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BY

Steven R. Koehler
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# GEOLOGIC SETTING, MINERALOGY, AND GEOCHEMISTRY OF FOUR RARE-ELEMENT PEGMATITES FROM THE PENOKEAN VOLCANIC BELT, FLORENCE COUNTY, WISCONSIN

Steven R. Koehler  Department of Plant and Earth Science, University of Wisconsin River Falls,  River Falls, Wisconsin 54022

## ABSTRACT

Rare-element permatites have intruded lower amphibolite facies metamorphic rocks of the Quinnesec Formation in northeastern Wisconsin.  Pegmatites dip at 29 to 70 degrees and intrude parallel to subparallel to foliation.  Lack of miarolitic cavities suggests these pegmatities crystallized at intermediate depths.  Metasomatic boron halos surround pegmatites that are bounded by schists.

Barren pegmatites predominate and are composed of quartz, cleavelandite, and microcline.  Complexly zoned pegmatites display similar characteristics but contain extensive areas of replacement and host exotic mineral species (amblygonite, beryl, spodumene, lepidolite, zinnwaldite, cassiterite, columbite-tantalite, and loellingite). Common accessory minerals include tourmaline and suites of primary and secondary phosphates.  Muscovite mineralization was sparse in observed pegmatites.

K-feldspar are enriched in Cs, Rb, and Li, with correspondingly moderate to low abundances of Ta.  K/Rb ratios were 19.8-5.6 and were lowest in zoned pegmatites. Metasomatic replacement assemblages showed extreme fractionation with the highest Rb, Cs, and Ta values.

## INTRODUCTION

The eastern half of Florence County, Wisconsin is largely underlain by the Michigamme Slate, the Badwater Greenstone, and by rocks of the Quinnesec Formation.  The Niagara Fault separates primarily metavolcanic Quinnesec Formation rocks of the Penokean volcanic belt, from primarily metasedimentary rocks of the Marquette Range Supergroup, to the north.  Metasediments of the Quinnesec Formation were derived from varied, discontinuous sources (Greenberg *et al*., 1983). Metagabbro/metadiabase sills and dikes are also prevalent features.  Greenschist facies metamorphism is widespread in the Penokean volcanic belt.  Areas of intense deformation or plutonic activity are characterized by lower amphibolite facies metamorphism.

Numerous bodies of granitic pegmatite have intruded the Quinnesec Formation at moderate to steep angles north and northwest of the Bush Lake Granite (Fig. 1). Pegmatites range from quartz/feldspar dikes to complexly zoned pegmatites with abundant replacement assemblages.  Pegmatites commonly contain tourmaline and diversified suites of primary and secondary Li/Mn/Fe phosphate minerals.  Substantial muscovite mineralization is lacking in all pegmatites.  No miarolitic cavities were observed in any of the intrusions, thus suggesting intermediated depths (3.5-7 km.) of formation (Cerny, 1982). Complexly zoned pegmatites are highly enriched in large ion lithophile elements (Cs, Rb, Li, Be, P, Ta), show extreme fractionation trends, and host exotic mineral species. Gerla (1988) states that these rare-element pegmatites are the first known from the Penokean volcanic belt.

## PREVIOUS WORK

Numerous M.S. and Ph.D. theses describe various aspects within the Penokean volcanic belt (Froelich, 1953; Cain, 1962; Davis, 1977; Cummings, 1978).

The Florence area has most recently been described in depth by Dutton (1971), who was particularly interested in stratigraphy, structure, and mineral resource potential of local iron formations. Scattered pegmatite and granite dikes were noted. Sims *et al*. (1984) analyzed the structure, geochronology, and regional geology of the Dunbar Gneiss dome. Numerous steeply dipping pegmatites intruding gneiss and amphibolite were reported. Gerla (1988) described the mineralogy of a complex pegmatite that Dutton (1971) observed.

Falster *et al*.(1988) described the Mn/Fe partitioning and phosphate mineralogy in a complex Li-rich pegmatite. Falster *et al*. (1989) investigated contact relationships between pegmatites and associated marble, gneiss, and schist in the formation of rhodizite.

Koehler (1989) investigated the economic potential of two pegmatites (No. 1 and 2) for possible economic tantalum mineralization. High Rb and Cs values with moderate Ta values were noted. K/Rb vs Cs ratios did compare favorably with similar data from the Tanco Pegmatite, Manitoba. Koehler (1990) examined the whole rock and trace element geochemistry of the Bush Lake Granite in establishing a "fertile" magmatic source for the rare element pegmatites.

## GEOLOGICAL SETTING OF THE PEGMATITES

Pegmatite dikes have intruded low to moderate grade metavolcanic and metasedimentary rocks of the early Proterozoic age Quinnesec Formation. Sims *et al*., (1984) received a U-Pb zircon age date of 1866+-39 Ma from the Quinnesec Formation. Prevalent lithologies consist of amphibolite, biotite schist, quartz-muscovite schist, and hornblende schist (Fig. 1). Minor units of quartzite, impure marble, iron formation, argillite, and greywacke do occur (Dutton, 1971; Davis, 1977; Cummings, 1978; and Greenberg *et al*., 1983). Sedimentary rocks, northwest of the Bush Lake Granite, have been subjected to lower amphibolite facies metamorphism. These units contain accessory garnet, hornblende, andalusite, and cordierite. This metamorphic assemblage is synonomous with Abakuma-type facies metamorphism. Cerny (1982) recognized that rare-element pegmatites commonly are confined to Abakuma facies metamorphic rocks.

Rare-element pegmatites are late to post tectonic features in relation to regional evolution (e.g. Cerny *et al*., 1981; and Cerny *et al*., 1988). Field evidence indicates these pegmatites intruded after peak metamorphism and are late-stage structure (Sims *et al*., 1982; and Sims *et al*., 1985). According to Sims et al. (1982) and Koehler (1990), these pegmatites are interpreted as being highly fractionated products of the Bush Lake Granite.

Well developed foliation is characteristic in these units. The quartz-muscovite schist unit consists of small (<0.5 mm) anhedral grains of quartz and elongate muscovite grains. A prominent crenulation cleavage is present throughout the entire unit. The hornblende schist unit consists of anhedral quartz with elongated, subhedral hornblende. Abundant euhedral garnet crystals to 1.0 cm are common in this unit. Amphibolite is a dark green, strongly foliated unit that outcrops frequently in the study area (Fig. 1). Biotite schist is characterized by anhedral quartz grains with subhedral biotite flakes. Grains are predominantly <3.0 mm in maximum dimension. Much of the Quinnesec Formation has been folded on large and small scales. Large scale folds are evident, with isoclinal folds being present in individual outcrops.

The location pegmatite No. 1 is the S1/2 NW 1/4 NE 1/4 of section 22, T 39 N, R 17 E. Exposed dimensions of this pegmatite are 6.5 ft. by 211 ft. (1.98 m by 64.3 m). Exposure of the third dimension (depth) is lacking, however some idea of internal zonation is exposed southern end of the outcrop. Folded foliation surrounding pegmatite No. 1 dips moderately to the southwest ($44^{o}$-$65^{o}$) (Fig. 2). Isoclinal folds are abundant in exposures surrounding the pegmatite. Intrusion of this dike into a quartz muscovite schist was subparallel to foliation. Contacts with the country rock are sharp but bulge in places. According to Joliff *et al*., (1986), these bulges suggest a relative ductile response of the country rock during pegmatite intrusion. A schist xenolith(0.1 m by 1.15 m in ) occurs near the central portion of the exposure (Fig. 2). Effects of boron metasomatism are evident in the quartz muscovite schist unit especially on the western margins of pegmatite No. 1. Radial clusters and single euhedral crystals of the blue tourmaline variety were noted in thin section and in outcrop. These crystals are discordant to foliation and are observed up to 60 cm from the schist-pegmatite contact.

Pegmatite No. 2 is located in the NE 1/4 NE 1/4 NW 1/4 of section 22, T 39 N, R 17 E. Exposed dimensions are 9.0 ft. by 100 ft. (2.75 m by 30.5 m). Again, due to the lack of a third dimension, an accurate description of internal structure is difficult. Foliation surrounding the pegmatite dips $50^{o}$-$70^{o}$to the southwest (Fig. 3). Contacts tend to bulge in many areas, however contacts are very sharp. Schist xenoliths 0.1 m by <1.0 m are found in scattered throughout the pegmatite, especially near the contacts.

Pegmatite No. 3 is a poorly exposed dike that outcrops in the SE 1/4 SE 1/4 SW 1/4 of section 22, T 39 N, R 17 E (Fig. 1). This pegmatite has intruded an amphibolite unit of the Quinnesec Formation. Due to the poor exposure, internal zonation, mineral assemblages, and overall dimensions were difficult to assess. Exposed dimensions are approximately 6.0 ft. by 150 ft., however pegmatitic float can be traced >400 ft. along strike.

Pegmatite No. 4 is located in the NW 1/4 NE 1/4 SE 1/4 of section 29, T 39 N, R 17 E (Fig. 1). Intrusion of this pegmatite was subparallel to foliation of a biotite schist unit. Contacts are relatively sharp when exposed. Boron metasomatism was evident by the formation of tourmaline in the biotite schist. Euhedral crystals of tourmaline were predominantly in clusters that were concordant to foliation. Description of internal zonation was futile due to lack of exposure.

## MINERALOGY

**Albite variety cleavelandite** $NaAlSi_3O_8$

Cleavelandite occurs as white, red, or grey, platey to lath shaped, subhedral crystals in all pegmatites. Hand samples are generally striated masses that contain crystals that attain lengths to 5.0 cm. Cleavelandite tends to decrease in abundance from the contacts inward in both pegmatites. Albite crystals are not compositionally zoned. Albite that occurs in spodumene-rich assemblages shows a well developed myrmekite texture. Polysynthetic twinning in saccharoidal albite is common in thin sections. Moller *et al*. (1987), suggests that polysynthetically twinned albite is secondary in origin. Anorthite composition ranged from $An_{0}$-$An_{10}$, as determined by the Michel-Levy technique.

**Amblygonite** $LiAlFPO_4$

This lithium phosphate occurs only in pegmatite No. 2. Masses of amblygonite are typically milky white, intergrown with quartz, and associate with spodumene. This mineral assemblage has been observed by London and Burt (1981) in similar pegmatites. Pods of amblygonite tend to concentrate on the hanging wall side of the intrusion (Fig. 3). Samples are 7.5 cm by 18.5 cm and are rimmed by an iron-manganese coating. Positive identification was supplemented by oil immersion analysis (n alpha=1.598, n beta=1.606, n gamma=1.612) and X-ray diffraction.

**Andesine** $Ab_{70}An_{30}$-$Ab_{50}An_{50}$

This plagioclase feldspar, which was also confirmed by Dutton (1971), occurs in the border zone of pegmatite No. 1. Grains are subhedral and commonly <2.5 mm in dimension. Anorthite content fluctuated from $An_{34}$-$An_{48}$, as determined by the Michel-Levy technique.

**Apatite** $Ca_5(PO_4)_3(F,Cl, OH)$

Beige, anhedral apatite occurs as nodules and irregular masses to 1.0 cm in pegmatite No. 1. Apatite primarily occurs in cleavelandite-quartz pegmatite in the wall zone. Scattered grains occur with blocky microcline in intermediate zones I and II. Positive identification was aided by X-ray diffraction.

**Bermanite** $MnMn_2(PO_4)_2(OH)_2 \times 4H_2O$

Bermanite, a secondary phosphate, is found as small (<1.5 mm), subhedral grains with spodumene, quartz, and microcline in pegmatite No. 2. Crystals are thin, tabular, and a distinctive red color in hand sample. Bermanite was identified by its characteristic optical properties in thin section and in refractive index oils (n alpha=1.687, n beta=1.723, n gamma=1.747), and by X-ray diffraction.

**Beryl** $Be_3Al_2(Si_6O_{18})$

Beryl occurs in pegmatite No. 1 and 2 as beige to white, subhedral crystals to 3.0 cm by 3.5 cm. Associated minerals include quartz, spodumene, and zinnwaldite in pegmatite No. 2. Positive identification was confirmed by X-ray diffraction and oil immersion tests (n omega=1.580, n epsilon=1.585).

In pegmatite No. 3, beryl occurs as beige, anhedral masses, <1.0 cm by <1.5 cm, with quartz and microcline. Identification was confirmed by oil immersion analysis (n omega=1.581, n epsilon=1.584).

**Cassiterite** $SnO_2$

Cassiterite occurs as black, anhedral crystals in pegmatite No. 1. Masses to 6.0 mm in maximum dimension commonly associated with blocky microcline and quartz. Identification was confirmed via X-ray diffraction.

**Columbite-Tantalite** $(Fe,Mn)Nb_2O_6$-$(Fe,Mn)Ta_2O_6$

Minerals of the columbite-tantalite series are found as small (<1.5 cm) grains in pegmatite No. 1 and 2. Crystals are black, subhedral, and platey, with some crystal faces being striated. Columbite-tantalite increases in abundance toward the center of these pegmatites and is associated with microcline, cleavelandite, and quartz. Saccharoidal albite zones, forming via replacement, contain abundant columbite-tantalite, with crystals attaining dimensions of 1.0 cm by 1.5 cm. X-ray diffraction has confirmed the presence of both species. Moderate enrichment in Mn has been detected along with Mn-Ta zoning in individual crystals.

Minerals of the columbite-tantalite series occur as black, subhedral crystals to 2.5 mm in maximum dimension in pegmatites No. 3 and 4. Columbite-tantalite associates with blue elbaite in saccharoidal albite.

**Cookeite** $(Li, Al_4)Si_3AlO_{10}(OH)_8$

Pink to pearly white, euhedral crystals of cookeite occur as single crystals or in clusters from <0.5 mm to 3.0 mm in diameter. Crystals intergrow with rubellite, microcline, and cleavelandite.

**Elbaite** $Na(Li,Al)_3Al_6B_3Si_6O_{27}(OH,F)_4$

Elbaite is a common accessory mineral especially in pegmatite No. 1. Euhedral crystals range in color from pink-blue-green. Crystals average 0.5 cm by 3.0 cm, with rare exceptions being 2.5 cm by 12.0 cm. Abundant pink elbaite occurs in the wall zone but becomes increasingly color zoned in intermediate zones. These crystals are highly fractured with fractures being filled by quartz. Blue elbaite is primarily concentrated in a replacement zone with muscovite and saccharoidal albite.Euhedral crystals 0.3 cm by 1.7 cm and radial clusters are typical in this replacement zone.

Blue elbaite, in pegmatite No. 2, is a common accessory mineral in all zones with the exception of intermediate zone II. Euhedral crystals 0.1 cm by 1.1 cm are most abundant when intergrown with saccharoidal albite.

In pegmatite No. 3 and 4, abundant 1.0 mm by 4.0 mm, euhedral crystals of blue elbaite are found associated with quartz and saccharoidal albite. Elbaite is commonly color zoned with a dark blue outer margin surrounding a light blue core.

**Epidote** $Ca_2(Al,Fe)Al_2O(SiO_4)(Si_2O_7)OH$

Epidote was reported by Gerla (1988) from pegmatite No. 1, however this occurrence hasn't been varified.

**Griphite** $Na_4Ca_2(Mn,Fe)_8(Al,Fe)_4(PO_4)_{12}$

This primary phosphate mineral occurs as yellow-brown to black, resinous crusts and nodules <1.0 cm in maximum dimension. Griphite is found in association with spodumene, microcline, and quartz in pegmatite No.1 and No. 2. Oil immersion tests aided in identification (n=1.637-1.640).

**Heterosite-Purpurite** $(Fe,Mn)(PO_4)$-$(Mn,Fe)(PO_4)$

Minerals of the heterosite-purpurite series are confined to intermediate zone I, in pegmatite No. 2 with spodumene, microcline, and zinnwaldite. Crusts <4.0 mm are generally purple to dark brown in hand sample. Minerals of this solid solution series likely formed from the oxidation of lithiophilite. Heterosite-purpurite displays red to dark red pleochroic colors and is nearly opaque when immersed in refractive index oils. Both end members were identified by X-ray diffraction.

In pegmatite No. 3, heterosite-purpurite is reddish-purple to dull brown and occurs as crusts in fractures or surrounding triphylite nodules. Crusts are predominantly <2.0 cm in any dimension and are abundant along cleavage planes in microcline. The presence of heterosite-purpurite appears to be due to the oxidation of triphylite.

**Hureaulite** $H_2(Mn,Fe)_5(PO_4)_4 x 4H_2O$

Hureaulite occurs as fiberous to powdery, orange to brownish orange, nodules in pegmatite No. 1. Crystals tend to be subhedral and are found in close proximity to lithiophilite. Identification was confirmed via X-ray diffraction.

**Hyalite** $SiO_2$ x $nH_20$

Hyalite forms thin, colorless coatings on fracture surfaces in both pegmatites. When exposed to short wave ultraviolet light, samples fluoresced brilliant green. Oil immersion analysis aided identification, with n=1.429-1.434 for those samples tested.

**K-feldspar variety Microcline** $KAlSi_3O_8$

Microcline is the most abundant mineral in pegmatites No. 1 and 2. Crystals are grey, subhedral, perthitic, and occur in masses that attain dimensions to 1.9 m. Microcline increases in size and abundance from the contact inward in both pegmatites.

Perthitic microcline in pegmatite No. 3 and 4 occurs as dull pink to grey, blocky, subhedral crystals to 12.5 cm. Microcline appears to be the dominant mineral in both pegmatites.

**Lepidolite** $K(Li,Al)_{2-3}(AlSi_3O_{10})(O,OH,F)_2$

Lepidolite occurs exclusively as an accessory mineral in pegmatite No. 1. Euhedral, pink to lilac, single crystals and books range from 0.5 mm-12.0 mm in maximum diameter. All zones contained lepidolite especially intermediate zone II. Identification was confirmed by X-ray diffraction.

**Lithiophilite** $Li(Mn,Fe)(PO_4)$

Lithiophilite is a primary phosphate mineral that occurs as <3.0 mm honey brown grains in the border and wall zones of pegmatite No. 1, 2, 3, and 4. Alteration of lithiophilite has produced thin black crusts that surround the original mineral. Positive identification was determined by oil immersion methods (n alpha=1.668-1.671, n beta=1.672-1.674, n gamma=1.681-1.684).

**Loellingite** $FeAs_2$

Loellingite occurs as 2.0 mm by 5.0 mm, elongate, silvery white, anhedral crystals in pegmatite No. 1. Loellingite associates with cleavelandite and and quartz in the outer margins of the pegmatite. Positive identification was enhanced by X-ray diffraction.

**Montmorillonite (Smectite)** $(Na,Ca)(Al,Mg)_2Si_4O_{10}(OH)xnH_2O$

Montmorillonite occurs as fine-grained nodules to 1.0 cm in pegmatite No. 1. Nodules are white to grey and occur with cleavelandite and microcline. Identification was confirmed by X-ray diffraction.

**Muscovite** $KAl_2(AlSi_3O_{10}(OH)_2$

Muscovite is present in minute quantities in pegmatite No. 1 as yellow-green, euhedral crystals to 1.0 cm in maximum diameter. Trueman *et al*., (1982) interpreted this type of mica to be characteristic of Be, (Nb, Ta) bearing and spodumene pegmatites. Felty masses of muscovite are common in a replacement unit in pegmatite No. 1 with blue elbaite. Muscovite (2m1 polytype) also occurs as pink masses to 3.5 cm that surround spodumene in pegmatite No. 1.

Light green to yellow, euhedral crystals of muscovite are abundant in 1.0 mm to 6.0 mm clusters in pegmatite No. 3. Muscovite commonly intergrows with blocky microcline.

Silvery white to dirty green muscovite occurs as an accessory mineral with blocky microcline in pegmatite No. 4. Euhedral crystals rarely exceed 1.0 cm in dimension.

**Pyrite** $FeS_2$

Pyrite occurs as brassy, euhedral, cubic-shaped crystals in pegmatite No. 3. Pyrite is scarce, but is found imbedded in blocky microcline, with individual crystals ranging from 0.5 mm to 3.5 mm in maximum dimension.

**Quartz** $SiO_2$

Quartz is typically grey, clear, anhedral is found in all zones of pegmatite No. 1. Theses crystals have a maximum dimension of 20.0 cm. Fine-grained quartz <2.0 mm is associated with microcline in saccharoidal assemblages in albite. Commonly quartz occurs as pods in microcline or as irregular veinlets.

In pegmatite No. 2 quartz is commonly milky-white, anhedral, and occurs as small grains .01 m in the border zone to masses >1.1 m in intermediate zone II. Spodumene, amblygonite, zinnwaldite, and microcline are primarily associated with quartz in this pegmatite.

Grey, anhedral masses of quartz to 6.0 cm are commonly intergrown with microcline in pegmatite No. 3.

Clear to milky quartz is common throughout pegmatite No. 4 as anhedral masses that attain dimensions to 3.0 cm. Quartz commonly intergrows with blocky microcline and saccharoidal albite.

**Schorl** $Na(Fe,Mn)_3Al_6B_3Si_6O_{27}(OH,F)_4$

Schorl is prevalent in pegmatite No. 2 as black, subhedral, pencil-shaped crystals that vary from 0.3 mm to <1.8 cm in width and attain lengths to 11.5 cm. Radial clusters are commonly found in microcline and cleavelandite.

Subhedral schorl is found with quartz and microcline near contacts of the biotite schist country rock in pegmatite No. 4. Individual crystals are very abundant and attain dimensions to 0.8 cm by 4.5 cm. In replacement assemblages, schorl has been oriented into thin lines. This may represent a crude flow texture. Schorl was also recognized in the biotite schist as 2.0 mm by 3.0 mm euhedral crystals paralleling foliation.

**Sicklerite** $Li(Mn,Fe)PO_4$

Sicklerite occurs in pegmatite No. 1 as yellow brown to dark brown alteration around lithiophilite. Nodules attain diameters to 9.0 mm. Positive identification was attained by X-ray diffraction.

**Spessartine** $Mn_2Al_2Si_3O_{12}$

Anhedral spessartine occurs as fractured, salmon pink grains to 1.8 cm in pegmatite No. 1. Microprobe analyses revealed an enrichment in Mn and Y. X-ray diffraction confirmed the identification.

Subhedral crystals of spessartine are red, <0.5 mm, and occur exclusively with albite and zinnwaldite in pegmatite No. 2. The existence of spessartine in an albite-zinnwaldite assemblage was observed by Norton (1983) as an unusual feature of the Londonderry pegmatite in Western Australia. Using oil immersion techniques, refractive indicies varied from 1.799-1.801.

Subhedral spessartine is a relatively rare accessory mineral in pegmatite No. 4. Individual crystals are wine red, resinous, and average 3.0 mm in diameter. Spessartine occurs with cleavelandite and is readily identified in thin section.

**Spodumene** $LiAlSi_2O_6$

Spodumene is present as milky-white to light pink, euhedral crystals that commonly attain widths to 3.5 cm and lengths to 16.5 cm in pegmatites No. 1 and 2. In pegmatite No. 2, one crystal measured 12.5 cm by 55 cm. Samples exhibited an orange fluorescence under short wave ultraviolet light. The presence of kunzite in pegmatite No. 1 suggests a slight enrichment of manganese in the magmatic fluids and a low Fe:Mn ratio (Deer *et al*., 1963). In pegmatite No. 1, few crystals of spodumene have altered to a fine-grained mixture of muscovite.

**Triphylite** $Li(Fe,Mn)(PO_4)$

In pegmatite No. 1, triphylite occurs as clove brown, highly altered nodules with blocky microcline in intermediate zones I and II.

Triphylite occurs as 4.0 mm by 5.0 mm clove green nodules in blocky microcline in pegmatite No. 3. Numerous nodules have been altered and are enclosed by crusts of heterosite-purpurite. Identification was enhanced by X-ray diffraction.

This primary phosphate occurs as clove brown to dark green nodules in microcline. Larger nodules measure 1.5 cm by 2.0 cm and are surrounded by black alteration rims.

**Varlamoffite** $(Sn,Fe)(O,OH)_2$

Varlamoffite occurs sparingly in pegmatite No. 1 as dull grey, anhedral grains to 5.0 mm in any dimension. Anhedral crystals occur with cleavelandite and microcline. Varlamoffite was confirmed by X-ray diffraction. An enrichment in tin was confirmed via SEM.

**Zinnwaldite** $K(Li,Al,Fe)_3(Al,Si)_4O_{10}(OH,F)_2$

Zinnwaldite occurs as brown-black, euhedral crystals, in small books and single crystals in pegmatite No. 2. Typically crystals are <4.5 mm in width and associate with beryl, spodumene, and quartz. Identification was enhanced by oil immersion techniques (n alpha=1.550, n beta=1.578, n gamma=1.581).

## PEGMATITE ZONATION

The definition of zones in each pegmatite was difficult to accuratly assess due to either the lack of outcrop or the lack of a definitive third dimension (depth). Therefore, only the zones in pegmatites No. 1 and 2 will be described. The description of mineral assemblages in each zone will be in part based on the observations and revisions made by Norton (1983).

Pegmatite No. 1 consists of five texturally and mineralogically distinct zones and one replacement body. The sequence of mineral assemblages from the contacts inward are: Border zone (cleavelandite, quartz), Wall zone (microcline, quartz), Intermediate zone I (quartz, microcline, cleavelandite, spodumene), and Intermediate zone II (lepidolite, cleavelandite, quartz, microcline) which is separated from the main dike by a schist xenolith. A replacement unit exists near the southern portion of the pegmatite, and consists of saccharoidal albite, muscovite, and quartz. Contacts between zones are very sharp in areas but become obliterated by secondary albitization.

The border zone (cleavelandite, quartz) is the outermost zone which contacts the quartz muscovite schist. This zone varies in width from 1.5 cm to 6.0 cm. Mineral grains are anhedral to subhedral with sizes ranging from 0.1 mm-2.0 cm. At the schist-pegmatite contact, <0.8 mm radial clusters of blue elbaite are common features. Anorthite content in plagioclase ranged from $An_{12}$-$An_{48}$. Muscovite is sparse in this assemblage with lithiophilite and fine grained lepidolite being notable accessories. Columbite-tantalite mineralization was noted, but grains were tiny (<0.4 mm). Numerous euhedral, pink elbaite crystals are oriented perpendicular to the contacts forming a distinctive comb structure (Fig. 4). This feature occurs primarily in the northern exposure of the pegmatite. Trueman *et al*., (1982) suggest the presence of pink elbaite is indicative of increased Li, Rb, Cs potentials.

The wall zone (microcline, quartz) consists primarily of subhedral microcline with minor amounts of anhedral quartz. Quartz grains are small (<3.5 cm), while microcline crystals may attain 16.0 cm in maximum dimension. Cleavelandite ($An_6$-$An_{10}$) occurs sparingly as saccharoidal masses. Columbite-tantalite, griphite, lithiophilite, elbaite, and lepidolite are accessory minerals. Muscovite is nearly absent in this zone. Large crystals of elbaite (2.5 cm x 12.5 cm) are found in the southern section of the pegmatite. Columbite-tantalite is present with blocky microcline and saccharoidal albite throughout the assemblage. Grains <1.0 mm are common with some grains measuring 4.0 mm by 4.0 mm.

Intermediate zone I (quartz, microcline, cleavelandite, spodumene) appears to have the most significant columbite-tantalite mineralization with the exception of the replacement unit. Mineral grains range in size from 0.5 mm to 45.0 cm with crystals being subhedral to euhedral in form. Anorthite content fluctuated from $An_4$-$An_9$. Common accessory minerals include pink/blue zoned elbaite, griphite, beryl, and lepidolite. Spodumene comprises approximately 20 % of this assemblage and is the primary lithium mineral in the zone. Phosphate mineralization is prevalent in and along fractures in blocky microcline. Columbite-tantalite grains (<2.0 mm) are commonly found associated with microcline and saccharoidal albite.

Intermediate zone II (lepidolite, cleavelandite, quartz, microcline) forms an offshoot from the main dike and outcrops in the southern margin of the exposure (Fig. 4). Blue elbaite and columbite-tantalite are accessory minerals. Columbite-tantalite mineralization is confined to fine grained saccharoidal albite areas. These grains are numerous but are commonly <1.0 mm. The entire zone is characterized by a textural banding that is parallel to the contacts. Duke *et al*., (1988) termed millimeter scale layers, within the textural banding, as line rock. Individual layers are 1-34 mm in width. The formation of line rock is attributed to modal variations of tourmaline, quartz, and feldspars (Duke *et al*., 1988).

A replacement body that contains abundant blue elbaite, felty textured muscovite, and saccharoidal albite is found to be replacing portions of the wall and border zones (Fig. 4). Radial clusters of blue elbaite (<4.5 cm in diameter) are a striking feature of this unit. According to Moller *et al*., (1987), the presence of monomineralic, felty muscovite (<2.0 mm) and saccharoidal albite signifies the assemblage as being a replacement body. The abundance of columbite-tantalite in combination with saccharoidal albite suggest this unit may have the most potential for economic Ta-mineralization at depth.

A zone that outcrops several meters east of the main pegmatite consists of microcline, quartz, muscovite, blue elbaite, and spessartine (Fig. 2). This zone doesn't correlate with any exposed assemblage within the main portion of the dike. Likely, at depth this zone joins with the main portion of the intrusion.

Pegmatite No. 2 is comprised of five distinct zones (Fig. 3). These zones are based on field observation and thin section analysis. The sequence of zones from the contacts inward are: Border zone (cleavelandite, quartz), Wall zone (microcline, quartz, cleavelandite), Intermediate zone I (microcline, cleavelandite, quartz), Intermediate zone II (quartz, microcline, cleavelandite, spodumene), and Intermediate zone III (quartz, amblygonite). The pegmatite-amphibolite contact is well defined but is somewhat irregular in shape. Contacts between mineral assemblages are commonly sharp and well exposed.

The border zone (cleavelandite, quartz) is the outermost assemblage in pegmatite No. 2. The width of this assemblage varies from 5.0 cm to 12.5 cm. Quartz grains are anhedral with plagioclase (cleavelandite) grains being subhedral. Individual grains tend to be <4.0 cm in maximum dimension. Lath-shaped crystals of cleavelandite are oriented perpendicular to the pegmatite-amphibolite contacts. Anorthite content in plagioclase ranged from $An_6$-$An_{10}$. Common accessory minerals include schorl and white mica. Subhedral schorl crystals (0.5 cm by 11.5 cm in maximum dimension) are abundant and occasionally occur as radial clusters. Schorl is oriented perpendicular to contacts of pegmatite and amphibolite xenolith. Near the southern end of the outcrop, schorl crystals are aligned parallel to country rock contacts, similar to a flow texture. Euhedral muscovite crystals are sparse and do not exceed 4.0 mm in width. Columbite-tantalite mineralization was lacking in this assemblage.

The wall zone (microcline, quartz, cleavelandite, spodumene) consists of large (>0.6 m in maximum dimension) subhedral microcline, with minor amounts of anhedral quartz, saccharoidal albite, and subhedral cleavelandite. Anorthite content of plagioclase ranged from $An_5$-$An_9$. This assemblage varies from 0.2 m to 1.8 m in width. The contact between the wall zone and border zone marks a distinct increase in grain size and a decrease in cleavelandite content. Quartz and cleavelandite are typically <1.5 cm in maximum dimension. Accessory minerals include schorl, heterosite-purpurite, zinnwaldite, and minor amounts of columbite-tantalite.

Intermediate zone I (Cleavelandite, microcline, quartz) is composed of blocky microcline, lath-shaped cleavelandite, and anhedral quartz. Schorl, zinnwaldite, and heterosite-purpurite are common accessory minerals. Schorl forms a distinct comb structure around an amphibolite xenolith near the southern portion of the exposure Fig. 6). Anorthite content from the cleavelandite ranged from $An_0$-$An_8$. The exposed portion of this zone occurs near the southern end of the exposure.

Intermediate zone II (quartz, microcline, cleavelandite, spodumene) consists of anhedral quartz intergrown with subhedral microcline and cleavelandite. Anorthite content in plagioclase varied from $An_0$-$An_6$. This zone hosts a diverse suite of accessory minerals which include beryl, amblygonite, zinnwaldite, columbite-tantalite, bermanite, spessartine, and blue elbaite. Beryl occurs as subhedral masses to 5.5 cm in maximum dimension. Columbite-tantalite increases in both size and abundance in this assemblage. However, grains are relatively <4.0 mm x 3.0 mm. In the northern portion of the exposure, schorl is oriented perpendicular to the pegmatite/amphibolite contact. This zone and associated mineral assemblage outcrops again in a roadcut (State Hwy. 101) approximately 1100 ft. (111.75 m) northwest along strike of pegmatite No. 2.

Intermediate zone III (quartz, amblygonite) is <1.1 m in width and is composed of white to grey anhedral quartz. This assemblage is exposed only near the southern margin of the outcrop. Pods of amblygonite are abundant with minor amounts of lath-shaped spodumene (Fig. 5). Columbite-tantalite mineralization was not observed in this assemblage.

## GEOCHEMISTRY

Geochemical analyses were used to investigate the accumulation of lithophile elements and identify the degree of fractionation in each intrusion. Pegmatites were also evaluated for their potential to host economic tantalum mineralization. Geochemical data from the four pegmatites was compared to findings and interpretations of Moller *et al*., (1987), Cerny *et al*., (1985), and Cerny *et al*., (1988). A total of 22 samples consisting of K-feldspar or muscovite were analyzed. Outcrop samples were selected for testing, with float pieces being ignored. Moller *et al*., (1987), stated that primary white mica was the most informative mineral in assessing the Ta-mineralization in pegmatites. Primary white micas are sparse in all pegmatites; therefore, only one primary white mica sample was tested from pegmatite No. 1. All sampled K-feldspars were microcline. Based on the findings of Trueman *et al.*, (1982), only similar, well exposed zones were sampled from the individual pegmatites.

In pegmatite No. 1, six samples of K-feldspar and three muscovite samples were analyzed. These samples represent the border, intermediate zones I and II, and a replacement assemblage. Six K-feldspar samples were analyzed from intermediate zone I and II in pegmatite No. 2. Four intermediate zone K-feldspars from pegmatite No. 3 and one sample from pegmatite No. 4 were analyzed from a blocky microcline assemblage.

Samples consisted of 10.0 g of finely powdered material that was sieved for size uniformity. Elemental concentrations were determined by neutron activation analysis by Bondar-Clegg and Company Ltd. Vancouver, British Columbia. Geochemical data appears in Table 1.

These pegmatites display extreme enrichment particularly in Rb and Cs (Fig. 6). Rb values tend to increase with increased fractionation of Cs. Low to moderate values for Ta were recorded. Extreme enrichment in Cs and Ta occur in metasomatic replacement bodies. K/Rb ratios range from 5.59 to 19.79 (Fig. 7). Higher K/Rb Values (14.77-19.79) are characteristic of mineralogically simple pegmatites (No. 3 and 4). Low K/Rb values (5.59-13.56) indicate highly fractionated pegmatites like No. 1 and 2. In figure, K-feldspar K/Rb vs. Cs values are lower than the Hagendorf-Sud pegmatite and the Rush Lake pegmatite group and plot near the Bernic Lake pegmatite group (Moller *et al*., 1987). The highly mineralized, tantalum-rich Tanco pegmatite displays extremely low K/Rb vs. Cs values and plots below values from this study (Fig. 8). Pegmatites spreading from a common source increase in textural diversification with progressive fractionation and enrichment in rare-elements. This scenario appears to be true as pegmatites eminate from the Bush Lake Granite.

Three white mica samples were analyzed from pegmatite No. 1. Two samples from a saccharoidal albite unit possessed high concentrations of Rb, Cs, Ta, and Sc. According to the criteria of Moller *et al*., (1987), these samples were judged to be secondary in origin. Within this replacement body, chemical data revealed an increase in Fe, Ta, Rb, Cs, Sc, Br, and Sb. Moller *et al*. (1987) found metasomatic replacement assemblages hosted the most economically important $Ta_2O_5$ mineralization.

Replacement units were observed in these pegmatites, but none with the proportions comparable to economic tantalum pegmatites (ie. Tanco, Harding, Wodgina, Witkopie).

## CONCLUSION

Two pegmatite dikes (No. 1 and 2) in Florence County, Wisconsin, display similar chemical characteristics to those pegmatites that host economic Ta-mineralization. These pegmatites have complex mineral assemblages and show signs of replacement. All pegmatites have been enriched in B, Cs, Be, Li, P, Rb, and contain columbite-tantalite mineralization. Rb-Cs concentrations were generally high in all samples, especially those secondary white micas. Moderate (>20 ppm) Ta concentrations were detected in less than half of the samples tested. Again, Ta values were highest in areas where secondary replacement had occurred. According to the K-feldspar geochemistry, these pegmatites likely don't host economic tantalum mineralization.

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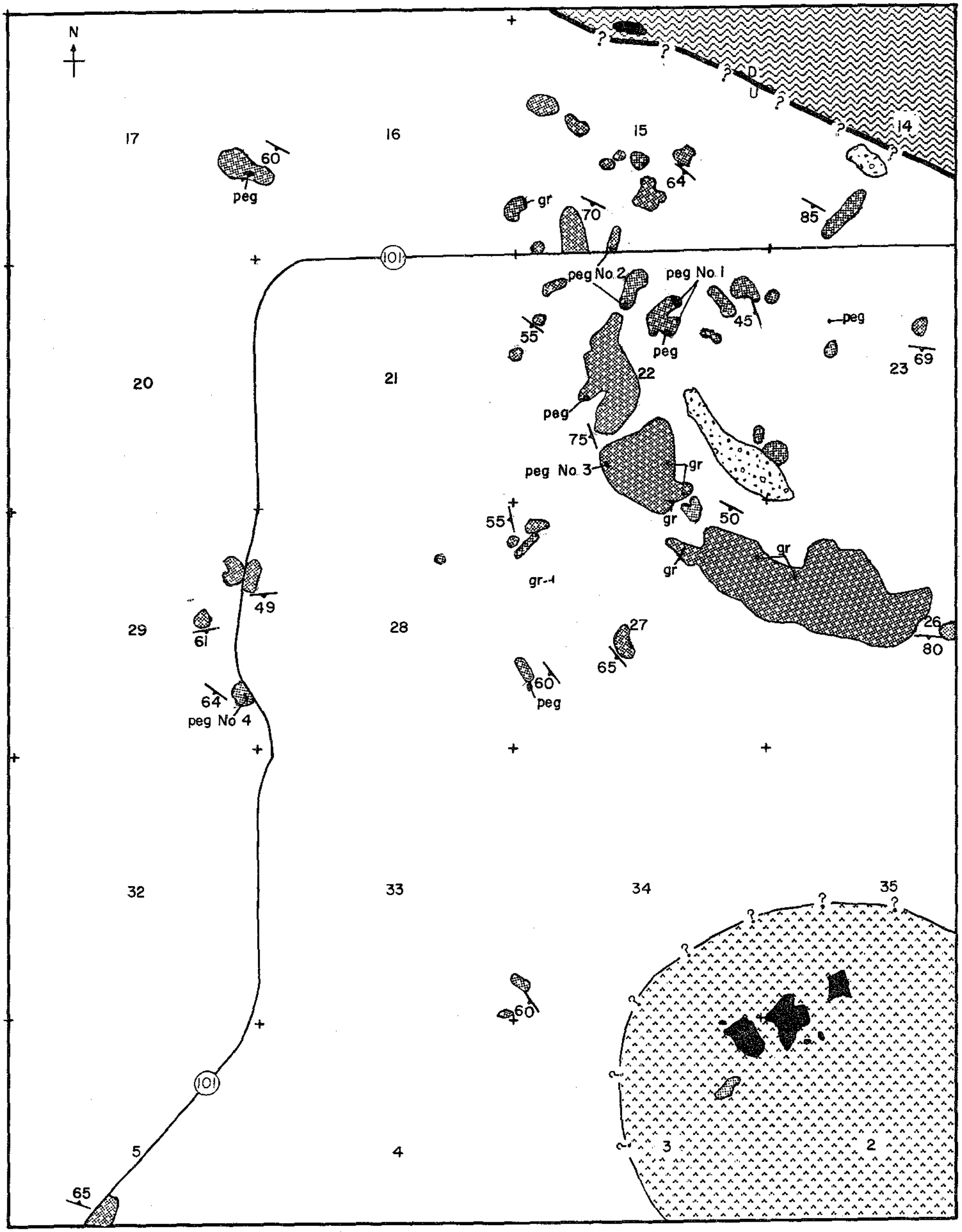


Figure 1. Geologic map of the study area showing outcrops, foliation trends, and pegmatite/granite dikes. (revised from Dutton, 1971)

## EXPLANATION

Intrusive rocks
gr, granite dike
peg, pegmatite dike

Michigamme Slate
bmq, quartzitic conglomerate
(dark indicates outcrop)

Bush Lake Granite
Biotite granite, locally grades into pegmatitic granite and pegmatite
(dark indicates outcrop)

Quinnesec Formation
Mafic and felsic metavolcanic and metasedimentary rocks
(stipple indicates outcrop)

Contact, dashed where inferred

Probable fault
D, downthrown side
U, upthrown side

57 Strike and dip of foliation

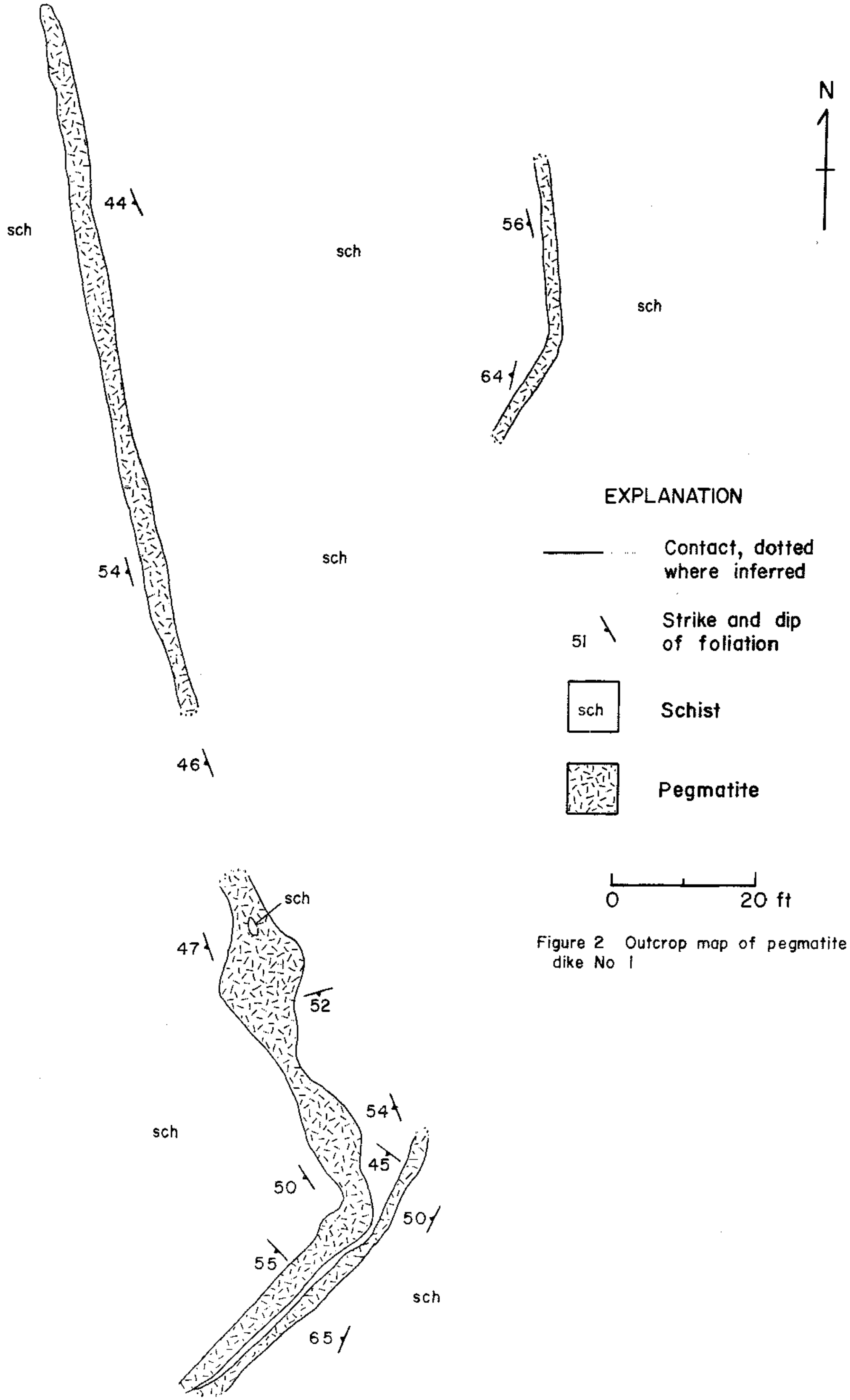


Figure 2 Outcrop map of pegmatite dike No 1

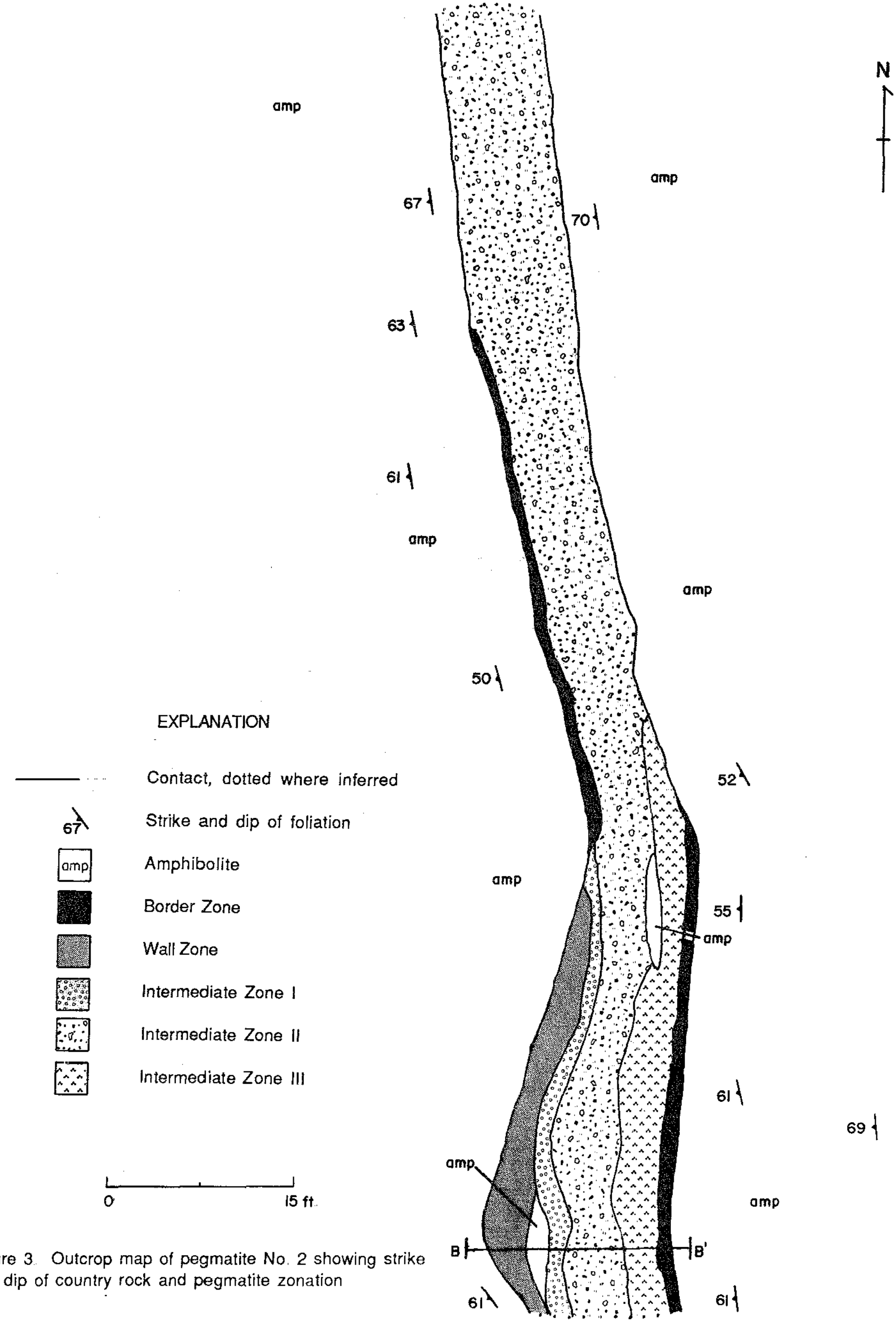


Figure 3. Outcrop map of pegmatite No. 2 showing strike and dip of country rock and pegmatite zonation

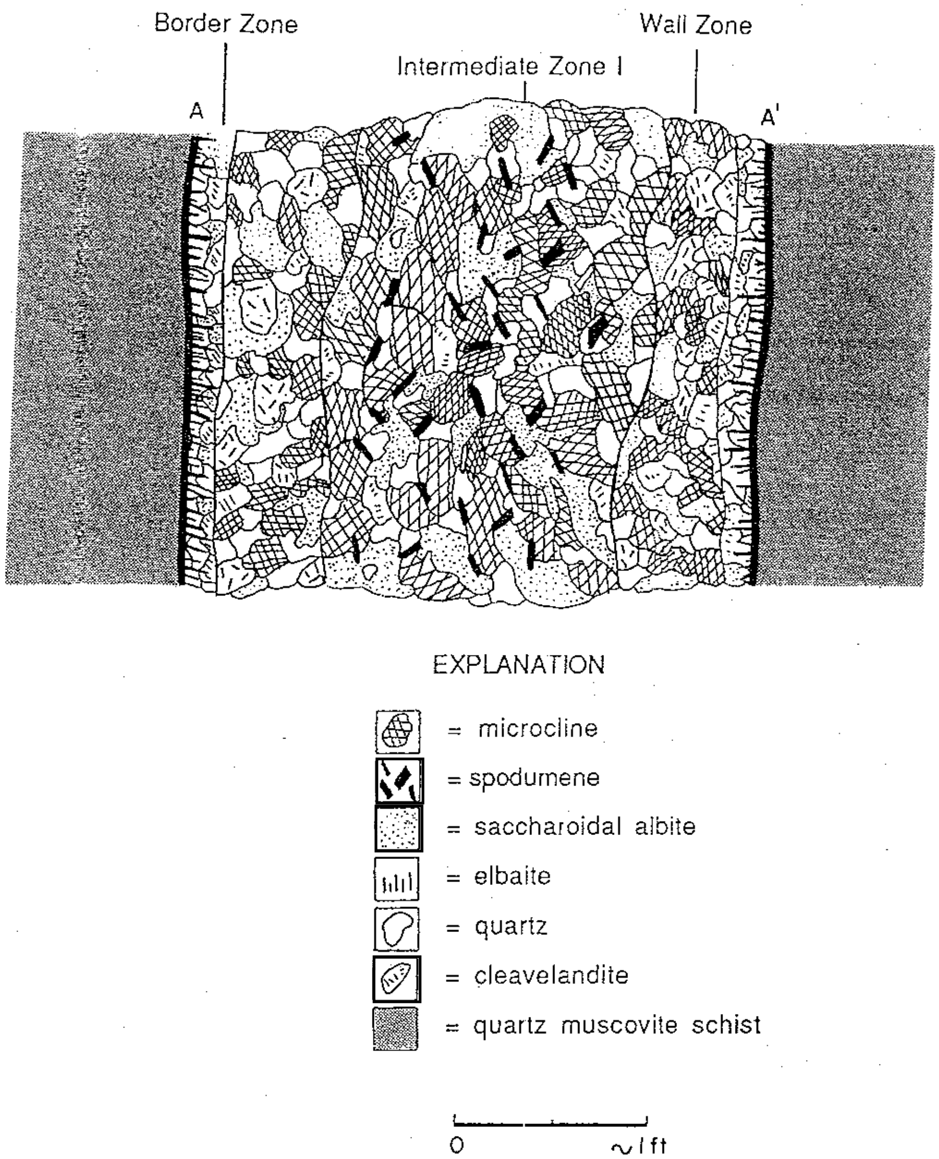


Figure 4. Schematic cross section A-A' of pegmatite No. 1 showing internal zoning and mineral assemblages

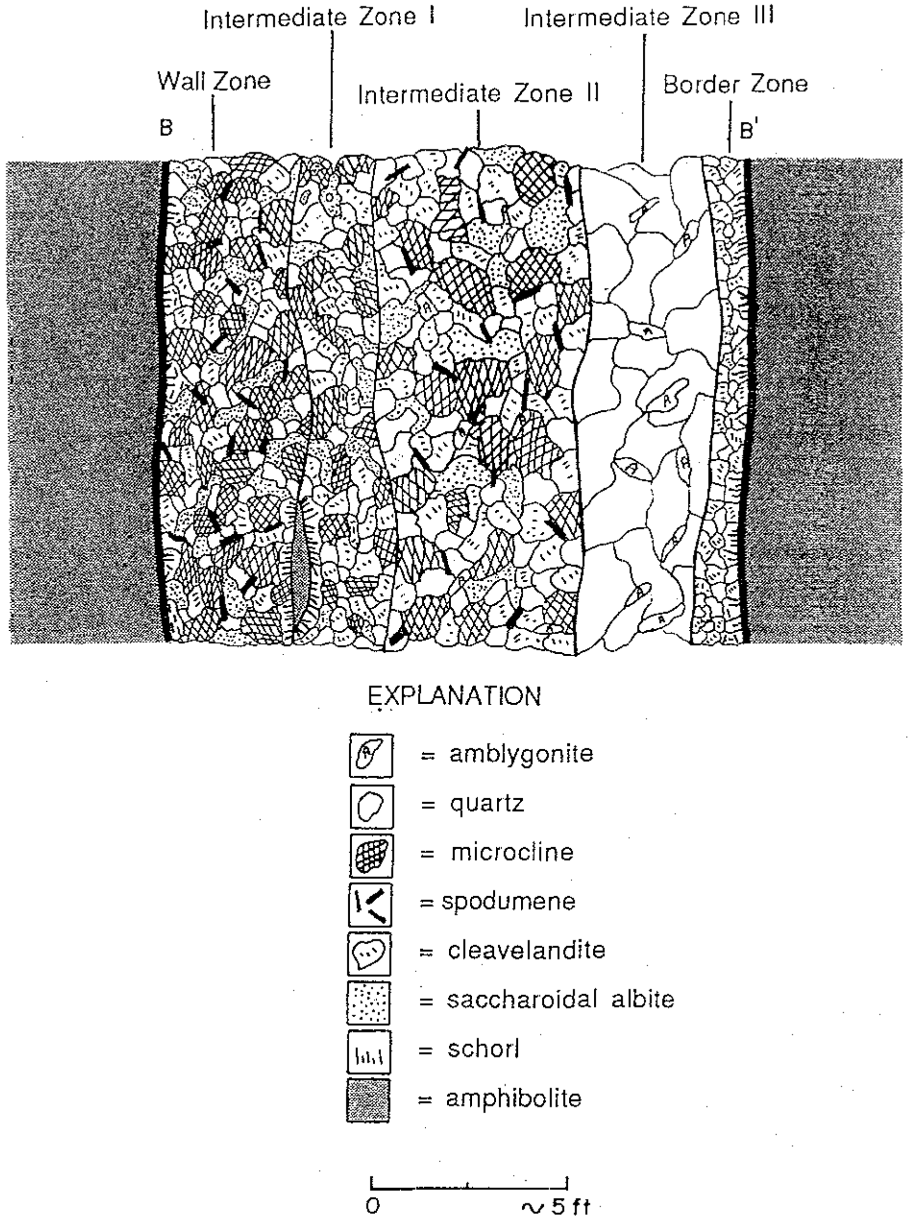


Figure 5 Schematic cross section B-B' of pegmatite No. 2 showing internal zoning and mineral assemblages.

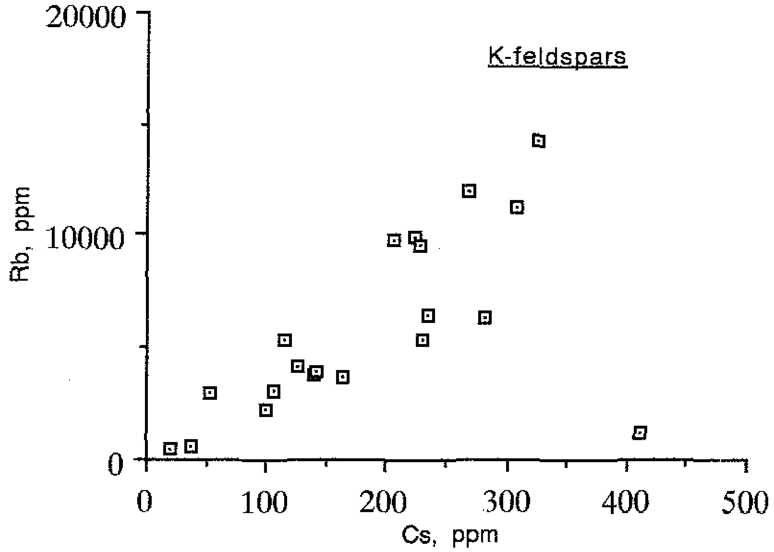


Figure 6. Rb vs Cs in K-feldspars from pegmatites No 1, 2, 3, and 4

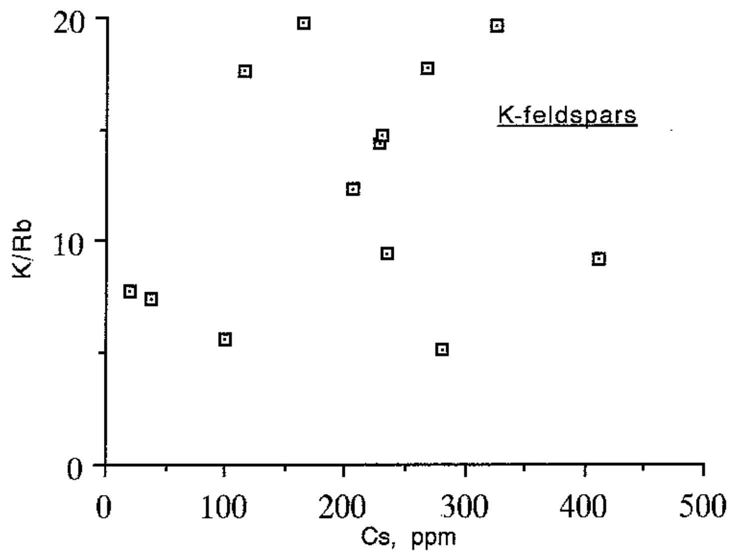


Figure 7 K/Rb vs Cs in K-feldspars from pegmatites No 1, 2, 3, and 4

## Table 1- Trace Element Geochemistry of K Feldspars

| Elements | | FLW100 | FLW102 | FLW103 | FLW105 | FLW107 | FLW110 | FLW111 | FLW114 |
|---|---|---|---|---|---|---|---|---|---|
| Au | ppb | 7 | <14 | 6 | <5 | 6 | 13 | <14 | 9 |
| Ag | ppm | <5 | <5 | <5 | <5 | <5 | 12 | <0.5 | <0.5 |
| As | ppm | 1 | <1 | <1 | <1 | <1 | 3 | <1 | 1 |
| Ba | ppm | <100 | <100 | 120 | <100 | <100 | <100 | <100 | <100 |
| Br | ppm | <1 | 4 | <1 | 2 | <1 | <1 | 1 | 2 |
| Cd | ppm | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| Ce | ppm | <10 | <26 | <10 | <10 | <10 | 22 | <26 | <10 |
| Co | ppm | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| Cr | ppm | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 |
| Cs | ppm | 21 | 1860 | 206 | 411 | 234 | 100 | 1800 | 281 |
| Eu | ppm | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 |
| Fe | pct | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 1.1 | <0.5 |
| Hf | ppm | <2 | <2 | <2 | <2 | <2 | <2 | <4 | <2 |
| Ir | ppb | <100 | <100 | <100 | <100 | <100 | <100 | <100 | <100 |
| K | pct | | | | 9.04 | 8.72 | | | |
| La | ppm | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 |
| Lu | ppm | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| Mo | ppm | <2 | 6 | <2 | 5 | 3 | 3 | <2 | <2 |
| Na | pct | 8.96 | 0.28 | 1.1 | 1 | 3.8 | 0.54 | 0.39 | 4.5 |
| Ni | ppm | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 |
| Rb | ppm | 470 | 10700 | 9860 | 11600 | 6430 | 2250 | 10700 | 6350 |
| Sb | ppm | <2 | 1.2 | 0.7 | 0.6 | 0.4 | 0.6 | 1.1 | 0.8 |
| Sc | ppm | <0.5 | 20 | 0.6 | 0.6 | <0.5 | 5 | 21 | 0.7 |
| Se | ppm | <25 | <47 | <10 | <10 | <10 | <23 | <48 | <10 |
| Sm | ppm | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 0.6 | <0.5 | <0.5 |
| Sn | ppm | <200 | <200 | <200 | <200 | <200 | <200 | <200 | <200 |
| Ta | ppm | 55 | 115 | <1 | 18 | 30 | 38 | 126 | 15 |
| Tb | ppm | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Te | ppm | <20 | <45 | <20 | <20 | <20 | <20 | <45 | <20 |
| Th | ppm | 1.6 | <0.5 | <0.5 | <0.5 | 1 | 10 | <0.5 | 0.9 |
| U | ppm | 3 | 1.9 | <0.5 | 1.5 | 0.5 | <0.5 | 2.3 | <0.5 |
| W | ppm | <2 | <2 | <2 | <2 | <2 | 6 | 5 | <2 |
| Yb | ppm | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 |
| Zn | ppm | <200 | <200 | <200 | <200 | <200 | <200 | <200 | <200 |
| Zr | ppm | <500 | <1100 | <1100 | <1100 | <1100 | <1100 | <1200 | <500 |

| FLW119 | FLW120 | FLW122 | FLW123 | FLW200 | FLW201 | FLW202 | FLW231 | FLW232 |
|---|---|---|---|---|---|---|---|---|
| <5 | <5 | 25 | <5 | <5 | <5 | <5 | <5 | <5 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 0.5 | 0.5 |
| 1 | 1 | 2 | <1 | <1 | <1 | <1 | 2 | 2 |
| <100 | <100 | <100 | <100 | <100 | <100 | 170 | <100 | <100 |
| <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 |
| 37 | 115 | 230 | 228 | 326 | 268 | 164 | 307 | 223 |
| <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 | <2 |
| <100 | <100 | <100 | <100 | <100 | <100 | <100 | <100 | <100 |
| | 6.68 | 5.01 | 9.07 | 7.35 | 8.91 | 6.43 | 6.32 | 6.92 |
| <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| <2 | <2 | 3 | 3 | 3 | 3 | <2 | <2 | <2 |
| 7.01 | 3.6 | 4.7 | 1.1 | 1.5 | 1.3 | 4.9 | 3.2 | 2.7 |
| <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 |
| 580 | 5430 | 5420 | 9580 | 14200 | 12000 | 3660 | 11300 | 9980 |
| 0.3 | 0.4 | 0.6 | 0.6 | 0.5 | 0.4 | 0.3 | 0.3 | 0.3 |
| 1.1 | 0.6 | 1.6 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| <200 | <200 | <200 | <200 | <200 | <200 | <200 | <200 | <200 |
| 24 | 3 | 41 | <1 | 5 | 2 | 20 | 41 | 69 |
| <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| <20 | <20 | <20 | <20 | <20 | <20 | <20 | <20 | <20 |
| 1.1 | 1.2 | 1.7 | <0.5 | <0.5 | <0.5 | 0.5 | <0.5 | <0.5 |
| 1 | 4.9 | 2.6 | <0.5 | <0.5 | <0.5 | 0.9 | 1.9 | 1.7 |
| <2 | <2 | 5 | 3 | <2 | <2 | <2 | <2 | <2 |
| <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 |
| <200 | <200 | <200 | <200 | <200 | <200 | <200 | <200 | <200 |
| <500 | <500 | <500 | <500 | <500 | <500 | <500 | <500 | <500 |

| FLW403 | FLW405 | FLW406 | FLW409 | FLW500 |
|---|---|---|---|---|
| 14 | 9 | <5 | <5 | <5 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| <1 | <1 | <1 | 2 | <1 |
| <100 | <100 | <100 | <100 | <100 |
| <1 | <1 | <1 | <1 | <1 |
| <10 | <10 | <10 | <10 | <10 |
| <10 | <10 | <10 | <10 | <10 |
| <10 | <10 | <10 | <10 | <10 |
| <50 | <50 | <50 | <50 | <50 |
| 142 | 127 | 139 | 107 | 52 |
| <2 | <2 | <2 | <2 | <2 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| <2 | <2 | <2 | <2 | <2 |
| <100 | <100 | <100 | <100 | <100 |
| 5.79 | 6.01 | 7.48 | 5.62 | 5.86 |
| <5 | <5 | <5 | <5 | <5 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| 3 | <2 | <2 | <2 | <2 |
| 1.2 | 2.8 | 3.7 | 1.4 | 2.1 |
| <50 | <50 | <50 | <50 | <50 |
| 3920 | 4160 | 3800 | 3170 | 2960 |
| 0.6 | 0.3 | 0.3 | 0.5 | 0.5 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| <10 | <10 | <10 | <10 | <10 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| <200 | <200 | <200 | <200 | <200 |
| 31 | 19 | 27 | 8 | 11 |
| <1 | <1 | <1 | <1 | <1 |
| <20 | <20 | <20 | <20 | <20 |
| <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| 1.4 | <0.5 | <0.5 | 0.8 | <0.5 |
| <2 | <2 | <2 | <2 | <2 |
| <5 | <5 | <5 | <5 | <5 |
| <200 | <200 | <200 | <200 | <200 |
| <500 | <500 | <500 | <500 | <500 |