- In garnet, zoning of Magnesium (increasing toward the rim) and Manganese (decreasing toward the rim) is consistent with garnet growth, i.e., garnet preserves original growth zoning (Figure 5 and Figure 8).
- The fine structure in zoning suggests diffusion did not significantly homogenize garnet compositions.

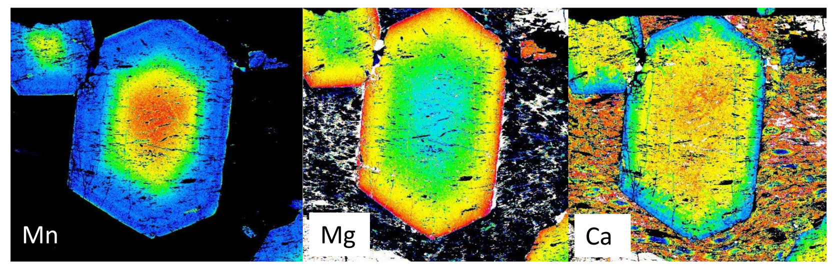


Figure 8: Composition maps of analyzed garnet from FH-1M series. "Warmer temperatures" (i.e, red) are higher concentrations of indicated element than "cooler coloers" (i.e., blue) are lower concentrations.

Sample	Hornblende	Kyanite	Staurolite	Garnet	Biotite	Chlorite	Paragonite	Plagioclase	Epidote	Ankerite	Quartz	Rutile	Ilmenite	Margarite
FH-1M	x	x	x	x	x	x			x	x	x		x	
FH-1M	x	x	x	x	x		x	x	x	x	x	x	x	x

Table 1: x indicates presence in mineral assemblage. * are also present as inclusions in garnet. () indicates mineral found is prograde. Colored (red) samples are findings from Selverstone et al. (1984). Table was reconstructed after Selverstone et al. (1984).

References

Schmid, S. M., Scharf, A., Handy, M. R., & Rosenberg, C. L. (2013). The Tauern Window (Eastern Alps, Austria): A new tectonic map, with cross-sections and a tectono-metamorphic synthesis. *Swiss Journal of Geosciences, 106*(1), 1-32. doi:10.1007/s00015-013-0123-y

Selverstone, J., Spear, F. S., Franz, G., and Morteani, G. (1984). High-Pressure Metamorphism in the SW Tauern Window, Austria: P-T Paths from Hornblende-Kyanite-Staurolite Schists. *Journal of Petrology,* v25 501-531 doi: 10.1093/petrology/25.2.501