Crystallization of an internally-zoned granitic pegmatite: Insights from fluid and melt inclusions, Emmons Pegmatite, Oxford County, Maine

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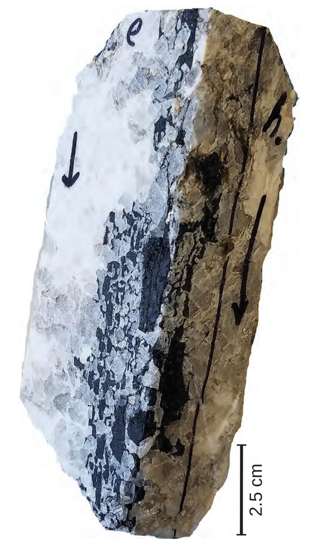
Introduction and Problem Statement

Pegmatites are intrusive igneous rock bodies known for their unique textures, including coarse crystals (2.5 cm to > 10 m) and intricate mineral intergrowths. These textures are thought to form due to rapid, undercooled crystallization as magma intrudes significantly colder rocks in the upper crust.

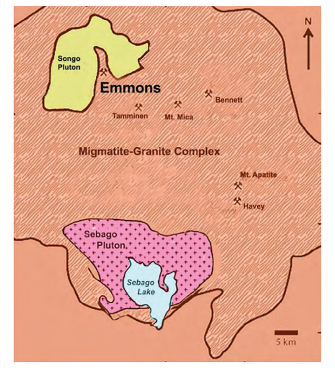
The Emmons pegmatite is mineralogically and texturally zoned from the border to the core. We focus on the progression from comb-texture, sub- to euhedral tourmaline to Quartz-Tourmaline Intergrowth (QTI) to massive quartz to constrain the poorly understood crystallization processes and related temperature and pressure conditions.

Specifically, QTI is a skeletal intergrowth of quartz and tourmaline that has not previously been studied in detail. Microscopic fluid and melt inclusions are well-preserved, especially in tourmaline, and can reveal chemical changes in the magma and temperature variations during crystallization. Growth zones in tourmaline can also indicate the relative timing of fluid entrapment and inclusions in both tourmaline and quartz, allowing us to interpret the crystallization processes.

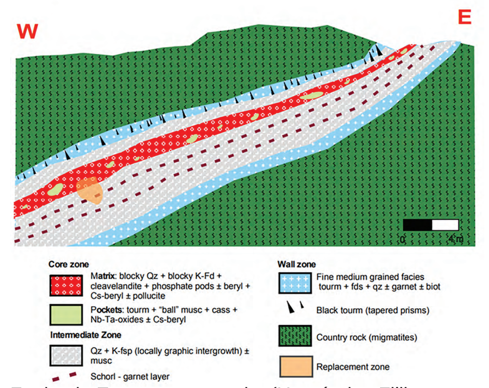


QTI in 3D - QTI extends laterally and longitudinally around the central tourmaline in the growth direction

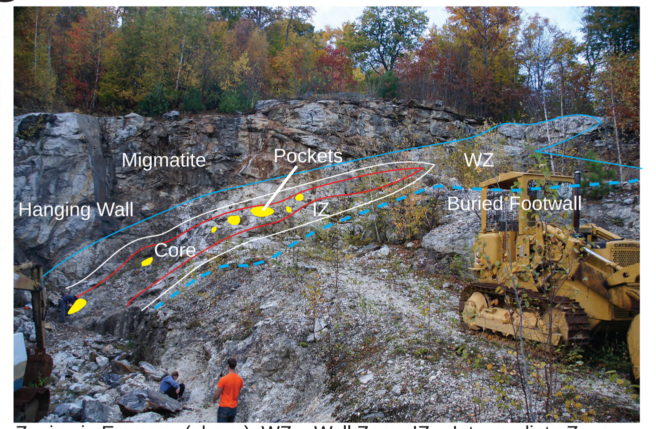
Emmons Pegmatite



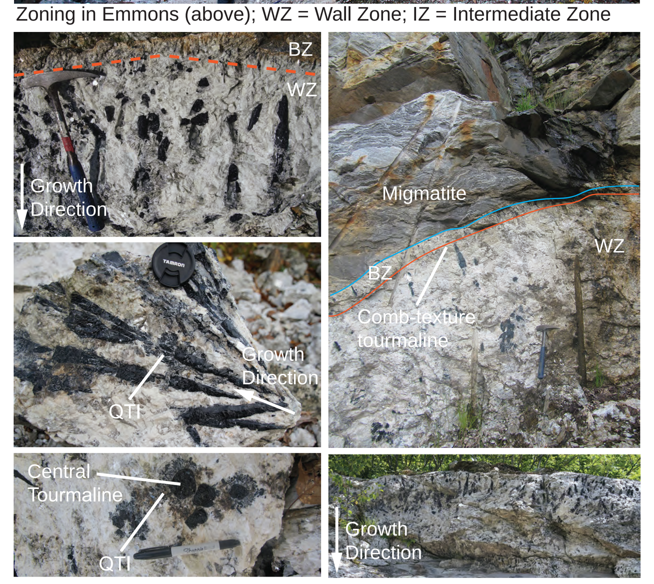
Regional view of Emmons and surrounding pegmatites (Falster, et al., 2019)



Zoning in Emmons pegmatite (Hernández-Filiberto, et al., 2021 and references therein)



Zoning in Emmons (above); WZ = Wall Zone; IZ = Intermediate Zone



(a) BZ/WZ contact in hanging wall (HW); (b) radiating growth of schorl tourmaline with multiple pulses of QTI from HW; (c) tourmaline and QTI perpendicular to growth direction (d) sharp contact between pegmatite and migmatite in HW; (e) comb-texture schorl tourmaline in HW wall zone

Location: Oxford County, Maine
(Oxford County Pegmatite Field)

Surface exposure: ~120 x 18 m

Age: ~260 Ma

Formation: Emmons is thought to have formed by partial melting of surrounding host rock

Classification:
- Lithium-Cesium-Tantalum (LCT) family
  - Miarolitic class
    - Lithium subclass

Emmons is internally zoned, meaning mineralogy and texture vary from the border to the wall, intermediate, and core zones. Sub- to euhedral, comb-texture schorl tourmaline is found in the border zone (BZ) and transitions to QTI in the wall zone (WZ). Massive quartz dominates in the core.

(Černý & Ercit, 2005; Falster, et al., 2019; Webber, et al., 2019)

Methods

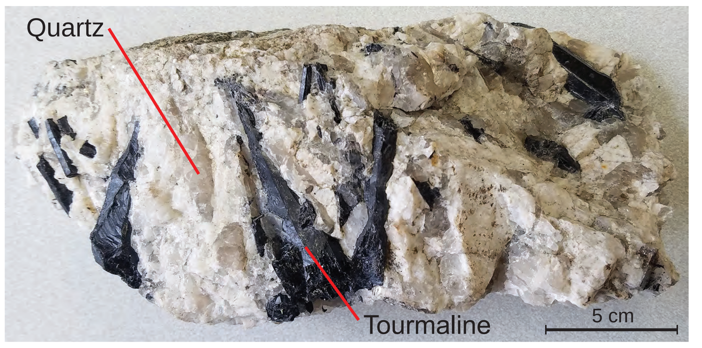
Petrography:
- Used Olympus BX51 petrographic microscope equipped with Olympus DP74 camera and operated with Stream Essentials software to document mineral textures, zoning, and inclusions

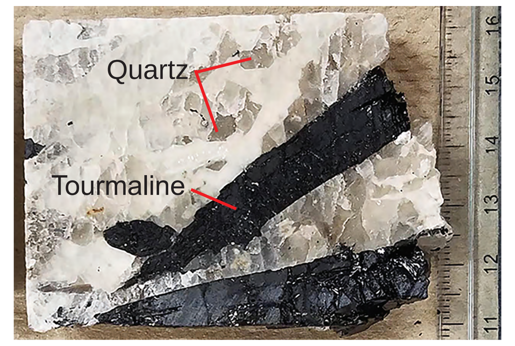
Fluid Inclusion Microthermometry
- Used Olympus BX51 petrographic microscope with specialized Linkam stage for fluid inclusion microthermometry with freezing-heating cycles performed between -120°C and +400°C
- Used synthetic fluid inclusions for calibration
- Processed microthermometric data with MacFlinCor software (Brown and Hagemann, 1994) to obtain the composition and density of FI's and calculate isochores

Scanning Electron Microscopy:
- Used Hitachi 3400N-II SEM instrument to (1) image and analyze melt inclusion composition in tourmaline and quartz, and (2) analyze tourmaline's composition in different growth zones

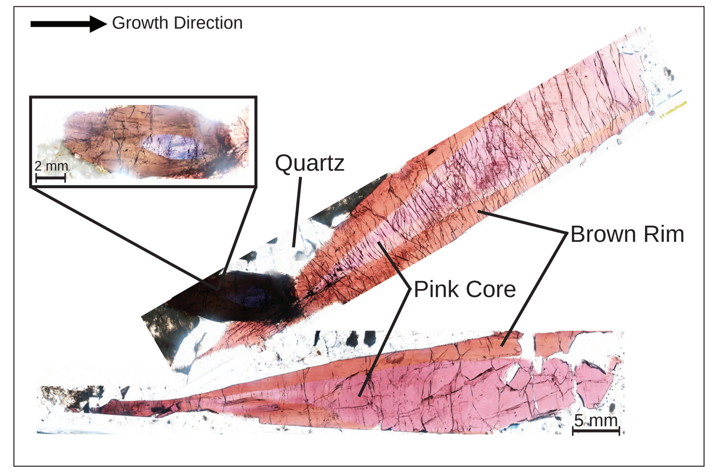
Quartz and Tourmaline Textures and Inclusions in 3 Emmons Pegmatite Zones

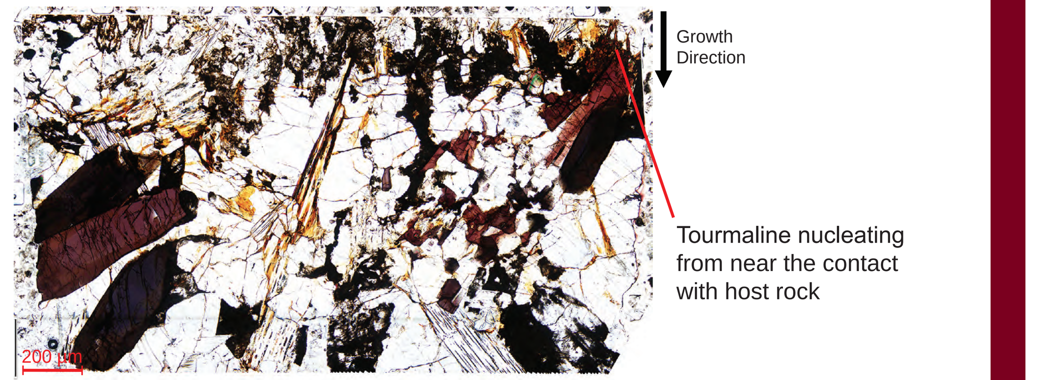
Border Zone





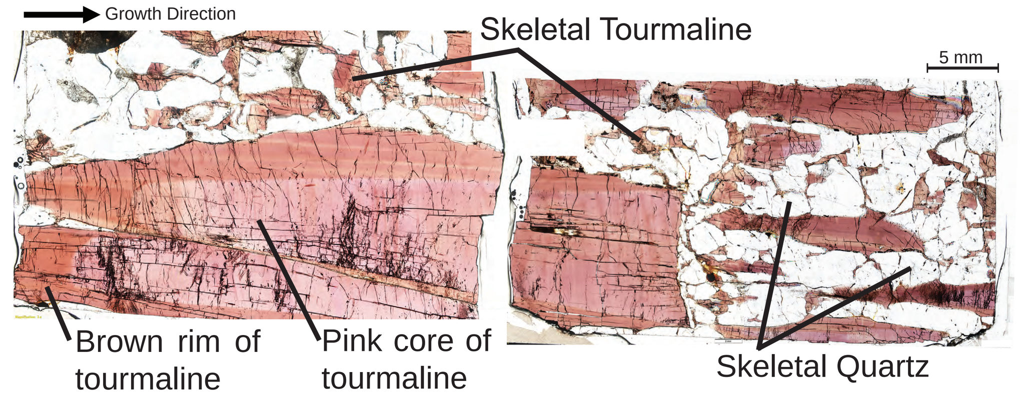
Sub- to euhedral tourmaline crystals lacking QTI are characteristic of the border zone (along with anhedral quartz, mica, and feldspar)

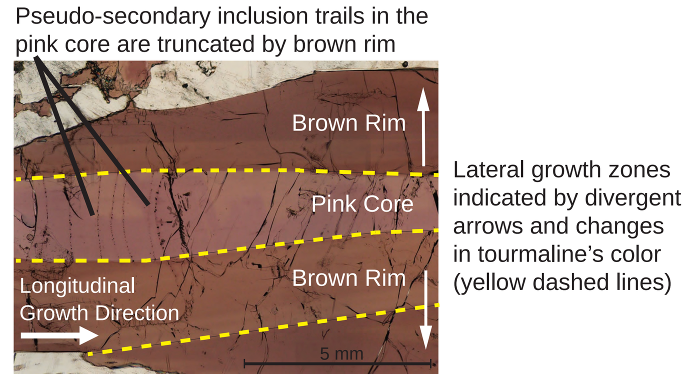




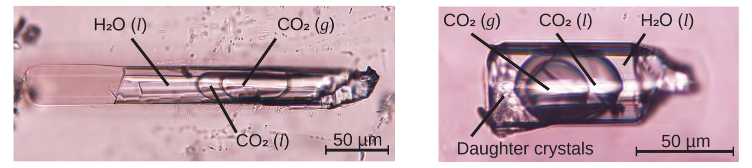
Tourmaline crystals of variable size start nucleating at/near the contact with host rock

Wall Zone

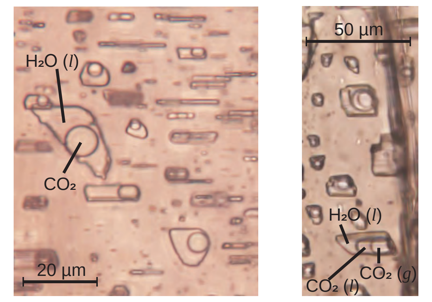




Example of inclusions in relation to growth zones in central tourmaline

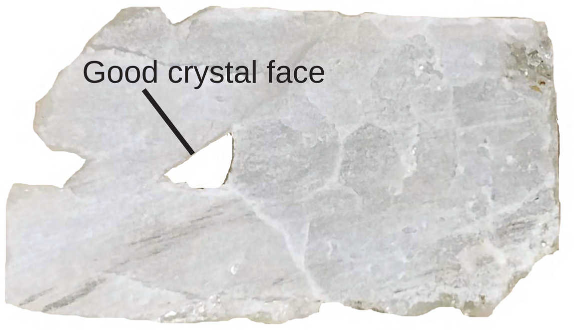


Primary, tubular FI in pink core of central tourmaline

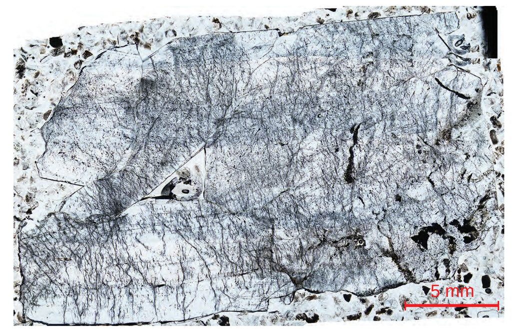


Primary FI in skeletal tourmaline

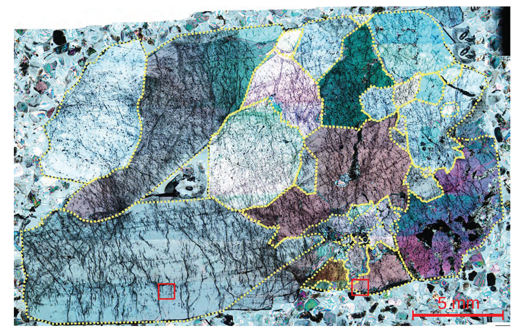
Core Zone



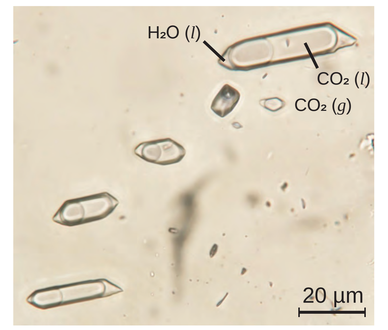
Massive quartz in the core may have good crystal faces around vugs, suggesting a fluid exsolved out of the magma



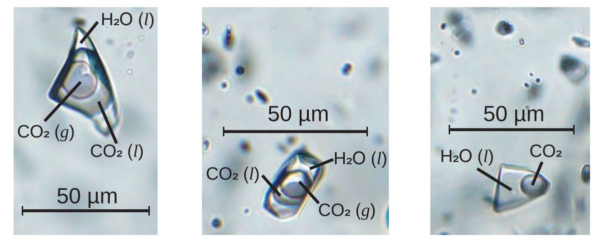
Plane-polarized light image



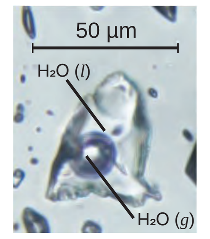
Cross-polarized light image with individual quartz crystals outlined in yellow



Primary FI in quartz



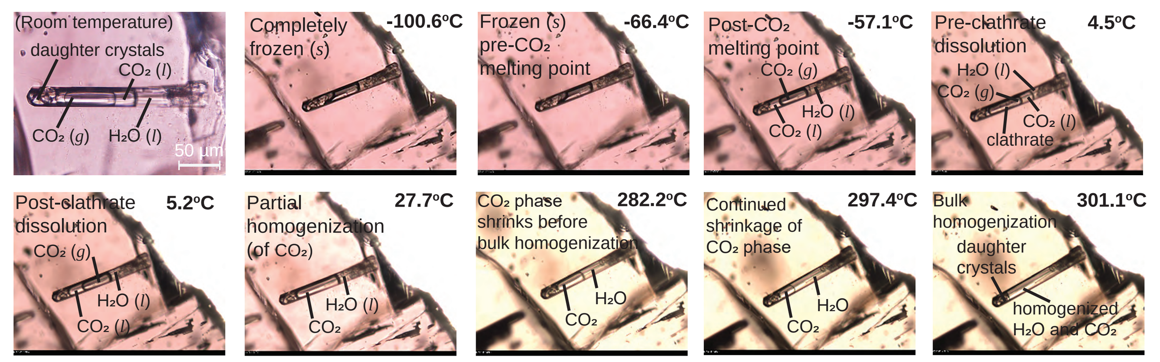
Primary mixed FI with variable CO2: (CO2 + H2O) ratios



Primary aqueous FI

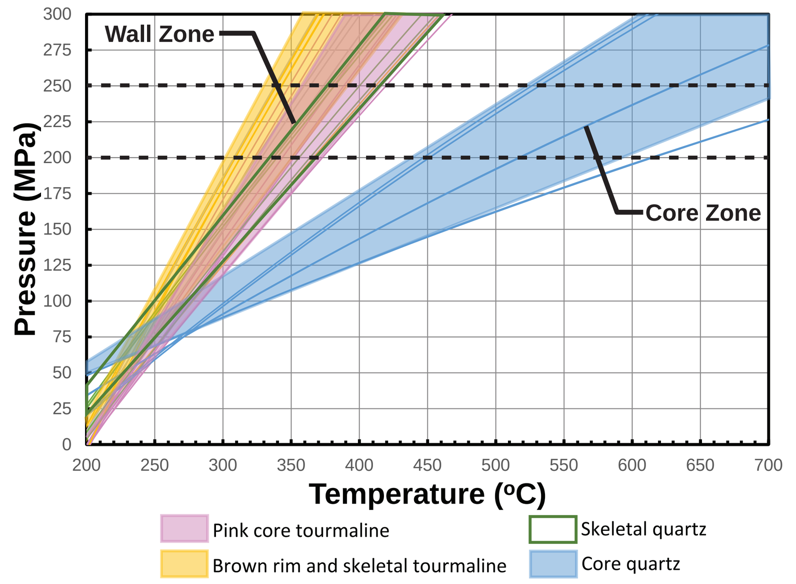
Fluid Inclusions

- Fluid inclusions (FI) are of the H_2O-CO_2-NaCl system, with low salinity
- During microthermometric analysis, freezing-heating cycles were performed between -120°C and +400°C
- Phases encountered included solid CO_2, ice, clathrate (CO_2•4.75 H_2O), CO_2 liquid and vapor, and aqueous liquid and vapor (example FI phase progression to right)
- Fluid inclusion assemblages (FIA's) were separated based on Goldstein and Reynolds textural criteria
- Fluid inclusion isochores and average $T_{trapping}$ were calculated for trapping pressures of 200 and 250 MPa using MacFlincCor



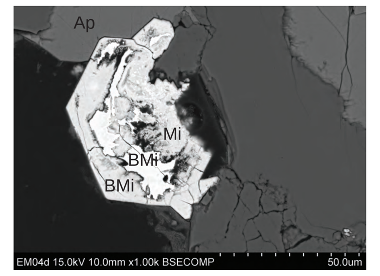
Setting	Textural Type	#FIA (#FI)	Average $T_{trapping}$ (°C) @ 200 Mpa	SD	Average $T_{Trapping}$ (°C) @ 250 MPa	SD	Average Salinity (wt% NaCl)	SD
Wall Zone	Pink Core Tourmaline	7 (19)	347.5	22.7	386.4	29.2	6.1	1.4
	Brown Rim Tourmaline	3 (9)	325.5	24.2	359.4	30.5	5.4	1.8
	Skeletal Tourmaline	4 (48)	324.3	14.1	359.4	17.2	4.6	2.0
	Skeletal Quartz	2 (15)	348.1	17.3	393.5	20.9	4.6	1.5
Pegmatite Core	Massive Quartz	2 (22)	514.0	73.6	625.9	108.8	2.3	0.2

FIA Isochores

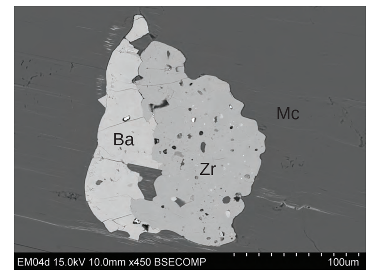


Entrapment pressure (200-250 MPa) is based on the estimated range of emplacement pressure for miarolitic pegmatites (London, 2008)

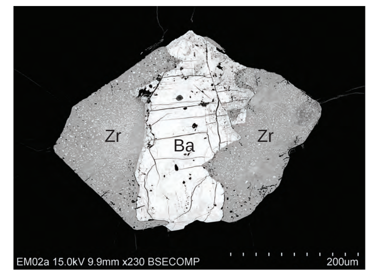
Melt Inclusions



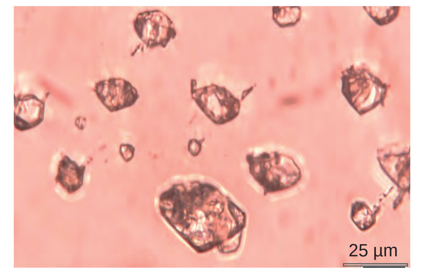
Subhedral MI with complex replacement texture (border zone, BSE image)



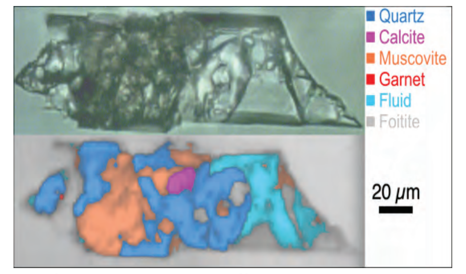
Multi-phase crystallized MI (border zone, BSE image)



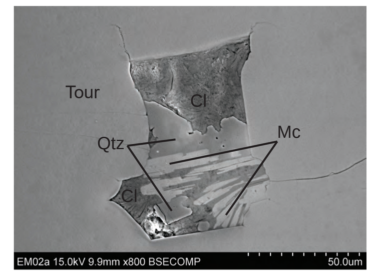
Subhedral MI in quartz (wall zone, BSE image)



Pink cores of tourmaline crystals from the border zone commonly have trails of pseudo-secondary MI's of similar, complex composition



Multi-phase crystallized MI mapped by high resolution Raman Spectroscopy (*Sirbescu and Hulsbosch, 2020*)

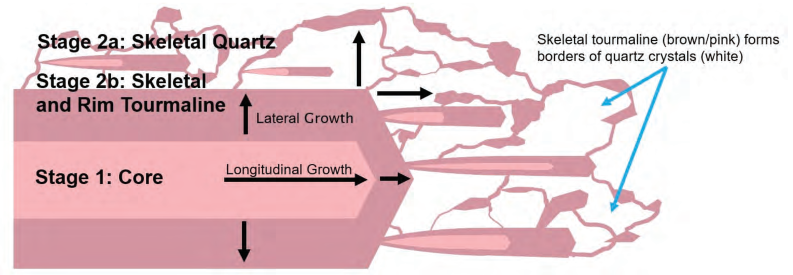


Multi-phase crystallized MI exposed at the surface of polished section (BSE image)

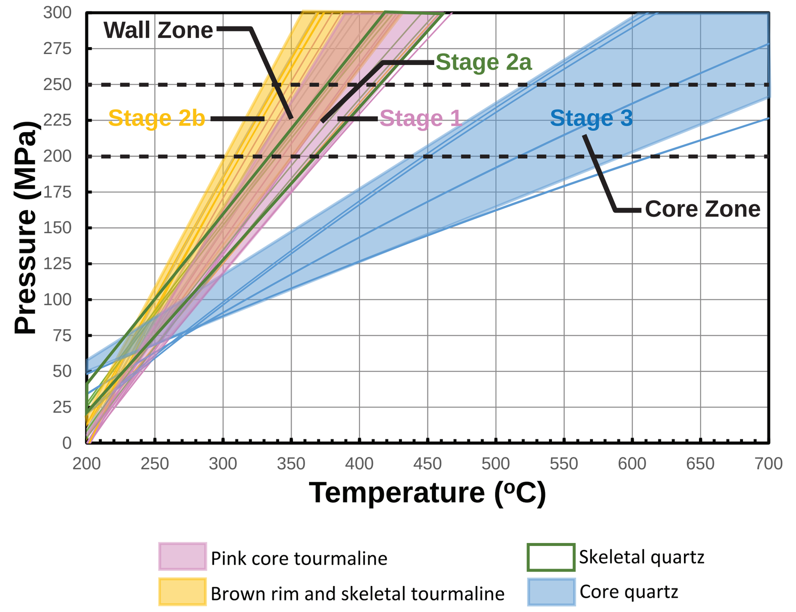
Tour = Tourmaline
Qtz = Quartz
Ap = Apatite
Mc = Mica
Zr = Zircon
Bd = Baddelyite
Mi = Microlite?
BMi = Bismutomicrolite?
Cl = Unknown Clay

Interpretations

- Growth zones and average FI entrapment temperatures suggest 3 main stages of crystallization
- Stage 1 of tourmaline core growth overlaps within error with stage 2 of brown rim and skeletal QTI development. Skeletal quartz, in part, may have developed slightly later
- Average entrapment temperatures in the wall zone are ~300 to 350°C below the equilibrium crystallization temperature for granitic magma (670°C), which is consistent with the current model of pegmatite formation by rapid, undercooled crystallization
- The quartz in the pegmatite's core zone crystallized at Stage 3 at higher temperature, as predicted by cooling models



Proposed Crystallization Process



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