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Original paper

Mineral chemistry, petrology and geochemistry of the Sebago granite–pegmatite system, southern Maine, USA

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The Permian (293 ± 2 Ma) Sebago Pluton is a homogeneous, two-mica granite situated in the Oxford pegmatite field, southwestern Maine. Surrounding the pluton is an area designated as the Sebago Migmatite Domain (SMD) dominated by metapelitic migmatites and diatexites with subordinate intrusions of heterogeneous, two-mica and biotite granites, pegmatitic leucogranites and granitic pegmatites. The Sebago Pluton plus the SMD formerly defined the extent of the Sebago Batholith. Most of the granitic pegmatites and bodies of pegmatitic leucogranites occur either within, or barely outside, the margins of the SMD. The pegmatitic leucogranite facies displays units typical of fertile granites (granites that produce granitic pegmatites) and include: megacrystic graphic K-feldspar, sodic aplite and potassic pegmatite pods hosting rare tourmaline, beryl and columbite–tantalite. Over 100 granitic pegmatite bodies (Sebago Pegmatite Group – SPG) intrude the outer portions of the SMD and neighboring granitoids and metasedimentary rocks. The pegmatite population includes mineralogically simple to complexly zoned pegmatites that are characterized by a LCT-type (Li, Cs and Ta) geochemical signature, extensive replacement of primary zones and gem-bearing miarolitic cavities.

Sebago granites are strongly peraluminous and show rare-element enrichment typical of evolved fertile granites (K/Rb = 87–257), Rb/Tl = 10.6–71.3, Ba/Rb = 0.18–5.04, Al/Ga = 1419–1749, Zr/Sn = 1.53–43.9). The SPG shows high levels of Be, Nb > Ta, P, Li and B with subordinate enrichment in Rb and Cs. Moderate to high levels of rare-element fractionation are encountered in pegmatitic K-feldspar (K/Rb ≈ 17, K/Cs ≈ 90, Rb/Tl ≈ 75), muscovite (K/Rb ≈ 6.6, K/Cs ≈ 14.8, Rb/Tl ≈ 127), beryl (Na/Li ≈ 1.77, Cs_2O ≈ 3.15 wt. %), garnet [Mn/(Mn + Fe) ≈ 0.60], manganotantalite and ixiolite/wodginite [Mn/Mn + Fe) ≈ 0.98, Ta/(Ta + Nb) ≈ 0.80–0.93].

Evidence that supports the pegmatitic leucogranites as the likely parent to the SPG includes the close spatial distribution of the pegmatites to the leucogranite bodies, texturally and mineralogically similar units observed within the leucogranite and the neighboring pegmatites plus gradual, yet overlapping, rare-element fractionation from the leucogranites to the associated pegmatites. A few pegmatites (e.g., the Lord Hill pegmatite and amethyst-bearing pegmatites) show NYF tendencies unlike any other pegmatites of the SPG. Differences in fractionation degree, evolution and/or relation to another fertile granite–pegmatite system may be responsible for this apparently anomalous group of pegmatite dikes.

Keywords: granite–pegmatite system, mineral chemistry, petrology, geochemistry, Sebago, southern Maine
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1. Introduction

The granitic pegmatites of southern Maine represent one of several major pegmatite regions within the Appalachian Province of the eastern United States. Widespread gemological and scientific interest in the granitic pegmatites of the Sebago area was stimulated by the discovery of gem-grade tourmaline at the Mt. Mica pegmatite in 1820 and subsequent feldspar and mica mining in the region. Unfortunately, very little geochemical data exist for the Maine pegmatites despite their popularity among mineral collectors and geoscientists. Most of the studies on Maine pegmatites were largely descriptive with an emphasis on characterizing their mineralogy (e.g., Bastin 1911; Landes 1925; Woodard 1951; Francis et al. 1991). The works of Cameron et al. (1954) and Barton and Goldsmith (1968) identified the general internal zonation of many Maine pegmatites enriched in the strategic metals Be, Nb, Ta and Li, but did not discuss the crystallization history or chemical evolution of the individual pegmatites. With few exceptions (e.g. Simmons et al. 1995; Wise 1995; Simmons et al. 2005), details on the mineral chemistry of pegmatites in the Sebago area are inadequate. Of the nearly 120 known pegmatite deposits in the Sebago area (Rand 1957; Thompson et al. 2000) only two (Lord Hill – Johnson 1998; Bennett – Wise and Rose 2000) have been studied sufficiently enough to characterize their geochemical evolution and crystallization history.

Several studies have addressed the petrogenesis of the Sebago granite (Hayward 1989; Tomascak et al. 1996a, b; Dorais and Paige 2000) considered by some to be the parental granite of the pegmatite population (e.g., Wise and Francis 1992). Although Guidotti et al. (1986) and

Wise and Francis (1992) suggested a cogenetic relationship among the pegmatites of the Sebago area, their claim is unsupported by geochemical, geochronological or isotopic data which would aid in evaluating potential links between granites and groups of diverse pegmatites even though physical transitions may not exist (e.g., Shearer et al. 1987). A rigorous investigation addressing the rare-element enrichment of the pegmatite population and their possible genetic connections to neighboring granitic intrusions (e.g., Sebago and Songo plutons) is not yet available.

Given the importance of granitic pegmatites to the gem mining industry in western Maine, it is essential that the mineralogy and chemical evolution of these deposits is understood if guidelines for future exploration are to be developed. This study employs new chemical data obtained from the Sebago granite and its nearby pegmatite population in an attempt to characterize the patterns of rare-element enrichment of the pegmatites and to provide a foundation for assessing their petrogenetic relationship with the Sebago granite.

2. General regional geological setting

Granitic pegmatites are widespread throughout southern Maine and the largest percentage is found adjacent to the Sebago granite in the southern portion of the Oxford pegmatite field (Figs 1–2; Wise and Francis 1992). The Oxford pegmatite field is underlain by rocks of the Central Maine Belt (CMB), a prominent NE–SW trending unit that extends from Connecticut to New Brunswick, Canada and occupies much of southern Maine. The CMB consists of deformed and metamorphosed Lower Paleozoic sedimentary rocks that experienced greenschist to upper amphibolite facies metamorphic conditions during the Acadian Orogeny (Solar and Brown 2001 and references therein). The resulting migmatite domains consist of stromatic migmatites, diatexites and schlieren granites. The CMB is intruded by Devonian to Permian age peraluminous granite, quartz monzonite, and granodiorite plutons which may have contributed to local deformation and contact metamorphism of the surrounding rocks. The granitoids range in composition from titanite-bearing granodiorites (e.g. Songo Pluton) to biotite–muscovite granites, some displaying the local development of a pegmatitic facies (e.g. Rumford Pluton). Pegmatites associated with the late Paleozoic plutonism are presently concentrated interior and marginal to the granitic plutons.

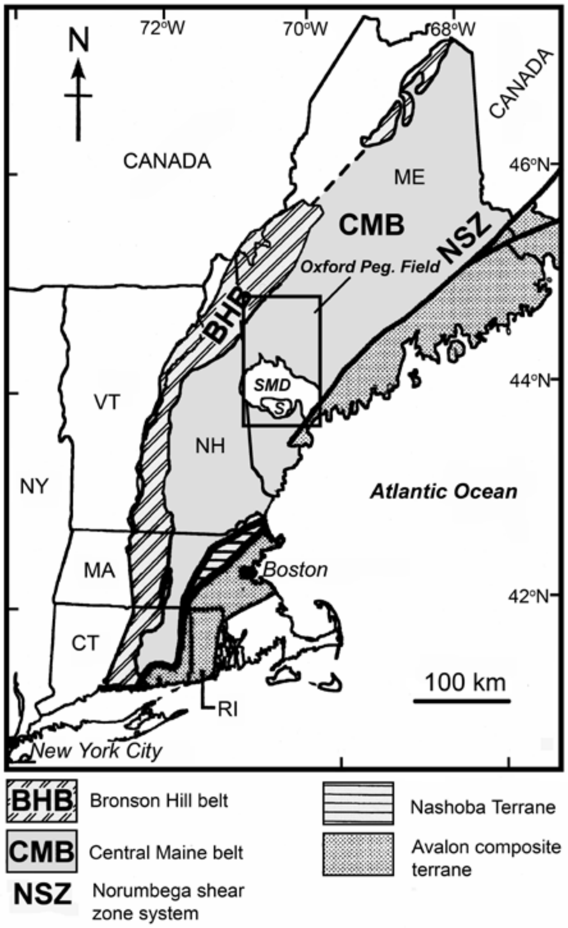

Fig. 1 Map of New England region showing the location of the Sebago Pluton (S) and Sebago Migmatite Domain (SMD) within the Oxford pegmatite field (rectangle). ME – Maine, NH – New Hampshire, VT – Vermont, NY – New York, MA – Massachusetts, CT – Connecticut, RI – Rhode Island. Map modified after Brown and Solar (1998).

The dominant igneous intrusion in the southern portion of the Oxford pegmatite field is the Sebago Pluton (formerly the Sebago Batholith). Previous studies showed the Sebago Pluton as a single large plutonic body with an areal extent of approximately ~2,700 km^2 (Osberg et al. 1985). However, recent work by Solar and Tomascak (2009), describes the Sebago Pluton (293 ± 2 Ma; Tomascak et al. 1996a) as a 400 km^2 granitic body surrounded by an envelope of migmatitic rocks referred to as the Sebago Migmatite Domain (SMD) (Fig. 2). They relegate the "true" Sebago Pluton to the southern portion of the former extent of the Sebago Batholith described by Osberg et al. (1985). According to Solar and Tomascak (2009), the Sebago Pluton is composed of two-mica granite that is both texturally and chemically homogenous. The SMD consists of metapelitic migmatite and diatexite that is intruded by smaller, texturally heterogeneous granite sheets, schlieren granites and pegmatite dikes.

Geophysical studies suggested that the Sebago granite is a thin sheet-like body approximately 0.5–2 km thick (Hodge et al. 1982) that dips about 3 degrees to the northeast (Carnese 1983). However, a later study by Behn et

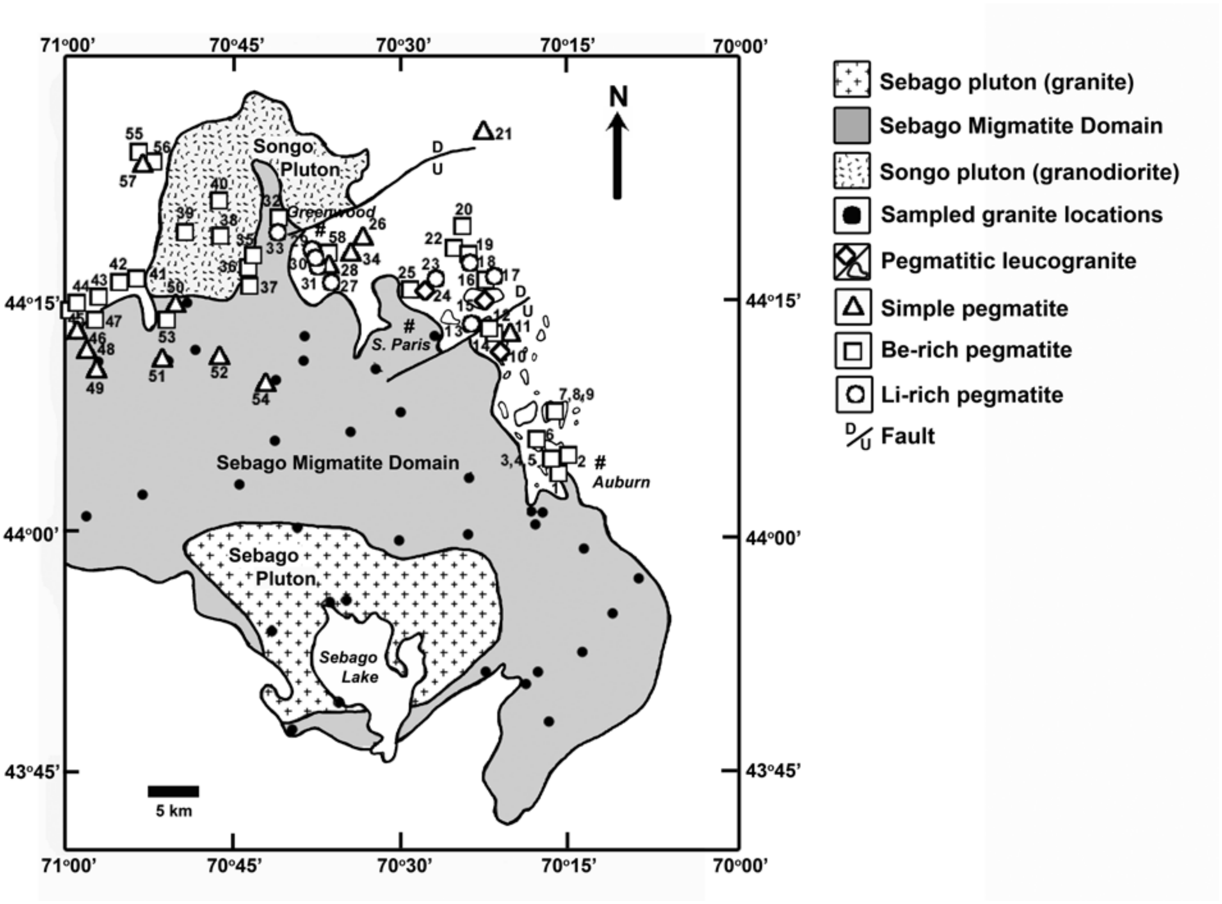

Fig. 2 Generalized geologic map of the southern portion of the Oxford pegmatite field. Note the relationship between the Sebago Pluton and Sebago Migmatite Domain of Solar and Tomascak (2009) to the adjacent Sebago Pegmatite Group. See Tab. 1 for key to numbered pegmatite locations.

al. (1998) indicates that both the northern and southern margins of the pluton dip shallowly beneath the cover of the metasedimentary rocks to form an arched body. Estimates of metamorphic pressures of the rocks immediately north of the pluton range from 3.3 to 3.8 kbars (Holdaway et al. 1988; Thomson and Guidotti 1989) suggesting emplacement depths of about 10–14 km.

3. Sebago granite–pegmatite System

3.1. Granites of the Sebago Pluton and Sebago Migmatite Domain

Tomascak et al. (1996b) and Solar and Tomascak (2001, 2009) divided the granite of the former Sebago Batholith into two groups based on geochemical, textural and isotopic data. The group 1 granites (Sebago Pluton *sensu stricto*) consist of fine- to medium-grained, homogeneous two-mica granites. They have ε_{Nd} values of -3.5 to -1.5. By comparison, group 2 granites (SMD granites) are texturally and chemically heterogeneous, two-mica granites associated with enclaves and schlieren that intruded the SMD as dikes to small, isolated bodies. They have ε_{Nd} values that range from -6.0 to -3.0. Biotite granites in the SMD have ε_{Nd} values of -4.6 to -3.8.

Along the outer margins of the SMD we observed several small satellite stocks (originally mapped by Creasy 1979) that exhibit textural features similar to those described by Černý and Meintzer (1988) for fertile granites parental to mineralized pegmatite populations. Specifically, the pegmatitic leucogranite facies of Černý and Meintzer (1988) have been identified at several places, most notably at Streaked Mountain. The pegmatitic leucogranite consists of coarse, blocky, graphic K-feldspar megacrysts surrounded by a medium-grained matrix of quartz, plagioclase and muscovite with accessory tourmaline and minor garnet and fluorapatite (Fig. 3). Locally, this facies grades into pegmatite pods consisting of blocky perthitic K-feldspar, quartz, muscovite with accessory tourmaline and garnet. Beryl and rare ferrocolumbite are locally present. An albitic aplite facies comprised of fine-grained albite, quartz and accessory garnet and tourmaline occurs as isolated blocks or

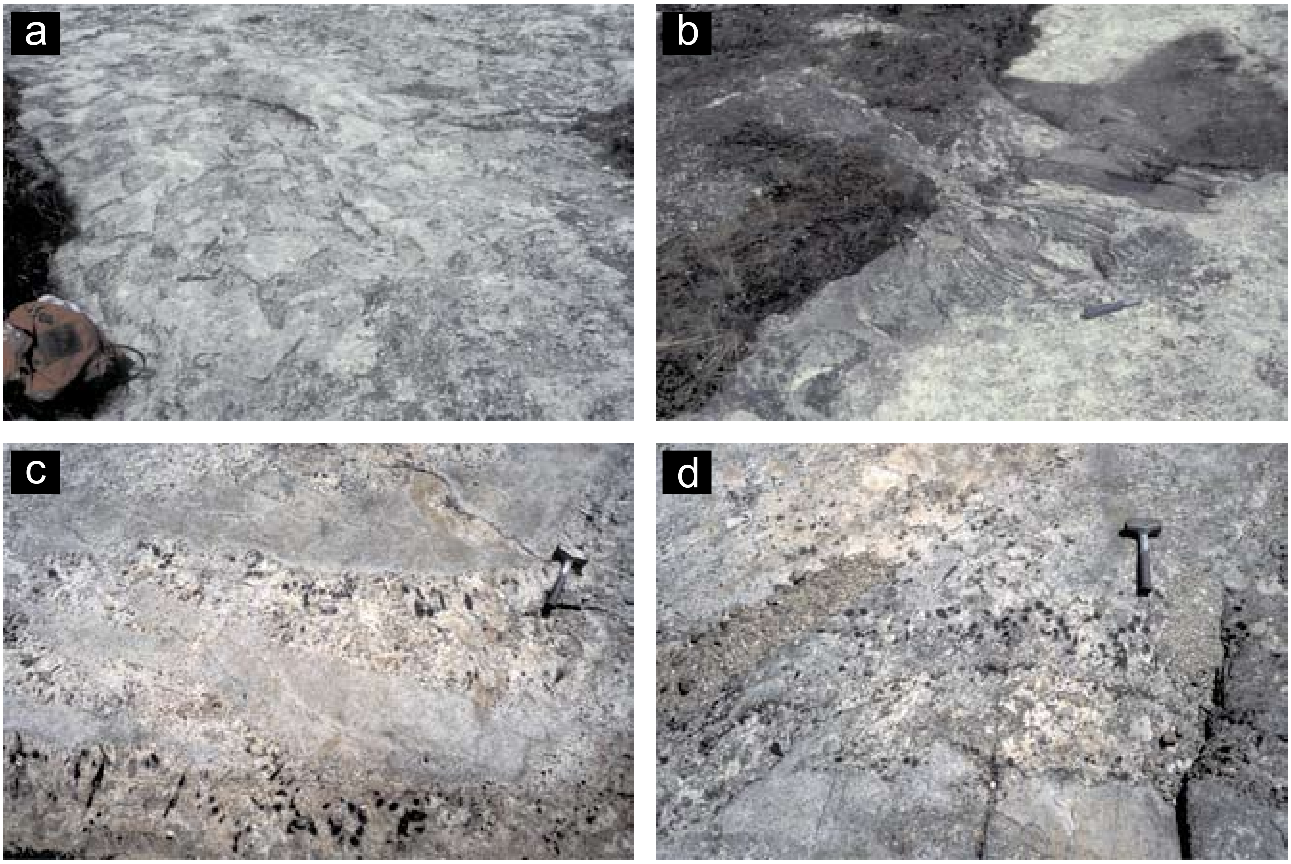

Fig. 3 Textural facies of pegmatitic leucogranites of the Sebago area. **a** – Light-colored megacrystic graphic K-feldspar in a darker matrix of medium-grained quartz, plagioclase and muscovite groundmass – Streaked Mountain. **b** – Raft of country-rock schist in megacrystic graphic K-feldspar facies – Streaked Mountain. **c** – Pavement outcrop showing interlayering of simple pegmatite veins and aplite – near Auburn. **d** – Pavement outcrop showing simple pegmatite vein with bands of almandine garnet along the upper and lower contacts with aplite and megacrystic K-feldspar facies – near Auburn.

interlayered with pegmatite veins within the pegmatitic leucogranite (Fig. 3). Xenoliths of schist are common in the pegmatitic leucogranites (Fig. 3b).

3.2. Distribution and classification of the Sebago Pegmatite Group (SPG)

Wise and Francis (1992) summarized the distribution of pegmatites surrounding the Sebago Pluton – SMD (formerly Sebago Batholith) and showed that the pegmatite population, henceforth referred to as the Sebago Pegmatite Group (SPG), consisted of spatially related clusters of mineralogically and texturally diverse pegmatites (Fig. 2). The pegmatites in the Sebago area fit into the classification of LCT family of rare-element granitic pegmatites, as described by Černý (1991) and Černý and Ercit (2005). In general, three categories of pegmatites distinguished by mineral assemblage and geochemistry have been recognized in the SPG (Tab. 1): (1) quasi-homogeneous, simple pegmatites, (2) beryl ± columbite ± phosphate-bearing and (3) complex Li-enriched pegmatites (spodumene and petalite subtypes). Miarolitic cavities hosting gem quality minerals are uncommon in most of the SPG and are best developed in the Li-enriched pegmatites.

Simple pegmatites are hosted mainly by the SMD and consist of perthitic K-feldspar, albite, quartz, muscovite and biotite. The internal zoning may be absent, or at best, poorly developed. K-feldspar crystals typically exhibit graphic textures, although small amounts of non-graphic, blocky K-feldspar may also occur. Quartz is ubiquitous, rarely forming well-developed pods or lenses. Isolated patches of rose quartz are rarely found at some localities. Albite typically occurs as anhedral interstitial grains and rarely as blocky crystals. Mica species are represented by biotite and muscovite. When present, biotite occurs as mm-size flakes to elongated blades several cm in length. In some cases, biotite books may be intergrown with, or overgrown by, muscovite. Muscovite is generally intergrown with quartz, but occurs as discrete crystals near the margins of quartz-rich pods. Black tourmaline (schorl–dravite) and almandine-rich garnet are common accessory minerals; in some pegmatites, fluorapatite may be locally abundant.

Tab. 1 Representative examples of rare-element pegmatites within the Sebago Group

Pegmatites	Subtype	Spodumene	Elbaite	Li-micas	Pollucite	Other noteworthy minerals
Simple pegmatites						
26 – A.C. Perham	SIM					
57 – Anderson	SIM					
52 – Burnell Hill	SIM					
46 – Colton Hill	SIM					Amethyst
11 – Conant	SIM					
49 – Creeper Hill	SIM					
50 – Foster Hill	SIM					
28 – Nubble	SIM					Trace chrysoberyl
21 – Ragged Jack Mountain	SIM					Minor chrysoberyl
51 – Sabbatus Mountain	SIM					
8 – Sahib	SIM					
10 – Streaked Mountain	SIM					Trace beryl
54 – South Waterford	SIM					
10 – Sturtevant	SIM					
48 – Wiley Mountain	SIM					Amethyst
34 – Witt Hill	SIM					Minor chrysoberyl, gahnite
Be-rich pegmatites						
22 – Bessey	BYL					
4 – Butler Hill	BYL					
44 – Deer Hill	BYL					Amethyst
45 – Eastman Prospects	BYL					Amethyst
53 – Forks Farm	BYL					
9 – Green	BYL					
35 – Guy Johnson	BYL					
7 – LaFlamme	BYL					
42 – Melrose	BYL					
55 – Peaked Hill	BYL					
6 – Pitts Tenney	BYL					
36 – Scribner	BYL					
32 – Tiger Bill	BYL			(x)	(x)	
37 – Wardwell	BYL					
56 – Wheeler	BYL					
25 – Whispering Pines	BYL					
41 – Willis Warren	BYL					
43 – Cole	BC					
16 – GE	BC		X		X	
2 – Greenlaw	BC	(x)	X	X		
58 – Heikkinen	BC					
14 – Hibbs	BC					
20 – Norman Jack	BC					
19 – Orchard Pit	BC		(x)			
39 – Pingree	BC					
24 – Slattery	BC					
40 – Songo Pond	BC					Rutile
3 – Turner	BC					
1 – Berry – Havey	BCP	(x)	X	(x)		Lithiophilite, montebrasite
38 – Bumpus	BCP					
47 – Lord Hill	BCP					Topaz, triplite
2 – Maine Feldspar	BCP	(x)	X	(x)	(x)	Gahnite
12 – Mt. Rubellite	BCP	(x)	X	X	(x)	Lithiophilite, montebrasite
5 – Pulsifer	BCP	(x)	X	X	(x)	Gahnite, montebrasite
Li-rich pegmatites						
27 – BB #7	SPD		(x)	X	(x)	Cassiterite, lithiophilite
18 – Bennett	SPD		X	X	X	Wodginite, lithiophilite
30 – Harvard	SPD		X	X	(x)	Montebrasite
29 – Hayes	SPD					
31 – Waisanen	SPD		(x)			Graftonite
33 – Emmons	PET	(x)	X	X	X	Wodginite, montebrasite
13 – Mt. Marie	PET	(x)	X	X	X	
23 – Mt. Mica	PET	(x)	X	X	(x)	Montebrasite
31 – Tamminen	PET	(x)	X	X	X	Montebrasite
17 – Westinghouse	PET		X		X	Chrysoberyl

Numbers refer to pegmatite locations in Fig. 2. Pegmatite subtypes: *SIM* – simple, *BYL* – beryl, *BC* – beryl–columbite, *BCP* – beryl–columbite–phosphate, *SPD* – spodumene, *PET* – petalite. Occurrence: X – common, (x) – minor.

The beryl-type pegmatites of the SPG are characterized by Be mineralization accompanied by Nb, Ta mineralization in the beryl–columbite subtype and also by the presence of phosphate minerals (e.g., triphylite–lithiophilite or triplite) in the beryl–columbite–phosphate subtype. Internal zonation of pegmatites of this category ranges from poor to well-developed with micas, tourmaline, and K-feldspar commonly replaced by albite, fine-grained (*saccharoidal*) and bladed *(cleavelandite)*.

Graphic K-feldspar is present, but the abundance of non-graphic, perthitic K-feldspar is considerably greater than that found in the simple pegmatites. Albite occurs in the same manner as in simple pegmatites; however the bladed variety (*cleavelandite)* is more common and may occur as isolated lenses or units. Platy muscovite and well-defined quartz or quartz + K-feldspar pods, lenses, or cores are prominent. The quartz is typically white to gray, but rose quartz and amethyst may also occur. Tourmaline (dravite, schorl and foitite), almandine and spessartine garnet, and Mn-bearing fluorapatite are the most common accessory minerals found; rare magnetite, zircon, pyrite, arsenopyrite and pyrrhotite may occur locally.

Beryl is typically pale green in color, although blue varieties are known from a few localities. When present, columbite group minerals vary from ferrocolumbite to manganocolumbite. The number of confirmed beryl–columbite–phosphate subtype pegmatites within the SPG is small, as the overall abundance of Fe-, Mn-, and Li-phosphate minerals is low. Triphylite is abundant in some pegmatites (e.g., BB#7) and lithiophilite is locally present at the Pulsifer and Emmons pegmatites. Only three pegmatites in the SPG (Pulsifer, Berry–Havey and Lord Hill) are known to contain triplite.

Pegmatites of the complex type are characterized by well-defined internal zonation and replacement textures, diverse mineralogy, and elevated enrichment in rare alkali elements (Li, Rb, Cs), high-field strength elements (Nb, Sn, Ta, Zr) and B, P and F. Li-rich pegmatites are found predominantly near the towns of Greenwood and South Paris.

Li-rich pegmatites are primarily of the spodumene-subtype (e.g., Harvard, BB#7, Hayes, Mt. Mica and Bennett), although petalite-subtype pegmatites (e.g., Mt. Marie, Tamminen, Emmons, Westinghouse) also occur. Blocky, perthitic, non-graphic K-feldspar is abundant, whereas, graphic K-feldspar is subordinate. Pods and lenses of albitic aplite and bladed albite are much more common relative to anhedral and blocky albite crystals. Miarolitic cavities and fractures, if present, may contain copious amounts of cleavelanditic albite. Books of platy muscovite are common, locally grading to pale purple lithium muscovite (3.0 to 4.0 wt. % Li_2O; Levinson 1953). Although lithium muscovite is relatively widespread, it does not occur in any great abundance, nor is it ever the dominant Li-aluminosilicate in any pegmatite. Biotite occurs rarely in the wall zones of Li-rich pegmatites as small (~ 2 mm long) black flakes. Beryl, columbite group minerals, Mn-rich garnet, elbaite and lithian muscovite and/or lepidolite (4.0 to 7.0 wt. % Li_2O; Levinson 1953) are the most common accessory minerals in these pegmatites. The color of beryl ranges from pale green through blue to colorless, white and pink. Tantalum and tin enrichment is expressed by the crystallization of manganotantalite, ferrotapiolite, wodginite and cassiterite, which sometimes show complex chemical zoning (Fig. 4). Local occurrences of pollucite and amblygonite-montebrasite further emphasize the highly fractionated nature of these pegmatites.

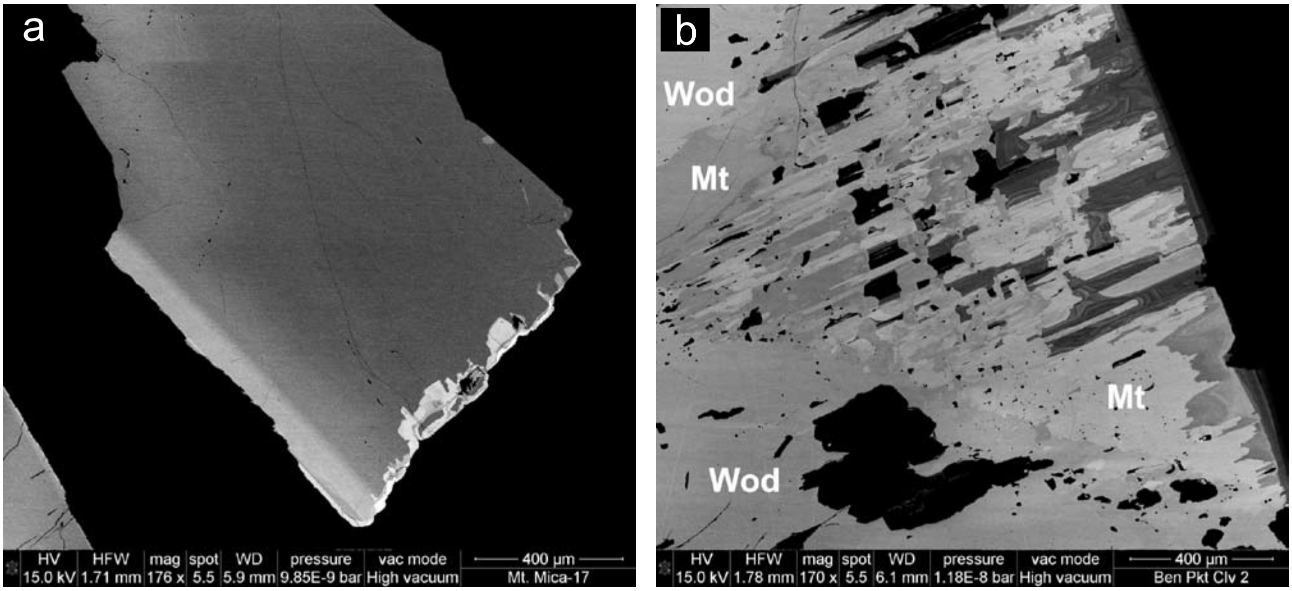

Fig. 4 Back-scattered electron (BSE) images of Nb–Ta oxide minerals from the Sebago pegmatite group. **a** – Zoned manganocolumbite crystal with minor late-stage irregular zoning (Mt. Mica pegmatite). **b** – Wodginite (Wod) in association with manganotantalite (Mt) (Bennett pegmatite). Note the irregular zoning patterns of manganotantalite caused by late-magmatic to subsolidus partial dissolution-reprecipitation.

4. Whole-rock and mineral chemistry

4.1. Analytical techniques

Fresh granite samples were slabbed, reduced to 0.7 cm sized pieces, and crushed in a steel jaw-crusher. After the crushed rock was quartered, a representative split was pulverized to a 0.074 mm powder in an alumina ceramic mill. The powder was analyzed for major and trace elements in our laboratory by X-ray fluorescence (XRF). Rare-earth elements were determined by ICP-MS method by SGS Canada Laboratories.

The following discussion on mineral chemistry is limited to primary phases that are routinely used to characterize the geochemical evolution of granitic pegmatites. K-feldspar and mica-group minerals were collected from the core–margin or cores of zoned pegmatites. In the case of unzoned or poorly zoned pegmatites commonly lacking well-developed core areas, K-feldspar and micas were sampled from blocky K-feldspar + quartz pods. Beryl, Nb-Ta oxides, garnet and tourmaline were collected from all texturally distinct zones or units when available.

Unaltered and inclusion-free K-feldspar, muscovite and lepidolite were hand-picked from pegmatite samples for trace-element analysis. Samples were pulverized, sieved to 0.074 mm, made into pressed pellets and analyzed using an automated Phillips X-ray fluorescence spectrometer (model PW1480). K-feldspar, mica-group minerals and beryl were analyzed for Ba, Cs, Ga, Ni, Nb, Pb, Rb, Sn, Sr, Ta, Tl, Zn and Zr. Lithium analyses were performed by direct current plasma-emission spectroscopy with a Spectrametrics Spectrascan V DCP in the laboratory of the Department of Earth and Environmental Sciences, University of New Orleans. Samples were digested either in HF or in a flux of Na_2CO_3/NaOH (1:1). Standards were prepared with similar contents of Na^+ and Cl^- ions to compensate for interferences.

Fragments and crystals of columbite–tantalite, tourmaline and garnet were placed in epoxy-filled Bakelite mounts, polished and analyzed using a JEOL Model JXA-8900R electron microprobe in the wavelength-dispersion mode. Four to six spots per grain were analyzed using an accelerating voltage of 15 kV, beam current of 20 nA and a beam diameter of approximately 1 micron. Counting times for background and peak determinations were 5–10 s and 15–40 s, respectively for the various analyzed elements. Crystals were analyzed using the following standards: hornblende (Si, Al, Na, K, Ca, Fe, Mg), garnet (Si, Al, Fe), ilmenite (Ti, Mn), synthetic $MnNb_2O_6$ (Mn, Nb), $CaTa_4O_{11}$ (Ta), Sc_2TiO_5 (Sc), and SnO_2 (Sn), gahnite (Zn), apatite (P, F) and scapolite (Cl). Data reduction was done using a conventional ZAF correction. The structural formula of tourmaline was calculated on the basis of 31 anions, assuming stoichiometric amounts of B_2O_3 as $(BO_3)^{-3}$ [B = 3 *apfu*], H_2O as $(OH)^-$ [i.e. OH + F = 4 *apfu*] and Li = 3–ΣY *apfu*.

4.2. Granite chemistry

Representative whole-rock analyses of granitic rocks from the Sebago Pluton and SMD are given in Tab. 2. In the QAP and Ab–An–Or diagrams (Streckeisen 1973; O'Connor 1965), all samples plot within the granite field (Fig. 5a–b). The granites are peraluminous (A/CNK varies from 1.06 to 1.31) (Fig. 5c) and display a typical calc-alkaline trend on the AFM diagram (Fig. 5d). The trace-element data for the granites of the Sebago Pluton and SMD show similar levels of Rb, Cs, Ba, Sr, Ga, Pb and Nb enrichment (Tab. 2), however, no systematic increases between groups of granites were observed. In general, group 1 granites have lower K/Rb than the biotite granites of SMD. The K/Rb values of the two-mica granites of the SMD overlap with those of the two-mica granites of the Sebago Pluton and the biotite granites of the SMD.

A number of diagrams have been used to discriminate the tectonic environment of granitic rocks. Figures 6a and 6b show that the granites of the Sebago Pluton and SMD plot largely in the volcanic arc and syn-collisional granite field of the Nb vs. Y and Rb vs. Y + Nb tectonic diagrams (Pearce et. al. 1984). Figure 6c (Batchelor and Bowden 1985) further supports a syn-collisional origin for the Sebago granites. Chondrite-normalized (Anders and Grevesse 1989) REE data for the Sebago granites are presented in Fig. 6d. The granites show uniform depletion of LREE and HREE, with LREE being more enriched relative to HREE. All granites display a negative Eu anomaly which varies more in the patterns of the SMD two-mica granites.

4.3. Pegmatite mineral chemistry

4.3.1. K-feldspar

K-feldspar from the intermediate and core zones of all sampled pegmatites contains fine- to coarse-textured perthite. The bulk composition of K-feldspar shows minor variations in Na and Ca across the pegmatite population. The Na_2O contents vary from 0.31 to 3.37 wt. %, whereas uniformly low levels of CaO (0.00–0.44 wt. %) are typical of all pegmatites. The SPG K-feldspar is enriched in Rb (up to 6677 ppm) and Cs (up to 1045 ppm). The highest Rb and Cs values are found in the Be- and Li-rich pegmatites of the SPG (Fig. 7a–b). The Ga and Tl contents (10 to 50 ppm and 2 to 71 ppm, respectively) are fairly low throughout most of the SPG. Anomalously high Ba and Sr concentrations characterize

Tab. 2 Representative whole-rock analyses of granitic rocks from the Sebago Pluton and SMD

Granite Type	Sebago Granite (2-mica granite)				SMD (biotite granite)			SMD (2-mica granite)		
Sample No.	SEBGR 40/A	SEBGR 41/A	SEBGR 42/A	SEBGR 43/A	CASCO 4/A	SEBGR 14/A	SEBGR 25/A	BLK CAT MTN 5/A	SEBGR 20/A	SEBGR 32/A
Major elements (wt. %)										
P_2O_5	0.12	0.12	0.15	0.11	0.09	0.08	0.09	0.11	0.09	0.09
SiO_2	71.82	72.05	72.38	74.20	74.08	73.36	70.19	71.98	73.73	72.12
TiO_2	0.22	0.20	0.18	0.11	0.12	0.23	0.34	0.30	0.27	0.28
Al_2O_3	15.11	14.81	15.10	14.90	14.48	14.54	16.37	15.44	13.60	14.84
Fe_2O_3	1.57	1.54	1.33	1.00	1.36	1.34	1.81	2.03	1.51	2.00
MnO	0.05	0.04	0.04	0.04	0.03	0.02	0.02	0.04	0.03	0.02
MgO	0.34	0.36	0.32	0.16	0.25	0.21	0.55	0.37	0.35	0.38
CaO	1.09	1.26	1.06	0.82	1.13	0.93	1.73	0.82	0.51	0.96
Na_2O	3.91	3.63	3.38	3.36	3.35	3.01	3.54	2.88	2.28	3.38
K_2O	5.13	5.22	5.77	4.95	5.43	5.65	5.52	5.70	6.71	5.57
LOI	0.58	0.61	0.56	0.66	0.39	0.59	0.45	0.74	1.12	0.54
Total	99.94	99.84	100.27	100.31	100.71	99.96	100.61	100.41	100.20	100.18
Trace elements (ppm)										
Rb	355	298	352	373	314	219	245	324	213	267
Cs	6	13	0	9	6	0	12	0	1	13
Ba	329	523	336	138	340	378	369	333	204	371
Sr	91	114	83	48	121	88	229	79	129	84
Ga	23	21	32	26	20	25	21	28	11	24
Tl	4	1	3	6	2	5	0	3	0	2
Pb	41	18	32	25	31	31	30	17	67	45
Nb	12	13	15	23	14	6	7	19	9	0
Ta	7	1	4	7	5	4	4	2	4	4
Sn	4	8	7	10	7	4	0	2	0	5
W	6	3	4	9	5	1	6	6	2	0
Cu	5	6	2	3	3	4	5	4	3	4
Cr	1	0	1	0	0	0	0	3	0	0
Co	0	0	0	0	0	0	0	1	0	1
Ni	1	1	1	0	1	0	2	4	0	1
V	14	15	9	7	9	6	18	13	1	8
Y	19	20	17	17	29	8	7	14	9	12
Zn	73	88	65	50	49	51	90	100	48	83
Zr	140	147	120	56	115	134	102	148	118	173
La	47.9	30.6	28.1	19.9	34.2	51.0	27.3	43.9	32.3	40.7
Ce	93.8	58.6	56.6	37.6	66.3	110.0	60.0	92.8	80.7	88.1
Pr	10.60	6.58	6.32	4.15	7.35	12.80	6.98	10.40	9.86	10.10
Nd	34.1	21.2	20.8	13.0	23.6	42.8	24.4	35.1	33.7	34.0
Sm	5.9	3.9	4.0	2.6	4.6	7.3	4.9	7.0	8.2	6.3
Eu	0.65	0.58	0.52	0.30	0.68	0.68	0.84	0.59	0.51	0.46
Gd	5.07	3.47	3.33	2.76	4.03	5.23	3.74	5.32	5.64	4.58
Tb	0.61	0.41	0.44	0.45	0.66	0.54	0.34	0.62	0.57	0.55
Dy	2.86	2.30	2.25	2.87	3.90	1.97	1.27	2.84	1.90	2.18
Ho	0.50	0.46	0.41	0.58	0.81	0.26	0.15	0.40	0.24	0.30
Er	1.20	1.36	1.07	1.62	2.37	0.58	0.31	0.74	0.51	0.51
Tm	0.17	0.19	0.15	0.27	0.37	0.06	0.05	0.08	0.05	0.05
Yb	1.0	1.2	1.0	1.8	2.4	0.3	0.3	0.4	0.4	0.3
Lu	0.15	0.17	0.14	0.26	0.36	0.07	0.05	0.08	0.07	0.05

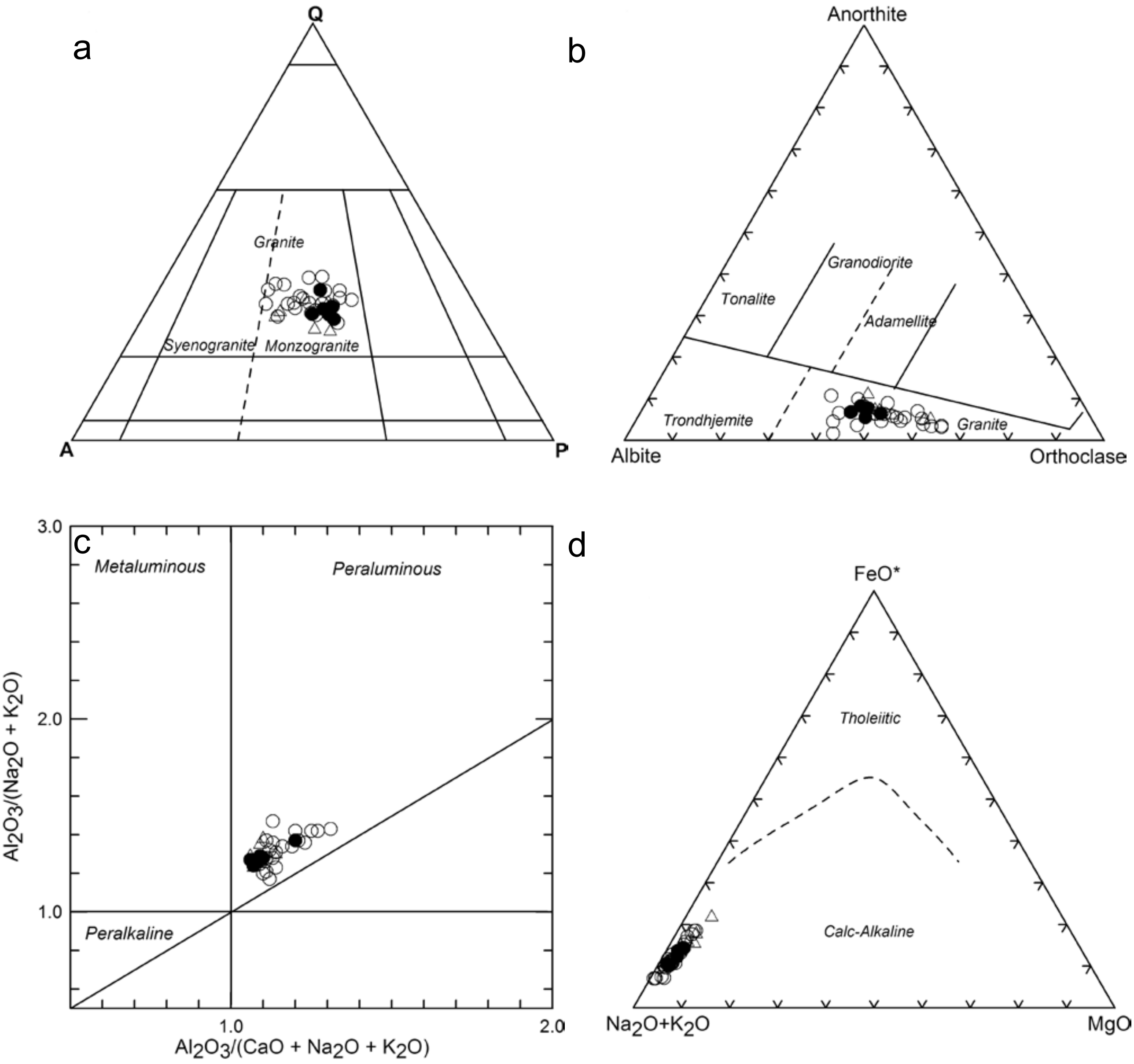

Fig. 5 QAP ternary plot based on modal compositions (Streckeisen 1979) (**a**) and normative Ab–An–Or (**b**) plot (O'Connor 1965) of the granites of the Sebago Pluton and Sebago Migmatite Domain. **c** – Alumina saturation (Shand index) diagram for the studied Sebago granites (modified after Maniar and Piccoli 1989). **d** – The AFM (Na_2O+K_2O–FeO^*—MgO) plot (from Irvine and Baragar 1971**)** illustrating calc-alkaline trend of Sebago and SMD granites. Symbols: *Dots* – group 1 two-mica granite, *circles* – group 2 two-mica granite, *open triangles* – group 2 biotite granite.

the Ragged Jack K-feldspar (Ba = 1239–1971 ppm and Sr = 310–360 ppm), but for much of the SPG Ba and Sr contents are typically lower than 300 ppm and 100 ppm, respectively. K-feldspar from the Sebago pegmatites commonly shows large variations in its K/Rb, K/Cs and K/Ba ratios (Tab. 3).

4.3.2. Muscovite

The principal primary mica species dominating the SPG is muscovite, although biotite and lepidolite are locally abundant in some pegmatites. Silver-colored platy muscovite is abundant in most pegmatites with the exception of the most primitive types (e.g. Conant, Songo Pond) where muscovite occurs only as a few scattered flakes. Yellowish muscovite is common only in highly-fractionated pegmatites, such as at Mt. Mica or Pulsifer, and is usually found near the margins of the core or along the edges of miarolitic cavities. Coarse-grained books of muscovite may show a diamond-shaped habit, sometimes with curved-faces; occasionally they are rimmed by a later generation of pale, lilac-colored muscovite. Lenses and pods of massive, me-

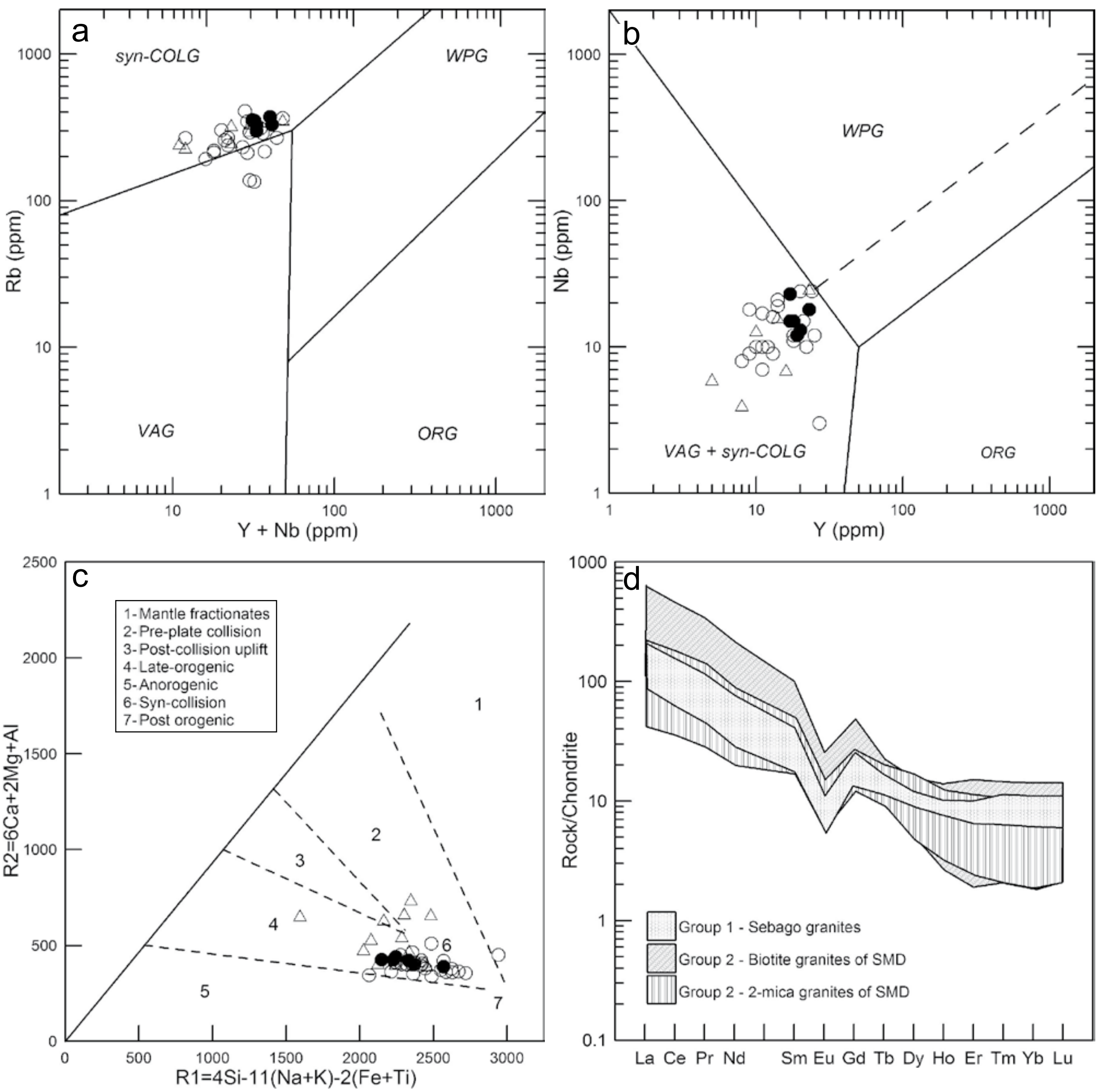

Fig. 6 Rb–Y + Nb (**a**) and Nb–Y (**b**) tectonic discrimination of the Sebago Pluton and granites of the Sebago Migmatite Domain (Pearce et al. 1984). **c** – R_1–R_2 diagram (Batchelor and Bowden 1985) of Sebago granites. **d** – Chondrite-normalized REE plot for studied granites of the Sebago Pluton and Sebago Migmatite Domain. REE concentrations are normalized to the chondritic values of Anders and Grevesse (1989). Symbols: *Dots* – group 1 two-mica granite, *circles* – group 2 two-mica granite, *open triangles* – group 2 biotite granite.

dium- to fine-grained silver- to lilac-colored, Li-enriched muscovite are restricted to highly-evolved pegmatites, particularly those containing spodumene or petalite, and are most common as late replacement units situated in the innermost intermediate zones.

Muscovite compositions show variable concentrations of Mg, Ti and Fe. Low MgO and TiO_2 characterize much of the pegmatite population with total MgO + TiO_2 typically < 0.75 wt. %. Overall, Fe concentrations range from 1.27 to 4.55 wt. % Fe_2O_3, but a few pegmatites in the western part of the group (e.g., Lord Hill, Songo Pond and Eastman) contain muscovite that exceeds 5 wt. % Fe_2O_3 (Tab. 4).

Figures 7 and 8 illustrate the fractionation of rare alkalis (Rb, Cs and Li), Ta, Sn and Zn in muscovite from the SPG. The K/Rb ratio, which serves as an effective fractionation indicator (Černý et al. 1981, 1985; Tomascak 1991) ranges from 155 to 10 for the SPG muscovites. Ru-

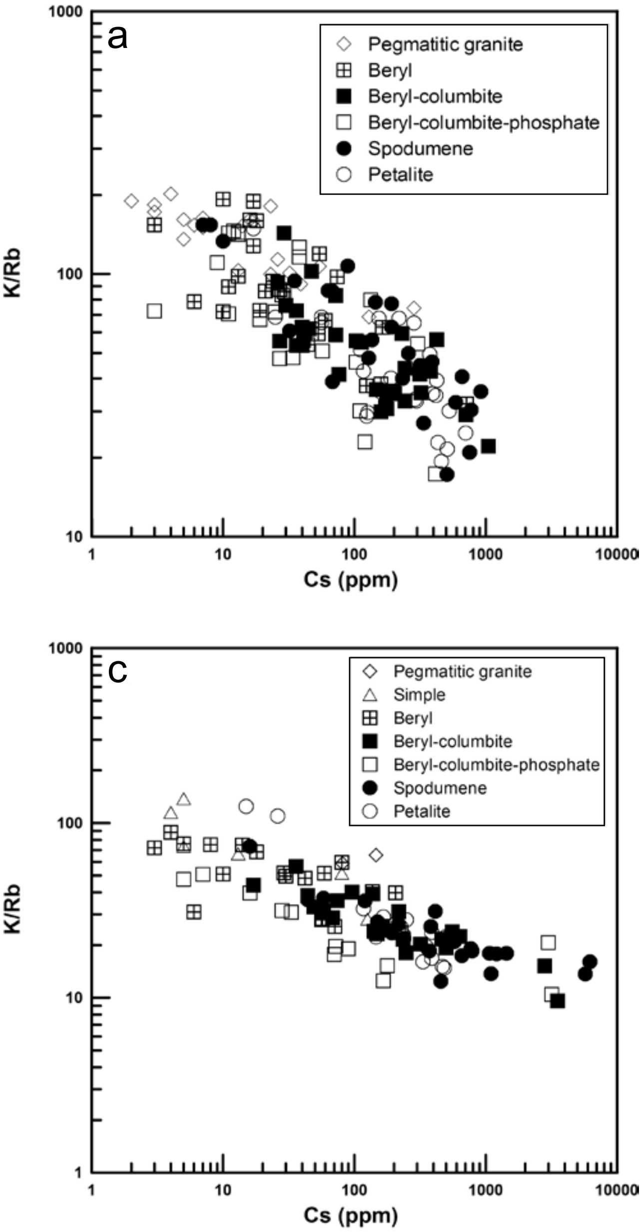

Fig. 7 Plot of K/Rb vs. Cs (**a**) and K/Rb vs. Tl (**b**) in K-feldspar from the Sebago group pegmatites. Plot of K/Rb vs. Cs (**c**) and K/Rb vs. Li (**d**) in muscovite from the Sebago group pegmatites.

bidium fractionation in the muscovites is similar to that observed in K-feldspar, and although most muscovites typically contain less than 5000 ppm Rb, extreme levels (>7500 ppm Rb) were observed in the most evolved pegmatites (e.g., Bennett, Hayes and BB#7).

Most of the SPG muscovites do not attain high levels of Li; Li_2O contents range from 0.20 wt. % to 0.62 wt. %. High Li contents (> 1.0 wt. % Li_2O) are generally found in muscovites from pegmatites carrying spodumene (e.g. Bennett), petalite (e.g. Emmons) or Li-phosphates (e.g., Berry–Havey). Despite the absence of Li minerals,

Tab. 3 Trace-element data for Sebago Pegmatite Group K-feldspars

	Pegmatitic granite	Be-pegmatites	Li-pegmatites
Rb (ppm)	503–1446	522–6079	666–6677
Cs	5–283	3–1045	7–917
Tl	3–9	3–43	5–71
Ba	1–199	1–537	2–423
Sr	4–85	4–255	8–106
K/Rb	68.8–201.7	17.3–192.9	17.3–154
K/Cs	345–3–48356.3	97.2–32957	122.8–14824.1
K/Ba	509.8–97708.8	178.7–99950.2	242.9–50805.2
Rb/Sr	5.9–289.2	5.6–878	6.3–413.8

Table is exclusive of anomalous Ragged Jack data: Rb = 275–294, Cs = 0–8, Tl = 0, Ba = 1239–1971, Sr = 310–360, K/Rb = 377–409, K/Cs = 0–13822, K/Ba = 56–91, Rb/Sr = 0.8

Tab. 4 Partial analysis of Sebago Pegmatite Group muscovites

	Pegmatitic granites	Simple pegmatites	Be-pegmatites	Li-pegmatites
Na_2O (wt. %)	0.41–0.65	0.37–0.68	0.51–0.70	0.49–0.61
Fe_2O_3*	1.46–3.85	1.27–3.19	2.06–4.17	2.03–4.55
MgO	0.07–0.49	0.07–0.74	0.06–0.72	0.07–1.15
TiO_2	0.01–0.16	0.03–0.68	0.05–0.58	0.07–1.28
Ba (ppm)	3–66	2–287	1–218	1–42
Cs	81–146	4–126	0–3533	15–6236
Ga	94–109	80–235	91–330	127–367
Li	447–867	61–1481	56–6553	439–7778
Nb	94–276	90–376	18–547	41–431
Rb	747–1613	701–3324	617–9600	768–7598
Sn	65–285	29–285	68–1783	70–1501
Sr	4–7	3–18	3–22	3–9
Ta	8–39	7–107	7–393	11–215
Tl	46–59	33–77	37–151	36–123
Zn	53–98	37–358	60–1138	57–947
Zr	8–13	3–16	1–145	3–68
K/Rb	58.7–128.6	28.2–137.8	9.6–155.4	12.4–124.5

* Table does not include anomalous Fe_2O_3 data for Bennett (4.90–5.24 wt. %), Lord Hill (3.13–7.10), Songo Pond (5.26–5.74), and Eastman (3.26–5.12) pegmatites.

muscovite from the Lord Hill pegmatite may contain up to 1.19 wt. % Li_2O. True lepidolite, $KLi_2Al(Al,Si)_3O_{10}(F,OH)_2$, (> 4.0 wt. % Li_2O) was found only as fine-grained veinlets cross cutting pollucite and kaolinized spodumene.

High cesium concentrations are best seen in muscovite from the highly fractionated and pollucite-bearing Bennett, Mt. Mica, Westinghouse and GE pegmatites, where Cs_2O values approach 1 wt. %. However, the Cs concentration for most muscovite in the SPG is generally < 400 ppm. Tin contents of muscovite range from ~25 to ~1800 ppm with the highest levels generally found in pegmatites that carry substantial amounts of columbite group minerals or cassiterite. The concentration of Nb and Ta in SPG muscovite typically lies in the interval 200–500 ppm and 10–100 ppm, respectively. Tantalum concentrations in muscovite generally increase with the degree of pegmatite fractionation in all pegmatite subtypes. Zinc shows similar patterns of enrichment as Sn and typically attains less than 500 ppm (Fig. 8).

4.3.3. Garnet

Garnet from the SPG is generally found in the wall and intermediate zones of both simple and complex pegmatites. It occurs as dark red to purple–red crystals as much as 3 cm in diameter in pegmatitic granite, whereas garnets from pegmatites are generally dark red and rarely pink or orange. Locally, some crystals display symplectic intergrowths with quartz or fluorapatite or are enveloped by a 1 to 2 mm thick rim of dark blue tourmaline. Concentrations of garnet along the margins of partially digested xenoliths of biotite schist may be found in some pegmatites. Garnet-rich bands (*garnet seams*) 1 to 5 cm thick, rarely occur in some pegmatites and pegmatitic leucogranites (Fig. 3d). Individual crystals within the *garnet seams* range in size from 2 mm to 3 cm and are associated with platy albite (*cleavelandite*), smoky quartz and schorl. Dark red garnet crystals, 1 mm or less in diameter, occur in schorl-bearing aplite in some zoned pegmatites (e.g. Bennett, Westinghouse, GE); garnetiferous aplite without schorl occurs locally at the Lord Hill pegmatite.

Garnet compositions for the Sebago pegmatites (Tab. 5) correspond typically to almandine with a few localities containing spessartine. Microprobe traverses across single crystals show chemical zoning expressed by Mn-enriched rims and Fe-enriched cores. Pyrope and andradite components are minor; combined MgO and CaO contents are generally less than 2 wt. %. Phosphorus concentrations range from < 0.1 to 0.64 wt. % P_2O_5 with nearly 25 % of analyses containing more than 0.2 wt. % (Wise 1994). The distribution of phosphorus within individual crystals is irregular and zonation is virtually absent. Pegmatites hosting multi-generations of garnet show systematic variations in Mn/(Mn + Fe) values, Mg and P. Early generations of garnet tend to have higher Mg and lower average P and Mn/(Mn + Fe) values than garnet found in later generations. Aside from local Mn enrichment (Mn/(Mn + Fe) > 0.5 in the Bennett, Westinghouse,

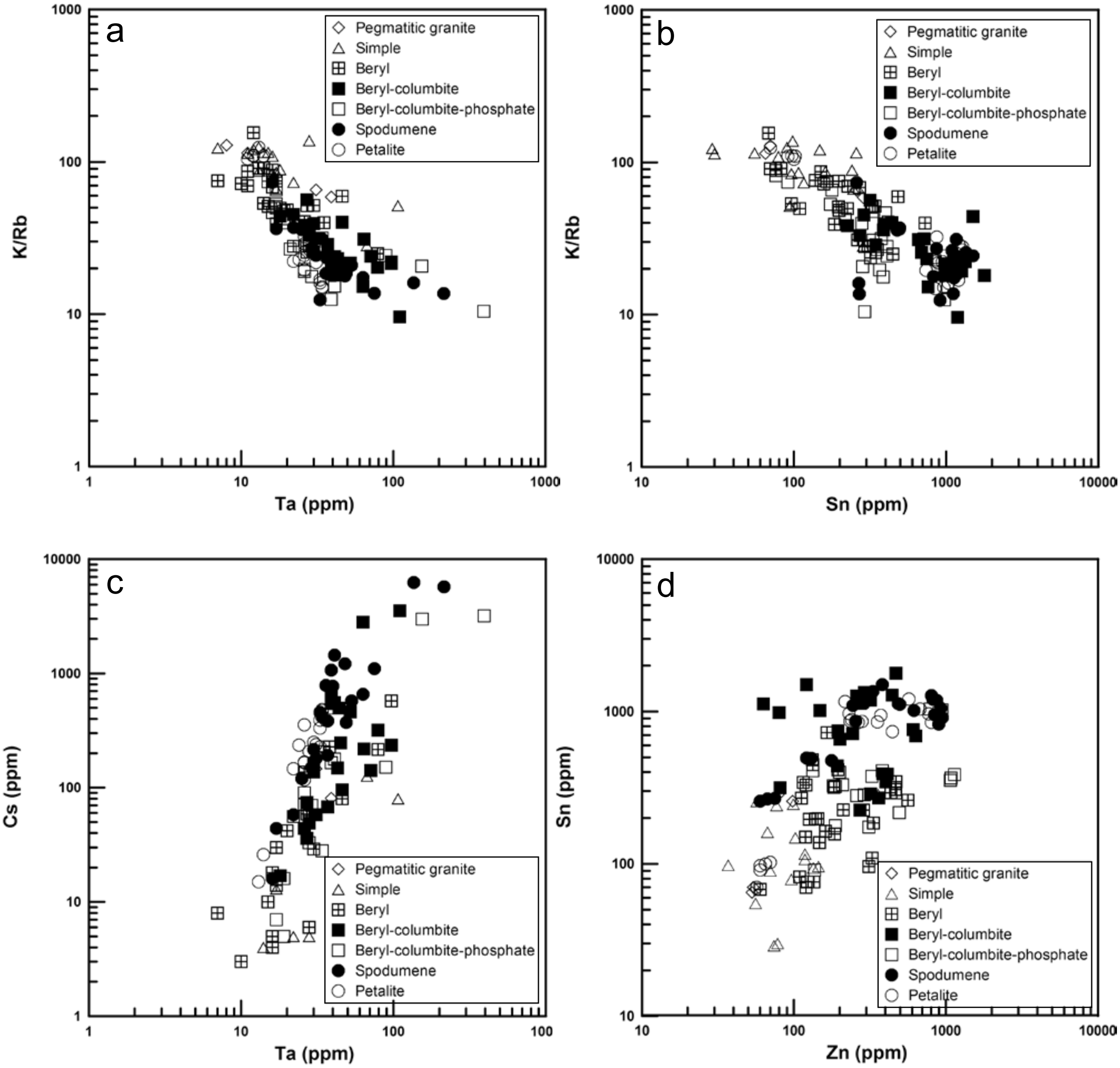

Fig. 8 K/Rb vs. Ta (**a**) and Sn (**b**) plot of Sebago Pegmatite Group muscovite. Cs vs. Ta (**c**) and Sn vs. Zn (**d**) for muscovite.

GE and Emmons pegmatites), Mn/(Mn + Fe) values are relatively uniform throughout the pegmatite group (Fig. 9). In contrast, P levels tend to be highest in pegmatites east of the Songo Pluton. No systematic difference in Mn or P contents was observed among different subtypes of rare-element pegmatites.

4.3.4. Beryl

Beryl is a widespread accessory phase found in moderately- to highly-evolved pegmatites of the SPG. Yellow, green and blue–green anhedral masses or columnar, hexagonal crystals (up to 8.2 m in length; Neumann 1952) are typical of simple pegmatites or the outer zones of evolved pegmatites. By comparison, inner zones of evolved pegmatites typically host blue and milky-white beryl. Beryl occurring in miarolitic cavities is typically blue, pink, white, colorless, rarely yellow-green (e.g. Orchard Pit) and is often etched. It can rarely be translucent to transparent and of good gem quality. Although beryl appears to be equally distributed over the entire pegmatite population, pink to colorless beryl is rarely found in pegmatites west of the Songo Pluton.

The chemical composition of the SPG beryl varies within narrow limits of their Na_2O, Fe_2O_3 and Ga contents (Tab. 6). For most beryl in the SPG, Rb content is

Tab. 5 Selected electron microprobe compositions of garnet from the Sebago Pegmatite Group

	1	2	3	4	5	6	7	8
P_2O_5	0.41	0.08	0.17	0.05	0.10	0.09	0.06	0.12
SiO_2	36.36	36.71	36.39	36.80	36.86	36.51	36.97	36.66
TiO_2	0.05	0.01	0.07	0.06	0.06	0.03	0.03	0.03
ZrO_2	0.00	0.00	0.05	0.00	0.00	0.02	0.00	0.03
Al_2O_3	21.24	21.26	21.30	21.25	21.41	21.24	21.27	21.01
Y_2O_3	0.00	0.13	0.00	0.00	0.04	0.01	0.00	0.00
FeO	24.37	28.30	20.21	34.06	29.94	28.29	26.98	24.47
MnO	17.57	11.73	22.22	6.82	10.03	13.17	12.99	16.53
CaO	0.19	0.71	0.20	0.72	0.43	0.44	0.41	0.27
MgO	0.07	0.52	0.04	0.33	1.17	0.49	1.07	0.94
Na_2O	0.00	0.00	0.00	0.00	0.01	0.05	0.00	0.02
Total	100.25	99.44	100.64	100.09	100.03	100.35	99.77	100.07
Number of cations on the basis of 12 oxygens								
P^{5+}	0.028	0.005	0.012	0.004	0.007	0.006	0.004	0.008
Si^{4+}	2.973	3.009	2.972	3.007	2.996	2.982	3.012	2.994
Z-site sum	3.001	3.014	2.984	3.011	3.003	2.988	3.016	3.002
Ti^{4+}	0.003	0.000	0.004	0.004	0.004	0.002	0.002	0.002
Zr^{4+}	0.000	0.000	0.002	0.000	0.000	0.001	0.000	0.001
Al^{3+}	2.047	2.054	2.051	2.046	2.051	2.045	2.043	2.022
Y^{3+}	0.000	0.006	0.000	0.000	0.002	0.000	0.000	0.000
Y-site sum	2.050	2.060	2.057	2.050	2.057	2.048	2.045	2.025
Fe^{2+}	1.666	1.940	1.380	2.327	2.035	1.932	1.839	1.671
Mn^{2+}	1.217	0.814	1.537	0.472	0.690	0.911	0.896	1.143
Ca^{2+}	0.016	0.062	0.017	0.063	0.038	0.039	0.036	0.024
Mg^{2+}	0.008	0.063	0.005	0.040	0.141	0.060	0.129	0.114
Na^{+}	0.000	0.000	0.000	0.000	0.002	0.008	0.000	0.003
X-site sum	2.907	2.879	2.939	2.902	2.906	2.950	2.900	2.955
Total	7.958	7.953	7.980	7.963	7.966	7.986	7.961	7.982
Mn/(Mn + Fe)	0.42	0.30	0.53	0.17	0.25	0.32	0.33	0.41
Ca/(Ca + Mg)	0.66	0.50	0.76	0.61	0.21	0.39	0.22	0.17

1 – Mt. Marie, 2 – Pulsifer, 3 – GE, 4 – Norman Jack, 5 – Tamminen, 6 – Tiger Bill, 7 – Bumpus, 8 – Songo Pond.

minimal (< 200 ppm) and its concentration increases with increasing Cs (Fig. 10a). The geochemical trend of Na/Li versus Cs observed in the Sebago data is consistent with beryl chemistry from other pegmatite fields (Fig. 10b; Černý 1975; Černý et al. 1981). In general, yellow, green and blue–green varieties of beryl have 1000–5000 ppm Cs. By comparison, the pink, white or colorless crystals found only in the most evolved pegmatites, such as the Bennett pegmatite, may contain between 1 and 3.0 wt. % Cs_2O.

4.3.5. Nb–Ta–Sn–Ti oxides

The Nb, Ta, Sn and Ti mineralization within the SPG is represented largely by the columbite-group minerals and, to a lesser degree, by cassiterite, ixiolite, wodginite, ferrotapiolite, and rutile. Columbite-group minerals occur as black, bladed to columnar, subhedral to euhedral crystals that are as large as 21 cm in maximum dimension. Most, however, are on the order of 0.5 to 2 cm in size. Cassiterite is found most often in Li-enriched pegmatites of the SPG group as black, dark brown or dark reddish-brown, anhedral masses ranging in size from 0.5 cm to approximately 3–4 cm in diameter. Exceptionally large cassiterite is unusual in the SPG; the BB#7 pegmatite produced a very large crystal nearly 20 cm in diameter and a mass of cassiterite weighing up to 90 kg was reported from the Bennett pegmatite (Landes 1925). Sharp pyramidal crystals, rarely twinned, occur locally in miarolitic cavities. The Bennett and Emmons pegmatites are the only localities in the SPG known to contain wodginite or ixiolite. Both minerals form subhedral masses or occur as inclusions in columbite–tantalite. Ferrotapiolite is rare and so far found only in the Bennett and Mt. Mica pegmatites, while small grains of Fe-enriched, niobian rutile has only been found at the Songo Pond pegmatite. All of the aforementioned

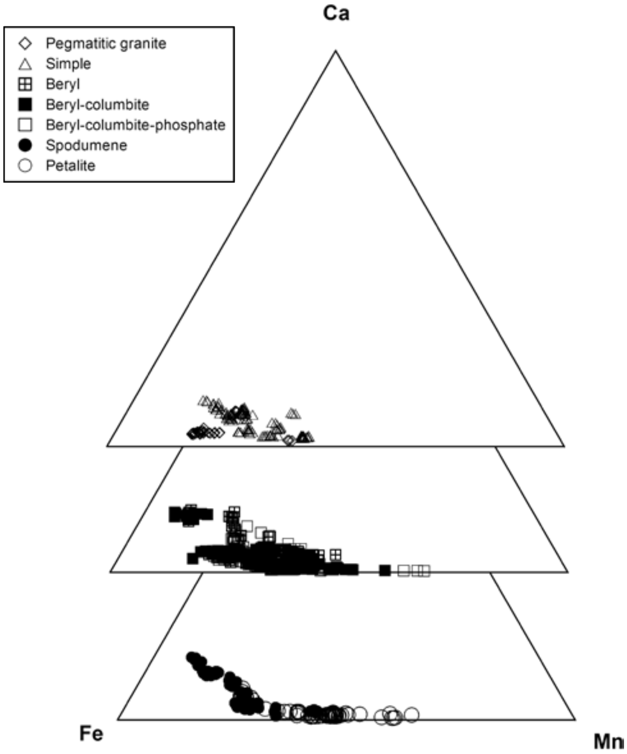

Fig. 9 Composition of garnet from the Sebago Pegmatite Group in the Fe–Mn–Ca triangle (atomic).

minerals are commonly found in assemblages dominated by platy albite although some may be found in milky to smoky quartz or in assemblages hosting fine- to medium-grained silver, pale-green or purple Li-enriched mica or lepidolite.

Electron microprobe analyses of columbite-group minerals reveal an extensive range of Mn/(Mn + Fe) and Ta/(Ta + Nb) values (Tab. 7). Compositions range from predominantly ferrocolumbite and manganocolumbite with narrow ranges of Nb–Ta substitution to subordinate manganotantalite with limited ranges of Fe–Mn substitution (Fig. 10c). Columbite-group minerals typically show a concomitant increase in Ta and Mn, which is a common trend displayed with progressive pegmatite fractionation. Total Fe_2O_3, Sc_2O_3, TiO_2, SnO_2 and WO_3 contents in the columbite-group minerals are generally less than 0.5 wt. %. Columbite-group minerals from pegmatites east of the Songo Pluton carry the highest SnO_2 values while TiO_2, Sc_2O_3 and Fe_2O_3 are the highest in pegmatites west of the Songo Pluton.

Tab. 6 Partial analysis of Sebago Group beryl

	Be-pegmatites	Li-pegmatites
Cs (ppm)	158–10596	435–29743
Ga	20–79	25–63
Li	261–3903	537–5513
Rb	17–447	63–325
Zn	37–575	22–461
Zr	1–148	2–208
Na/Li	0.96–9.38	0.83–6.65

Cassiterite is more common in beryl-, spodumene- and petalite-bearing pegmatites, whereas ferrotapiolite, wodginite and ixiolite are rare. Cassiterite contains low to moderate amounts of Nb and Ta; maximum Nb_2O_5 and Ta_2O_5 contents are 1.79 wt. % and 7.07 wt. %, respectively. All wodginite and ixiolite from the Emmons and Bennett pegmatites are Sn-rich and contain up to 19.19 wt. % SnO_2, 12.08 wt. % Nb_2O_5 and typically low TiO_2 contents (0.0–2.55 wt. %). The Songo Pond rutile contains 12.38–19.11 wt. % Nb_2O_5, 4.44–14.56 wt. % Ta_2O_5 and up to 1.73 wt. % SnO_2, 1.27 wt. % WO_3 and 0.64 wt. % Sc_2O_3.

4.3.6. Tourmaline

Tourmaline occurs as a common accessory phase in nearly all of the pegmatites of the SPG with the exception of those that intrude the SMD west of the Songo Pluton where tourmaline is generally scarce. Pegmatites west of the Songo Pluton carry only Mg- and Fe-dominant tourmaline, whereas pegmatites from the rest of the group may contain substantial amounts of Li-rich tourmalines. Tourmaline is found as single, prismatic crystals (up to 54 cm long; Simmons et al. 2005), sometimes growing perpendicular to the pegmatite margin, as radial aggregates, or as graphic intergrowths with quartz. The most common tourmaline species are schorl and elbaite; dravite and foitite are rare. Tourmaline from the simple pegmatites is typically schorl, while those from the more mineralogically and texturally diverse pegmatites often display various colors typical of elbaite which reflects changes in the tourmaline chemistry. From the pegmatite margins to the core, the color of tourmaline frequently varies systematically from black (schorl or foitite) to dark blue (schorl–elbaite) to green (elbaite) to pink (elbaite) and ultimately colorless (elbaite). Normal zoning (e.g. Fe-enriched cores relative to the rims) is common, but reverse, patchy and oscillatory zoning also occurs. Tourmalines from miarolitic cavities may be of gem-quality and can show considerable etching effects. Crystals of brown dravite commonly occur at the margins of xenoliths and pegmatite-host rock contacts, except at the Songo Pond pegmatite, where dravite is unrelated to any xenoliths or contacts. Foitite was identified from some primitive pegmatites (e.g. Sahib and Green) and from the wall zones of Li-enriched pegmatites (e.g. Mt. Marie and Mt. Rubellite pegmatites).

Chemical variation of tourmaline within the SPG is extensive (Tab. 8). This variation is due largely to Mg–Fe–Al–Li substitution in the *Y*-site of the tourmaline

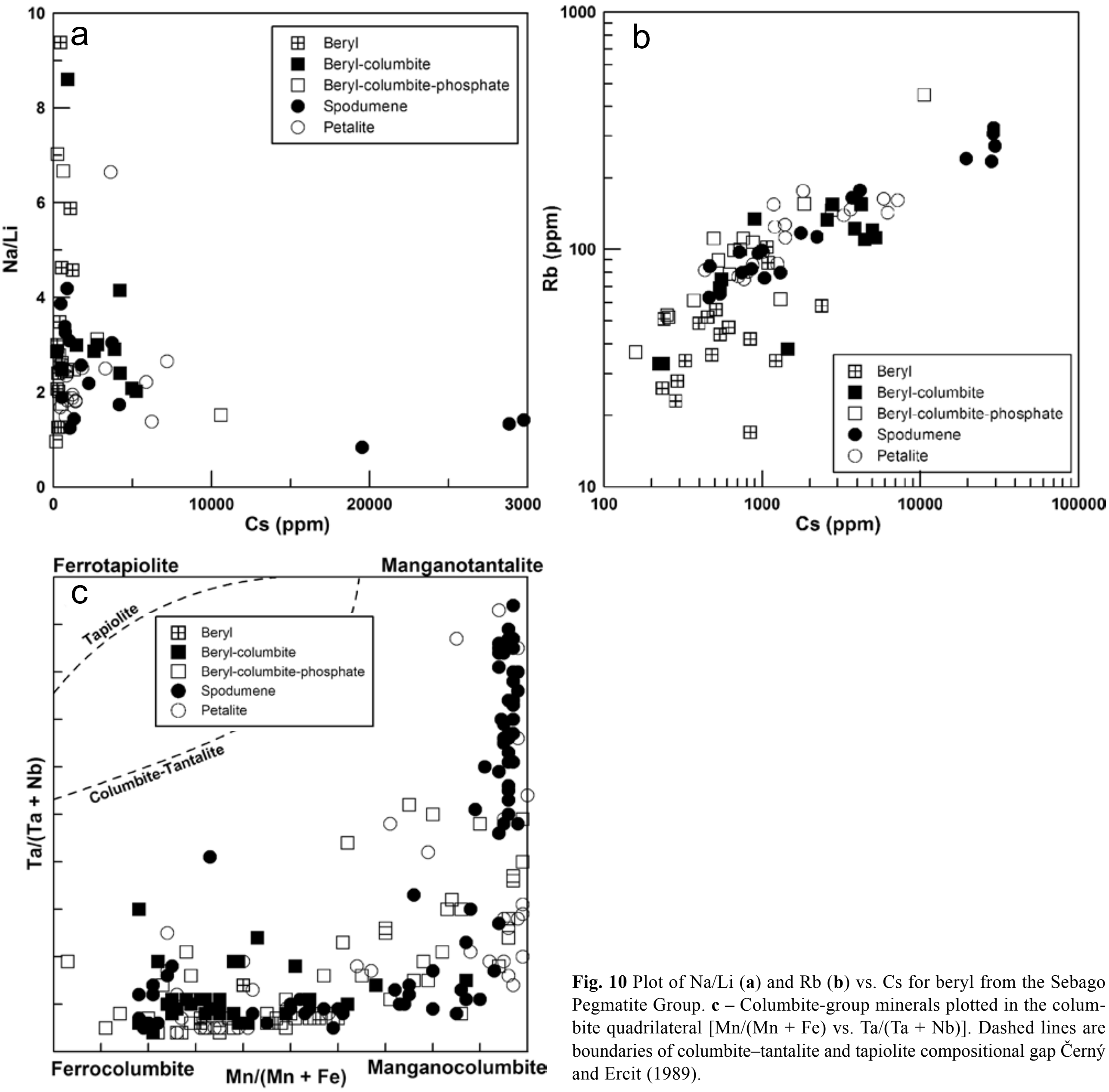

Fig. 10 Plot of Na/Li (**a**) and Rb (**b**) vs. Cs for beryl from the Sebago Pegmatite Group. **c** – Columbite-group minerals plotted in the columbite quadrilateral [Mn/(Mn + Fe) vs. Ta/(Ta + Nb)]. Dashed lines are boundaries of columbite–tantalite and tapiolite compositional gap Černý and Ercit (1989).

structure and, to a lesser degree, to the incorporation of *X*-site vacancies, which result in significant foitite or rossmanite components in the tourmaline chemistry. Overall, *X*-site vacancies range from 0.20 to 0.50 *apfu* for schorl and 0.06–0.48 *apfu* for elbaite. Regardless of the extent of *X*-site vacancies, Na is always greater than Ca in all tourmalines examined; most contain almost no Ca (Fig. 11). Most of the tourmalines in the SPG contain low Mg ≤ 0.60 *apfu*, except for schorl and foitite which may have up to 1.44 *apfu* Mg, and the occasional dravite with > 2.5 *apfu* Mg. Ti (≤ 0.15 *apfu*) and Zn (≤ 0.21 *apfu*) are also low and only reach their maximum concentration in schorl from simple pegmatites. High F contents (0.90–1.11 *apfu*) and moderate Mn contents (0.33–0.45 *apfu*) are typical of elbaite in the Li-enriched pegmatites of the SPG (Tab. 8).

The general crystallization sequence of tourmaline is consistent with that described by Selway (1999) and proceeds as follows: foitite → schorl → elbaite (Fig. 12). Black tourmaline that forms part of the garnet seam assemblage (e.g. Pulsifer and Mt. Mica pegmatites), or as the poikilitic grains making the texturally "spotted" aplite (e.g. Bennett and Westinghouse pegmatites) show compositions (schorl) that are similar to those from their wall zones despite having crystallized during a later stage of pegmatite consolidation. A thick band of black

Tab. 7 Selected electron microprobe compositions of columbite–tantalite from the Sebago Pegmatite Group

	1	2	3	4	5	6	7	8	9	10
WO_3	0.00	0.00	0.00	0.00	0.00	0.00	1.18	0.04	0.00	0.49
Nb_2O_5	69.36	63.72	66.47	58.49	7.29	46.37	66.62	27.71	65.19	66.91
Ta_2O_5	9.76	16.78	9.39	21.49	78.89	33.76	10.29	56.10	12.56	10.10
TiO_2	0.17	0.12	1.26	0.50	0.00	1.11	0.60	0.11	1.08	1.05
SnO_2	0.08	0.08	0.38	0.86	0.76	0.22	0.17	0.07	0.09	0.17
Sc_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.03	0.00	0.15
Fe_2O_3*	0.85	0.90	2.45	1.24	0.35	1.18	1.73	0.50	1.76	2.82
FeO	10.70	5.64	13.19	6.10	0.08	14.08	7.97	0.24	12.89	10.59
MnO	9.14	13.73	5.14	12.49	14.37	3.37	11.10	15.94	5.90	7.84
MgO	0.00	0.00	0.02	0.00	0.00	0.03	0.09	0.02	0.02	0.04
CaO	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.01	0.03
Total	100.06	100.97	98.32	101.19	101.74	100.12	99.85	100.76	99.50	100.19
Number of cations on the basis of 24 oxygens										
W	0.000	0.000	0.000	0.000	0.000	0.000	0.072	0.003	0.000	0.029
Nb	7.307	6.843	7.078	6.394	1.052	5.398	7.050	3.577	6.954	7.011
Ta	0.618	1.084	0.602	1.413	6.854	2.364	0.655	4.356	0.806	0.637
Ti	0.030	0.021	0.224	0.091	0.000	0.215	0.106	0.024	0.192	0.183
Sn	0.007	0.008	0.036	0.083	0.096	0.022	0.016	0.008	0.008	0.016
Sc	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.007	0.000	0.030
B-site sum	7.962	7.956	7.940	7.981	8.002	7.999	7.919	7.975	7.960	7.906
Fe^{3+}	0.149	0.161	0.434	0.225	0.084	0.229	0.305	0.108	0.312	0.492
Fe^{2+}	2.084	1.121	2.596	1.233	0.022	3.032	1.561	0.056	2.544	2.053
Mn	1.804	2.763	1.026	2.558	3.888	0.735	2.201	3.855	1.180	1.539
Mg	0.000	0.000	0.008	0.000	0.000	0.012	0.031	0.009	0.008	0.014
Ca	0.000	0.000	0.006	0.005	0.000	0.000	0.000	0.000	0.002	0.007
A-site sum	4.037	4.045	4.070	4.021	3.994	4.008	4.098	4.028	4.046	4.105
Total	11.999	12.001	12.010	12.002	11.996	12.007	12.017	12.003	12.006	12.011
Mn/(Mn + Fe)	0.45	0.68	0.25	0.64	0.97	0.18	0.54	0.96	0.29	0.38
Ta/(Ta + Nb)	0.08	0.14	0.08	0.18	0.87	0.30	0.09	0.55	0.10	0.08

1 – Berry–Havey, 2 – Turner, 3 – GE, 4 – Westinghouse, 5 – Bennett, 6 – Heikkinen, 7 – BB #7, 8 – Waisanen, 9 – Cole, 10 – Pingree.
* Calculated Fe_2O_3.

tourmaline that borders the spotted aplite body in the Bennett pegmatite was also shown to be schorl. Pink or green tourmalines that crystallized in miarolitic cavities of the Sebago pegmatites are always elbaite, and many have compositions that evolve towards rossmanite. On the other hand, dravite from the Songo Pond pegmatite primarily shows the *Y*-site substitution of Fe for Mg with compositions evolving towards schorl.

4.3.7. Zr, P, Li and Cs phases

Zircon is widespread, but uncommon in the Sebago pegmatites. All of the examined zircons were collected from beryl–columbite–phosphate, spodumene and petalite subtype pegmatites. Zircon crystals were typically 0.1–0.5 mm across, black to brownish in color with short prismatic morphology. BSE images show variable internal structures that include largely metamict cores with unzoned, irregularly zoned or oscillatory zoned rims. The chemical composition of zircon shows low to moderate Hf contents with up to 5.3 wt. % HfO_2; the range of 100Hf/(Hf + Zr) values is 1.5–5.4.

Fluorapatite is the most abundant and most widespread primary phosphate in the SPG. It occurs throughout both Li-poor and Li-rich pegmatites as light to dark green crystals, while dark blue, white, and purple fluorapatite is typically found in late-formed miarolitic cavities. Most of the examined fluorapatites are Mn-enriched, with up to 10.22 wt. % MnO. Members of the triphylite–lithiophilite series are generally found in spodumene- and petalite-bearing pegmatites. Chemical analyses of triphylite–lithiophilite from the SPG have Mn/(Mn + Fe) ratios of 0.40–0.97 (Moore 2000). Masses of snow-white montebrasite, up to 10 cm across, are also found predominantly

Tab. 8 Selected electron microprobe compositions tourmaline from the Sebago Pegmatite Group

	1	2	3	4	5	6	7	8
SiO_2	34.50	35.33	35.96	35.20	34.91	37.04	37.08	37.46
TiO_2	0.27	0.21	0.12	0.23	0.06	0.02	0.11	0.00
B_2O_3	10.12	10.39	10.51	10.47	10.34	10.80	10.72	11.07
Al_2O_3	31.25	33.92	34.09	34.36	33.52	38.07	36.81	42.14
FeO	15.03	13.71	11.35	11.80	15.11	3.75	6.47	0.05
MgO	1.67	1.25	2.92	2.54	0.88	0.01	0.00	0.03
CaO	0.04	0.06	0.08	0.13	0.07	0.08	0.19	0.26
MnO	0.28	0.19	0.12	0.11	0.16	2.25	0.62	1.11
ZnO	0.23	0.21	0.08	0.07	0.30	0.18	0.12	0.00
Li_2O	0.07	0.15	0.11	0.18	0.11	1.52	1.50	1.83
Na_2O	2.35	1.60	1.46	1.86	1.97	2.57	2.57	1.65
K_2O	0.00	0.02	0.01	0.06	0.05	0.03	0.02	0.00
H_2O	3.25	3.59	3.62	3.58	3.23	2.92	3.17	3.44
F	0.50	0.00	0.00	0.07	0.71	1.07	1.11	0.80
Total	99.56	100.63	100.43	100.66	101.42	100.94	100.50	99.84
O=F	–0.21	–0.00	–0.00	–0.03	–0.30	–0.72	–0.47	–0.34
Total	99.35	100.63	100.43	100.63	101.12	100.22	100.03	99.50
Structural formula based on 31 anions (O, OH, F)								
Si^{4+}	5.928	5.908	5.949	5.842	5.870	5.961	6.010	5.883
Al^{3+}	0.072	0.092	0.051	0.158	0.130	0.039	0.000	0.117
T–site sum	6.000	6.000	6.000	6.000	6.000	6.000	6.010	6.000
B^{3+}	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Al^{3+}	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
Z–site sum	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
Al^{3+}	0.256	0.593	0.595	0.562	0.512	1.181	1.032	1.683
Ti^{4+}	0.035	0.026	0.015	0.029	0.008	0.002	0.013	0.000
Mg^{2+}	0.428	0.312	0.720	0.628	0.221	0.002	0.000	0.007
Mn^{2+}	0.041	0.027	0.017	0.015	0.023	0.307	0.085	0.148
Fe^{2+}	2.160	1.917	1.570	1.638	2.125	0.505	0.877	0.007
Zn^{2+}	0.029	0.026	0.010	0.009	0.037	0.021	0.014	0.000
Li^{+}	0.051	0.099	0.073	0.119	0.075	0.982	0.978	1.156
Y–site sum	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Ca^{2+}	0.007	0.011	0.014	0.023	0.013	0.014	0.033	0.044
Na^{+}	0.783	0.519	0.468	0.598	0.642	0.802	0.808	0.502
K^{+}	0.000	0.004	0.002	0.013	0.011	0.006	0.004	0.000
X–site sum	0.790	0.534	0.484	0.634	0.666	0.821	0.842	0.546
OH^{-}	3.728	4.000	4.000	3.963	3.622	3.135	3.431	3.603
F^{-}	0.272	0.000	0.000	0.037	0.378	0.865	0.569	0.397

1 – Songo Pond, 2 – Green, 3 – Mt. Marie, 4 – Witt Hill, 5 – Maine Feldspar, 6 – Berry–Havey, 7 – Harvard, 8 – Bennett.
B_2O_3, Li_2O, and H_2O for tourmaline calculated based on stoichiometry.

in Li-rich pegmatites, but may also occur in some beryl–columbite–phosphate subtype pegmatites. Negligible amounts of graftonite, $(Fe^{2+},Mn,Ca)_3(PO_4)_2$, and triplite $(Mn,Fe^{2+},Mg,Ca)_2(PO_4)(F,OH)$, occur locally within the Sebago pegmatites. The Tamminen and Waisenen pegmatites are the only localities known to contain graftonite. Glass and Fahey (1937) reported a manganoan graftonite with a Mn/(Mn + Fe) ratio of 0.48 from the Tamminen locality. Large masses of primary triplite have been found at the Lord Hill pegmatite and have Mn/(Mn+ Fe) values of 0.74–0.77 (Johnson 1998).

Pollucite occurs rarely in only the most chemically evolved Sebago pegmatites (e.g. Bennett, General Electric, Emmons, Mt. Marie, Mt. Mica). It is found as anhedral masses near the core and is typically associated with quartz, albite, K-feldspar, spodumene, petalite and lepidolite. Pollucite easily succumbs to alteration, often leaving a mass of clay as the only clue of its former presence (e.g, Bennett pegmatite). Primary pollucite from the SPG has an average CRK (where CRK = 100(Cs + Rb + K)/ Σcations and Σcations = Li + Na + K + Cs + Rb + Ca) of 76.9–87.3 and Si/Al = 2.31–2.56 (Teertstra *pers. comm.*). End-member $CsAlSi_2O_6$ with CRK = 99, occurs locally as a product of low-temperature hydrothermal alteration of primary pollucite (Teertstra and Černý 1995).

5. Discussion

5.1. Patterns of rare-element enrichment in the SPG

Geochemical indicators, such as K/Rb and K/Cs in K-feldspar and micas, Nb/Ta in columbite group minerals, Zr/Hf in zircon and Fe/Mn in garnet, serve as important tools which, along with field relationships, have proven invaluable in establishing fractionation trends of rare-elements in individual pegmatites and granite–pegmatite systems (e.g., Trueman and Černý 1982; Černý et al. 1985; Černý 1991) and developing models for the petrogenesis and evolution of granite–pegmatite systems (e.g., Legg and Namateba 1982; Shearer et al. 1985; Černý 1991; Jolliff et al. 1992; Alfonso et al. 2003). Fertile granites that are parental to mineralized pegmatites often exhibit gradual changes in fractionation indicators and levels of lithophile rare-elements enrichment with progressive evolution of its pegmatite progeny (Černý and Meintzer 1988).

As reflected in their accessory mineralogy and trace element chemistry of K-feldspar and muscovite, the overall geochemical signature of the SPG can be characterized as generally peraluminous with considerable enrichment in Be, Nb > Ta, P, Li, Cs and B with only modest enrichment in Rb, Sn and F. The mineral assemblages and chemical data indicate that many of the Sebago pegmatites are moderately to highly fractionated. Fractionation of Fe–Mn in garnet, Nb–Ta oxide minerals, and phosphates proceeds towards Mn enrichment as shown by the presence of spessartine, manganoan fluorapatite, lithiophilite, and manganocolumbite–manganotantalite. Extreme Mn enrichment is typical of lepidolite-bearing units rich in fluorine, thus the occurrence of Mn-dominant phases strongly suggests that the pegmatite melts were substantially enriched in F for at least a part of their crystallization history. Although many of the highly fractionated pegmatites are apparently enriched in F, they do not compare with the extreme level of F enrichment present within the Lord Hill pegmatite.

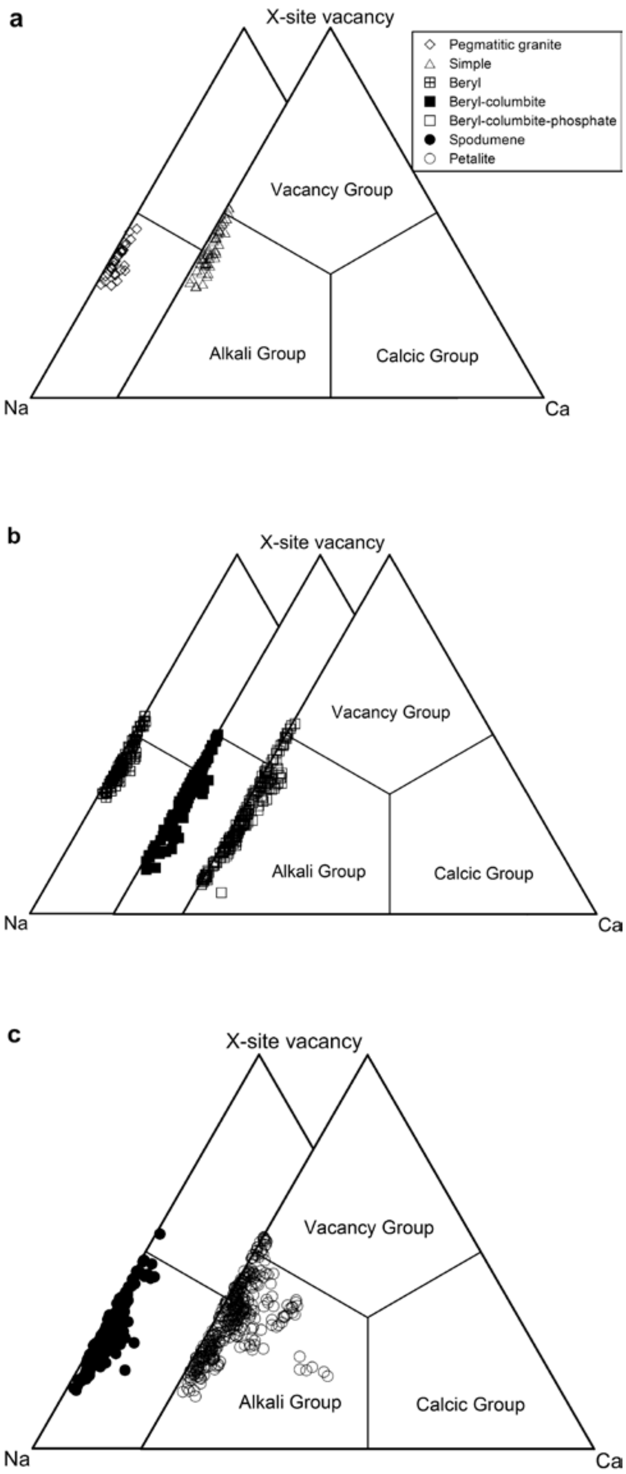

Fig. 11 Tourmaline compositions from Sebago Pegmatite Group plotted in the Na–Ca–vacancy ternary diagram.

The degree of Nb–Ta fractionation within the SPG is generally moderate as shown by the predominance of columbite over tantalite in most pegmatites. Only the most evolved pegmatites show significant Ta enrichment whereby manganotantalite occurs as an abundant phase. Columbite-group minerals crystallized from F-enriched melts display distinctive curved fractionation trends

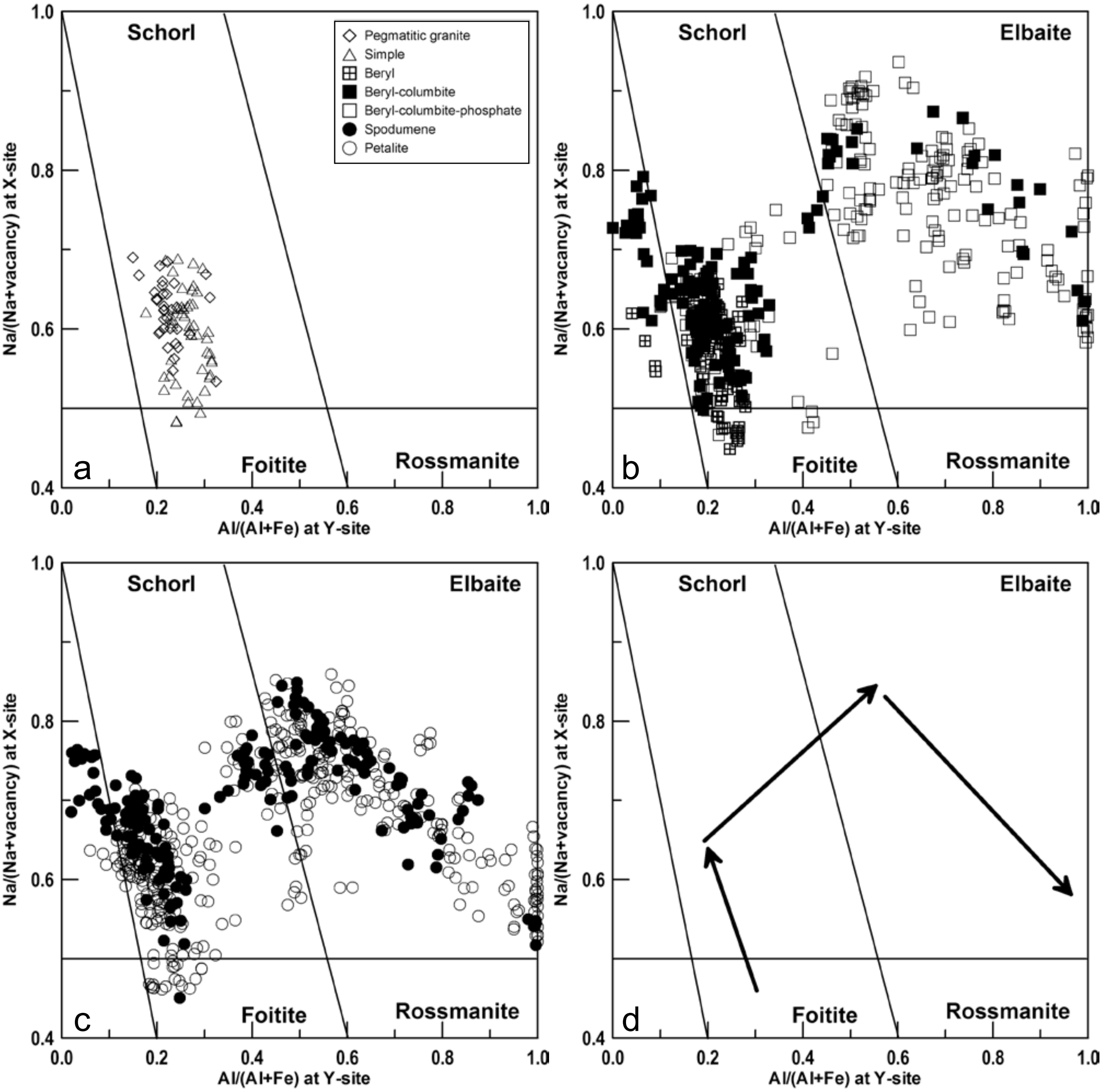

Fig. 12 Tourmaline compositions plotted in the Na/(Na + vacancy) at X-site vs. Al/(Al + Fe) at the Y-site for: pegmatitic granites and simple pegmatites (**a**), Be-rich pegmatites (**b**), and Li-rich pegmatites (**c**). **d** – General crystallization sequence of tourmaline for the Sebago Pegmatite Group. All diagrams modified after Selway (1999).

characterized by the initial crystallization of Mn–Nb dominant phases with extremely low Ta contents and subsequently evolving to Mn–Ta dominant members with very little Nb (e.g., Černý 1989). This fractionation trend is clearly observed in columbite-group minerals from a number of pegmatites in the SPG. With the exception of the Lord Hill pegmatite, columbite from the western part of the field show a fairly restricted level of Mn fractionation compared to the rest of the SPG.

Phosphorus mineralization is prevalent throughout the SPG as fluorapatite, but the most evolved pegmatites also contain primary Li-phosphates. Triplite is found in small quantities in a few pegmatites in the SPG, where its presence is largely the result of secondary alteration of lithiophilite and amblygonite–montebrasite. By comparison, primary triplite at Lord Hill suggests that, during its crystallization history, the pegmatite melt was saturated in P and F.

The presence of Li-alumosilicates, Li-phosphates and pollucite strongly supports at least moderate levels of Li and Cs fractionation within the SPG. The pegmatites along the northwestern margin of the SMD do not attain significant levels of Li and Cs enrichment relative to the remainder of the pegmatite population. Boron activity was high in the pegmatite melts as evidenced by ubiquitous tourmaline crystallization in many of the pegmatites and pegmatitic leucogranites. The level of F enrichment is low to moderate for much of the SPG, although high F manifests itself as F-rich topaz (F = 13 and 19 wt. %; Francis and Pittman 1995; Johnson 1998) and triplite-bearing assemblages in a few pegmatites.

5.2. The relation between the Sebago Pluton, SMD and the SPG

The Sebago pegmatites represent a diverse group of dikes characterized by barren pegmatites transitional to Be pegmatites with subordinate Ta and P mineralization, and complex Li-enriched pegmatites that host spodumene or petalite. Wise and Francis (1992) suggested that the SPG constitutes a regionally zoned pegmatite population around the apparently parental “Sebago Batholith”, however our fieldwork does not support their observations. The majority of pegmatites of the SPG intrude metasedimentary rocks of the CMB along the northern margins of the SMD. Along the northwestern margin of the SMD, the pegmatites are generally of the simple to slightly Be-enriched type; whereas pegmatites hosting Li mineralization are concentrated along the northeastern margin. Generally the SPG can be categorized as belonging to the rare-element class of LCT pegmatites of Černý and Ercit (2005) which presumably are related to a fertile *S*-type granite.

A small cluster of pegmatites within the northwestern part of the SPG exhibits chemical and mineralogical features more akin to the NYF geochemical family of granitic pegmatites that are typically affiliated with *A*-type granites generated in late-tectonic to anorogenic environments (Černý and Ercit 2005). The Lord Hill pegmatite, for example, contains topaz, fluorite, phenakite, and triplite. On the other hand, the Deer Hill, Intergalactic and Colton Hill pegmatites uniquely host amethyst which is generally absent in LCT pegmatite fields worldwide and considered by Brown (1999) to be representative of NYF family pegmatites. Differences between these pegmatites and the rest of the SPG may be attributed to different degrees of fractionation of a common parental melt, local contamination of pegmatite melts or derivation from a completely different source.

Our field observations indicate that many of the same textural features documented from worldwide fertile granites that are considered to be parental to populations of LCT rare-element granitic pegmatites (e.g., Yellowknife field, Northwest Territories, Canada, Meintzer et al. 1984; Greer Lake, Manitoba, Černý et al. 1981, 2005; Harney Peak granite, South Dakota, Shearer et al. 1987; Albuquerque Batholith, Spain, London et al. 1999; Kymi stock, Finland, Haapala and Lukkari 2005) have been identified in pegmatitic leucogranites of the Sebago area. Field investigations of these granites and pegmatites indicate that the fertile granite textural facies of Černý and Meintzer (1988) are prominently developed within small stocks of pegmatitic leucogranites that are best exposed within the metasedimentary rocks of the SMD and CMB along their northeastern contact. We also observed similar fluorapatite + albite-bearing units, aplitic pods with poikilitic schorl, and discontinuous bands of garnet in both the pegmatitic leucogranites and some of the neighboring pegmatite bodies (e.g., Bennett, Westinghouse, Pulsifer) which may signify a genetic connection. This, plus the close proximity of pegmatitic leucogranites to the SPG, provides additional evidence which supports these granites as being the likely source of the pegmatite population.

Outcrops of granite within the SMD may contain small, localized veins of texturally and mineralogically simple pegmatites. However these outcrops do not transition into pegmatitic textures and in no way resemble the features of the pegmatitic leucogranites observed in the outer margins of the SMD. This evidence implies, but does not confirm, that the two granite types are unrelated. Furthermore, the works of Tomascak et al. (1996b) and Solar and Tomascak (2009) do not indicate any direct relationship between granites of the Sebago Pluton and granites of the SMD.

The relationship between the Sebago Pluton, the SMD granites and the SPG remains unclear and requires further investigation. The composition of the main and accessory minerals indicates that the pegmatitic leucogranites are direct precursors to the majority of pegmatites of the SPG. Geochemical data also suggest that the pegmatites of the western portion of the SPG may be different from the rest of the pegmatite population. The unique mineralogy and geochemistry of the Lord Hill and amethyst-bearing pegmatites of the western part of the SPG implies that they could have originated from *A*-type granitic magmas in contrast to other pegmatites of the SPG which apparently evolved from *S*-type granitic magmas. However, anorogenic magmatism has not been documented in the western part of the pegmatite group and the nearest *A*-type granite occurs as part of the White Mountain Batholith located west of the SPG in New Hampshire. Additional investigation of the western SPG pegmatites and granites from the SMD and the White Mountain Batholith is needed in order to gain a better understanding of the origin and evolution of this part of the Sebago pegmatite population.

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