Trace-element modeling of the petrogenesis of granophyres and aplites in the Notch Peak granitic stock, Utah

Peter I. Nabelek

Department of Geology, University of Missouri–Columbia, Columbia, Missouri 65211

Abstract

The petrogeneses of a granophyre and an aplite in the Notch Peak stock, Utah, were modeled using published experimental data for mineral/melt, mineral/fluid, and melt/fluid partitioning of alkali, alkaline-earth and rare-earth elements. The stock ranges in composition from granite to quartz monzonite. The granophyre occurs along a horizontal contact of the granite with overlying impermeable limestones and contains graphic intergrowths of alkali feldspar and quartz, displaying unidirectional solidification structures. Calculations suggest that the granophyre formed by 2–13% crystallization from an aqueous fluid that exsolved from the magma during emplacement and was trapped beneath the limestones. The observed strong enrichment of Ba and Sr in the granophyre relative to the granite is due to large alkali feldspar/fluid partition coefficients for these elements, while the depletion of large-ion-lithophile elements is due to their small solubility in aqueous fluids. On the other hand, the aplite, one of many crosscutting the stock, is depleted in Ba, Sr, and the REEs, while the concentration of highly charged elements, Zr, Ta, Hf, Th, and U, is about the same as in the major lithologic units in the stock. It is not possible to explain the alkaline-earth element and REE concentrations in the aplite by any model that employs mineral/melt partition coefficients for anhydrous melts. However, the "minimum granite" composition and the large concentration of the highly charged elements are difficult to explain by direct crystallization from aqueous fluids. It is apparent that the partition coefficients of Ba, Sr, and the REEs between minerals and melt significantly increase when the system becomes saturated with chlorine-rich aqueous fluids.

The results of this study have implications for the petrogenesis of pegmatites and other aplites because many have depletion and enrichment characteristics similar to the aplite and granophyre at Notch Peak. It is shown that rocks that are the result of fractionation off anhydrous melts can be distinguished on the basis of their major- and trace-element chemistries from those that crystallized in the presence of aqueous fluids or those that crystallized directly from the fluids.

Introduction

The common association of pegmatites, aplites, and granophyres with granitic rocks has been recognized for a long time, but it was the work of Richard Jahns and coworkers that demonstrated the importance of aqueous fluids in the petrogenesis of these rock types. Jahns and Burnham (1957, 1969) suggested on the basis of experimental work that pegmatites and aplites crystallize when a separate supercritical aqueous-fluid phase forms during the late stages of crystallization of a granite. The time of separation depends on the solubility of fluids (e.g., water) in the magma at a given confining pressure on the system. A review of pegmatite petrogenesis (Černý, 1982) shows that pegmatites and associated rocks have been described primarily in terms of mineralogy and major-element chemistry; however, the abundances of trace elements have not been generally used to their full potential to further elucidate the petrogenesis of these rocks.

The use of trace elements to model the petrogenesis of igneous rocks has been extensive but generally confined to modeling crystal/melt processes mainly in mafic and intermediate rocks (Arth, 1976; Hanson, 1980). Recently published experimental data on partitioning of several trace elements between minerals and fluid and melt and fluid (e.g., Carron and Lagache, 1980; Volfinger, 1976) also permit the modeling of crystallization processes that involve fluids.

The purpose of this paper is to model the petrogenesis of aplites and granophyres associated with the Notch Peak granitic stock, House Range, western Utah, and to demonstrate the feasibility of using trace elements in modeling the petrogenesis of pegmatitic rocks. Pegmatites in the Notch Peak stock occur only as occasional pods; thus, it is difficult to obtain a representative whole-rock sample. It is, however, easier to model the petrogenesis of aplites and granophyres because they can be sampled as whole rocks. Furthermore, the clearly defined mutual relationships among the aplites, granophyres, and the host intrusion can be used to constrain possible petrogenetic models. In addition, the petrogenesis of the stock and the nature
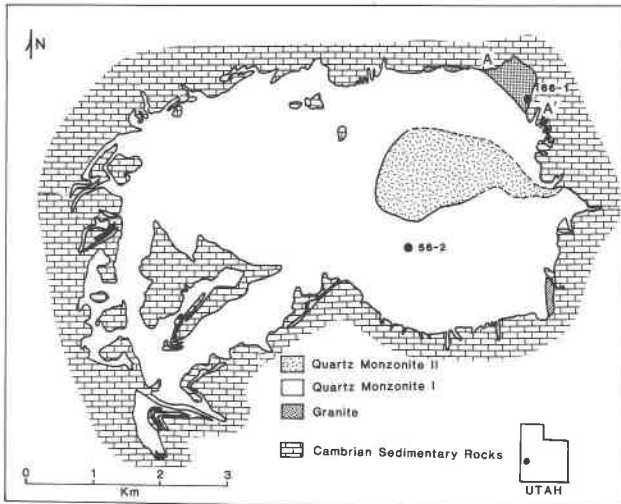
Fig. 1.   Geologic map of the Notch Peak stock with locations of the aplite and granophyre samples discussed in this article.

Fig. 2.   Cross-section through the granite body. Note the location of the granophyre below limestone beds.

of fluid flow in the Notch Peak complex are well understood from previous studies (Nabelek et al., 1983, 1984, ms.).

ANALYTICAL METHODS

The analyses of Si, Ti, Fe, Mn, Ca, K, Nb, Cu, Ga, Y, and Pb were conducted at Battelle-Northwest, Richland, Washington, using an energy-dispersive X-ray fluorescence Kevex Model 810 system with zirconium and silver secondary sources. Al, Mg, and Na were analyzed on samples dissolved in lithium metaborate flux by atomic absorption. U.S. Geological Survey standards were used as working standards. Replicate standard and sample analyses yield uncertainties of less than 10% for Mn, Nb, Cu, and Ga; 5% for Si and Ti; 3% for K, Ca, Al, Na, Mg, Pb, and Y; and 1% for Fe.

Other elements were analyzed by instrumental neutron activation analyses (INAA) of 0.5–1.0-g irradiated aliquots of about 5-kg homogenized whole-rock powders. The gamma-rays emitted from the samples were counted by Ge(Li) detectors using the sequential counting technique described by Laul (1979). Zn, Sb, Rb, Sr, and Zr data were obtained by coincidence-noncoincidence counting, which resulted in reduction of the Compton background. Corrections were made for La, Ce, Nd, Sm, and Zr formed by fission of ^{235}U and as activation products of ^{238}U as a result of irradiation. U.S. Geological Survey standards GSP-1, BHVO-1, and International Atomic Energy Agency standard Soil-5 were used to monitor the accuracy and precision of the results. The one-standard-deviation uncertainties on replicate standard analyses are 1–2% for Na, Ce, Co, Sc, and Zn; 3% for Ba, Eu, Tb, and Rb; 4–5% for Sr, La, Sm, Yb, Lu, Hf, Ta, Th, U, and Cs; and less than 10% for Nd and Zr. K, Na, Rb, Ba, Sr, and Zn were analyzed by more than one method. The replicates are well within the stated analytical uncertainties. For consistency, only the INAA data are reported.

GEOLOGY

The geology of the Notch Peak stock is described in detail in Nabelek et al. (ms.) and therefore only a short summary is presented here. The Jurassic stock intruded interbedded Cambrian
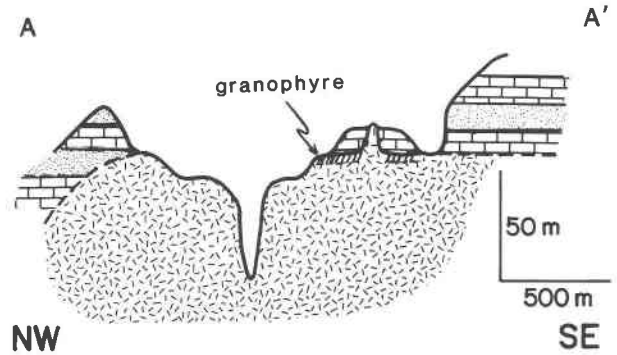
limestones and argillites at a depth of approximately 4–6 km. The stock is a composite body consisting of a granite and two different intrusions of quartz monzonite. The crosscutting relations indicate that the granite intruded first, followed by quartz monzonite I and then by quartz monzonite II (Fig. 1).

All three lithologic units are texturally and mineralogically similar. The granite tends to be porphyritic (Fig. 3a), while quartz monzonite I has a seriate texture and is mineralogically and texturally the most homogeneous of the three intrusions. Quartz monzonite II is porphyritic near the contact with quartz monzonite I but becomes seriate toward the core. Euhedral oligoclase, equant quartz, and minor biotite crystallized early in the paragenetic sequence in all three lithologic units. Although perthite grains are the largest, they apparently crystallized late in the paragenetic sequence. Titanite, apatite, and zircon are accessories. The core of quartz monzonite II contains extensively chloritized biotite and sericitized plagioclase. Nabelek et al. (1983) have shown that this alteration is primarily due to interaction with fluids that exsolved during crystallization from deeper parts of the magma chamber. The presence of a free fluid phase is also suggested by miarolitic cavities, containing quartz and microcline, that are especially common in the granite. In addition, the granite is cut by quartz veins, one about 3 m across. The petrogenetic modeling of major- and trace-element data from the stock (Nabelek et al., ms.) suggests that the three intrusions are cogenetic and represent various stages of crystallization and emplacement of a chemically fractionated diapir.

The granophyres are located at horizontal contacts with sedimentary rocks. Particularly good examples are the samples 166-1A and 166-1B. These sample were collected from an approximately 1-m-wide granophyre that occurs along the horizontal contact between the granite and the limestone layers of the wall rock which form the roof of the magma chamber (Fig. 2). The location of the granophyre near the top of the granite intrusion is similar to that in other plutons, including gabbros (e.g., Carmichael et al., 1974). The granophyre consists solely of graphic intergrowths of alkali feldspar and quartz (Fig. 3b). The contact between the granophyre and sedimentary layers is sharp. The contact between the granophyre and the granite is about 10 cm thick and is characterized by rhythmic, about 1-cm-thick granophyric and aplitic layers (Fig. 3c). The fine-grained aplitic layers (not to be confused with the aplite dikes discussed below) appear to have acted as nucleation sites for fanning-out alkali feldspars with intergrown quartz. The growth direction of the feldspars is away from the wall-rock contact.

Aplites occur as dikes cutting all three lithologic units and often cross contacts between the units. The dikes generally strike north
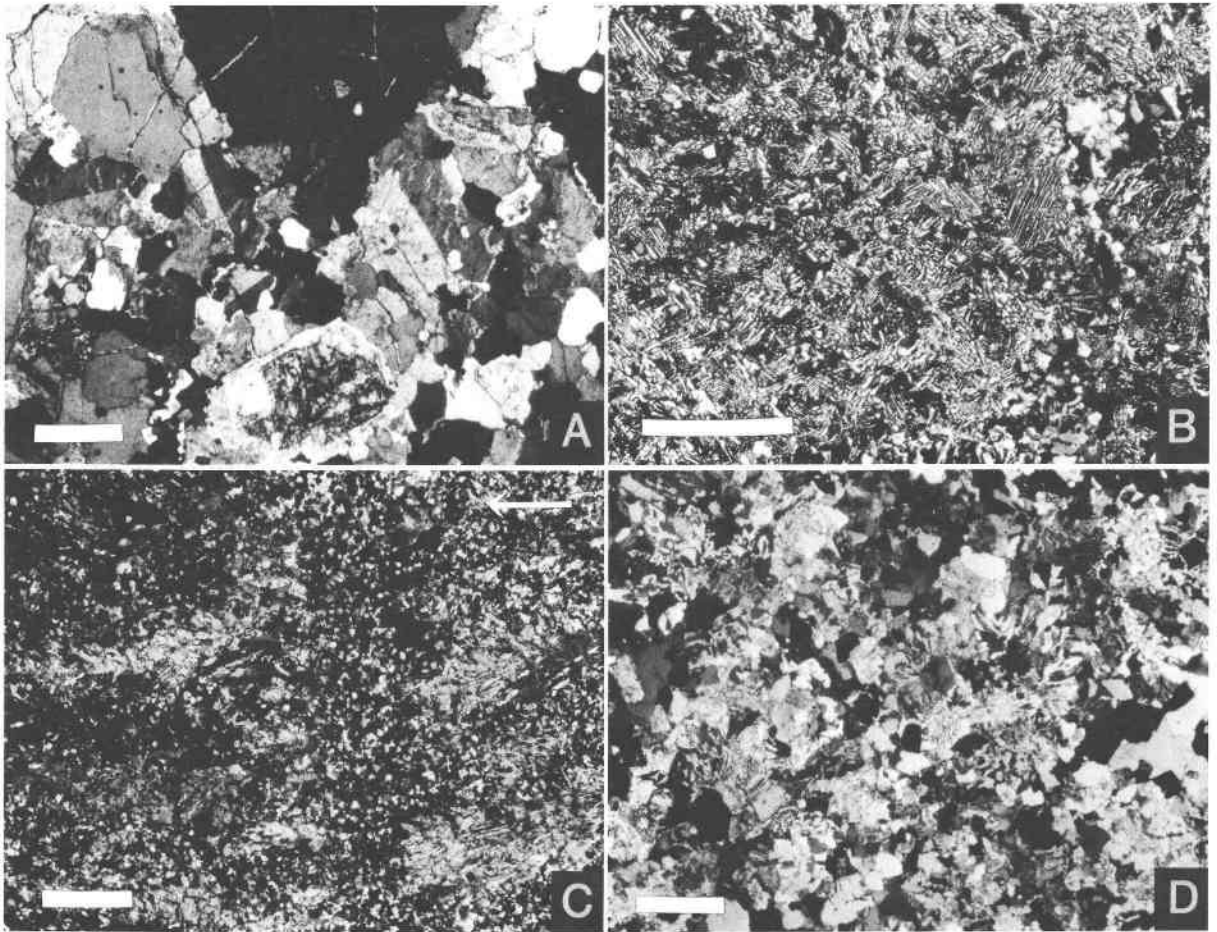
Fig. 3.   (A) Typical texture of the granite. (B) Texture of the granophyre. (C) Rhythmic zone between the granophyre and the granite. The direction from the wall-rock contact is shown by the arrow. (D) Texture of the aplite. The scale bars denote 1 mm.

with vertical dips and vary in width from about 10 cm to 2 m. These features suggest that they were emplaced in fractures during the last stages of solidification of the stock. The aplites have an equigranular sugary texture with grains no more than 1 mm in maximum dimension. The cores of several larger dikes have a coarse pegmatitic texture. The mineralogy includes albite, quartz, and graphic intergrowths of quartz and alkali feldspar (Fig. 3d).

COMPOSITIONS

Granophyres

The data for the two analyzed samples of the granophyre (166-1A and 166-1B) are shown in Tables 1 and 2. The normative Q-Ab-Or values are plotted in Figure 4, along with fields for granite, quartz monzonite I, and quartz monzonite II. The granophyre data lie off the granite field and away from the 200-MPa P_{H_2O} minimum on the Q-Or cotectic. The granophyre contains very little Fe_2O_3 and CaO relative to the granite and almost no MgO; MnO was undetected.

The trace-element abundances in the granophyre are also significantly different from those in the granite or the other two lithologic units. The rare-earth-element (REE) patterns are subparallel to those of the granite but at con-

centrations ten times smaller (Fig. 5). The granophyre pattern has, however, a strong positive Eu anomaly, whereas the granite pattern has a negative Eu anomaly. Other high-valence large-ion-lithophile trace elements and transition metals (Zr, Hf, Nb, Co, Ta, Sc, U, Th) are also depleted in the granophyre relative to the granite. Zr values in parts per million (ppm) are 20–24 in the granophyre vs. 115–220 in the granite (see Table 2). On the other hand, the alkaline-earth trace elements are significantly enriched in the granophyre relative to the granite. The granite contains 180–400 ppm Ba, the granophyre about 3000 ppm, and Sr is enriched approximately three times in the granophyre relative to the granite. Rb has similar concentrations in both (Table 2).

Aplites

One aplite sample was analyzed for major and trace elements (Tables 1 and 2). Although the aplites cut all three main lithologic units, it is best to compare the aplite chemistry to that of quartz monzonite I as this unit composes the bulk of the stock. Furthermore, the quartz monzonites were the last units emplaced (Nabelek et al., ms.);

Table 1.   Major-element concentrations and normative values

	granophyres 166–1A	166–1B	aplite 56–2	average granite	average QMI
(wt. %)					
SiO$_2$	77.3	77.5	78.0	75.9	73.9
Al$_2$O$_3$	10.9	11.8	12.6	12.6	13.9
TiO$_2$	0.16	0.13	0.09	0.19	0.27
Fe$_2$O$_3$	0.38	0.36	0.92	1.19	2.09
MgO	0.03	0.01	0^b	0.21	0.53
CaO	0.21	0.28	0.37	1.10	1.68
Na$_2$O	2.07	2.48	3.48	3.56	3.93
K$_2$O	7.78	8.15	4.90	5.27	3.51
P$_2$O$_5$	N.A.^{a}	N.A.^{a}	0.02	0.07	0.11
Total	98.8	100.7	100.4	99.3	99.9
(CIPW norm)					
Q	37.4	34.4	38.4	32.6	33.4
Or	46.0	48.1	29.0	31.1	20.8
Ab	12.9	15.2	29.4	30.1	33.3
An	–	–	1.7	2.9	7.6
Ac	1.1	1.0	–	–	–
Ns	0.78	1.1	–	–	–
Di	0.16	0.05	–	1.7	–
Wo	0.12	0.37	0.26	–	–
Hy	–	–	–	0.36	1.3
He	–	–	0.92	–	2.0
Mt	–	–	–	0.67	–
Il	0.01	0.01	0.02	0.37	0.09
Ru	–	–	0.08	–	0.23
Tn	0.38	0.31	–	–	–
Ap	–	–	0.05	0.17	0.26
C	–	–	0.94	–	0.81
Total	98.8	100.5	100.8	100.0	99.8

^{a} Phosphorus was not analyzed in the granophyre.
^{b} Below detection limit.

Table 2.   Trace-element concentrations in parts per million (ppm)

	granophyres 166–1A	166–1B	aplite 56–2	granite range^a	QMI range^a
Y	1.3	1.3	N.A.	6.4–13.9	8.1–14.6
Sr	450	410	26	100–190 (150)	260–410 (300)
Rb	210	180	290	195–345 (260)	160–230 (200)
Ba	3320	2760	50	180–400 (270)	260–710 (500)
Cs	3.5	1.3	4.5	2.9–9.9	2.8–9.4
Th	5	4	22	22–40	21–49
U	1.0	1.8	22	3.8–14.0	3.4–8.6
Zr	24	20	220	115–220	97–170
Hf	0.82	0.63	3.1	3.4–4.8	2.6–4.2
Nb	3.4	2.6	N.A.	20–31	16–32
Ta	0.56	0.43	1.8	1.7–2.7	1.3–8.6
Ga	14	13	N.A.	15–17	14–18
Sc	0.23	0.17	2.4	2.1–3.7	2.8–4.0
Co	0.31	0.26	0.67	1.4–2.9	2.5–4.2
Sb	0.08	0.09	0.97	0.07–0.74	0.07–0.28
Pb	28	34	N.A.	22–36	20–35
Cu	7	9	N.A.	6–45	6–10
Zn	4	0.4	10	10–22	11–36
La	3.38	3.35	14.2	18.5–39.1	27.2–48.5
Ce	5.93	5.26	24	35–84 (62)	48–130 (84)
Nd	3.1	2.8	8.4	11–30 (18)	18–34 (26)
Sm	0.36	0.36	1.58	1.73–5.19 (2.72)	2.45–5.51 (3.98)
Eu	0.40	0.38	0.13	0.32–0.86 (0.45)	0.67–0.98 (0.76)
Tb	0.03	0.02	0.04	0.16–0.40^b	0.25–0.45^b
Yb	0.15	0.14	0.64	0.83–1.75 (1.14)	0.89–1.52 (1.24)
Lu	0.04	0.04	0.24	0.16–0.33 (0.24)	0.17–0.29 (0.24)

^{a} Parentheses indicate average values used in calculations as C_0's.
^{b} Extrapolated values of Gd were used instead of Tb in calculations. The values were 1.67 for granite and 2.49 for quartz monzonite I.
N.A. signifies "not analyzed".

therefore, the aplites most likely formed in the last stages of crystallization of the quartz monzonites. For these reasons, the aplite that is modeled was collected in quartz monzonite I (Fig. 1). The aplite contains very little Fe$_2$O$_3$ and CaO and contains no measurable MgO and only trace amounts of MnO and P$_2$O$_5$. Its normative values plot near the piercing point for Ab/An = 5.2 on the Q-Ab-Or diagram (Fig. 4).

The trace-element systematics of the aplite are quite different from those in the granophyre. The concentrations of Zr, U, Th, Sc, Ta, and Hf are similar to the ones in quartz monzonite I but are significantly higher than in the granophyre. Ba and Sr have very low concentrations in the aplite at 50 and 26 ppm, respectively. The 290 ppm of Rb are within the range of the concentrations in the quartz monzonite I and are only slightly larger than in the granophyre. The light REEs are depleted approximately five times relative to the quartz monzonite I, and the REE pattern has a slightly negative Eu anomaly (Fig. 5). There is a pronounced relative enrichment of the heavy REEs.

PARTITION COEFFICIENTS

Several models for the petrogenesis of the granophyre and the aplite that include mineral/melt, fluid/melt, and fluid/mineral equilibria are explored in this paper. Mineral/melt trace-element partition coefficients for the phases involved (Table 3) are fairly well known and have been used with success in many petrogenetic studies. The data of Carron and Lagache (1980) for the partitioning of Rb, Sr, and Ba between hydrothermal solutions and feldspars and hydrothermal solutions and melts at 700–800°C and 200 MPa permit numerical modeling of processes that

involve fluids. Unfortunately, these authors did not give the analytical data but presented only exchange distribution coefficients that they defined as

$$K_D(s/f) = K_d(s/f)[(Na + K)_f/(Na + K)_s],   (1)$$

where $K_d(s/f)$ is C_s/C_f; C_f is the concentration of a trace element in the fluid, and C_s is the concentration in the mineral in weight proportions. Carron and Lagache defined an analogous equation for the partitioning of a trace element between melt and fluid:
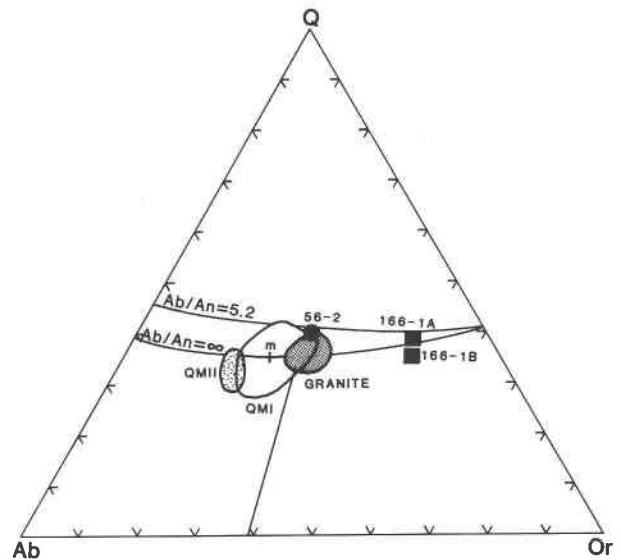

Fig. 4.   Diagram of the normative Q-Ab-Or values. Shown are fields for the major units in the stock and values for the aplite sample 56-2 and the granophyre samples 166-1A and 166-1B. The boundary for Ab/An = 5.2 is after von Platen (1965); Ab/An = ∞ is after Tuttle and Bowen (1958); both are at 200-MPa pressure.
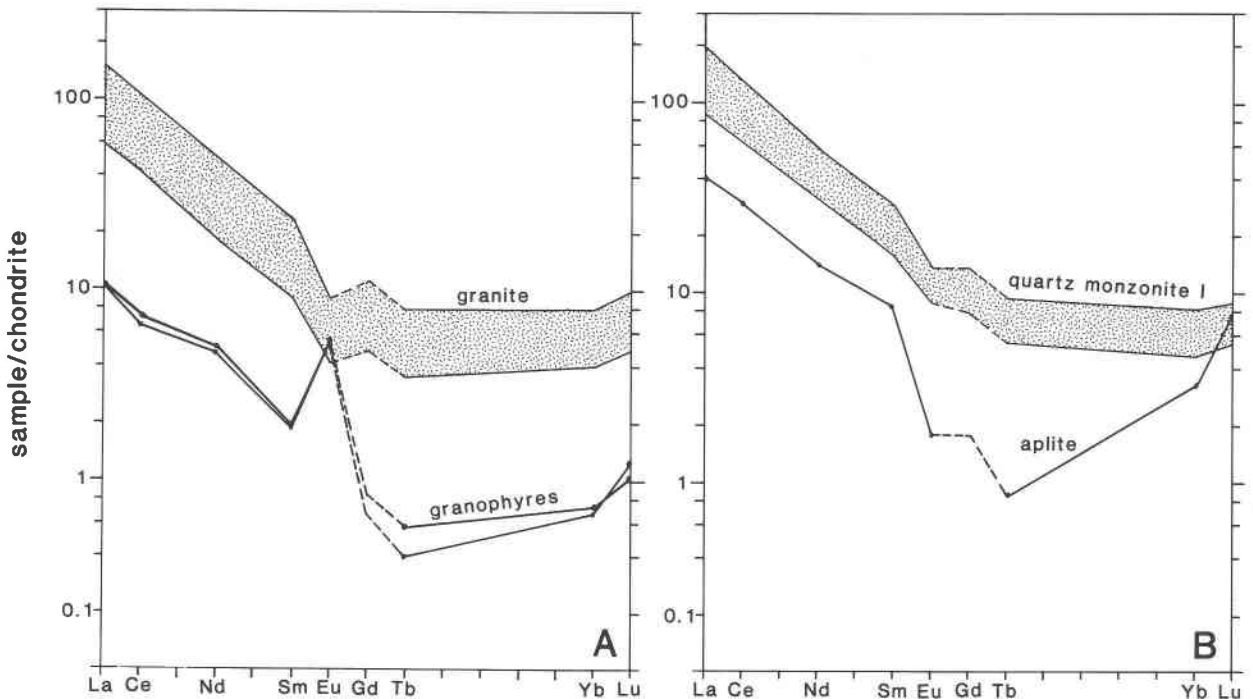
Fig. 5. (A) REE patterns for the granophyre samples. The field for granite samples is shown for comparison. (B) REE pattern for the aplite sample 56-2. The field for the host quartz monzonite I is shown for comparison.

$$K_D(m/f) = K_d(m/f)[(Na + K)_f/(Na + K)_m]. \quad (2)$$

For the purposes of this study, the Nernst partition coefficients, $K_d(s/f)$ and $K_d(m/f)$, are more useful. By inverting Equations 1 and 2,

$$K_d(s/f) = K_D(s/f)/[(Na + K)_f/(Na + K)_s] \quad (3)$$

$$K_d(m/f) = K_D(m/f)/[(Na + K)_f/(Na + K)_m]. \quad (4)$$

It is therefore necessary to determine the Na + K in the feldspars, melt, and fluids at Notch Peak.

The partition coefficients between melt and fluid (Table 4) were calculated using the granite value of 70 000 ppm of Na + K and $K_D(m/f)$ values for $Q_{40}Ab_{30}Or_{30}$ melt compositions as determined by Carron and Lagache (1980). 59 000 ppm of Na + K were assumed to be in the fluid since Carron and Lagache (1980) utilized $2M$ chloride solutions in their experiments and a $2M$ chloride solution in equilibrium with a melt with the composition of the Notch Peak granitic rocks has molar K/(K + Na) of about 0.4.

The most useful mineral/fluid $K_d(s/f)$ values are for Ab_{100}, as an analogue to oligoclase, and $Ab_{25}Or_{75}$ compositions. There are approximately 88 000 ppm of Na in albite and 128 000 ppm of Na + K in $Ab_{25}Or_{75}$. 59 000 ppm of Na + K in the fluid were also used to calculate the mineral/fluid K_d values, since it was assumed that the fluid was also in equilibrium with a near-minimum melt. Possible errors resulting from this assumption are not significant because it can be shown that if Na/K in the fluid varies anywhere between 0 and infinity, the Ba and Sr $K_d(s/f)$

values remain large and the Rb $K_d(s/f)$ for K-feldspar does not differ much from one.

The partitioning of the alkali and alkaline-earth trace elements between feldspars and fluid and melt and fluid depends on the chlorinity of the solution to satisfy stoichiometry (e.g., Holland, 1972). The exact chlorinity of the solutions at Notch Peak is not known, but fluid-inclusion data from the contact-metamorphosed argillite country rocks suggest that salinities of the infiltrating fluids, which were derived from the stock (Nabelek et al., 1984), were as high as 20 wt% total dissolved salts or an approximately $3M$ solution (Feldman and Papike, 1981). This suggests that the calculated K_d values may be somewhat too large.

The amount of anorthite component in the system is small (Table 1). Therefore, the partition coefficients for all elements, except perhaps Sr, probably can be approximated by those for albite/fluid. Quartz is assumed to remove insignificant quantities of alkali and alkaline-earth elements from the melt or fluid. The relative effect of the other phases in the rocks is also considered to be insignificant, except for Rb where the biotite/fluid partition coefficient is about four times larger than for orthoclase/fluid and for Ba where the biotite/fluid partition coefficient is about the same as for orthoclase/fluid (Volfinger, 1976).

PETROGENESIS OF APLITES

The occurrence of aplites throughout the stock as dikes, all striking essentially north, suggests that the bulk of them crystallized from either a residual melt or an exolved fluid

Table 3.   Mineral/melt partition coefficients used in calculations*

	PLAG	KFLD	BIOT	CPX	TITN	ZIRC	APAT
Rb	0.04	0.7	3.3	0.03	0	0	0
Sr	4.4	3.9	0.1	0.52	0	0	0
Ba	0.3	6.1	6.4	0.13	0	0	0
Ce	0.27	0.044	0.32	0.5	53	2.6	35
Nd	0.21	0.025	0.29	1.1	88	2.2	57
Sm	0.13	0.018	0.26	1.7	102	3.1	63
Eu	2.15	1.13	0.24	1.6	101	3.1	31
Gd	0.097	0.011	0.28	1.9	102	12	56
Yb	0.049	0.006	0.44	1.6	37	270	24
Lu	0.046	0.006	0.33	1.5	27	323	20

* From compilations by Arth (1976) and Hanson (1980).

Table 4.   Mineral/fluid and melt/fluid partition coefficients used in calculations*

	$Or_{75}Ab_{25}$/fluid	Ab_{100}/fluid	biot/fluid	melt/fluid
Rb	1.7	0.06	6.8	1.4
Sr	370	35	–	2.9
Ba	270	7	270	4.5
Ce	–	–	–	5.3
Eu	–	–	–	8.3
Gd	–	–	–	5.6
Yb	–	–	–	12.5

* See text for derivation of the partition coefficients

phase within fractures in the nearly totally crystallized magma. Therefore, the petrogenesis of the representative aplite sample 56-2 is best modeled in terms of equilibrium between the melt or fluid and the solidified quartz monzonite. The composition of the quartz monzonite I sample used for modeling is very close to the average quartz monzonite composition. The granite cannot be treated as a melt formed along a fractionation path of the stock toward crystallization of the aplite because the granite was the first of the major lithologic units to have solidified.

Crystal/melt fractionation

The aplites compose only a minute portion of the stock, certainly no more than 1%. It seems therefore appropriate to model the trace-element concentrations in the aplite by the batch-equilibrium equation of Shilling (1966),

$$C_m/C_0 = 1/[D(1 - F) + F], \tag{5}$$

if the process of melt separation was sudden, as it may have been during fracturing of the stock. C_m in Equation 5 is the concentration of a trace element in the melt, C_0 is the concentration of the trace element in the system, D is the weighted sum of mineral/melt partition coefficients according to the fraction of each phase in the solid, and F is the fraction of melt. In the less likely case of complete disequilibrium between the interior of the solid phases in the quartz monzonite and the residual melt, the trace-element concentration in the melt can be modeled using the fractionation equation of Rayleigh (1886);

$$C_m/C_0 = F^{(D-1)}. \tag{6}$$

The representative quartz monzonite I trace-element concentrations (Table 2) were used for C_0, while normative mineral proportions (Table 5) in conjunction with the mineral/melt partition coefficients (Table 3) were used to calculate D.

A comparison of the model trace-element concentrations in the aplite, which were calculated using Equation 5 (Table 6; Fig. 6) with the observed concentrations (Table 2; Fig. 5), shows that the model concentrations of Rb, Sr, Ba, and the REEs, for both F values of 0.01 and 0.3, are significantly higher than those in the aplite.

Leeman and Phelps (1981) and Mahood and Hildreth (1983) have shown that in very high silica systems (more than about 74 wt% SiO_2), trace-element partition coefficients may become very large. For example, Leeman and

Phelps reported sanidine/melt Ba partition coefficients of about 22, and Michael (1984) reported calculated orthoclase/melt Ba and Sr $K_d(s/m)$ values of 20 and 6, respectively. The values for other elements are not significantly different from those listed in Table 3. When Michael's partition coefficients are used to model the trace-element concentrations using Equation 5, the Ba and Sr concentrations become 86 and 96, respectively, for $F = 0.01$. These values are closer but still 1.7 and 3.7 times larger than the observed concentrations. The problem with the high model Rb and REE concentrations, however, still remains.

The model concentration of Ba, calculated with the use of the Rayleigh fractionation equation and K_d values from Table 3, matches closely the concentration in the aplite. The model concentration of Sr is, however, an order of magnitude smaller than the observed value, whereas the model Rb concentration is unreasonably high and the model chondrite-normalized REE plot is not shown in Figure 6 because it falls off the scale.

The results for Rb and the REEs, except for the direction of the Eu anomaly, are somewhat better if it is assumed that the analyzed aplite sample is the product of 5% fractional crystallization from the residual melt. This result was obtained by calculating the bulk trace-element concentration in the crystallizing solid using the Rayleigh fractionation law (Hoefs, 1980),

$$\bar{C}_s = C_0(1 - F^D)/(1 - F). \tag{7}$$

The normative proportion of minerals used in the calculation is listed in Table 5. The Sr and Ba values are, however, much larger than the observed concentrations (Table 6). The results do not improve with larger amounts of crystallization because the Sr and Ba concentrations cannot decrease below the values in the starting melt.

The model REE results have to be interpreted with some caution. A large proportion of the REE in granitic

Table 5.   Mineral proportions used in calculations*

	granophyre	QMI	Aplite
Q	0.40	0.33	0.38
Or	0.60	0.28 ·	0.40
Ab	0	0.33	0.20
Apat	0.005	0.0025	0.0005
Titn	0	0.0025	0
Zirc	0	0.00026	0.00044
Biot	0	0.03	0

* All pyrox. components from Table 1 were assigned to biotite and albite component was proportioned to make K-feldspar = Or_{75}.

Table 6. Calculated trace-element concentrations in aplite and granophyre modeling

	aplite models					granophyre models		
	1A	1B	1C	1D	2	3A	3B	4
Rb	776	420	6319	160	330	78	78	186
Sr	117	143	0.21	280	3	347	540	52
Ba	313	351	31	572	6	755	3240	60

1A: in resid. melt formed by 99 per cent equil. crystalliz. of qtz. monz..
1B: in resid. melt formed by 70 per cent equil. crystalliz. of qtz. monz..
1C: in resid. melt formed by 99 per cent fract. crystalliz. of qtz. monz..
1D: in rock formed by 5 per cent fractional crystalliz. from melt formed as in 1A.
2: in fluid which is in equilibrium with solidified quartz monzonite.
3A: in rock formed by nearly 0 per cent crystalliz. from granite melt assuming Ba and Sr alk. feld./melt K_d's are 6.12 and 3.87, resp..
3B: in rock formed as in 3A but with Ba and Sr K_d's of 20 and 6, resp..
4: in fluid in equilibrium with granite melt.

rocks is often confined to minor phases, such as allanite or monazite. However, the error introduced into the calculations by this possibility is probably small for the Notch Peak rocks, because it can be easily shown from mineral-separates data (Nabelek et al., ms.) that essentially all the REEs are confined to titanite and apatite, which were incorporated into the present calculations.

Michael (1984) modeled the petrogenesis of aplite dikes around the margin of the Cordillera Paine granite, Chile. Those aplites have very similar chemistry and chemical relation to the host granite as the aplites at Notch Peak. Michael concluded, primarily on the basis of low Ba and Sr concentrations in the aplite, that the aplites are the crystallizaton product from a residual melt derived by fractional crystallization of the host granite. Although he ascribed low REE concentrations in the aplite to their removal by allanite in the granite, he did not model the REEs rigorously and the Rb concentrations not at all. As shown above, it is especially the concentration of these incompatible elements that suggests, at least for the Notch Peak situation, that the model of crystallization of the aplites from a polymerized, anhydrous residual melt is inappropriate.

Crystallization from fluid

At the other extreme is the possibility that the aplite crystallized from an aqueous fluid, because it is thought that the fracturing of a solidifying pluton is often accompanied by flow of a fluid into the fractures (e.g., Norton and Taylor, 1979). Such a fluid probably can be assumed to be in equilibrium with the nearly solidified host rock. The concentrations of trace elements in a fluid phase in equilibrium with the quartz monzonite I (Table 6; Fig. 7) were calculated using Equation 5 and the same parameters as in the calculation of concentrations in a residual melt (previous section), except that mineral/fluid partition coefficients were used (Table 4). There are no direct determinations of mineral/fluid REE K_d(s/f) values for alkali feldspars. Therefore, these were approximated by dividing mineral/melt partition coefficients (Table 3) by fluid/melt partition coefficients (Flynn and Burnham, 1978; Table 4). The melt/fluid partition coefficients used are from a run conducted at 125 MPa and 800°C with $0.914M$ Cl
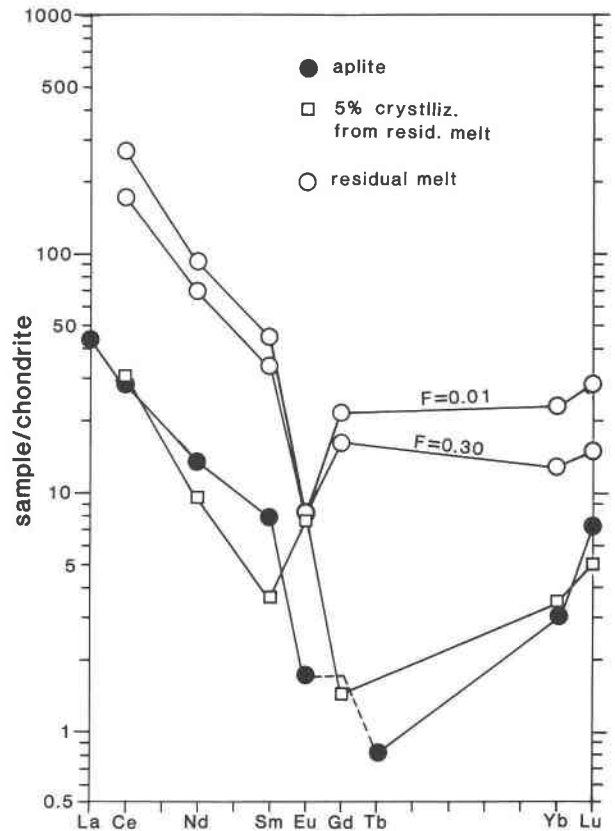

Fig. 6. Model REE patterns for residual melts formed by 70 and 99% crystallization of quartz monzonite I and a calculated pattern for 5% crystallization from the 1% residual melt. The observed aplite pattern is shown for comparison.

fluid. Note the very small calculated concentrations of Ba, Sr, and REEs in the fluid.

The second stage of aplite petrogenesis that was modeled was crystallization from the fluid. Owing to the limited solubility of aluminosilicates in fluids, the aplite clearly could not have formed by 100% crystallization of the fluid. The concentrations of the trace elements in the bulk aplite were calculated assuming Rayleigh fractionation (Eq. 7).

The calculated fractionation curves for Ba and Sr (Fig. 8) demonstrate that the concentrations of these elements rapidly decrease in the crystallizing solid to levels found in the aplite. In fact, their concentrations in the aplite might suggest, if this model is correct, that the aplite formed by 12–14% crystallization from the fluid. The concentration of Rb cannot be used to estimate the amount of crystallization, because the Rb fractionation curve is essentially flat. Nevertheless, the calculated concentration of about 290 ppm is in agreement with the observed value.

The calculated REE concentrations and the shape of the pattern for 13% fractional crystallization are also in good agreement with those observed (Fig. 7). The relative enrichment of the heavy REEs is due to crystallization of zircon. Although zircon occurs in only a small proportion
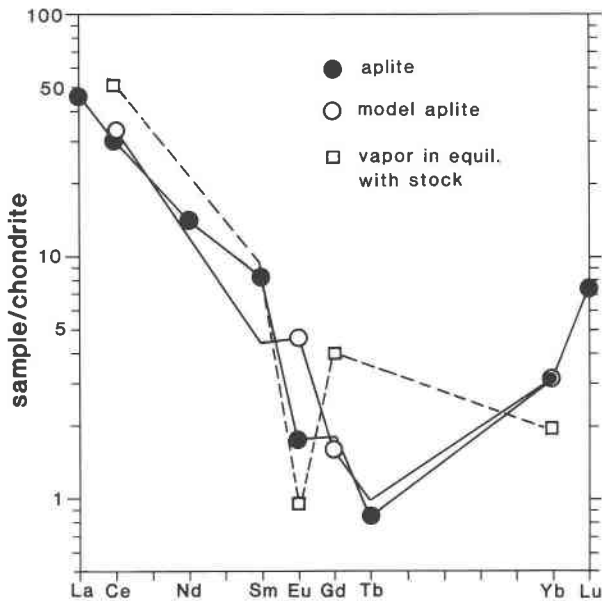
Fig. 7. Model REE patterns for a fluid in equilibrium with solidified quartz monzonite and for an aplite formed by 13% fractional crystallization from the fluid. The observed pattern is shown for comparison.
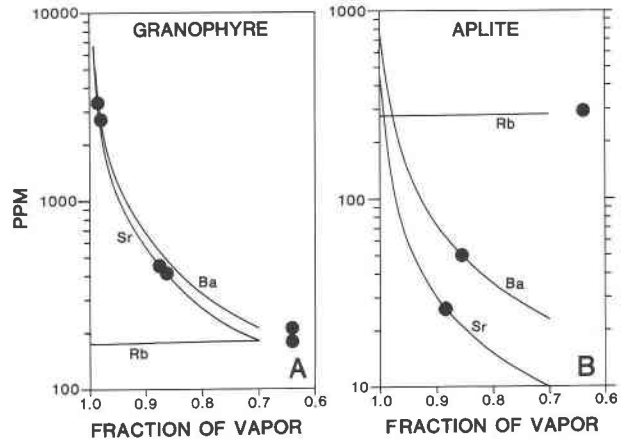

Fig. 8. Plots of calculated concentrations of Ba, Sr, and Rb in model granophyre and aplite during crystallization from fluids. The black circles denote the concentrations of Ba and Sr in the samples. The observed values may bracket the amount of crystallization. The Rb concentrations, also denoted by black circles, cannot be used to estimate the percentage of crystallization; therefore, their position in terms of F has no significance. See text for further discussion.

in the aplite (the amount was calculated from Zr concentration assuming stoichiometric zircon), its preference for the heavy REEs has an especially significant effect on the shape of the pattern in a system where all other minerals have REE K_d(s/f) values much less than 1. Thus, zircon essentially behaves as a cumulate. The largest discrepency is in the calculated and observed Eu values. However, the partitioning of Eu between phases is very sensitive to f_{O_2} and is thus more difficult to model accurately. A similar enrichment of the heavy REEs was observed in quartzo-feldspathic veins in the Cortlandt Complex of New York that include garnet as the only phase with a strong preference for the heavy REEs (Bender, 1980).

These calculations point to a model of crystallization of the Notch Peak aplites from an aqueous-fluid phase that exsolved during the waning stages of crystallization of the stock. Owing to very large Ba and Sr crystal/fluid partition coefficients and moderately large coefficients for the REEs, the presumed fluid was depleted in these elements, which resulted in their small observed concentrations in the aplite.

There are difficulties with this fluid model, too. The required 13% solubility of aluminosilicates in the hydrothermal fluid is two to three times larger than that predicted by Luth and Tuttle (1969). In addition, the position of the normative Q-Ab-Or values of the aplite near the ternary 200-MPa minimum for Ab/An = 5.2 (Fig. 4) is difficult to explain by crystallization from a fluid in equilibrium with the quartz monzonite I whose Ab/An is approximately 5. Luth and Tuttle (1969) suggested that the composition of the fluid phase in equilibrium with a solid granite just below the solidus lies close to the quartz apex.

Furthermore, the relatively large quantities of Zr, Hf, Sc, Sb, Ta, U, and Th do not appear to be consistent with crystallization from a fluid because these elements are thought to have small solubilities in aqueous fluids.

Discussion of aplite petrogenesis

It is apparent that neither the residual anhydrous melt model nor the model of crystallization from hydrothermal fluids is satisfactory to explain the petrogenesis of the aplites. The correct model must explain the "minimum granite" composition of the aplite (Fig. 4); the relatively large concentration of the highly charged Zr, Hf, Th, U, Sc, Sb, and Ta; and the small concentration of the REEs, Ba, and Sr. To explain these characteristics, it is suggested that the aplites crystallized from a melt saturated with a Cl-rich aqueous fluid that intruded fractures in the last stages of crystallization of the stock.

The discussion by Lagache and Carron (1982) of their earlier experimental results (Carron and Lagache, 1980) implies that the crystal/melt partition coefficients (Table 3) used here thus far to model the petrogenesis of the aplite may be appropriate to model crystallization of a fluid-undersaturated melt but not the formation of a residual melt saturated with a Cl-rich aqueous fluid. Lagache and Carron obtained their mineral/melt partition coefficients indirectly by assuming that

$$C_s/C_m = (C_s/C_f) \times (C_f/C_m) \qquad (8)$$

because they did not obtain direct measurements of mineral/melt partition coefficients. If the assumption in Equation 8 is correct, then the Ba, Sr, and Rb quartz monzonite/aplite melt bulk distribution coefficients (D) are approximately 17, 39, and 0.46, respectively. The Ba and Sr D values are little more than an order of magnitude

larger than the D values derived using partition coefficients from Table 3, while the Rb D is about twice as large. If these D values and an F value of 0.01 are used in Equation 5, the model melt has 30, 9, and 430 ppm of Ba, Sr, and Rb, respectively. These values are reasonably close to the measured concentrations. If Lagache and Carron's partition coefficients are correct, then these results suggest that the aplite did indeed crystallize from an aqueous-fluid-saturated melt.

The reason for the apparent difference between mineral/anhydrous melt and mineral/Cl-rich-fluid-saturated melt partition coefficients is not clear. Chlorine does not greatly affect the melt structure because it partitions preferentially into the aqueous-fluid phase (e.g., Kilinc and Burnham, 1972). However, a large concentration of chlorine in the fluid phase may affect the partitioning of alkaline-earth elements in the solid-melt-fluid system.

The partitioning between minerals and melt may be also affected by changes in the melt structure when associated with a free fluid phase. Stolper (1982) has shown that at high water contents, a substantial fraction of water dissolved in a silicate melt may be in the form of molecular H_2O. Perhaps under such conditions, alkaline-earth elements are substantially rejected from the melt structure while the effect on Rb and Cs is smaller, as evidenced by their similar concentrations in the quartz monzonite and the aplite.

The structure of the silicate melt may also be affected by fluorine, which preferentially dissolves in melts (e.g., Bailey, 1977). However, there is no strong evidence for substantial amounts of fluorine in the Notch Peak complex. Thus, its effect remains speculative.

It appears, therefore, that the retention characteristics of Ba, Sr, and Rb in a melt saturated with a Cl-rich fluid are similar to those in an aqueous fluid. This is substantiated by melt/fluid partition coefficients that are no more than 5 (Table 4). The REE melt/fluid partition coefficients are not much larger; therefore, the REE bulk partition coefficients (D) between the quartz monzonite and a melt saturated with a Cl-rich fluid may also be greater than unity. The melt should have, therefore, a REE pattern similar to the one calculated for a fluid in equilibrium with the solidified quartz monzonite (Fig. 7). The relative enrichment of the heavy REEs, which is observed in the aplite pattern, nevertheless needs to be explained by accumulation of zircon.

The partitioning behavior of highly charged elements such as Zr, Th, Hf, Ta, and U between minerals and melt may not be affected much by saturation of the system with Cl-rich fluids because these elements may behave as network-formers. In a melt with a high H_2O content, their solubility may in fact increase to a limited extent, as it does, for example, for Zr (Watson and Harrison, 1983).

The model for the petrogenesis of the Notch Peak aplite may be applicable to the petrogenesis of many pegmatites. Aplites throughout the world have elemental enrichment and depletion characteristics, relative to the host granites, similar to those of the Notch Peak aplites. Moreover many large pegmatites also have generally small concentrations of alkaline-earth elements and lower concentrations of the REEs than the associated parental rocks and tend to be enriched in highly charged elements (e.g., Walker, 1984). However, the petrogenesis of such pegmatites may be difficult to model numerically to a large precision because, as shown here, the partition coefficients of trace elements between minerals and anhydrous granitic melts may not be applicable. Furthermore, direct measurements of partition coefficients between minerals and melts saturated with Cl-rich fluids are still lacking. Mineral/fluid and melt/fluid coefficients may nevertheless be used to bracket the most plausible models.

PETROGENESIS OF GRANOPHYRE

The very low concentrations of large-ion-lithophile elements in the granophyre preclude that the granophyre represents a residual melt formed on crystallization of the stock, because crystal/melt fractionation processes in granitic rocks generally lead to enrichment of such elements (see, for example, the previous section on aplites). However, the granophyre may be an early-crystallized rock that formed by fractionation from the granite melt, or it may be a rock that crystallized from an aqueous fluid that exsolved sometime during solidification of the stock and subsequently pooled under a limestone bed (Fig. 2) that was impermeable to fluids (Nabelek et al., 1984). Both possibilities are numerically modeled here.

Crystallization from melt

The position of the normative composition of the granophyre on the 200-MPa Q-Or cotectic boundary on the granite ternary diagram (Fig. 4) and the positive Eu anomaly in the REE pattern (Fig. 5) could be consistent with crystal accumulation from the granite magma. Crystal accumulation is best modeled by Rayleigh fractionation where the average concentration of a trace element in the solid, $\bar{C}_s$, is given by Equation 7. The maximum and minimum possible concentrations of compatible and incompatible trace elements, respectively, in the granophyre (Fig. 9, Table 6) were obtained by multiplying D by C_0 using the average trace-element concentrations in the granite (Table 2) for C_0, the partition coefficients listed in Table 3, and the normative mineral proportions in the granophyre (Table 5) for D. The proportion of apatite was obtained by point counting because phosphorus analyses were not obtained for the granophyre samples.

The calculated Ba and Sr concentrations are not as large as in the granophyre, whereas the calculated Rb concentration is about three times less than the observed value (compare with Table 2). The calculated REE pattern is, however, very close to the observed pattern. When Michael's (1984) Ba and Sr $K_d(s/f)$ values of 20 and 6, respectively, are used, the calculated concentrations are 3240 ppm for Ba and 540 ppm for Sr. These values are close enough to the measured concentrations to suggest that the granophyre may have formed by fractional crystallization of the granite magma. However, other features of the

granophyre, which are discussed below, preclude this possibility.

Crystallization from fluid

The granophyre may have crystallized from a fluid that exsolved from the granite magma on emplacement. This involves a two-stage process: (1) formation of the fluid and (2) crystallization of the granophyre. It is possible to calculate the concentration of Ba, Sr, Rb, Ce, Eu, Gd, and Yb in the fluid using Equation 5, with the substitution of C_f for C_m, and melt/fluid partition coefficients from Table 4. The calculated concentrations, assuming an F value of 0.01, are listed in Table 6, and the REE pattern is shown in Figure 9.

The concentrations of trace elements in the granophyre on crystallization from the fluid are best modeled using Equation 7. The Rb, Sr, and Ba $K_d(s/f)$ values used are given in Table 4. The $D(s/f)$ values used were calculated by multiplying the $K_d(s/f)$ values by the mineral proportions shown in Table 5. The mineral/fluid REE $K_d(s/f)$ values were again approximated by dividing mineral/melt partition coefficients (Table 3) by fluid/melt partition coefficients (Flynn and Burnham, 1978; Table 4). As discussed in the section on the petrogenesis of the aplites, this method may lead to some error. The calculated REE pattern is shown in Figure 9, and the fractionation curves for Rb, Sr, and Ba in Figure 8.

The fractionation curves indicate that the large concentrations of Ba and Sr are easily obtained on crystallization from a fluid phase, even if the concentration of these elements in the fluid phase is relatively small (Table 6). This is due to the extremely large alkali feldspar/fluid partition coefficients. There is, however, some discrepancy in the amount of crystallization indicated by the Ba and Sr data: the concentration of Ba indicates 2% and the concentration of Sr 13% crystallization. These values may bracket the solubility of aluminosilicates in the fluid, although errors in the partition coefficients used may lead to somewhat incorrect results and explain the discrepancy. The calculated Rb concentration is very similar to the observed values, suggesting that this model may be correct. The observed Rb concentrations again cannot be used to constrain the amount of crystallization, because they remain essentially constant with fraction of fluid remaining.

The 2–13 wt% crystallization necessary to reproduce the concentrations of Ba and Sr encompasses the 5 wt% solubility of aluminosilicates in pure water vapor at magmatic temperatures at 200 MPa obtained by Luth and Tuttle (1969). The solubility of aluminosilicates in Cl-rich fluids is not known, but it is probably larger.

The calculated REE pattern (Fig. 9) is for 5% crystallization, and it fits well the observed pattern in both the shape (as much as the shape can be determined from the four calculated REEs) and the concentrations. The similarity in the REE pattern to the one obtained by modeling crystallization from melt is in part due to the way the REE mineral/fluid partition coefficients were approximated.
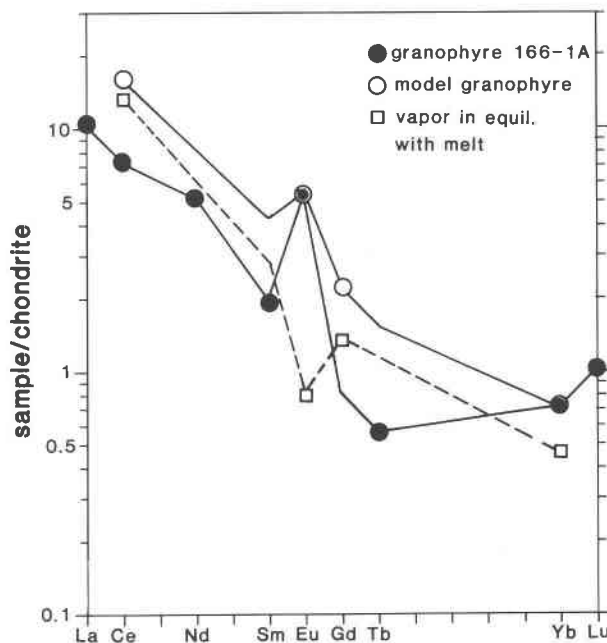

Fig. 9. Model REE patterns for a fluid in equilibrium with the granite melt and for granophyre crystallized from the fluid. The model granophyre pattern is for 5% fractional crystallization. The observed pattern is shown for comparison. The REE pattern for fractional crystallization from the granite melt (not shown) coincides with the pattern for the model granophyre crystallization from the fluid.

It is not necessary that the fluid from which the granophyre crystallized exsolved while the granite was still mostly molten. Satisfactory results are also obtained if the fluid was in equilibrium with the already-solidified stock. This is the same situation as in the fluid model for the petrogenesis of the aplite, which was previously discussed. If it is assumed that the value of F approaches 1 and that the concentrations of Rb, Sr, and Ba in the fluid are 330, 3, and 6 ppm, respectively, concentrations of 337, 666, and 972 ppm, respectively, are obtained for the granophyre. The Rb and Sr concentrations match the observed concentrations relatively well. The calculated Ba concentration would match the measured values well if about 20 ppm of Ba were dissolved in the fluid. Given the probable error in the partition coefficients used, such variation in the Ba concentration in the fluid is reasonable. It, therefore, does not matter when in the crystallization history of the stock the fluid from which the granophyre crystallized exsolved and pooled below the roof of the magma chamber.

Discussion of granophyre petrogenesis

The preceding calculations suggest that the granophyre formed by probably less than 5% crystallization from a fluid phase that exsolved from the granite magma while the magma was still largely molten or during later crystallization of the stock. However, if large Sr and Ba min-
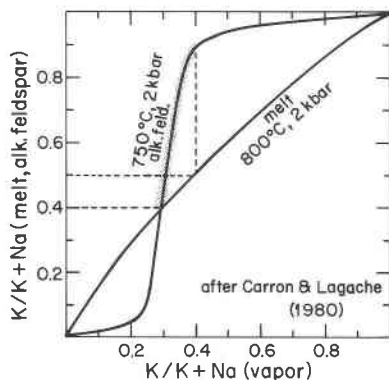
Fig. 10. Plot of equilibrium molar compositions of coexisting fluid-melt and fluid–alkali feldspar. The stippled part of the feldspar-fluid curve denotes possible compositions of feldspar in equilibrium with fluid that exsolved from the granite magma.

eral/melt partition coefficients are used, the model results are also consistent with a very small amount of fractional crystallization from the granite melt. The textures, major-element, and other trace-element data suggest, however, that the granophyre crystallized from a fluid phase.

The position of the normative compositions of the granophyre on the Q-Or cotectic to the right of the ternary minimum (Fig. 4) is inconsistent with a small amount of fractional crystallization because the granite contained quartz and feldspar phenocrysts when it was emplaced. If fractional crystallization occurred, it is expected that plagioclase would be a cumulate phase, not K-feldspar. In addition, the texture of the granophyre (Fig. 3b) is clearly not a cumulate texture.

The high K/Na composition of the granophyre is better explained by crystallization from a fluid phase. An alkali feldspar that crystallizes from an aqueous fluid will tend to be more potassic than the fluid (e.g., Orville, 1963; Carron and Lagache, 1980; Fig. 10). The K/Na of a fluid in equilibrium with a melt is approximately 0.75 of the molar ratio in the melt (Holland, 1972; Carron and Lagache, 1980). The granite magma at Notch Peak has molar K/(K + Na) between 0.4 and 0.5; therefore, a fluid in equilibrium with the granite magma should have molar K/(K + Na) between about 0.3 and 0.4. A feldspar that crystallizes from such a fluid should have K/(K + Na) between 0.4 and 0.9 (Fig. 10). The K/(K + Na) of the granophyre is about 0.7 and is within the predicted range. The fact that the granophyre lies on the Q-Or cotectic suggests that the fluid was also saturated with quartz.

The small concentrations of Mg, Ca, and the large-ion-lithophile trace elements in the granophyre are also better explained by crystallization from a fluid than from a melt. The Mg and Ca fluid/melt partition coefficients are much less than one, even at high Cl concentrations (Holland, 1972), indicating that the solubility of these elements in a fluid is very small. Thus, a rock that crystallizes from a fluid is not expected to contain phases such as plagioclase, biotite, and probably zircon and titanite because the con-

centrations of their essential structural constituents in the fluid may be too small for saturation. Apatite may be an exception, because the solubility of phosphorus in a fluid may be relatively large. Phosphorus forms similar structural units in melts to silicon (Hess, 1980) and, by analogy, probably in fluids where silica solubility at magmatic conditions is about 5 g per 1 kg of pure H_2O (Holland and Malinin, 1979). Some evidence for this is the fact that apatite is often found in pegmatites, including pegmatite fracture fillings that apparently crystallize from fluids (e.g., Walker, 1984).

The relatively large concentrations of the chalcophile elements, especially of Pb, in the granophyre is also consistent with the fluid model. Urabe (1985) has shown that at relatively high chlorinities, chalcophile elements, especially Pb, partition preferentially into the fluid phase over the melt. The Pb in the granophyre may be stored in the K-feldspars and some in the apatites. Thus, the chemistry and texture of the granophyre at Notch Peak are best explained by crystallization from a fluid phase that exsolved from the melt some time during crystallization of the stock and that subsequently pooled below the roof of the magma chamber.

CONCLUSIONS

Granophyres and aplites compose only a small portion of the Notch Peak stock. Trace-element modeling of their petrogeneses using available mineral/melt, mineral/fluid, and melt/fluid partition coefficients provides significant constraints on the nature of the media from which they crystallized. The extreme enrichment of Ba and Sr, the low concentrations of large-ion-lithophile elements, and the high K/Na ratio of the granophyre are best explained by crystallization from a fluid that exsolved from the crystallizing stock and pooled under the roof of the magma chamber.

The aplite dikes at Notch Peak are apparently the result of crystallization from a melt saturated with Cl-rich fluids that intruded fractures in the waning stages of crystallization of the stock. The large concentration of highly charged large-ion-lithophile elements in the aplite and the aplite's "minimum granite" composition strongly suggest that it crystallized from a melt. This melt either had retentive characteristics for the alkaline-earth elements and REEs approaching those of a halide-rich fluid, or the presence of the fluid affected the mineral/melt partitioning such that the concentrations of these trace elements in the aplite can be modeled only in terms of crystallization from a fluid phase. The aplite texture may be merely a reflection of rapid nucleation and crystallization on "pressure" quenching during fracturing of the stock.

This study shows that the petrogenesis of granophyres, aplites, and pegmatites can be constrained by modeling their trace-element contents. It is shown that pegmatitic rocks that crystallize from fluids can be distinguished from those that crystallize from residual pegmatitic melts when their trace-element characteristics are compared to their parental magmas. Owing to the large Ba and Sr alkali

feldspar/fluid partition coefficients and the apparently large alkali feldspar/pegmatitic melt partition coefficients, fractional crystallization from pegmatitic melts and fluids can lead to large gradients of Ba and Sr in large pegmatites. It is also shown that irrespective of which medium the pegmatites crystallize from, their REE concentrations probably will be lower than those in the parental magma. Direct measurements of trace-element partition coefficients between minerals and fluids saturated with Cl-rich fluids and the determination of the concentration of all the elements in such fluids are needed for more precise modeling.

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