Tourmaline as a Recorder of Geochemical Evolution and an Exploration Tool in the Petalite-Subtype Prof Pegmatite, Revelstoke, Southeastern British Columbia (NTS 082M/01)

C.M. Breasley[1], Department of Earth, Ocean and Atmospheric Sciences, The University of British Columbia, Vancouver, British Columbia, cbreasley@eoas.ubc.ca

L.A. Groat, Department of Earth, Ocean and Atmospheric Sciences, The University of British Columbia, Vancouver, British Columbia

T. Martins, Manitoba Geological Survey, Winnipeg, Manitoba

R.L. Linnen, Department of Earth Sciences, Western University, London, Ontario

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Introduction

The Prof pegmatite is a petalite-subtype pegmatite located in southeastern British Columbia (BC). This pegmatite was recently discovered to contain petalite, marking it as the first known pegmatite in BC to contain significant lithium mineralization (Breasley et al., 2024). The pegmatite contains a suite of minerals indicative of a highly evolved geochemical pegmatitic melt including petalite, elbaite, lepidolite and Ta-Nb oxides. The multiple textural and geochemical varieties of tourmaline within the Prof pegmatite record a complex geochemical history of crystallization and metasomatism. This paper presents the preliminary results of a study into the tourmalines of the Prof pegmatite, and forms part of the lead author's Ph.D. research into lithium mineralization in petalite-subtype pegmatites across Canada.

Regional Geology

The Prof pegmatite is located on Boulder mountain[2], west of Revelstoke, BC. It is situated in the Monashee Complex, a division of the larger Shuswap Complex, which contains two major culminations: the Thor-Odin dome in the south and the Frenchman Cap dome in the north (Figure 1). Boulder mountain is located between these two structural culminations within the Monashee Complex cover sequence (Norlander et al., 2002). The cover sequence contains a variety of schists, quartzite and calcsilicate and quartzofeldspathic gneisses, which overlie the higher grade ortho- and paragneisses and migmatites of the Monashee Complex basement (Hinchey et al., 2006). These basement rocks underwent high-grade metamorphism and deformation and have experienced multiple periods of anatexis (Hinchey et al., 2006). Between 60 and 50 Ma, the Monashee Complex experienced rapid exhumation and decompression, leading to the dome expressions seen today (Spalla et al., 2011). Anatexis was a major process during this time period and is recorded in the form of migmatites, leucosomes and pegmatites (Hinchey, 2005). Pegmatites of the region have been dated, for example, the aplite-pegmatites in the Blanket Mountain and Grizzly flats[3] area (25 km south of Boulder mountain) crystallized between 52.2 ±0.5 Ma and 50.2 ±0.5 Ma (U-Pb zircon dating; Johnston et al., 2000). Additionally, the youngest S-type granite of the region, the Ladybird suite (Hinchey and Carr, 2006), has a zircon U-Pb age of 62.1 ±0.3 Ma for the granites and as young as 55.5 ±0.3 Ma for associated pegmatites (Carr, 1992). Eocene-age normal brittle faults cut through some of the pegmatites in the region (Kruse and Williams, 2005; Hinchey et al., 2006).

Prof Pegmatite

The Prof pegmatite lies within an extensive field of pegmatites, which has not been explored in detail. The pegmatites on Boulder mountain were briefly described by Lane (2017) and the Prof pegmatite was described in detail by Breasley et al. (2024). The Prof pegmatite is a bilobate intrusion 70 m long and 5 m wide that strikes 60° and was divided into four mineralized zones by Breasley et al. (2024): 1) border zone, 2) intermediate zone including the graphic and overgrowth subzones, 3) central zone and 4) quartz zone. The border zone forms a millimetre-scale band surrounding the pegmatite and contains quartz, K-feldspar, muscovite and dravite-schorl (Mg- and Fe-bearing tourmaline) with minor magnetite and biotite. Within the interme-

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[1]*The lead author is a 2024 Geoscience BC Scholarship recipient.*

[2]*Latitude 51.005292, longitude -118.394507*

[3]*Latitude 50.820186, longitude -118.349559*

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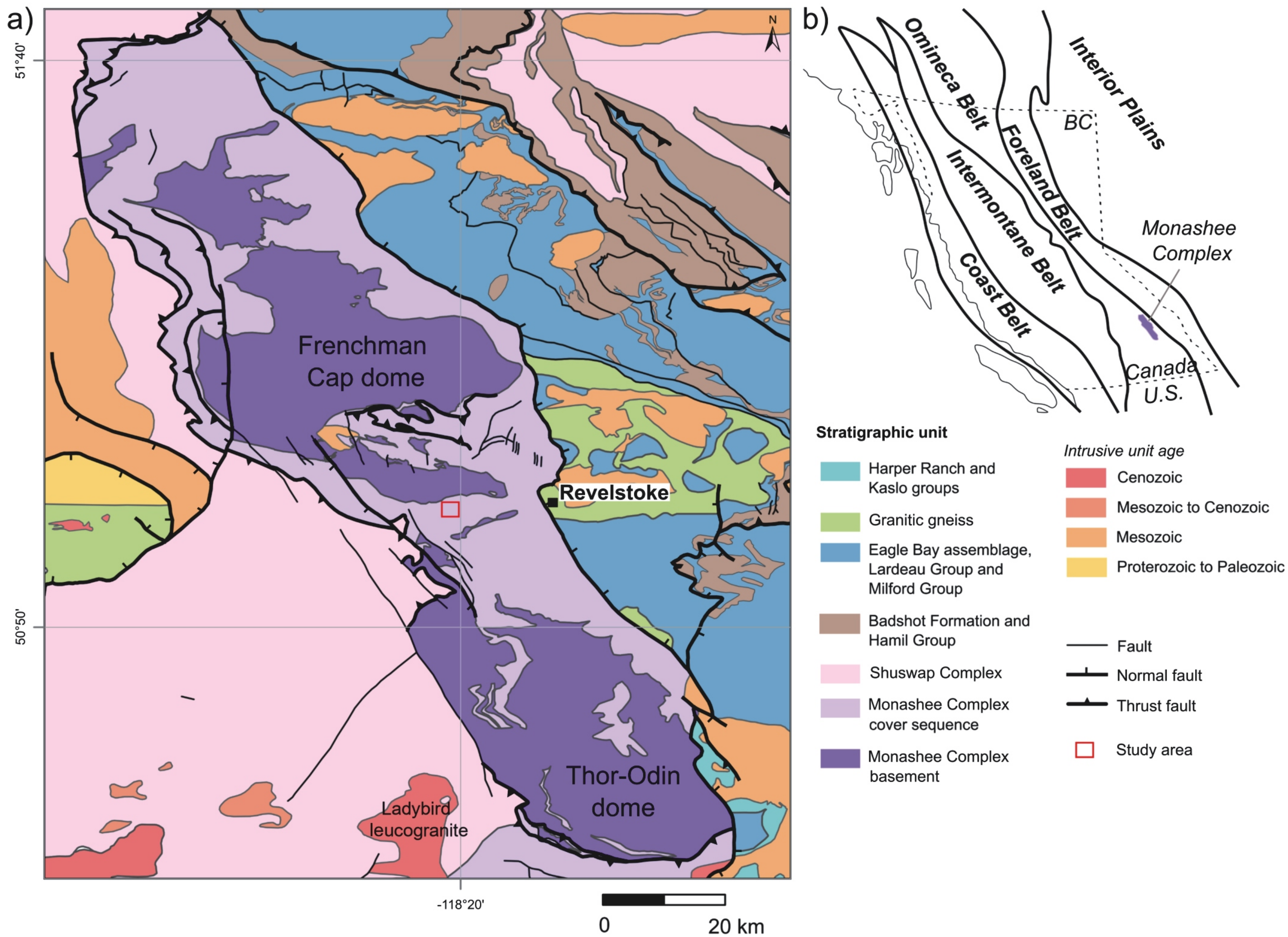

Figure 1. a) Regional geology of the Revelstoke area (modified after Wheeler and McFeely, 1991). The red square shows the location of Boulder mountain (unofficial name) and the Prof pegmatite. **b)** The overview map shows the location of the Monashee Complex in relation to the morphogeological belts of British Columbia.

diate zone, the graphic subzone contains graphic intergrowths of K-feldspar and quartz and hosts multiple aplite bands, which contain quartz, perthite, albite and schorl-dravite. The overgrowth subzone lacks graphic intergrowths and contains more abundant tourmaline. Multiple minerals form rims around older phases in this subzone. The central zone hosts an evolved pegmatite core, which contains the main lithium mineralization of petalite, elbaite (Li-bearing tourmaline) and lepidolite. A subzone found at the contact between the intermediate zone and the central zone is termed the distal tourmaline subzone, due to the abundance of different coloured tourmalines. The quartz zone is 1–3 m thick and is almost monomineralic with minor beryl, schorl and mica. Three phases of metasomatism altered the Prof pegmatite including an albitization event, a later more Na-Li-F–enriched metasomatic event and a sericitization event (Breasley et al., 2024).

Methods

During fieldwork in 2021, 2022 and 2023, a representative sample set of tourmalines was collected from the Prof pegmatite. Samples of tourmalines with variable colours and textures and from different zone locations form the basis of this study. Mineral compositions were determined using a JEOL Ltd. JXA-iHP200F field emission electron probe microanalyzer in the Department of Earth, Ocean and Atmospheric Sciences at The University of British Columbia (Vancouver, BC). Compositional data were acquired for tourmalines and X-ray intensities were processed together within the Probe for EPMA software (Probe Software, Inc.). The instrument was operated at an accelerating voltage of 15 kilovolts (kV) with a beam current of 15 nanoamperes (nA) and a beam diameter of 5 µm. Tourmaline compositions were quantified and corrected using the following standards: albite (CMTaylor) for Si *K*α, Na *K*α; corundum (CMTaylor) for Al *K*α; spessartine (CMTaylor) for Mn *K*α; $ScPO_4$ (National Museum of Natural History [NMNH] 168495) for Sc *K*α; $RbTiPO_5$ (Astimex Standards Ltd.) for Rb *L*α; pollucite (SPI Supplies [SPI]) for Cs *L*α; chromium oxide (SPI) for Cr *K*a; diopside (SPI) for Ca *K*α, Mg *K*α; fluorite (SPI) for F *K*α; hematite (SPI) for Fe *K*α; rutile (SPI) for Ti *K*α; orthoclase (SPI) for K *K*α; tugtupite (SPI) for Cl *K*α; and Cu (JEOL (Germany) GMBH) for Cu *K*α. Structural formulae were calculated on the basis of 31 anions, assuming stoichiometric amounts of H_2O as (OH), that is, OH + F = 4 atoms per formula unit (apfu), B_2O_3 (B = 3 apfu) and Li_2O (as Li^+; MacDonald et al., 1993; Burns et al., 1994). The amount of Li assigned to the Y mineralogical site corresponds to the ideal sum of the cations occupying the T + Z + Y mineralogical sites (15 apfu) minus the sum of the cations actually occupying these sites (Li = 15 – [T + Z + Y] or Li = 15 – [Si + Al + Mg + Fe + Mn + Zn + Ti + Sc + Cr]); the calculation was iterated to self-consistency.

Preliminary Results

All tourmalines from the Prof pegmatite were identified as part of the alkali group, with dravite, schorl, elbaite, fluor-elbaite and fluor-schorl compositions being identified. Petrographic and composition details for each zone of the pegmatite are given below. Geochemical points for representative samples are shown in Table 1.

Border Zone

Tourmalines of the border zone typically contain concentric zoning and occur throughout the border zone as individual black crystals, either disseminated or in a comb structure oriented perpendicular to the contact. Detailed compositions of these tourmalines are yet to be analyzed, but they were shown to be dravite-schorls from Raman spectroscopy.

Intermediate Zone

Tourmalines are highly variable in the intermediate zone and occur in comb structures (Figure 2a), in aplite bands (Figure 2b) and as individual millimetre-scale crystals disseminated throughout the zone. The tourmalines typically have a strong concentric zonation but locally contain no zonation (Figure 3a, b). In the aplitic portions of the intermediate zone, the tourmaline cores contain high contents of Mg and Fe and are dravites. These tourmalines are typically black in representative samples and appear brown to deep blue in thin section. These dravites are often surrounded by a dull brown-green rim in representative samples. This corresponds to schorl compositions with Fe > Mg or Li+Al at the Y mineralogical site. Locally, the dravites and schorls are coated by a final F- and Li-rich tourmaline rim with a fluor-elbaite composition (Figure 3a), which is often colourless in thin section and cannot be distinguished by eye in representative samples.

Central Zone

Multiple colours of tourmaline exist in the central zone of the Prof pegmatite including green tourmalines in the more distal regions of the zone, pale pink tourmalines and rare blue tourmalines. These tourmalines are all elbaite to fluor-elbaite in composition. A variety of these multicoloured tourmalines are located in the distal tourmaline subzone, which is close to the contact with the intermediate zone. Tourmalines of the core of the central zone form elongate radial sprays or distinct isolated crystals (Figure 2c). These pink tourmalines can either show oscillatory zonation or can contain abundant quartz (Figure 3c) and, rarely, both of these textures can be seen within individual crystals (Figure 3d). The fluor-elbaite commonly host elevated Mn concentrations (up to 0.32 apfu).

Table 1. Selected compositions of tourmalines from the Prof pegmatite, southeastern British Columbia. Oxides are in wt. %, ions are in atoms per formula unit (apfu), B = 3 apfu and Li = 15 – (T+Z+Y). Abbreviations: n.d., no data; r, vacancy; T, Z and Y, mineralogical sites.

Thin section ID	PFS1A	PFS1A	PFL2A	P34A
Zone (subzone)	Intermediate (graphic)	Intermediate (graphic)	Central, core	Quartz
Position within mineral	Middle	Middle	Core	Middle
Point	49	50	51	78
Mineral	Dravite	Schorl	Fluor-elbaite	Fluor-schorl
Oxide/ion				
SiO_2	34.42	34.36	37.43	34.08
TiO_2	0.46	0.71	0.02	0.01
Al_2O_3	32.73	33.26	41.23	33.77
Sc_2O_3	0.01	0.03	0.01	n.d.
FeO	7.87	9.8	0.02	13.14
MgO	6.19	4.38	n.d.	0.2
CaO	0.85	0.5	0.36	0.08
MnO	0.05	0.1	1.44	1.13
Na_2O	2.09	2.04	2.05	2.18
K_2O	0.08	0.07	0.02	0.04
Rb_2O	0.07	0.05	0.02	0.06
F	0.54	0.41	1.32	1.01
H_2O*	3.36	3.41	3.25	3.08
B_2O_3*	10.48	10.45	11.23	10.32
Li_2O*	0.31	0.31	2.4	0.72
Total	99.52	99.91	100.82	99.82
T: Si	5.7	5.72	5.79	5.74
Al	0.29	0.29	0.21	0.26
B	3	3	3	3
Z: Al	6	6	6	6
Mg	n.d.	n.d.	n.d.	n.d.
Y: Al	0.1	0.24	1.31	0.45
Ti	0.06	0.09	n.d.	n.d.
Mg	1.53	1.09	n.d.	0.05
Mn	0.01	0.01	0.19	0.16
Fe^{2+}	1.09	1.36	n.d.	1.85
Li*	0.3	0.21	1.5	0.49
Total Y	3	3	3	3
X: Ca	0.15	0.09	0.06	0.02
Na	0.67	0.66	0.62	0.71
K	0.02	0.02	n.d.	0.01
Rb	0.01	n.d.	n.d.	n.d.
r	0.16	0.23	0.32	0.26
OH	3.71	3.78	3.35	3.46
F	0.28	0.22	0.65	0.54

*calculated value

Quartz Zone

Large blue-black tourmalines are present at the edges of the quartz zone and have a fluor-schorl composition.

Discussion

The Prof pegmatite contains multiple minerals that record the fractionation and geochemical evolution of melt, as evidenced by their incompatible element contents. The geochemical evolution of the micas and Nb-Ta oxides of the pegmatite are described in detail in Breasley et al. (2024).

Tourmalines are a common mineral that can record geochemical evolution trends in pegmatites. They are a useful mineral to analyze in pegmatites as they have the potential to form throughout all stages of crystallization, if there is sufficient B in the system, capturing the geochemical environment throughout the paragenesis of the pegmatite, from emplacement to the final stages of metasomatism. In general, tourmalines show a trend of Fe- and Mg-bearing schorl to dravite to Li-bearing elbaites with melt evolution. This has been noted by multiple authors in the literature (Jolliff et al., 1986; Selway et al., 1999; Roda-Robles et al.,

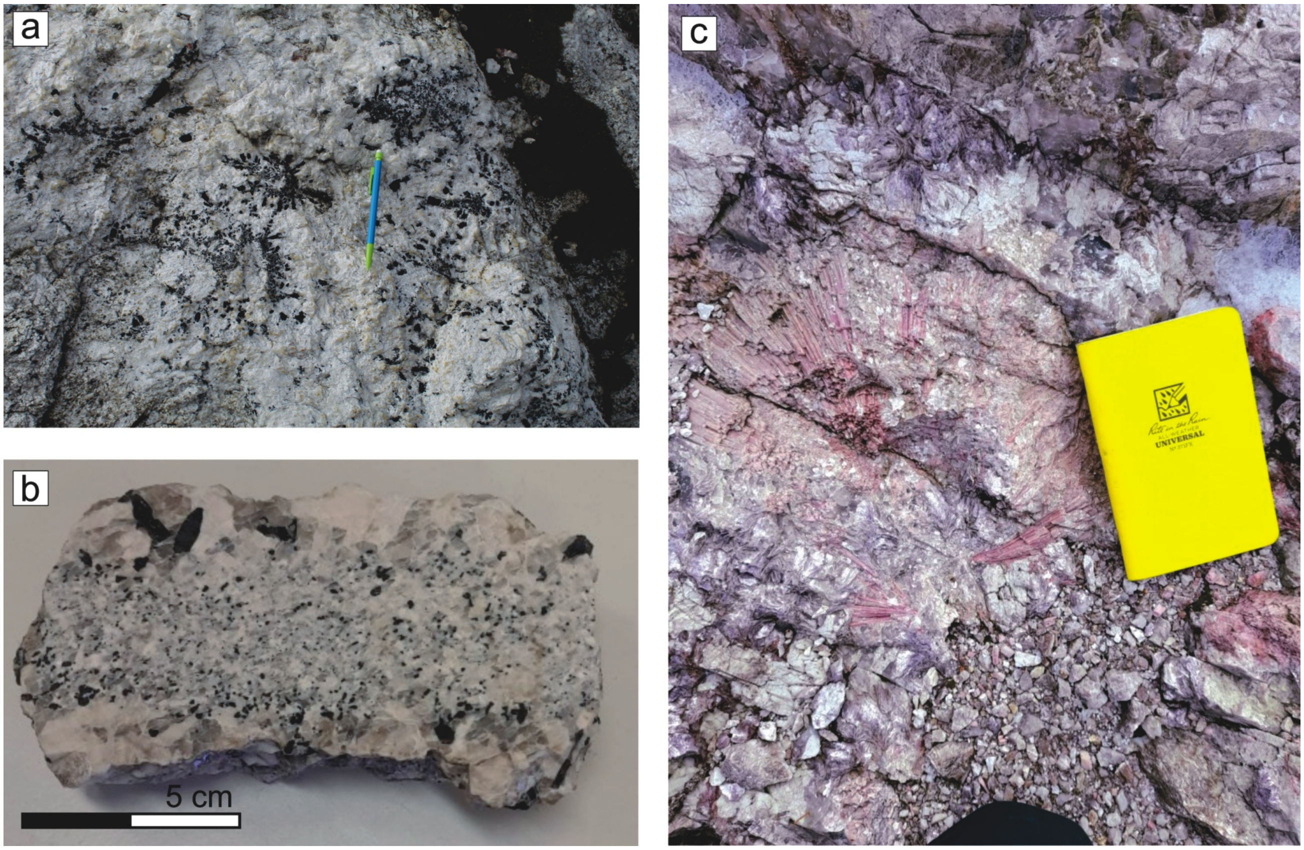

Figure 2. Outcrop and representative samples from the Prof pegmatite, southeastern British Columbia: **a)** tourmalines in a comb structure mark the contact zone between the subzones of the intermediate zone; graphic subzone to the left and overgrowth subzone to right; pencil is 14 cm long; **b)** aplite band from the graphic subzone, composed of tourmaline, feldspars and quartz; **c)** evolved core of the central zone containing radial pink elbaites with purple lepidolite roses and white feldspar; notebook is 12 cm high.

2015) and common elements that reflect the geochemical change of pegmatitic systems include Fe, Mn, Li, Al and F. Due to the abundance, textural varieties and geochemical variation of tourmalines at the Prof pegmatite, tourmaline is a highly valuable mineral to study to reveal insights into the geochemical change throughout the paragenetic crystallization sequence of the pegmatite.

The dravite and schorl within the Prof pegmatite are interpreted to be primary magmatic in nature due to their association with blocky minerals and the pristine nature of the crystals. The elbaites show complex textural relationships and exhibit oscillatory zonation and can be found with abundant quartz inclusions. The elbaites show evidence of primary magmatic origins due to their oscillatory zoning, which is not usually found in replacement minerals (corresponding to the blue/green crystals). In addition to this, the elbaites, which contain abundant quartz inclusions and appear more internally mottled (pink in colour), are found associated with crosscutting veins containing albite and lepidolite. This could indicate that these elbaites are secondary metasomatic in origin. Both of these textures can be observed within a single crystal (Figure 3d), with a relic crystal partially altered to tourmaline and quartz.

Three geochemical plots in Figure 4 show the tourmaline composition from different zones within the Prof pegmatite. The tourmalines in general show an increase in F, Mn and Na and a decrease in Fe as the pegmatite crystallized. These trends indicate that the process of incompatible element accumulation in the residual melt was significant (Selway et al., 1999). Locally, tourmalines within the intermediate zone, which have been influenced by the previously mentioned late-stage Li- and F-rich metasomatism, contain an entire progression from more primitive Fe- and Mg-bearing dravites and schorls to more evolved elbaite rims. Figure 4a, b and c all show that the intermediate zone crystallized first, recorded as comparatively low values of F, Mn, Na and elevated values of Fe in tourmalines. The initial low values and vertical spread in Mn and F in the intermediate zone can potentially be explained by garnets preferentially incorporating Mn during contemporaneous crystallization (Tindle and Breaks, 2000). A similar trend is seen in Na values, which can be attributed to primary albite crystallization in the intermediate zone. The elevated Fe values in the intermediate zone are unsurprising, as this is a more compatible element and is preferentially taken into the tourmaline crystal lattice before more incompatible elements such as Mn. At the conclusion of the primary crystal-

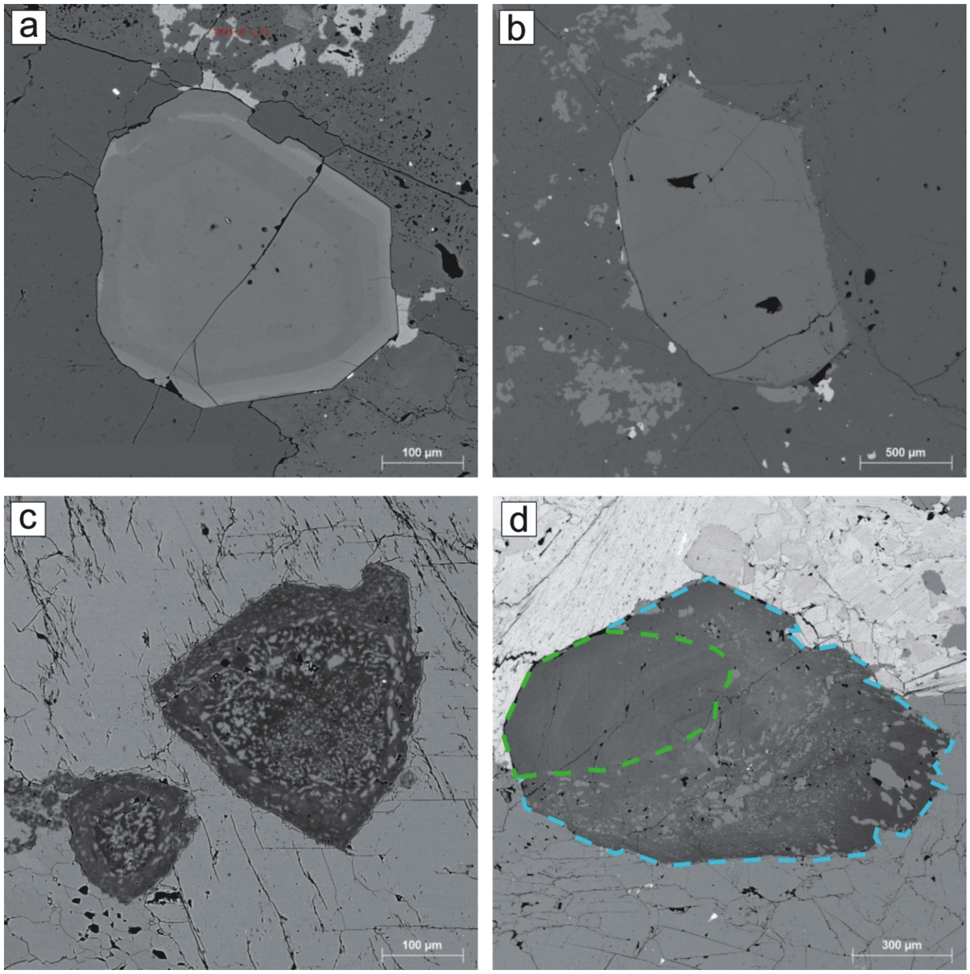

Figure 3. Backscattered-electron images of textural varieties of tourmaline from the Prof pegmatite, southeastern British Columbia: **a)** concentric-zoned dravite-schorl core with fluor-elbaite rim from the intermediate zone (thin section PFS1A); **b)** unzoned schorl from the intermediate zone (thin section PFS1C); **c)** mottled fluor-elbaite with abundant quartz inclusions from the central zone (thin section PFL1A); **d)** two generations of fluor-elbaite with preserved primary oscillatory zonation (green dashed line) and secondary included recrystallization (blue dashed line; thin section P28B), from the central zone.

lization of the intermediate zone, garnet and primary albites stopped crystallizing, allowing Mn and Na values to increase in the residual melt. As the central zone crystallized, the F, Mn and Na content of tourmalines increased, and this can also be correlated with later stage metasomatism of the pegmatite recorded in fluor-elbaite rims. The quartz zone contains fluor-schorls, which are thought to be a product of country rock contamination of the pegmatite coupled with later stage metasomatic recrystallization as observed in other pegmatites (Selway et al., 2000a). The most evolved tourmalines in the Prof pegmatite are fluor-elbaites, a trend which is commonly seen in evolved pegmatites (Selway et al., 2000a; Henry and Dutrow, 2011).

The texture of the comb-structured tourmalines in the Prof pegmatite is commonly seen in pegmatites such as the Tanco pegmatite, Manitoba (Selway et al., 2000b) and in Minas Gerais, Brazil (Webber and Simmons, 2007). This texture is also associated with rapid crystallization of an undercooled melt (Baker and Freda, 1999).

Conclusions

This ongoing study highlights the importance of understanding the mineralogy and paragenesis of pegmatites when exploring pegmatite fields in southeastern British Columbia. Preliminary conclusions from this study are summarized below:

- The Prof pegmatite hosts a textural and geochemical suite of tourmalines that recorded magmatic and metasomatic crystallization processes throughout the entire paragenetic sequence of the deposit.
- Fluorine in tourmalines is a good elemental tracer of geochemical evolution in the pegmatite as concentrations increase throughout the crystallization sequence.

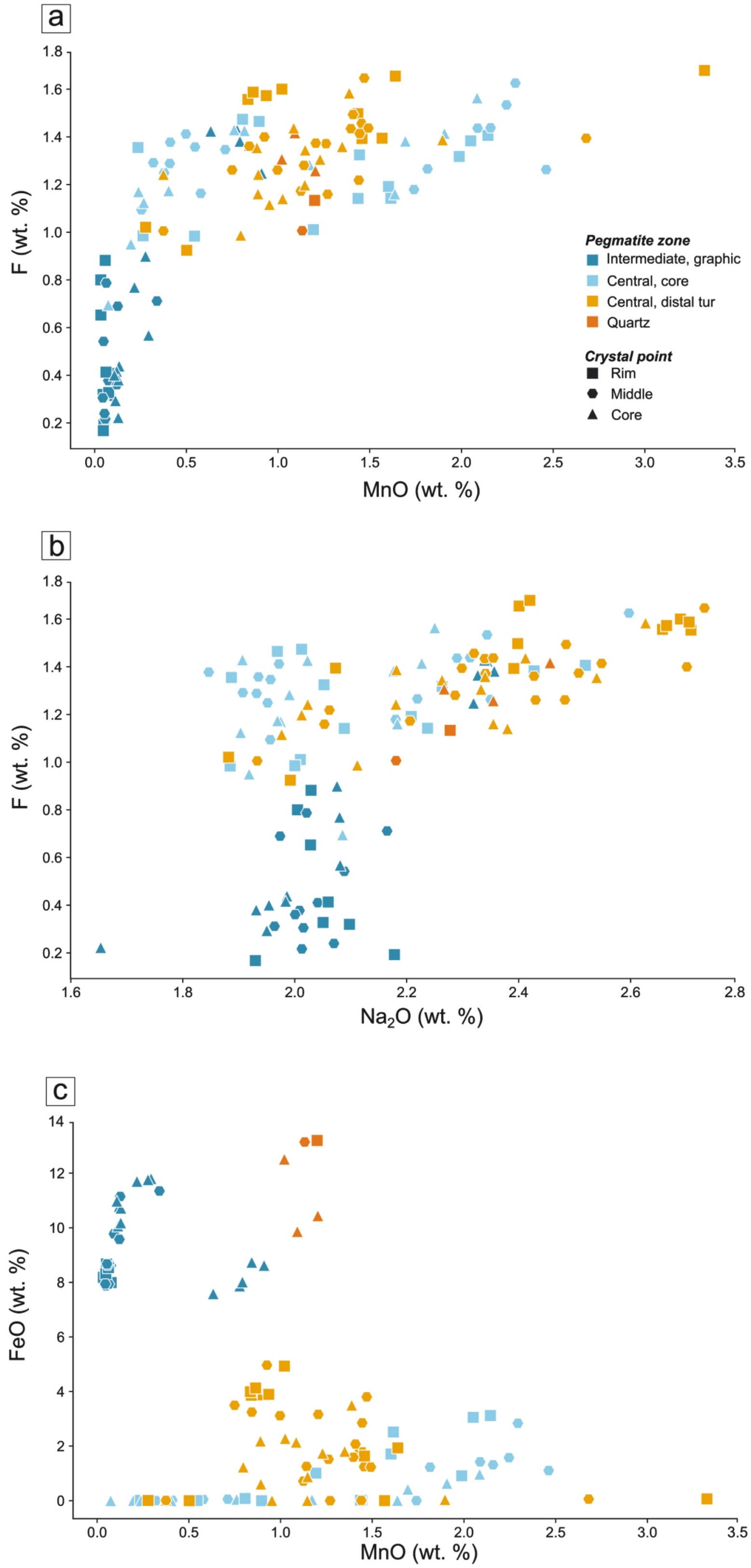

Figure 4. Plots of tourmaline geochemistry from the Prof pegmatite with colour indicating the pegmatite zone/subzone and the shape reflecting the electron probe microanalysis point position within the mineral: **a)** F versus MnO, **b)** F versus Na_2O, **c)** FeO versus MnO. Abbreviations: distal tur, distal tourmaline subzone; graphic, graphic subzone.

The Prof pegmatite lies within an extensive unmapped field of pegmatites on Boulder mountain. Geochemical analysis of tourmalines within other pegmatites of the field can be used as an exploration tool via plotting data against established evolution trends from the Prof pegmatite. The presence of F- and Li-enriched rims on tourmalines in seemingly barren pegmatite surficial expressions could reflect Li mineralization at depth. This Li enrichment has the potential to be expressed as spodumene, the higher pressure lithium aluminosilicate of petalite.

Future Work

Future work aims to further investigate the tourmaline geochemistry of the Prof pegmatite in depth and provide an overview of the tourmaline textures and geochemical evolution throughout crystallization. Future analyses will include using laser-ablation, inductively coupled plasma–mass spectrometry (LA-ICP-MS) to determine accurate lithium concentrations within the tourmalines. Additional data will be collected from the tourmalines of the border zone to make the dataset more complete. Once all geochemical data has been collected, links between the Prof pegmatite and the neighbouring pegmatites on Mount Begbie, described and analyzed by Dixon et al. (2014), will be drawn. These pegmatites are hypothesized to be connected to the Prof pegmatite's field, and comparing the tourmalines will provide geochemical evidence for a link between them.

This work will provide vital geochemical information, which could be used as an exploration tool for the region. Tourmalines from multiple pegmatites within the Prof pegmatite's field could be analyzed and plotted against the known tourmalines from the Prof pegmatite to show how comparatively geochemically evolved the system is. The more geochemically evolved a pegmatitic is, the more likely it is to host increased levels of incompatible elements such as Li, Cs or Ta. Therefore, understanding the tourmaline geochemistry can help vector for more economic mineralization in the region.

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