Mineralogy of Ti-bearing, Al-deficient tourmaline assemblages associated with lamprophyre dikes near the O’Grady Batholith, Northwest Territories, Canada

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Calc-alkaline lamprophyre dikes are hosted by tourmalinized metasedimentary rocks in the Northwest Territories, Canada. Some of these lamprophyre dikes are cross-cut by aplite and pegmatite dikes, as well as tourmaline-bearing quartz veins that were all derived from the nearby granitic O’Grady Batholith. The lamprophyre dikes are composed of actinolite to magnesio-hornblende, plagioclase, K-feldspar and quartz with minor phlogopite (up to 4.13 wt. % TiO2), titanite, apatite, pyrite, allanite-(Ce), and zircon. A zone near the margin of one of the dikes has been altered to tourmaline associated with actinolite to magnesio-hornblende, clinohlore, titanite and quartz, with minor clinopyroxene and apatite. Two generations of tourmaline are recognized: Tur I occurs in quartz at the margin of the dike and Tur II forms a massive aggregate with common inclusions of other minerals in an altered lamprophyre zone near the margin of the dike. The vast majority of the analyzed tourmaline is Al-deficient, with less than 6 apfu Al at the Z site (on average 5.691 apfu in Tur I and 5.601 apfu in Tur II). Tur I is mostly dravite with uvite, plus minor feruvite and fluor-uvite, while Tur II contains a greater proportion uvite, feruvite, and fluor-uvite. The most evolved tourmaline compositions observed are feruvite with up to 2.17 wt. % TiO2, and fluor-uvite with up to 0.84 wt. % F. The tourmaline composition reflects the unique geochemical environment in which it crystallized; from Tur I to Tur II, tourmaline becomes richer in Ca-, Fe-, and Ti, presumably due to the reaction of B-bearing fluids with the Al-poor, Ca-, Mg–Fe-, and Ti-bearing minerals in the lamprophyre dike. The high F contents of some tourmaline species suggest that it crystallized from fluids derived from the aplite and pegmatite dikes.

Keywords: dravite, uvite, feruvite, fluor-uvite, lamprophyre dikes, O’Grady Batholith

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1. Introduction

Tourmaline-supergroup minerals are complex borosilicates that occur in a wide variety of host environments. Tourmaline has been extensively studied, in part because of its ability to incorporate numerous elements into its crystal structure, making it an ideal monitor of its local environment (van Hinsberg et al. 2011).

Mineralogical studies related to the O’Grady Batholith, a metaluminous composite intrusion that is a member of the Selwyn Plutonic Suite in the Northwest Territories, Canada, have focused on pegmatite dikes that occur both within the Batholith and in the country rocks surrounding it (e.g., Groat and Ercit 1996; Ercit et al. 2003; Scribner et al. 2014). During field work in 2013, lamprophyre dikes were discovered near the O’Grady Batholith in the Nááts’ihch’oh National Park Reserve, Northwest Territories, Canada (62°46′8.33″ N, 128°56′9.07″ W; Fig. 1).

Upon further examination of the samples, tourmaline was found along the margin of one of the lamprophyre dikes and in an altered lamprophyre zone near its margin. The study area also contains aplite dikes, pegmatite dikes, and late-stage tourmaline-bearing quartz veins, all of which are hosted by metasedimentary rocks. Tourmaline is ubiquitous in the study area, occurring within, or at the margin of, nearly all units. The host rocks are almost completely metasomatized to tourmaline and quartz.

The goals of this study were to characterize the mineralogy of the newly discovered lamprophyre dikes and the associated tourmaline. Furthermore, having recognized that the association of tourmaline with a lamprophyre dike is unusual, we studied the influence of the lamprophyre dike on the composition of tourmaline. This paper presents detailed chemical analyses of minerals in the lamprophyre dikes and the tourmaline that occurs along the margin of one of these dikes.
2. Geological setting

The study area lies within the Selwyn Basin that covers an area of c. 700 × 200 km in the central Yukon Territory and southwestern Northwest Territories (Figs 1–2). The basin is defined by Neoproterozoic to Middle Devonian slope-to-basin facies sequences that are overlain by Mississippian to Jurassic shelf and basinal strata in isolated occurrences (Gordey and Anderson 1993; Mair et al. 2006). The lamprophyre dikes and other intrusive rocks of the O'Grady Batholith are hosted in weakly metamorphosed sedimentary rocks of the Mount Christie Fm. that are Mississippian to Permian in age (Gordey and Anderson 1993). Small- to large-scale northwest-trending folds were produced by the regional deformation that occurred from the Jurassic to the Cretaceous (Gordey and Anderson 1993).

During a mid-Cretaceous period of granitic magmatism, the Selwyn Plutonic Suite was emplaced at an epizonal to mesozonal depth. The Selwyn Plutonic Suite has been subdivided into the Tombstone Suite, Tungsten Suite, and Tay River Suite (Gordey and Anderson 1993). The Tombstone Suite has considerable lithological variation, but hornblende–biotite granodiorite and quartz monzonite are the most common phases. The Tungsten Suite is dominated by peraluminous two-mica granitoid (Hart et al. 2000). Granitic pegmatites are associated with all members of the Selwyn Plutonic Suite (Gordey and Anderson 1993).

2.1. O’Grady Batholith

The O’Grady Batholith, part of the Tombstone Suite, is a composite intrusion that is hosted by variably hornfelsed shale, silty shale, and minor chert of the Mount Christie Fm. (Gordey and Anderson 1993) (Fig. 2). The majority of the Batholith is composed of a Kfs-phyric hornblende granite (hornblende quartz syenite of Gordey and Anderson 1993) that grades, via a foliated transitional phase, to an equigranular, hornblende–biotite granodiorite on the margins. The study area is underlain by the megacrystic hornblende granite phase of the O’Grady Batholith (K–Ar hornblende age of 95 ± 1 Ma; Hunt and Roddick 1987).

2.2. Aplite and pegmatite dikes, quartz veins

Aplite and pegmatite dikes are late-stage differentiates of the O’Grady Batholith. The aplite dikes are 0.2–1 m thick and composed of quartz, K-feldspar, plagioclase, and tourmaline, with lesser amounts of mica, calcite, and zircon. Tourmaline in the aplite dikes is fluorschorl with minor zones of schorl. Fluorine reaches a maximum content of 1.30 wt. % F (0.706 apfu) in the core of a crystal (Scribner 2014). The pegmatite dikes are mostly 20–30 cm thick but some reach 1 m in thickness. They are composed of quartz, albite, muscovite, and tourmaline, with lesser amounts of K-feldspar, calcite, and apatite. Tourmaline in the pegmatite dikes has foitite cores and schorl rims. The rims have a high F content and can reach fluor-schorl (up to 1.03 wt. % F; 0.544 apfu) (Scribner 2014).

The aplite dikes, pegmatite dikes, and lamprophyre dikes are all hosted by the metasomatized sedimentary host rocks of the Mount Christie Fm. The host rocks are composed almost entirely of tourmaline and quartz. Tourmaline is mainly dravite with small zones of schorl. In contrast to the aplite and pegmatite dikes, the F content of tourmaline in the host rocks is low with a maximum of 0.25 wt. % (0.132 apfu) in dravite (Scribner 2014). Quartz veins, often tourmaline-bearing, cross-cut all units in the study area. Tourmaline growing into a quartz vein that cross-cuts the host rock has uvite cores and dravite rims. This tourmaline also has a low F content, reaching a maximum of 0.42 wt. % (0.224 apfu) in dravite (Scribner 2014).

2.3. Lamprophyre dikes

Anderson (1983) identified lamprophyre dikes associated with the Northern Nahanni Pluton (part of the Tay River Suite), which is located c. 14.5 km E of the study area. The dikes were described as coeval with the other aplite...
and biotite–plagioclase porphyritic dikes in the region (87–93 Ma; Anderson 1983), although the parental intrusion was not specified. Hunt and Roddick (1987) noted biotite lamprophyre dikes associated with the Pelly River (~37 km W of the study area) and Lened (~46 km SE) plutons, also part of the Tay River Suite. K–Ar dating on biotite yielded ages of 91 ± 2 and 91 ± 1 Ma, respectively. Lamprophyre, aplite, porphyritic, and aplitic monzogranite dikes are described as cospatial and younger than the Selwyn Plutonic Suite with an expanded age range of 84–96 Ma (Gordey and Anderson 1993).

The crosscutting relationships in the study area indicate that the aplite and pegmatite dikes, as well as tourmaline-bearing quartz veins, are younger than the lamprophyre dikes.

3. Analytical methods

The compositions of amphibole-supergroup minerals, feldspars, chlorite-group minerals, titanite, and micas were analyzed using a CAMECA SX-50 electron microprobe operating in wavelength-dispersion mode at the University of British Columbia. Data reduction was done using the ‘PAP’ method (Pouchou and Pichoir 1985). The following analytical conditions were used: acceleration voltage 15 kV, beam current 20 nA (10 nA for chlorite and mica), peak counting time 20 s (40 s for F in tourmaline and amphibole; 60 s for F and 40 s for Cl in chlorite; 40 s for F, Cl, Rb, and Cs in mica), background count time 10 s (20 s for F in tourmaline and amphibole; 30 s for F and 20 s for Cl in chlorite; 20 s for F, Cl, Rb, and Cs in mica), spot diameter 5 μm (10 μm for chlorite and mica). The following standards were used for each mineral (all X-ray lines were K unless otherwise stated): amphibole (phlogopite, F, TAP; albite, Na, TAP; kyanite, Al, TAP; diopside Mg, Si, TAP; diopside, Ca, PET; scapolite, Cl, PET; orthoclase, K, PET; rutile, Ti, PET; magnesiochromite, Cr, LiF; rhodonite, Mn, LiF; fayalite, Fe, LiF; Ni-olivine, Ni, LiF); feldspar (albite, Na, TAP; anorthite, Al, TAP; diopside, Mg, TAP; anorthite, Si, TAP; anorthite, Ca, PET; orthoclase, K, PET; rhodonite, Mn, LiF; fayalite, Fe, LiF);
### Tab. 1 Representative analyses and structural formulae of amphibole-supergroup minerals, feldspars, chlorite-group minerals, titanite, and mica-group minerals

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<td>Act</td>
<td>Kfs</td>
<td>Pl</td>
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<td>Clc</td>
<td>Clc</td>
<td>Ttn</td>
<td>Ttn</td>
<td>Phil</td>
<td>Phil</td>
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<td>–</td>
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<td>–</td>
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<td>51.86</td>
<td>63.08</td>
<td>47.63</td>
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<td>30.00</td>
<td>29.09</td>
<td>30.02</td>
<td>29.95</td>
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<td>TiO2</td>
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<td>b.d.</td>
<td>b.d.</td>
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<td>35.93</td>
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<td>–</td>
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<tr>
<td>Al2O3</td>
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<td>2.49</td>
<td>17.79</td>
<td>32.71</td>
<td>26.56</td>
<td>19.14</td>
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<td>2.57</td>
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<td>Cr2O3</td>
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<td>6.33</td>
<td>0.11</td>
<td>b.d.</td>
<td>b.d.</td>
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<tr>
<td>Fe2O3 (mol.)</td>
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<td>b.d.</td>
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<td>0.31</td>
<td>0.20</td>
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<td>17.20</td>
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<td>b.d.</td>
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<td>CaO</td>
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<td>Na2O</td>
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<td>0.37</td>
<td>2.52</td>
<td>6.33</td>
<td>0.11</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.31</td>
<td>0.20</td>
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<td>K2O</td>
<td>0.24</td>
<td>0.35</td>
<td>0.01</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.23</td>
<td>0.19</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>F</td>
<td>0.65</td>
<td>0.35</td>
<td>0.01</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.23</td>
<td>0.19</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.31</td>
<td>0.20</td>
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<tr>
<td>Cl</td>
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<td>0.35</td>
<td>0.01</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.23</td>
<td>0.19</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.31</td>
<td>0.20</td>
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<td>–</td>
<td>–</td>
<td>11.13</td>
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<td>–O=F,Cl</td>
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<td>–</td>
<td>–</td>
<td>b.d.</td>
<td>–</td>
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<tr>
<td>Total</td>
<td>98.92</td>
<td>98.86</td>
<td>99.29</td>
<td>98.73</td>
<td>99.37</td>
<td>99.14</td>
<td>97.13</td>
<td>97.45</td>
<td>98.92</td>
<td>101.10</td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviations of mineral names are Whitney and Evans (2010)**

The formulae for amphibole were calculated on the basis of 15 cations, feldspar on the basis of 5 cations, chlorite on the basis of 10 cations, titanite on the basis of fully occupied Y and Z cation sites (general formula XY(ZO₄)O), and mica on the basis of 7 cations

Barium, Rb, and Cs were also sought in mica but were below the detection limit in all analyses

*H₂O content calculated based on stoichiometry; **ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit; – = not measured
Amphibole is the main matrix mineral and also occurs as aggregates of elongated grains up to 2 mm across. Plagioclase also occurs in the matrix and rarely as subhedral phenocrysts. Other matrix minerals include K-feldspar, quartz, and titanite, while diopside and apatite are rarer and form small (< 50 μm) subhedral grains that are disseminated throughout. Pyrite is variable in abundance: in some dikes it can be distinguished in hand sample while in others it occurs in trace amounts. When present, biotite forms large (1–2 mm long), anhedral phenocrysts that have been partially resorbed, and smaller (< 1 mm long) platy crystals in the matrix, both of which are deep red-brown in color.

The main minerals in the lamprophyre dikes were analyzed using EMPA. Representative compositions can be found in Tab. 1, and all analyses are provided in the Electronic Supplementary Material on the Journal of Geosciences website.

**Amphiboles** show Mg/(Fe + Mg) of 0.62–0.79 both in the unaltered dikes and the tourmalinized zone in one of the dikes. They are calcic amphiboles with minor amounts of Na + K (max. 0.20 apfu ³Na, 0.07 apfu ³K), classifying them as actinolite to magnesio-hornblende (Fig. 3a). The compositional variability reflects mainly the Tschermak’s substitution (³R²⁺ + ³Al)(²R²⁺ + ³Si) with boron content fixed at 3 apfu. This assumes no Li or vacancies at the Y site and no ³B at the T site. The absence of Li at the Y site is assumed valid because of the lack of any Li-enriched minerals in all examined units. The assumption that the B site is fully occupied by B and that there is no B in the tetrahedral site was deemed to be valid for most occurrences of tourmaline (Hawthorne and Dirlam 2011). Furthermore, the uncommon tourmaline specimens that contain tetrahedral B are Al-rich (e.g., Ertl et al. 2006), whereas all tourmaline species analyzed in this study are Al-deficient.

**4. Results**

**4.1. Petrology and mineral chemistry of the lamprophyre dikes**

The lamprophyre (specifically spessartite) dikes trend north–south, range from 2–6 m in width, and are hosted by metasedimentary rocks. They are composed of amphibole, plagioclase, K-feldspar, and quartz, with minor titanite, and rare diopside, apatite, pyrite, allanite-(Ce), and zircon. Phlogopite is common in some dikes and rare in others. A zone near the margin of one of the lamprophyre dikes that has been altered to tourmaline also contains amphibole, chlorite, titanite, and quartz, with minor clinopyroxene and apatite.

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The lamprophyre (specifically spessartite) dikes trend north–south, range from 2–6 m in width, and are hosted by metasedimentary rocks. They are composed of amphibole, plagioclase, K-feldspar, and quartz, with minor titanite, and rare diopside, apatite, pyrite, allanite-(Ce), and zircon. Phlogopite is common in some dikes and rare in others. A zone near the margin of one of the lamprophyre dikes that has been altered to tourmaline also contains amphibole, chlorite, titanite, and quartz, with minor clinopyroxene and apatite.

Amphibole is the main matrix mineral and also occurs as aggregates of elongated grains up to 2 mm across. Plagioclase also occurs in the matrix and rarely as subhedral phenocrysts. Other matrix minerals include K-feldspar, quartz, and titanite, while diopside and apatite are rarer and form small (< 50 μm) subhedral grains that are disseminated throughout. Pyrite is variable in abundance: in some dikes it can be distinguished in hand sample while in others it occurs in trace amounts. When present, biotite forms large (1–2 mm long), anhedral phenocrysts that have been partially resorbed, and smaller (< 1 mm long) platy crystals in the matrix, both of which are deep red-brown in color.

The main minerals in the lamprophyre dikes were analyzed using EMPA. Representative compositions can be found in Tab. 1, and all analyses are provided in the Electronic Supplementary Material on the Journal of Geosciences website.
generations is highly variable (Tab. 2). Tur I is mainly pale brown–green in color in plane-polarized light with patchy chemical zoning. It also contains small dark brown zones that tend to be more prominent closer to the margin of the dike (Fig. 5). The composition of Tur I is mostly Ca,WO-rich dravite with small patches of feruvite and fluor-uvite; one analytical spot reaches oxy-dravite (Figs 6–7). Tur I also contains small dark brown patches of Fe-rich uvite and feruvite. Some grains of Tur I are zoned with pale blue dravite cores, a darker blue–green intermediate uvite zone, and pale blue dravite rims (Fig. 5). An oxy-dominant species (oxy-dravite) occurs at the outermost rim of a poorly-zoned crystal of Tur I. Tur II has partially replaced the lamprophyre dike (Fig. 5) and frequently encloses grains of actinolite to magnesiohornblende, clinochlore, titanite, and quartz (+ diopside, apatite). Dravite is still a common constituent of Tur II, but it contains more patches of uvite, feruvite, and fluor-uvite than Tur I (Figs 6–7).

The compositions of the two tourmaline types are very similar, but from Tur I to Tur II there is generally a slight increase in Ca/(Ca + Na) and in F/OH, corresponding to a shift from more alkali-group tourmaline in Tur I to more calcic-group tourmaline in Tur II (Fig. 6a). $X$ site vacancy is low in both tourmaline generations, but is highest in dravite from Tur I (0.176 apfu). Fluorine and calculated O$_2^-$ increase at the W site, with a maximum 0.447 apfu F (0.84 wt. % F) in fluor-uvite from Tur II (Fig. 6b).

Overall, Mg/(Mg + Fe$^{2+}$) decreases slightly from Tur I to Tur II, but many species in Tur II are still Mg-dominant (Fig. 6c). All analyzed tourmalines are Al-poor, and Al content generally decreases from Tur I to Tur II, consistent with the observed negative correlation between Al and Ca/(Ca + Na) (Fig. 7a). The highest Al (6.146

4.2. Tourmaline

Two textural generations of tourmaline associated with one of the lamprophyre dikes are recognized: Tur I occurs with quartz as subhedral grains up to 5 mm across at the margin of the lamprophyre dike whereas Tur II forms a massive aggregate with common inclusions of other minerals in an altered lamprophyre zone near the margin of the dike (Figs 4–5). The composition of both generations is highly variable (Tab. 2). Tur I is mainly pale brown–green in color in plane-polarized light with patchy chemical zoning. It also contains small dark brown zones that tend to be more prominent closer to the margin of the dike (Fig. 5). The composition of Tur I is mostly Ca,WO-rich dravite with small patches of feruvite and fluor-uvite; one analytical spot reaches oxy-dravite (Figs 6–7). Tur I also contains small dark brown patches of Fe-rich uvite and feruvite. Some grains of Tur I are zoned with pale blue dravite cores, a darker blue–green intermediate uvite zone, and pale blue dravite rims (Fig. 5). An oxy-dominant species (oxy-dravite) occurs at the outermost rim of a poorly-zoned crystal of Tur I. Tur II has partially replaced the lamprophyre dike (Fig. 5) and frequently encloses grains of actinolite to magnesiohornblende, clinochlore, titanite, and quartz (+ diopside, apatite). Dravite is still a common constituent of Tur II, but it contains more patches of uvite, feruvite, and fluor-uvite than Tur I (Figs 6–7).

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Overall, Mg/(Mg + Fe$^{2+}$) decreases slightly from Tur I to Tur II, but many species in Tur II are still Mg-dominant (Fig. 6c). All analyzed tourmalines are Al-poor, and Al content generally decreases from Tur I to Tur II, consistent with the observed negative correlation between Al and Ca/(Ca + Na) (Fig. 7a). The highest Al (6.146
### Tab. 2 Representative analyses and structural formulae of tourmaline

<table>
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<td>0.350</td>
<td>0.468</td>
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Formulae were calculated on the basis of 15 Y + Z + T cations [general formula XY₃Z₆(T₆O₁₈)(BO₃)₃V₃W].

Phosphorus, V, Cr, Mn, Zn, K, and Cl were also sought but were below the detection limit in all analyses.

*B₂O₃ fixed at 3 apfu B; **ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula but Fe₂O₃ values are typically zero or within overall analytical uncertainty; ***H₂O content calculated based on stoichiometry; b.d. = below detection limit.
apfu)) was found in the dravitic outer rim of the single zoned crystal of Tur I, whereas the lowest total Al content observed was 5.321 apfu (26.35 wt. % Al₂O₃) in feruvite from Tur II. Titanium slightly increases from Tur I to Tur II, and is positively correlated with both Ca (Fig. 7b) and Fe₆⁺ (Fig. 7c). Accordingly, the analyses with the highest Ti content are all feruvite from the small dark brown zones in Tur I (max. 2.05 wt. % TiO₂; 0.263 apfu Ti) and within Tur II (max. 2.17 wt. % TiO₂; 0.278 apfu Ti).

5. Discussion

5.1. Origin of tourmaline assemblages

The overall mineralogy of the studied dikes is consistent with calc-alkaline lamprophyles, specifically spessartites (Rock 1991): amphiboles are abundant and dominate over biotite mica, most minerals are Ca-rich, and Mg predominates over Fe. More specifically, amphiboles are magnesio-hornblende and actinolite, two species known to occur in calc-alkaline lamprophyles (Rock 1991). Phlogopite in the dikes contains high Ti (max. 4.13 wt. % TiO₂; average 3.34 wt. %, n = 15) and minor F (max. 1.08 wt. %; average 0.66 wt. %) with low CI (max. 0.15 wt. %; average 0.12 wt. %). Phlogopite enriched in Ti and F is common in all lamprophyre varieties (Rock 1991).

The lamprophyre dikes being younger than the O’Grady Batholith (megacrystic hornblende granite phase = 95±1 Ma; Hunt and Roddick 1987) is consistent with other lamprophyre dikes associated with plutons of the Selwyn Plutonic Suite. Gordey and Anderson (1993) concluded that lamprophyre, aplite, porphyritic, and aplitic monzogranite dikes were younger than the Selwyn...
Lamprophyre dikes and associated Al-deficient tourmaline, Northwest Territories, Canada

Plutonic Suite because they either cross-cut the plutons or are cospatial with them and intrude their contact aureoles. Therefore, we infer that the lamprophyre dikes are likely slightly younger than the O’Grady Batholith but older than the other units that were derived from the Batholith (aplite and pegmatite dikes, quartz veins).

Both Tur I and Tur II have high F contents, however the lamprophyre dikes do not contain any F-rich minerals. Phlogopite does host up to 1.08 wt. % F, but the specific dike that the tourmaline is associated with contains only rare phlogopite. Fluorine-rich tourmaline occurs in the pegmatite and aplite dikes, reaching compositions of fluor-schorl, while tourmaline in the metasedimentary host rock and quartz veins is relatively poor in F (Scribner 2014). Therefore, the derivation of F should be external, with the only obvious source in the study area being in the pegmatite and aplite dikes.

From Tur I to Tur II, there is a change from alkali- to calcic-group tourmaline species and increase in Ti. This enrichment in Ca and Ti reflects the progressive reaction of B-bearing fluids with Ca- and Ti-rich minerals in the lamprophyre dike; patchy zoning of the uvitic tourmaline can be attributed to a strongly selective Ca and Ti partitioning to the –c pole of tourmaline crystals (e.g. Henry and Dutrow 1996; van Hinsberg et al. 2006). Calcium amphiboles (actinolite to magnesio-hornblende with up to 0.40 wt. % TiO₂, average 0.23 wt. %) are one of the main minerals in the lamprophyre dikes, while calcic plagioclase is common in the matrix. The lamprophyre dike also contains titanite as a common accessory and rare phlogopite that is Ti-rich (up to 4.13 wt. % TiO₂). These minerals could have provided Ca and Ti, allowing for the crystallization of evolved tourmaline

Fig. 6 Compositional variation of both tourmaline generations (I): a – Classification diagram based on the dominant occupancy of the X site (Henry et al. 2011). There is a change from more alkali- to calcic-group species from Tur I to Tur II; b – General series of tourmaline species based on the occupancy of the W site. There is a trend towards fluor- and oxy-species from Tur I to Tur II; c – Binary plot Ca/(Ca + Na) vs. Mg/(Mg + Fe²⁺). Most analyzed tourmalines are Mg-dominant, but Mg/(Mg + Fe²⁺) decreases from Tur I to Tur II.
species such as feruvite at the margin of the lamprophyre dike.

All tourmaline species have low Al due to the lack of Al-rich minerals in the dike, but there is a decrease in Al content from Tur I to Tur II with progressive reaction of the B-bearing fluids with the lamprophyre dike. In the majority of tourmalines of both generations, Mg predominates over Fe, which is consistent with the presence of Mg-dominant actinolite, magnesio-hornblende, and clinochlore in the host lamprophyre dike. The slight increase in Fe relative to Mg in Tur II is most likely due to the addition of Fe from a hydrothermal fluid (supported by presence of Fe-oxides in the quartz together with Tur I; Figs 4–5), and partially also due to Mg/Fe partitioning between tourmaline and chlorite whereby tourmaline has a slight preference for Fe (Henry and Dutrow 1996; van Hinsberg et al. 2006).

5.2. Uncertainties in tourmaline composition

Several uncertainties must be pointed out regarding the compositions of the studied tourmalines. Despite very reasonable sums of tourmaline analyses, their stoichiometry is slightly offset from ideal since values for Si are sometimes slightly higher than 6 apfu (see Tab. 2 and Electronic Supplementary Material). However, the observed range of values (5.951–6.084 apfu, average 6.010 apfu) represents very small deviations, well within analytical error of Si (c. 2.6 rel. % of the value). The deviations from ideal 6 apfu Si do not largely affect the formula classification, except slightly overestimated $\text{WO}$. On the other hand, the $\text{WO}$ contents may very likely be largely underestimated due to unknown oxidation state of Fe. Since $\text{Fe}_{\text{tot}}$ ranges between c. 1.1 and 1.5 apfu (Fig. 7), in the case of $\text{Fe}^{3+}/\text{Fe}_{\text{tot}} = 0.25$ the $\text{WO}$ for all measured tourmalines would increase by 0.14–0.19 apfu. In most analyses it would be then higher than 0.5 apfu and the tourmaline classified as feruvite would potentially represent a new species (Mg-analogue of lucchesiite; see Bosi et al. 2017).

5.3. Feruvite assemblages worldwide

The metasomatic overprint of lamprophyre dikes near the O’Grady Batholith resulted in a mineral assemblage with Fe-rich uvite and feruvite. Iron-rich, Al-deficient calcic tourmalines (feruvite and lucchesiite) are relatively rare worldwide and form in specific environments. Gadas
et al. (2014) distinguished three feruvite parageneses: 1) quartz–tourmaline veins in hydrothermally altered Ca, Al, Fe, Mg-rich host rocks; 2) exocontacts of graniticpegmatites hosted by meta-andesite and amphibolite; and 3) primitive pegmatites, sometimes affected by contamination from host skarn lithologies. The latter two parageneses may also host lucchesiite (Bosi et al. 2017). The studied occurrence belongs to the first group, where tourmaline forms at the expense of minerals in a mafic rock. It is also very similar to feruvite from the Sullivann mine, British Columbia, Canada (Jiang et al. 1996) that occurs in parts of a tourmalinite body adjacent to gabbro sills. In this case, feruvite formed by reaction of Fe-rich hydrothermal fluids with Ca-rich minerals in gabbro and the host rocks (Jiang et al. 1996). Similarly, Manning (1991) reported feruvite in host rocks adjacent to hydrothermal tourmaline (schorl–dravite) breccias in SW England and ascribed its origin to overprint of the host rocks by oxidizing fluids generated from granites.

5.4. Ti-rich tourmaline

Of the studied tourmaline, the highest TiO₂ contents were found in feruvite (up to 2.17 wt. %). This is similar to other feruvite localities; the feruvite holotype contains 2.2 wt. % TiO₂ (Grice and Robinson 1989), and even higher contents were found at the Sullivan mine, British Columbia (2.61 wt. %; Jiang et al. 1996) and in uvite from tourmalinite in Piedmont Belt, South Carolina (3.25 wt. %; Mittwede 1984). Similarly, lucchesiite (Gadas et al. 2014; Bosi et al. 2017) from both type localities contains up to 2.61 and 0.65 wt. % TiO₂, respectively. Feruvite associated with lucchesiite at Mirosňov contains up to 1.35 wt. % TiO₂ (Gadas et al. 2014). In pegmatite tourmalines from Třebíč Pluton, high TiO₂ contents (up to 3.80 wt. %) were reported in Ca-rich, Fe³⁺-bearing, Al-deficient schorl–dravite (Novák et al. 2011; Čopjaková et al. 2013).

However, high Ti contents are not restricted to Ca-rich tourmalines: up to 4.70 wt. % TiO₂ (0.64 apfu Ti) was found in a bosiite-like mineral in the exocontact of an elbaite-subtype pegmatite by Flégr et al. (2016), and Žáček et al. (2000) reported up to 3.6 wt. % TiO₂ in povondraite–oxy-dravite–dravite with no or very low Ca contents. Konzett et al. (2012) found up to 3.42 wt. % TiO₂ in a single grain of Al-deficient, Fe-bearing dravite (with 5.2 apfu Al, 2.53 apfu Mg, 0.73 apfu Fe³⁺, and 0.23 apfu Ca) associated with Ca, Ti-bearing dravite with elevated Sr (0.053 apfu; 0.56 wt. % SrO). The highest TiO₂ contents (up to 4.07 wt. % TiO₂) were encountered by Lottermoser and Plimer (1987) in the core of metasomatic dravite found within contact rocks included in a diatreme at Umburatana, South Australia.

Therefore, high contents of Ti are typically restricted to Al-deficient tourmalines (e.g., Gadas et al. 2014) that can also have high Fe³⁺ (Flégr et al. 2016; Bosi et al. 2017), rather than to specific tourmaline species or groups; high Ti occurs in both calcic and sodic tourmalines. On the other hand, the combination of high Fe contents with significant Mg at the Z site is a feature common to most Ti-rich tourmaline occurrences. We suggest that this compositional preference is caused by the small ionic radius of the Ti⁺⁺ cation, compared to relatively large cations such as Fe²⁺, Mg²⁺, and Fe³⁺, whereby the incorporation of Ti⁺⁺ partially reduces strain in the tourmaline structure.

6. Conclusions

1) The calc-alkaline lamprophyre dikes near the O’Grady Batholith are hosted by tourmalinized sedimentary rocks. The lamprophyre dikes are likely younger than the O’Grady Batholith, assuming that the relative ages of the Batholith and the associated lamprophyre dikes are the same as for other plutons in the Selwyn Plutonic Suite. In any case, the cross-cutting relationships indicate that the lamprophyre dikes are older than aplite and pegmatite dikes, as well as the tourmaline-bearing quartz veins that were all derived from the O’Grady Batholith.

2) Two generations of tourmaline are associated with one of the lamprophyre dikes. Tur I occurs along the margin of the dike and Tur II occurs within an altered lamprophyre zone still near its margins. Dravite is common in both generations, but the proportion of more evolved tourmaline species, namely uvite, feruvite, and fluor-uvite, increases in Tur II. Fluor-uvite occurs in both generations of tourmaline. The high F contents of some tourmaline species from both generations suggests that they crystallized from fluids derived from nearby aplite and pegmatite dikes.

3) The lamprophyre dike represented a unique geochemical environment that allowed for the crystallization of uncommon tourmaline species. The progressive reaction of metasomatic fluids with the Ca-, Mg–Fe-, and Ti-bearing minerals in the dike presumably resulted in the crystallization of increasingly Ca-, Fe-, and Ti-rich tourmaline. All tourmaline is Al-deficient due to the lack of Al-rich minerals in the dike. The most evolved compositions of tourmaline associated with the lamprophyre dike are feruvite with up to 2.17 wt. % TiO₂, and fluor-uvite with up to 0.84 wt. % F.

4) Mutual relationships of tourmaline assemblages in the area are rather complex and desire further clarification using modern methods. The authors are currently preparing a manuscript on the regional tourmaline composition including the isotopic signature of tourmaline from all rock types and units.
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References


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Mittweide SK (1984) Significance of tourmaline compositions from the inner Piedmont geologic belt of South Carolina. Southeast Geol 24: 207–210


