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# A STUDY OF FELDSPAR PHASES IN THE HIGH-SILICA, HIGH-LEVEL ACKLEY GRANITE, SOUTHEASTERN NEWFOUNDLAND

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## ABSTRACT

Mineralogical and chemical studies of feldspar phases within the highly evolved, volatile-rich, polyphase Devono-Carboniferous Ackley Granite, southeastern Newfoundland, reveal a complex physicochemical history. The two oldest units (≥390 Ma) are characterized by triclinic alkali feldspar ($0.8 < \Delta < 0.93$), with coarse film perthite and zoned, sodic plagioclase ($An_{12-46}$). In contrast, younger units (≤374 Ma) are characterized by orthoclase, in places characterized by film perthite, with only local, incipient development of triclinic alkali feldspar. Plagioclase compositions within the younger units show a continuum from $An_{28}$ to end-member albite. Albite is considered to have formed by interaction of primary sodic plagioclase with late-stage, high-temperature (≥450°C), saline magmatic fluids generated during resurgent boiling. Whereas ordered, triclinic alkali feldspar within the older units is consistent with the presence of deformational textures, the occurrence of orthoclase within the younger units saturated with volatiles is consistent with the widespread development of postmagmatic albite formed within the stability field of orthoclase (*i.e.*, >450°C). Subsequent cooling through the microcline-stable regime was rapid owing to the shallow level of emplacement, and led to the development of "stranded" orthoclase. Bulk compositions of the alkali feldspars reflect decreasing mol.% Or toward more evolved compositions, consistent with phase equilibria (*i.e.*, indicates lower T of formation), and together with coexisting plagioclase phases, indicate minimum T of 550–700°C for crystallization. In contrast, subsolidus re-equilibration continued to 350° to 400°C based on the composition of coexisting albite lamellae and host orthoclase. Trace-element chemistry of the alkali feldspar samples reflects progressive geochemical evolution of mineral phases, in parallel with the whole-rock geochemistry. However, local fluctuations of elemental concentrations (to several 100 ppm) of Ba, Rb and Sr are considered to reflect modification of the melt chemistry by local saturation in fluid. Although the *REE* contents and chondrite-normalized patterns are generally typical of alkali feldspar, the enrichment of some samples in *HREE* [$(Tb/Lu)_N$ less than 1] is considered to reflect the influence of exsolved fluids on *REE* partitioning such that alkali feldspar with similar bulk compositions have highly variable concentrations of *HREE*.

*Keywords:* alkali feldspar, Al–Si order, geochemistry, granite, Ackley Granite, Newfoundland.

## SOMMAIRE

Une étude minéralogique et chimique des feldspaths dans le massif granitique relativement évolué et enrichi en phase volatile de Ackley, dans le secteur sud-est de Terreneuve, d'âge dévono-carbonifère, révèle une évolution physico-chimique compliquée. Les deux unités les plus anciennes (≥390 Ma) possèdent un feldspath alcalin triclinique ($0.8 < \Delta < 0.93$), dans lequel la texture perthitique est grossière et en pellicules, et un plagioclase sodique zoné ($An_{12-46}$). Par contre, les phases plus tardives (≤374 Ma) contiennent de l'orthose, dont la texture perthitique est en pellicules, avec développement local seulement d'un feldspar triclinique. La composition du plagioclase coexistant définit un continuum entre $An_{28}$ et de l'albite pure. L'albite résulterait de l'interaction du plagioclase sodique primaire avec une saumure orthomagmatique à une température élevée (≥450°C) suite son exsolution du magma. Tandis que la présence d'un feldspath alcalin triclinique ordonné dans les phases précoces concorde avec les signes de déformation, la présence d'orthose dans les phases tardives saturées en phase volatile concorde avec le développement répandu d'albite postmagmatique à l'intérieur du champ de stabilité de l'orthose, c'est-à-dire au dessus de 450°C. Un refroidissement rapide par la suite à travers le champ de stabilité du microcline a conservé l'orthose sous forme métastable. La composition globale des échantillons de feldspath alcalin indique une diminution dans la proportion d'Or vers les compositions de plus en plus évoluées, selon les prédictions des études de l'équilibre des phases, indiquant une plus faible température de formation. L'équilibre avec le plagioclase coexistant indique une température minimale de cristallisation entre 550° et 700°C. Par contre, le ré-équilibrage subsolidus a continué jusqu'à 350° ou 400°C, d'après la composition des lamelles d'exsolution d'albite coexistantes avec l'orthose. La géochimie des échantillons de feldspath alcalin change selon l'évolution progressive des phases minérales, en parallèle avec la géochimie des roches totales. Toutefois, les fluctuations en concentrations de Ba, Rb, et Sr (jusqu'à plusieurs centaines de ppm) résulteraient d'une modification de la composition du magma suite à une saturation locale en phase fluide. Quoique les teneurs en terres rares et les spectres normalisés en fonction de teneurs chondritiques sont en général typiques de feldspath alcalin, l'enrichissement des terres rares lourdes dans certains échantillons [$(Tb/Lu)_N < 1$] témoignerait de l'influence d'une phase volatile exsolvée sur le coefficient de distribution des terres rares, de sorte que les échantillons de feldspath alcalin de composition globale à peu près constante montrent une grande variabilité dans leurs teneurs.

(Traduit par la Rédaction)

*Mots-clés*: feldspath alcalin, degré d'ordre Al–Si, géochimie, granite, Ackley, Terre-Neuve.

## INTRODUCTION

The Ackley Granite, southeastern Newfoundland (Fig. 1), is a post-tectonic, predominantly high-silica, biotite ± hornblende granite complex that represents the product of crystallization of a zoned, 2700-km$^2$ body of magma (Dickson 1983, Whalen 1983, Tuach *et al.* 1986, Tuach 1987). Geochemical gradients from

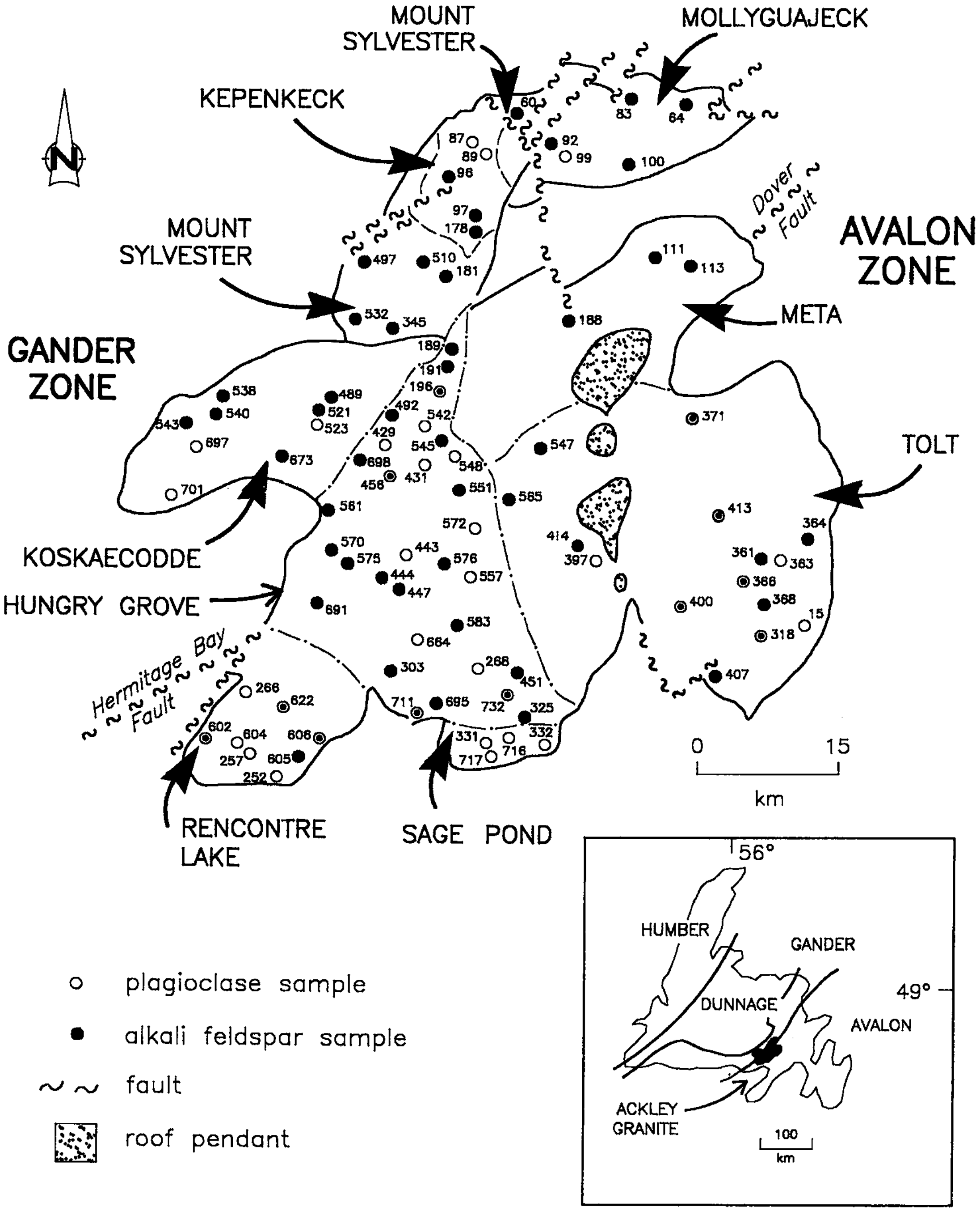

FIG. 1. Location of the Ackley Granite in southeastern Newfoundland, at the boundary between the Gander and Avalon tectonic zones. Map of the Ackley Granite shows the outline of the different units (after Tuach 1987) and sample locations for the study of alkali feldspar and plagioclase.

north to south culminate in the development of highly evolved granites spatially associated with extensive zones of greisen with Sn–W and Mo mineralization (Whalen 1980, 1983, Tuach 1984, 1987). Tuach (1987) has suggested affinities with the A-type of granite (Whalen *et al.* 1987).

The geometry of the pluton and excellent density of sampling (*i.e.*, one sample per 4 km$^2$, 357 station localities), in addition to the presence of compositional zonation, make the Ackley Granite an excellent site for studies of igneous petrology. Whereas whole-rock chemistry (Dickson 1983, Whalen 1983, Tuach *et al.* 1986) and some isotopic (O, Sr; Tuach *et al.* 1985, Tuach 1987) work has been done, the mineralogical phases remain essentially unstudied. This study focuses on the chemical and physical variations in the feldspars, and the insight that they provide concerning the magmatic trends and subsolidus adjustments that have affected the Ackley Granite.

## GEOLOGICAL SETTING AND SUBDIVISIONS OF THE ACKLEY GRANITE

The Ackley Granite is one of several Devonian granitoid bodies intruded into the Gander Zone and western side of the Avalon Zone in southeastern Newfoundland (Fig. 1). In the Gander Zone, the country rocks include mid-Ordovician and older metamorphosed and deformed sedimentary rocks of the Gander Group and volcano-sedimentary rocks of the Baie d'Espoir Group. In the Avalon Zone, the country rocks include Late Precambrian volcanic and sedimentary rocks of the Long Harbour and Love Cove groups, sedimentary rocks of the Late Precambrian Musgravetown Group, and Cambrian or older Youngs Cove Group (Williams 1971). Although mid-Paleozoic deformation and metamorphism were broadly contemporaneous (*ca.* 360–400 Ma) within, respectively, both the western Avalon Zone and the eastern Gander Zone, they were more intense and of higher grade in the latter. The Ackley Granite is largely undeformed and is inferred to be younger than the regional deformation and metamorphism. Undeformed, fossiliferous Late Devonian sedimentary rocks of the Cinq Isles and Great Baie de L'Eau formations outcrop south of the Ackley Granite.

The Ackley Granite was originally subdivided by Dickson (1983) into ten major lithological units on the basis of textural and mineralogical features, with contacts interpreted to be gradational. Dickson recognized the granite as being epizonal, with a narrow contact aureole containing cordierite and andalusite. Subsequently, Tuach (1987), Tuach *et al.* (1986) and Kontak *et al.* (1988) modified the subdivisions of the granite on the basis of more detailed petrographic, isotopic and geochronological studies (Fig. 1). $^{40}$Ar/$^{39}$Ar dating indicates that the intrusion is polyphase, with distinct magmatic events recognized at ≥390 Ma (Koskaecodde and Mollyguajeck units), 378–374 Ma (Kepenkeck – Mount Sylvester, Meta, Hungry Grove, Sage Pond and Rencontre Lake units) and 355 Ma (Tolt unit). Mineralization (Sn, W, Mo), concentrated along the southern margin of the granite, is dated at 372 Ma (Kontak *et al.* 1988), thus coincident with the 374 Ma plutonic event.

## MINERALOGY OF THE ACKLEY GRANITE

The granite (Table 1) contains biotite throughout, with both hornblende and muscovite of restricted distribution, and accessory titanite, allanite, apatite, zircon and magnetite. In general, the Koskaecodde unit is a coarse-grained, K-feldspar-phyric biotite–hornblende granodiorite, whereas the Mollyguajeck unit is a medium- to coarse-grained, K-feldspar-phyric biotite monzogranite with minor hornblende granodiorite. The adjacent Mount Sylvester – Kepenkeck unit is a medium- to coarse-grained, biotite ± muscovite, K-feldspar-phyric monzogranite. The bulk of the Ackley Granite underlies the area to the south of the Hermitage Bay Fault and is dominated by medium- to coarse-grained, equigranular to K-feldspar-megacrystic biotite monzogranite to alkali feldspar granite. There is a general southward decrease in grain size and increasing abundance of miarolitic cavities in the southern part of the Hungry Grove unit, culminating in highly variable textures in the Rencontre Lake and Sage Pond units. These two units contain fine- to medium-grained, equigranular to K-feldspar-megacrystic biotite monzogranite and alkali feldspar granite, with some pegmatitic segregations, miarolitic cavities, breccias and granophyre. These features, in conjunction with the general textural and chemical zonation, and the presence of roof pendants, reflect close proximity to the original top of the magma chamber. Of particular relevance to this study are the occurrence of deformational fabrics in quartz, plagioclase and biotite, and the dominance of grid-twinned microcline in the two older units; such twinning is rarely seen in the rest of the Ackley Granite.

The *alkali feldspar* in all units of the Ackley Granite consists of microcline and orthoclase perthite, and there is a notable reddening of the feldspar grains toward the southern part of the intrusive complex. In the older units, coarse flame and patch perthite dominate, almost to the exclusion of other types. In the younger unit, the most common types of perthite are flame and patch, and these generally increase in proportion toward the southern part of the intrusive complex. Film perthite occurs within isolated areas or between flame and patch types; this phenomenon is mostly confined to less evolved samples and is rarely seen in southern, most evolved part of the Ackley Granite.

The distribution of perthite within the Ackley Granite shows a general relationship with geochemical

TABLE 1. SUMMARY OF RELEVANT FEATURES FOR UNITS OF THE ACKLEY GRANITE

| | | | | [2]Textures | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Phase** | **[1]Age (Ma)** | **Grain Size** | **[4]Mineralogy** | **Defm** | **Rap** | **Miar** | **Gran/Grap** | **Pegm** | **Brec** | **Apl** |
| Koskaecodole | >410 (Bt) | coarse | Qz-Pl-Kf-Bt±Hb | ✓ | | | | | | |
| Mollyguajeck | >390 (Bt) | coarse | Qz-Pl-Kf-Bt±Hb | ✓ | | | | | | |
| Mt. Sylvester | 374 (Bt) | medium to coarse | Qz-Pl-Kf-Bt±Ms | | | | | | | |
| Kepenkeck | 367 (Bt)<br>378 (Ms) | coarse | Qz-Pl-Kf-Bt±Ms | | | | | | | |
| Meta | - | coarse | Qz-Pl-Kf-Bt±Hb | | ✓ | | | | | |
| Tolt | 355 (Bt) | medium to coarse | Qz-Pl-Kf-Bt | | ✓ | | ✓ | | | |
| [3]Hungry Grove | 367 (Bt) | coarse to fine | Qz-Pl-Kf-Bt | | ✓ | ✓ | ✓ | | | ✓ |
| Rencontre Lake | 372 (Ms)<br>368 (Bt) | medium to fine | Qz-Pl-Kf-Bt±Hb | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Sage Pond | 374 (Hb)<br>372 (Bt)<br>374 (Ms) | medium to fine | Qz-Pl-Kf-Bt | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

[1] Age: Total fusion $^{40}$Ar/$^{39}$Ar ages (Kontak et al. 1988); Ms from Rencontre Lake and Saga Pond represent mineralized greisens.
[2] Textures: Summarized from Tuach (1987), Dickson (1983) and own observations.
[3] Hungry Grove: Textures vary from north to south such that more evolved facies (texturally) occur in the south.
[4] Mineralogy: Kf here indicates dominantly microcline perthite in older phases
Abbreviations: Defm = deformation; Rap = rapakivi; Miar = miarolitic; pegm = pegmatitic; Brec = breccia (fluidized); Apl = aplitic; gran = granophyric; grap = graphic

evolution such that more evolved units are characterized by volumetrically more perthite that is coarser and of a greater variety (*i.e.*, several types). This trend is similar to observations made by Weiss & Troll (1989) with respect to perthite within the zoned Ballachulish Complex of Scotland. Coarsening of the perthitic texture in parallel with geochemical evolution is, as suggested by Parsons (1978), consistent with an increasingly more active role of fluids in the more evolved units.

In light of the following section on geochemistry, it is noted that rare micro-inclusions of biotite and quartz are encountered.

## Analytical Techniques

High-quality separates of K-feldspar were prepared by pulverizing and sieving (–20 to +65 mesh) followed by hand picking under a binocular microscope and cleaning with deionized water and drying. The separates were prepared for chemical analysis and X-ray diffraction (XRD) by crushing to –200 mesh. The X-ray work was done at Memorial University using a Philips diffractometer and the following operating conditions: Cu$K\alpha$ radiation, goniometer speed of 1° 2$\theta$/minute, chart recorder speed of 1 cm/minute. A total of 61 separates were scanned over the intervals 10° to 60° 2$\theta$, with several diffractograms prepared for each sample to check for homogeneity. Where triclinic domains are present, the apparent degree of "triclinicity" ($\Delta$) was calculated using the relationship of Goldsmith & Laves (1954): $\Delta = 12.5\,[d(131) - d(1\bar{3}1)]$.

Major and minor element chemistry of the K-feldspar separates was determined at Memorial University using atomic absorption spectrometry (AAS) and the methods of Langhyr & Paus (1968), except for $P_2O_5$, which utilized a modification of the technique of Shapiro & Brannock (1962). In all cases, total iron is reported as $Fe_2O_3$. Concentrations of the trace elements, including the rare-earth elements (*REE*), were determined using inductively coupled plasma – mass spectrometry (ICP–MS) at Memorial University using procedures outlined in Jenner *et al.* (1990). In order to determine the potential variation that may occur as a result of heterogeneity with respect to sample size in perthitic feldspar, two separates were analyzed several times (NS–85–18 and NS–85–44A). For sample NS–85–18, grains ($n$ = 1 to 18) of differing size (<1 mm to 5 mm) and total weight (0.093 to 0.944 g) were analyzed, whereas for sample NS–85–44A, powdered material of 0.0204 to 1.0023 g was analyzed. Analytical results (Table 2, Fig. 2)

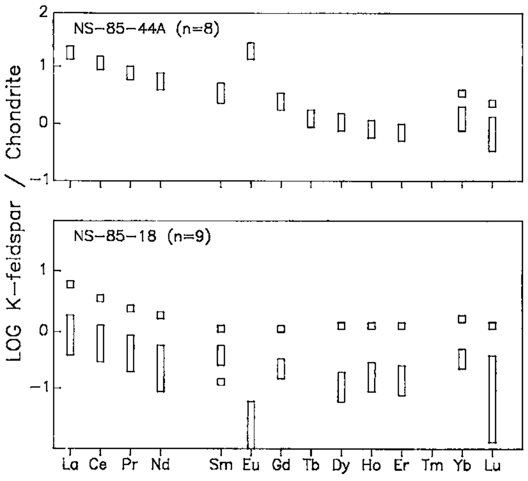

FIG. 2. Chondrite-normalized plots of *REE* data for K-feldspar samples used as intralaboratory standards during the course of the present study. Analyses by ICP–MS (Jenner *et al.* 1990). Where a small box deviates from the larger box, there is but a single sample represented. In the cases of sample NS–85–18, the same analytical data apply in all cases.

indicate good reproducibility of the data, with the values of relative standard deviation (% RSD) related to the absolute concentration of the element.

Electron-microprobe analyses of plagioclase and K-feldspar were carried out at Memorial University using a three-spectrometer JEOL JXA–50A automated electron microprobe with Krisel programming and at Dalhousie University, Halifax, using a JEOL 733 Superprobe. At Memorial University, natural silicate minerals were used as standards, and operating conditions were as follows: accelerating voltage 15 kV, sample current 0.02 μA, and a beam diameter of 5 μm. The data were corrected on-line by the Bence & Albee (1968) method. At Dalhousie University, an energy-dispersion spectrometer (EDS) was used with an accelerating voltage of 15 kV, a beam current of 10 nA, a counting time of 40 seconds and a beam diameter of 1–3 μm. Data were processed using the Tracor Northern ZAF matrix-correction program. At both institutions, accuracy and precision were monitored by analyzing well-characterized standards.

TABLE 2. GEOCHEMICAL DATA FOR K-FELDSPAR STANDARDS

| | NS-85-18 (n = 9) | | | NS-85-44A (n = 8) | | |
|---|---|---|---|---|---|---|
| | $\overline{X}$ | 1σ | % RSD | $\overline{X}$ | 1σ | % RSD |
| Li | 5.5 | 0.8 | 14.5 | 6.7 | 0.6 | 9.8 |
| Rb | 2273 | 238 | 10.5 | 282 | 7.4 | 2.6 |
| Sr | 5.6 | 0.5 | 9.5 | 196 | 4.1 | 2.1 |
| Ba | 18.1 | 3.1 | 17.1 | 1790 | 67.0 | 3.7 |
| Pb | 6.3 | 2.2 | 36.1 | 48.8 | 8.9 | 18.2 |
| Cs | 16.0 | 1.4 | 9.1 | 2.83 | 0.08 | 3.7 |
| Th | 0.37 | 0.3 | 81.0 | 1.10 | 0.34 | 30.9 |
| U | 0.74 | 0.23 | 31.9 | 0.53 | 0.07 | 13.2 |
| Y | ND | | | 0.87 | 0.43 | 49 |
| Zr | 4.23 | 3.02 | 71.6 | 8.3 | 2.6 | 31.5 |

ND = not determined. Concentrations in ppm.

## STRUCTURAL STUDIES OF ALKALI FELDSPAR

The degree of Al/Si order in the alkali feldspar phases has been determined by a combination of XRD studies ($n$ = 61) and petrographic observations ($n$ = 110); results are summarized in Figure 3. As shown in the studies of Jiránek (1982) and Černý & Chapman (1984, 1986), inferences on the presence of triclinic domains can be made from the shape of the (131) reflection; a similar methodology is used herein.

In Figure 3A, the distribution of the dominant polymorph is shown, whereas in Figure 3B, representative diffractograms are presented. Microcline is the dominant phase in the older units (*Koskaecodde* and *Mollyguajeck*), whereas orthoclase is present in the rest of the Ackley Granite (Fig. 3A). For two of the five samples studied by XRD from the Koskaecodde phase, only microcline is present (Δ = 0.80, 0.85). The remaining three samples from this phase consist of variable mixtures of microcline and orthoclase, with apparent Δ values of 0.63, 0.65 and 0.70. Several samples from along the eastern part of this unit proximal to its contact with the Hungry Grove unit contain orthoclase only (sample 492 in Fig. 3B). For the Mollyguajeck unit, samples studied by XRD indicate that microcline (Δ = 0.87 ± 0.05, $n$ = 4) dominates. For the samples examined petrographically, either microcline, orthoclase, or mixtures of the two occur, with orthoclase dominating along the northern part of this phase near the contact with the younger Mount Sylvester unit.

The *Mount Sylvester – Kepenkeck unit* is dominated by orthoclase, from both petrographic observations and the eight diffractograms. The broadening of the (131) peak in the diffractogram for sample 510 (Fig. 3B), indicative of a triclinic component, is an exception for samples from this unit, as other samples do not exhibit this phenomenon.

Orthoclase dominates in the *Meta unit*, with minor amounts of triclinic phases manifested by (1) a slight broadening of the (131) peak, and (2) the weak development of microcline twinning in petrographic studies. Where peaks could be distinguished in alkali feldspar phases, apparent Δ values of 0.60 ± 0.06 ($n$ = 3) are calculated. All samples studied by XRD from the *Tolt unit* consist of orthoclase; however, a few samples oriented along a northeastern trend are observed to contain variable proportions of microcline in thin section. Of the 12 samples studied by XRD, all have diffractograms typical of orthoclase, with only very slight broadening of the (131) peak observed (apparent Δ value of 0.71 in one sample).

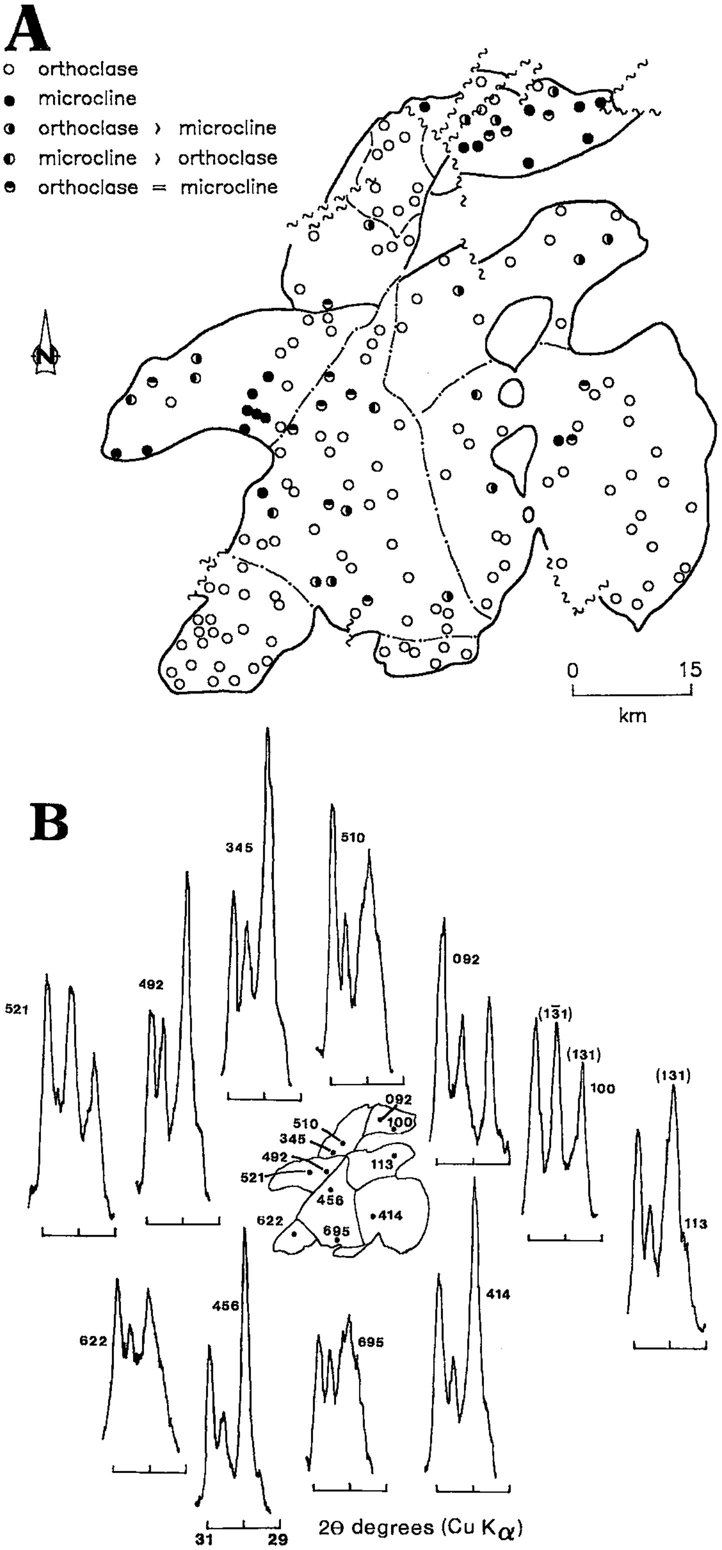

FIG. 3. A. Summary of XRD and petrographic observations of samples from the Ackley Granite. Note that the two older units are dominated by a triclinic K-feldspar, whereas the younger units mostly contain monoclinic K-feldspar. B. Diffractogram traces of representative samples of K-feldspar samples from different units of the Ackley Granite. The (*hkl*) lines labeled for two of the samples, a monoclinic and triclinic phase, pertain to K-feldspar.

The *Hungry Grove unit* is dominated by orthoclase, except in a few cases, where partial to complete dominance of triclinic alkali feldspar occurs (Fig. 3A). However, from north to south there is a clear change from a sharp (131) reflection, indicative of a single monoclinic phase, to the broad (131) reflections characteristic of mixed monoclinic – triclinic domains (Fig. 3B, compare samples 456 and 695).

The *Rencontre Lake unit* is similar to the Hungry Grove, in that orthoclase dominates. However, the slight broadening of the (131) peak noted in two of the four diffractograms obtained indicate trace amounts of triclinic domains (sample 622 in Fig. 3B). Petrographic observations of an additional 18 samples indicate that orthoclase occurs, apparently without microcline.

In the *Sage Pond unit*, no samples of alkali feldspar separates have been studied by XRD because the fine-grained nature of the granite precluded preparation of clean separates. However, petrographic study of six samples indicates that orthoclase is here also the dominant polymorph.

In summary, the distribution of alkali feldspar polymorphs in the Ackley Granite appears to reflect the age differences of the units. The two oldest units, the Koskaecodde and Mollyguajeck, are dominated by triclinic feldspar, whereas the younger units are dominated by orthoclase, almost to the exclusion of microcline. However, there is local development of triclinic domains, but more common is the mixture of the two phases, with the monoclinic variety dominant.

## GEOCHEMISTRY OF THE ALKALI FELDSPAR

Bulk separates of alkali feldspar ($n$ = 61) have been analyzed for major, minor and trace elements. The data are summarized diagrammatically; the complete dataset is available from the Depository of Unpublished Data, CISTI, National Research Council, Ottawa, Ontario K1A 0S2.

### *Major-element chemistry*

Representative bulk compositions of perthitic K-feldspar from the different units are presented in Table 3, and the bulk compositions are summarized graphically in Figures 4 (Or–Ab–An plot) and 5 (mol.% Or). Compositional variability within a single unit is limited, with variation typically <10–15 mol.% Or. In the two older units (Koskaecodde and Mollyguajeck), the alkali feldspar has the most potassic bulk composition ($Or_{70-80}$), except for three samples of $Or_{55-65}$ composition. The more potassic samples of these two units are located toward the margins of the units.

Samples from the younger units of the Ackley Granite fall in the range $Or_{52-70}$, but for individual units the spread is much smaller. For example, in the Meta unit, the perthite has a range of $Or_{60-67}$, whereas in the Hungry Grove unit, it is $Or_{55-63}$, except for a single sample of $Or_{70}$. In addition, there is a systematic change within the Hungry Grove unit, with less potassic compositions in the southern part. In contrast, a pattern of elevated Or content occurs in the Tolt unit toward the southeast. Other oxides are generally low, with maximum values of 0.05 wt.% $P_2O_5$, 0.08% $TiO_2$, 0.02% MnO and 0.09% MgO, whereas up to 0.5 wt.% $Fe_2O_3$ is noted. The ferromagnesian elements are attributed to trace amounts of biotite inclusions that are zonally arranged along the inner margins of alkali feldspar crystals. The low P contents contrast with values of up to 2 wt.% $P_2O_5$ in alkali feldspar reported in peraluminous granite suites (Kontak *et al.* 1991b,

TABLE 3. REPRESENTATIVE COMPOSITIONS OF K-FELDSPAR SEPARATES, ACKLEY GRANITE

| SAMPLE<br>UNIT | 521<br>Kosk | 092<br>Molly | 096<br>Kep | 510<br>MtSyl | 188<br>Tolt | 545<br>HunGr | 413<br>Meta | 622<br>RenL |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ wt% | 68.60 | 63.80 | 63.80 | 66.20 | 65.30 | 66.20 | 66.20 | 66.00 |
| $TiO_2$ | 0.06 | 0.16 | 0.04 | 0.08 | 0.04 | 0.06 | 0.06 | 0.04 |
| $Al_2O_3$ | 16.40 | 18.10 | 19.70 | 18.40 | 18.90 | 18.70 | 18.60 | 18.60 |
| $Fe_2O_3$ | 0.23 | 0.65 | 0.50 | 0.48 | 0.17 | 0.38 | 0.20 | 0.12 |
| MnO | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 |
| MgO | 0.06 | 0.20 | 0.08 | 0.10 | 0.02 | 0.00 | 0.00 | 0.03 |
| CaO | 0.16 | 0.60 | 0.48 | 0.48 | 0.32 | 0.26 | 0.16 | 0.32 |
| $Na_2O$ | 2.64 | 1.96 | 4.25 | 3.54 | 3.47 | 4.44 | 4.14 | 4.22 |
| $K_2O$ | 11.32 | 12.92 | 9.76 | 10.90 | 11.72 | 9.94 | 10.67 | 10.50 |
| $\Sigma$ | 99.29 | 98.40 | 98.63 | 100.20 | 99.95 | 99.99 | 100.04 | 100.01 |
| END-MEMBER PROPORTIONS (Mol %) | | | | | | | | |
| Or | 73.2 | 78.8 | 58.7 | 65.3 | 67.9 | 58.8 | 62.4 | 61.1 |
| Ab | 25.9 | 18.2 | 38.9 | 32.2 | 30.06 | 39.9 | 36.8 | 37.3 |
| An | 0.9 | 3.1 | 2.4 | 2.4 | 1.6 | 1.3 | 0.8 | 1.6 |

Kosk: Koskaecodde; Molly: Mollyguajeck; Kep: Kepenkeck; MtSyl: Mt. Sylvester; HunGr: Hungry Grove; RenL: Rencontre Lake

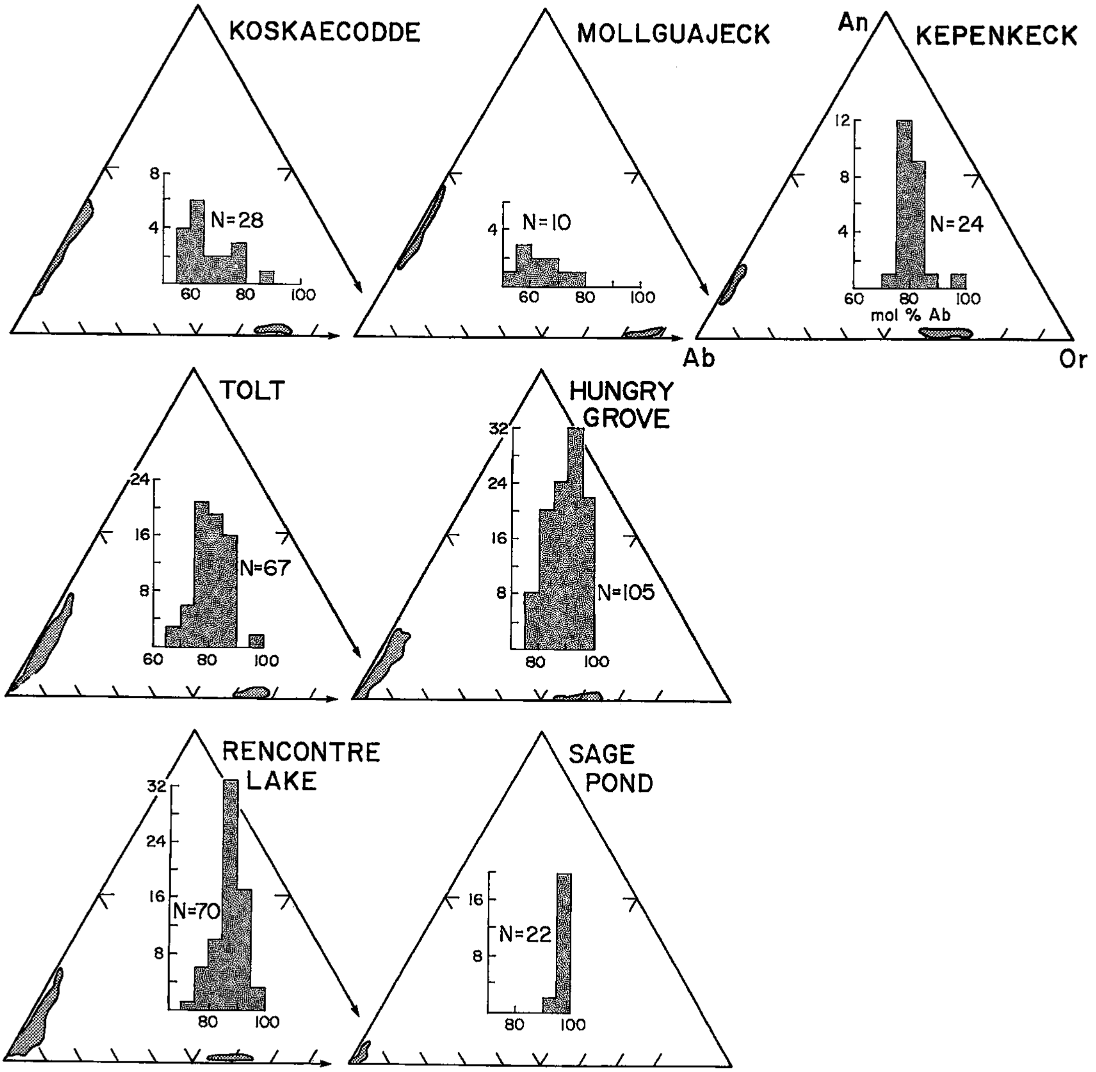

FIG. 4. Triangular plots and histograms compositions of plagioclase and bulk alkali feldspar for each unit of the Ackley Granite.

London *et al.* 1990, London 1992), but are in keeping with the A-type nature of the Ackley Granite (Tuach *et al.* 1986). Although Fe can readily substitute into the feldspar structure (Smith 1974), high Fe contents are correlated with a distinct reddening or turbidity, which suggests trace amounts of hematite either as free grains or as a phase within fluid inclusions (*e.g.*, Martin & Lalonde 1979, Lalonde & Martin 1983, Worden *et al.* 1990). There is no systematic distribution of the Fe contents that might reflect, for example, a build-up of fluid in the southern, more evolved parts of the granite.

### *Trace-element chemistry*

A detailed examination of the trace-element content of alkali feldspar is given by Smith (1974, 1983), Smith & Brown (1988) and Černý *et al.* (1985). This section focuses upon the relative enrichment and depletion of elements within the Ackley Granite. Because of the potential effect of contaminants on the trace-element chemistry, detailed petrographic studies addressed the presence of accessory mineral phases. On the basis of microscopic observations and back-

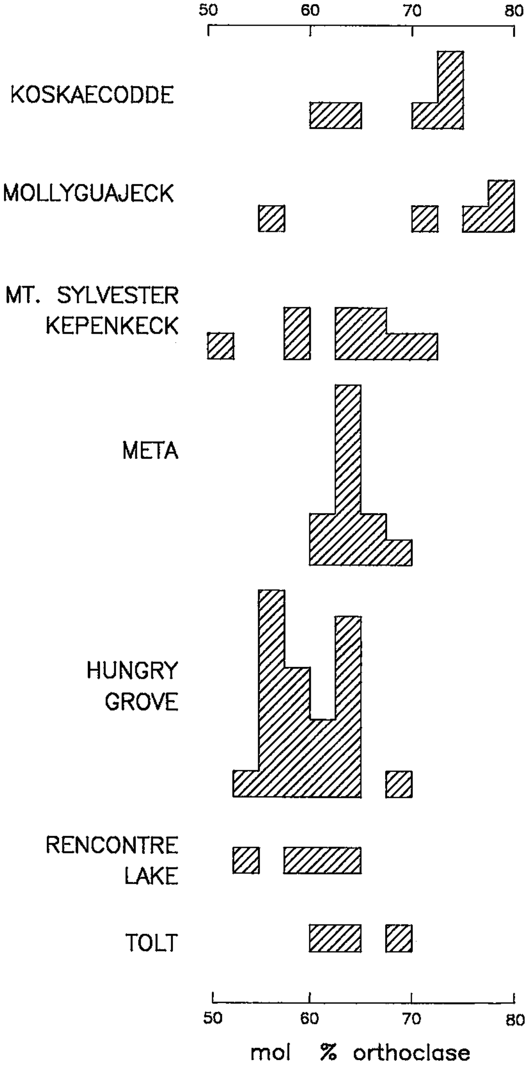

FIG. 5. Summary of end-member, bulk composition (in mol.% Or) for alkali feldspar samples from different units of the Ackley Granite.

scattered imaging with the electron microprobe, accessory phases were not observed in samples examined. Therefore, the trace-element chemistry, unless noted otherwise, is considered to reflect structurally bound elemental concentrations and crystal–melt partitioning rather than putative contaminants.

Trace-element data for alkali feldspar separates are summarized in Figures 6, 7 and 8. In Figure 9, results for Rb, Sr and Ba are plotted separately for the Hungry Grove unit. The trace elements follow general trends defined by whole-rock analyses in the Ackley Granite, as outlined by previous investigators.

*Barium* is most strongly enriched in samples from the Koskaecodde unit and the central part of the Mount Sylvester – Kepenkeck unit, with values of 1500 to 4000 ppm (Fig. 6A). A trend of depletion is seen from mafic to felsic rocks in the Rencontre Lake unit, and there is a crude decrease from north (≤2800 ppm) to south (<200 ppm) in the Hungry Grove unit (Fig. 9). Comparison of the histograms for Ba and Sr (Figs. 6A, B) and a binary plot (Fig. 9) indicate that these two elements are geochemically coupled. In Figure 8B, a plot of Ba *versus* Rb/Sr, a single trend is defined by the data, with a strong inverse correlation.

The distribution of *strontium* is generally a converse of the Rb trends, with the highest values for the relatively primitive samples; the overall range is from <50 to *ca.* 600 ppm (Fig. 6B). The highest concentrations are found in samples from the central part of the Mount Sylvester – Kepenkeck unit, which contain more Sr than hornblende-bearing samples from the Koskaecodde and Rencontre Lake units, and are generally enriched three to four times over the rest of the samples. In the Hungry Grove unit, there is a trend of decreasing Sr toward the southern, more evolved part of this unit (Fig. 9).

*Rubidium* shows a large overall range from less than 200 ppm to greater than 700 ppm, with most samples having between 300 and 500 ppm (Fig. 6C). Several units display Rb enrichment or depletion that is in accordance with whole-rock fractionation trends within the granite (Tuach 1987), notably the Mount Sylvester – Kepenkeck unit, the Rencontre Lake unit and the Hungry Grove unit; the latter unit shows increasing Rb contents toward the south (Figs. 8A, 9).

The *Rb/Sr* ratio (Fig. 6D) of the samples magnifies the trends for Rb and Sr such that clear patterns emerge for the data from the Mount Sylvester – Kepenkeck, Hungry Grove and Rencontre Lake units, as the Rb/Sr ratio increases toward more fractionated parts of the units (left to right in Fig. 6D). Also, the more evolved nature of the latter two units, as well as the Tolt unit, is evident compared to the rest of the Ackley Granite (Fig. 8). It is also evident in Figure 8 that samples with elevated Rb/Sr values fall on the extensions defined by data with lower Rb/Sr values (*e.g.*, Figs. 8A, C).

There is an overall range of 2 to 12 ppm for *cesium* in K-feldspar, with the most enriched samples coming from a variety of units, but mostly the Hungry Grove (Fig. 6E), in samples with the highest Rb/Sr values (Fig. 8C). For the Hungry Grove and Rencontre Lake units, the trend of Cs enrichment is consistent with other indices of fractionation (whole-rock and mineral chemistry).

The abundance of *lithium* throughout the various units is generally erratic (Fig. 6F), but there is some correlation with Rb. Lithium is markedly depleted in

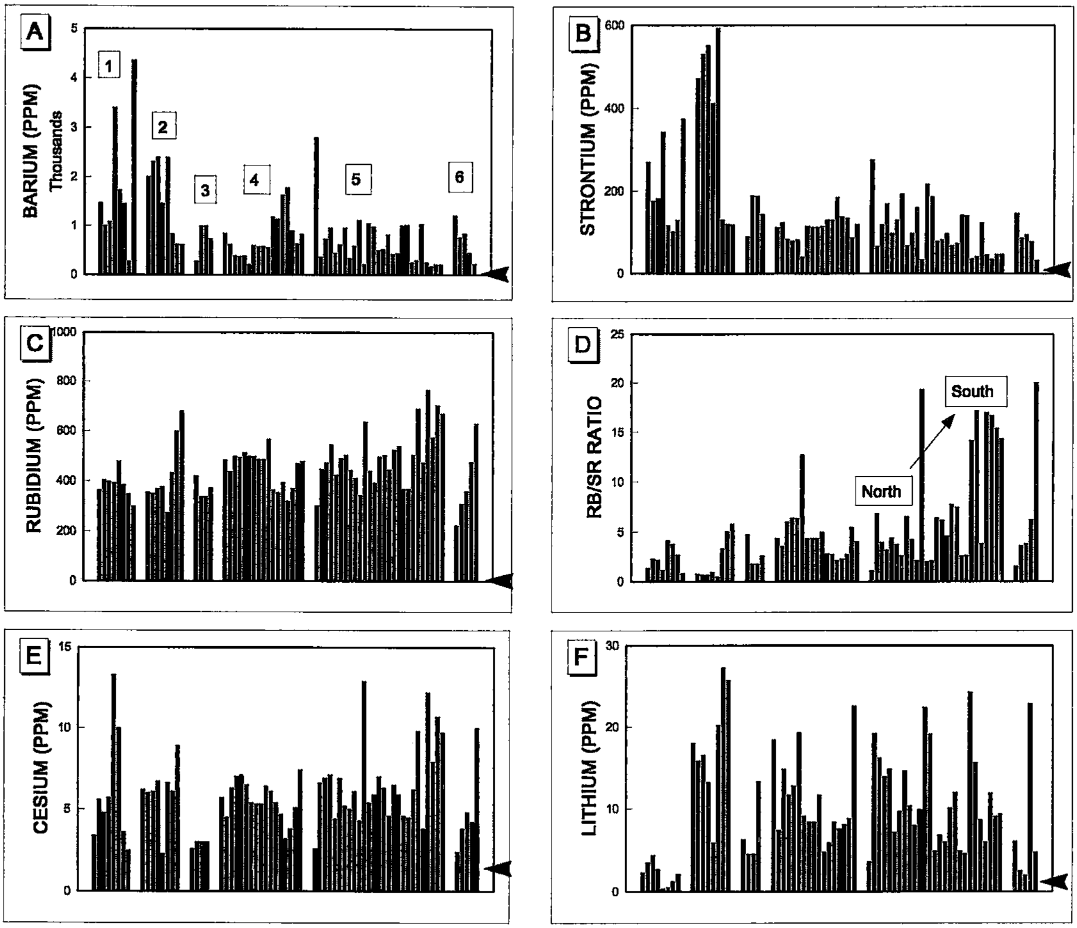

FIG. 6. Histograms summarizing the trace-element chemistry of alkali feldspar separates from different units of the Ackley Granite. For each unit, the samples are arranged in order of increasing fractionation based on whole-rock geochemistry (Dickson 1983, Tuach 1987). For the Hungry Grove unit, samples are arranged from north to south in the unit (labeled and see arrow). The arrrowhead on the sides of the diagrams indicate detection limits. Numbers refer to units: (1) Koskaecodde – Mollyguajeck, (2) Mount Sylvester – Kepenkeck, (3) Meta, (4) Tolt, (5) Hungry Grove, (6) Rencontre Lake.

the two oldest units (<4 ppm) compared to the rest of the Ackley Granite (4 to 28 ppm), in contrast to other *LILE* (Rb, Cs), which are not relatively depleted in the older units.

The concentration of *thorium* (Fig. 7A) is between 1 and 14 ppm, and there is apparently no consistent pattern of enrichment or depletion. Although not shown, U is generally below 1 ppm (*i.e.*, the detection limit) except for a few samples that have up to 3 ppm U.

Elevated contents of *molybdenum* (10 to 55 ppm) are characteristic of all samples from the Ackley Granite (Fig. 7B). However, there is no obvious increase in Mo concentration proximal to mineralized zones. Although the enrichment of Mo might be considered to reflect mechanical contamination, several points militate against this: (1) about 78% of the samples have values of 10 to 30 ppm, thus a very narrow spread, (2) other samples of K-feldspar processed with the Ackley samples (Kontak & Strong 1988) do not show such elevated values (*i.e.*, <5 ppm), thus ruling out contamination, and (3) none of the granite samples selected show signs of mineralization. Similarly, elevated Mo contents for K-feldspar have been reported by Tauson *et al.* (1970), as reported by Smith (1974).

*Zirconium* varies from 5 to 35 ppm and is erratically distributed throughout the phases, but the relative depletion of Zr in the oldest units is noted (Fig. 7C). The large range and variance of values, plus the

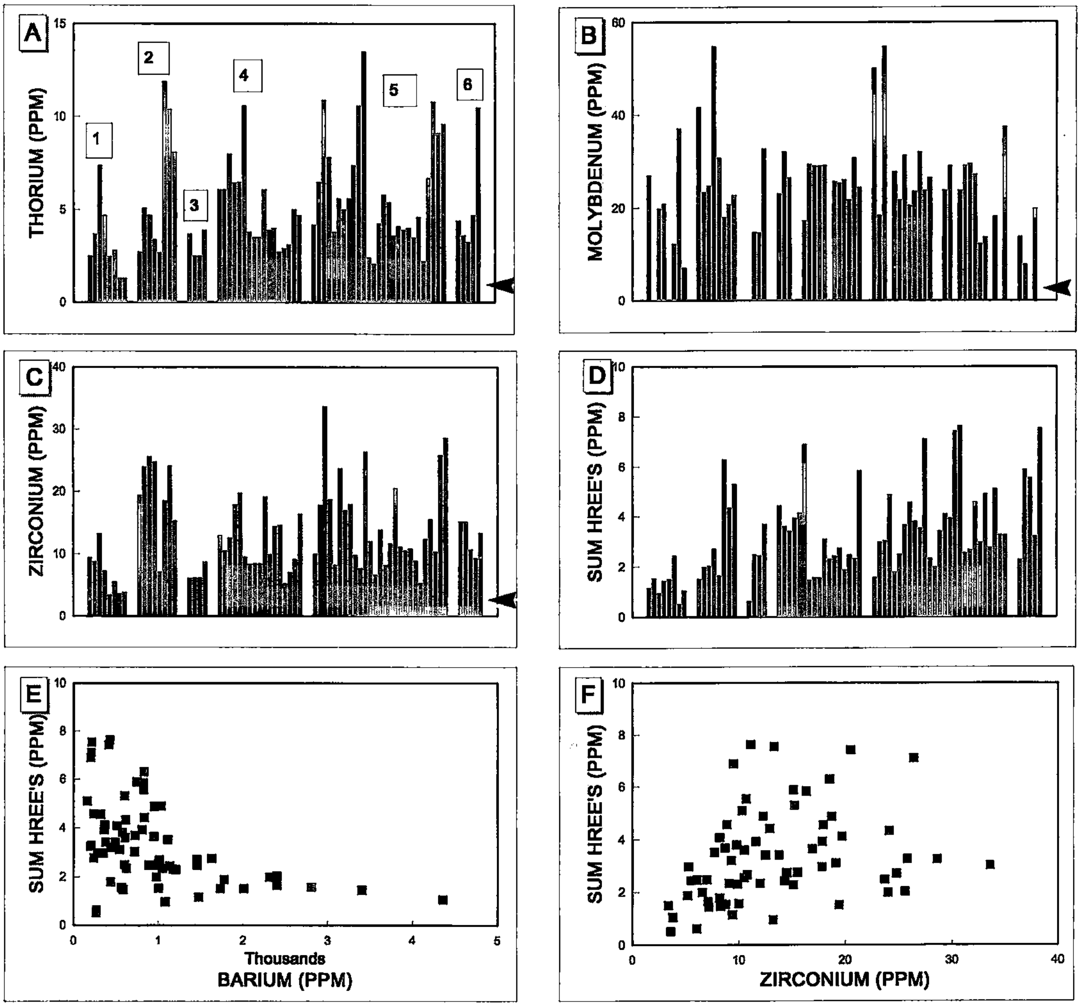

FIG. 7. Histograms and binary plots summarizing the trace-element chemistry of alkali feldspar separates from different units of the Ackley Granite. For each unit, the samples are arranged in order of increasing degree of fractionation on the basis of whole-rock geochemistry (Dickson 1983, Tuach 1987). For the Hungry Grove unit, samples are arranged from north to south. The arrowhead on the sides of the diagrams indicate detection limits. Numbers refer to units: (1) Koskaecodde – Mollyguajeck, (2) Mount Sylvester – Kepenkeck, (3) Meta, (4) Tolt, (5) Hungry Grove, (6) Rencontre Lake.

absence of clearly defined trends (Fig. 8E), are suggestive of the presence of micro-inclusions of zircon; a positive correlation between Zr and Hf (not shown) also suggests contamination. However, recently Smith & Brown (1988) have noted the presence of up to 100 ppm in alkali feldspar and pointed out that consistency of analysis suggests the potential for incorporation of this element in the feldspar structure. Thus, the present data-base does not permit a more definitive statement concerning the nature of Zr within the feldspar samples.

Levels of *lead* (25 to 35 ppm) and *gallium* (30 to 50 ppm) are very consistent within the Ackley Granite, and there is no systematic change in the abundance of these elements. Similarly, *thallium* (1–3 ppm) shows no systematic enrichment or depletion in samples from different units.

The spatial variation of Ba, Sr and Rb are examined in more detail for the Hungry Grove unit (Fig. 9). There is a general north-to-south trend of enrichment or depletion for all three elements, and a binary plot of Ba *versus* Sr concentrations indicates that these elements are chemically coupled. However, there are "rapid" local variations of Ba, Sr and Rb superimposed

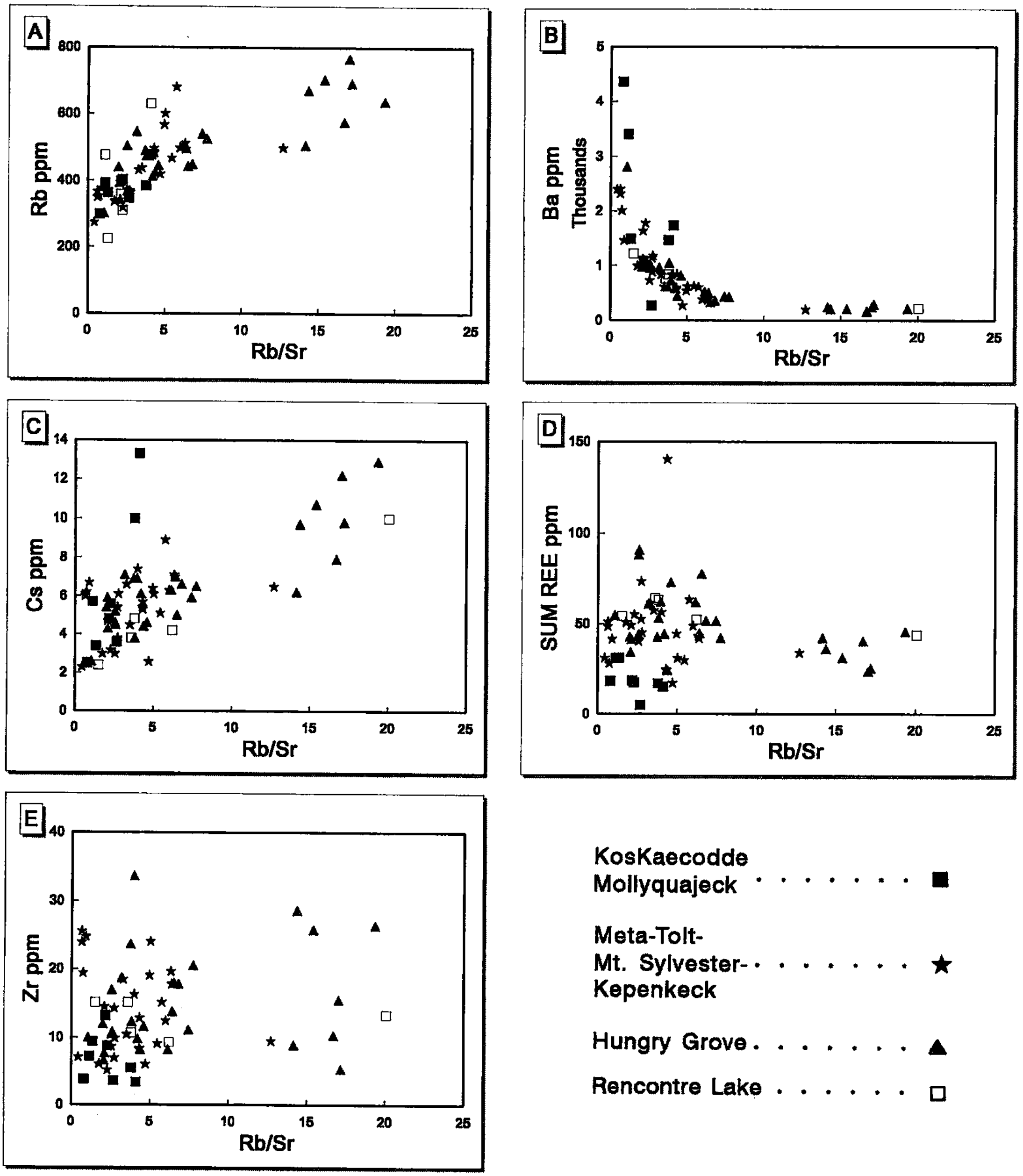

FIG. 8. Binary plots summarizing trace-element chemistry of alkali feldspar as a function of Rb/Sr ratio.

on the broad trends of enrichment or depletion defined by Tuach *et al.* (1986). These data suggest, therefore, that "rapid" spatial variations of either a chemical (*i.e.*, bulk chemistry of the magma) or physical (*i.e.*, T) nature may have occurred, assuming no postmagmatic modification. Smith & Brown (1988), in discussing large variations in Sr and Ba contents of alkali feldspar from the same intrusive suite, also suggested that such processes could alter the $K_D$ of these elements, resulting in the observed trends.

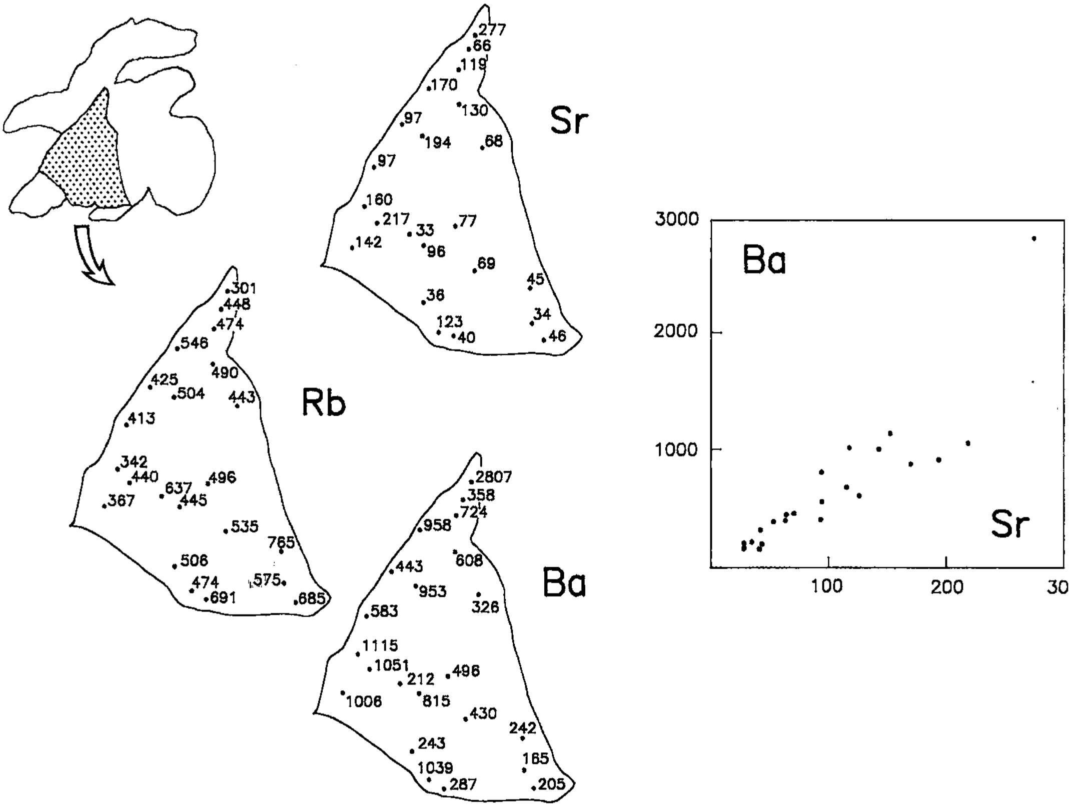

FIG. 9. Selected trace-element data (Rb, Sr, Ba) for alkali feldspar separates from the Hungry Grove unit. Data for Ba and Sr also are summarized in a binary plot. All data are in ppm.

### *Rare-earth-element chemistry*

Rare-earth-element (*REE*) data for the suite of alkali feldspar are summarized in Figures 7, 8, 10 and 11. In general, the data resemble patterns for alkali feldspar from intrusive (*e.g.*, Shearer *et al.* 1985, Smith & Brown, 1988, Kontak *et al.* 1991a) and extrusive (Leeman & Phelps 1981) felsic rocks, but there are systematic changes that occur within the different units. There is a trend of increasing Σ*REE* toward the more evolved parts of the granite (Figs. 10, 11), which is best illustrated in a binary plot of Ba concentation *versus* Σ*HREE* (Fig. 7E). However, the lack of a positive correlation of Σ*REE* or Σ*HREE* with Zr (*e.g.*, Fig. 7F) suggests that this enrichment is not due solely to micro-inclusions of *REE*-bearing phases. In addition, using *REE* analysis of zircon from granitic rocks (*e.g.*, Gromet & Silver 1983) and Zr contents of alkali feldspar, mass-balance calculations indicate that zircon contamination cannot account for the *HREE* contents given the levels of Zr.

In the Koskaecodde unit, the alkali feldspar is characterized by a strongly fractionated pattern ($La_N$ from 11 to 32, $La/Yb_N$ from 2 to 47), a strongly positive Eu anomaly except for sample 521, which is notably depleted in the *LREE* (Σ*REE* of 4.8 ppm compared to a range of 15 to 31 ppm). Sample 521 also is depleted in Ba (270 ppm) compared to the rest of the samples, and has a markedly lower $(Eu/Eu^*)_N$ value. All the feldspar separates from this unit are distinct from those of the other units of the Ackley Granite in that they have $(Tb/Yb)_N$ greater than 1, compared to values of less than 1 for the rest of the samples. The single sample from the Mollyguajeck unit has a *REE* pattern similar to those for the Koskaecodde unit, with $La_N = 18$, $(Eu/Eu^*)_N = 10.6$ and $(La/Yb)_N = 11$.

Samples from the Mount Sylvester – Kepenkeck unit have similar, strongly fractionated *LREE* patterns, with $(La/Yb)_N$ in the range 4 to 27, and similar $(Eu/Eu^*)_N$ values. Three of the samples (497, 345, 532) show relative enrichment in the *HREE* and have $Yb_N$ values of 4.6 to 9.1, compared to 1.4 to 1.8 for the other

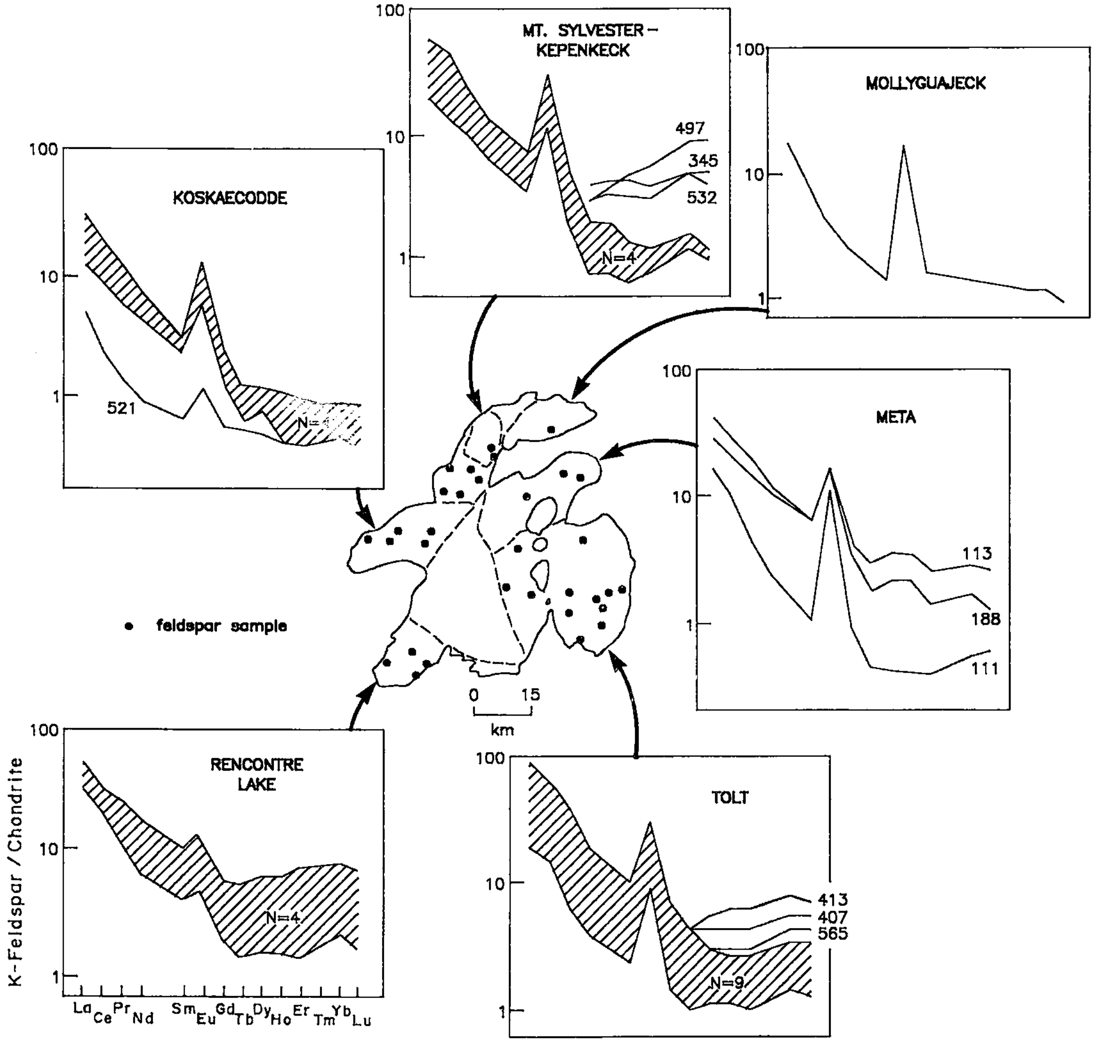

FIG. 10. Chondrite-normalized *REE* plots for alkali feldspar separates from different units of the Ackley Granite; data for the Hungry Grove unit are given in Figure 11. The numbers refer to specific samples, which are discussed in the text.

samples. In addition, these three samples have strong concave-upward *HREE* patterns, with $(Yb/Tb)_N$ greater than 1 rather than equal to 1 as for the other samples. The *HREE*-enriched samples show enrichment or depletion compared to the other samples with respect to Ba (609–840 *versus* 1458–2402 ppm), Rb (432–681 *versus* 274–450 ppm), Sr (118–130 *versus* 471–593 ppm), and Th (8–11 *versus* 2–5 ppm). The chemical distinction of samples from the Mount Sylvester unit compared to the Kepenkeck unit was also noted by Tuach (1987), who interpreted it to indicate a genetic affiliation with rocks of the northern part of the Hungry Grove unit. A similar conclusion is suggested by the *REE* and associated trace-element data presented here.

Samples from the Meta unit all have broadly similar *REE* patterns, although one sample (111) is relatively depleted in Σ*REE* compared to the other two (17 *versus* 40 and 50 ppm Σ*REE*); in fact, this sample has the lowest Σ*HREE* for the entire Ackley Granite. All three samples have strongly fractionated *LREE* patterns and $(La/Yb)_N$ in the range 10 to 31, have positive $(Eu/Eu^*)_N$ values, and unfractionated *HREE* patterns, with $(Tb/Yb)_N$ in the range of 1.

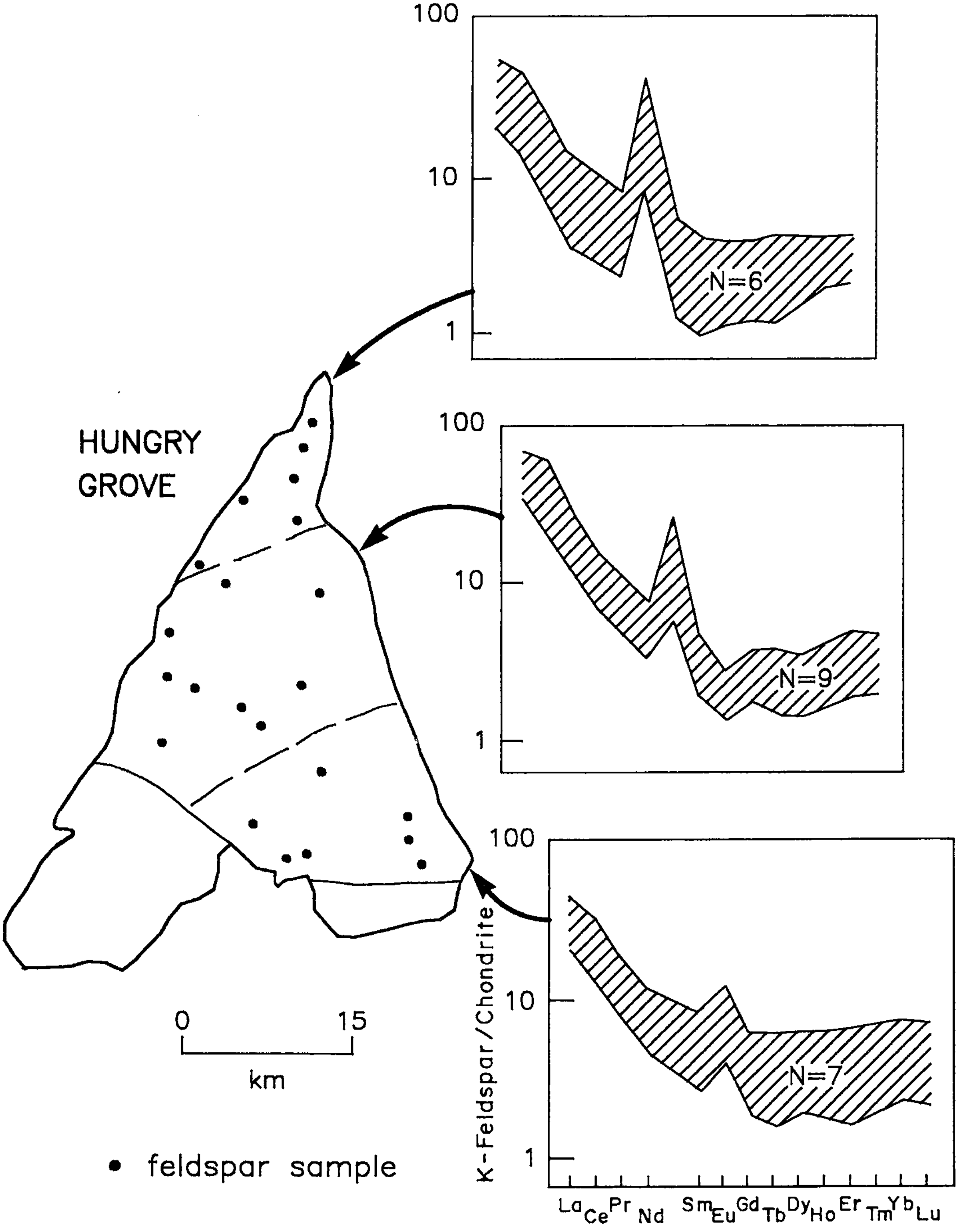

FIG. 11. Chondrite-normalized *REE* plots for alkali feldspar separates from the Hungry Grove unit of the Ackley Granite. The samples have been arbitrarily arranged into three subgroups to show the gradual north-to-south change in the *REE* patterns, as discussed in the text.

In the Tolt unit, samples generally have similar *REE* patterns with strongly fractionated *LREE* patterns, positive Eu anomalies, and unfractionated *HREE* patterns, with $(Tb/Yb)_N$ equal to about 1, except for three samples in which this value is less than 1 (samples 413, 407, 565). There is no geographical association among these three samples (Fig. 1) or associated pattern of enrichment or depletion for the other trace elements. For the grouping of samples from the Tolt unit (Fig. 10), there is a complete continuum for *REE* patterns such that the *HREE* enrichment illustrated by the three samples (413, 407, 565) reflects a gradual process.

Samples from the Rencontre Lake unit give a pattern

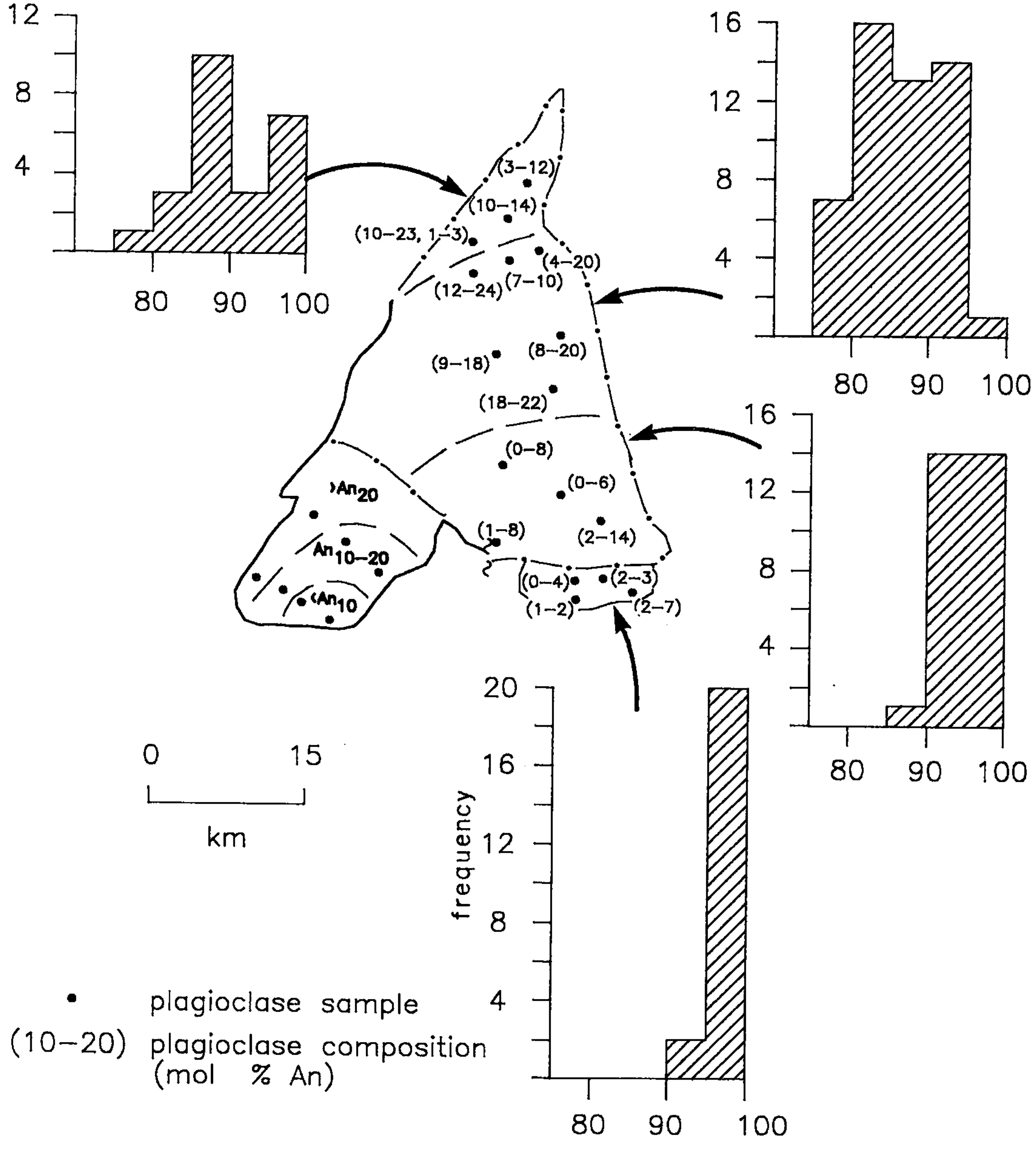

FIG. 12. Summary of compositional data on plagioclase for samples from the Hungry Grove, Rencontre Lake and Sage Pond units of the Ackley Granite. Note the gradual change from oligoclase to albite compositions from north to south. The subdivisions of the Hungry Grove unit are arbitrary, as discussed with respect to Figure 11.

similar to the other feldspar patterns in the units discussed above, but have smaller Eu anomalies. However, these data are wholly consistent with whole-rock *REE* data for this unit (Tuach 1987).

Samples from the Hungry Grove unit are subdivided into three groups (Fig. 11) in order to evaluate the changes in levels of the *REE* that accompany fractionation, as defined by Tuach *et al.* (1986) and Tuach (1987). There is a southward increase in the *HREE* and a decrease in $(Eu/Eu^*)_N$ and $(Tb/Yb)_N$, consistent with the pervasive development of albitic plagioclase (see below) and patterns of enrichment or depletion of associated trace elements (*e.g.*, Rb, Sr, Ba; Fig. 9). The *REE* patterns for the southernmost part of the Hungry Grove unit are similar in all respects to those from the Rencontre Lake unit.

The *REE* data in K-feldspar from the Ackley Granite compare favorably with whole-rock data from the same granite presented by Tuach (1987); both data sets distinguish the older suites with their more fractionated patterns [*i.e.*, greater $(La/Lu)_N$ values] and distinguish the Mount Sylvester unit based on its *HREE* enrichment. The data presented here are considered to reflect *REE* variations within the magma at the time of K-feldspar crystallization, rather than later processes. Thus, the *HREE* enrichment observed in some units is interpreted to reflect similar enrichment within the melt. As discussed above, the enrichment of the *HREE* cannot be satisfactorily accounted for by putative contamination by zircon.

## PLAGIOCLASE COMPOSITIONS

Plagioclase compositions (core and rim; 326 analyses in 38 samples) have been determined by electron microprobe for samples from all units of the Ackley Granite (Figs. 1, 4 and 12; representative compositions in Table 4). The spatial coverage emphasizes the southern part of the intrusion, within which mineralization occurs.

Plagioclase in the older units is the most calcic, and ranges from $An_{12}$ to $An_{46}$, with the maximum intra-sample variability being *ca.* 20 mol.% An. The most calcic sample is from the western part of the

TABLE 4. REPRESENTATIVE RESULTS OF ELECTRON-MICROPROBE ANALYSES OF PLAGIOCLASE AND ALKALI FELDSPAR, ACKLEY GRANITE

| SAMPLE<br>UNIT<br>FELDSPAR | 523<br>Kosk<br>Pl | 697<br>Kosk<br>Pl | 99<br>Molly<br>Pl | 99<br>Molly<br>Pl | 89<br>Kep<br>Pl | 89<br>Kep<br>Pl | 366<br>Tolt<br>Pl | 413<br>Tolt<br>Pl | 602<br>RenL<br>Pl | 252<br>RenL<br>Pl | 542<br>HunGr<br>Pl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 58.81 | 60.80 | 57.55 | 62.36 | 61.05 | 63.22 | 61.33 | 68.79 | 62.87 | 67.85 | 63.54 |
| $Al_2O_3$ | 26.34 | 23.94 | 26.24 | 23.37 | 23.77 | 22.10 | 24.34 | 19.88 | 23.28 | 20.30 | 22.40 |
| CaO | 7.75 | 4.91 | 9.02 | 4.16 | 5.24 | 3.32 | 5.87 | 0.40 | 4.17 | 0.74 | 2.69 |
| $Na_2O$ | 6.73 | 8.27 | 6.66 | 9.14 | 8.53 | 9.58 | 7.79 | 11.18 | 8.81 | 10.61 | 10.18 |
| $K_2O$ | 0.31 | 0.27 | 0.30 | 0.12 | 0.24 | 0.25 | 0.36 | 0.18 | 0.45 | 0.15 | 0.27 |
| $\Sigma$ | 99.94 | 98.19 | 99.77 | 99.15 | 98.83 | 98.47 | 99.67 | 100.43 | 99.58 | 99.65 | 99.08 |
| END-MEMBER PROPORTION (Mol %) | | | | | | | | | | | |
| An | 38.2 | 24.3 | 56.2 | 21.7 | 24.9 | 15.8 | 28.8 | 1.9 | 20.2 | 3.5 | 12.5 |
| Ab | 60.1 | 74.2 | 42.1 | 77.7 | 73.7 | 82.9 | 69.1 | 97.2 | 77.3 | 95.7 | 86.1 |
| Or | 1.8 | 1.5 | 1.7 | 0.6 | 1.4 | 1.3 | 2.1 | 0.9 | 2.5 | 0.7 | 1.4 |

| SAMPLE<br>UNIT<br>FELDSPAR | 268<br>HunGr<br>Pl | 717<br>Sage<br>Pl | 332<br>Sage<br>Pl | 542<br>HunGr<br>Ab (B) | 542<br>HunGr<br>Ab (B) | 542<br>HunGr<br>Kfs | 268<br>HunGr<br>Ab (B) | 443<br>HunGr<br>Ab (B) | 443<br>HunGr<br>Ab (B) | 332<br>Sage<br>Kfs | 332<br>Sage<br>Ab (B) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 67.40 | 67.73 | 67.34 | 64.12 | 63.39 | 64.89 | 65.04 | 65.75 | 67.28 | 64.06 | 67.62 |
| $Al_2O_3$ | 19.88 | 19.79 | 20.16 | 22.30 | 22.81 | 18.62 | 20.81 | 20.87 | 19.86 | 18.34 | 19.44 |
| CaO | 0.13 | 0.11 | 1.08 | 2.59 | 3.49 | 0.00 | 1.62 | 1.54 | 0.52 | 0.00 | 0.00 |
| $Na_2O$ | 11.22 | 10.77 | 10.30 | 10.00 | 9.56 | 1.13 | 10.53 | 10.63 | 11.54 | 0.73 | 10.48 |
| $K_2O$ | 0.15 | 0.18 | 0.34 | 0.21 | 0.19 | 15.33 | 0.17 | 0.26 | 0.11 | 16.11 | 0.18 |
| $\Sigma$ | 98.78 | 98.58 | 99.22 | 99.22 | 99.44 | 99.98 | 98.19 | 99.07 | 99.34 | 99.25 | 97.74 |
| END-MEMBER PROPORTION (Mol %) | | | | | | | | | | | |
| An | 0.5 | 0.5 | 5.3 | 12.1 | 16.8 | 0.0 | 8.0 | 7.2 | 2.3 | 0.0 | 0.00 |
| Ab | 98.8 | 98.5 | 92.8 | 86.9 | 82.4 | 10.3 | 91.2 | 91.2 | 96.8 | 93.8 | 99.1 |
| Or | 0.7 | 1.0 | 1.9 | 1.0 | 0.8 | 89.7 | 0.8 | 1.6 | 0.9 | 6.2 | 0.9 |

Kosk: Koskaecodde; Molly: Mollyguajeck; Kep: Kepenkeck; HunGr: Hungry Grove; RenL: Rencontre Lake; Sage: Sage Pond; Pl: plagioclase grain; Ab: albite exsolution; B: bleb perthite; Kfs: K-feldspar.

Koskaecodde unit (sample 701, $An_{34-41}$), whereas the least calcic sample is from a nearby location (sample 697, $An_{13-26}$). Petrographic observations indicate that delicate zonation is present (*i.e.*, normal and reverse types) in plagioclase from these units.

Plagioclase compositions for the northern part of the Ackley Granite proper (Kepenkeck and Mount Sylvester units) range from $An_{14}$ to $An_{26}$, with intrasample variability similar in the two samples analyzed.

The southern part of the Ackley Granite incorporates five units, for which data are summarized in Figures 4 and 12. The Tolt unit ($n = 8$) has an overall range of plagioclase composition from $An_5$ to $An_{35}$, but no single sample covers this broad spectrum, and the intrasample range varies from $An_3$ to $An_{17}$. There is a pronounced concentration of data in the range $An_{10-25}$, with only a few compositions extending to more calcic values. For the Hungry Grove unit, the data have been subdivided into three populations (Fig. 12), as dis-

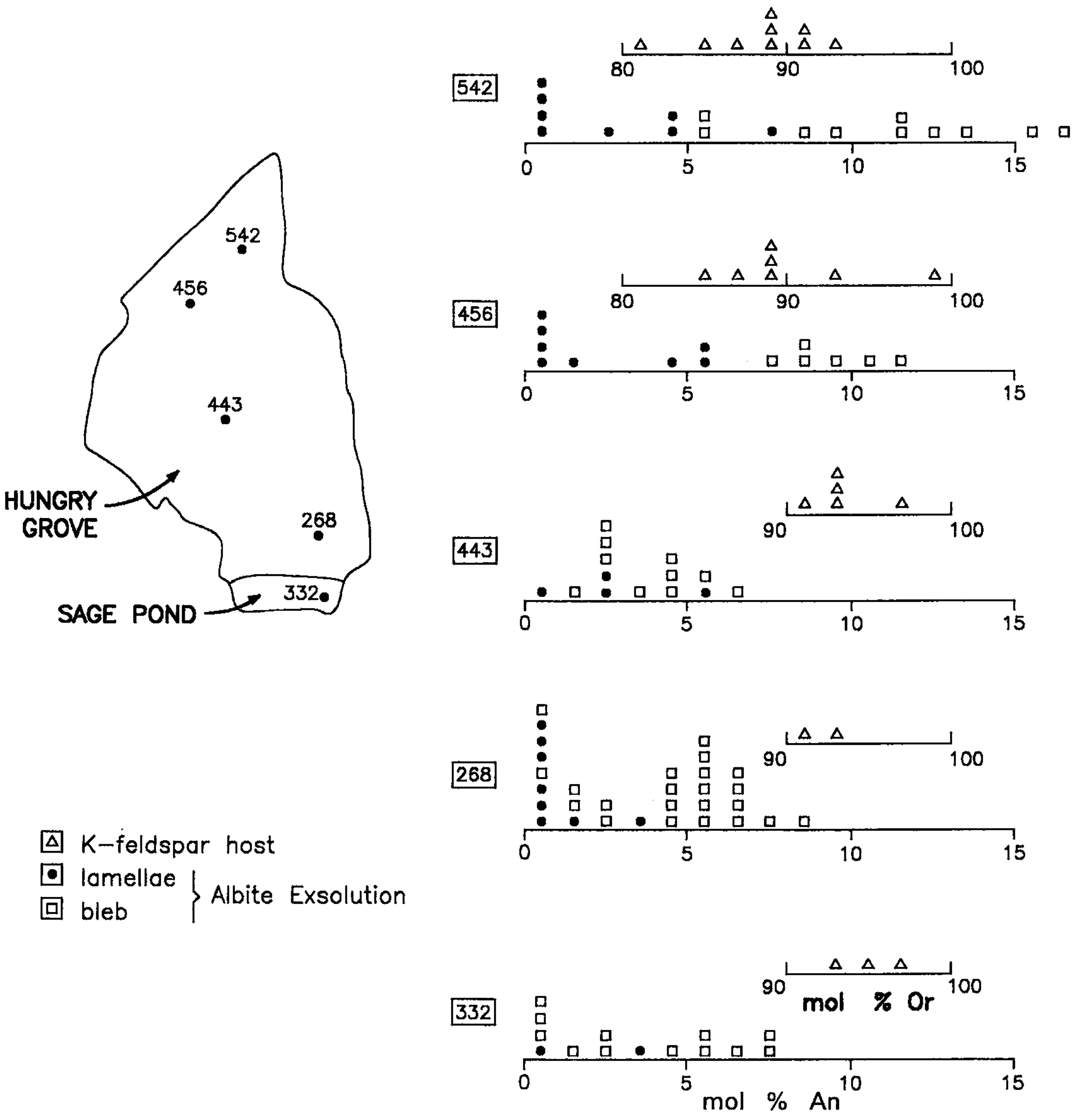

FIG. 13. Histogram plots of compositions (derived from electron-microprobe data) of K- and Na-rich phases of perthitic feldspar in samples from the Hungry Grove and Sage Pond units.

cussed above for the *REE*. The extreme northern part, which corresponds to Unit 12 in Dickson's (1983) classification, has plagioclase of $An_{3-23}$ with peaks at $An_{<5}$ and $An_{10-20}$; the albitic compositions are found in sample 196 only. The middle part has a range in plagioclase composition of $An_{4-24}$, but only a single analysis indicates a composition more sodic than $An_5$. In marked contrast, plagioclase of the southernmost part of the Hungry Grove unit is, except for a single analyses of $An_{14}$, more sodic than $An_8$.

The Sage Pond unit contains plagioclase more sodic than $An_5$, except for two analyses of $An_7$ from the same sample (332). Despite the sodic composition of the plagioclase, it is emphasized that there is a consistently small amount of calcium ($An_{1-3}$) in most samples. In the southernmost unit (Rencontre Lake), the composition of plagioclase ranges from $An_1$ to $An_{28}$. However, the albite component progressively increases toward the southeast (*i.e.*, toward the area of mineralization), such that three zones can be recognized, containing $An_{>20}$, $An_{10-20}$ and $An_{<10}$, respectively (Fig. 12).

## COMPOSITION OF PHASES IN THE PERTHITIC FELDSPAR

Compositions of the K- and Na-rich phases in alkali feldspar have been determined for samples from the Hungry Grove ($n$ = 4) and Sage Pond ($n$ = 1) units to assess the degree of low-temperature equilibration (Fig. 13, representative compositions in Table 4). Albite lamellae range from $An_{17}$ to $An_0$ composition, and there are two trends: (1) coarse blebs are relatively enriched in Ca compared to flame and film perthite, and (2) the coarse lamellae or blebs in alkali feldspar from samples in the less evolved part of the granite (*i.e.*, northern part) are the most enriched in Ca. There is also a trend observed in terms of the composition of the K-rich phase, with increasing mol.% Or occurring in samples from the more evolved part of the granite. The data indicate that the alkali feldspar from the more evolved part of the Ackley Granite has equilibrated to lower temperatures.

Figure 14, a photomicrograph of perthitic orthoclase, illustrates the nature of the Ca-rich blebs. Note that the clear parts of the blebs have compositions of $An_{11-17}$, whereas the pitted wing areas are $An_{<3}$ in composition. In this particular sample, most of the perthite lamellae are characterized by such a pitted or porous texture. Similar pits or micropores in alkali feldspar have also been discussed by Worden *et al.* (1990) and Waldron *et al.* (1994); these authors favor a secondary origin for the pores, which reflect fluid infiltration that promoted microperthite development and subgrain growth. With respect to the Ca-rich nature of the blebs, it is noted that similar types of perthite blebs of Ca-rich nature (to $An_{17-31}$) have been described in both granitic and metamorphic (*i.e.*, granulitic) rocks by Yund & Ackermand (1979) and Yund *et al.* (1980), respectively. These authors attribute the formation of these Ca-rich blebs to early heterogeneous nucleation in the high-temperature part of the ternary miscibility gap (Seck 1971). The extended time at high temperatures, compared to the case of the Ca-poor film perthite, resulted in the exsolution-related domains becoming blebby in response to minimization of the interfacial energy.

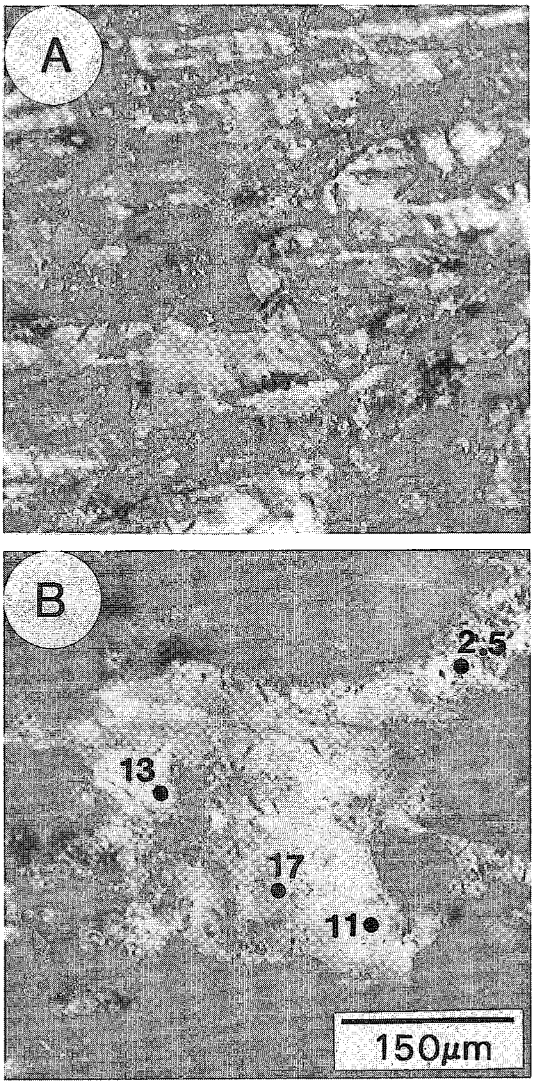

FIG. 14. Photomicrographs of perthitic feldspar (sample 542) from the Hungry Grove unit. Figure 14B is an enlargement of the central part of Figure 14A and shows the development of a porous texture in parts of the albite domains. Numbers in Figure 14B refer to mol.% An, as determined from electron-microprobe analysis.

## DISCUSSION

### *Al–Si order relationships in the alkali feldspar*

The degree of Al–Si order in the alkali feldspar of the Ackley Granite indicates two types of granite, dominated by microcline and orthoclase, respectively. In units dominated by microcline, the inversion to a triclinic phase is considered to have developed in concert with deformation. Samples from the Koskaecodde unit proximal to its intrusive contact with the Hungry Grove unit indicate that reheating led to development of orthoclase. For the remainder of the Ackley Granite, orthoclase dominates, with minor domains of triclinic feldspar, including areas proximal to mineralization.

The problem of partially ordered (*i.e.*, stranded) feldspars in large granitic intrusions has received considerable discussion (*e.g.*, Parsons & Boyd 1971, Cherry & Trembath 1978, Parsons 1978, Ferguson 1979, Parsons & Brown 1984, Stevenson & Martin 1988, Brown & Parsons 1989). It is generally agreed that several physical and chemical parameters influence rates of Al–Si ordering, including rate of cooling, stress, bulk-rock composition, fluid chemistry and fluid–rock interaction (also see Guidotti *et al.* 1973, Stewart & Wright 1974, Martin 1969, 1974, 1984, Worden *et al.* 1990). For the Ackley Granite, several of these factors may have been important. The inversion of stranded orthoclase (Martin 1974) to ordered microcline requires disruption of the crystal structure and is, therefore, potentially inhibited because of an energy barrier. In situations where energy is contributed to the local environment (*e.g.*, deformation, strain about perthite lamellae) and the temperature is within the stability field of microcline (*i.e.*, ≤450°C; Bambauer & Bernotat 1982, Bernotat & Bambauer 1982), fully ordered K-feldspar forms, as in deformation regimes (*e.g.*, Blasi *et al.* 1980, Kontak *et al.* 1984) and metamorphic terranes (Guidotti *et al.* 1973, Bernotat & Bambauer 1982, Bambauer & Bernotat 1982, Bambauer *et al.* 1984). Within the microcline-dominant units of the Ackley Granite, deformation textures indicate post-intrusion stress, and the presence of triclinic feldspar indicates that much of this occurred below the orthoclase–microcline inversion temperature. These data suggest that the older units of the granite had different thermal histories, consistent with their older $^{40}$Ar/$^{39}$Ar ages (Kontak *et al.* 1988). The redevelopment of orthoclase in parts of the Koskaecodde unit indicates that a thermal aureole involving temperatures greater than 450°C is associated with the Hungry Grove unit; this hypothesis supports the geochronological work cited above. Earlier studies have documented similar situations in contact aureoles (Wright 1967, Steiger & Hart 1967, Tilling 1968, Bonin & Martin 1974, Jiránek 1982, Bambauer *et al.* 1984).

The most intriguing aspect of this study is the dominance of orthoclase even though part of the intrusion has been pervasively infiltrated in part by high-temperature, saline-rich fluids (Tuach 1987). Parsons (1980), Parsons & Brown (1984) and Brown & Parsons (1989) emphasized the importance of late-stage fluids in the ordering process. Observations from both laboratory studies (Martin 1969) and nature (White & Martin 1980, Martin & Bowden 1981, Lalonde & Martin 1983) indicate that an alkaline fluid enhances Al–Si ordering, just as a peraluminous bulk composition of a rock inhibits it (*e.g.*, Guidotti *et al.* 1973, Kontak *et al.* 1984). In the case of the Ackley Granite, both the bulk composition of the granite and the presence of a late-stage fluid should have facilitated ordering, yet apparently they did not. The high level of emplacement and rapid cooling of the granite, as evidenced by the petrology of the rocks and concordant hornblende, muscovite and biotite Ar–Ar ages, respectively, suggest that the cooling rate of the granite was faster than the kinetics of the ordering process.

### *Sodic plagioclase within the Ackley Granite*

Albitization of calcic plagioclase is a common and pervasive feature within highly evolved felsic suites (White & Martin 1980, Van de Pijpekamp 1982, Witt 1988, Taylor & Pollard 1988, Kontak 1990, 1993, Schwartz & Surjono 1990). However, there has been little investigation of this phenomenon, and it is not clear if some of the albite may in fact represent a liquidus phase. Based on experimental study of a highly evolved, F-rich, subsolvus granite from Cornwall, Weidner & Martin (1987) proposed a magmatic origin for the albite. In contrast, Pichavant *et al.* (1987) interpreted the albite in the Li- and F-rich Beauvoir granite to represent a metasomatic feature based on experimental studies.

Observations of albitic plagioclase in the Ackley Granite that are relevant to understanding its origin are: (1) the lack of associated alteration, such as pervasive chloritization of biotite or formation of epidote, the latter being predicted from experimental observations (Moody *et al.* 1985) over the interval 300–500°C; (2) the absence of porosity, since the reaction of calcic plagioclase to albite involves a change in volume, unless a constant-volume reaction is involved (Boles 1982), and (3) lack of a compositional gap in the peristerite region (Figs. 4, 12).

These features are consistent with a high-temperature origin for the albitization, consistent with experimental data (Orville 1963, Lagache & Weisbrod 1977, Moody *et al.* 1985). Tuach (1987) documented the presence of a high-temperature, saline (to 60–70 wt.% eq. NaCl) fluid occurring in secondary fluid inclusions within magmatic quartz in the evolved units of the Ackley Granite. The formation of albite is here considered to reflect high-temperature exchange equilibria between a more calcic plagioclase and an exsolved, saline fluid coincident with resurgent boiling of the Ackley Granite, which may have occurred simultaneously with the onset of mineralization in the southernmost part of the intrusion. The continuum in the plagioclase compositions suggests that the temperature remained above the peristerite solvus at *ca.* 400–450°C (Smith & Brown 1988), which is also supported by the presence of orthoclase over microcline.

### *Geothermometry*

The compositions of coexisting plagioclase and alkali feldspar have been used to estimate temperatures for some of the units (Fig. 15). In order to estimate temperature, the bulk composition of an alkali feldspar has been paired with a range of compositions determined for plagioclase in each sample. Since alkali feldspar appears to have been a late primary phase, rim compositions of plagioclase have been used for geothermometry. In Figure 15, some of the data fall outside the range of equilibrium conditions (*e.g.*, Hungry Grove unit), which results from the continued re-equilibration of plagioclase at subsolidus conditions to an albitic composition. The maximum temperatures (up to 700°C) are preserved in the Tolt unit, whereas temperatures of *ca.* 650°C and 550°C are estimated for the Rencontre Lake and Hungry Grove units. These temperatures are interpreted as follows: (1) the Tolt unit was spatially outside the main hydrothermal system and, therefore, did not equilibrate to a lower temperature, and (2) the Rencontre Lake and Hungry Grove units re-equilibrated to lower a temperature during the infiltration of late-stage fluids, which pro-

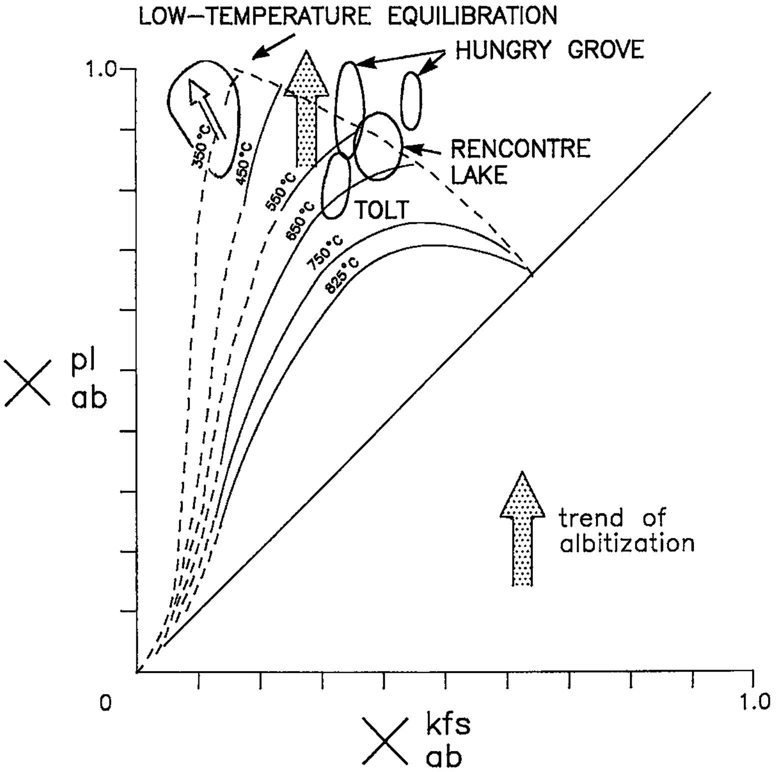

FIG. 15. Partitioning of albite between coexisting alkali feldspar and plagioclase in samples from various units of the Ackley Granite. Higher temperatures are determined using bulk compositions of alkali feldspar coexisting with plagioclase, whereas a low-temperature equilibration is determined for perthitic orthoclase using EMPA data for both K- and Na-rich phases. Contours of temperatures are taken from Brown & Parsons (1981). The low-temperature data for the Hungry Grove and Sage Pond units are based on perthite and show a north-to-south progression in terms of decreasing temperature.

moted the development of albite. Thus the increasing development of sodic plagioclase within the Hungry Grove unit from north to south probably reflects pervasive infiltration of fluid within this part of the intrusion. Similarly, the trend in the Rencontre Lake unit (Fig. 12) also reflects re-equilibration of the plagioclase with a fluid phase, thus shifting the equilibria in Figure 15.

The low-temperature equilibration of alkali feldspar, as reflected petrographically by the presence of albite lamellae, has been estimated for the Hungry Grove unit by using the composition of the host alkali feldspar phase and albite exsolution lamellae. These data indicate a range of temperatures that reflects the trend of changing perthite composition (Figs. 13, 15). Since the range of data lies below the calibration for the binary in Figure 15, the lowest temperatures of re-equilibration are based instead on the alkali feldspar solvus (Smith & Brown 1988) and are estimated at 350° to 400°C; lower temperatures would require near pure end-member albite and K-feldspar. Similarly, low temperatures are recorded in other granites using the same technique (*e.g.*, Ferry 1978, 1985). Thus, the inferred range of postmagmatic temperatures based on chemical equilibria of the feldspar phases supports the overall lack of triclinic feldspar; the intrusive units cooled quickly after emplacement, and there was insufficient time for development of ordered K-feldspar to form.

### *Implications of chemistry of the alkali feldspar*

The trace-element chemistry of the alkali feldspar within the different units shows systematic variations that are consistent with previous whole-rock data and the generally inferred evolution of the Ackley Granite. However, the data for Rb, Sr and Ba for the Hungry Grove unit (Fig. 9) indicate that the smooth trend-surfaces generated by the work of Whalen (1983) and Tuach *et al.* (1986) may be too simplistic; instead, more complicated distributions of elements are inferred. This latter assumption depends, of course, on the premise that the various distribution-coefficients for these elements remained constant throughout this unit; the bulk compositions of the samples support this assumption (Fig. 5). The abrupt variations in concentrations observed may reflect the role of fluids in the late-stage evolution of the Ackley Granite, for which there is abundant corroboration from petrographic observations.

The *REE* show large, but systematic, variations within all units of the Ackley Granite. Enrichment in *HREE* occurs in all units of the main Ackley Granite except the two older ones (Koskaecodde and Mollyguajeck). The strongest enrichment in the *HREE* show a systematic negative correlation with Ba, and does not seem to be due to micro-inclusions of zircon. Enrichment of the *HREE* may occur by complexing with Cl (Flynn & Burnham 1978), and is commonly observed where granitic rocks have interacted with saline, magmatic fluids, as in granite-hosted mineral deposits (Taylor & Fryer 1983). Thus, *HREE* enrichment in alkali feldspar of the Ackley Granite is considered to reflect localized enrichment due to separation of a fluid phase. Since the major- and trace-element chemistry of the alkali feldspar is considered to reflect dominantly magmatic processes, this fluid is inferred to have been late magmatic in origin, *i.e.*, it coexisted with the melt, and enhanced enrichment of the *HREE*. Fluids of similar composition were involved in greisen formation, as there is a similar *HREE*-enriched signature for these rocks in the Ackley Granite (Tuach 1987).

The systematic decrease in the positive Eu anomaly of the alkali feldspar in the Ackley Granite is correlated with the geochemical evolution; the anomaly is smallest in the Hungry Grove and Rencontre Lake units. As there is no correlation between bulk composition and the magnitude of the positive Eu anomaly, the relative depletion of Eu cannot be attributed to subsequent re-equilibration, as might be the case if albitization of the K-feldspar had occurred (*cf.* Fowler & Doig 1983). However, the positive correlation between Eu/Eu* and Ba suggests that decreasing $\mathrm{Eu_N}$ was probably a primary feature of the magma.

## CONCLUSIONS

Feldspar phases within the highly evolved Ackley Granite reflect a complex physical, thermal and chemical history. The two oldest units (≥390 Ma) are characterized by triclinic alkali feldspar and relatively calcic plagioclase ($\mathrm{An_{12-46}}$). In contrast, the younger units (≤374 Ma) comprising the pluton are characterized by "stranded" orthoclase, with only local, incipient development of triclinic alkali feldspar. Whereas the formation of the triclinic polymorph in the older units is related to deformation, the stranding of the monoclinic polymorph in the younger units that were once saturated with volatiles is related to rapid postmagmatic cooling of the granite. Plagioclase compositions within the younger units show a continuum from $\mathrm{An_{28}}$ to end-member albite, with the latter reflecting interaction of original plagioclase with a late-stage, saline magmatic fluid, preserved as secondary fluid inclusions in magmatic quartz, at a temperature above the peristerite solvus. Thus the environment of albitization is consistent with the stranding of monoclinic alkali feldspar.

The trace-element chemistry of the alkali feldspar reflects chemical evolution toward more evolved phases in the southern part of the granite, paralleling trends defined by whole-rock chemistry. However, the elemental concentrations of Ba, Rb and Sr are considered to reflect modification of the melt chemistry by local saturation of the magma in a fluid phase and, therefore, localized patterns of enrichment or depletion of elements. The distribution of *HREE* elements similarly reflects the influence of exsolved fluids on the partitioning, such that alkali feldspar samples with similar bulk compositions have highly variable concentrations of the *HREE*.

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