Metamorphic Petrology GLY 262

$P-T-t$ paths
Pressure-Temperature-Time (P-T-t) Paths

The complete set of T-P conditions that a rock may experience during a metamorphic cycle from burial to metamorphism (and orogeny) to uplift and erosion is called a pressure-temperature-time path, or P-T-t path.
Pressure-Temperature-Time (P-T-t) Paths

Metamorphic P-T-t paths may be addressed by:

1) Observing partial overprints of one mineral assemblage upon another

The relict minerals may indicate a portion of either the prograde or retrograde path (or both) depending upon when they were created.
Pressure-Temperature-Time (P-T-t) Paths

Metamorphic P-T-t paths may be addressed by:

2) Apply conventional geothermobarometry or pseudosection approach to the core vs. rim compositions of chemically zoned minerals to document the changing P-T conditions experienced by a rock during their growth.
Chemical zoning profiles across a garnet from the Tauern Window. After Spear (1989)
Pressure-Temperature-Time (P-T-t) Paths

Metamorphic P-T-t paths may be addressed by:

3) Use of quantitative phase diagrams (pseudosections)
Thin-section petrography determines that the mineral assemblage includes bi, g, sill, pl, q.

Where does it plot?
However on closer inspection you find garnet and K-feldspar is partially replaced by muscovite.

This texture implies garnet is not stable! But muscovite is!
Where does it plot?
Leucosome are crystallized melt.

When melt crystallizes it expels free H$_2$O leading to retrogression of adjacent minerals. In this case K-feldspar to muscovite.
Where does it plot?
Further petrographic analysis reveals inclusions of kyanite within garnet.

Inclusions with other minerals (usually inside garnet) provide information on the prograde P-T evolution.
Where does it plot?
Even without using mineral chemistry and modelled isopleths we have defined a P-T path!
IF THE PETOGRAPHY IS WRONG THE INTERPRETATION OF THE THERMODYNAMIC MODELLING WILL ALSO BE WRONG
Pressure-Temperature-Time (P-T-t) Paths

Metamorphic P-T-t paths may be addressed by:

- Even under the best of circumstances (1) overprints and (2) geothermobarometry can usually document only a small portion of the full P-T-t path (3) A pseudosection approach to thermobarometry supercedes conventional approaches but still tricky to derive a complete P-T-t path

- May have to rely on “forward” heat-flow models for various tectonic regimes to compute more complete P-T-t paths, and evaluate them by comparison with the results of the backward methods
• 1)-3) provide P-T estimates with *relative* timing.

• Combine P-T path with absolute dating methods to derive P-T-t path
e.g. U-Pb dating of metamorphic minerals
Pressure-Temperature-Time (P-T-t) Paths

- Plate tectonics: regional metamorphism is a result of crustal thickening and heat input during orogeny at convergent plate boundaries (not simple burial)

- Heat-flow models have been developed for various regimes, including burial, progressive thrust stacking, crustal doubling by continental collision, and the effects of crustal anatexis and magma migration

  Higher than the normal heat flow is required for typical greenschist-amphibolite medium P/T facies series

  Uplift and erosion has a fundamental effect on the geotherm and must be considered in any complete model of metamorphism
Schematic pressure-temperature-time paths based on heat-flow models. The Al$_2$SiO$_5$ phase diagram and two hypothetical dehydration curves are included. Winter (2001) An Introduction to Igneous and Metamorphic Petrology, Prentice Hall.
Schematic pressure-temperature-time paths based on a crustal thickening heat-flow model. The $\text{Al}_2\text{SiO}_5$ phase diagram and two hypothetical dehydration curves are included. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.
Path (a) is considered a typical P-T-t path for an orogenic belt with crustal thickening

- During thickening pressure increases $>>$ temperature, because of the time lag required for heat transfer (pressure equilibrates nearly instantaneously, but heat conducts very slowly through rocks)
- Thus the thickened crustal block quickly $\rightarrow P_{\text{max}}$ while remaining relatively cool
- The increased thickness of crust is rich in LIL and radioactive elements, so the heat flux increase
- Subduction zone magmatism may also deliver heat. The new geotherm is higher, but transient, and lasts only as long as the thickened crust and subduction-related heat generation lasts
– Erosion soon affects the thickened crust and the pressure begins to decrease before the rocks can equilibrate with the higher orogenic geotherm
– T still increasing due to the slow heat transfer (most models address heat transfer by conduction only), so that the P-T-t path has a negative slope following P_{max}
– Reach T_{max} when cooling effect of uplift and erosion catches up to the increased geotherm, so that the thermal perturbation of crustal thickening is dampened and begins to fade
– P-T-t path follows positive slope as both T and P fall while rock moves -> surface & geotherm relaxes
Pressure-Temperature-Time (P-T-t) Paths

Most examples of crustal thickening have the same general looping shape, whether the model assumes homogeneous thickening or thrusting of large masses, conductive heat transfer or additional magmatic rise.

Paths such as (a) are called “clockwise” P-T-t paths in the literature, and are considered to be the norm for regional metamorphism.
Path (b): rocks heated and cooled at virtually constant pressure by *magmatic intrusion at shallow levels*

- This may be an appropriate P-T-t path for contact metamorphism
- Depending upon the extent of magmatic activity and its contribution to the crustal mass, any number of paths transitional between (a) and (b) can be imagined, representing a gradation from high-pressure (Barrovian) regional metamorphism to “regional contact metamorphism” with numerous plutons, to local contact metamorphism
Schematic pressure-temperature-time paths based on a heat-flow model for some types of granulite facies metamorphism.
Path (c): “anticlockwise” P-T-t path

– Typically occurs in high-grade gneisses and granulite-facies terranes, and is believed to result from the intrusion of relatively large quantities of (usually mafic) magma into the lower and middle crust

– The rapid introduction of magmatic heat and mass causes both the pressure and temperature to increase in unison below the intrusions

– Followed by nearly isobaric cooling because the high density of the mafic magma does not lead to crustal buoyancy, so that uplift and erosion are limited
Pressure-Temperature-Time (P-T-t) Paths

- Broad agreement between the forward (model) and backward (geothermobarometry) techniques regarding P-T-t paths
- The general form of a path such as (a) therefore probably represents a typical rock during orogeny and regional metamorphism
Pressure-Temperature-Time (P-T-t) Paths

1. Contrary to the classical treatment of metamorphism, temperature and pressure do not both increase in unison as a single unified “metamorphic grade.”

Their relative magnitudes vary considerably during the process of metamorphism.
Pressure-Temperature-Time (P-T-t) Paths

2. $P_{\text{max}}$ and $T_{\text{max}}$ do not occur at the same time

   In the usual “clockwise” P-T-t paths, $P_{\text{max}}$ occurs much earlier than $T_{\text{max}}$.

   $T_{\text{max}}$ should represent the maximum grade at which chemical equilibrium is “frozen in” and the metamorphic mineral assemblage is developed.

   This occurs at a pressure well below $P_{\text{max}}$, which is uncertain because a mineral geobarometer should record the pressure of $T_{\text{max}}$.

   “Metamorphic grade” should refer to the temperature and pressure at $T_{\text{max}}$, because the grade is determined via reference to the equilibrium mineral assemblage.
Pressure-Temperature-Time (P-T-t) Paths

3. Some variations on the cooling-uplift portion of the “clockwise” path (a) indicate some surprising circumstances.

For example, the kyanite $\rightarrow$ sillimanite transition is generally considered a prograde transition (as in path $a_1$), but path $a_2$ crosses the kyanite $\rightarrow$ sillimanite transition as temperature is decreasing. This may result in only minor replacement of kyanite by sillimanite during such a retrograde process.
Pressure-Temperature-Time (P-T-t) Paths

3. Some variations on the cooling-uplift portion of the “clockwise” path (a) indicate some surprising circumstances.

If the P-T-t path is steeper than a dehydration reaction curve, it is also possible that a dehydration reaction can occur with decreasing temperature (although this is only likely at low pressures where the dehydration curve slope is low).