

Pegmatite-wallrock interactions, Black Hills, South Dakota: Interaction between pegmatite-derived fluids and quartz-mica schist wallrock

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ABSTRACT

Fluid exsolution during the crystallization of a volatile-rich pegmatitic melt can result in the formation of extensive dispersion halos around the pegmatite through fluid transport of relatively incompatible elements out of the pegmatite system. The consequence of interaction between pegmatite-derived fluid and quartz-mica schist surrounding selected Black Hills pegmatites (Etta, Bob Ingersoll No. 1, and Peerless pegmatites) is alteration of primary metamorphic mineral assemblages to secondary mineral assemblages and modification of the original compositions of primary metamorphic minerals.

The alteration assemblages are in immediate contact with the pegmatite and consist of either B-rich assemblages (quartz + biotite + muscovite + tourmaline and quartz + muscovite + tourmaline) or aluminous, B-poor assemblages (muscovite + plagioclase + quartz). Both assemblages result from the instability of biotite with increasing B_2O_3 and/or $[Al/(Na + K)]$.

The modification of mineral compositions through mineral-fluid exchange reactions (e.g., biotite Rb/K, F/OH) results in the formation of extensive exomorphic halos around the pegmatites. The compositional characteristics of the dispersion halos are related to pegmatite mineralogy. The dispersion halo associated with the Etta pegmatite (spodumene-bearing) is enriched in alkali elements (Li, Rb, Cs), As, and U, whereas the dispersion halos associated with the Bob Ingersoll No. 1 and Peerless pegmatites (lepidolite- or lithia mica-bearing, spodumene-absent) are enriched in alkali elements (Li, Rb, Cs), As, U, B, and F. The dispersion halos extend 21 to 90 m from the pegmatite contact along sampling traverses. The relative mobilities suggested from the enrichment of the quartz-mica schist and its mineral components are $As = U < B = F < Rb \leq Cs < Li$.

The extent of fluid infiltration into the country rock surrounding the pegmatites and fluid composition can be approximated through trace-element modeling. At the pegmatite contact, less than one equivalent mass of fluid equilibrated with the schist. The pegmatite-derived fluids have relatively high solute concentrations (>1000 ppm) and exhibit compositional differences between pegmatites. The most noticeable differences in fluid composition are the high B content and low ratio f_{H_2O}/f_{HF} ratio of fluids derived from the Bob Ingersoll No. 1 and Peerless pegmatites compared to the Etta pegmatite. The low f_{H_2O}/f_{HF} ratio of the fluid phase may be responsible for the stability of lepidolite and lithia mica relative to spodumene in the Bob Ingersoll No. 1 and Peerless pegmatites.

INTRODUCTION

Migration of pegmatite-derived fluids out of pegmatite bodies and into the surrounding country rock can form extensive alteration aureoles. Alteration surrounding pegmatites has been attributed to fluids derived by exsolution from the crystallizing volatile-rich granitic magma (Jahns, 1982). The extent of dispersion-aureole development and its characteristics are partially dependent upon the structural and compositional properties of the wallrock. Laul et al. (1984) demonstrated the comparative extent of fluid migration between pegmatite and amphibolite and be-

tween pegmatite and quartz-mica schist. In that study, migration was interpreted as being retarded in the amphibolite compared to the quartz-mica schist.

Because of the enrichment of the pegmatite magma and coexisting aqueous fluids in relatively incompatible elements such as Li, Rb, Cs, B, Ta, and Nb, fluid transport of these constituents out of the pegmatite system and subsequent interaction between the fluid and country rock does result in the modification of the original compositions of the primary mineral phases (e.g., biotite: Mg/Fe, K/Rb) or conversion of the primary mineral assemblage

to a secondary assemblage. Extensive modification of primary mineral-phase compositions results in the formation of exomorphic aureoles in the surrounding country rock. The composition of the fluids is a function of magma composition, and therefore the diagnostic elements of the alteration aureoles are related to pegmatite type (Beus, 1960). Alkali halos surrounding granitic pegmatites in Canada (Goad and Černý, 1981; Kretz, 1965), the Soviet Union (Beus and Sitnin, 1968; Ovchinnikov, 1976) and the Black Hills, South Dakota (Gilani, 1979; Papike et al., 1983; Tuzinski, 1983; Shearer et al., 1984; Laul et al., 1984) have been described. The results of Soviet and Canadian studies have been reviewed by Trueman and Černý (1982).

Alteration mineral assemblages around pegmatites are most commonly (1) a series of tourmaline-rich assemblages resulting from the transportation of B into the country rock (Page et al., 1953; Shearer et al., 1984) and (2) a series of retrograde metamorphic assemblages resulting from low-temperature re-equilibration of primary metamorphic assemblages with pegmatite aqueous solutions. Although not as common, the development of holmquistite assemblages in amphibolite wallrock has been described by several researchers (Heinrich, 1965; London, 1984).

Development of dispersion halos around pegmatites may also provide a valuable analogue to the behavior of nuclear waste in a geologic environment. One of the major concerns in storing nuclear waste in a geologic repository is the possibility of migration of radionuclides under specific physical and chemical conditions in the geologic environment over time scales of 10^3 – 10^7 yr. The questions regarding the fate of nuclear wastes in geologic confinement over a geologic time frame can be addressed from studies of the behavior of various trace elements, which are natural analogues of the long-lived fission products, activation products, and transuranic elements in nuclear waste. In most cases, the analogue for a radionuclide is its respective stable isotope.

As part of a comprehensive study of thermally induced chemical migration around pegmatites, we have selected a number of different pegmatites intruded into various metamorphic and igneous rocks. This study reports on the interaction between pegmatites and quartz-mica schist country rock. Of particular interest are the following questions: (1) What are the extent and type of compositional gradients surrounding pegmatites? (2) What are the mineralogical alterations associated with pegmatite-schist interaction? (3) What are the compositions of the fluids causing the alteration? (4) What are the relative mobilities of elements? (5) What is the degree of fluid-rock interaction?

GEOLOGY OF THE PEGMATITES

Three zoned pegmatites were selected for detailed study of the characteristics and development of dispersion halos in quartz-mica schist: Etta pegmatite, Peerless pegmatite, and Bob Ingersoll No. 1 pegmatite. The pegmatites are located in southwestern

South Dakota, within the southern portion of the Precambrian dome of the Black Hills (Fig. 1). These pegmatites are members of a well-known pegmatite field distributed in the country rock surrounding the Harney Peak Granite (Norton, 1975). Approximately 20 000 pegmatites are spatially and probably genetically associated with the Harney Peak Granite. Riley (1970) reported a Sr-isochron age of 1703 m.y. for a suite of Harney Peak Granite samples. Unzoned pegmatites constitute the majority of the pegmatites and are mineralogically and geochemically similar to the Harney Peak Granite (Redden et al., 1982). Zoned pegmatites make up approximately 1% of the total pegmatite population. The pegmatite field has been classified as a rare-element type with mineralogical characteristics ranging from barren to Li-, Rb-, Cs-, Be-, Ta-, and Nb-enriched types (Černý, 1982). The pegmatites of the field exhibit a regional mineralogical and geochemical zonal distribution with barren pegmatites near the Harney Peak Granite and Li-enriched pegmatites on the periphery of the field (Norton, 1975). This zonation has been observed in many other pegmatite districts (Černý et al., 1981; Goad and Černý, 1981) and has been attributed to the ability of highly fractionated (Li-rich) volatile-enriched granitic melt to migrate farther from the "parent intrusion." This zonal distribution suggests a genetic link between the pegmatites and the central granite body. The geology of the southern Black Hills and the Harney Peak Granite and associated pegmatites has been discussed in detail by Page et al. (1953), Norton (1975), Norton et al. (1962), Redden (1963, 1968), Kleinkopf and Redden (1975), Černý (1982), and Redden et al. (1982).

The Etta, Peerless, and Bob Ingersoll No. 1 pegmatites are large, zoned pegmatites located north and northeast of the Harney Peak Granite near Keystone, South Dakota. The schist into which the pegmatites were intruded has been regionally metamorphosed to staurolite grade.

The Etta pegmatite is shaped like an inverted teardrop with a maximum diameter of 76 m, extending to a depth of approximately 69 m. The pegmatite consists of six zones: (1) microcline-biotite; (2) quartz-muscovite-albite; (3) perthite-quartz-spodumene; (4) quartz-cleavelandite-spodumene; (5) quartz-spodumene; and (6) a monomineralic core consisting of quartz. The geology of the Etta pegmatite has been discussed by Schwartz (1925) and Norton et al. (1964).

The Bob Ingersoll No. 1 is shaped like an inverted teardrop with a maximum diameter of 30 m, extending to a depth of approximately 80 m. There are six zones present in the pegmatite: (1) quartz-cleavelandite-muscovite (border zone); (2) cleavelandite-quartz-muscovite (wall zone); (3) perthite (first intermediate zone); (4) quartz-cleavelandite-amblygonite (second intermediate zone); (5) quartz-cleavelandite (third intermediate zone); and (6) quartz-cleavelandite-lepidolite zone (core). The geology of the pegmatite has been summarized by Page et al. (1953) and Jolliff et al. (1986).

The Peerless pegmatite, a large complex pegmatite, has an anticlinal shape in cross section and is partly discordant with the quartz-mica schist country rock. The pegmatite consists of seven coherent zones, two replacement units, and two types of fracture-filling units: (1) quartz-muscovite-plagioclase zone (border zone); (2) albite-quartz-muscovite zone (wall zone); (3) cleavelandite-quartz-muscovite zone (first intermediate zone); (4) perthite-cleavelandite-quartz zone (second intermediate zone); (5) cleavelandite-quartz zone (third intermediate zone); (6) quartz-microcline zone and quartz zone (fourth intermediate zone); (7) lithia mica-cleavelandite zone (core); (8) lithia mica-cleavelandite-quartz replacement unit; (9) muscovite-cleavelandite replace-

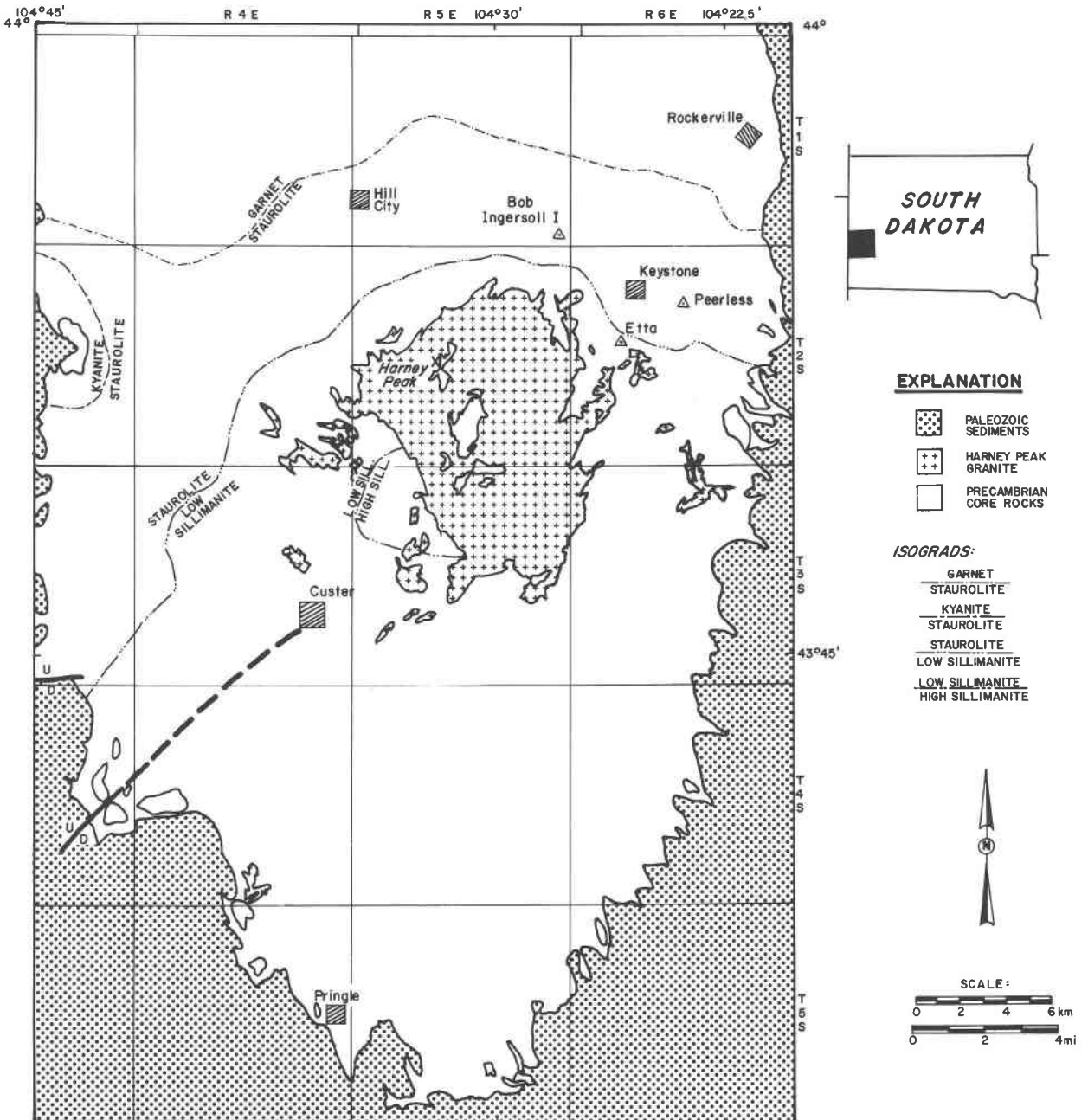


Fig. 1. Generalized geology of the southern Black Hills, South Dakota. Metamorphic isograds and Harney Peak Granite are shown (after Norton, 1975). Three pegmatite sites for the halo study are shown.

ment unit; (10) quartz fracture-filling unit; and (11) tourmaline-quartz fracture-filling unit (Sheridan et al., 1957).

The relatively exotic mineral assemblages associated with the pegmatites and the low K/Rb ratios of potassium feldspar (Shearer et al., 1983, 1985) indicate that these pegmatites are strongly fractionated. Table 1 compares the characteristics of the three pegmatites.

ANALYTICAL METHODS

Samples of schist were collected along traverses extending outward from the pegmatite contacts. At the Etta pegmatite and the

Bob Ingersoll No. 1 pegmatite sites, samples were collected within the main adits that extend outward from the pegmatites (Figs. 2A and 2B, respectively). At the Peerless pegmatite (Fig. 2C), two sampling traverses were selected. Traverse one is a vertical traverse that yielded samples collected above the pegmatite and parallel to foliation in the schist, and traverse two is a horizontal traverse perpendicular to foliation in the schist. Modal data were collected by optical point count with a grid spacing of 50 μm .

Major-element mineral chemistry was determined with the ARL-SEM-Q electron microprobe at the U.S. Geological Survey, Denver, and the MAC electron microprobe at the South Dakota

Table 1. Characteristics of the Etta, Bob Ingersoll No. 1, and Peerless pegmatites

Pegmatite	Pegmatite type	Shape	Approximate range in K-feldspar chemistry	Tourmaline occurrence and F content	Country rock
Etta	Li (spodumene)-, Nb-Ta-, Sn-bearing, zoned pegmatite	Inverted teardrop	K/Rb = 50 - 20 Cs = 600 - 900 ppm	Minor accessory in wall zone	Quartz-mica-plagioclase schist
Bob Ingersoll 1	Li (lepidolite)-, Be-Nb-, Ta-, Sn-bearing zoned pegmatite	Inverted teardrop	K/Rb = 40 - 30 Cs = 400 - 600 ppm	Wall zone to core F wt.% = 0.8-1.5	Quartz-mica-plagioclase schist
Peerless	Be-bearing zoned pegmatite, Lithia mica	Lenticular	K/Rb = 80 - 40 Cs = 150 - 500 ppm	Wall zone, pockets F wt.% = 0.6-1.7	Quartz-mica-plagioclase schist

School of Mines and Technology (SDSM&T) using an accelerating voltage of 15 kV and a sample current of 10 nA. Mineral and oxide standards were used. Data were reduced using the MAGIC IV program (at the USGS) and the Bence-Albee method (1968) at SDSM&T.

Biotite and muscovite were separated for trace-element analysis using a FRANZ isodynamic magnetic separator. Separates were then further purified through hand-picking. Separates were point counted to estimate purity. In all cases, mineral-separate purity was $\geq 98\%$. Interlayered biotite and muscovite and apatite-zircon inclusions were the main source of contamination.

Whole-rock powders and mineral separates were analyzed by neutron activation analysis, X-ray fluorescence, AA-ICP, and wet chemistry to ensure reproducibility, to utilize the best technique available for each element, and to evaluate analytical error. A total of 20 major, minor, and trace elements were analyzed at Battelle, Pacific Northwest Laboratories, by sequential instrumental neutron activation analysis (INAA) using a high-efficiency 130-cm³ Ge(Li) detector (25% FWHM 1.8 keV for 1332 keV of ⁶⁰Co), a 4096 channel analyzer, and coincidence-noncoincidence Ge(Li) = NAI (TI) counting systems (Laul et al., 1984; Laul, 1979). Energy-dispersive X-ray fluorescence (Battelle, Pacific Northwest) using pressed disks of rock or mineral powder was used to determine 29 major, minor, and trace elements. AA-ICP (SDSM&T) sample solutions for Na, Mg, Rb, Cs, Si, and Al were prepared using a modified lithium metaborate dissolution technique (Medlin et al., 1969). Lithium metaborate fusion solutions were analyzed for F by standard electrode. AA-ICP sample solutions for Li and B were prepared using an acid dissolution technique. Ferrous iron was determined (SDSM&T) using a HF dissolution and potassium dichromate titration technique (Goldich, 1984). In all whole-rock and mineral-separate analyses, USGS standards BCR-1, AGV-1, G2, and GSP-1 were used to monitor accuracy and precision.

CHARACTERISTICS OF THE COUNTRY ROCK

Structural relationship between pegmatites and country rock

In the three pegmatites studied, the pegmatite-country rock contacts are easily discernible. The contacts, however, are irregular in shape due to bulges, tongues, and "screens" of schist that extend into the pegmatite. The schist is predominantly massive with locally well-developed schistosity. The conformable nature of the schistosity around the pegmatite and within the "screens" suggests ductile behavior of the schist during the intrusion of the granitic magma (Page et al., 1953).

At the Etta pegmatite, schistosity and bedding generally strike between north and northeast and dip steeply to the east (60°-85°). Adjacent to the pegmatite, the schistosity is commonly parallel to the pegmatite contact. The sampling traverse of the schist at the Etta pegmatite cuts across both bedding and schistosity.

Bedding in the schist surrounding the Bob Ingersoll No. 1 pegmatite generally strikes east to northeast and dips moderately to the south (50°-70°). Adjacent to the pegmatite, schistosity is generally parallel to the pegmatite contact. The sampling traverse is approximately perpendicular to schistosity.

The average strike of bedding and schistosity of the country rock surrounding the Peerless pegmatite is generally east. Bedding dips steeply to the south (70°-85°). The dip of the schistosity is commonly at a lower angle than bedding. Near the flank of the pegmatite, the attitude of the schistosity becomes parallel or nearly parallel to the contact. The schistosity is commonly perpendicular to the contact at the roof of the pegmatite. Sampling traverses of the schist at this site are parallel (traverse 1) and perpendicular (traverse 2) to schistosity.

Mineral assemblages in country rock

The metamorphic rocks adjacent to the pegmatites consist of either a prograde metamorphic assemblage, a retrograde metamorphic assemblage, or an alteration assemblage. The prograde mineral assemblages are a direct response to the regional metamorphism that reached staurolite grade in the immediate vicinity of the pegmatites. Estimates of the temperature of peak metamorphism in the staurolite zone in areas west of the Harney Peak Granite range from 515 to 565°C (Willibey, 1975). The retrograde assemblages and textures do not appear to be related to the intrusion of individual pegmatites, although changes in mineral chemistries may have resulted through continuous retrograde reactions during postmetamorphic re-equilibration with pegmatite-derived aqueous fluids. Alteration assemblages are directly related to pegmatite intrusion. Modal data for the country rock surrounding the Etta, Bob Ingersoll No. 1, and Peerless pegmatites are shown in Tables 2, 3, and 4, respectively. Modes for the country rock traverses are plotted against distance in Figure 3.

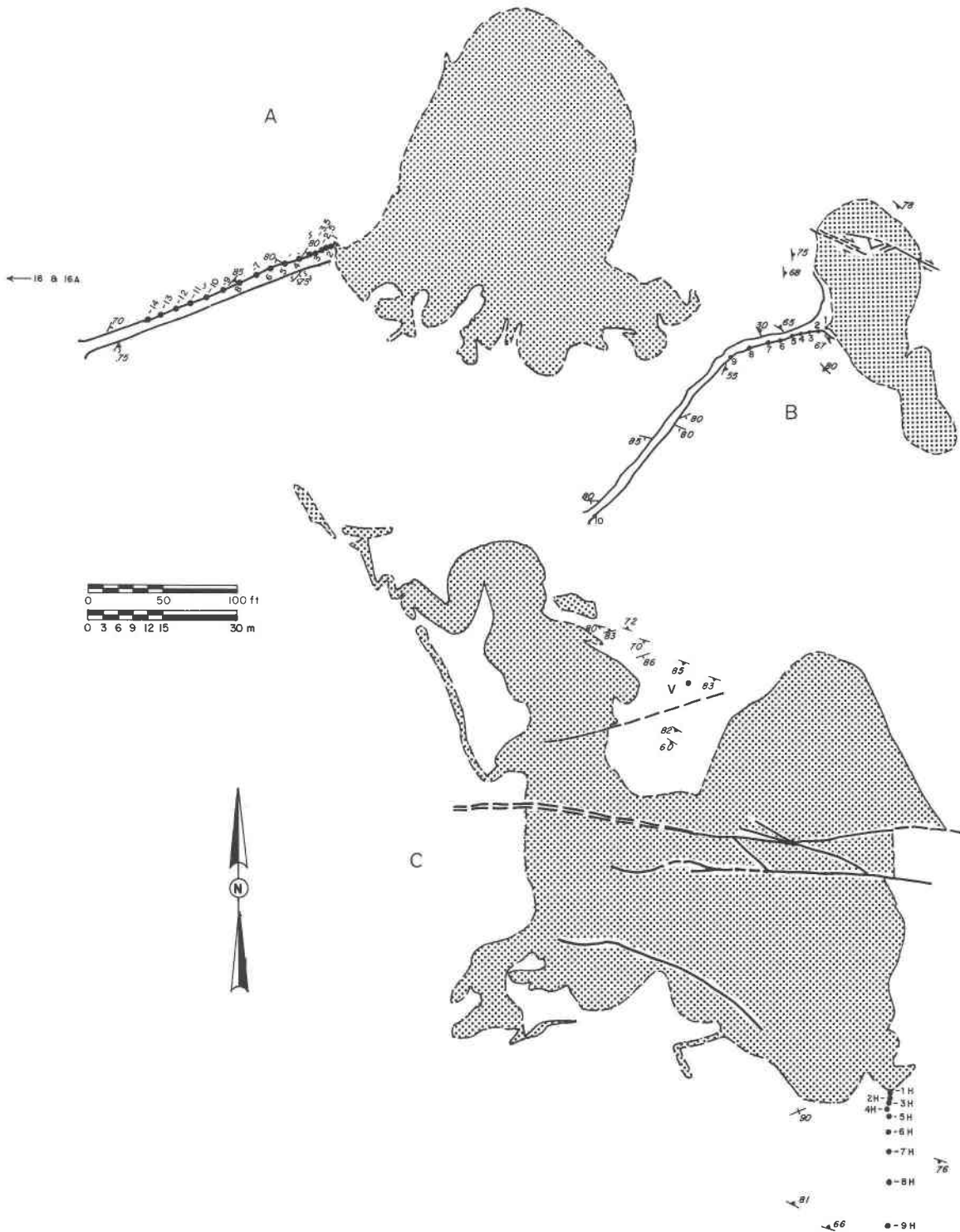


Fig. 2. Outlines of the Etta (A), Bob Ingersoll No. 1 (B), and Peerless (C) pegmatites are shown illustrating sample traverses (Sheridan et al., 1957).

The dominant prograde metamorphic assemblage in the country rock surrounding the Etta pegmatite consists of quartz + plagioclase + muscovite + biotite. Biotite-rich assemblages (e.g., Table 2, E3.5) occur as layers that are

oriented nearly perpendicular to the sampling traverse. Preferred orientation of the biotite gives these layers a strong schistosity. Poikilitic tourmaline is a common accessory mineral and is fairly abundant in the biotite-rich

Table 2. Modal data of the schist along Etta pegmatite traverse. Sample E1 is from the border zone of the pegmatite

Sample No.	E1	E2	E2.5	E3	E3.5	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E16	E16A
Distance*	-0.9	0	1.5	3.0	4.5	6.0	9.1	12.2	15.2	19.8	23.2	26.5	29.9	33.5	36.9	39.0	91.4	95.0
Quartz	32.1	45.6	37.1	29.0	30.2	33.6	55.7	52.1	35.8	30.4	44.2	56.6	27.2	59.1	59.8	62.3	50.2	52.8
Plagioclase	59.6	12.1	9.3	26.2	15.6	6.5	22.0	31.9	9.0	17.1	14.8	28.3	28.3	10.4	13.1	17.6	12.6	14.9
Muscovite	6.7	30.9	20.1	5.3	23.2	30.7	10.7	Tr	22.2	17.7	13.1	1.0	14.4	17.5	14.5	10.0	20.0	14.1
Biotite	Tr	6.8	31.2	34.3	26.1	21.4	11.0	15.3	27.2	32.3	25.4	12.5	27.0	12.6	11.2	9.0	16.7	17.8
Tourmaline	1.3	Tr	1.5	4.5	3.8	3.8	0.0	0.4	5.1	0.8	1.2	0.9	0.5	0.2	0.5	0.9	0.3	0.1
Chlorite	0.0	0.0	0.0	0.0	0.5	4.0	0.0	0.0	0.0	0.0	0.2	0.0	0.6	0.0	0.0	0.0	0.0	0.0
Acc. Min.**	0.3	4.6	0.8	0.7	0.6	Tr	0.6	0.3	0.7	1.7	1.1	0.7	2.0	0.2	0.9	0.2	0.2	0.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*Meters from pegmatite contact

**Accessory Minerals: hematite, anatase, zircon, sulfides, apatite

layers. The distribution of tourmaline in the schist surrounding the Etta pegmatite is not systematic and appears not to be directly related to pegmatite-derived fluids.

The country rock surrounding the Bob Ingersoll No. 1 pegmatite consists of the following prograde metamorphic assemblages: quartz + biotite + muscovite, quartz + biotite + garnet, quartz + biotite + muscovite + staurolite, and quartz + biotite + muscovite + garnet + staurolite. Plagioclase, tourmaline, and chlorite are accessory minerals. Chlorite generally occurs as rims on garnet or as xenoblastic porphyroblasts. This is suggestive of a retrograde origin for the chlorite that occurs in these textural relations.

The dominant prograde mineral assemblage in the schist surrounding the Peerless pegmatite is quartz + biotite + muscovite. Other less common assemblages include quartz + biotite + muscovite + garnet, quartz + biotite + muscovite + staurolite, and quartz + biotite + muscovite + staurolite + garnet. Staurolite is partially or totally pseudomorphed by intergrowths of biotite and muscovite. Chlorite is closely associated with the staurolite pseudomorphs, occurs as rims around garnet, and may form xenoblastic porphyroblasts.

Alteration assemblages in the schist surrounding the Peerless pegmatite occur primarily in schist "screens" and at country rock-pegmatite contacts. The alteration assemblages are better developed in the schist along the flanks of the pegmatite (i.e., horizontal traverse) rather than the top of the pegmatite (i.e., vertical traverse). With increasing alteration (increasing B), the sequence of alteration assemblages is quartz + biotite + muscovite + tourmaline to quartz + muscovite + tourmaline. The alteration assemblage at the contact of the Bob Ingersoll No. 1 pegmatite is predominantly quartz + biotite + tourmaline ± muscovite (Table 3, B11). Tuzinski (1983) and Jolliff et al. (1986) noted that this alteration assemblage occurred along the flanks and top of the pegmatite. Tuzinski (1983) also noted that the biotite in this alteration zone was "bleached." The country rock in immediate contact with the Etta pegmatite is altered to a muscovite + plagioclase + quartz assemblage with a granular texture. Tour-

maline occurs as an accessory mineral in this type of alteration assemblage. The most extensive alteration is along the southern border of the pegmatite where a thickness of 3 m is common (Norton et al., 1964).

Geochemistry of the schist surrounding the pegmatites

The major-, minor-, and trace-element analyses of the schist collected along sampling traverses are present in Tables 5, 6, 7 (Etta), 8, 9 (Bob Ingersoll No. 1), 10, and 11 (Peerless). The schists at all sites have a variable major-element character (e.g., SiO₂ between 58 and 82%, Al₂O₃ between 8 and 18%). These sharp contrasts in major-element chemistry are reflected by modal variations in biotite and quartz between layers. The schist at the pegmatite contacts appears to be more oxidized than the schist further from the contact. Shearer et al. (1984) noted similar oxidation of the minerals in the schist adjacent to the Tip Top pegmatite. The oxidation at the sites of this study may be recent.

To evaluate trace-element background concentration in the schist, several samples were collected at distances (~60–100 m) from the pegmatites that should be beyond the dispersion halos. These samples are E16, E16A, and B110. The whole-rock concentrations of alkali elements of these background samples are similar to the schist background levels obtained by Tuzinski (1983).

The elements As, U, Li, Rb, and Cs form dispersion halos in the schist adjacent to the Etta pegmatite (Table

Table 3. Modal mineralogy of country rock along Bob Ingersoll No. 1 traverse

Sample No.	B11	B12	B13	B14	B15	B16	B17	B18	B19	B110
Distance*	0	1.5	3.0	4.5	6.0	9.1	12.2	16.8	21.3	62.5
Quartz	31.4	42.1	54.8	37.9	35.2	60.8	39.0	34.0	27.5	30.5
Plagioclase	0.5	0.0	0.0	Tr	0.0	0.0	0.0	1.1	0.0	0.0
Potassium Feldspar	Tr	0.0	0.0	Tr	0.0	0.0	0.0	0.0	0.0	0.0
Muscovite	12.4	23.7	1.4	0.0	10.5	0.0	23.0	18.7	38.5	45.2
Biotite	26.4	22.5	27.1	30.4	45.4	34.4	27.4	33.8	17.4	16.6
Chlorite	0.0	6.0	3.4	0.1	2.4	1.0	1.8	0.3	7.7	1.4
Tourmaline	26.9	1.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Staurolite	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.5	5.1	1.7
Garnet	1.4	1.9	10.3	24.4	1.3	0.4	5.7	7.3	2.1	0.0
Accessory Minerals**	1.0	2.3	2.8	7.2	4.4	3.4	3.1	3.3	1.7	4.6
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*Meters from pegmatite contact

**Zircon, ilmenite, sulfides, anatase, apatite

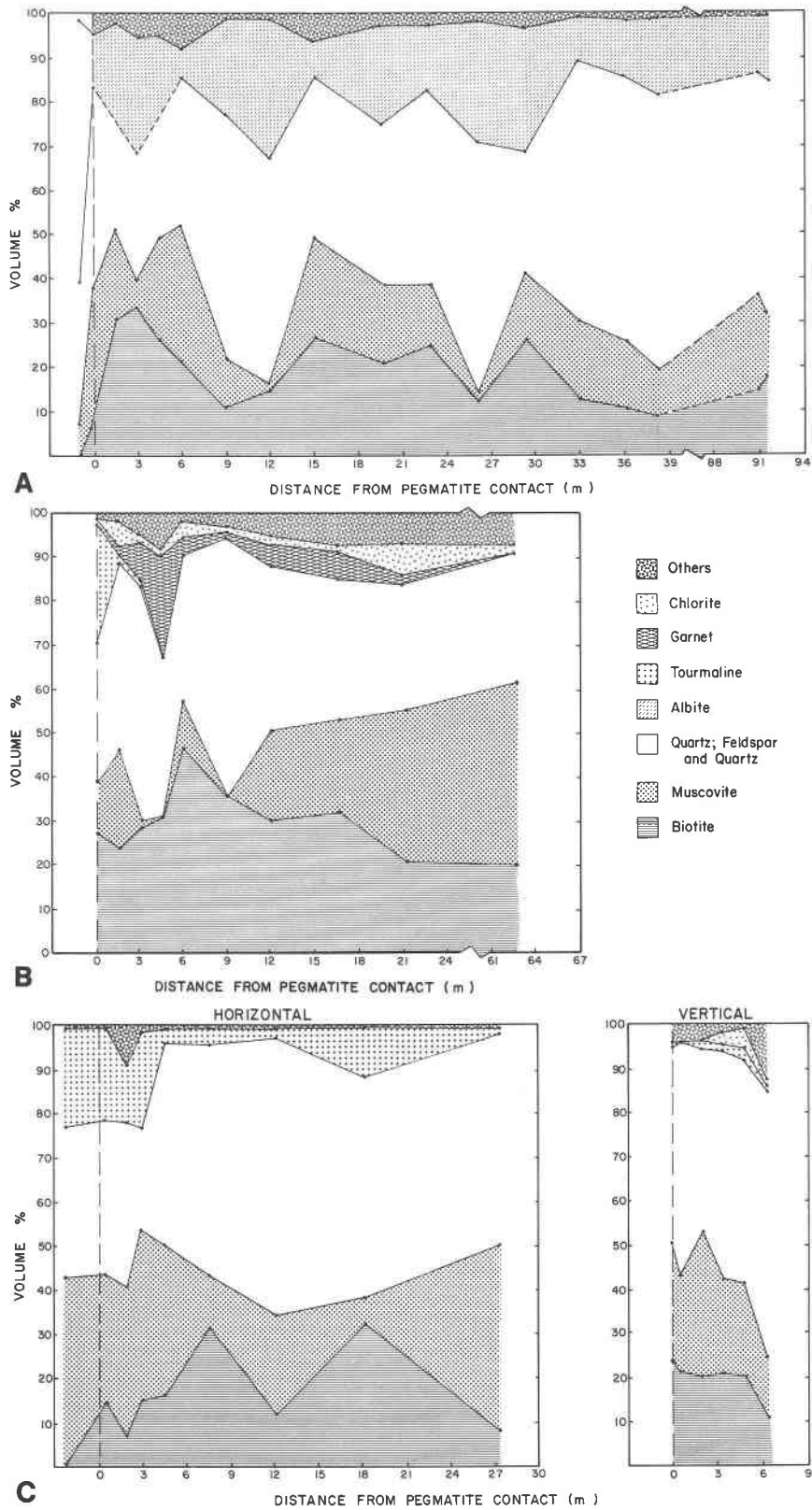


Fig. 3. Modal mineralogy of the schist along the Etta pegmatite traverse (A), Bob Ingersoll No. 1 traverse (B), and the horizontal and vertical Peerless pegmatite traverses (C). In (B) and (C), feldspar and quartz are combined because of the low modal abundance of feldspar in those traverses.

Table 4. Modal mineralogy of schist from horizontal (H) and vertical (V) traverses at the Peerless pegmatite

Sample No.	2H	3H	4H	5H	6H	7H	8H	9H	Screen	4V	5V	6V	7V	8V	9V
Distance*	0.6	1.8	3.0	4.5	7.6	12.2	18.3	27.4	--	6.6	5.0	3.5	2.0	0.5	0.0
Quartz	34.5	36.0	23.0	45.0	50.5	62.0	49.0	48.0	33.5	59.1	49.3	51.0	40.9	52.1	43.4
Plagioclase	Tr	Tr	1.0	1.0	1.5	Tr	Tr	Tr	Tr	13.9	0.0	1.9	1.7	2.6	0.4
Potassium feldspar	Tr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Tr	0.0	0.2	0.4
Muscovite	28.0	34.0	37.5	33.5	11.5	22.0	6.0	41.0	42.5	12.8	21.3	21.1	32.5	20.8	26.1
Biotite	16.0	8.0	16.5	17.5	32.5	13.0	33.5	9.5	Tr	12.2	20.4	21.2	20.5	22.3	24.5
Chlorite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	5.7	2.8	0.0	0.0	0.0
Tourmaline	21.0	13.0	21.0	3.0	4.0	3.0	11.5	1.0	23.0	0.2	1.6	1.4	1.3	0.0	0.2
Garnet	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	2.7
Accessory minerals**	0.5	9.0	1.0	Tr	Tr	Tr	Tr	0.5	1.0	0.4	1.7	0.6	3.1	2.0	2.3
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*Meters from pegmatite contact

**Zircon, hematite, sulfides. In sample 3H accessory minerals include alteration products of biotite

6, Fig. 4). Uranium appears to exhibit only a slight enrichment in the country rock immediately adjacent to the pegmatite, while As enrichment extends out to approximately 12 m along the traverse. This is similar to the As enrichment observed in the amphibolite surrounding the Tin Mountain pegmatite (Laul et al., 1984; Walker, 1984). The whole-rock concentrations of Li, Rb, and Cs at the Etta site are high compared to schist background levels, and the enrichments of these elements extend out to greater than 7 m. However, the alkali-element whole-rock concentration appears to be strongly dependent upon mineral abundances, and thus the determination and interpretation of the alkali dispersion halo is complex. Li, Rb, and Cs are highly correlated to the modal abundance of sheet silicates (biotite + muscovite), indicating that sheet silicates effectively concentrate these elements (Fig. 4). Analysis of the sheet silicates would, therefore, better define the extent of the dispersion halo around the Etta pegmatite.

Although several biotite-rich layers in the schist are enriched in B and anomalously high F is noted in a single sample along the traverse, there is no systematic relationship between the B and F content of the schist and distance from the pegmatite contact. In addition, there is no correlation between high B and high F in the schist surrounding the Etta, and the anomalous enrichments are much lower than observed in the schist surrounding the other pegmatites of these studies.

Rare-earth-element abundances for the schist surrounding the Etta pegmatite are given in Table 7, and the chondrite-normalized REE patterns are illustrated in Figure 5. All samples are similar to the North American Shale Composite (Haskin and Paster, 1979) with only slight negative Eu anomalies and La/Yb ratios ranging from 14 to 17. As illustrated in Figure 5, the chondrite-normalized REE patterns and the absolute abundances are extremely similar in all the schist samples and show no systematic variation with distance from the pegmatite indicative of migration of these elements.

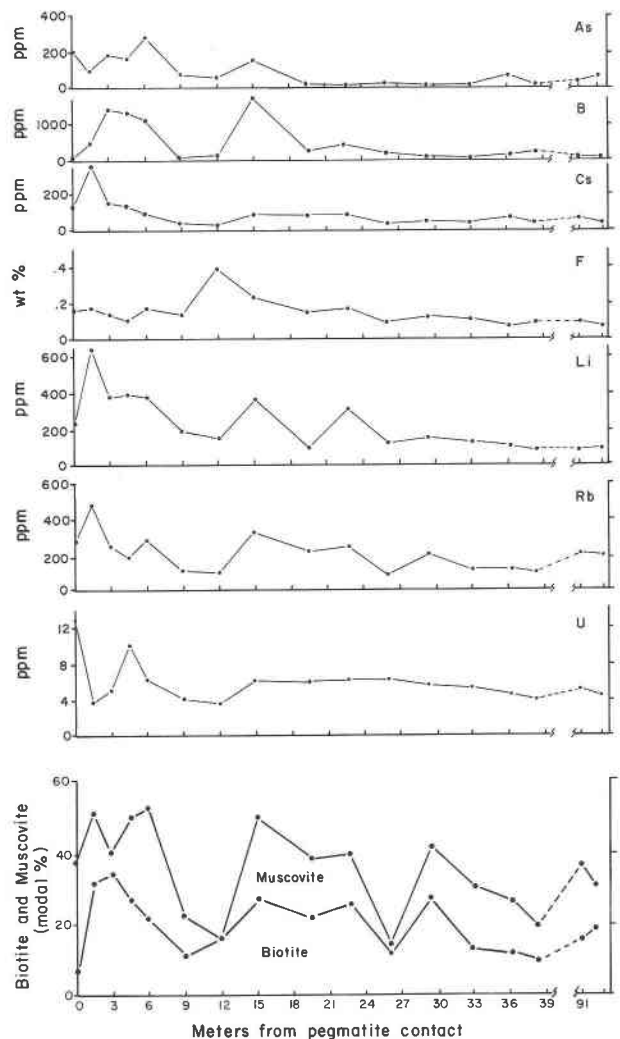


Fig. 4. Trace-element variations (As, B, Cs, F, Li, Rb, and U) and modal abundance of biotite and muscovite in quartz-mica schist with distance from the Etta pegmatite-schist contact.

Table 5. Major-element analyses of quartz-mica schist along the Eita pegmatite traverse

Sample No.	E1	E2	E2.5	E3	E3.5	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E16	E16A
Distance*	-0.9	0	1.5	3.0	4.5	6.0	9.1	12.2	15.2	19.8	23.2	26.5	29.9	33.5	36.9	39.0	91.4	93.0
SiO ₂	75.73	70.67	63.83	68.76	62.79	62.46	79.98	80.20	63.52	69.95	68.02	78.94	75.08	75.00	78.12	79.04	75.04	73.76
TiO ₂	0.06	0.64	0.59	0.62	0.71	0.66	0.26	0.36	0.66	0.60	0.62	0.40	0.42	0.55	0.48	0.38	0.56	0.48
Al ₂ O ₃	13.30	15.11	15.51	15.12	18.78	17.46	9.86	8.98	16.68	13.96	16.68	10.30	11.12	13.58	10.93	10.32	12.17	13.34
Fe ₂ O ₃	0.20	4.11	4.02	2.44	1.34	2.71	0.68	0.17	3.47	1.54	1.89	0.30	0.65	0.97	0.96	0.40	1.17	1.62
FeO	0.43	1.31	5.09	4.41	5.35	6.07	2.49	2.85	4.79	3.91	3.15	2.73	4.00	2.81	2.37	2.24	2.85	3.25
MnO	0.03	0.02	0.06	0.05	0.06	0.09	0.04	0.03	0.07	0.05	0.04	0.04	0.04	0.03	0.05	0.03	0.04	0.04
MgO	0.09	0.62	1.83	1.31	1.63	1.98	0.65	0.56	1.48	1.32	1.51	0.75	1.41	1.02	0.75	0.71	1.30	0.76
CaO	0.95	0.54	0.27	0.73	0.50	0.41	0.69	0.74	0.45	0.63	0.44	0.10	0.98	0.55	0.79	0.60	0.27	0.55
Na ₂ O	6.58	2.29	1.50	2.90	2.04	1.60	2.30	2.70	1.40	2.41	2.63	3.72	2.14	1.96	2.42	2.38	0.60	1.70
K ₂ O	1.42	4.00	6.00	3.80	5.10	5.10	2.00	1.55	5.60	4.05	4.95	1.50	3.19	3.67	2.72	2.10	4.50	3.40
P ₂ O ₅	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Total	98.77	99.31	98.50	100.14	98.50	98.54	98.95	98.14	98.12	98.42	99.93	98.76	98.63	100.14	99.59	98.20	98.50	98.90

*Meters from pegmatite contact

Table 6. Trace-element abundances of quartz-mica schist along the Eita pegmatite traverse (all in parts per million except for F)

Sample No.	E1	E2	E2.5	E3	E3.5	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E16	E16A
As	13	200	90	180	160	280	64	50	150	11	12	15	10	9	60	15	37	60
B	401	45	480	1400	1310	1085	55	130	1720	210	400	190	90	65	110	200	70	32
Ba	N.A.	700	960	650	750	950	450	280	950	N.A.	660	N.A.	N.A.	N.A.	412	260	800	750
Ca	30	116	130	123	90	150	68	75	137	110	80	50	70	90	70	70	80	82
Ce	16	140	380	150	148	100	43	37	95	83	91	39	50	45	74	55	69	41
Cu	5	7	15	11	22	44	38	11	6	11	6	14	50	20	15	10	N.A.	12
F (wt.%)	0.15	0.17	0.18	0.14	0.11	0.17	0.14	0.40	0.23	0.15	0.17	0.09	0.12	0.11	0.068	0.10	0.10	0.081
Ga	20	16	20	15	21	22	12	9	19	14	18	9	12	14	11	10	17	13
Li	143	237	659	379	409	380	184	153	370	100	309	131	152	125	109	87	84	87
Ni	5	25	40	35	40	40	30	20	40	33	50	20	35	20	50	20	27	27
Pb	15	17	7	15	25	12	20	18	10	15	10	50	17	22	22	19	5	15
Rb	16	270	480	250	191	280	120	100	330	215	249	95	214	121	122	103	204	190
Sr	140	130	100	155	130	70	110	130	75	120	80	170	110	95	120	110	18	80
Th	N.A.	16	18	17	N.A.	21	13	12	20	19	19	19	21	15	17	22	16	18
U	N.A.	13	3.8	5.1	10	6.3	4	3.7	6.2	6.1	6.2	6.3	5.7	5.2	4.7	4.1	5	4.5
V	<20	60	70	100	80	90	<40	<40	80	<40	60	<40	60	<40	<40	<40	45	<40
Zn	20	70	100	90	110	110	50	50	110	105	90	50	92	62	50	41	91	65

N.A. = Not analyzed

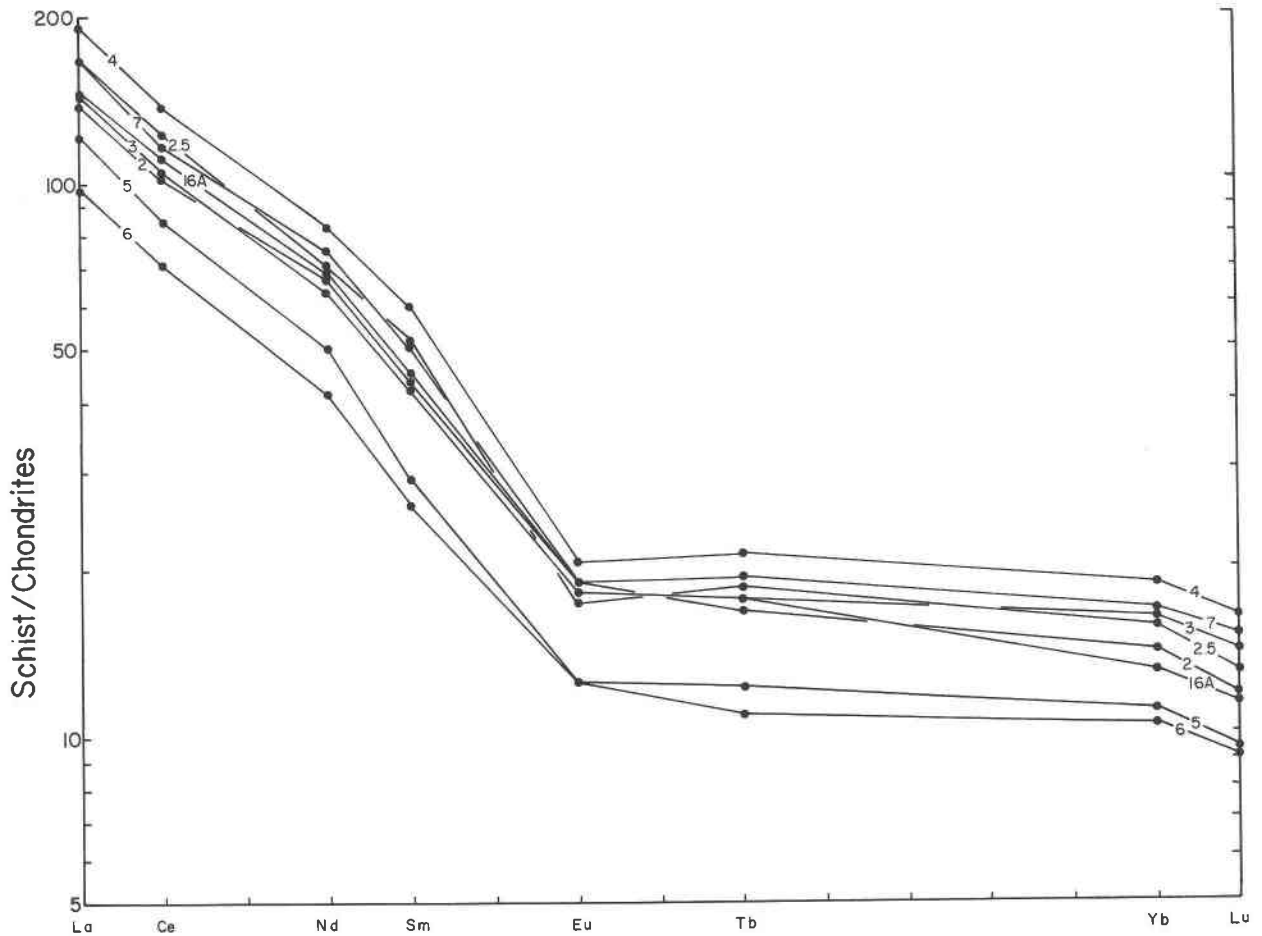


Fig. 5. Rare-earth-element concentrations in the schist along the Etta pegmatite traverse. REEs are normalized to chondrite abundances.

The dispersion of trace elements around the Bob Ingersoll No. 1 pegmatite (Fig. 6) exhibits both similarities to and differences from the trace-element dispersion halo developed around the Etta pegmatite. Similar enrichments of the schist surrounding the Bob Ingersoll No. 1 and Etta pegmatites are observed for U, As, Li, Cs, and Rb. The country rock immediately adjacent to the pegmatite is enriched in U and As. The dispersion of alkali elements is better defined in the schist around the Bob Ingersoll No. 1 pegmatite than around the Etta because of the more constant biotite + muscovite modal proportions in the schist along the traverse. The country rock is

enriched in Li to distances greater than 21 m from the contact. Rb and Cs enrichment of the country rock extends out to at least 9 m from the contact (Fig. 6). Enrichment of the country rock in F and B clearly occurs at the Bob Ingersoll No. 1 site. The F and B halos extend along the traverse to a distance of between 1 and 3 m from the pegmatite contact (Fig. 6). This is in contrast to the Etta

Table 7. REE abundances of quartz-mica schist along Etta pegmatite traverse

Sample No.	E2	E2.5	E3	E4	E5	E6	E7	E16A
La	45.50	55.00	46.50	63.00	39.50	30.00	54.50	47.00
Ce	90.00	105.00	90.00	120.00	75.00	62.00	100.00	98.00
Nd	40.00	42.00	38.00	50.00	30.00	25.00	45.00	41.00
Sm	8.00	9.30	7.70	10.80	5.30	4.70	9.20	8.00
Eu	1.30	1.20	1.30	1.40	0.86	0.85	1.30	1.20
Tb	0.78	0.87	0.80	1.00	0.57	0.51	0.90	0.80
Yb	2.80	3.10	3.20	3.70	2.20	2.10	3.30	2.60
Lu	0.40	0.44	0.48	0.55	0.32	0.31	0.51	0.39

Table 8. Major-element analyses of quartz-mica schist from the Bob Ingersoll No. 1 traverse

Sample No.	B11	B12	B13	B14	B15	B16	B17	B18	B19	B110
Distance*	0	1.5	3.0	4.5	6.0	8.1	12.2	16.8	21.3	62.5
SiO ₂	58.30	71.70	71.30	61.40	63.40	75.70	70.10	64.40	65.80	67.50
TiO ₂	0.77	0.56	0.60	0.71	0.79	0.62	0.67	0.79	0.81	0.61
Al ₂ O ₃	16.20	10.30	9.70	14.80	17.00	9.20	13.50	16.00	17.60	18.80
Fe ₂ O ₃	2.52	3.45	5.46	4.84	2.06	1.83	1.63	0.97	2.16	1.44
FeO	5.92	8.41	6.78	10.67	7.95	6.72	6.90	9.02	4.71	2.21
MnO	0.13	0.17	0.18	0.21	0.07	0.01	0.02	0.08	0.06	0.03
MgO	1.37	1.24	1.02	1.63	1.05	1.05	0.92	1.11	0.85	0.49
CaO	0.42	0.41	0.43	0.63	0.50	0.59	0.15	1.00	0.20	1.10
Na ₂ O	1.66	0.15	0.12	0.25	0.72	0.20	0.26	1.50	0.47	1.25
K ₂ O	2.47	2.40	2.20	3.31	4.00	2.60	3.80	3.73	4.35	3.60
P ₂ O ₅	0.11	0.09	0.12	0.14	0.10	0.12	0.04	0.16	0.09	0.11
TOTAL	89.87	98.88	97.91	98.59	97.64	98.64	97.99	98.76	97.10	97.14

*Meters from the pegmatite contact

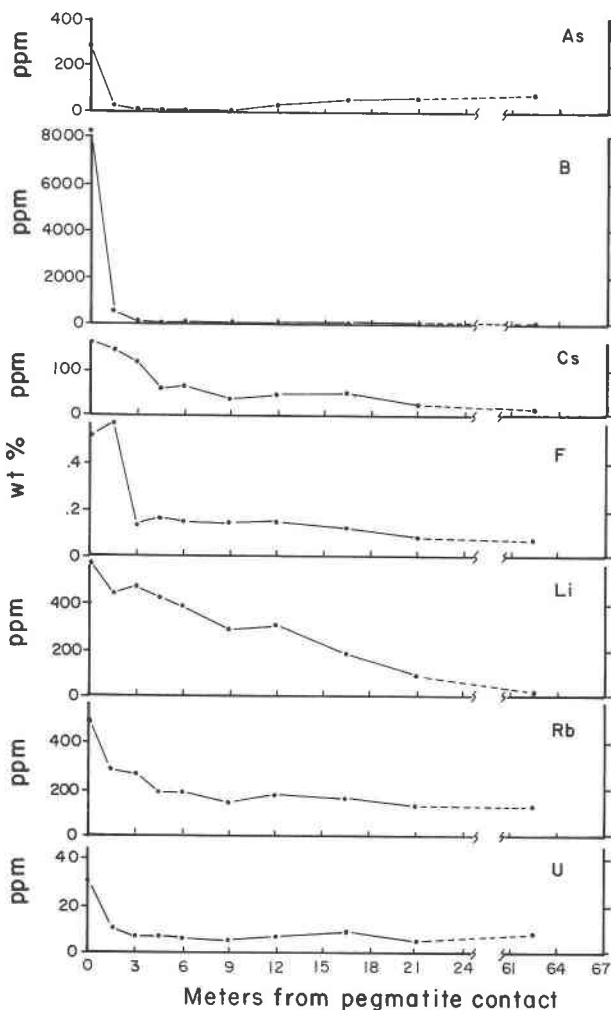


Fig. 6. Trace-element variations (As, B, Cs, F, Li, Rb, and U) in quartz-mica schist with distance from the Bob Ingersoll No. 1 pegmatite-schist contact.

traverse, which does not display systematic distributions of F and B.

The concentrations of Rb, Cs, Li, F, U, and As in the country rock collected along the vertical and horizontal

Table 9. Trace-element analyses of quartz-mica schist from the Bob Ingersoll No. 1 traverse (all values in parts per million except for F)

Sample No.	B11	B12	B13	B14	B15	B16	B17	B18	B19	B110
As	280	18	9.4	<2	5.1	<2	24	8	0	65
B	8318	465	75	31	29	36	21	32	21	23
Ba	270	200	270	340	150	200	415	460	600	470
Cr	50	<30	<30	<40	44	<30	<30	<30	<74	110
Cs	160	140	120	57	62	35	49	50	25	<23
Cu	30	24	48	11	7	130	28	18	11	5
F (wt.%)	0.52	0.57	0.13	0.16	0.15	0.14	0.15	0.12	0.082	0.068
Ga	29	12	12	16	18	10	14	18	24	19
Li	590	440	470	425	390	280	305	190	95	20
Nb	30	8.1	7.6	10	11	19.2	12	11	11	11
Ni	43	22	30	40	43	35	40	44	40	24
Pb	41	8	5	13	24	18	13	34	17	25
Rb	490	290	270	190	190	145	180	164	135	130
Sr	80	17	10	45	74	94	28	150	51	106
U	31	10	<8	<8	7.8	<6	7.1	9.5	<5	8
V	120	60	<40	<50	80	<40	100	100	120	70
Y	22	21	21	20	22	18	12	22	17	18
Zn	150	50	50	64	67	48	41	46	160	40
Zr	140	190	190	140	140	210	140	130	140	240

Table 10. Major- and trace-element analyses of the schist along vertical traverse at the Peerless pegmatite

Sample No.	9V	8V	7V	6V	5V	4V
Distance	0	0.5	2.0	13.5	5.0	6.6
SiO ₂	75.60	70.80	63.00	69.00	69.52	75.50
TiO ₂	0.40	0.45	0.52	0.64	0.65	0.60
Al ₂ O ₃	15.00	16.00	17.40	15.00	15.43	12.90
Fe ₂ O ₃	1.28	1.73	2.81	1.74	0.43	1.21
FeO	1.10	3.39	5.57	3.20	3.93	3.67
MnO	0.03	0.05	0.08	0.06	0.05	0.04
MgO	0.50	1.64	2.39	1.31	1.20	1.28
CaO	0.50	0.81	0.62	0.57	0.36	0.95
Na ₂ O	0.22	1.50	1.06	0.98	0.64	2.00
K ₂ O	3.84	4.03	5.70	4.39	3.95	2.85
Total	98.47	100.40	99.15	96.89	96.16	101.00
As	180	270	270	270	260	185
B	1100	45	350	330	460	100
Ba	470	404	670	470	450	300
Cr	70	100	130	90	81	70
Cs	36	120	73	110	81	82
Cu	19	12	<10	27	23	37
F (wt.%)	0.22	0.23	0.26	0.19	0.21	0.16
Ga	17.8	17.1	24.8	13.3	12.5	10.5
Li	173	344	391	197	301	275
Mo	<2	3.3	5.2	4.1	4.0	4.0
Nb	22.1	12.3	16.7	12.7	13.0	8.7
Ni	21	44	50	35	37	35
Pb	12.4	21.7	10.4	19.6	19.1	26.0
Rb	180	270	270	270	88	185
Sr	85	140	80	80	85	140
U	<2	3	5	4	4	4
Y	23.1	23.8	21.8	21.3	21.0	21.3
Zn	88	135	120	78	85	41
Zr	190	200	150	190	180	205

*Meters from the pegmatite contact

traverses at the Peerless pegmatite are illustrated in Figure 7. Along the vertical traverse, individual samples show little to no enrichment above background levels. There is also no systematic variation with distance from the pegmatite contact. The schist samples exhibiting the least enrichment of alkali elements are closer to the contact. In contrast, the schist along the horizontal traverse (perpendicular to schistosity) exhibits systematic enrichment of B, F, Rb, Cs, and Li near the pegmatite contact. Rb, Cs, and Li enrichments extend out along the traverse to greater distances than B and F enrichments (Fig. 7). This is similar to the pattern exhibited by country rock surrounding the Bob Ingersoll No. 1 pegmatite. Although modal variation of sheet silicates in the schist along this traverse does affect the interpretation of the extent of enrichment, the alkali-element enrichment along the traverse extends to at least 13 m whereas F and B enrichment extends to approximately 8 m.

To summarize the trace-element whole-rock data: (1) the dispersion halo surrounding the Etta pegmatite is enriched in alkali elements (Li, Rb, Cs) As and possibly U. (2) The dispersion halos surrounding the Bob Ingersoll No. 1 and Peerless pegmatites are enriched in Li, Rb, Cs, As, B, F, and possibly U. (3) Elements such as REE, Ba, Sr, and Th do not appear to form dispersion halos.

Mineral chemistry

The major- and trace-element chemistry of the mineral components of the schist may better define the extent of country-rock alteration. It has been demonstrated that in

Table 11. Major- and trace-element analyses of schist from horizontal traverse at the Peerless pegmatite ("screen" is a schist screen extending into pegmatite)

Sample No.	1H	2H	3H	4H	5H	6H	7H	8H	9H	Screen
Distance*	0	0.6	1.8	3.0	4.5	7.6	12.2	18.3	27.4	--
SiO ₂	62.68	64.43	64.79	62.16	63.81	69.21	72.75	70.51	70.58	69.96
TiO ₂	0.68	0.88	0.73	0.97	0.85	0.89	0.51	0.76	0.58	0.51
Al ₂ O ₃	19.31	15.07	15.07	14.97	13.20	12.01	13.85	14.57	14.93	8.02
Fe ₂ O ₃	1.61	3.89	5.93	3.50	2.51	2.10	1.31	1.48	1.11	5.97**
FeO	2.95	4.56	4.47	5.57	7.05	5.05	3.25	5.06	4.07	--
MnO	0.11	0.16	0.19	0.17	0.13	0.13	0.10	0.12	0.10	0.04
MgO	1.30	2.17	2.49	2.13	2.13	1.58	1.38	1.48	1.38	1.53
CaO	0.05	0.11	0.25	0.90	0.55	1.01	0.21	0.09	0.62	0.16
Na ₂ O	0.33	0.70	0.51	0.55	3.08	1.40	1.83	0.44	0.34	0.34
K ₂ O	6.68	5.53	3.07	7.03	4.59	5.15	2.81	4.28	4.37	5.47
TOTAL	95.70	97.50	97.50	97.95	97.90	98.53	98.00	98.79	98.08	92.00
B	6572	6336	3820	5410	840	855	408	2950	84	9220
Cs	149	188	132	241	297	279	142	126	70	171
F (wt.%)	1.05	0.57	0.34	1.03	0.67	0.41	0.14	0.36	0.29	0.72
Li	1229	535	949	1067	778	501	286	414	318	2589
Rb	392	219	149	356	288	277	123	128	121	1100

*Meters from pegmatite contact
**Total Fe as Fe₂O₃

quartz-mica schist assemblages, Li, Rb, and Cs are preferentially incorporated into the sheet-silicate structures (Papike et al., 1984). The sheet-silicate chemistry, therefore, provides information concerning the extent of halo development without bias from the modal mineralogy. In addition, the migration of aqueous solutions away from the pegmatites and into the surrounding country rock may result in the initiation of continuous retrograde metamorphic reactions. Fe-Mg exchange reactions have been noted in biotite and tourmaline surrounding the Tip Top pegmatite (Shearer et al., 1984). Determination of the extent of Fe-Mg exchange reactions may contribute to understanding halo development.

Table 12. Microprobe analyses of biotite from the Etta pegmatite traverse (cation formulae are calculated on the basis of 11 oxygens)

Sample No.	E2	E3	E4	E6	E7	E8	E14
SiO ₂	36.49	36.30	36.19	36.89	36.10	36.23	35.87
TiO ₂	1.76	1.67	1.47	1.68	1.59	1.51	1.70
Al ₂ O ₃	19.95	19.17	18.86	18.96	19.24	19.00	19.45
FeO*	19.99	20.44	21.43	21.38	21.43	21.23	21.48
MnO	0.20	0.19	0.21	0.21	0.20	0.24	0.23
MgO	8.11	8.37	8.00	7.67	7.73	8.13	8.76
Na ₂ O	0.02	0.06	0.06	0.06	0.06	0.06	0.07
K ₂ O	9.07	9.09	9.17	9.07	9.10	9.38	8.79
Total	95.59	95.29	95.39	95.92	95.45	95.78	96.35
Si	2.752	2.760	2.768	2.796	2.757	2.759	2.713
Al (IV)	1.248	1.240	1.232	1.204	1.243	1.241	1.287
Σ Tet.	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Al (VI)	0.531	0.478	0.468	0.490	0.488	0.464	0.446
Ti	0.100	0.096	0.085	0.096	0.092	0.085	0.095
Fe	1.263	1.303	1.369	1.357	1.367	1.354	1.359
Mn	0.014	0.014	0.014	0.014	0.014	0.014	0.014
Mg	0.914	0.951	0.910	0.865	0.881	0.924	0.986
Σ Oct.	2.822	2.842	2.846	2.822	2.842	2.841	2.900
Na	0.003	0.009	0.009	0.009	0.009	0.009	0.009
K	0.873	0.877	0.891	0.874	0.881	0.915	0.845
Σ A site	0.876	0.886	0.900	0.883	0.890	0.924	0.854
Fe/(Fe+Mg)	0.58	0.58	0.60	0.61	0.61	0.60	0.58

*Total iron as FeO

Major-element chemical compositions and cation formulae of the biotites and muscovites from the schist surrounding the pegmatites are presented in Tables 12, 13 (Etta), 14 (Bob Ingersoll No. 1), and 15 (Peerless). The mica analyses show a divergence from trioctahedral (biotite) and dioctahedral (muscovite) ideality. Biotites exhibit a greater divergence from ideality than the coexisting muscovites. The deviation from trioctahedral and dioctahedral mica ideality in the biotite and muscovite, respectively, and the extent of celadonite substitution in muscovite are not related to distance from the pegmatite-country-rock contact.

The Fe/(Fe + Mg) ratios of biotite from the schist of the Etta and Peerless pegmatite traverses show only minor

Table 13. Microprobe analyses of muscovite along the Etta pegmatite traverse (cation formulae are calculated on the basis of 11 oxygens)

Sample No.	E1	E2	E3	E4	E7	E8	E14
SiO ₂	46.84	46.71	46.98	47.54	46.91	46.82	46.08
TiO ₂	0.58	0.59	0.61	0.58	0.39	0.38	0.63
Al ₂ O ₃	34.75	35.92	34.71	34.17	34.84	35.00	36.63
FeO*	1.51	1.33	1.02	1.11	1.10	1.31	1.10
MnO	0.05	0.02	0.01	0.02	0.00	0.00	0.02
MgO	0.68	1.14	1.23	1.06	0.76	0.85	0.88
Na ₂ O	0.47	0.59	0.63	0.54	0.84	0.66	0.56
K ₂ O	10.65	10.09	10.35	10.01	10.52	10.41	9.67
Total	95.53	96.39	95.54	95.03	95.36	95.43	95.57
Si	3.110	3.064	3.110	3.152	3.115	3.105	3.039
Al (IV)	0.890	0.936	0.890	0.848	0.885	0.895	0.961
Σ Tet.	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Al (VI)	1.831	1.841	1.820	1.825	1.842	1.842	1.886
Ti	0.030	0.030	0.030	0.030	0.020	0.020	0.030
Fe	0.084	0.075	0.056	0.064	0.060	0.076	0.059
Mn	0.003	0.001	0.000	0.001	0.000	0.000	0.001
Mg	0.068	0.110	0.123	0.104	0.076	0.084	0.087
Σ Oct.	2.016	2.057	2.029	2.024	1.998	2.022	2.063
Na	0.064	0.079	0.080	0.072	0.112	0.088	0.071
K	0.902	0.843	0.875	0.845	0.894	0.885	0.816
Σ A site	0.966	0.922	0.955	0.917	1.006	0.973	0.887

*Total iron as FeO

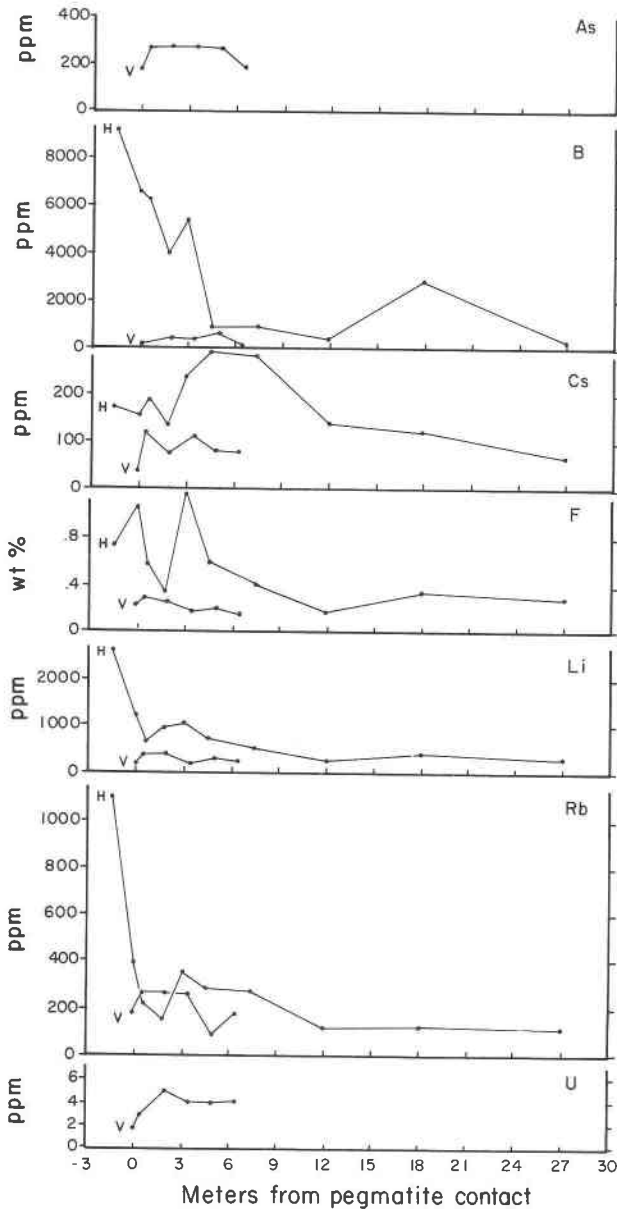


Fig. 7. Trace-element variation (As, B, Cs, F, Li, Rb, and U) in quartz-mica schist along the vertical (V) and horizontal (H) traverses at the Peerless pegmatite site.

variability and no relationship with distance from the pegmatite contact (Tables 12 and 15). In contrast, the $Fe/(Fe + Mg)$ ratios of the biotite from the schist at the Bob Ingersoll No. 1 site decrease from the pegmatite-schist contact [$Fe/(Fe + Mg) = 0.74$] to relatively unaltered schist [$Fe/(Fe + Mg) = 0.57$]. The decrease in this ratio is greatest within 1.5 m of the pegmatite contact, but the ratio continues to decrease to a distance of greater than 21 m (Fig. 8). Mn^{2+} decreases from 0.31 cations/formula unit to 0.00 cations/formula unit as the $Fe/(Fe + Mg)$ ratio decreases. Both tourmaline and chlorite (Table 16) exhibit a similar decrease in $Fe/(Fe + Mg)$ and Mn with

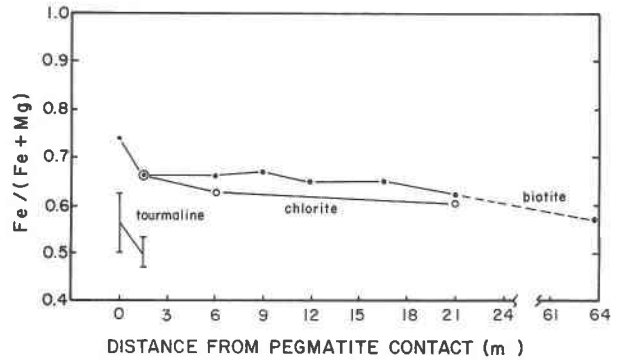


Fig. 8. Variation in the $Fe/(Fe + Mg)$ ratio in biotite, chlorite, and tourmaline along the Bob Ingersoll No. 1 traverse.

distance from the pegmatite contact (Fig. 8). In comparison, the $Fe/(Fe + Mg)$ ratios for the country-rock tourmaline at the Etta pegmatite exhibit little variation (0.40 to 0.45).

Trace-element analyses of biotite and muscovite separates from the Etta traverse are presented in Tables 17 and 18, respectively. The alkali-element content of the biotite and the muscovite is strongly enriched near the pegmatite contact (Fig. 9). The sheet silicates do not show any F enrichment. Li, Rb, and Cs are partitioned into the biotite structure rather than the muscovite structure. In both biotite and muscovite, Li content \geq Rb content $>$ Cs content.

The abundances of alkali elements and F in biotite from the schist adjacent to the Bob Ingersoll No. 1 pegmatite and in biotite and muscovite from the schist adjacent to the Peerless pegmatite are shown in Tables 14 and 15. The biotites and muscovites near the pegmatite contacts are enriched in Li, Rb, Cs, and F (Figs. 10 and 11). In the biotite of the Bob Ingersoll No. 1 traverse and the biotite and muscovite of the horizontal Peerless traverse, Li content $>$ Rb content $>$ Cs content.

DISCUSSION

Relationship between pegmatite mineralogy and dispersion-halo characteristics

The relationship between pegmatite mineralogy and halo compositional characteristics has been summarized by Beus and Sitnin (1968) and Trueman and Černý (1982). As observed by Beus and Sitnin (1968), B dispersion halos are associated with aplites and barren pegmatites; B, Li, Sn, and B dispersion halos are associated with beryl-columbite pegmatites; and B, Li, Sn, Cs, Be, and Rb dispersion halos are associated with Ta-bearing pegmatites. These halos are in effect related to the degree of fractionation of the pegmatite (Trueman and Černý, 1982), but are also related to the activities of other components and to post-intrusion fluid evolution. The mineralogies of the pegmatites indicate that the bulk composition of the Peerless and Bob Ingersoll No. 1 pegmatites was enriched in B and F compared to the Etta pegmatite bulk composition.

Table 14. Analyses of biotite and muscovite along the Bob Ingersoll No. 1 traverse (cation formulae are calculated on the basis of 11 oxygens)

Sample No.	Biotite								Muscovite		
	B11	B12	B15	B16	B17	B18	B19	B110	B12	B17	B19
SiO ₂	36.33	35.46	35.65	35.01	34.42	35.26	35.01	36.07	45.18	44.24	44.67
TiO ₂	1.33	1.54	1.49	1.53	1.53	1.63	1.62	1.66	0.33	0.31	0.22
Al ₂ O ₃	20.34	19.72	20.39	18.70	20.72	21.21	19.76	20.10	35.73	37.58	36.25
FeO	22.86	23.19	21.93	24.09	23.63	21.38	22.84	20.26	0.95	1.17	0.96
MnO	0.31	0.06	0.03	0.04	0.00	0.00	0.01	0.01	0.00	0.00	0.06
MgO	4.53	6.76	6.33	6.69	7.20	6.36	7.86	8.43	0.44	0.48	0.44
Na ₂ O	0.16	0.10	0.10	0.11	0.12	0.07	0.22	0.06	1.04	1.46	1.35
K ₂ O	9.34	9.17	9.21	9.59	9.32	9.31	9.79	9.81	10.69	9.66	10.14
Total	95.20	96.00	95.13	95.76	96.94	95.22	97.11	96.40	94.36	94.90	94.09
Si	2.797	2.714	2.736	2.697	2.527	2.696	2.564	2.704	3.042	2.955	3.012
Al	1.203	1.286	1.264	1.303	1.473	1.304	1.436	1.296	0.958	1.045	0.988
Σ Tet.	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Al	0.645	0.493	0.580	0.395	0.321	0.607	0.536	0.493	1.879	1.913	1.894
Ti	0.076	0.090	0.085	0.088	0.084	0.094	0.090	0.095	0.016	0.016	0.012
Fe	1.472	1.486	1.406	1.551	1.451	1.369	1.399	1.270	0.053	0.064	0.053
Mn	0.019	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
Mg	0.518	0.773	0.723	0.769	0.790	0.726	0.858	0.977	0.049	0.048	0.046
Σ Oct.	2.730	2.847	2.794	2.803	2.646	2.796	2.883	2.835	1.997	2.041	2.009
Na	0.028	0.018	0.018	0.019	0.018	0.009	0.035	0.009	0.138	0.193	0.178
K	0.916	0.893	0.904	0.944	0.873	0.910	0.916	0.937	0.922	0.826	0.875
Σ A site	0.944	0.911	0.922	0.963	0.891	0.919	0.951	0.946	1.060	1.019	1.053
Fe/(Fe + Mg)	0.74	0.66	0.66	0.67	0.65	0.65	0.62	0.57			
Cs	988	545	125	95	160	130	122	100	130	N.A.	N.A.
F (wt.%)	1.59	0.65	0.28	0.32	0.33	0.29	0.42	0.35	0.22	N.A.	N.A.
Li	2270	1412	1025	974	1030	810	770	440	200	N.A.	N.A.
Rb	1890	1030	395	345	410	360	377	380	362	N.A.	N.A.

Tourmaline is a common accessory-mineral phase in the wall zone of the Peerless pegmatite and occurs in every zone but one of the Bob Ingersoll No. 1 pegmatite. Tourmaline in both pegmatites is enriched in F (Jolliff et al., 1986). Amblygonite-montebrazite series minerals [LiAl(F,OH)PO₄] also occur in both the Peerless and Bob Ingersoll No. 1 pegmatites.

The contrast in F content, as suggested by the dispersion halos, is also indicated by the occurrence of spodumene in the Etta pegmatite in contrast to lepidolite or lithia muscovite in the Bob Ingersoll No. 1 and Peerless pegmatites, respectively. London (1982a) has shown that high activity of F and H stabilizes lepidolite assemblages relative to spodumene assemblages. The relationship between activity of F and Li-mineral stability in pegmatites has been described by Černý and Burt (1984) in their comparison of the Kings Mountain pegmatite, North Carolina (low activity of F, spodumene is the stable Li phase), and the Brown Derby pegmatite swarm, Colorado (high activity of F, lepidolite is the stable Li phase).

The activities of both B and F remained high during the entire crystallization of the Bob Ingersoll No. 1 pegmatite. This is indicated by the continuous crystallization

of F-rich tourmaline and the crystallization of a lepidolite core (Jolliff et al., 1986). However, this is not the case for the Peerless pegmatite. Here the termination of tourmaline stability following wall-zone crystallization suggests a decrease in the activity of B. The high activity of P in the Peerless pegmatite resulted in the crystallization of amblygonite-montebrazite, thus decreasing the activity of F in the melt. A low F activity continued following phos-

Table 15. Selected major- and trace-element abundances of biotite and muscovite from the horizontal Peerless traverse

Sample No.	Biotite						
	1H	2H	4H	5H	6H	7H	9H
Fe/(Fe+Mg) atomic	0.60	0.57	0.68	0.63	0.66	0.58	0.59
MnO (wt.%)	0.15	0.11	0.17	0.11	0.14	0.14	0.14
F (wt.%)	1.89	1.14	1.64	1.04	1.04	0.58	0.84
Li (ppm)	1857	1280	1642	1471	1469	1338	1373
Rb (ppm)	3733	1942	2962	1763	1709	1482	1062
Cs (ppm)	1250	887	1147	570	995	840	559
Sample No.	Muscovite				Screen		
	1H	2H	3H	4H			
F (wt.%)	0.97	0.32	0.37	0.66	2.56		
Li (ppm)	527	108	75	251	970		
Rb (ppm)	1369	462	460	1157	2242		
Cs (ppm)	231	148	134	212	409		

Table 16. Representative tourmaline and chlorite analyses from the Etta and Bob Ingersoll No. 1 traverses (tourmaline structural formula based on 29 oxygens and 3 borons per unit formula; chlorite based on 14 oxygens per unit formula)

Sample No.	Tourmaline								Chlorite		
	E2	E3	E14	B11	B11	B12	B12	B12	B15	B19	
SiO ₂	35.71	35.61	35.80	34.06	35.29	35.16	34.79	24.07	23.69	23.82	
TiO ₂	0.79	1.06	0.77	0.69	0.59	1.35	0.88	0.05	0.05	0.08	
Al ₂ O ₃	33.34	33.35	33.74	32.34	32.41	32.04	33.34	23.46	23.93	24.13	
FeO	8.57	8.85	7.64	11.45	9.33	10.60	8.94	32.14	30.93	30.45	
MnO	0.10	0.03	0.03	0.17	0.05	0.09	0.07	0.04	0.04	0.04	
MgO	6.82	6.95	6.43	3.89	5.21	5.30	5.63	9.37	10.11	10.83	
CaO	0.41	0.45	0.32	0.04	0.18	0.09	0.89	0.00	0.00	0.00	
Na ₂ O	2.19	2.10	2.11	2.44	2.18	2.27	1.84	0.00	0.00	0.00	
K ₂ O	0.02	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Total	87.95	88.44	86.88	85.08	85.24	86.90	86.31	89.13	88.75	89.35	
Si	5.778	5.726	5.818	5.786	5.897	5.812	5.739	Si	2.582	2.538	2.526
Al	0.222	0.274	0.182	0.214	0.103	0.188	0.261	Al	1.418	1.462	1.474
Σ Tet.	6.000	6.000	6.000	6.000	6.000	6.000	6.000	Σ Tet.	4.000	4.000	4.000
B	3.000	3.000	3.000	3.000	3.000	3.000	3.000	Fe	2.883	2.773	2.701
Al (Z site)	6.000	6.000	6.000	6.000	6.000	6.000	6.000	Mn	0.000	0.000	0.000
								Mg	1.496	1.615	1.713
Al	0.134	0.046	0.337	0.262	0.280	0.058	0.221	Al	1.548	1.558	1.541
Fe	1.156	1.189	1.044	1.622	1.305	1.470	1.229	Tl	0.003	0.003	0.006
Mn	0.010	0.000	0.000	0.020	0.000	0.010	0.010	Σ Oct.	5.930	5.949	5.961
Mg	1.642	1.662	1.562	0.990	1.295	1.302	1.388				
Tl	0.097	0.129	0.094	0.087	0.075	0.169	0.109				
Σ Y site	3.039	3.026	3.037	2.981	2.955	3.009	2.957				
Ca	0.068	0.077	0.066	0.010	0.030	0.020	0.159				
Na	0.680	0.657	0.659	0.796	0.703	0.735	0.595				
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000				
Σ X site	0.748	0.734	0.725	0.806	0.733	0.755	0.754				

phate crystallization and is recorded by the F-poor lithia muscovites in the Peerless core and replacement units (Sheridan et al., 1957; unpub. data of the authors). It is therefore indicated that pegmatite-derived fluids were dispersed into the country rock surrounding the Peerless peg-

matite prior to phosphate stability and tourmaline instability.

On the basis of these three pegmatites, the relationships between pegmatite mineralogy and dispersion-halo chemical characteristics are (1) Cs-, Rb-, and Li-enriched coun-

Table 17. Trace-element analyses of biotite from the quartz-mica schist along the Etta traverse

Sample No.	E2	E2,5	E3	E3,5	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E16	E16A
As	61	86	30	20	50	130	70	100	9	20	5	<3	10	34	52	40	80
Ba	590	1100	920	1050	900	1000	1550	950	770	760	1320	880	850	970	890	1000	1200
Co	34	41	27	31	29	48	34	29	N.A.	27	N.A.	N.A.	37	N.A.	N.A.	N.A.	32
Cr	220	180	226	220	178	274	342	205	205	205	349	212	253	349	260	130	180
Cs	820	980	570	550	30	37	340	300	280	250	260	280	90	20	22	20	190
Cu	21	16	7.3	16	0.1	60	173	7.3	23.1	10	33.7	9.2	35.3	0.4	4	N.A.	40
F (wt.%)	0.41	0.37	0.66	0.41	0.41	0.35	0.79	0.34	0.31	N.A.	N.A.	N.A.	0.43	N.A.	0.31	0.30	0.34
Ga	30	34	34	26	32	40	35	27	28	31	37	28	27	32	35	30	30
Li	1398	1269	1178	N.A.	1260	N.A.	1263	1031	N.A.	699	886	912	677	750	598	491	510
Mo	<3	3	12	3	<3	10	10	<4	<3	5	6	5	4	6	8	3	<2
Nb	36	44	64	44	51	52	56	50	43	37	63	44	51	50	55	44	40
Ni	130	100	110	140	140	130	120	135	140	115	120	105	130	120	130	130	120
Pb	20	18	13	17	11	21	13	11	17.6	6.8	20	12	18	17	19	25	20
Rb	1010	1100	770	790	700	790	730	780	770	590	770	730	640	790	690	610	670
Sc	19	28	25	25	23	25	36	22	N	23	N.A.	N.A.	18	N.A.	N.A.	N.A.	22
Sr	20	55	37	18	21	40	20	60	30	40	16	14	70	45	30	9	25
Tn	3.9	7.4	8.1	7.5	14	7	7.3	8.3	N.A.	9.6	N.A.	N.A.	9	N.A.	N.A.	N.A.	7.2
U	2.7	2.7	<4	3	5.5	4.5	4	3	N.A.	<2	N.A.	N.A.	2	N.A.	N.A.	N.A.	3.4
V	250	220	280	200	250	220	230	200	250	220	330	230	210	310	240	180	190
Y	6	12	18	11	15	18	11	11	17	12	10	10	7	13	13	10	11
Zn	360	310	330	380	370	350	370	400	420	340	370	390	390	360	350	450	330
Zr	80	105	110	100	100	230	120	130	100	130	170	110	160	230	190	140	170

N.A. = Not analyzed

Table 18. Trace-element analyses of muscovite from the quartz-mica schist along the Etta traverse

Sample No.	E2	E2.5	E3	E4	E7	E9	E12	E16A
As	70	100	85	80	81	12	6.5	80
Ba	2200	2300	1460	1300	1870	1600	1600	2400
Co	4.9	13	9	8.6	N.A.	3.8	7.1	5.1
Cr	180	220	230	240	170	210	230	240
Cs	140	150	50	47	60	25	20	19
Cu	24	27	15	11	50	21	17	27
F (wt.%)	0.11	0.09	0.13	N.A.	N.A.	N.A.	0.14	0.1
Ga	45	46	50	46	50	N.A.	44	N.A.
Li	649	548	303	292	245	170	145	116
Mo	<3	3.7	3.5	5.3	<4	N.A.	7.6	N.A.
Nb	1.7	13	25	20	23	23	20	19
Ni	13	20	13	17	15	17	10	17
Pb	16	21	20	21	22	20	21	19
Rb	550	430	230	250	350	250	230	270
Sc	41	45	31	32	N.A.	37	32	40
Sr	65	85	110	70	60	50	110	71
Th	7.5	8.3	11	12	N.A.	12	10	3.1
U	5.5	3	4	3	N.A.	<2	2	1.5
Y	8	16	15	21	12	N.A.	19	18
Zn	50	45	27	65	50	40	40	46
Zr	N.A.	120	140	130	100	N.A.	180	N.A.

N.A. = Not analyzed

try rock surrounds large, zoned, chemically evolved pegmatites; (2) B and F enrichments of the country rock commonly occur together; (3) F dispersion halos are associated with lepidolite- or lithia mica-bearing pegmatites; and (4) F dispersion halos are apparently not associated with spodumene-bearing pegmatites.

Reaction assemblages

Replacement of original metamorphic assemblages with a variety of alteration assemblages is a common feature of country rock adjacent to pegmatites. The character of the alteration assemblages is dependent upon bulk country-rock composition and the composition of the pegmatite-derived fluid. Prograde metamorphic assemblages in mica schist are commonly replaced by tourmaline-enriched assemblages. For example, at the Tip Top pegmatite, a series of tourmaline-rich assemblages is documented (Shearer et al., 1984). With increasing alteration (increasing B_2O_3), there is a succession of four mineral assemblages: (1) original metamorphic assemblage (quartz + biotite \pm potassium feldspar) plus anomalously high amounts of tourmaline; (2) quartz + biotite + tourmaline; (3) tourmaline + quartz + muscovite; and (4) tourmaline + quartz (Shearer et al. 1984).

At the Peerless and Bob Ingersoll No. 1 pegmatites, the alteration assemblages at the pegmatite-schist contact and within schist "screens" extending into the pegmatites essentially consist of quartz + muscovite + tourmaline. This assemblage appears to be the result of biotite instability with increasing $\mu_{B_2O_3}$ and decreasing μ_K . The increase in the Al/K ratio results in a more aluminous bulk rock composition, increasing the abundance of muscovite. Exomorphic muscovites are commonly developed around rare-element pegmatites (e.g. Neiva, 1980; Černý et al., 1981). London (1984) proposed a vector system to represent reaction assemblages around pegmatites. In this system, biotite instability results from decreasing the chemical potential of the exchange operator μ_{KNa-1} and increasing the chemical potential of the exchange oper-

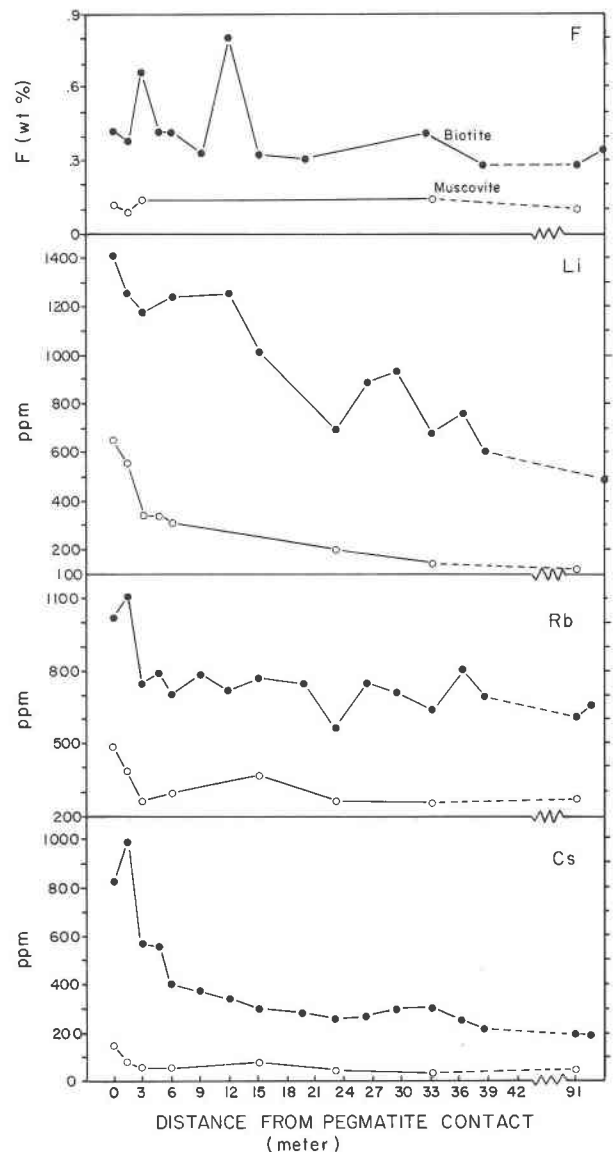


Fig. 9. Alkali-element and F content of biotite and muscovite separates from the schist along the Etta pegmatite traverse.

ator $\mu_{AlFe^{2+}_3}$ vector. Shearer et al. (1984) proposed that the breakdown of biotite may be approximated by the reaction $2 \text{annite} + \text{SiO}_2 + 5\text{Al}_2\text{SiO}_5 + 2\text{NaCl} + 6\text{H}_3\text{BO}_3 = 2 \text{tourmaline} + 2\text{KCl} + 7\text{H}_2\text{O}$, where NaCl and H_3BO_3 are components added to the schist by pegmatite-derived fluids and Al_2SiO_5 results from feldspar breakdown reactions. Of course, other biotite breakdown reactions are possible.

The reaction assemblage at the contact of the Etta pegmatite (E2) appears to be a function of a relatively low μ_K . The increase in the Al/K ratio of the country rock may result in the stability of exomorphic muscovite at the expense of primary metamorphic biotite. The low $\mu_{B_2O_3}$ of the pegmatite-derived fluid results in the minor amounts of tourmaline in the reaction assemblage.

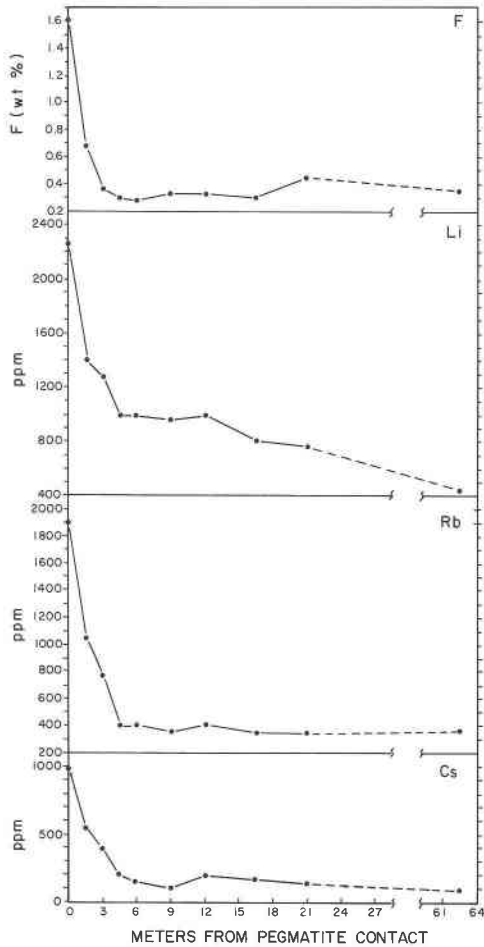


Fig. 10. Alkali-element and F content of biotite separates from the schist along the Bob Ingersoll No. 1 pegmatite traverse.

Extent of element migration

The extent of trace-element enrichment and therefore the relative mobility of trace elements can generally be determined from trace-element enrichment of the schist and refined from the trace-element enrichment of the mineral-phase components of the schist. The individual sampling traverses of this study cannot adequately describe the complete three-dimensional nature of the halos surrounding these pegmatites. This thereby limits the determination of the absolute migration distances of individual elements along all horizontal traverses; however, relative mobilities of trace elements may be determined.

Although all the horizontal traverses show trace-element enrichment in the country rock, the Bob Ingersoll No. 1 traverse is the least complex. The whole-rock and biotite data from the Bob Ingersoll No. 1 (Figs. 6, 9) indicate that along the traverse As and U enrichment occurs less than 1.5 m, F and B enrichment extends to between 1.5 and 3 m, Rb enrichment extends to between 3 and 4.5 m, Cs enrichment extends to between 6 and 9 m, and Li enrichment extends farther than 21 m from the

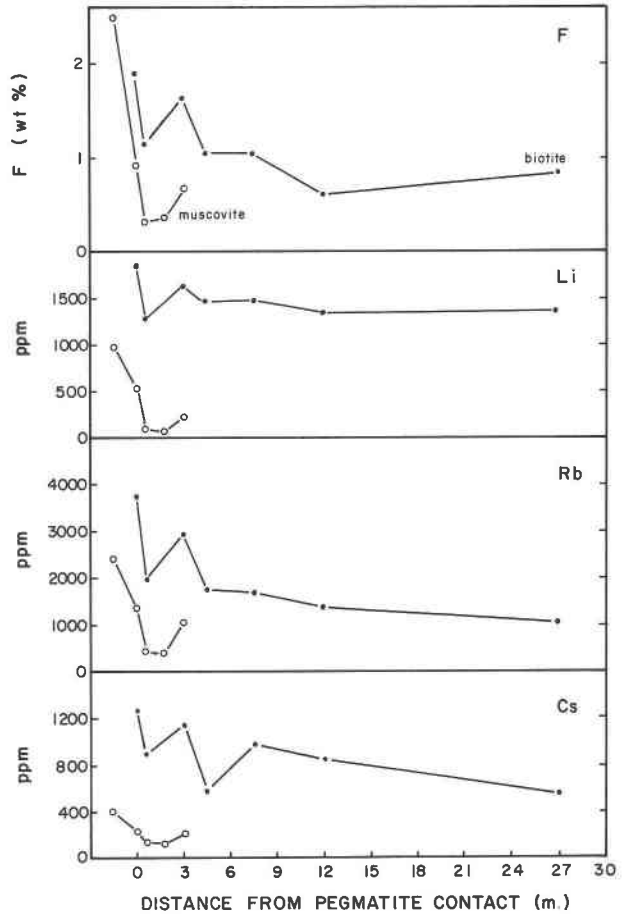


Fig. 11. Alkali-element and F content of biotite and muscovite separates from the schist along the horizontal Peerless pegmatite traverse.

pegmatite contact. As indicated by the extent of F enrichment, the f_{H_2O}/f_{HF} ratio of the pegmatite-derived aqueous solution is modified after penetrating the schist by approximately 3 m.

The horizontal traverses at the Etta and Peerless pegmatites indicate variability in the enrichment distances of Rb and Cs. In a comparison of these sites to the Bob Ingersoll No. 1, (1) As enrichment extends to greater distances at the Etta pegmatite; (2) at the Peerless pegmatite, F and B enrichment extends out to greater distances; and (3) although the background levels and noise appear to be higher at the Peerless and Etta pegmatites, the relative extent of alkali-element enrichment is $Li > Cs \geq Rb$.

In a study of the alkali-element dispersion halos around the Bob Ingersoll claim, Tuzinski (1983) concluded that the relative extent of alkali-element enrichment was $Li > Rb > Cs$. These results agree with the relative mobilities of alkali elements through compact clay and shale membranes experimentally determined by Kharaka and Berry (1973). Our observations at the Etta pegmatite, Peerless pegmatite, and Bob Ingersoll No. 1 pegmatite (this study), and studies at the Tin Mountain pegmatite (Walker, 1984;

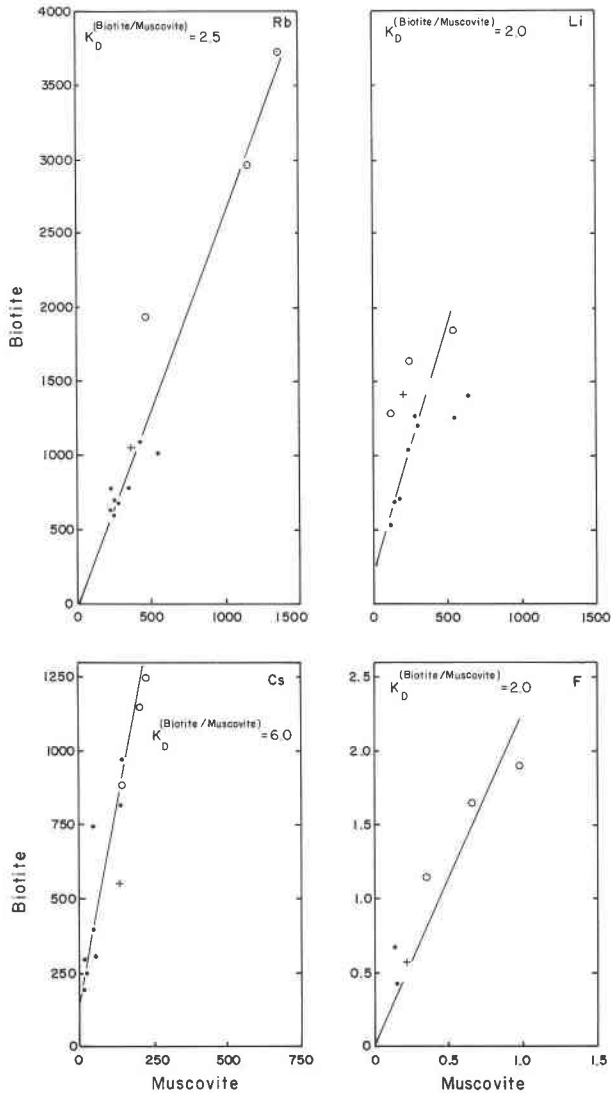


Fig. 12. Comparison of Rb, Li, Cs, and F concentrations in coexisting biotite and muscovite from the Etta (●), Bob Ingersoll No. 1 (+), and Peerless (○) traverses. The biotite/muscovite partition coefficients (K_D) are as follows: Rb, 2.5; Li, 2.0; Cs, 6.0; F, 2.0.

Laul et al., 1984) indicate that the relative mobilities of Rb and Cs are variable (e.g., $Cs \geq Rb$). This behavior may be expected on the basis of (1) similar ionic radii ($Rb = 1.48 \text{ \AA}$; $Cs = 1.67 \text{ \AA}$) and hydrated radii ($Rb = Cs = 2.28 \text{ \AA}$), (2) the varied alkali-element concentration in the pegmatite fluids, and (3) the varied mineralogical and geochemical characteristics of the country rock.

Partitioning of alkali elements and F between biotite and muscovite

Li, Rb, Cs, and F in the pegmatite-derived fluid phase are systematically distributed between coexisting biotite and muscovite in the country rock. All four elements preferentially enter the biotite structure. This partitioning of the alkali elements and F into biotite over muscovite has

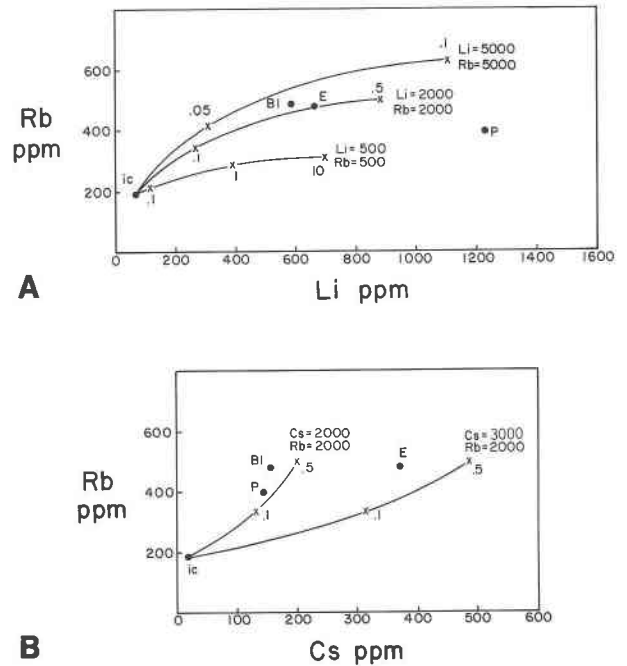


Fig. 13. Modeling of fluid-rock interactions in schist with Li- and Rb-bearing (A) and Cs- and Rb-bearing (B) fluids with a series of hypothetical fluid compositions: (A) Rb = 5000 ppm, Li = 5000 ppm; Rb = 2000 ppm, Li = 2000 ppm; and Rb = 500 ppm, Li = 500 ppm. (B) Rb = 2000 ppm, Cs = 3000 ppm; Rb = 2000 ppm, Cs = 2000 ppm. Curves indicate the compositional paths of the schist equilibrating with infiltrating fluids of different compositions. Tic marks represent N , the ratio of mass of fluid to rock.

been documented by studies of natural materials as well as by experimental studies (de Albuquerque, 1975; Muller, 1966; Munoz and Ludington, 1977; Volfinger, 1976; Volfinger and Robert, 1980). These elements (Fig. 12) are concentrated into biotite compared to muscovite by the following average ratios (biotite/muscovite): Cs = 6, Rb = 2.5, Li = 2, and F = 2. These ratios are similar to those determined in other studies, and this distribution can be rationalized in terms of the crystal chemistry of biotite and muscovite (Papike et al., 1984).

The interlayer site in trioctahedral biotite would be expected to be held open by the completely filled octahedral layer, which is occupied by the relatively large Fe^{2+} and Mg^{2+} cations. In contrast, the interlayer site in dioctahedral muscovite is smaller (more collapsed) because of the tetrahedral rotation necessary to accommodate $1/3$ vacancies and the relatively small Al cation in its octahedral layer. As a result, the large Cs ($r = 1.67 \text{ \AA}$) and Rb ($r = 1.48 \text{ \AA}$) cations tend to be excluded from the muscovite structure relative to the biotite structure. Aspects of articulation between tetrahedral and octahedral sites in micas have been discussed by Hewitt and Wones (1972), Robert (1976), Radoslovich and Norrish (1962), and Bailey (1984). The experimental determination of the relative distribution of Cs and Rb between biotite and muscovite

tends to agree with our analytical data. Volfinger (1976) determined the distribution of Cs and Rb between phlogopite and muscovite to be 7–10 and 2.4–3.2, respectively. The comparison of biotite and muscovite data from granitic rocks suggests that Rb concentrates in biotite by a factor of approximately 2 (de Albuquerque, 1975).

Li substitutes into the octahedral sites of the micas, and a number of coupled substitutions have been suggested (e.g., Foster, 1960; Burt and Burton, 1984). The exchange operators resulting in Li substitution into muscovite all involve octahedral-tetrahedral exchanges, whereas Li can be substituted into biotite through octahedral-octahedral site exchange operators. Fluid-crystal exchange may prefer substitutions involving only octahedral sites. Based on coexisting biotite-muscovite pairs from granitic rocks, de Albuquerque (1975) calculated a (biotite/muscovite)_{Li} ratio of approximately 5. A (biotite/muscovite)_{Li} ratio of 5.2 can be calculated from biotite/fluid and muscovite/fluid distribution coefficients determined by Volfinger and Robert (1980).

The preferential substitution of F into biotite compared to muscovite has been reported in a number of other petrologic studies. Nemeč (1980) reported that in amphibolite-grade orthogneiss, the biotite concentrates F compared to the coexisting phengitic muscovite by a ratio of greater than 2. In high-grade pelitic schists, Evans (1969) found the biotite/muscovite F ratio to be approximately 4.8. The preferential distribution of F in biotite compared to muscovite has been discussed by Munoz and Ludington (1977).

Fluid composition and fluid-rock interaction

Many of the mineralogical and textural characteristics of pegmatites (coarse-grained textures, zonation, mineralization, and dispersion halos) have been attributed to the exsolution of a water-rich fluid phase from a water-saturated silicate melt (Beus, 1960; Jahns and Burnham, 1969; Chakoumakos, 1978; Jahns, 1982). Although the fluid phase is an important component in the pegmatite, the compositional evolution of the fluid and fluid compositional differences between pegmatite types have been addressed in relatively few studies (Kozłowski and Karwowski, 1973; Bazarov, 1975; London, 1986). All these studies have been based on fluid inclusions within pegmatite minerals. An alternative method for constraining pegmatite-fluid compositions is to evaluate dispersion halos using geochemical modeling.

Alkali-element concentrations in the fluid phase may be constrained by using the relationship defined by Nabelek (1983):

$$C_f^i = C_f^i D - e^{-N/D} (C_f^i D - C_i^i), \quad (1)$$

where C_f^i is the final concentration of the trace element in the enriched rock, C_i^i is the initial concentration of the trace element in the fluid, D is the rock/fluid bulk distribution coefficient calculated from mineral/fluid distribution coefficients (Volfinger and Robert, 1980; Carron and Lagache, 1980), N is an equivalent mass of fluid rel-

ative to the rock, and C_i^i is the initial concentration of a trace element in the rock prior to fluid enrichment. This equation is analogous to Taylor's (1977) equation for calculating water/rock ratios in an open system for stable-isotope data. This relationship has been used by Walker (1984) to estimate fluid composition and fluid-rock ratios necessary to form the dispersion halo around the Tin Mountain pegmatite, Black Hills, South Dakota. Walker (1984) also emphasized several important problems inherent in trace-element modeling of rock/fluid interaction. However, problems resulting from country-rock heterogeneity (e.g., calculation of D) were not considered by Walker (1984). As has been demonstrated, the trace-element enrichment of the country rock adjacent to the pegmatites is strongly dependent upon modal mineralogy; therefore, a single "average" modal composition introduces some error into the calculations.

Assuming an unaltered rock composition of Li = 70, Rb = 190, and Cs = 20 ppm (Tuzinski, 1983) and a series of hypothetical initial fluid compositions (C_f^i), rock-enrichment curves may be constructed from Equation 1 (Fig. 13). The curves in Figure 13 illustrate paths of alkali-element whole-rock enrichment with increasing fluid-rock interaction. The alkali-element enrichments observed in the schist at the pegmatite contacts indicate that the fluid was highly enriched in alkali elements.

The results in Figure 13 are nonunique; however, minimum alkali concentrations may be calculated. By making N very large, Equation 1 is reduced to

$$C_f^i = C_f^i D, \quad (2)$$

where C_f^i is equal to the minimum fluid alkali-element concentration (Walker, 1984). By this method the approximate minimum concentrations of alkali elements in the fluid phase were as follows: at the Etta pegmatite, Cs = 3800 ppm, Rb = 800 ppm, and Li = 700 ppm; at the Bob Ingersoll No. 1 pegmatite, Cs = 1600 ppm, Rb = 800 ppm, and Li = 650 ppm; and at the Peerless pegmatite, Cs = 1500 ppm, Rb = 650 ppm, and Li = 1300 ppm.

The alkali-element modeling presented in Figure 13 indicates less than one equivalent mass of water equilibrated with the schist samples from near and within the pegmatite contact. This implies that even less rock-fluid interaction occurred at distances of 30 m. Similar fluid/rock ratios were determined by Walker (1984) at the Tin Mountain pegmatite. In addition, studies by Ferry (1978) of fluid interaction between granite and sedimentary rocks during metamorphism indicate fluid/rock ratios of less than unity.

The relative B content of the initial fluid phase may be indicated by the concentration of B or the modal abundance of tourmaline in the altered rock. The high concentration of B in the schist surrounding the Bob Ingersoll No. 1 and Peerless pegmatites indicates that their fluids were higher in B than the fluids derived from the Etta pegmatite. The B₂O₃ content of the Bob Ingersoll No. 1 and Peerless fluids may approach the fluid-saturation values experimentally determined by Pichavant (1981).

Re-equilibration of the sheet silicates in the country rock with pegmatite-derived aqueous solutions has resulted in F-(OH) exchange. The extent of the F-(OH) exchange is dependent upon (1) the activity of the F ion; (2) cation characteristics of the octahedral sheet; and (3) temperature of the exchange (Munoz, 1984). The relation between F intercept value [$IV(F) = 1.42X_{Mg} + 0.42X_{An} + 0.20X_{Sid} - \log(X_F/X_{OH})$], temperature, and the f_{H_2O}/f_{HF} ratio of the fluid has been calibrated by Munoz and Luddington (1974). Examples of the calculation of f_{H_2O}/f_{HF} ratios based on the F content of micas are numerous (e.g., Munoz, 1984; Zaw and Clark, 1978; Valley et al., 1982).

Calculation of $\log f_{H_2O}/f_{HF}$ for the initial fluids indicates low f_{H_2O}/f_{HF} contents of the fluids derived from the Peerless and Bob Ingersoll No. 1 pegmatites ($f_{H_2O}/f_{HF} \approx 3.80$ at 530°C) and a relatively high f_{H_2O}/f_{HF} for the fluid derived from the Etta pegmatite ($f_{H_2O}/f_{HF} \approx 4.4$ at 530°C). In addition, the f_{H_2O}/f_{HF} ratios in the fluids from the Bob Ingersoll No. 1 and Peerless pegmatites increase considerably with distance from the pegmatite. This considerable increase in f_{H_2O}/f_{HF} indicates that F is efficiently incorporated into the sheet silicates and that the dilution of pegmatite fluid with the surrounding country-rock waters occurred quite close to the pegmatite contact.

The high alkali-element and B concentrations of the pegmatite-derived fluids suggested by these exercises contrast with the relatively low solubilities suggested from geothermal systems (e.g., Ellis, 1979). The high solubility of many elements may be a result of the strong complexing ability of B and F. As an example, the solubility of SiO_2 in aqueous fluids has been shown to strongly increase with the addition of B_2O_3 in the system $SiO_2-B_2O_3-H_2O$ (Pichavant, 1981) and with the increase of F in aqueous systems (Wyllie and Tuttle, 1961). The high B_2O_3 content and low f_{H_2O}/f_{HF} values in fluids associated with the Bob Ingersoll No. 1 and Peerless pegmatites may imply relatively high SiO_2 and Al_2O_3 solubilities.

The alkali-element concentrations calculated for these pegmatite fluids, however, do not have the high solute concentrations indicated by fluid inclusions from the Tanco pegmatite (London, 1982b, 1986). Either the concentrations of alkali elements never reached the solute concentrations recorded at the Tanco pegmatite, or the solutions that reached the country rock were not yet as evolved. As was previously mentioned, the period of fluid migration into the country rock surrounding the Peerless pegmatite was restricted—a conclusion based on the high F content of the fluids, the melt saturation of P in the intermediate zones (amblygonite-montebasite-bearing zones), and the low F content of zones preceding phosphate crystallization (particularly the core). It may be suggested, therefore, that the fluids at the Peerless pegmatite did not evolve to the extent of those in the Tanco pegmatite.

SUMMARY

The results of this study indicate the following: (1) Dispersion halos are well developed around Black Hills peg-

matites. The compositional characteristics of the halos are related to the mineralogy of the associated pegmatite and pegmatite-fluid composition. (2) The relative mobilities for the components that define the dispersion halos are $As = U < B = F < Rb \leq Cs < Li$. The extent of the dispersion halos is strongly dependent upon the mechanism of migration and the relative rock reactivity to the solutions. (3) Cs, Rb, Li, and F in solution preferentially enter biotite over coexisting muscovite. (4) Trace-element modeling suggests that less than one equivalent mass of water equilibrated with the schist samples from near the pegmatite contact. (5) Pegmatite-derived fluids are complex with high solute concentrations. Compositional differences are observed among fluids from different pegmatites.

ACKNOWLEDGMENTS

We acknowledge the valuable contribution of the following individuals: V. Jensen, word processing; R. Talbot, drafting; and C. Larive, fluorine determinations. This paper was improved by the reviews of J. A. Redden, P. Nabelek, D. M. Burt, and D. London. This research was supported by the U.S. Department of Energy under DOE grant DE-FG01-84ER13259 (Papike) and contract DE-AC06-76-RLO1830 (Laul), which we gratefully acknowledge.

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MANUSCRIPT RECEIVED MARCH 18, 1985

MANUSCRIPT ACCEPTED OCTOBER 23, 1985