Graftonite - beusite is relatively widespread in the LCT family of granitic pegmatites of the Bothnian basin and of the Utti-Mysingen field in Sweden. It commonly constitutes the matrix containing either coarse lamellae of sarcopside, which in turn hosts fine lamellae of triphylite, or abundant lamellae of triphylite with bimodal size-distribution. Deformed and recrystallized granular aggregates of graftonite with triphylite, wolfeite and sarcopside are rare. Graftonite - beusite is systematically Ca,Mn-rich and Mg-poor relative to sarcopside, which in turn is slightly Mn-rich and distinctly Mg-poor relative to the Li-concentrating triphylite. Bulk compositions of the lamellar aggregates, crystal-chemical and textural relationships among the individual phosphates, and cation distribution-coefficients indicate two patterns of exsolution that generated the lamellar intergrowths from disordered homogeneous precursors: Ca,Li-poor graftonite exsolved lithian sarcopside, which in turn broke down to sarcopside with triphylite lamellae, and Ca,Li(Mn)-rich graftonite - beusite exsolved triphylite directly. In regional zoning of pegmatite groups, Ca-bearing graftonite - beusite is either the first Fe,Mn(Li)-phosphate encountered in the beryl-columbite pegmatites, or it is found within the zone of beryl-columbite-triphylite pegmatites. Appreciable concentrations of Ca, Fe, Mn (and in part Mg), but low levels of F and Na, are required to stabilize graftonite - beusite. Good correlation of the Mn/(Mn + Fe) values of the phosphates with those of garnet suggests that the homogeneous graftonite - beusite precursor could have been generated by phosphorus-induced destabilization of garnet.

Keywords: graftonite, beusite, triphylite, sarcopside, phosphates, exsolution, granitic pegmatite, regional zoning, Sweden.

Sommaire

La solution solide graftonite – béùsite est relativement répandue parmi les pegmatites granitiques de type LCT dans le bassin de Bothnie et dans le champ de Utò – Mysingen, en Suède. Un de ces minéraux forme l’hôte de lamelles substantielles de sarcopside, qui à son tour contient de fine lamelles de triphylite, ou bien des lamelles abondantes de triphylite dont la taille montre une distribution bimodale. Les agrégats déformés, recristallisés et granulaires de graftonite avec triphylite, wolfeite et sarcopside sont rares. La série graftonite – béùsite s’avère systématiquement enrichie en Ca et Mn, et appauvrie en Mg par rapport au sarcopside qui, à son tour, est légèrement enrichie en Mn et fortement appauvrie en Mg par rapport à la triphylite.

1 E-mail address: smeds@uppsala.mail.telia.com
2 Permanent address: Geological Institute of the Slovak Academy of Sciences, Dúbravská cesta 9, SK-842 26 Bratislava, Slovak Republic. E-mail address: geoluh@savba.savba.sk
3 E-mail address: cernyp@ms.umanitoba.ca
4 Present address: c/o 235 Knowles Avenue, Winnipeg, Manitoba R2G 1C8.
The main objectives of this study, complementary to the concurrent work of M.A. Wise (in prep.), are to establish the types of intergrowths of graffonite – beusite with other phosphates in the Swedish pegmatites, the composition of their component minerals and their bulk composition, to examine their origin, and to establish the position of graffonite – beusite on a regional scale of cogenetic pegmatite groups.

**INTRODUCTION**

Lamellar intergrowths of graffonite, \((\text{Fe,Mn,Ca})_3(\text{PO}_4)_2\), or beusite, \((\text{Mn,Fe,Ca})_3(\text{PO}_4)_2\), with sarcopside \((\text{Fe,Mn,Mg})_2(\text{PO}_4)_2\) or triphylite \(\text{Li(Fe,Mn)P}_4\) (or both) are a relatively rare component of granitic pegmatites. Occurrences of these phosphate intergrowths are known solely from the LCT family of pegmatites (peraluminous, derived mainly from S-type granites; cf. Černý 1991); they may be locally abundant, but are virtually missing in other populations of LCT pegmatites, which may be as extensive as entire pegmatite provinces.

The first (and for 20 years the only) locality of graffonite known in Sweden was the Berg pegmatite in the vicinity of Sollefteå (Lundqvist et al. 1990). The other localities in the Bothnian basin were identified by the first author during a prospecting program conducted in 1981–1986. In the same period, the fifth author found the first occurrences of graffonite in the Utö–Mysingen region, in outcrops along a field-trip path visited by many geologists over the past 200 years, and additional localities have been discovered since.

Although described in the literature from several occurrences in reasonable detail, the quantitative aspects of graffonite – beusite and their lamellar intergrowths with other phosphates are poorly understood, as is their position in the paragenetic evolution of individual pegmatites and regional populations of pegmatites. Thus the main objectives of this study, complementary to the concurrent work of M.A. Wise (in prep.), are to establish the types of intergrowths of graffonite – beusite with other phosphates in the Swedish pegmatites, the composition of their component minerals and their bulk composition, to examine their origin, and to establish the position of graffonite – beusite on a regional scale of cogenetic pegmatite groups.
volcanic units (Lundqvist et al. 1990). Felsic metavolcanic rocks yield an age of 1874 ± 6 Ma (U–Pb zircon; Welin 1987). During the Svecofennian orogeny, the metasedimentary rocks were intruded by early orogenic granitic plutons with minor gabbro, and subsequently folded and to a great extent migmatized. After the major phases of folding and metamorphism, they were intruded by numerous late-orogenic granite massifs, collectively named the Härnö granites. They constitute a peraluminous suite of biotite-, two-mica-, muscovite-, and commonly garnet-bearing bodies, formed 1822 ± 5 Ma ago (U–Pb, monazite) through partial melting of metagraywackes, with a probable contribution from early orogenic granitic lithologies (Claesson & Lundqvist 1990, 1995). The granites commonly evolve to a pegmatitic facies, and are typically accompanied by extensive schorl- and garnet-bearing pegmatitic granites and pegmatites. The
pegmatites yield U–Pb ages from columbite between 1803 and 1794 Ma (Romer & Smeds 1994, 1997).

Approximately 100 dikes of rare-element pegmatites are hosted by andalusite-grade terranes of the basin (Smeds 1990, 1992, 1993). The dikes commonly contain minerals of Sn or Li, or both. Phosphates of the graftonite–beusite series occur in five areas: Sollefteå, TJålmsjön – Rotbäcken, Räggen, Sidensjö – Hinnsjön and Bräntlandet (Figs. 2 to 5). The graftonite–beusite-bearing pegmatite bodies are poorly zoned to well differentiated, with fine-grained border zones coarsening (locally through graphic units) to intermediate zones and a blocky K-feldspar + quartz core, segregated in some cases into feldspathic, phosphate-bearing core-margin and quartz core proper. The beryl-type dikes that carry the Ca–Fe–Mn-rich phosphates (Table 2) are located either closely adjacent to the Härnö peraluminous granites and associated barren pegmatites (Sollefteå), or within the beryl + columbite + triphylite regional zone (Räggen, Sidensjö – Hinnsjön). In other cases, the relationships between granites and different categories of pegmatites are not clearly defined at the present level of erosion (TJålmsjön – Rotbäcken, Bräntlandet).
The Utö – Mysingen field

The bedrock of northern Utö (Fig. 6) comprises intricately folded Proterozoic metatuffitic rocks, associated with marble, skarn, oxide-facies iron formation, metasedimentary rocks and quartz porphyry (Stålhos 1982). The metasedimentary rocks are mainly well-preserved meta-argillites with muscovite, andalusite, cordierite and, locally, sillimanite. The sillimanite + cordierite + garnet-bearing metasedimentary rocks of the islets northwest of Utö Island, and of the southern part of the Utö – Nåttarö chain of islands, are migmatized; they represent the southeasternmost part of the mainland sillimanite + cordierite + garnet + K-feldspar migmatites of the Sörmland gneisses to the northwest (Stålhos 1982).

A fine- to medium-grained, mildly peraluminous and garnetiferous two-mica granite, the Mysingen granite, outcrops on some islets in Mysingen Bay (Fig. 6). The Runmaren pegmatitic granite, located between the Mysingen granite and the rare-element pegmatites of northern Utö, consists of a mélange of fine-grained aplite, medium-grained two-mica granite, pegmatitic granite with graphic K-feldspar + quartz, and discrete pods of blocky potassic pegmatite.

TABLE 2. PRIMARY ASSEMBLAGE OF GRAFTONITE BEARING-DIKES IN SWEDEN

<table>
<thead>
<tr>
<th>Berg</th>
<th>BrG</th>
<th>TIS</th>
<th>SID</th>
<th>RAG</th>
<th>Smeds</th>
<th>PRH</th>
<th>AhN</th>
<th>SMH</th>
<th>Ran</th>
<th>NRR</th>
<th>BTS</th>
<th>NTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Muscovite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Garnet*</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Schorl</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Beryl</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Zircon</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Spinel</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Rutile</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cazetrite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Columbite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Monazite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Triphylite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Graphite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Beusite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sarcopside</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Rutile</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Columbite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Monazite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Triphylite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Graphite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Beusite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sarcopside</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Rutile</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Triphylite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Apatite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Zwieselite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Amblygonite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sulfides</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>sulfosilicates</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

On the islets adjacent to and on the northwestern shore of northern Utö, bodies of school-bearing pegmatite exhibit textural features of a pegmatitic granite similar to those of the Runmaren intrusion. The most fractionated pegmatites of the region reside inside the northern part of Utö. Thus the pegmatites of the Utö – Mysingen field, dated at 1822–1815 Ma (U–Pb columbite: Romer & Smeds 1994) can be divided into four regional zones (Smeds & Černý 1992). From northwest to southeast, the zones consist of the (1) barren pegmatites in the Mysingen granite, (2) barren pegmatites in the Runmaren pegmatitic granite, (3a) pegmatite dikes with schorl + beryl + columbite + (Fe,Mn,Ca)-phosphates + triphylite, subparallel but discordant to the NE-trending foliation of the paragneissesa, (3b) dikes containing schorl – columbite – triphylite subparallel but discordant to the north-easterly trending main foliation of the metatuffitic formation, and also discordant in the east–west direction, and (4) the Li-rich pegmatites of Utö at Nyköping-sgruvan with Li-aluminosilicates and pollucite, plus some other dikes (Smeds & Černý 1989, Teertstra et al. 1996), all discordant in the east–west direction to the metamorphic host-rocks.

In the southern part of the Utö archipelago (Utö sensu lato), the pegmatites correlate with the above-mentioned zone 3a. Two distinct bodies of pegmatitic granite are known in this region, the Mälsten and Sandskär intrusions, with associated pegmatite populations that tend to be slightly zoned down the regional metamorphic gradient to the southeast.
All graftonite-bearing pegmatites are confined to the zone 3a. They can roughly be described as poorly zoned assemblages of leucogranite, sodic aplite, aplite with blocky K-feldspar units, units of graphic K-feldspar + quartz megacrysts in leucogranitic matrix, and blocky quartz + K-feldspar. This last unit of potassic pegmatite pods carries the phosphates. The Norro quarry (Eriksson 1946) is the only exception, containing a zone with cassiterite, amblygonite and other phases indicative of a perceptibly higher level of fractionation (Nysten & Gustafsson 1993).

General

Summarizing the above observations, we can conclude that the graftonite–beusite-based intergrowths are found as irregular nodules in blocky pods of K-feldspar + quartz (± book muscovite, albite to oligoclase), or locally in the adjacent intermediate unit of the parent pegmatites. Textural relationships indicate that the nodules enclose microscopic monazite-(Ce), and crystallized simultaneously with the adjacent quartz, feldspars and muscovite. Wolfeite, zwieselite, ferroan wagnerite and fluor- (to hydroxyl-)apatite are the most commonly associated phosphates, locally with minor pyrite, arsenopyrite and (locally Cd-rich) sphalerite. The phosphates are found mainly along margins of the graftonite – beusite nodules. They apparently formed later than the graftonite – beusite, as also shown by local replacement of this phase by veinlets and dendritic aggregates of wolfeite.

Most of the phosphates were affected by secondary alteration, which generated minerals of the alluaudite group and ferrisicklerite – sicklerite series, rarely arrojadite, phosphoferrite – reddingite, and probable ludlamite. However, the secondary phosphates are beyond the scope of this study.

EXPERIMENTAL METHODS AND TREATMENT OF THE DATA

Electron-microprobe analyses of the phosphates were carried out in the wavelength-dispersion mode on a Cameca SX–50 instrument, with beam diameter of...
1–2 μm and an accelerating potential of 15 kV, a sample current of 20 nA and a counting time of 20 s (40 s for F). The following standards were used: fluorapatite (for PKα, CaKα, FKα), almandine (FeKα), spessartine (MnKα), forsterite (MgKα) and gahnite (ZnKα). The following trace elements (<0.1 wt.% of oxide) were sought but not detected: Si (Kα, diopside), Al (Kα, pyrope), Sr (Lα, SrBa2Nb9O12), Ba (Lα, NaBa2Nb9O12), Ba (Kα, NaScSiO4), Y (Lα, YAG), La, Ce and Nd (Lα, monazite), Na (Kα, albite), K (Kα, orthoclase) and Cl (Kα, tugtupite). Data were reduced using the PAP routine of Pouchou & Pichoir (1985).

Electron-microprobe analyses of the associated garnet were performed under conditions listed in Teertstra et al. (1996).

The conditions for the ICP (inductively coupled plasma) and INA (instrumental neutron-activation) analysis of K-feldspar from the Räggen and Sidensjö areas are quoted in Smeds (1992), those for the feldspar samples from the other occurrences in the Bothnian Basin and the Utö – Mysingen field are given in Černý et al. (1984).

The identities of the examined phosphates were verified by X-ray powder diffraction, using a Philips PW 1710 diffractometer.

Modal analyses were carried out with a Kontron–IBAS image-analysis system, using the differences in brightness of the back-scattered-electron images between garnetite or sarcopside and triphylite, or the differences in Ca distribution between Ca-rich garnetite and Ca-poor sarcopside. Areas of the scanned fields were in the range 16.8–88.6 mm². Some of the modal data are subject to experimental error introduced by the presence of alteration products indistinguishable from the primary phases. This is particularly noticeable in the analysis of triphylite lamellae in sarcopside, which were represented by the dark products of their oxidation and whose proportion is commonly low, thus increasing the relative error.

Densities of the phosphates, required for calculation of bulk composition of the intergrowths, were taken or interpolated from the literature. The microscopic scale of the aggregates made attempts at measurement of densities impractical. However, any error introduced in the density data is probably much smaller than the error involved in the modal analysis.

**TEXTURAL RELATIONSHIPS**

Three types of phosphate intergrowths involving garnetite – beusite were observed: (i) garnetite – beusite with lamellae of sarcopside, which in turn host lamellar triphylite, (ii) garnetite – beusite enclosing lamellae of triphylite, and (iii) granular aggregates of garnetite, triphylite and wolfeite.

**Graftonite – beusite + sarcopside + triphylite**

Graftonite – beusite is the principal host phase in these intergrowths. Sarcopside commonly forms a single set of subparallel platy lamellae, 30 to 500 μm thick. The lamellae are somewhat irregular in shape, with local bulges, constrictions and multipronged splits, but overall they are fairly straight in all sections observed (Fig. 7A). The individual lamellae, enclosed in extensive monocrystalline volumes of the garnetite – beusite host, commonly share a uniform optical orientation. A granular texture within the lamellae or the host phase is rare, and is associated with incipient deformation.

Triphylite constitutes one set (rarely, two sets) of lamellae 10 to 50 μm thick, hosted almost exclusively by sarcopside (Figs. 7A, B). The only triphylite observed in the surrounding garnetite – beusite represents straight but short extensions of the sarcopside-hosted lamellae, restricted to only the most immediate vicinity of sarcopside. The triphylite lamellae are usually flat and slightly lenticular, gradually tapering out toward their terminations. They typically pinch out at the boundary of sarcopside with garnetite – beusite, and swell inward (Figs. 7A, B). The triphylite lamellae are extensively altered to minerals of the ferrisicklerite – sicklerite series, but the electron-microprobe data on fresh relics identify triphylite as the primary phase.

**Graftonite – beusite + triphylite**

In this type, garnetite – beusite hosts three types of triphylite lamellae. A single set of platy lamellae between 100 and 1000 μm thick is most common (Fig. 7C); the lamellae are straight to gently sinuous. This type is routinely accompanied by much finer lamellae of the same orientation, between 5 and 50 μm thin. Locally, the difference between the two varieties is blurred by gradual change in size, but in most cases, the difference is quite distinctive (Fig. 7C). Accicular to rod-shaped individuals of triphylite, elongate parallel to the lamellae, constitute the third variety. They vary considerably in size, from ~30 × 40 to ~200 × 500 μm in cross section, flattened parallel to the associated lamellae of the first and second types (Fig. 7D).

An optical examination reveals that the individual lamellae of triphylite are monocrystalline in all three textural types. The optical orientation of platy triphylite is largely uniform over large volumes of garnetite – beusite, but the acicular to rod-shaped triphylite commonly shows a distinctly different orientation. Undulose extinction of the lamellae is locally widespread, and is occasionally transitional into randomly oriented subgrains. Extensive granular aggregation, which also disturbs the otherwise smooth contacts with garnetite – beusite, seems to be restricted to phosphate nodules affected by deformation. In these
Fig. 7. Back-scattered-electron images of the graftonite–beusite-based intergrowths. A. Graftonite with coarse and bifurcating lamellae of sarcopside, which contain thin, in part oxidized lamellae of triphylite (black); Berg. B. Detail of oxidized triphylite lamellae (black) in sarcopside, tapering off toward the contact of sarcopside with graftonite (left side); Berg. C. Coarse and fine lamellae of triphylite (black) in graftonite; Bötsudden. D. Lamellae and rods of triphylite (black) in graftonite; Bötsudden. E. Granular aggregate of graftonite, triphylite and wolfeite, rimmed by apatite (dark grey); Räggen GDB. F. Detail of E, showing variable composition of the graftonite (shades of medium grey); Räggen GDB. Scale bars represent 500 μm in A, C, D and E, 100 μm in B, and 50 μm in F.
cases, the normally single-crystal graftonite – beusite host also may show a granular texture.

Granular aggregates

As mentioned above, granular aggregates are rarely observed, and only on a microscopic scale in phosphates affected by deformation. The single distinct exception is the phosphate nodule from Råggen. It is mainly granular, and consists of an intimate mixture of graftonite, triphylite, rare sarcopside, and wolfeite, rimmed by apatite. Graftonite is the dominant phase, coarser-grained than the subordinate triphylite and wolfeite (≤150 and ≤70 μm, respectively). The fabric of the aggregate shows distinct preferred orientation of the constituent grains, suggestive of stress-controlled crystallization (Figs. 7E, F). A strikingly undulose extinction of the individual grains, shear zones, and kinking of associated muscovite also indicate stress-induced deformation. A lamellar intergrowth of graftonite and triphylite was encountered only in a single small aggregate.

### Table 3. Representative Chemical Compositions of Phosphates in the Lamellar Graftonite-Beusite+Sarcopside+Triphylite Intergrowths from Swedish Pegmatites

<table>
<thead>
<tr>
<th></th>
<th>BRG</th>
<th>BRL</th>
<th>AHN</th>
<th>NRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt.%</td>
<td>Gra</td>
<td>Sar</td>
<td>Tph</td>
<td>Gra</td>
</tr>
<tr>
<td>P2O5</td>
<td>40.40</td>
<td>40.19</td>
<td>45.47</td>
<td>40.89</td>
</tr>
<tr>
<td>FeO</td>
<td>24.84</td>
<td>39.34</td>
<td>27.53</td>
<td>45.20</td>
</tr>
<tr>
<td>MnO</td>
<td>24.26</td>
<td>11.40</td>
<td>19.94</td>
<td>10.91</td>
</tr>
<tr>
<td>MgO</td>
<td>0.88</td>
<td>2.35</td>
<td>0.66</td>
<td>1.84</td>
</tr>
<tr>
<td>CaO</td>
<td>7.69</td>
<td>0.00</td>
<td>0.00</td>
<td>10.07</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.09</td>
<td>0.00</td>
<td>0.00</td>
<td>0.24</td>
</tr>
<tr>
<td>Li2O</td>
<td>-</td>
<td>9.70</td>
<td>-</td>
<td>9.57</td>
</tr>
<tr>
<td>SUM</td>
<td>98.36</td>
<td>97.90</td>
<td>98.81</td>
<td>98.97</td>
</tr>
</tbody>
</table>

Atomic contents normalized to 8 oxygen atoms. *calculated by charge-balancing for 8 oxygen atoms and a fixed content of 2 lithium atoms. Locality acronyms: see Table 2; other symbols: see Table 3.

### Table 4. Representative Chemical Compositions of Phosphates in the Lamellar Graftonite – Triphylite Intergrowths from Swedish Pegmatites

<table>
<thead>
<tr>
<th></th>
<th>TJS</th>
<th>SID</th>
<th>PRH</th>
<th>RAN</th>
<th>BTS</th>
<th>NTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt.%</td>
<td>Gra</td>
<td>Sar</td>
<td>Tph</td>
<td>Gra</td>
<td>Sar</td>
<td>Tph</td>
</tr>
<tr>
<td>P2O5</td>
<td>40.93</td>
<td>45.73</td>
<td>45.90</td>
<td>41.12</td>
<td>47.91</td>
<td>41.54</td>
</tr>
<tr>
<td>FeO</td>
<td>24.94</td>
<td>34.34</td>
<td>25.92</td>
<td>21.38</td>
<td>24.21</td>
<td>28.64</td>
</tr>
<tr>
<td>MnO</td>
<td>18.17</td>
<td>7.60</td>
<td>18.47</td>
<td>24.18</td>
<td>12.31</td>
<td>17.14</td>
</tr>
<tr>
<td>MgO</td>
<td>0.44</td>
<td>0.13</td>
<td>0.34</td>
<td>1.13</td>
<td>4.79</td>
<td>1.95</td>
</tr>
<tr>
<td>CaO</td>
<td>9.50</td>
<td>0.06</td>
<td>0.00</td>
<td>10.86</td>
<td>0.02</td>
<td>9.52</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.04</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Li2O</td>
<td>-</td>
<td>9.58</td>
<td>-</td>
<td>9.60</td>
<td>-</td>
<td>9.89</td>
</tr>
<tr>
<td>SUM</td>
<td>98.71</td>
<td>99.32</td>
<td>98.44</td>
<td>100.34</td>
<td>98.68</td>
<td>99.13</td>
</tr>
</tbody>
</table>

Atomic contents normalized to 8 oxygen atoms. *calculated by charge-balancing for 8 oxygen atoms and a fixed content of 2 lithium atoms. Locality acronyms: see Table 2; other symbols: see Table 3.
TABLE 5. REPRESENTATIVE CHEMICAL COMPOSITIONS OF PHOSPHATES IN THE GRANULAR INTERGROWTHS

<table>
<thead>
<tr>
<th>wt. %</th>
<th>Gra</th>
<th>Gra</th>
<th>Tph</th>
<th>Wol</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2O5</td>
<td>40.85</td>
<td>41.60</td>
<td>46.52</td>
<td>31.94</td>
</tr>
<tr>
<td>FeO</td>
<td>24.01</td>
<td>20.78</td>
<td>32.32</td>
<td>39.27</td>
</tr>
<tr>
<td>MnO</td>
<td>22.21</td>
<td>20.37</td>
<td>10.74</td>
<td>20.14</td>
</tr>
<tr>
<td>MgO</td>
<td>0.21</td>
<td>0.09</td>
<td>1.11</td>
<td>0.96</td>
</tr>
<tr>
<td>CaO</td>
<td>10.47</td>
<td>15.33</td>
<td>0.21</td>
<td>0.16</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.27</td>
<td>0.10</td>
<td>0.11</td>
<td>0.21</td>
</tr>
<tr>
<td>Li2O</td>
<td>-</td>
<td>-</td>
<td>9.70</td>
<td>-</td>
</tr>
<tr>
<td>H2O</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.97</td>
</tr>
<tr>
<td>SUM</td>
<td>98.04</td>
<td>98.27</td>
<td>100.71</td>
<td>96.65</td>
</tr>
</tbody>
</table>

Atomic contents normalized to 8 oxygen atoms;
1 calculated by charge-balancing for 8 oxygen atoms and a fixed content of 2 lithium atoms;
2 calculated by charge-balancing for 5 oxygen atoms and a fixed content of 1 H⁺.

RAG=Råggen, Wol=wolfeite. Other symbols: see Table 3.

Fig. 8. Compositions of graftonite (Gra), sarcopside (Sar) and triphylite (Tph) in the Fe – Mn – Mg and Fe – Mn – Ca (at.) diagram, averaged per locality or per specific sample (see Table 1 for locality acronyms). A. Compositions of phosphates composing the graftonite + sarcopside + triphylite intergrowths (in the Ca diagram, the virtually Ca-free sarcopside and triphylite plot collectively within the ranges indicated by heavy bars along the Fe–Mn sideline). B. Compositions of phosphates composing the graftonite – beusite + triphylite intergrowths.

CHEMICAL COMPOSITION OF THE MINERALS

Representative compositions of graftonite, beusite, sarcopside, triphylite and wolfeite are shown in Tables 3, 4 and 5.

Compositions of individual phases

Minerals of the graftonite – beusite series belong in most cases to graftonite proper, but a few samples from Persholmen, Sidensjö and Berg are slightly Mn-dominant and are classified as beusite. The Ca content varies from 11 to 32 mol.% Ca3(PO4)2. The Mg content is highly variable but moderate; it tends to show modestly positive correlation with Ca. Zinc is the only minor element detected in some samples in quantifiable concentrations.

Sarcopside invariably shows Fe dominant over Mn. The Mg content is variable and generally high, attaining on average 20 mol.% of Mg3(PO4)2 at Persholmen. In contrast, Ca and Zn contents are negligible.

Triphylite also is Fe-dominant in all samples examined. Calcium and Zn contents are as low as in sarcopside, but the Mg content is in some cases very high, up to 37 mol.% of the LiMgPO4 component at Bötssudden.
Wolfeite from Räggen is strongly Fe-dominant, and its F content is below the detection limit under the conditions of routine electron-microprobe analysis (0.3 wt%); thus the mineral seems to represent a virtually pure (OH) end-member. The Mg and Ca contents are minor, <3 mol.% Mg₂(P₈O₁₆)(OH) and <0.25 mol.% Ca₂(P₂O₇)(OH).

Cation partitioning among coexisting phases

In the graftonite–beusite–sarcopside triphylite intergrowths shown in Figure 8A, graftonite–beusite shows strong preference for Mn, whereas both sarcopside and triphylite are Fe-rich. Graftonite also concentrates Ca, to its virtual exclusion from the other two phosphates. In contrast, Mg is strongly preferred by triphylite; sarcopside and particularly graftonite–beusite are Mg-poor.

Figure 8B shows the compositional relationships in the graftonite + triphylite intergrowths. They are very close to those observed between these two minerals in the lamellar intergrowths, in which graftonite shows strong preference for Ca and Mn, whereas triphylite concentrates Fe and Mg.

The cation distribution between graftonite and triphylite in the granular aggregates from Räggen is analogous to that observed in the lamellar intergrowths, in particular to that shown in Figure 8B for the Täljämsjön compositions. However, the Räggen graftonite is distinctly heterogeneous (Table 5), and the cation partitioning may be affected by the presence of wolfeite. Also, grains of different phases that may represent minerals coexisting at a very local scale are difficult to identify. Thus the Räggen compositions were not included in quantitative aspects of partitioning.

Table 6 shows the distribution coefficients for the major cations (except Li) in coexisting graftonite–beusite, sarcopside and triphylite. As suggested by the graphic representation of the phosphates compositions in Figure 8, the distribution coefficients are in most cases quite uniform across diverse localities, with only small deviations from average values. This applies to Kᵢ values of Fe and Mn, in particular; the Kᵢ values also are statistically identical for corresponding pairs of minerals in both types of intergrowths. In contrast, Kᵢ for Mg displays a much broader spread of values.

Bulk compositions of the intergrowths

Table 7 shows the modal proportions of selected intergrowths of phosphates that were considered suitable for image analysis, and the bulk compositions calculated from the compositions, modes and densities of the individual phases. Figure 9 summarizes the relationships between the compositions of the composite minerals and the calculated bulk-compositions of the intergrowths.

The bulk composition of the graftonite + sarcopside + triphylite intergrowths is variable in terms of the Ca and Li contents, controlled by the proportions of graftonite–beusite and triphylite, respectively. The cation contents of the bulk compositions normalized to 8 atoms of oxygen total very close to 3, as the two main phases have the same stoichiometry, R₂•3P₂O₈. The slight excess of cations is proportional to the content of graftonite–beusite and sarcopside in the intergrowths.
Li, hosted by triphylite LiR²⁺PO₄ with a higher cation:oxygen ratio. This excess of cations, close to 50% of the total Li determined, is enhanced in the bulk compositions of the subsystem sarcopside + triphylite, in which the proportion of triphylite lamellae is increased relative to that of their sarcopside host.

In contrast to the preceding cases, the phase proportions in the graftonite + triphylite intergrowths are very similar in three out of four analyzed samples, but the ratio (Fe,Mn,Mg)/Ca is distinctly different. The above-mentioned type of cation excess, equal to 50% of the total Li present, is very prominent in these intergrowths.

Level of Fractionation of the Graftonite–Beusite-Bearing Pegmatites

Two geochemical aspects of the environments generating graftonite – beusite are of interest: (i) the K/Rb value of K-feldspar indicative of the general grade of geochemical evolution of pegmatites, which decreases from barren to lithium-enriched dikes, and (ii) the Mn/(Mn + Fe) value of garnet as the main ferromangananoan phase consistently present in the phosphate-bearing pegmatites.

The K/Rb value of blocky K-feldspar is somewhat variable among the various graftonite–beusite-bearing pegmatites. The overall variation extends from 78 to 234, but the ranges are smaller in individual dikes (Table 8). The data are intermediate relative to the ranges shown by the total zoned populations of the parent pegmatite groups, which is consistent with the intermediate location of the phosphate-bearing pegmatites in the regional zoning patterns.

Geochemical data from a single locality provide the only information about the relationship between the graftonite – beusite + sarcopside + triphylite and graftonite – beusite + triphylite intergrowths. At St. Persholmen, the first type [with Mn/(Mn + Fe) of 0.40 to 0.38 for graftonite and 0.18 to 0.17 for sarcopside] was found in a blocky pod with K/Rb of the K-feldspar varying from 234 to 196, whereas the second type [with Mn/(Mn + Fe) of 0.55 to 0.51 for beusite and 0.40 to 0.28 for triphylite] is hosted by another pod in which the K-feldspar has a K/Rb value of 114 to 102. The higher degree of alkali fractionation in the K-feldspar correlates with the Mn- and Li-enriched, Fe-depleted phosphates.

Correlation of Mn/(Mn + Fe) in garnet with that of the graftonite–beusite-based intergrowths is somewhat complicated. In some of the pegmatite bodies examined, garnet is found in the blocky core-margin assemblages, but usually separate from the phosphate nodules; it was found in contact with the phosphates only in one occurrence, at Nåttarö. In other dikes, garnet occurs only in the outer zones, characterized by a granitic to aplitic texture. As garnet commonly undergoes enrichment in Mn relative to Fe during the course of solidification of individual pegmatite bodies, compositional correlation with the phosphates located in separate units is rather tenuous. Also, the systematic differences in Mn/(Mn + Fe) between the individual phases of the phosphate
Table 8 Fractionation Indicators in Phosphates, Garnet, and Blocky K-Feldspar from the Graftonite-Beusite Bearing Pegmatites of Sweden

<table>
<thead>
<tr>
<th>Phosphates</th>
<th>Garnet</th>
<th>K-feldspar</th>
</tr>
</thead>
<tbody>
<tr>
<td>graftonite</td>
<td>sarcopside</td>
<td>triphylite</td>
</tr>
<tr>
<td>K/Rb</td>
<td>K/Rb</td>
<td></td>
</tr>
</tbody>
</table>

**Mn/(Mn+Fe)**

- Berg: 0.41-0.51, 0.26-0.32, 0.26-0.32, 0.40-0.50, 0.36-0.38
- Brittiandet: 0.39-0.42, 0.20-0.23, 0.18-0.19
- Råggen, GDB: 0.33-0.49, 0.20-0.21, 0.16-0.30
- Sidensjö beusite peg: 0.57-0.60, 0.40-0.44
- Tjälmsjön: 0.38-0.42, 0.17-0.21, 0.37-0.39
- Stora Persholmen: 0.38-0.36, 0.17-0.19, 0.28-0.39, 0.24-0.26
- Angsholmarna: 0.36-0.49, 0.16-0.19, 0.13-0.25, 0.37-0.38
- Norra Smedshjäll: 0.40-0.43, 0.20-0.22, 0.15-0.16, 0.24-0.25
- Råne: 0.41-0.47, 0.20-0.22, 0.17-0.23
- Norrö: 0.36-0.39, 0.17-0.22, 0.14-0.21, 0.33-0.35
- Bötsudden: 0.38-0.46, 0.26-0.28, 0.15-0.26, 0.36-0.38
- Nätårö: 0.47-0.52, 0.27-0.31, 0.31-0.34

All data in wt.% ratios; * garnet coexisting with graftonite.

Discussion

Crystal-chemical relationships of the phosphates

The composition of the monoclinic graftonite – beusite (Ca,Fe,Mn)₃(PO₄)₂ is very variable in terms of Mn/(Mn + Fe), Ca content (0 to 0.98 Ca atoms per formula unit, apfu), and Mg content. The largest of the three cation sites, M₁, accommodates preferentially Ca in the sequence Ca > Mn > Fe; coordination decreases with diminishing Ca content from 8- to 6-fold, tending to 5-fold (Calvo 1968, Wise et al. 1990, Steele et al. 1991). The M₂ site is 5-fold-coordinated and prefers Fe (Nord & Ericsson 1982), whereas M₃ is 6- to 5-fold coordinated and is the second choice for Mn (after M₁), at least in Ca-free phases. The structure contains open interstices that could accommodate additional cations of small to medium radius (less than or equal to ~0.70 Å).

The composition of triphylite (– lithiophilite) Li(Fe,Mn)PO₄ is less variable relative to graftonite – beusite, complicated only by a largely subordinate Mg substitution for (Fe,Mn). The orthorhombic structure corresponds to that of an olivine or, more specifically, monticellite (Finger & Rapp 1970), based on octahedrally and tetrahedrally coordinated sites within a hexagonally closest-packed array of oxygen atoms.

Natural sarcopside (Fe,Mn,Mg)₃(PO₄)₂ is Mn-poor, and its Mg content varies considerably but is minor. The stoichiometry of sarcopside is identical with that of graftonite – beusite, but the mineral is isotypic with triphylite – lithiophilite (Mrose & Appleman 1961, Moore 1972). The only structural difference is a slight monoclinic distortion, and ordered vacancies in 50% of the M₁ octahedral positions; thus the derivation of triphylite from sarcopside is achieved by the substitution Li⁺(Fe²⁺)⁺₁. Sarcopside can be considered a polymorph of Ca-free graftonite, which is so far known only from meteorites (Steele et al. 1991).

In contrast to the above relationships, graftonite – beusite and triphylite differ in both structure and stoichiometry. However, Li can be accommodated in the M₂ sites of graftonite – beusite and in adjacent interstices by the substitution Li⁺(Fe²⁺)⁺₁, as suggested by Moore (1982) and confirmed by M.A. Wise (in prep.).

Origin of the graftonite–beusite-based intergrowths

The phosphate intergrowths have been interpreted in three ways: (i) exsolution was advocated by Peacor & Garske (1964), Hurlbut (1965) and Hurlbut & Aristarain (1968) for graftonite + sarcopside, Peacor
(1969) for sarcopside + triphylite, Fransolet (1977) for sarcopside + triphylite, Wise & Černý (1990) for (ggraftonite–) beusite + triphylite, and by Moore (1972) for all of these cases; (ii) metasomatic replacement was favored by Fransolet (1977), except for the case of sarcopside in triphylite, and Malló et al. (1995) for triphylite + sarcopside; (iii) simultaneous crystallization was considered a possibility for quasi-graphic or “pegmatitic” textures by Peacock (1969), Huvelin et al. (1971) and Fransolet (1977). However, the work of Wise (in prep.) and our results confirm exsolution as the exclusive process, as far as lamellar intergrowths are concerned.

In the *g*raftonite–*beusite* + *sarcopside* + *triphylite* aggregates, exsolution proceeds in two stages: a homogeneous precursor unmixes to graftonite–beusite + lithium sarcopside, and triphylite exsolves from the lithium sarcopside. Textural relationships and stoichiometry, subparallel orientation of tie-lines connecting the compositions of coexisting phases (Fig. 8A) and uniform distribution-coefficients (Table 6) in various bodies of pegmatites, indicative of local equilibrium among the intergrown phosphates, all clearly point to exsolution of lithium sarcopside from graftonite–beusite. This interpretation also is supported by crystallographic control of orientation in graftonite + sarcopside intergrowths (Hurlbut 1965). Experimental work strongly suggests that sarcopside may be stable only at low subsolidus temperatures, as it is routinely generated under hydrothermal conditions at 500 to 300°C from a graftonite–beusite phase synthesized at ~800°C (Ericsson et al. 1986, Charalampides et al. 1988). A high-temperature, homogeneous, and relatively Ca,Mn-poor, Fe,Mg-enriched, Li-bearing graftonite phase evidently crystallizes in natural assemblages, probably with a highly disordered structure. This primary precursor exsolves into a Ca,Mn-enriched, Li-free graftonite host with virtually Ca-free, Fe,Mg-enriched and Li-bearing lamellae of disordered sarcopside (Wise, in prep.). The subsequent exsolution of triphylite from Li-bearing sarcopside concludes the overall trend toward stoichiometric and structurally ordered low-temperature phases.

For the graftonite–beusite + triphylite intergrowths, single-stage exsolution is supported by uniform distribution-coefficients of cations (Table 6), subparallel arrays of tie-lines connecting coexisting phases (Fig. 8B), inverse correlation between size and density of distribution of triphylite lamellae (Figs. 7C, D), and a structurally controlled orientation of the intergrown phosphates (Hurlbut & Aristarain 1968, Wise & Černý 1990), rarely violated by either incoherent nucleation of the precipitate or recrystallization. The homogeneous precursor must have been again a graftonite–beusite-like phase, but in most cases richer in Ca and generally much more enriched in Li relative to the lithian-sarcopside-exsolving phase above (Fig. 9). The Li incorporation attained up to 42% of the *M*2 site population in the homogeneous parent (Table 7, PRH), which subsequently exsolved triphylite.

**Graftonite–beusite in the regional zoning of pegmatite populations**

The graftonite–beusite series and the exsolved sarcopside are among the geochemically most primitive phosphates of the rare-element pegmatites, exhibiting moderate to high contents of Ca and Mg. Consequently, in regional zoning of co-genetic pegmatite groups of the LCT family (Fig. 10), graftonite–beusite should signal the onset of the beryl–columbite–phosphate subtype, developing outward from the beryl–columbite category (Trueman & Černý 1982, Černý 1991). The exsolution lamellae of triphylite would then represent the first Li-bearing phase, preceding discrete grains of triphylite, which in turn precede the appearance of lithium silicates (Moore 1982). Unfortunately, there is virtually no information available about the regional setting of the reported graftonite–beusite occurrences in the literature. Meintzer (1987) and Wise & Černý (1990) reported the beusite + triphylite intergrowth from the inner boundary of triphylite occurrences within the beryl–columbite (–phosphate) zone of the PEG group, Yellowknife field, with most of the triphylite localities spread outward, including the outermost zone of spodumene-bearing pegmatites. The occurrences of graftonite in the pegmatite field of the southern Black Hills, in South Dakota, reside in the beryl–columbite–phosphate pegmatites, exterior to the parent granite and to the immediately adjacent barren pegmatites.

In the Swedish pegmatite populations studied here, two patterns of the graftonite–beusite position in zoned pegmatite populations can be distinguished. In some cases, the graftonite–beusite-based intergrowths are the first Fe,Mn-phosphates encountered in the beryl-type pegmatites, before the appearance of discrete triphylite. In other terranes, graftonite–beusite is found within the regional zone of beryl–columbite–triphylite pegmatites.

The first case is best exemplified by the Uto–Mysingen field. It is well documented in the Runmare group, and also suggested in the southern Mälsten–Sandskär group (Smeds et al. 1996). A narrow zone of beryl–columbite–graftonite–beusite pegmatites follows after barren dikes, whereas pegmatites with discrete triphylite are disposed still farther to the southeast (Fig. 6). The same pattern is shown at Sollefttä; the Berg pegmatite is closely adjacent to (or within) a pegmatitic granite, but the triphylite-bearing dikes are ~8–10 km to the west (Fig. 2).

In contrast, the Räggen graftonite-bearing dike is well within the beryl–columbite–triphylite regional zone of a well-zoned pegmatite group, despite the uncertain provenance of the drift boulder that represents the GDB locality (Fig. 4). The erosional surface exposes here a section through the regional zoning
The stabilization of the homogeneous precursors of the intergrowths requires appreciable enrichment of Ca and Mg, and low concentrations of F and Na, to prevent crystallization of apatite, wyllieite, fillowite, griffithite, wagnerite or triplite – zwieselite. Such conditions are encountered in relatively poorly evolved pegmatite-forming melts, generating oligoclase-bearing beryl – columbite pegmatites. However, these conditions are inconsistent with more fractionated pegmatites, particularly those hosting the Mn-dominant beusite. Very localized depletion in F may be responsible for these cases, although coexistence of beusite with F-bearing triplite and Na-bearing fillowite is locally observed (Černý et al. 1998). At the Swedish localities, a late increase in F and Na generates rims of fluorapatite, zwieselite and ferroan wagnerite around the graftonite–beusite-based intergrowths.

In view of the general character of the graftonite–beusite-bearing pegmatites, their overall level of fractionation should be moderate. This is well borne out by the K–Rb data on blocky K-feldspar (Table 8). Note that the feldspar of the beusite-bearing pegmatites usually shows somewhat lower K/Rb values, and that the regional zoning of the pegmatite groups with beusite commonly extends into spodumene- or petalite-bearing dikes. This applies not only to the Swedish pegmatite populations examined here (Sidensjö – Hinnsjön, Runmaren), but also to other terranes (Los Aleros in Argentina: Hurlbut & Aristarain (1968); Kitee – Tohmajärvi, southeastern Finland: Kallio & Alviola (1975); Eriijärvi, southern Finland: Lahti (1981); PEG group in the Yellowknife field: Wise (1987, Wise & Černý 1990); Turkestan Range: Beus (1950)). However, exceptions are documented from several terranes (Anderson et al. 1998, Černý et al. 1998); differential depth of erosion affecting individual pegmatite groups may play a significant role here.

London et al. (1995) examined silicate – phosphate equilibria in peraluminous pegmatite-forming melts and established a reaction relationship involving biotite, which converts with increasing P content to equivalent Fe–Mn–Mg phosphates (such as triplite, graftonite –

---

**FIG. 10.** Schematic distribution of graftonite–beusite occurrences in regional zoned populations of granitic pegmatites. Heavy arrow shafts: main distribution, heavy dashes: local extensions, light dashes: relatively rare extensions of the main ranges.
sarcopside, triphylite – lithiophilite) at -0.8 wt.% P₂O₅ in the melt. They also documented a reaction of spessartine (– almandine) to mangananapatite, beusite or the above phosphates at -0.4 to <2.0 wt.% P₂O₅ in the melt, with the higher values associated with the Fe-bearing phosphates. Our compositional data indicate that the precursors of the graftonite–beusite-based intergrowths were generated by local phosphorus-induced destabilization of garnet. Except for a single case in the Nättårö pegmatite, the phosphate nodules occur separated from garnet, and the Mn/(Mn + Fe) value of the broadly associated garnet is close to or overlaps that of the phosphate intergrowths.

**CONCLUSIONS**

(1) Phosphates of the graftonite – beusite series are found in twelve bodies of the LCT-family pegmatites of the Bothnian basin and of the Utö – Mysingen field, in north-central and south-central Sweden, respectively. They constitute a matrix hosting either coarse lamellae of sarcopside, which themselves contain finely lamellar triphylite, or abundant lamellae of triphylite with a bimodal size-distribution. Deformed and recrystallized granular aggregates of graftonite with triphylite, wolfeite and rare sarcopside were encountered at a single locality.

(2) The graftonite – beusite matrix is invariably Ca- and Mn-rich, whereas sarcopside is virtually Ca-free and Mn(Fe)-enriched; triphylite also is Ca-free and shows an even stronger preference for Fe and particularly Mg.

(3) Crystal-chemical relationships among the above phosphates show a diversity of structural and stoichiometric relationships that indicate solid-solution potential for triphylite in sarcopside, lithian sarcopside in graftonite – beusite, and triphylite in graftonite – beusite. Voids in the graftonite – beusite structure can accommodate half of the Li required for the Li₂⁺ substitution.

(4) Textural relationships, bulk compositions, subparallel orientation of tie-lines connecting compositions of coexisting phases, and rather uniform distribution-coefficients for the cations indicate an exsolution origin of both types of lamellar intergrowths. A two-stage process initially generates lamellae of Li-bearing sarcopside from a relatively Ca,Li-poor disordered graftonite-type precursor; the Li-bearing sarcopside subsequently exsolves triphylite. A single-stage exsolution yields triphylite lamellae from a Ca,Li(Mn)-rich graftonite – beusite precursor.

(5) In regionally zoned groups of cogeneric pegmatites, the Ca-bearing graftonite – beusite is the first Fe,Mn(Li)-phosphate encountered in the beryl – columbite subtype of pegmatites, before the appearance of discrete grains of triphylite, or within the zone of beryl – columbite – triphylite pegmatites. This is in accord with appreciable concentrations of Ca, Fe, Mn (and in part Mg), but low levels of F and Na, which are required to stabilize graftonite – beusite, and which are not routinely attained in bodies of more fractionated pegmatite.

(6) The generally good correlation of Mn/(Mn + Fe) of the phosphate aggregates examined with those of broadly associated garnet supports the thesis of London et al. (1995) that these phosphates are generated by phosphorus-induced destabilization of garnet.

**ACKNOWLEDGEMENTS**

Our thanks are due to the management of the former LKAB Prospektering AB, which gave SAS an opportunity to examine the pegmatites at the time when most of the Li–Sn-pegmatites of north-central Sweden were found and explored, and to its manager Lars-Göran Ohlsson for a general permission to publish any scientifically significant data on these localities. The Linné and Ötterborg travel grants from the Uppsala University to SAS for field work in the Utö and Sidensjö areas, respectively, are gratefully acknowledged. The Stockholm Archipelago Foundation and its ranger of Utö, Bengt Söderlund, provided generous boat transport in this area. Field work of PU and PČ was funded by the NSERC Research Grants to the latter. NSERC Research, Major Installation and Equipment Grants to PČ, and NSERC Equipment plus Infrastructure Grants to F.C. Hawthorne, supported the laboratory studies. Faculty of Science, University of Manitoba Postdoctoral Fellowship and NSERC Research Grants to PČ supported PU’s work on this project. The final version of the manuscript considerably benefited from the thorough reviews by C. Francis, R.F. Martin and D.R. Peacor. C. Wernström and H. Weiss contributed the drafted figures.

**REFERENCES**


Received July 9, 1997, revised manuscript accepted March 1, 1998.