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STRUCTURAL AND TEXTURAL EVOLUTION OF THE STRANGE LAKE PERALKALINE RARE-ELEMENT (NYF) GRANITIC PEGMATITE, QUEBEC–LABRADOR

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ABSTRACT

The Strange Lake peralkaline complex, on the Quebec–Labrador border west of Nain, hosts magmatic rare-element (NYF) pegmatite–aplite lenses. The largest pegmatite–aplite lens, the Main Lens, hosts significant rare-metal (Zr, Y, Nb, Be and *REE*) mineralization. It forms a partly eroded dome-shaped body that is commonly 6 to 10 m thick. Layering within the lens consists of an aplite footwall zone, a pegmatite–aplite central contact zone, and a pegmatite hanging-wall zone. The footwall zone contains two chilled units, representing influxes of parental magma, and flow-lineated aplite units, representing differentiates of parental magma. The hanging-wall zone contains a lineated aplite unit on the upper contact and a massive pegmatite unit, representing a volatile-rich, less dense differentiate of the parental magma. Extremely enriched residual magma collected in the pegmatite–aplite contact zone to form red aplite–pegmatite units. Mineral variation within the lens defines systematic trends in mineral abundances and textures. Albite abundances increase and K-feldspar abundances decrease upward in the footwall zone, whereas the uppermost unit contains mostly albite. Conversely, feldspar in the pegmatite–aplite contact zone and the hanging-wall pegmatite unit is mostly K-feldspar. The central unit of the lens has low abundances of both feldspar and quartz. Zr-silicate mineral morphology varies, changing from squat grains in the chill units to elongate grains in the pegmatite–aplite contact zone. Crystal–liquid differentiation produced incompatible-element-enriched residual melts in a boundary layer at the footwall crystallization interface. These less dense melts moved both vertically and laterally to the upper part of the lens to form rare-metal-enriched magmatic mineralization in the pegmatite–aplite contact zone. Models of formation and classification of granitic pegmatite, recently developed from observations on mainly subaluminous to peraluminous compositions, also apply to peralkaline pegmatites in the Strange Lake peralkaline complex.

Keywords: magmatic rare-metal mineralization, rare-element granitic pegmatite–aplite, Strange Lake peralkaline complex, Labrador, Quebec, residual melts, Zr-silicate morphology.

SOMMAIRE

Le complexe hyperalcalin de Strange Lake, sur la frontière Québec – Labrador à l'ouest de Nain, renferme des lentilles de pegmatite–aplite à concentrations d'éléments incompatibles. La lentille la plus étendue renferme une zone minéralisée en Zr, Y, Nb, Be et terres rares. Elle affleure en forme de dôme de 6 à 10 m en épaisseur. La partie inférieure est aplitique, le centre est composé d'une intercalation de pegmatite–aplite, et la partie supérieure est pegmatitique. La paroi inférieure contient deux bordures figées, témoignant de deux venues de magma granitique, et des unités aplitiques montrant des textures de flux, qui représenteraient un magma plus évolué. La zone supérieure de la lentille contient une unité d'aplite à linéation primaire au contact et un niveau de pegmatite massive qui représenterait un liquide moins dense enrichi en phase volatile et dérivé du magma parent. Le magma le plus fortement différencié a cristallisé dans la zone centrale sous forme d'horizons d'aplite et de pegmatite rouges. La zonation interne de la lentille témoigne de variations systématiques en minéralogie et en texture. La proportion de l'albite augmente, et celle du feldspath potassique diminue, vers le centre dans la zone inférieure, tandis que la zone supérieure contient surtout de l'albite. Par contre, la zone centrale à intercalations de pegmatite et d'aplite et l'unité pegmatitique près de la paroi supérieure contiennent surtout du feldspath potassique. L'unité centrale de la lentille contient de plus faibles teneurs en feldspath et quartz. La morphologie des zirconosilicates montre aussi une zonation, de cristaux trappus dans les bordures figées à cristaux allongés dans la zone centrale à intercalations de pegmatite et d'aplite. Un processus de différenciation impliquant une interaction cristal–liquide rend compte de l'enrichissement en éléments incompatibles résiduels dans un liseré de liquide formé à la paroi inférieure. Ce magma moins dense a ensuite migré verticalement et horizontalement vers la partie supérieure de la lentille pour y cristalliser sous forme de zone à minéralisation primaire dans les intercalations pegmatite–aplite. Les modèles de formation et de classification de pegmatite granitique, développés récemment à partie de travaux sur des compositions métalumineuses et hyperalumineuses, semblent tout-à-fait appropriées pour décrire les roches hyperalcalines à texture pegmatitique du complexe de Strange Lake.

(Traduit par la Rédaction)

Mots-clés: minéralisation primaire, éléments incompatibles, pegmatite–aplite granitique, complexe hyperacalin, magma évolué, morphologie des zirconosilicates, Strange Lake, Labrador, Québec.

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INTRODUCTION

Recent investigators of the evolution of rare-element granitic pegmatites have concluded that these rocks represent crystallized residual magmas derived from felsic magma chambers (*e.g.*, London 1990, 1992, Congdon & Nash 1991, Černý 1991a, b). This conclusion limits the possible mechanisms of formation of rare-element granitic pegmatites, and implies that extreme enrichment in rare metals, such as *REE*, Zr, Nb and Y, in batches of residual magma leads to the formation of some rare-metal-enriched pegmatites and related mineralization.

One or a combination of the following liquid–liquid and crystal–liquid mechanisms may produce residual incompatible-element-enriched magmas, parental to granitic pegmatites, in high-level magma chambers: (1) diffusion- and temperature-controlled liquid fractionation (*e.g.*, Hildreth 1981), (2) vapor-assisted liquid differentiation (*e.g.*, Larsen & Sørensen 1987), (3) fractional crystallization (*e.g.*, Larsen & Sørensen 1987, Congdon & Nash 1991), (4) boundary-layer (*i.e.*, *in situ* crystallization) formation (*e.g.*, Langmuir 1989, Wolff *et al.* 1990), and, (5) liquid immiscibility (*e.g.*, Torokhov 1993). Most of these mechanisms may also produce zoning in a felsic magma chamber (*e.g.*, Larsen & Sørensen 1987, Wolff *et al.* 1990, Congdon & Nash 1991), involving a volatile-enriched residual magma at or near the top of the chamber. Such a residual magma commonly produces granitic pegmatites (Černý 1991b) that continue the internal differentiation process through one or a combination of the mechanisms listed above.

Alternatively, a metasomatic–hydrothermal process, associated with late magmatic volatile-enriched fluid (derived from residual magma?), has also been proposed to form rare-metal mineralization in pegmatite veins and lenses (*e.g.*, Drysdall *et al.* 1984, Salvi & Williams-Jones 1990, Nassif 1993). This process either forms these pegmatites or metasomatically overprints previously formed pegmatites (*e.g.*, Černý 1991b). Abundant evidence for the magmatic origin of the rare-element class of granitic pegmatites (Černý 1991a) argues against formation of these pegmatites by metasomatism. However, new data are needed to determine whether a metasomatic overprint or a magmatic process forms the rare-metal mineralization hosted by these magmatic pegmatites.

Rare-element-enriched pegmatite–aplite veins, lenses and patches, belonging to the NYF family of Černý (1991a), host rare-metal mineralization in the Strange Lake peralkaline complex (Miller 1986); moreover, the largest pegmatite–aplite lens, here called the Main Lens, contains significant rare-metal mineralization (Miller 1988). These pegmatite–aplite lenses display the characteristics of magmatic rare-element pegmatites (Černý 1991a). However, these observations originate from an extrapolation based on pegmatites of mainly metaluminous to peraluminous composition, studied by Černý (*e.g.*, 1991a, b) and London (*e.g.*, 1990, 1992), to pegmatites of peralkaline composition. This study provides additional data on peralkaline rare-element pegmatites to complement sketchy data in the literature (see Černý 1991a, c, and references therein).

This contribution focuses on the structure, mineralogy, geology and petrography of the Strange Lake Main Lens pegmatite–aplite and its rare-metal mineralization. Conclusions drawn from these data have bearing on the following: (1) the evolution of layering in the pegmatite–aplite lens, (2) the origin of the pegmatite–aplite-forming magma, and (3) the metasomatic *versus* magmatic origin of the associated rare-metal mineralization.

GEOLOGY OF THE STRANGE LAKE PERALKALINE COMPLEX AND ASSOCIATED RARE-METAL MINERALIZATION

The Strange Lake rare-metal deposit, of Mesoproterozoic age (1240 ± 2 Ma; Miller *et al.* 1996) occurs on the Quebec–Labrador border in north-central Labrador (Fig. 1). It contains significant tonnages of potentially economic Zr–Y–Nb–Be–*REE* mineralization (Miller 1988). Several nearby Mesoproterozoic peralkaline suites also contain rare-metal mineralization: the Ilímaussaq and Motzfeldt intrusive complexes in Greenland (Steenfelt 1991), the Nuiklavik volcanic rocks of the Flowers River Igneous Suite, Labrador (Miller 1993), and the Red Wine Intrusive Suite in the Letitia Lake area, Labrador (Miller 1987, 1988).

Several investigators have studied the geology of the Strange Lake (or Lac Brisson) peralkaline complex (Currie 1985, Miller 1986, Pillet *et al.* 1989, 1992, Nassif 1993, Boily & Williams-Jones 1994) and proposed different schemes of classification for the various phases of the complex. Miller (1986, 1988, 1990, Hill & Miller 1990, Birkett *et al.* 1992, Miller *et al.* 1996) described the geology of the complex and the rare-metal (Zr–Y–Nb–Be–*REE*) mineralization using a scheme based on the abundances of rare-metal-bearing or "exotic" minerals (*e.g.*, fluorite, gittinsite, zircon, gadolinite, aegirine, arfvedsonite, elpidite). He defined three major granitic phases: 1) a phase relatively poor in exotic minerals (EP: rare-metal-poor, early phase, containing less than 5% by volume of such exotic minerals), a phase relatively enriched in exotic minerals (ER: rare-metal-rich, late phase, parental to rare-metal pegmatite–aplite, that contains greater than 15% of the exotic minerals), and a phase with intermediate contents of exotic minerals (EI: intermediate rare-metals and age, containing 5 to 15%). Chemical and textural differences and the presence or absence of certain minerals also help distinguish these phases (Miller 1985, 1986, Birkett *et al.* 1992, Pillet *et al.*

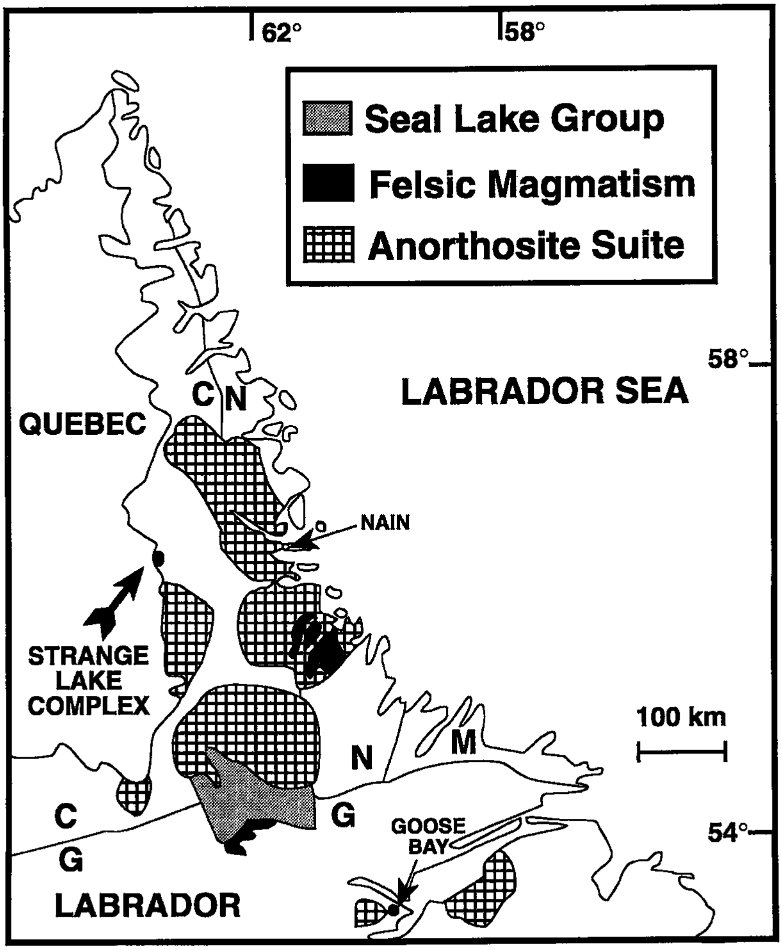

FIG. 1. Location map of the Strange Lake peralkaline complex, Labrador–Quebec. Structural provinces: C: Churchill, N: Nain, G: Grenville, M: Makkovik.

1992, Nassif 1993). Each phase contains several subphases defined by texture (*e.g.*, fine-grained, porphyritic, aplitic and pegmatitic phases; Miller 1986).

Rare-metal mineralization occurs in five modes in and near the central ER stock (Miller 1988): (1) lenses, up to 20 m thick, that extend from the upper part of the stock into the surrounding rocks, (2) pegmatite and pegmatite–aplite zones, 3 to 10 m thick, that occur at or near the upper and lower contacts, (3) pegmatite–aplite dykes, 2 to 3 m thick, located within the stock, (4) small, mostly pegmatitic, veins and dykes, usually less than 0.5 m thick, that cut the EP phase south of the ER stock, and (5) zones of pegmatite granite in the upper portion of the stock. High-grade mineralization commonly occurs in mode 1 (Miller 1985, 1986), whereas lower grade mineralization occurs in modes 4 and 5.

A compositionally and texturally zoned pegmatite–aplite lens (mode 1: Main Lens), located in the central portion of the complex (Fig. 2), contains the most significant mineralization; moreover, although sources report no tonnage estimates, the lens contains the following grades: 3.25% ZrO_2, 0.60% Y_2O_3, 0.56% Nb_2O_5, 0.12% BeO and 1.30% *REE* (Miller 1988). The Main Lens and smaller bodies emanate from a stock of medium-grained ER peralkaline granite (0.7 km^2; approximately 0.175 km^3). Figure 2 illustrates the close spatial relationship between this stock and mineralized pegmatite–aplite bodies. Most significant lenses occur within or near the central stock (*i.e.*, marginal or interior pegmatites), whereas veins located more than

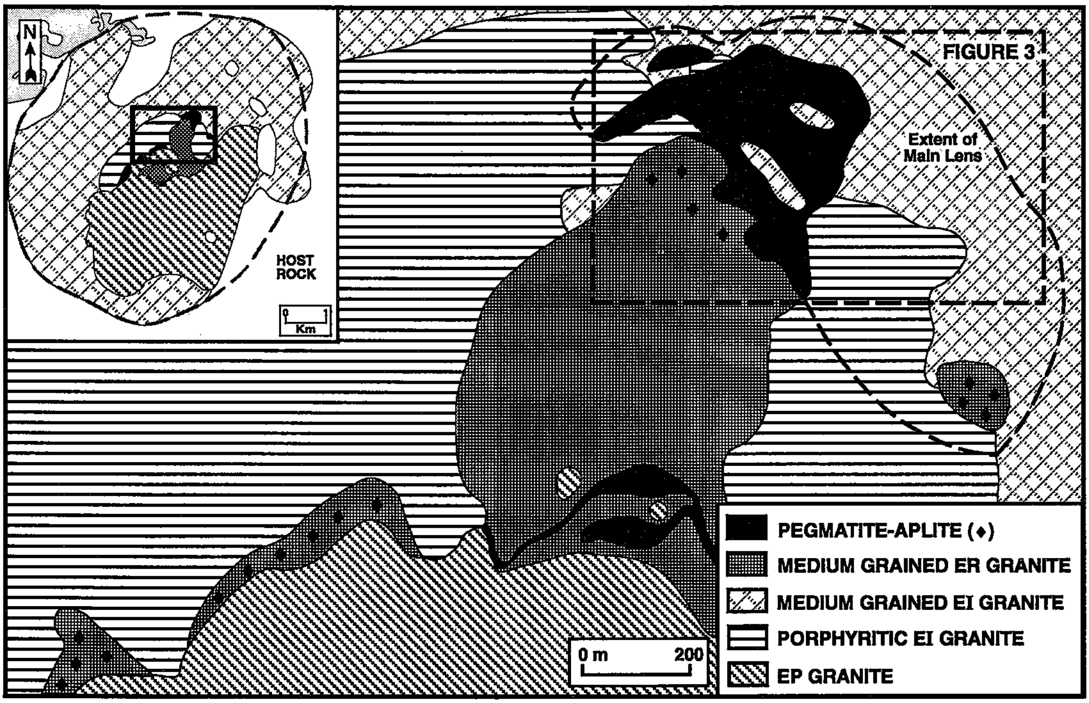

FIG. 2. General geology and rare-metal mineralization near the central stock of medium-grained ER granite. Note the outline of the Main Lens in the northeastern part of the figure.

1 km away (*i.e.*, exterior pegmatites) are usually less than 0.5 m thick. All pegmatite–aplite bodies occur within (*i.e.*, internal pegmatites) the Strange Lake peralkaline complex.

GEOLOGY OF THE MAIN LENS

The Main Lens occurs on the northeastern contact of the central medium-grained ER stock (Fig. 2). This lens extends from the ER granite stock into or near the contact between two subphases of the surrounding EI granite (*i.e.*, the contact between porphyritic and medium-grained subphases of EI granite; Fig. 2). Figure 3 illustrates the subcrop, the isopach contours and the maximum extent (0 isopach contour) of the Main Lens, as interpreted from drilling data. These data indicate that the lens underlies an area of approximately 0.75 km^2, has an apparent maximum thickness of 20 m, is most commonly 6 to 10 m thick, and has a volume of approximately 0.003 km^3. The subcrop map also indicates that approximately one quarter of the lens has been unroofed. Eroded material from the lens forms a well-defined boulder train, at least 40 km long (McConnell & Batterson 1987, Batterson 1989), that led to the discovery of the Main Lens mineralization.

Representative cross-sections through the Main Lens and the adjacent ER granite illustrate some notable aspects of the structure (Fig. 4): (1) the lens dips toward the north in the northern part, and toward the east in the eastern part; (2) the lens rapidly pinches out to the west, north and east; (3) the lens appears to bifurcate in its central part, and (4) the lens pinches out southward, where it commonly occurs at the upper contact of medium-grained ER granite and rarely at the lower contact. These observations indicate that the pegmatite–aplite lens forms a shallow-dipping domed structure, which plunges toward the east. The cross-sections also indicate that the pegmatite–aplite lens originates in the roof zone of the adjacent medium-grained ER granite.

Cross-cutting relationships suggest that the pegmatite–aplite lens crystallized at the same time and just after the medium-grained ER granite; furthermore, the contacts between these two subphases of ER granite are commonly sharp. Drill-core and the bulk-sample trench clearly reveal sharp footwall and hanging-wall contacts between the lens and EI granite host. In some places, the host contains increased concentrations of exotic minerals up to 10 cm from the contact; however, this alteration is usually less than 1 cm thick or absent.

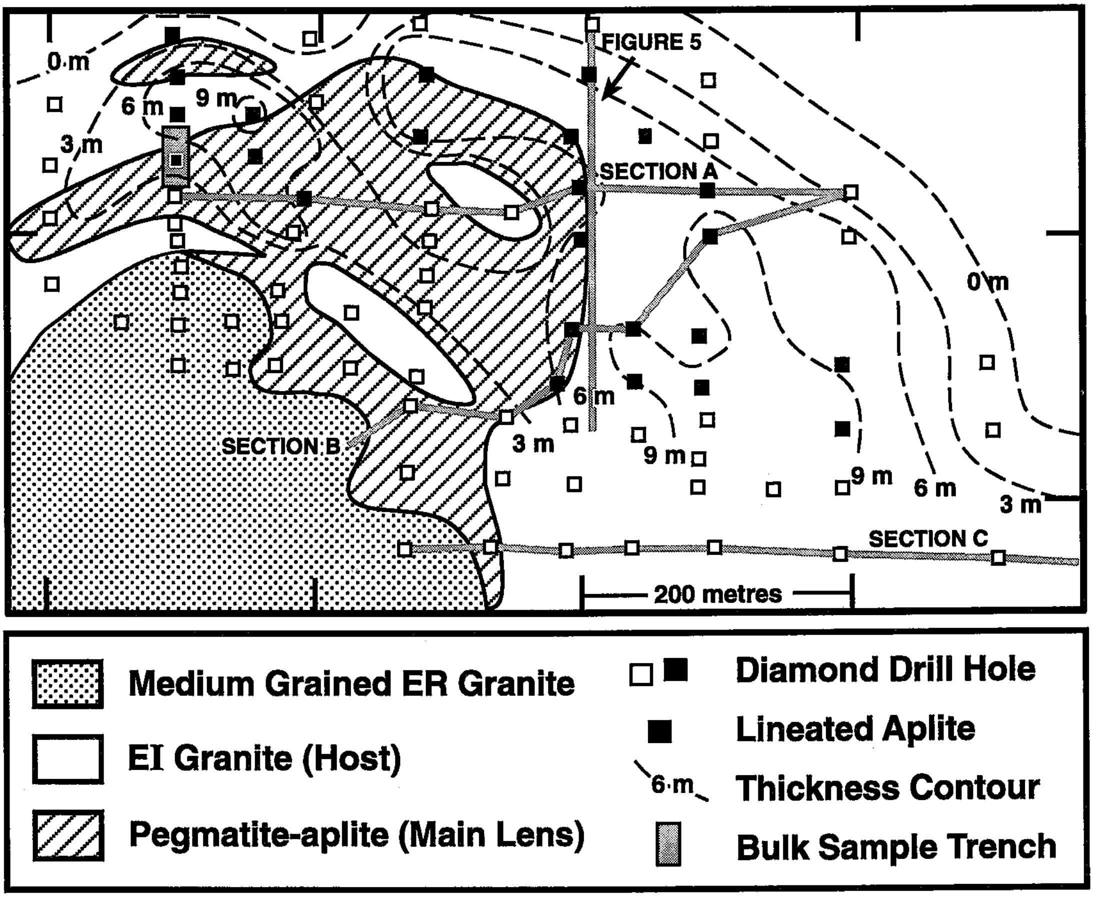

FIG. 3. Bedrock geology of the Main lens, with lateral extent (thickness = 0 m) and thickness contours (isopachs). Note that lineated aplite (Units 3, 4 and 5) only occurs where the lens is between 3 and 10 m thick. Figure 2 outlines the location of Figure 3.

INTERNAL LAYERING IN THE MAIN LENS

Detailed mapping in the bulk-sample trench and drill-core data indicate that the pegmatite–aplite lens has well-defined vertical and lateral layering. The lens exhibits constant vertical zoning where it is 3 to 20 m thick (*i.e.*, where the medium-grained ER granite is absent), and in its thicker, upper limb (Fig. 4B). An upper pegmatite hanging-wall section (Table 1) and a lower aplite footwall section characterize the vertical zoning. Figure 5, a detailed cross-section through the lens, and Figure 6, a detailed plan view of the bulk-sample trench, depict the main textural zones in this part of the lens.

Lateral zoning in the Main Lens follows the following pattern from southwest to northeast: (1) where the lens is greater than 20 m thick, medium-grained ER granite, medium-grained pegmatite and layered pegmatite–aplite occur; (2) where the lens is 3 to 20 m thick, medium-grained units are absent, and layered pegmatite–aplite, including lineated aplite and, in some areas, the red pegmatite–aplite assemblage, occur; (3) where the lens is 0.5 to 3 m thick, lineated aplite is absent, and massive pegmatite– aplite units are dominant, and (4) where the lens is less than 0.5 m thick, pegmatite with or without minor aplite dominates until the lens pinches out.

The Main Lens contains three vertical zones: footwall, pegmatite–aplite contact and hanging wall (Table 1). Textural distinctions lead to the definition of several members in each zone. Sample units, numbered 1 to 10, represent subdivisions of the lens on the basis of texture, mineralogy, and color (Table 1; located in Fig. 6).

The footwall zone, which has an apparent thickness ranging from less than 1 to 7 m, consists of the following aplite members: very fine-grained (Unit 1), massive (Unit 2), lineated K-feldspar-rich (Unit 3), and

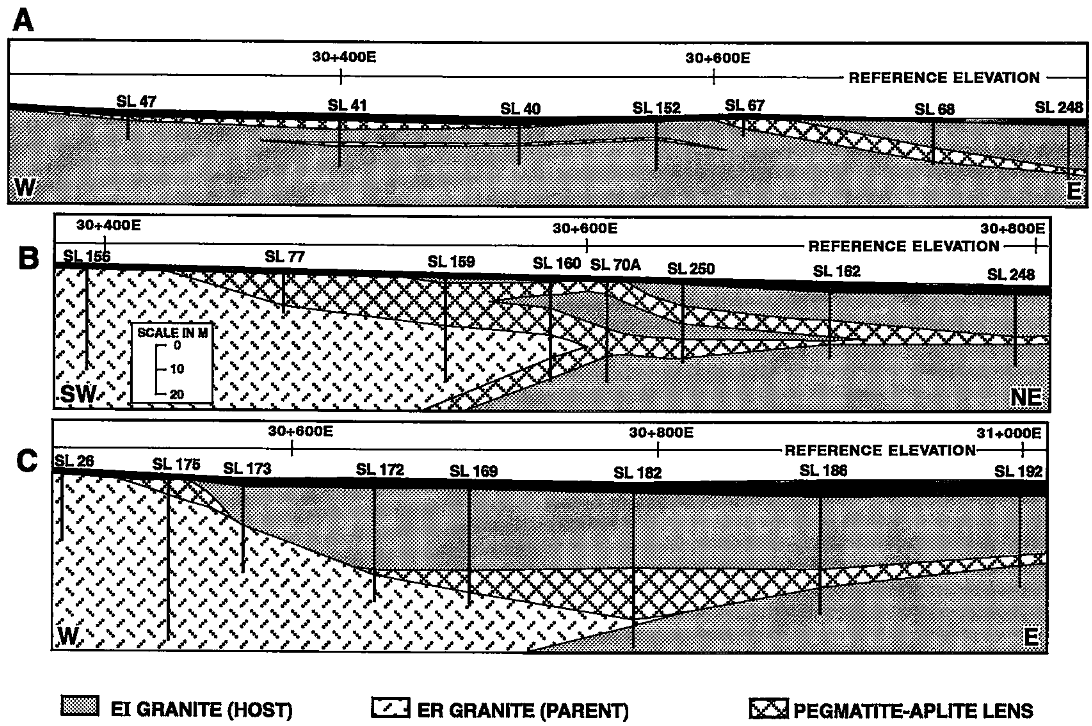

FIG. 4. Geological cross-sections through the Main lens: Section 41+650N (Section A), a section running SW to NE (Section B) and Section 41+350N (Section C). Figure 3 shows the locations of these sections.

lineated K-feldspar-poor (Units 4 and 5). Phenocrysts of albite, pseudomorphs after narsarsukite, bastnäsite, pseudomorphs after Zr-silicate, thorite, and aegirine exhibit a common preferred orientation that defines the lineated texture; the long axis of phenocrysts parallels the lens contacts. Upwardly increasing abundance or stronger orientation of these elongate minerals results in a gradational enhancement of the lineated texture from poorly developed in Unit 3 to well developed in Unit 5.

A reddish brown, red or purplish-red color characterizes the pegmatite–aplite contact zone, which commonly consists of an aplite member (Unit 6) and a pegmatite member (Unit 7). The distinctive coloration occurs as a result of disseminated hematite within pseudomorphs after Zr-silicate, thorite, and fluorite.

The hanging-wall zone consists of a massive, inhomogeneous, pegmatite member (Unit 9), and a discontinuous, very fine-grained, lineated aplite member (Unit 10A), which form a zone that ranges in thickness from 0.5 to 8 m. Autoliths (less than 2 to 5 cm wide) of aplite (Unit 10B), which represent disaggregated fragments of the very fine-grained aplite member, occur in the pegmatite member (Unit 9) near the hanging-wall contact.

VARIATION IN MINERAL PROPORTIONS

The mineral assemblages in the Main Lens are complex (Table 2); however, abundances of many minerals systematically vary vertically (Table 3). These changes generally correlate with the observed vertical changes in texture. Some of the most significant changes include the following: variation in the modes of feldspars and mafic minerals, and variation in the relative proportion of albite to total feldspar, and of aegirine to total mafic minerals. Tables 1 and 3 and Figure 7 summarize these variations.

Rock-forming minerals in the Main Lens include K-feldspar, albite, quartz and gittinsite. K-feldspar is the most abundant feldspar throughout the lens, except in albite-rich lineated aplite in the footwall (Units 4 and 5) and hanging-wall zones (Units 10A and 10B), which contain little or no K-feldspar (Tables 1, 3). The abundance of albite (Table 3) increases from Unit 1 to Units 4 and 5, peaks in Unit 10, and is very low in the pegmatite–aplite contact zone (Units 6 and 7). Quartz abundance is relatively constant in the lower aplite units, and variable, although difficult to estimate, in the pegmatite members. The modal proportion of quartz

(Table 3) is low in the red pegmatite (Unit 7) and the upper lineated aplite (Unit 10). The abundance of gittinsite + quartz pseudomorphs after Zr-silicate drops from 28.7% in Unit 1 (Table 3) to 13.5% in the red pegmatite (Unit 7).

The Main Lens also exhibits a systematic variation in the proportion of the mafic minerals (*i.e.*, aegirine/[aegirine + arfvedsonite]; Table 1). Aplite at the base of the footwall zone (Unit 1) contains no aegirine and abundant arfvedsonite, whereas the pegmatite–aplite contact zone (Units 6 and 7) and the adjacent lineated aplite, at the top of the footwall zone (Unit 5), mostly contain aegirine and little or no arfvedsonite. Other members have proportions that vary between these extremes. Primary aegirine occurs in the pyroxene-rich units, whereas secondary pyroxene after arfvedsonite and arfvedsonite occur everywhere else (Tables 2, 3).

Accessory minerals, which have abundances up to 10 % (Fig. 7, Table 3), also exhibit variations in mode, particularly in the aplite units: (1) thorite is abundant in the pegmatite–aplite contact zone and in the upper lineated aplite of the footwall zone (Unit 5), (2) Ca–Y silicate, gadolinite, kainosite, and many other rare-metal-bearing minerals accompany thorite, (3) primary fluorite is abundant in the pegmatite members, and generally lower, but erratic, in the aplite members, (4) pyrochlore contents increase from the footwall (Unit 1) toward the red aplite member (Unit 6), (5) abundances of pseudomorphs after narsarsukite are the highest on the outer contacts (Units 1, 2 and 10), and (6) rare-metal accessory minerals (excluding pseudomorphs after Zr-silicate and narsarsukite) dramatically increase from the footwall contact (less than 2% to 7%) to the red pegmatite (50%; Table 3).

Even though mineral abundances within the lens generally vary from bottom to top, the upper part of the lens exhibits a striking symmetry (Fig. 7). There, K-feldspar-poor (albite-rich) lineated aplite (Units 5 and 10) flank K-feldspar-rich (albite-poor) pegmatite and aplite (Units 6, 7 and 9). The central unit (Unit 7) in this symmetrical relationship contains the highest

TABLE 1. SUMMARY DATA FOR IDEALIZED SECTION OF THE MAIN LENS PEGMATITE-APLITE

ZONE	MEMBER (Thickness)	GRAINSIZE	TEXTURAL FEATURES	ALBITE RATIO*	PYROXENE RATIO°	COMMENTS
HANGINGWALL	Lineated Aplite Unit 10 (< 0.2 m)	< 1 mm long	aligned albite; interstitial Zr-silicate.	1.00	0.44	thin discontinuous; autoliths in Unit 9.
	Pegmatite Unit 9 (0.5 - 8 m)	< 1 - 15 mm long	K-feldspar, quartz, Zr-silicate ± aegirine are large grains; albite and most accessories are small grains.	0.42	1.00	mineral distribution is variable; colour is variable; autoliths of Unit 10 < 10 cm wide; fluorite rich.
PEGMATITE APLITE CONTACT	Red Pegmatite Unit 7 & 8 (0.5 - 3.5 m)	2 - 8 mm long	leifite?, CaY Silicate & K-feldspar are large equant grains; elongate Zr-silicate & narsarsukite?	0.00	1.00	thorite and fluorite rich; enriched in rare metals; Unit 8 = pegmatite vein.
	Red Aplite Unit 6 (< 0.5 m)	< 3.5 mm long; commonly < 0.5 - 2.0 mm	snowball quartz up to 15 mm; faint lineation in some places.	0.08	0.98	thorite rich; enriched in rare metals; primary CaY Silicate - locally common.
FOOTWALL	Lineated K-spar poor Aplite Unit 4 & 5 (0.5 - 4.0 m)	< 3.5 mm long; commonly < 1 - 2.0 mm	snowball quartz up to 10 mm; leifite pseudomorphs < 7 mm; Zr-silicate, thorite, albite, narsarsukite? & aegirine are aligned.	0.95 0.64	0.99 0.91	Unit 5 is enriched in rare metals.
	Lineated Aplite K-spar Rich Unit 3	< 3 mm long commonly < 1.0 - 2.0 mm	snowball quartz up to 10 mm; Zr-silicate, narsarsukite? & albite are aligned.	0.39	0.23	
	Massive Aplite Unit 2 (0 - 3 m)	< 2.5 mm long; commonly < 0.3 - 2.0 mm	snowball quartz up to 10 mm; unoriented elongate minerals;	0.25	0.03	red spots (hematite & fluorite) are common; commonly 1-m-thick; arfvedsonite ≈ 0.5 and 2.0 mm.
	Very Fine Grained Aplite Unit 1 (1 - 3 m)	< 2.0 mm long; commonly < 0.2 - 1.5 mm	snowball quartz up to 5 mm; unoriented elongate minerals; local comb-structure	0.25	0.00	massive texture.

* albite / (albite + K-feldspar) (mode %)

° clinopyroxene / (pyroxene + amphibole) (mode %)

concentrations of "other" minerals, mainly rare-metal-bearing minerals, and the lowest concentration of quartz. These relationships suggest a genetic connection among the units of the upper part of the lens (Units 5 to 10); similarly, systematic variations in mineral abundances among the aplite horizons in the lower part of the lens (Units 1 to 5) suggest a genetic connection among these units.

Mineral Paragenesis

Mineral textures define four periods of mineral formation: (1) an early period of crystallization that resulted in subhedral to euhedral grains of variable but commonly small grain-size, (2) a main-stage period of crystallization that formed a framework of touching subhedral to euhedral grains, (3) a late period of crystallization that resulted in anhedral to subhedral interstitial grains, and (4) a replacement period that resulted in pseudomorphic replacement of minerals at the magmatic stage (supersolidus reaction), the subsolidus stage (autometasomatic fluid) or in a later stage by fluids from an external source. Figure 8 summarizes the paragenesis of major minerals, on the basis of the four periods outlined above.

The early-crystallizing minerals, thorite, pyrochlore, and monazite, occur as subhedral to euhedral grains, commonly less than 0.5 mm across. Thorite and pyrochlore are poikilitically enclosed in most main-stage minerals, but not commonly in late-stage minerals. Monazite occurs as widespread, but sparse grains, that commonly impinge upon main-stage minerals. The small grain-size suggests that these minerals crystallized over a short interval.

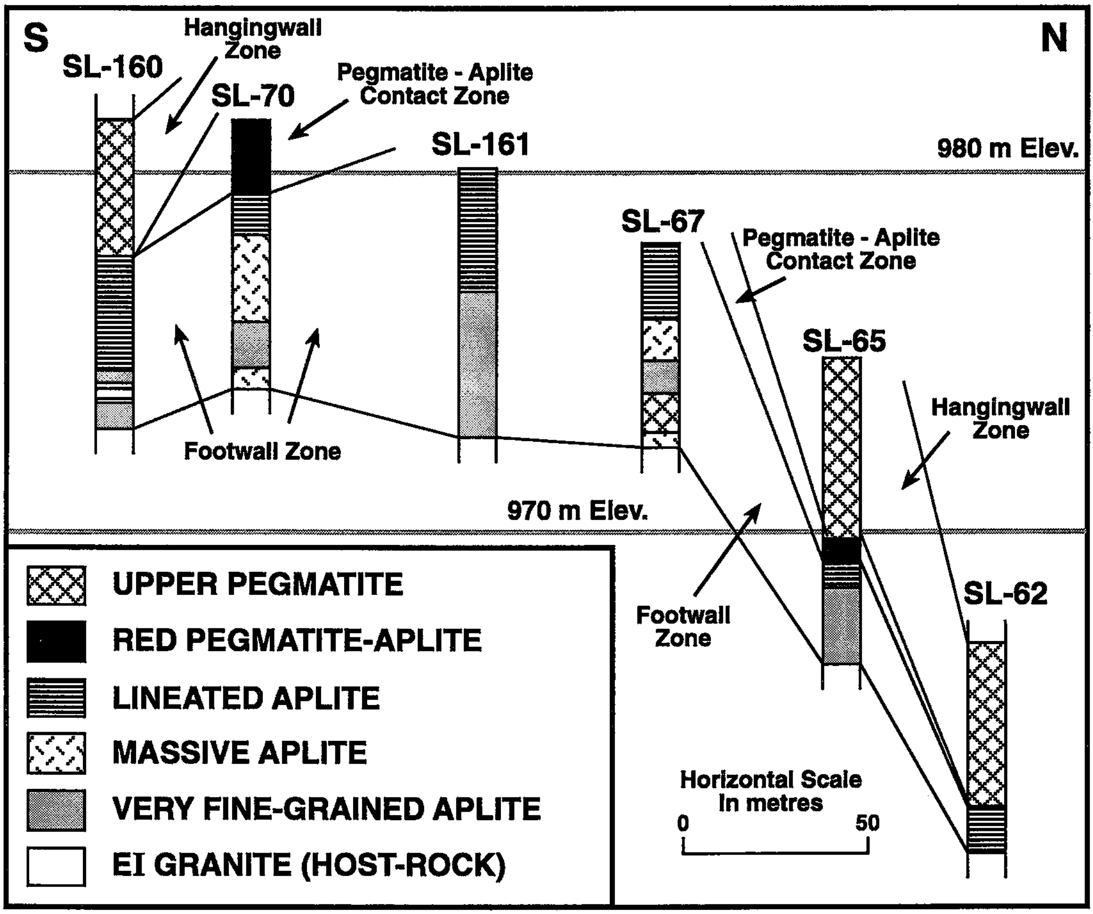

FIG. 5. Detailed diamond-drill-hole cross-section 30+600E. This section, located in Figure 3, illustrates the relationships among the various aplite and pegmatite units. Note that D.D.H. SL–160 and D.D.H. SL–62 are the only holes in this section that cut the hanging wall (*i.e.*, where erosion has not exposed the lens). The vertical exaggeration is approximately ten.

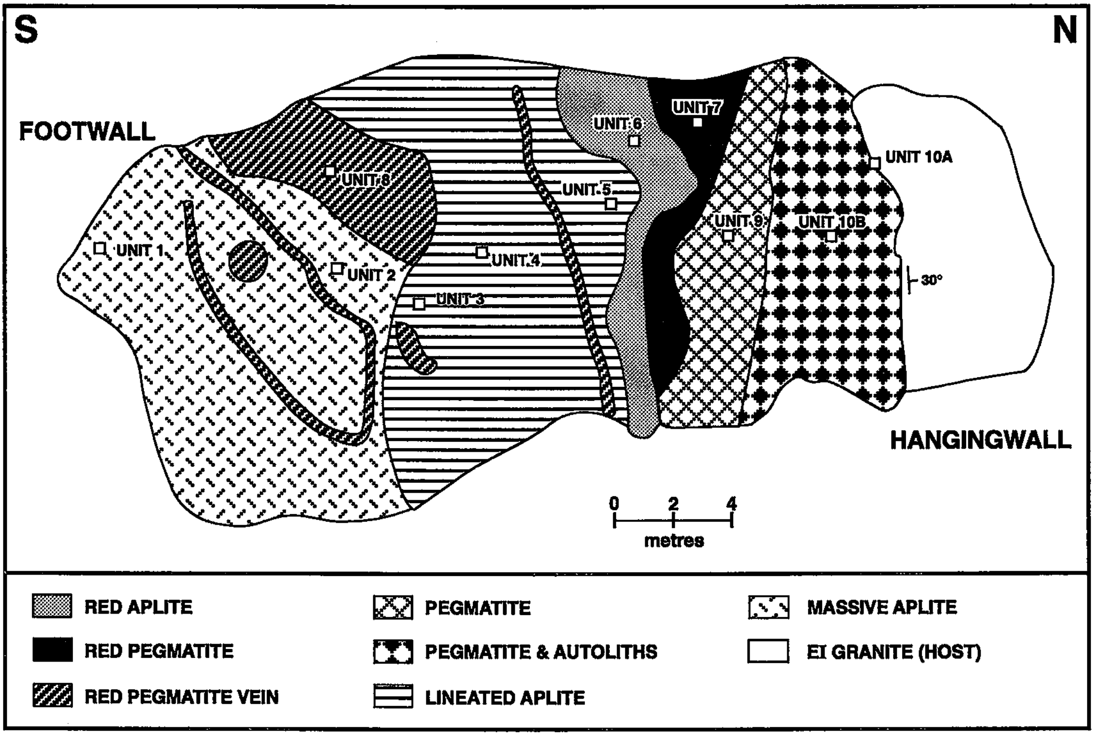

FIG. 6. Geology of the bulk-sample trench. This plan map (see Fig. 3 for trench location) further illustrates the relationships among the various aplite and pegmatite units.

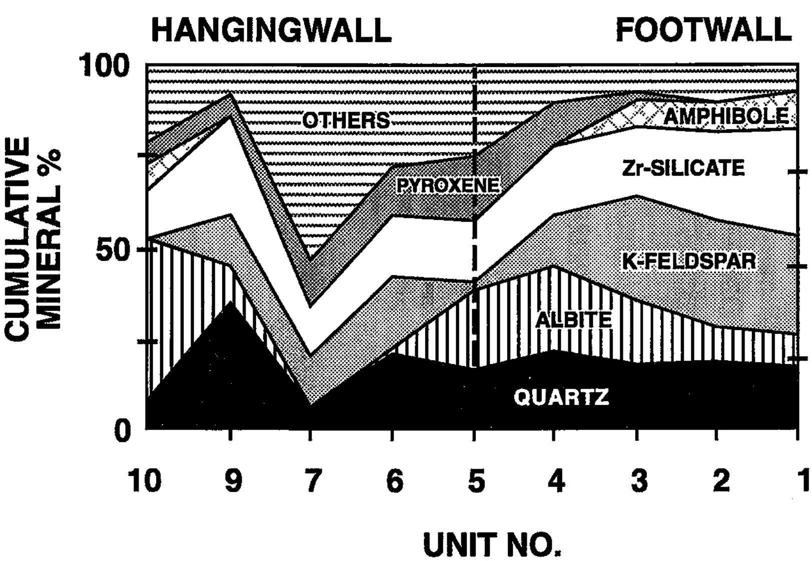

FIG. 7. Variation in mineral modes, as illustrated by cumulative mineral % *versus* vertical location in the trench (Unit No.; Unit 1 at the footwall and Unit 10 at the hanging wall). Note the symmetrical relationship in the hanging-wall portion of the lens among Units 5 to 10.

TABLE 2. SUMMARY OF MINERAL HABITS AND TEXTURES, MAIN LENS PEGMATITE-APLITE

Mineral	Habit	Alteration	Occurrence	Aplite Size	Pegmatite Size
Quartz (P)	snowball-like; optically continuous grains	none	common	2 - 10	< 15
	small interstitial grains	none	common	< 0.5	—
Albite (P)	elongate prismatic grains; singly & in masses; orientated in some units	rare	common	< 2	< 2
K-feldspar (P)	equant sub-euhedral grains	sericitic dusting	common	< 1 - 6	< 10
Arfvedsonite (P)	an-subhedral grains; commonly interstitial	aegirine	locally common	< 1	< 5
Aegirine (P)	elongate prismatic grains	none	peg-aplite contact	< 3	< 3
Aegirine (S)	patchy replacement of arfvedsonite	none	locally common	< 0.5	< 0.5
Elpidite (P)*	prismatic & boat-shaped grains	armstrongite	replaced	< 3	< 10
Armstrongite (P)*	elongate prismatic & boat-shaped grains	gittinsite + qtz ± fl.	replaced	< 1 - 1.5	—
Armstrongite (S)*	replaces elpidite	gittinsite + qtz ± fl.	replaced	< 3	< 10
Narsarsukite (P)	elongate prismatic grains	titanite + qtz ± fl.	replaced	< 2	< 6
Leifite (P)*	equant hexagonal; poikilitic grains	CaY Silicate + fl.	peg-aplite contact replaced	< 7	< 7
Gittinsite (S)*	subhedral grains & sheaf-like aggregates; after armstrongite	zircon	common	< 0.2	< 0.2
Titanite (S)	patchy an-subhedral aggregates; replaces narsarsukite?	none	common	< 0.2	< 0.2
Pyrochlore (P)*	sub-euhedral square and octahedral single grains and rare aggregates	none	common	< 0.1	< 0.3
Kainosite (S)*	sheaf-like aggregates	?	peg-aplite contact		
Fluorite (P)	late interstitial patches	none	locally common	< 0.5	< 20
Fluorite (S)	replaces armstrongite, narsarsukite?	none	widespread	< 0.1	< 0.1
Thorite (P)	elongate prismatic and square grains	metamict	peg-aplite contact	< 0.1 - 1	< 0.1 - 1
Gadolinite (P)*	boitryoidal single grains and rims	?	peg-aplite contact	< 0.1	< 0.1
Monazite*	subhedral prismatic grains	none	sparse	< 0.5	< 0.5
CaY-silicate (P)*	prismatic-elongate grains	catapleite	peg-aplite contact	< 1.5	—
CaY-silicate (S)*	replaces leifite; radiating aggregates	?	peg-aplite contact	< 1	< 1
Galena (P)	sub-euhedral cubes	?	pegmatite zone	—	< 1
Zircon*	spheroids replacing gittinsite	?	common	< 0.1	< 0.1

* = potential ore minerals; S = secondary; P = primary; qtz = quartz; fl. = fluorite; peg = pegmatite; Size in mm.
Elpidite - $Na_2ZrSi_6O_{15}{\bullet}3H_2O$; Armstrongite - $CaZrSi_6O_{15}{\bullet}3H_2O$; Narsarsukite - $Na_2(Ti,Fe)Si_3O_{10}(OH,F)$; Leifite - $Na_2(Si,Al,Be)_7(O,OH,F)_{14}$; Gittinsite - $CaZrSi_2O_7$; Kainosite - $Ca_2[Ce,Y]Si_4O_{12}[CO_3]{\bullet}H_2O$; Gadolinite - $Y_2FeBe_2Si_2O_{10}$; Monazite - $[Ce,La,Y,Th]PO_4$; CaY-silicate - $(Y,Ca,Na,REE)_4Si_5O_{14}{\bullet}4H_2O$, I.M.A. approved mineral (#93-034), officially un-named.

Two types of texture characterize the results of main-stage crystallization: (1) a "snowball" texture (Kovalenko & Lapides 1974, Pollard 1989; Fig. 9, Unit 1), and (2) a "crystal framework" texture consisting of linked subhedral to euhedral grains (Bryon *et al.* 1994). Minerals that commonly form the "crystal framework" texture include the following: albite, K-feldspar, Zr-silicates, aegirine, narsarsukite, kainosite, leifite and gadolinite.

Quartz forms anhedral grains, with ragged boundaries, that poikilitically enclose a number of other minerals ("snowball" texture). This texture suggests that the quartz formed by late-stage growth from an interstitial residual melt. However, when compared to nearby zones, where a feldspar and a Zr-silicate "crystal framework" formed, the lower abundances (see Table 3; compare data from Quartz-rich and Quartz-poor areas in Units 1 and 2) and the smaller size of included grains in quartz indicate that quartz occupies zones where a similar framework of crystals is absent. Thus, quartz must form part of the "crystal framework" in the main stage of crystallization. This means that fewer nuclei of quartz crystallized, compared to other main-stage minerals, resulting in relatively larger grains that included and terminated the growth of smaller grains. Other minerals (*e.g.*, feldspar and Zr-silicate), growing between quartz crystals, had a longer period to grow relative to grains included in quartz crystals; thus they are generally larger, occur in larger numbers, and form another part of the "crystal framework" (Fig. 9). A study of "mineral densities", sizes, and numbers in an ongonite dyke from Mongolia (Kovalenko & Lapides 1974) revealed similar relationships between quartz in the "snowball" texture and feldspar.

"Crystal framework" minerals, in particular albite and Zr-silicate, form many more nuclei and much smaller grains (Table 2) that impinge on each other because of competition for space. Textural observations show, for instance, that albite grains (Units 4 and 5) forced Zr-silicate and aegirine grains into the interstices between albite aggregates. In these

TABLE 3. MINERAL MODES IN THE MAIN LENS PEGMATITE-APLITE

Unit	Qtz	Ab	Kfs	Arm (psd)	Arf	Ae	Nrs (psd)	Pcl	Lft (psd)	CaY	Thr	Fl	Mon	Other	Tot. Feld	Tot. Maf	Tot. Acc.	Tot. R. M.	Elong. Min.	1	2
Unit 10A	4.0	48.3	0.0	16.5	8.0	6.2	10.9	0.8	0.0	0.0	0.0	0.0	0.0	5.3	48.3	14.2	6.1	33.5	81.9	0.07	0.10
Unit 10B	11.3	40.8	0.1	9.8	6.7	4.8	15.6	0.0	0.0	0.0	0.0	5.0	0.0	5.9	40.9	11.5	10.9	36.3	71.0	0.18	0.17
Unit 9	34.8	10.2	13.9	27.3	0.0	5.5	3.8	0.4	2.5	0.0	0.0	1.5	0.1	0.0	24.1	5.5	4.5	35.6	46.8	0.55	0.07
Unit 7*	6.2	0.0	14.2	13.5	0.0	12.4	5.4	1.2	41.9	0.0	3.2	0.9	0.1	1.0	14.2	12.4	48.3	67.2	34.5	0.09	0.70
Unit 6*	21.0	1.7	19.3	16.3	0.3	13.3	6.4	3.0	2.1	12.2	3.5	0.3	0.0	0.6	21.0	13.6	21.7	44.4	41.2	0.33	0.34
Unit 5*	16.7	21.8	2.2	17.0	0.1	17.4	5.6	2.7	12.4	2.7	0.9	0.4	0.2	0.0	24.0	17.5	19.3	41.9	62.7	0.28	0.32
Unit 4*	21.4	23.8	13.5	18.3	1.1	11.6	4.4	1.2	1.9	0.0	0.0	1.4	0.4	0.9	37.3	12.7	5.8	28.5	58.1	0.33	0.09
Qtz-rich	32.2	20.0	5.5	21.2	0.5	13.6	3.7	3.1	0.0	0.0	0.0	0.0	0.2	0.0	25.5	14.1	3.3	28.2	58.5	0.53	0.05
Qtz-poor	10.6	38.4	3.1	29.8	0.5	7.7	0.7	0.0	6.9	0.0	0.0	1.9	0.4	0.0	41.5	8.2	9.2	39.7	76.6	0.17	0.15
Unit 3*	17.8	17.8	28.1	19.0	7.3	2.2	6.0	0.9	0.0	0.0	0.0	0.2	0.1	0.7	45.9	9.5	1.9	26.9	45.0	0.27	0.03
Unit 2*	18.9	9.6	28.9	24.3	7.7	0.2	8.6	0.9	0.0	0.0	0.0	0.9	0.0	0.0	38.5	7.9	1.8	34.7	42.7	0.32	0.03
Unit 1*	17.3	8.8	27.1	28.7	10.3	0.0	6.0	0.5	0.0	0.0	0.0	0.3	0.0	1.0	35.9	10.3	1.8	36.5	43.5	0.31	0.03
Qtz-rich	33.2	10.8	20.7	25.5	5.1	0.0	4.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	31.5	5.1	0.5	30.2	40.5	0.51	0.01
Qtz-poor	6.3	11.1	36.6	32.2	7.2	0.0	6.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.7	7.2	0.0	38.8	49.9	0.12	0.00
ER	24.5	14.7	32.6	19.6	7.1	0.4	0.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	47.3	7.5	0.2	20.7	15.6	0.34	0.00

Unit 10A - fine grained lineated aplite on hangingwall contact; Unit 10B - fine grained lineated aplite autoliths in Unit 9 pegmatite;
ER = ER medium grained granite; average of 4 samples;
Qtz = quartz; Ab = albite; Kfs = K-feldspar; Arm = armstrongite; Arf = arfvedsonite; Ae = aegirine; Nrs = narsarsukite;
Pcl = pyrochlore; Lft = leifite; CaY = CaY Silicate ; Thr = thorite; Fl = fluorite; Mon = monazite; Other - unknown or unidentified minerals.
psd - pseudomorphosed mineral: Arm = gittinsite + quartz after armstrongite?; Nrs = titanite + quartz ± fluorite after narsarsukite?;
Lft = CaY Silicate + fluorite after leifite?
* average of three thin sections cut orthogonal to each other;
Tot. Feld. = albite + K-feldspar; Tot. Maf. = amphibole + clinopyroxene
Tot. Acc. - total accessories: pyrochlore + leifite + CaY Silicate + thorite + fluorite + monazite + other
Tot. R. M. - total rare metal minerals: accessories + armstrongite? + narsarsukite?
Elong. Min. - elongate minerals: albite + armstrongite? + narsarsukite? + thorite + pyroxene
1 = Quartz / (Albite + K-feldspar + Quartz + Tot. Acc.)
2 = Tot. Acc. / (Albite + K-feldspar + Quartz + Tot. Acc.)

restricted spaces, Zr-silicate grains impinged on aegirine, and albite impinged on both aegirine and Zr-silicate, indicating that these minerals formed simultaneously.

Fluorite, some quartz, and arfvedsonite are among the last minerals to crystallize from the magma (Fig. 8); consequently, all three minerals form anhedral irregular grains between grains of the "crystal framework". Fluorite is commonly interstitial to late-stage quartz. Late-crystallizing minerals are not abundant in the pegmatite–aplite lens.

Numerous pseudomorphic replacements occur in the Main Lens (Table 2), including gittinsite + quartz after a Zr-silicate (Fig. 9), titanite + quartz ± fluorite after narsarsukite, Ca–Y silicate + fluorite after leifite, aegirine after arfvedsonite, and zircon after secondary gittinsite and armstrongite. The pseudomorphic replacement of a precursor by two or more minerals usually indicates replacement in the subsolidus stage; however, textural evidence from the medium-grained ER granite indicates that armstrongite replaces elpidite in the supersolidus stage (Birkett *et al.* 1992), and that gittinsite and quartz replace armstrongite in the subsolidus stage.

Zr-Silicate Morphology

The morphology of the Zr-silicate precursor to gittinsite + quartz pseudomorphs varies substantially throughout the Main Lens (Fig. 9). Comparison of these morphological characteristics helps to evaluate the cause of morphological variation, and determine the precursor mineral. In previous studies, gittinsite + quartz pseudomorphs were considered to have formed after either elpidite (*e.g.*, Miller 1986, Salvi & Williams-Jones 1990) or armstrongite (Birkett *et al.* 1992). Figure 10 illustrates the results of L/W (maximum dimension/minimum dimension) measurements of gittinsite + quartz pseudomorph grains in the Main Lens, elpidite grains from other parts of the Strange Lake peralkaline complex, and elpidite and armstrongite grains from an isolated part of the Main

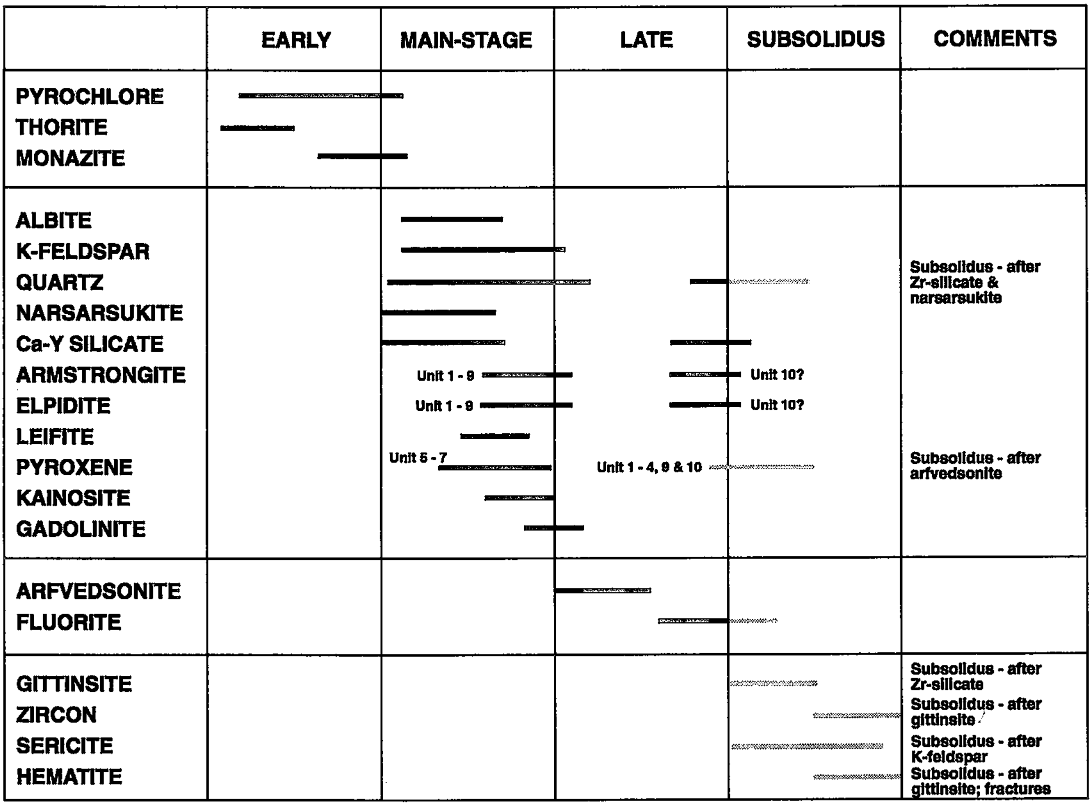

FIG. 8. Generalized paragenetic relationships of selected minerals in the Main Lens pegmatite–aplite.

Lens (D.D.H. LB 30).

The data indicate (Fig. 10) that the subhedral to euhedral pseudomorphs in aplite horizons of Units 1 and 2 (minimum L/W = 1.0) match the morphology of elpidite grains from both aplite and pegmatite, and armstrongite from aplite (minimum L/W ≈ 1.0; similar average and range). Pseudomorph morphology, except maximum data, in the aplite horizons of Units 3 and 4 matches that of elpidite in D.D.H. LB 30. Morphological data from Units 5, 6, 7 and 9 are substantially different from those of the lower units (*cf.* Fig. 9, Units 1 and 6) and primary elpidite and armstrongite (Fig. 10). Two interpretations of these data are evident: (1) two precursor minerals occur (elpidite and armstrongite), both exhibiting complex spatial relationships, and (2) one precursor mineral occurs (elpidite or armstrongite), exhibiting morphological changes between Units 1 and 2 and other units because of different conditions of crystallization (*e.g.*, zircon in various occurrences of felsic magma; Pupin 1980). Differentiation between these two interpretations requires further morphological and textural data for primary elpidite and armstrongite crystals, and further documentation of the formation of gittinsite + quartz pseudomorphs after Zr-silicate.

The L/W frequency distribution graphs (Fig. 10) and the increase in L/W average values indicate that the precursor mineral's habit became more elongate from the contacts of the lens toward the red aplite (Unit 6). This suggests that physical and chemical conditions in the magma (*e.g.*, variation in T and composition; Pupin 1980) systematically controlled changes in crystal habit from the contacts to the lens core; however, reference populations of elpidite, which came from both aplite and pegmatite, support only limited changes in elpidite morphology under different conditions of crystallization (*i.e.*, those conditions responsible for aplite *versus* pegmatite textures). Unaltered armstrongite is absent in pegmatites; thus its morphological characteristics in pegmatites are uncertain.

Textural relationships between primary Zr-silicates and secondary Zr-silicates indicate that zircon and gittinsite only replace armstrongite (this study and T.C. Birkett, pers. comm., 1994). Elpidite grains do not display replacement by gittinsite, whereas armstrongite

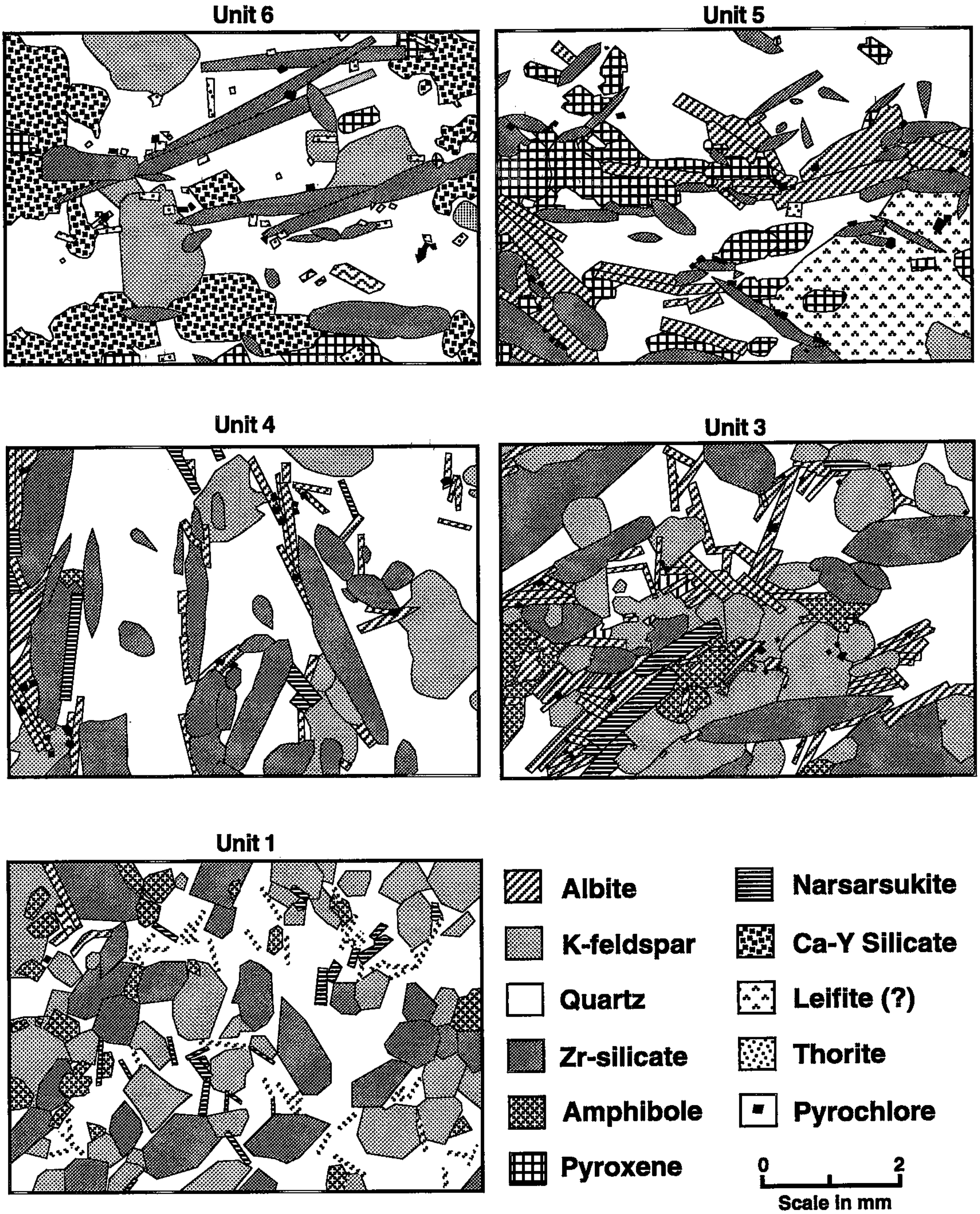

FIG. 9. Tracings of scanned photomicrographs of thin sections, illustrating some textures and the mineralogy of aplite in the Main Lens pegmatite–aplite.

displays partial replacement in rocks where both elpidite and armstrongite occur. These observations, and the fact that both armstrongite and gittinsite are CaZr silicates, whereas elpidite is a NaZr silicate, favor armstrongite as the more likely Zr-silicate precursor of gittinsite + quartz pseudomorphs.

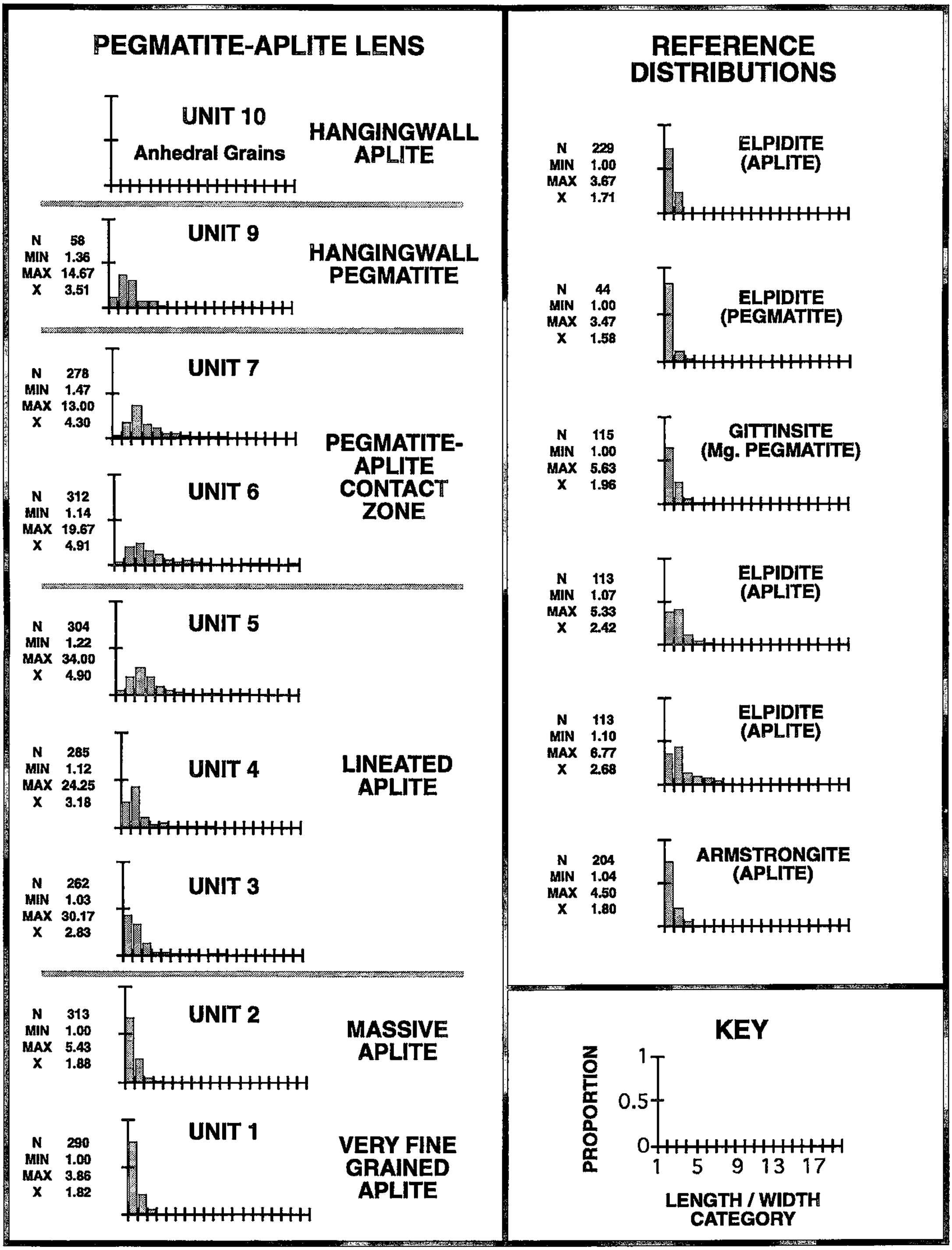

FIG. 10. Length/width distribution graphs and summary statistical data for Zr-silicate crystals, illustrating the variation in morphology in the Main Lens. The six reference distributions represent unaltered elpidite (4), unaltered armstrongite (1) and altered Zr-silicate (1) from various units throughout the Strange Lake peralkaline complex. N: number of measured crystals, MIN: minimum value, MAX: maximum value, and X: average value.

Relative Age Relationships

Table 4 outlines the relative age relationships found among different units of the Main Lens. These observations indicate the following relationships: (1) the units of the footwall zone (Units 1 to 5) form a sequence that youngs upward, (2) crystallization in the hanging-wall zone (Units 9 and 10) was coincident with the crystallization of Unit 5, and (3) the pegmatite–aplite contact zone (Units 6 and 7) was the last to crystallize. A previous interpretation (Miller 1990), based on location of the contact and similar grain-size, suggested that the hanging-wall lineated aplite (Unit 10) was coeval with the very fine-grained aplite of the footwall (Unit 1). Other textural and mineralogical characteristics, however, such as different proportions of the feldspars (Table 3, Fig. 7) and the presence or absence of mineral lineation, indicate that Unit 1 and Unit 10 are not coeval. Furthermore, these characteristics indicate that the lineated aplite of the hanging wall is similar to the lineated K-feldspar-poor aplite units of the footwall (Units 4 and 5), and that these units are coeval.

Discussion

Classification of the Main Lens pegmatite–aplite

The Main Lens pegmatite–aplite shows most of the characteristics of the gadolinite subtype, rare-earth type, and NYF family of the rare-element class of pegmatites as defined by Černý (1991a). Characteristics of the Strange Lake peralkaline complex and the Main Lens that match those of the rare-element class and NYF family include the following: (1) the structural setting is high-level (Miller 1986), (2) the Main Lens and related bodies occur within or marginal to the parent ER granite, (3) the Strange Lake complex is an anorogenic peralkaline granite (*e.g.*, Miller 1986), and, (4) the chemical signature of the granite, of the related mineralization, and of the Main Lens (Miller 1986) resembles that outlined by Černý (1991a: Nb<Ta, enrichment in Y, *HREE*, Be, F, U, Th, Ti, Zr). The close correspondence of the Main Lens to a well-defined class of pegmatite makes it amenable to chemical, structural, mineralogical, and petrographic comparison with other examples of its family, class and type.

Evolution of internal layering in the pegmatite–aplite lens

Rare-element granitic pegmatites, which are well-known for their heterogeneous, complex internal structure, exhibit homogeneous, zoned or layered structures (Černý 1991a). The structural arrangement of units in the Main Lens, aplitic footwall and pegmatitic hanging wall, is typical of layered pegmatites of all compositions (Jahns 1982, Černý 1991a). Studies of layered peralkaline (rare-element, NYF) granitic pegmatites are rare, however; the well-studied examples involve layered peraluminous (rare-element, LCT) granitic pegmatites: *e.g.*, the Little Three pegmatite–aplite, California (Stern *et al.* 1986) and the

TABLE 4. SUMMARY OF AGE RELATIONSHIPS, MAIN LENS PEGMATITE-APLITE

Unit*•	Description	Comments
Unit 6 & 7	Pegmatite-aplite Contact Zone	Red pegmatite veins (Unit 8) cut all aplites except red aplite (Unit 6); Unit 6 and 7 have a gradational contact.
Unit 9	Upper Pegmatite	Cuts all aplites except Unit 6; grades into the Unit 7 pegmatite.
Unit 4, 5 & 10	Lineated albite-rich aplite	Unit 10 autoliths occur in Unit 9. These units have a lineated texture and little or no K-feldspar.
Unit 3	Lower lineated unit	Gradational contact.
Unit 2	Massive aplite	Crosscuts Unit 1; gradational contact with Unit 3.
Unit 1	Very fine grained aplite	Chilled against lower contact.

* The oldest units appear at the bottom of the table and the youngest at the top.

• Relative ages are established by field and drill core data.

Calamity Peak layered granite–pegmatite complex, Black Hills, South Dakota (Duke *et al.* 1992). Layering in the Main Lens peralkaline pegmatite is similar to layering in many peraluminous pegmatites.

Pegmatite–aplite lenses generally display two levels of layering: (1) a layered structure consisting of aplitic footwall and pegmatitic hanging wall, and (2) nearly monomineralic aplitic layers oriented parallel to contacts. A layered structure is prominent in the Main Lens. Mineral layering, such as unidirectional or comb textures found in aplite (Kirkham & Sinclair 1985), occurs only sporadically in the Main Lens, although these textures are common in other pegmatite–aplite bodies (London 1992). Textural variations and patterns of mineral distribution in aplitic units (Table 3, Fig. 7) indicate that monomineralic layers are absent.

In a recent review of pegmatite genesis, London (1992) outlined four major mechanisms that may explain layering in igneous (*e.g.*, pegmatite–aplite) bodies: (1) cumulus processes (fractional crystallization), (2) pressure fluctuations (during equilibrium crystallization), (3) nonequilibrium sequential crystallization caused by significant undercooling below the liquidus (*in situ* crystallization), and (4) flow segregation. Any of these mechanisms may be responsible for layering in the Main Lens.

Other authors have rejected the cumulus or fractional crystallization process (London 1992) because differences in density of crystals and magma are too small and viscosities too high in pegmatite-forming magmas (Jahns & Tuttle 1963). However, experimental evidence (Dingwell *et al.* 1985, Baker & Vaillancourt 1995) clearly indicates that F-rich peralkaline magmas have much lower viscosities than subalkaline, peraluminous and metaluminous magmas. This finding demonstrates that peralkaline pegmatite-forming magmas could potentially exhibit enhanced fractional crystallization over other compositions. The morphology of Zr-silicate grains (main-stage paragenesis), however, indicates that gravity-driven processes (mixing or segregation of crystal populations) were absent, as each unit contains discrete populations of crystals. Each population crystallized *in situ*.

Pressure fluctuations were insignificant in producing layering in the Main Lens because of the absence of fluid saturation during main-stage crystallization. Miarolitic cavities, characteristic of fluid saturation in pegmatites (London 1992), are rare in the Main Lens, although they exist in other parts of the Strange Lake peralkaline complex (*e.g.*, Černý *et al.* 1991, Nassif 1993). London's work (*e.g.*, 1992) also indicates that fluid-undersaturated magmas more readily form the textures and geochemical features of granitic pegmatites. Fluid inclusions from quartz in pseudomorphs document the presence of an aqueous fluid (Salvi & William-Jones 1990, 1992), but this fluid probably relates to either a subsolidus stage or a very late fluid in equilibrium with the pegmatite-forming melt.

London (1992) advocated nonequilibrium sequential crystallization as a viable mechanism for pegmatite differentiation based on water-undersaturated experiments on Macusani glass (London *et al.* 1989). These experiments produced textural and mineral zones similar to those observed in many pegmatite–aplite bodies (Černý 1991a, b, London 1992). London (1992) and Černý (1991a) expressed the opinion that these experimental results apply to all types of pegmatite-forming magma (*e.g.*, the Strange Lake peralkaline magma), even though the experiments involved only peraluminous compositions.

Flow segregation may be significant in forming lineated units in the Main Lens (Units 3, 4, 5, 6, 7 and 10), where elongate early- to main-stage minerals exhibit a common preferred orientation; however, evidence for mineral segregation is lacking, whether operating alone or in cooperation with the cumulus process.

Structural, cross-cutting, petrographic, and mineralogical data outlined above provide information to construct a model of formation for the pegmatite–aplite lens. Figure 11 illustrates the four stages of this model.

Stage A begins with flow of residual magma, produced in the crystallizing ER stock, into the fracture zone between two subphases of the EI granite. Forceful emplacement of magma in an expanding fracture produced a semiclosed system. Rapid freezing along the cooler, less turbulent, lower contact of the channel way produced a very fine-grained aplitic chilled margin (Unit 1); thus, it approximates the bulk composition of the initial magma (compare Unit 1 and ER granite modes; Table 3). High flux of magma precluded crystallization along the upper contact. Unit 2, which is very similar to Unit 1 in mineralogy and mineral proportions (Fig. 7, Table 3), represents the bulk composition of a second influx of magma.

In Stage B, crystal formation on the footwall, migration of incompatible elements (*e.g.*, F, Y, Ca, *REE*, Th) toward the hanging wall, magma flow, and cooling (Fig. 11B) began to modify the parent magma. Magma flow continued to prevent crystallization on the hanging wall. A process of crystal–liquid differentiation produced a less dense residual magma in the boundary layer (*e.g.*, Baker & McBirney 1985), at the crystallization front, near the footwall, that rose upward and concentrated incompatible elements near the hanging wall. Magma flow may have affected the orientation of elongate minerals crystallizing at the main stage, and, perhaps, was important in the separation of incompatible-element-rich magma from crystals (Unit 3). The local occurrence of massive aplite (Unit 2) between Unit 1 and the contact (Fig. 5) indicates that Unit 2 is not part of a continuous unbroken sequence of crystallization between Unit 1 and other aplite members. Unit 2 probably forms the

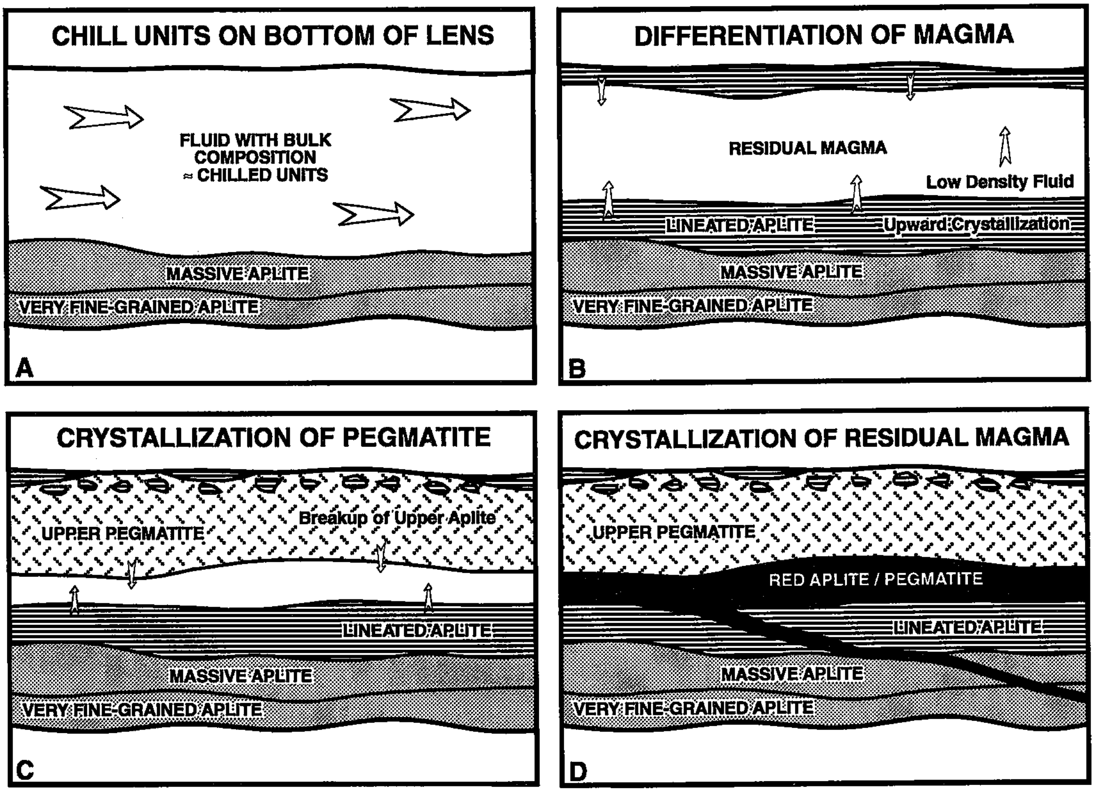

FIG. 11. Model illustrating the evolution of internal layering in the Main lens. Diagram A illustrates the initial stage, which starts with introduction of magma, and, the last stage, diagram D, illustrates the final crystallized product.

base of such a continuous sequence of crystallization, and represents the final influx of magma into the Main Lens. The Main Lens was a closed system at the end of this stage.

Stage C involved the solidification of the upper pegmatite (Unit 9) and the formation of albite-rich lineated aplite (Units 4, 5 and 10). Crystallization of magma at this time produced Unit 4 and then, later, both Units 5 and 10. The preferred orientation of elongate minerals indicates that magma flow continued during this stage. Breakup of Unit 10 aplite and the solidification of the hanging-wall pegmatite resulted in entrapment of aplite fragments in the upper parts of this pegmatite (Unit 9). Higher concentrations of the volatile components and incompatible elements, higher temperatures, and slower cooling rates promoted coarse grain-sizes, whereas lower concentrations of volatiles and incompatible elements and lower temperatures promoted aplitic grain-sizes (London 1992). Solidification of the hanging-wall and footwall zones confined the remaining residual magma to the pegmatite–aplite contact zone. Aegirine, the dominant mafic mineral in Units 4 and 5, formed at the expense of arfvedsonite (Table 3, Fig. 7). Units 5 and 10 represent the final stages of a trend toward low K-feldspar, higher albite, and lower Zr-silicate contents (Table 3).

The final stage (D) resulted in the formation of the highly fractionated red pegmatite–aplite in the contact zone. The pegmatite-forming magma (Units 7 and 9) also exploited cooling fractures to cross-cut aplite members as veins and dykes during Stages C and D (Figs. 5, 6). The same processes of differentiation that formed the hanging-wall – footwall pegmatite–aplite pair probably produced this pegmatite–aplite pair; accordingly, each pair involves the formation of fine-grained, relatively volatile-poor lower components, and coarser-grained, relatively volatile-rich upper components. These processes produce declining abundances of albite, K-feldspar, and Zr-silicate, and increasing concentrations of a wide variety of rare-metal minerals (*e.g.*, thorite, leifite, and Ca–Y silicate; Table 3, Fig. 7). Red aplite (Unit 6) contains abundant quartz, which occurs as large snowball grains, whereas the related red pegmatite (Unit 7) contains minor quartz (Table 3), which occurs as late interstitial grains.

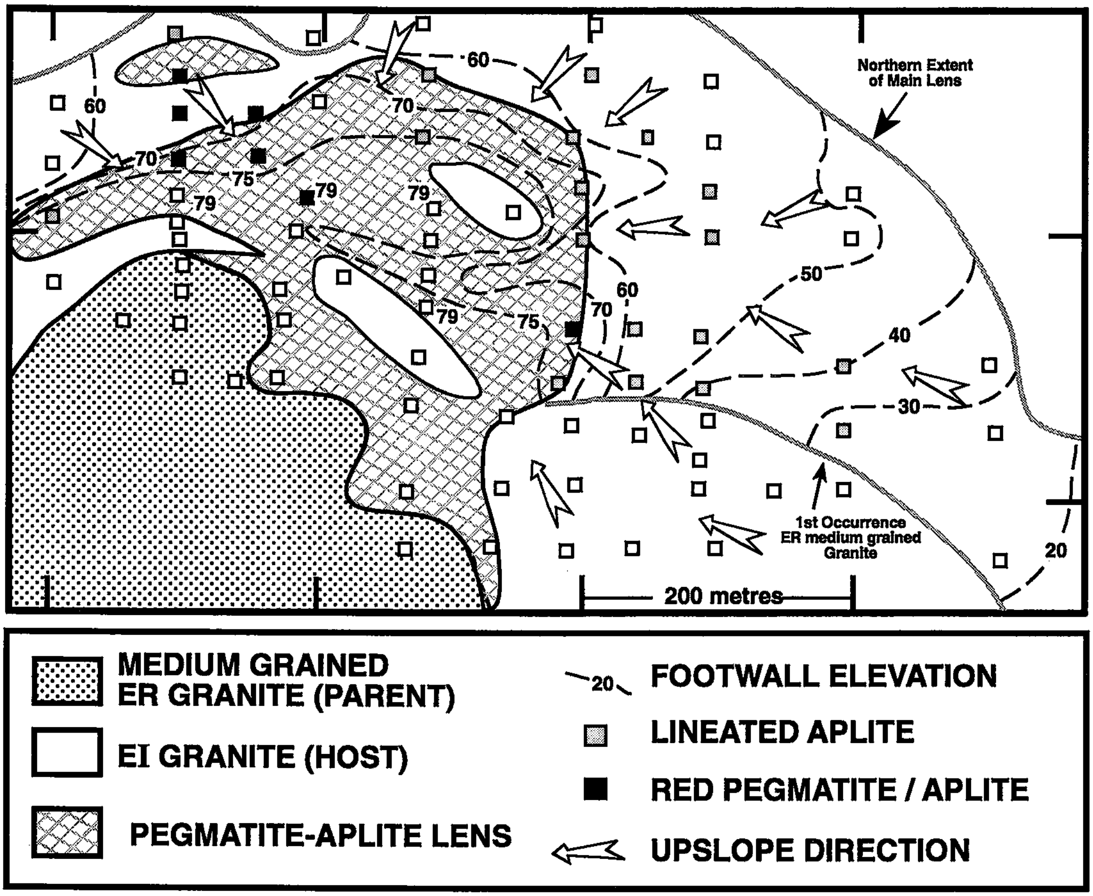

FIG. 12. Elevation contours of the footwall contact of the Main Lens illustrating the direction of movement of less dense and less viscous residual magma in the lens. The red pegmatite–aplite of the pegmatite–aplite contact zone represents crystallized residual magma. Portions of the unroofed part of the lens lack the pegmatite–aplite contact zone.

Subsequent subsolidus processes and, possibly, concurrent late crystallization (supersolidus) processes produced a number of pseudomorphic minerals (*e.g.*, gittinsite plus quartz formed after Zr-silicate). Birkett *et al.* (1992) have shown that gittinsite plus quartz is absent from many parts of the ER stock, thus implying that the pseudomorph-forming events were mainly subsolidus. These events also affected only some pegmatite–aplite bodies (*e.g.*, some parts of the Main Lens; Birkett *et al.* 1992), thus indicating that the formation of pegmatite–aplite bodies and any metasomatic processes are unrelated.

Even though closure of the lens prevented influx of magma before Stage C began, textural evidence indicates continued movement of magma within the lens. The low viscosity (Dingwell *et al.* 1985, Baker & Vaillancourt 1995) and low density (Dingwell *et al.* 1993) of F-rich and H_2O-rich peralkaline residual melts promoted magma movement; consequently, mineral lineation indicates flow in the lens. Generally lower viscosity of all batches of magmas in the lens system enhanced the movement of rising lower-density residual melts. Upslope directions in the Main Lens (Fig. 12; see also Figs. 4 and 5) indicate that rising low-viscosity – low-density melts gathered in the northwestern portion of the lens, where both the red aplite–pegmatite and lineated aplite occur. This mechanism accounts for the lateral zonation as well as the vertical zonation in the Main Lens.

Evolution of the pegmatite–aplite-forming magma

The occurrence of pegmatite–aplite within the spatially related ER stock (Fig. 2) and the physical connection between the Main Lens and this stock indicate that the stock is the source of the pegmatite–aplite-forming magma (Fig. 4). The similar chemistry and mineralogy of both the ER stock and ER pegmatite–aplite bodies further strengthen this conclusion (Miller 1986, Miller and Birkett, in prep.).

Integration of geological and structural data from both the Main Lens and the nearby ER intrusive unit defines a sequence of events that led to the formation of the Main Lens. This sequence of events consists of three stages (Fig. 13).

The initial stage involved the intrusion of an ER magma along the contact between previously crystallized EI and EP phases of the peralkaline granite. Fracturing occurred along the contact zone between these phases and along the contact between subphases of the EI granite. Incompatible and volatile elements concentrated mainly in the upper portion of the magma chamber, in a residual magma. This process, near the roof zone, was similar to that postulated for the Main Lens and, on a smaller scale, in other parts of the magma chamber (*i.e.*, to form pegmatite–aplite lenses and pods on the lower contacts and in the central parts of the stock).

Stage two involved the movement of incompatible-element- and volatile-rich residual magma into the fractures formed along contact zones. Most of the magma body solidified at this time, and, thus, no longer affected the formation of residual magma in the roof zone. The final stage resulted in the formation of pegmatite and pegmatite–aplite lenses in fracture zones, along the roof of the magma chamber and cross-cutting the previously solidified portions of the chamber.

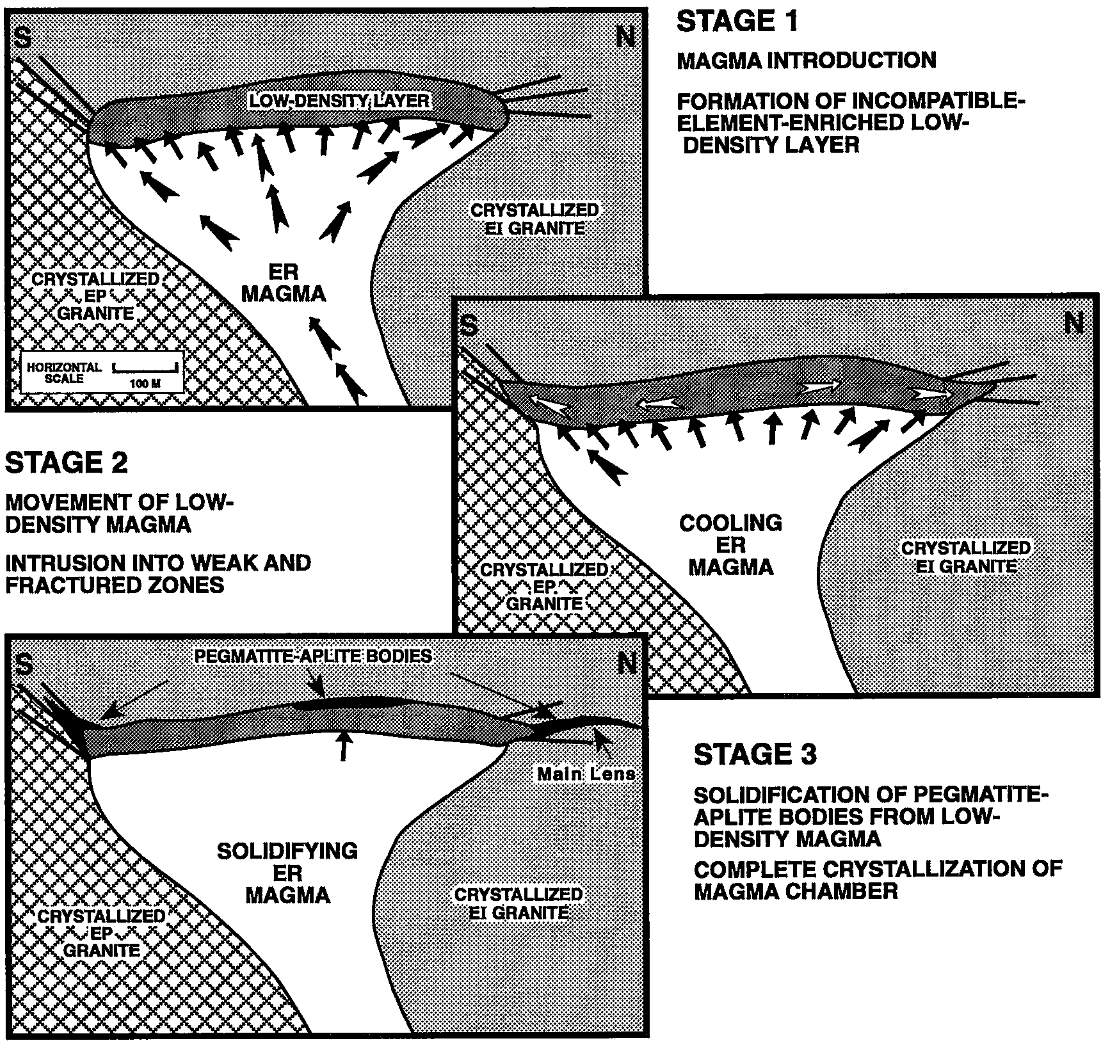

FIG. 13. General model for the evolution of the ER stock and the Main Lens pegmatite-forming magma.

Magmatic rare-metal mineralization

A number of rare and unusual minerals concentrate rare metals in the Strange Lake peralkaline complex (Table 2). The main ore minerals include the following: Zr: gittinsite; Nb: pyrochlore; Be: gadolinite; and, Y: Ca–Y silicate, kainosite, gadolinite. Most of these ore minerals are either primary minerals or are pseudomorphs after primary minerals that contain essential rare-metal elements.

The rare metals, as represented by total accessory minerals (Table 3; "Others" minus pseudomorphs after narsarsukite in Fig. 7), exhibit a dramatic increase from the contacts (Units 1 and 10) to the core of the lens (red pegmatite; Unit 7). In the core, the rare-metal-bearing minerals are twice as abundant as in either Units 5 or 6, and have an order-of-magnitude higher values than in any of the other units. This reflects the incompatibility of most rare metals in quartz, the feldspars, and Zr-silicate, the main-stage minerals crystallizing at the contact with the incompatible-element-enriched boundary layer; consequently, rare metals appeared either as late-stage minerals from residual liquid trapped between main-stage crystals in the earlier-formed units, or as main-stage minerals from residual melt collected in the pegmatite–aplite contact zone.

Zr-silicates exhibit a trend opposite to the other rare-metal minerals, as they decrease toward Unit 7. This finding indicates that Zr acts as a compatible element in the pegmatite–aplite lens; moreover, it indicates that Zr saturation occurs on the liquidus of the parent pegmatite-forming magma and subsequent differentiates (except Unit 10; Fig. 8).

Figure 14 illustrates the increase of rare-metal minerals (excluding Zr-minerals) from the bottom of the lens to the pegmatite–aplite contact zone. It also illustrates a constant ratio of quartz to quartz + feldspar + rare-metal accessory minerals, and a reciprocal decrease in feldspar proportion as rare-metal minerals increase from Unit 1 to Unit 6. Unit 7 crystallized from the most incompatible-element-enriched residual melt. A dramatic increase in the proportion of rare-metal minerals occurred in this unit at the expense of both quartz and feldspar.

If the arguments made by others concerning the residual magmatic origin of rare-element pegmatites (*e.g.*, Congdon & Nash 1991, Černý 1991a, b, London 1992) are accepted, then, by the same token, the Main Lens pegmatite–aplite also must have a residual magmatic origin. The structure, internal layering, relationship to parent body, and mineral variations within the Main Lens are comparable to those of other rare-element pegmatites (see Černý 1991a, b; *e.g.*, Little Three pegmatite–aplite intrusive body: Stern *et al.* 1986; the Calamity Peak layered granite–pegmatite complex: Duke *et al.* 1992), supporting a magmatic origin.

Systematic variation of mineral modes (Table 3, Figs. 7, 14), morphologies (Fig. 10), and textures indicate that magmatic processes, rather than

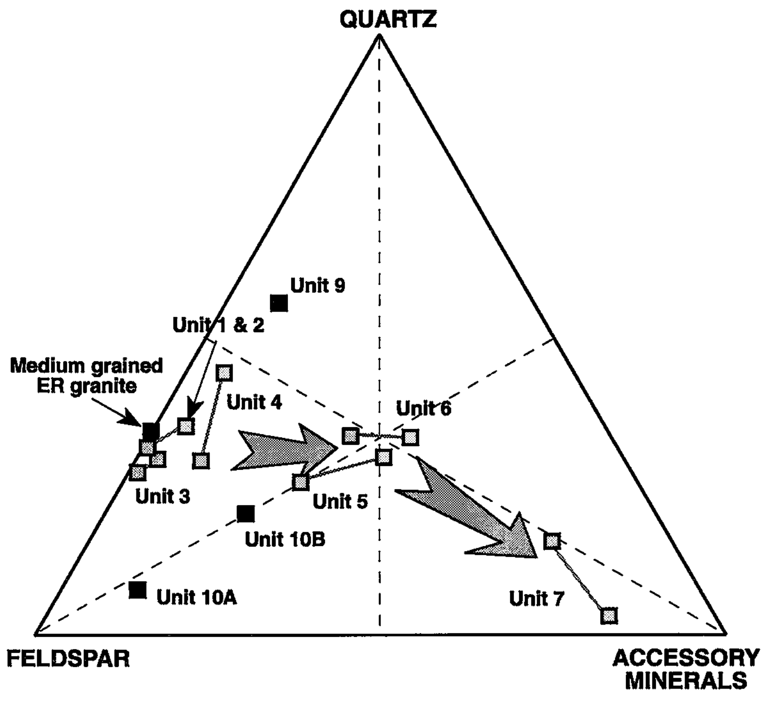

FIG. 14. Differentiation of the Main Lens magma as observed in mineral modes: Quartz – Feldspar (Albite + K-feldspar) – Total Accessory Minerals. Bars illustrate variability within a unit. Grey arrows illustrate the trend toward increasing proportion of accessory minerals and rare metals from the contacts of the Main Lens to the red pegmatite core.

subsolidus rare-metal metasomatism, were responsible for the distribution of primary and pseudomorphic precursor rare-metal and other minerals in the Main Lens. A subsolidus or supersolidus process, which may have involved late F- and, perhaps, Ca-bearing hydrothermal solutions (Birkett *et al.* 1992, Salvi & Williams-Jones 1990), produced rare-metal pseudomorphs after rare-metal minerals (*e.g.*, gittinsite after Zr-silicate). There is no evidence of significant remobilization of rare-metals (*e.g.*, Y or *REE*; Salvi & Williams-Jones 1990, Boily & Williams-Jones 1994) during this late event. The late pseudomorphism possibly relates to late H_2O saturation of the magma in some parts of the Main Lens (London 1992). The parent pegmatite-forming magma crystallized primary rare-metal minerals containing Zr (Zr-silicate), Nb (pyrochlore), Be (leifite?), and Y (Ca–Y silicate and kainosite?).

The geology, textures, and mineralogy of the Main Lens do not support the occurrence of a substantial subsolidus mass-transfer event. This event should produce veins (*e.g.*, fluorite veins; St. Lawrence peralkaline granite: Collins & Strong 1988) or channelways with demonstrably metasomatic or hydrothermal mineralogy (*e.g.*, greisen zones: Kontak 1994) near the Main Lens. Those environments that contain extensive hydrothermal systems commonly produce chlorite or sericite pseudomorphs after feldspar [*e.g.*, peralkaline calderas: *e.g.*, Miller (1994), Abdel-Rahman & Miller (1994), under volcanogenic massive sulfide deposits: *e.g.*, Barrett & MacLean (1994), porphyry deposits: *e.g.*, Titley (1994)]. This is not so for the Main Lens. The absence of these metasomatic indicators argues against substantial transport of rare metals during a subsolidus metasomatic event.

Conclusions

The structure, mineralogy, field, and petrographic characteristics of the Main Lens pegmatite–aplite in the Strange Lake peralkaline complex provide the following conclusions concerning the formation of peralkaline rare-element (NYF) pegmatites and associated rare-metal mineralization:

(1) the pegmatite–aplite lens is mineralogically complex, contains many rare and unusual rare-metal-enriched minerals, and displays systematic vertical variations in mineral assemblages, proportions, sizes, and morphology;

(2) the residual magma that differentiated from the connected medium-grained ER peralkaline granite produced the pegmatite-forming magma;

(3) differentiation within the pegmatite–aplite lens produced both vertical and lateral zoning; the vertical zoning consists of an aplite footwall zone and a pegmatite hanging-wall zone;

(4) an incompatible-element-enriched boundary layer at the footwall front of crystallization produced differentiated pegmatite-forming magma; the boundary layer concentrated less dense residual magma that rose in the denser bulk magma, and, collected in the hanging-wall zone and higher-elevation parts of the lens (*i.e.*, the northwestern part of the lens);

(5) rare-metal mineralization is magmatic in origin; in essence, the processes that formed incompatible-element-enriched residual magma produced economically interesting concentrations of rare metals, such as Y, Nb, Be, *REE*, and Zr;

(6) the pegmatite-forming model of London (1992) and Černý (1991a, b), mainly derived for subaluminous to peraluminous compositions, also applies to pegmatites of peralkaline composition.

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References

Abdel-Rahman, A.M. & Miller, R.R. (1994): Extreme Na-depletion in peralkaline volcanic rocks of the Flowers River Cauldron Complex, Labrador. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **19**, A1.

Baker, B.H. & McBirney, A.R. (1985): Liquid fractionation. III. Geochemistry of zoned magma and the compositional effects of liquid fractionation. *J. Volcanol. Geotherm. Res.* **24**, 55-81.

Baker, D.R. & Vaillancourt, J. (1995): The low viscosities of F + H_2O-bearing granitic melts and implications for melt extraction and transport. *Earth Planet. Sci. Lett.* **132**, 199-211.

BARRETT, T.J. & MACLEAN, W.H. (1994): Chemostratigraphy and hydrothermal alteration in exploration for VMS deposits in greenstones and younger volcanic rocks. *In* Alteration and Alteration Processes Associated with Ore-forming Systems (D.R. Lentz, ed.). *Geol. Assoc. Can., Short Course Notes* **11**, 433-467.

BATTERSON, M.J. (1989): Glacial dispersal from the Strange Lake alkalic complex, northern Labrador. *In* Drift Prospecting (R.N.W. DiLabio & W.B. Coker, eds.). *Geol. Surv. Can., Pap.* **89-20**, 31-40.

BIRKETT, T.C., MILLER, R.R., ROBERTS, A.C. & MARIANO, A.N. (1992): Zirconium-bearing minerals of the Strange Lake Intrusive Complex, Quebec–Labrador. *Can. Mineral.* **30**, 191-205.

BOILY, M. & WILLIAMS-JONES, A.E. (1994): The role of magmatic and hydrothermal processes in the chemical evolution of the Strange Lake plutonic complex, Québec–Labrador. *Contrib. Mineral. Petrol.* **118**, 33-47.

BRYON, D.N., ATHERTON, M.P. & HUNTER, R.H. (1994): The description of the primary textures of "Cordilleran" granitic rocks. *Contrib. Mineral. Petrol.* **117**, 66-75.

ČERNÝ, P. (1991a): Rare-element granitic pegmatites. I. Anatomy and internal evolution of pegmatite deposits. *Geosci. Can.* **18**, 49-67.

________ (1991b): Rare-element granitic pegmatites. II. Regional to global environments and petrogenesis. *Geosci. Can.* **18**, 68-81.

________ (1991c): Fertile granites of Precambrian rare-element pegmatite fields: is geochemistry controlled by tectonic setting or source lithologies. *Precambr. Res.* **51**, 429-468.

________, HAWTHORNE, F.C., JAMBOR, J.L. & GRICE, J.D. (1991): Yttrian milarite. *Can. Mineral.* **29**, 533-541.

COLLINS, C.J. & STRONG, D.F. (1988): A fluid inclusion and trace element study of fluorite veins associated with peralkaline St. Lawrence granite, Newfoundland. *In* Recent Advances in the Geology of Granite-Related Mineral Deposits (R.P. Taylor & D.F. Strong, eds.). *Can. Inst. Min. Metall., Spec. Pap.* **39**, 291-302.

CONGDON, R.D. & NASH, W.P. (1991): Eruptive pegmatite magma: rhyolite of the Honeycomb Hill, Utah. *Am. Mineral.* **76**, 1261-1278.

CURRIE, K.L. (1985): An unusual peralkaline granite near Lac Brisson, Quebec–Labrador. *Geol. Surv. Can., Pap.* **85-1A**, 73-80.

DINGWELL, D.B., KNOCHE, R. & WEBB, S.L. (1993): The effect of F on the density of haplogranite melt. *Am. Mineral.* **78**, 325-330.

________, SCARFE, C.M. & CRONIN, D.J. (1985): The effect of fluorine on viscosities in the system Na_2O–Al_2O_3–SiO_2: implications for phonolites, trachytes and rhyolites. *Am. Mineral.* **70**, 80-87.

DRYSDALL, A.R., JACKSON, N.J., RAMSAY, C.R., DOUCH, C.J. & HACKETT, D. (1984): Rare element mineralization related to Precambrian alkali granites in the Arabian Shield. *Econ. Geol.* **79**, 1366-1377.

DUKE, E.F., PAPIKE, J.J. & LAUL, J.C. (1992): Geochemistry of a boron-rich peraluminous granite pluton: the Calamity Peak layered granite – pegmatite Complex, Black Hills, South Dakota. *Can. Mineral.* **30**, 811-833.

HILDRETH, W. (1981): Gradients in silicic magma chambers: implications for lithospheric magmatism. *J. Geophys. Res.* **86**, 10153-10192.

HILL, J.D. & MILLER, R.R. (1990): A review of Middle Proterozoic epigenic felsic magmatism in Labrador. *In* Mid-Proterozoic Laurentia – Baltica (C.F. Gower, T. Rivers & B. Ryan, eds.). *Geol. Assoc. Can., Spec. Pap.* **38**, 417-431.

JAHNS, R.H. (1982): Internal evolution of granitic pegmatites. *In* Granitic Pegmatites in Science and Industry (P. Černý, ed.). *Mineral. Assoc. Can., Short Course Handbook* **8**, 293-327.

________ & TUTTLE, O.F. (1963): Layered pegmatite–aplite intrusives. *Mineral. Soc. Am., Spec. Pap.* **1**, 78-92.

KIRKHAM, R.V. & SINCLAIR, W.D. (1988): Comb quartz layers in felsic intrusions and their relationship to porphyry deposits. *In* Granite-Related Mineral Deposits (R.P. Taylor & D.F. Strong, eds.). *Can. Inst. Min. Metall., Spec. Pap.* **39**, 50-71.

KONTAK, D.J. (1994): Geological and geochemical studies of alteration processes in a fluorine-rich environment: the East Kemptville Sn–(Zn–Cu–Ag) Deposit, Yarmouth County, Nova Scotia, Canada. *In* Alteration and Alteration Processes Associated with Ore-Forming Systems (D.R. Lentz, ed.). *Geol. Assoc. Can., Short Course Notes* **11**, 261-314.

KOVALENKO, V.I. & LAPIDES, I.L. (1974): Physical conditions of crystallization of a topaz-bearing quartz keratophyre (ongonite) dike. *Dokl. Acad. Sci. USSR, Earth Sci. Sect.* **215**, 154-157.

LANGMUIR, C.H. (1989): Geochemical consequences of in situ crystallization. *Nature* **340**, 199-205.

LARSEN, L.M. & SØRENSEN, H. (1987): The Ilímaussaq intrusion – progressive crystallization and formation of layering in an agpaitic magma. *In* Alkaline Igneous Rocks (J.G. Fitton & B.G.J. Upton, eds.). *Geol. Soc., Spec. Publ.* **30**, 473-488.

LONDON, D. (1990): Internal differentiation of rare-element pegmatites; a synthesis of recent research. *In* Ore-Bearing Granite Systems; Petrogenesis and Mineralizing Processes (H.L. Stein & J.L. Hannah, eds.). *Geol. Soc. Am., Spec. Pap.* **246**, 35-50.

________ (1992): The application of experimental petrology to the genesis and crystallization of granitic pegmatites. *Can. Mineral.* **30**, 499-540.

________, MORGAN, G.B., VI & HERVIG, R.L. (1989): Vapor-undersaturated experiments with Macusani glass + H_2O at 200 MPa, and the internal differentiation of granitic pegmatites. *Contrib. Mineral. Petrol.* **102**, 1-17.

MCCONNELL, J.W. & BATTERSON, M.J. (1987): The Strange Lake Zr–Y–Nb–Be–*REE* deposit, Labrador: a geochemical profile in till, lake and stream sediment, and water. *J. Geochem. Explor.* **29**, 105-127.

MILLER, R.R. (1985): Geology of the Strange Lake alkalic complex and the associated Zr–Y–Nb–Be–*REE* mineralization. *In* Granite-Related Mineral Deposits: Geology, Petrogenesis and Tectonic Setting (R.P. Taylor & D.F. Strong, eds.). *Can. Inst. Min. Metall., Extended Abstr.*, 193-196.

________ (1986): Geology of the Strange Lake Alkalic Complex and the associated Zr–Y–Nb–Be–*REE* mineralization. *Nfld. Dep. Mines, Mineral Develop. Div., Rep.* **86-1**, 11-19.

________ (1987): The relationship between Mann-type Nb–Be mineralization and felsic peralkaline intrusives, Letitia Lake Project, Labrador. *Nfld. Dep. Mines, Mineral Develop. Div., Rep.* **87-1**, 83-91.

________ (1988): Yttrium (Y) and other rare metals (Be, Nb, REE, Ta, Zr) in Labrador. *Nfld. Dep. Mines, Mineral Develop. Div., Rep.* **88-1**, 229-245.

________ (1990): The Strange Lake pegmatite–aplite hosted rare-metal deposit, Labrador. *Nfld. Dep. Mines Energy, Geol. Surv. Branch, Rep.* **90-1**, 171-182.

________ (1993): Rare-metal mineralization in the Nuiklavik volcanic rocks of the Flowers River Igneous Suite. *Nfld. Dep. Mines Energy, Geol. Surv. Branch, Rep.* **93-1**, 363-371.

________ (1994): Extreme Na-depletion in the peralkaline volcanic rocks of the Middle Proterozoic Flowers River Cauldron Complex, Labrador. *Nfld. Dep. Mines Energy, Geol. Surv. Branch, Rep.* **94-1**, 233-246.

________, HEAMAN, L.M. & BIRKETT, T.C. (1996): U–Pb zircon age of the Strange Lake Peralkaline Complex: implications for Mesoproterozoic peralkaline magmatism in north-central Labrador. *Precambr. Res.* (in press).

NASSIF, G.J. (1993): *The Strange Lake Peralkaline Complex, Quebec–Labrador: the Hypersolvus–Subsolvus Granite Transition and Feldspar Mineralogy.* M.Sc. thesis, McGill Univ., Montreal, Quebec.

PILLET, D., BONHOMME, M.G., DUTHOU, J.L., & CHENEVOY, M. (1989): Chronologie Rb/Sr et K/Ar du granite peralcalin du lac Brisson, Labrador central, Nouveau-Québec. *Can. J. Earth Sci.* **26**, 328-332.

________, CHENEVOY, M. & BÉLANGER, M. (1992): Pétrologie du granite peralcalin du Lac Brisson, Labrador central, Nouveau-Québec. I. Mode de mise en place et évolution chimique. *Can. J. Earth Sci.* **29**, 353-372.

POLLARD, P.J. (1989): Geologic characteristics and genetic problems associated with the development of granite-hosted deposits of tantalum and niobium. *In* Lanthanides, Tantalum and Niobium (P. Möller, P. Černý & F. Saupé, eds.). *Soc. Geol. Appl. Mineral Dep., Spec. Publ.* **7**, 240-256.

PUPIN, J.P. (1980): Zircon and granite petrology. *Contrib. Mineral. Petrol.* **73**, 207-220.

SALVI, S. & WILLIAMS-JONES, A.E. (1990): The role of hydrothermal processes in the granite-hosted Zr, Y, *REE* deposit at Strange Lake, Quebec/Labrador: evidence from fluid inclusions. *Geochim. Cosmochim. Acta* **54**, 2403-2418.

________ & ________ (1992): Reduced orthomagmatic C–O–H–N–NaCl fluids in the Strange Lake rare-metal granitic complex, Quebec/Labrador, Canada. *Eur. J. Mineral.* **4**, 1155-1174.

STEENFELT, A. (1991): High-technology metals in alkaline and carbonatitic rocks in Greenland: recognition and exploration. *J. Geochem. Explor.* **40**, 263-279.

STERN, L.A., BROWN, G.E., JR., BIRD, D.K., JAHNS, R.H., FOORD, E.E., SHIGLEY, J.E. & SPAULDING, L.B., JR. (1986): Mineralogy and geochemical evolution of the Little Three pegmatite–aplite layered intrusive, Ramona, California. *Am. Mineral.* **71**, 406-427.

TITLEY, S.R. (1994): Evolutionary habits of hydrothermal and supergene alteration in intrusion-centred ore systems, southwestern North America. *In* Alteration and Alteration Processes Associated with Ore-forming Systems (D.R. Lentz, ed.). *Geol. Assoc. Can., Short Course Notes* **11**, 237-260.

TOROKHOV, M.P. (1993): The role of liquid immiscibility in the accumulation of rare metals in peralkaline granitic and alkaline natural compounds. *In* Rare Earth Minerals: Chemistry, Origin and Ore Deposits. *Mineral. Soc. G. Brit. Ire., Natural Hist. Mus., IGCP Project 282 and IGCP Project* 314, A143-A144 (abstr.).

WOLFF, J.A., WÖRNER, G. & BLAKE, S. (1990): Gradients in physical parameters in zoned felsic magma bodies: implications for evolution and eruptive withdrawal. *J. Volcanol. Geotherm. Res.* **43**, 37-55.

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