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FENITIZATION IN THE HEATHER ANN  
COMPLEX, THOMPSON FALLS, MONTANA

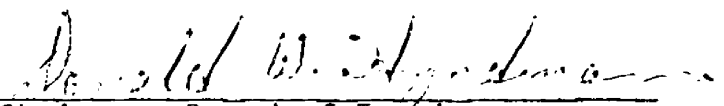
by

Donald J. Schissel  
B.A., Amherst College, 1974

presented in partial fulfillment of the  
requirements for the degree of

Master of Science  
UNIVERSITY OF MONTANA  
1981

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## ABSTRACT

Schissel, Donald J.

Geology

### Fenitization in the Heather Ann Complex, Thompson Falls, Montana

The Heather Ann alkalic complex near Thompson Falls, Montana is 95 km south of the Rainy Creek complex in the western Montana alkalic belt. Here quartzite wall-rocks of the upper Burke Formation of the Proterozoic Belt Supergroup are fenitized by solutions from an alkali-feldspar syenite. The metasomatized aureole is 15-30 m thick and displays a field sequence of localized quartz-fenite, banded fenite, and syenite-fenite from outside towards the syenite contact. Mineralogically, aegirine, Mg-arfvedsonite, albite, and microcline appear in the quartzites replacing relict quartz and biotite. Whole-rock chemical analyses show near straight line increases in sodium, potassium, aluminum, and ferric iron with increasing fenitization. Fenitization results from the exsolution of a carbon-dioxide-rich fluid phase enriched in these elements from the intrusive syenite as a result of a decrease in the carbon-dioxide solvent ability of that magma at lower pressure conditions. Fenitization provides good evidence for alkali mobility and its importance in the differentiation of alkalic magmas.

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## CHAPTER I

### INTRODUCTION

Fenitization is the process of alkali metasomatism of the country rocks surrounding alkalic complexes. Nearly all carbonatites are enveloped by a fenite aureole, but also ijolites, nepheline syenites, and syenites commonly possess fenitized border zones. Brögger in 1921 first introduced the term fenitization to describe the wall-rock alteration around the Fen alkalic complex. At this type locality, granitic gneisses are transformed into fenites which consist of orthoclase, albite, aegirine, and soda-amphibole. This metasomatism was attributed to the infiltration of alkaline solutions into the wall-rocks for 100-400 m outwards from the crystallizing ijolite magma (Heinrich, 1966).

Carbon-dioxide plays an important role in the petrogenesis of alkalic rocks and carbonatites (Rock, 1976). The high solubility of carbon-dioxide in alkalic rocks also has broad implications for the process of fenitization. Carbon-dioxide solubility in alkali silicate magmas is quite different from water solubility;  $\text{CO}_2$  solubility is only 10-20% the amount of water solubility (Mysen, 1976). A carbonated magma at upper-mantle pressures will be very close to  $\text{CO}_2$  saturation due to the small solvent ability of that magma. On the other hand, water solubility is much greater and not near saturation at upper-mantle conditions. Mysen (1975) stresses that if a carbonated magma

near saturation is intruded to lower-pressure conditions,  $\text{CO}_2$  solubility would decrease forcing the exsolution of a  $\text{CO}_2$ -rich fluid phase. This fluid phase enriched in alkali carbonate complexes is probably responsible for the metasomatism commonly found around alkalic complexes. In summary, fenitization is a process by which  $\text{CO}_2$ -saturated magmas re-adjust to lower  $\text{CO}_2$  solubility by exsolving a fluid phase which fenitizes their border zones.

### General Statement

This is a petrologic and chemical study of the fenitized country rocks surrounding the alkali-feldspar syenite in the Heather Ann complex near Thompson Falls, Montana. The host rocks in most studies of fenitization consist of high-grade metamorphic rocks such as gneisses or amphibolites. These country rocks are so chemically and mineralogically diverse that the changes occurring due to metasomatism are difficult to interpret. Fenites formed from chemically simple rocks, such as quartzites, are invaluable because they allow a more careful study of the process of fenitization. There are relatively few occurrences of these types of fenites (Baker, 1953; Deans and others, 1972). The best-studied fenites formed from quartzites occur at the Borralan complex in Scotland (Woolley and others, 1972) and near Sudbury, Ontario (Siematkowska and Martin, 1975). Unfortunately, the field exposure at both of these localities is poor and the relationship between the alkalic rocks and the metasomatized quartzites is only inferred.

In the present study, solutions from the alkali-feldspar syenite have fenitized quartzites of the Burke Formation of the Precambrian Belt Supergroup. The Heather Ann complex affords a worthwhile area for the study of the fenitization process because of the simple bulk chemistry and mineralogy of the quartzites and the good field exposure. Field work was completed during the summer of 1980 and consisted of sampling and mapping the fenite zone on the southeast contact of the complex.

#### Field Relations

Fenitized country rocks are well exposed on the southeastern contact of the alkali-feldspar syenite. The intrusive syenite forms a discordant contact with the Belt rocks, which comprise the northeast arm of an anticline. The Belt rocks maintain their regional strike of approximately N60W and dip of 45° NE. The syenite contact dips outwards at approximately 40°. This dip is based on the V-outcrop pattern of the intrusive syenite contact.

The best exposure of the fenite zone is on Fenite Ridge, located approximately 700 meters southeast of Haines Point (Fig. 3). This is where five samples were collected for whole-rock analyses through the fenite zone. The fenitizing solutions metasomatize both the Burke and Revett formations of the Belt Supergroup along this contact. This study describes only the fenitization of the upper Burke Formation on account of its better exposure.

### Previous Work

Burlington Northern Minerals discovered the Heather Ann complex in 1970 by noticing a large aeromagnetic anomaly over the complex similar to the signature over the Rainy Creek alkalic complex 100 km to the north. Canadian-Superior Company drilled the nordmarkite-alkali feldspar syenite contact in 1974 for copper mineralization. In 1979, Peter Mejstrick of Burwest Corporation completed the general geologic map of the complex, which is presented in Figure 3 with minor revisions in the southeast quadrant by the author. No work has been published on the complex to date.

### Location

The Heather Ann alkalic complex is located in the central part of T22N and R31W in Sanders County, Montana (Fig. 1). It is accessible from Thompson Falls by driving north on Highway 200 and turning west on the Beaver Creek turnoff road leading to Haines Point and the Heather Ann complex. The area is heavily forested and rugged. The highest elevation on the property is Haines Point at 1560 meters. The complex is drained by Emma Creek, Haines Gulch, and Little Beaver Creek.

### Regional Setting

The recently discovered Heather Ann alkalic complex is a member of a belt of alkalic rocks which extends from northwest Montana to east-central Idaho. There are several well known alkalic complexes in



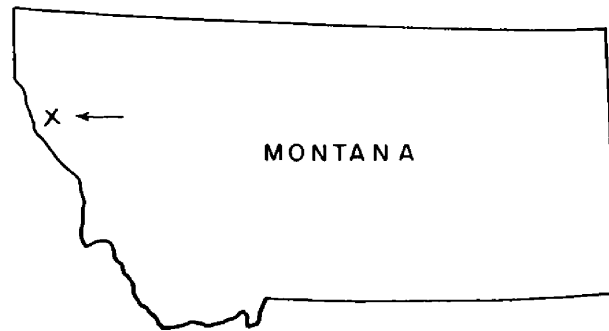
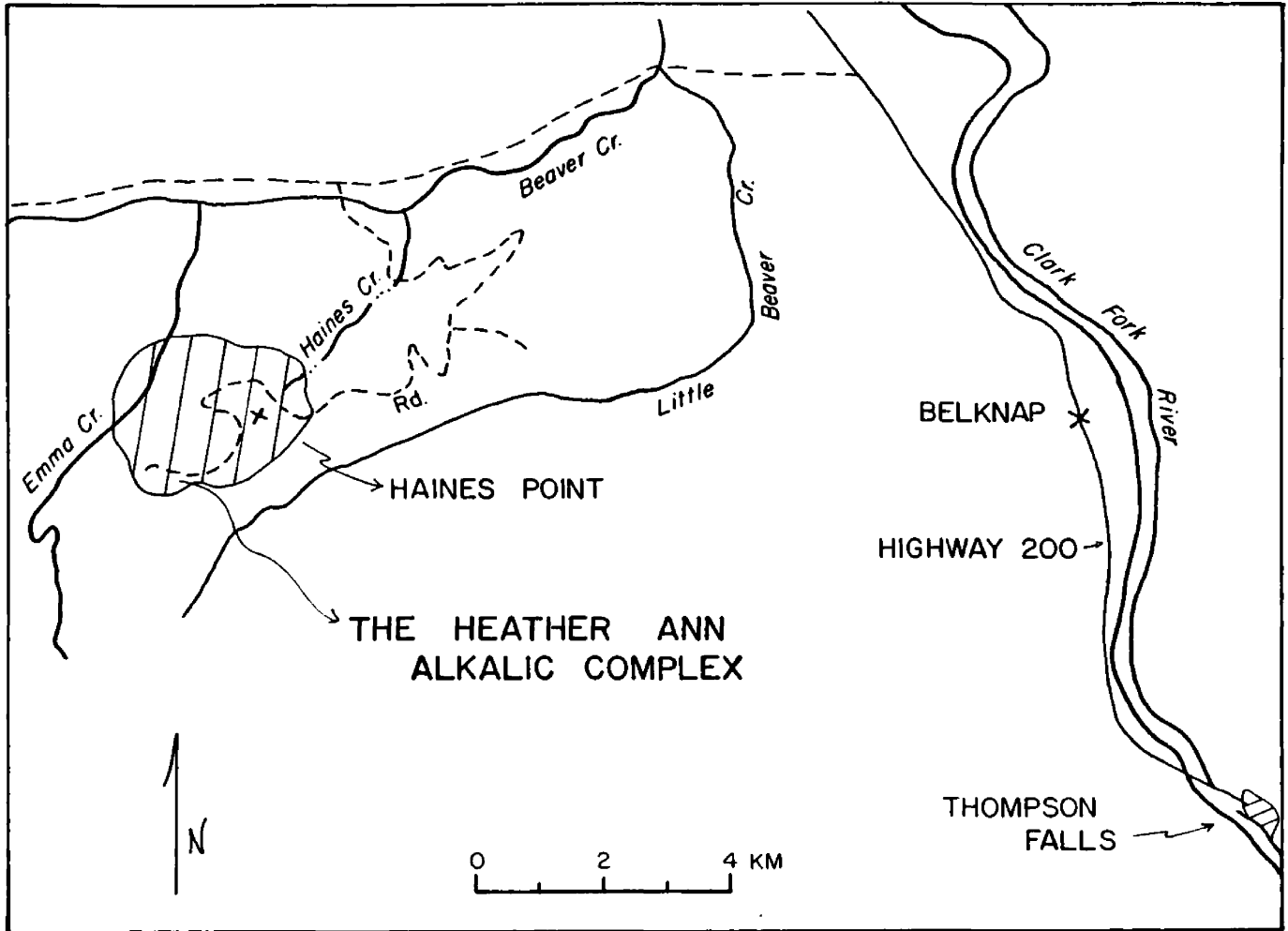


Figure 1. Index map of western Montana showing location of Heather Ann alkalic complex.

this belt. The Rainy Creek igneous complex, near Libby Montana, consists of pyroxenite, nepheline syenite, and syenite (Boettcher, 1966). The Heather Ann complex is 100 km south of the Rainy Creek complex. To the south, the Snowbird carbonatite occurs near Lolo Pass, Idaho (Claybaugh and Sewell, 1964). The Skalkaho alkalic complex near Hamilton, Montana is another pyroxenite-syenite body similar to the Rainy Creek complex (Lelek, 1979). Finally, the Ravalli-Lemhi carbonatite district extends from Deep Creek in Ravalli County, Montana south into Lemhi County, Idaho near the town of North Fork. The district is 29 km long and 7 km wide and contains over thirty-four carbonatite occurrences ranging in thickness from several centimeters to three meters (Heinrich, 1966).

The Twenty-Odd stock, near Trout Creek, Montana and twenty-four kilometers north of the Heather Ann complex, is included as a possible member of this alkalic belt. It has not been well mapped but consists in part of an alkali monzonite with soda-amphibole (Mejstrick, pers. comm., 1980).

The age of this alkalic belt is not well understood. S.S. Goldrich (Boettcher, 1966) dated the Rainy Creek complex at 94 million years using the Sr-Rb method on unaltered biotite from the biotite core. Jaffe and others (1959) received a Pb-alpha age determination of 95 million years on monazites from the Ravalli-Lemhi district. The age of the Heather Ann complex is unknown, but from these scattered dates, it seems plausible that the age of the Montana-Idaho alkalic belt, and perhaps the Heather Ann complex, could be upper Cretaceous.

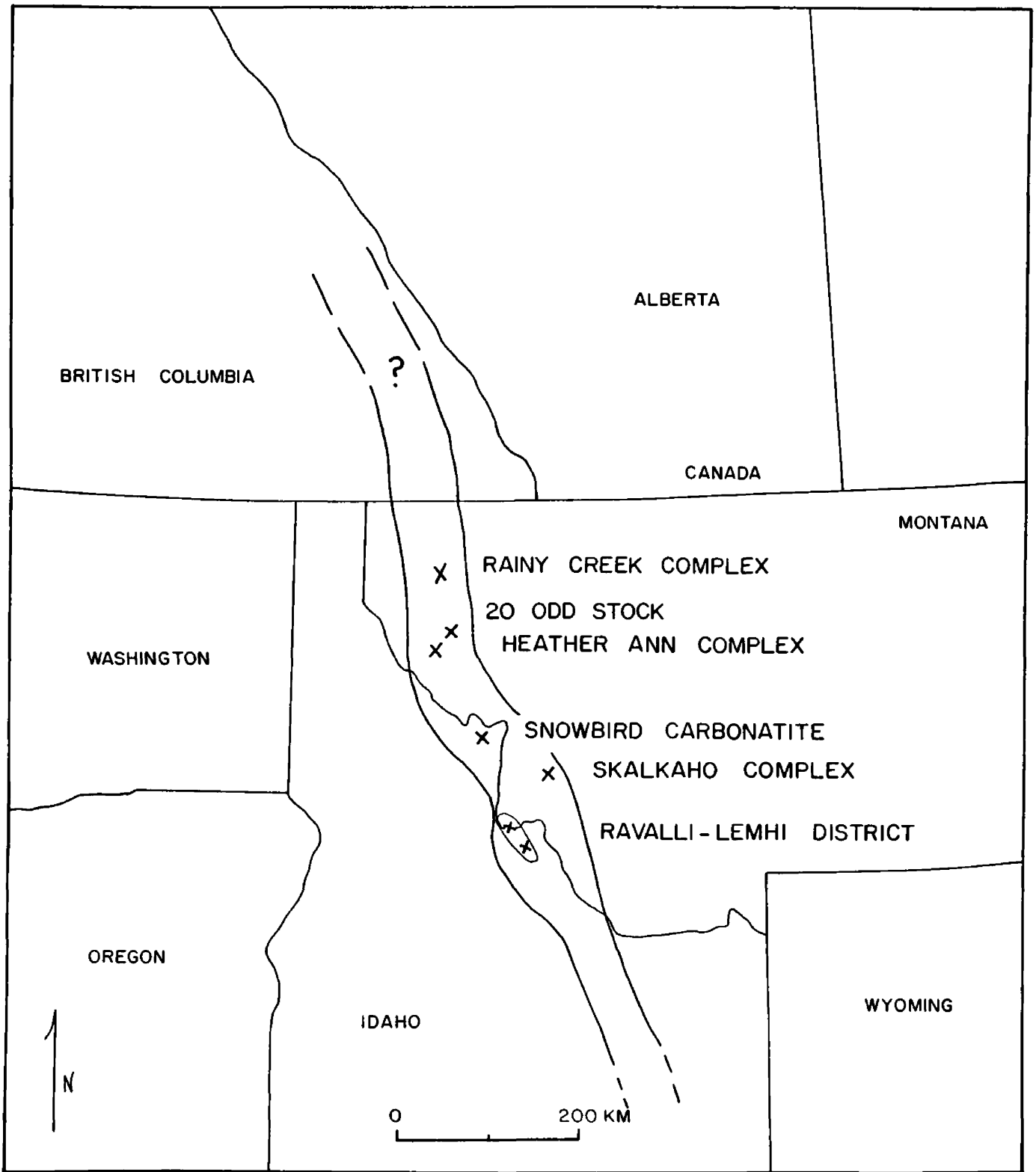


Figure 2. Western Montana-Idaho alkalic belt.

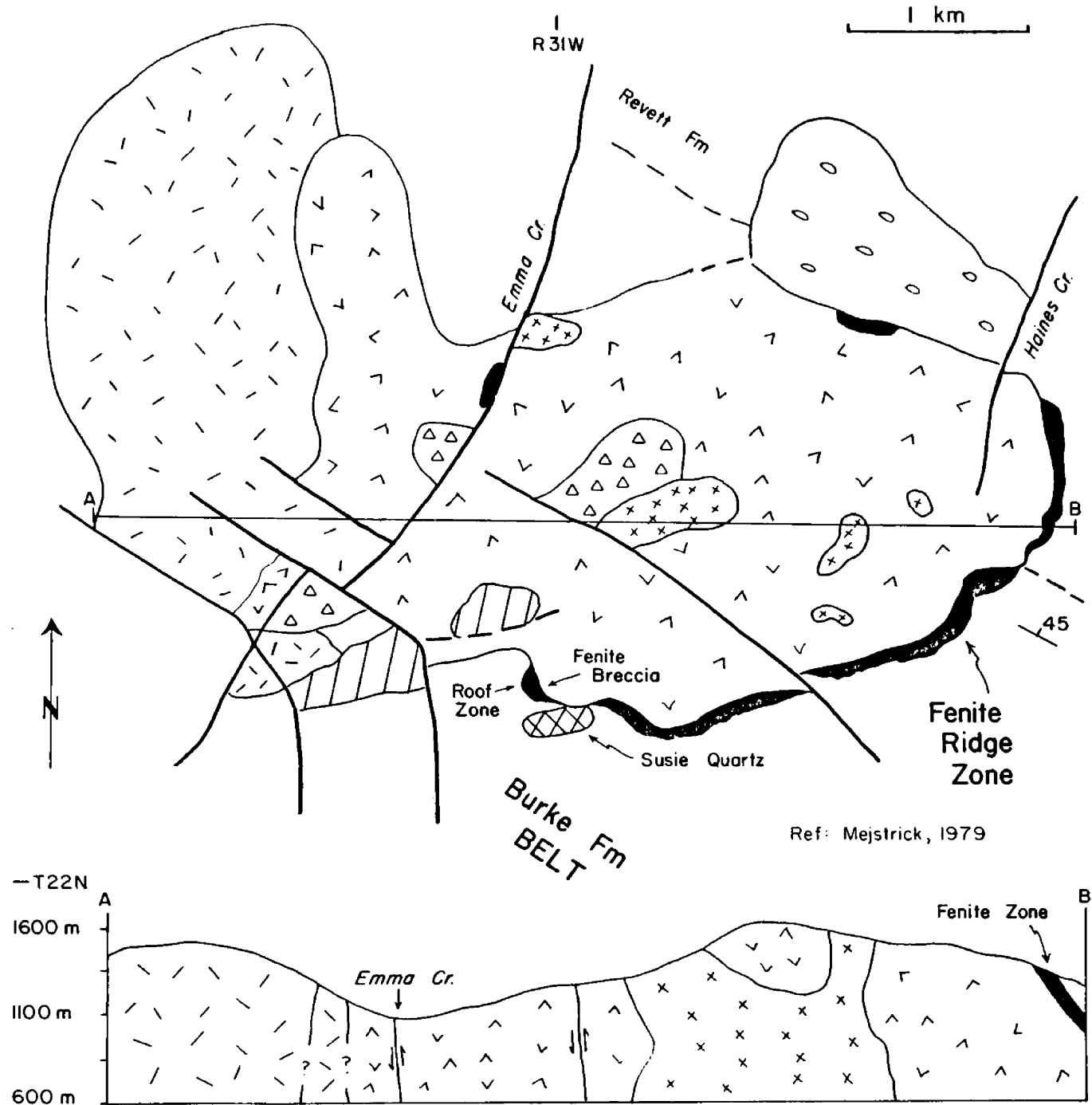
## CHAPTER II

### GENERAL GEOLOGY

The Heather Ann complex is a composite of five igneous intrusions. In order of earliest to latest, these are: alkali-feldspar syenite, nepheline syenite, nordmarkite, quartz syenite, and quartz monzonite. These rocks have intruded the Revett and Burke formations of the Precambrian Belt Supergroup of western Montana. The Heather Ann complex forms a roughly circular body approximately ten square kilometers in area. The five separate intrusions have rounded outlines in plan view with outward dipping contacts. The presence of miarolitic cavities in the quartz syenite indicates a shallow emplacement for the complex as a whole.

The classification of alkalic rocks is cumbersome, but as reviewed by Sorenson (1974), the rocks of the Heather Ann complex are classified as alkalic because they contain alkali pyroxene, alkali amphibole, and feldspathoid. These rocks are further classified as miaskitic based on the chemical data of  $K + Na < Al$  and  $K + Na > 1/6 Si$ . The nepheline syenite may be agpaitic in areas. This classification agrees with the observation of Heinrich (1966) that fenitization is most prevalent around miaskitic alkalic complexes.

The order of emplacement observed in the Heather Ann complex begins with a saturated syenite and undersaturated nepheline syenite followed by the intrusion of quartz-oversaturated phases. This trend



**GENERAL GEOLOGIC MAP: HEATHER ANN ALKALIC COMPLEX**

**EXPLANATION**

- |  |                         |  |                   |
|--|-------------------------|--|-------------------|
|  | Alkali Feldspar Syenite |  | Quartz Monzonite  |
|  | Nepheline Syenite       |  | Fenite            |
|  | Nordmarkite             |  | Susie Quartz      |
|  | Quartz Syenite          |  | Muscovite Syenite |

Figure 3.

from undersaturated to oversaturated magma types is common. Several other alkalic complexes showing this same trend are: the Oslo province (larvikite, pulaskite, nordmarkite, ekerite); Red Hill, N.H. (syenite, nepheline syenite, syenite, granite); the Borralan complex in Scotland (nepheline syenite, syenite, quartz syenite); and the Ilimaussuaq complex in south Greenland (lujaurite, foyaite, pulaskite, arfvedsonite granite) (Kempe and Deer, 1976).

To date, neither mafic alkaline rocks nor carbonatites have been discovered in the Heather Ann complex. Still alkaline pyroxenites could exist at depth below the present level of erosion. If such mafic rocks exist at depth, the Heather Ann complex may represent the upper syenite section of a syenite-pyroxenite complex similar to the Rainy Creek complex to the north and the Skalkaho complex to the south.

### Regional Structure

Harrison, Griggs, and Wells (1974) recently mapped the geology of the Thompson Falls area on the Wallace Quadrangle. On this map, the Heather Ann complex intrudes the east arm of an anticline trending N30E. The complex lies seven kilometers northwest of the north-south-trending Moyie thrust which ends to the south in the right-lateral Ninemile fault. High angle faults off the Moyie thrust have overturned Belt rocks in the vicinity of the complex. Harrison and others (1980) have interpreted this faulting with juxtaposed strata as listric normal faults.

The emplacement of the Heather Ann complex and the Twenty-Odd stock to the north are probably related to the Moyie thrust. There is little evidence of forcible shouldering aside of the Belt rocks peripheral to the Heather Ann complex. Moreover, there is only a minor zone of stoping near the roof zone of the alkali-feldspar syenite. Both diapirism and stoping fail to explain the mode of emplacement of the Heather Ann complex. In this area, numerous Jurassic and Tertiary intrusives have been emplaced along thrust faults (Harrison and others, 1980). The Twenty-Odd stock near Trout Creek, Montana has been emplaced along the Moyie Thrust. Similarly, the Moyie thrust may have been the main conduit for the Heather Ann complex.

### Major Rock Types

#### Alkali-Feldspar Syenite

This rock type is in the core of the complex, and seems to be the largest and earliest intrusion. It is a gray, homogeneous, and medium-grained rock which consists of 80-95% potassium-feldspar perthite, 3-10% plagioclase ( $An_{10-20}$ ), 7-10% aegirine and aegirine augite, tr-2% biotite, 1-3% magnetite, and trace amounts of sphene, zircon, and apatite. The potassium feldspar is slightly altered to sericite. The fenitized country rocks on the southeast rim of the complex are everywhere in contact with the alkali feldspar syenite suggesting a close genetic link between the two.

### Nepheline Syenite

The nepheline syenite intrudes the alkali feldspar syenite and is exposed in the core of the complex near Haines Point. It consists of 60-75% perthite, 15-30% nepheline locally altered to zeolite with minor cancrinite, 2-5% plagioclase ( $An_{10-20}$ ), tr-5% aegirine, 1-2% biotite, 1-2% magnetite, and trace amounts of sphene and apatite. The texture of the nepheline syenite ranges from fine- to medium-grained with pegmatitic patches. Deuteric metasomatism in the crystallizing magma has formed the pegmatitic zones in which the potassium feldspar crystals are 2-8 cm long, bladed aegirine crystals are 2-6 cm long, and nepheline is 1-2 cm long.

Chemically, the Heather Ann nepheline syenite has a  $K_2O:Na_2O$  ratio as high as 2:1. This ratio is reversed in most other nepheline syenites. This nepheline syenite is similar chemically to the alkali feldspar syenite. The major difference is that nepheline normally crystallizes in the sodium-enriched and silica-depleted magma.

### Nordmarkite

The nordmarkite intrudes the northern part of the complex. It is a gray-green and medium-grained rock, which consists of 80-85% potassium feldspar, 2-5% plagioclase, 3-10% quartz, 3-10% aegirine and aegirine-augite, and trace amounts of magnetite, iron oxides, sphene, and zircon. The nordmarkite has a subhedral igneous texture with distinctive rounded eyes of quartz  $\frac{1}{2}$  cm in diameter. The nordmarkite marks the first presence of quartz-oversaturated rocks in the complex. The pyroxene is typically altered to iron oxide.



TABLE 1. Chemical compositions of the alkali-feldspar syenites and nepheline syenites of the Heather Ann complex.\*

	<u>Alkali-Feldspar Syenite</u>	<u>Nepheline Syenite</u>
SiO <sub>2</sub>	57.40-61.70	55.50-56.80
TiO <sub>2</sub>	0.05- 0.09	0.05- 0.10
Al <sub>2</sub> O <sub>3</sub>	16.00-18.80	21.50-23.00
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	3.05- 8.58	2.06- 4.51
MnO	0.13- 0.24	0.03- 0.04
MgO	0.25- 1.28	0.18- 0.28
CaO	0.46- 2.30	0.40- 1.00
Na <sub>2</sub> O	2.48- 3.98	4.75- 6.37
K <sub>2</sub> O	9.00-10.90	10.30-10.80
	range of 6 samples	range of 3 samples

\*Source: Burwest Corportation

### Quartz Syenite

The quartz syenite is exposed in two small stocks on the southwest edge of the complex. It is a light-colored and medium-grained rock which consists of 60-65% potassium feldspar, 15-25% plagioclase, 10-15% aegirine and aegirine-augite, 2-5% quartz, and trace amounts of biotite, sphene, apatite, and magnetite. There are also numerous miarolitic cavities in this rock, suggesting a shallow emplacement.

### Quartz Monzonite

The intrusion of quartz monzonite is on the western edge of the complex. It is a pinkish-gray and medium-grained rock which consists of 45-60% potassium feldspar, 20-40% plagioclase, 2-10% quartz, tr-5% augite, tr-5% arfvedsonite, tr-3% aegirine and aegirine augite, tr-1% biotite, and trace amounts of magnetite, sphene, and apatite. The composition of this rock type is variable and quartz content is particularly irregular. The rock is fresh and unaltered. A contact metamorphic aureole of phyllitic biotite hornfels surrounds the quartz monzonite intrusion. The hornfels unit extends 300-700 meters outwards in plan view from the quartz monzonite contact.

### Susie Quartz

The Susie quartz body is located near the roof-zone of the complex. It is in contact with unfenitized Belt rocks to the south and fenites to the north and west and consists of white-bull quartz. It has been drilled and evaluated as a possible source of silica. Drill data delineates the size of the body to be approximately eighty million tons (Dick Moses, pers. comm.). This quartz body and the many quartz veins, 6-80 cm wide, associated with it cross cut both the alkali feldspar syenite and fenites. Fenites are locally isolated in the quartz veins near the contact indicating that silica veining post-dated fenitization. The quartz phase seems to be related to a late-stage silicification event in which hydrothermal waters leached silica from the Belt quartzites.

TABLE 2. Chemical Compositions of nordmarkites and quartz monzonites of the Heather Ann complex.

	<u>Nordmarkites</u>	<u>Quartz Monzonites</u>
SiO <sub>2</sub>	63.60-64.70	66.20-67.90
TiO <sub>2</sub>	less than 0.05	0.05- 0.01
Al <sub>2</sub> O <sub>3</sub>	17.70-19.20	17.30-19.60
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	1.31- 0.34	1.43- 2.17
MnO	0.01- 0.09	0.04- 0.05
MgO	0.13- 0.34	0.22- 0.34
CaO	0.08- 0.32	0.54- 1.10
Na <sub>2</sub> O	1.62- 2.05	5.40- 6.21
K <sub>2</sub> O	12.30-13.80	5.51- 8.18
	range of 3 samples	range of 3 samples

\*Source: Burwest Corporation

## CHAPTER III

### SEQUENCE OF FENITIZATION

The sequence of fenitization in the Heather Ann complex proceeds from an outer zone of mild metasomatism and veining inwards to a zone of complete chemical and mineralogical change. Fenitization metasomatizes the quartzite into a rock similar to a syenite in chemical composition. This process gradually, disrupts and alters all relict sedimentary structures. The fenite zone is exposed for approximately 80-100 meters outwards from alkali-feldspar syenite contact. However, the fenite zone is only 15-30 meters thick and encloses the intrusive syenite like a dome. Brecciation and shattering of the host quartzites occur in the roof zone of the complex where they are accompanied by active fenitization.

The generalized sequence of fenite zones which surround the alkali-feldspar syenite from outside -----> inwards is:

1. Quartzite country rocks of the Burke Formation
2. Localized spotted fenites with a network of fenite veins
3. Banded fenite
4. Syenite-fenite
5. Alkali-feldspar syenite with minor auto-metasomatism

Figure 4 displays this sequence of fenite zones. Later-stage feldspathic-fenite-veins cross-cut the earlier fenite zones in some areas.

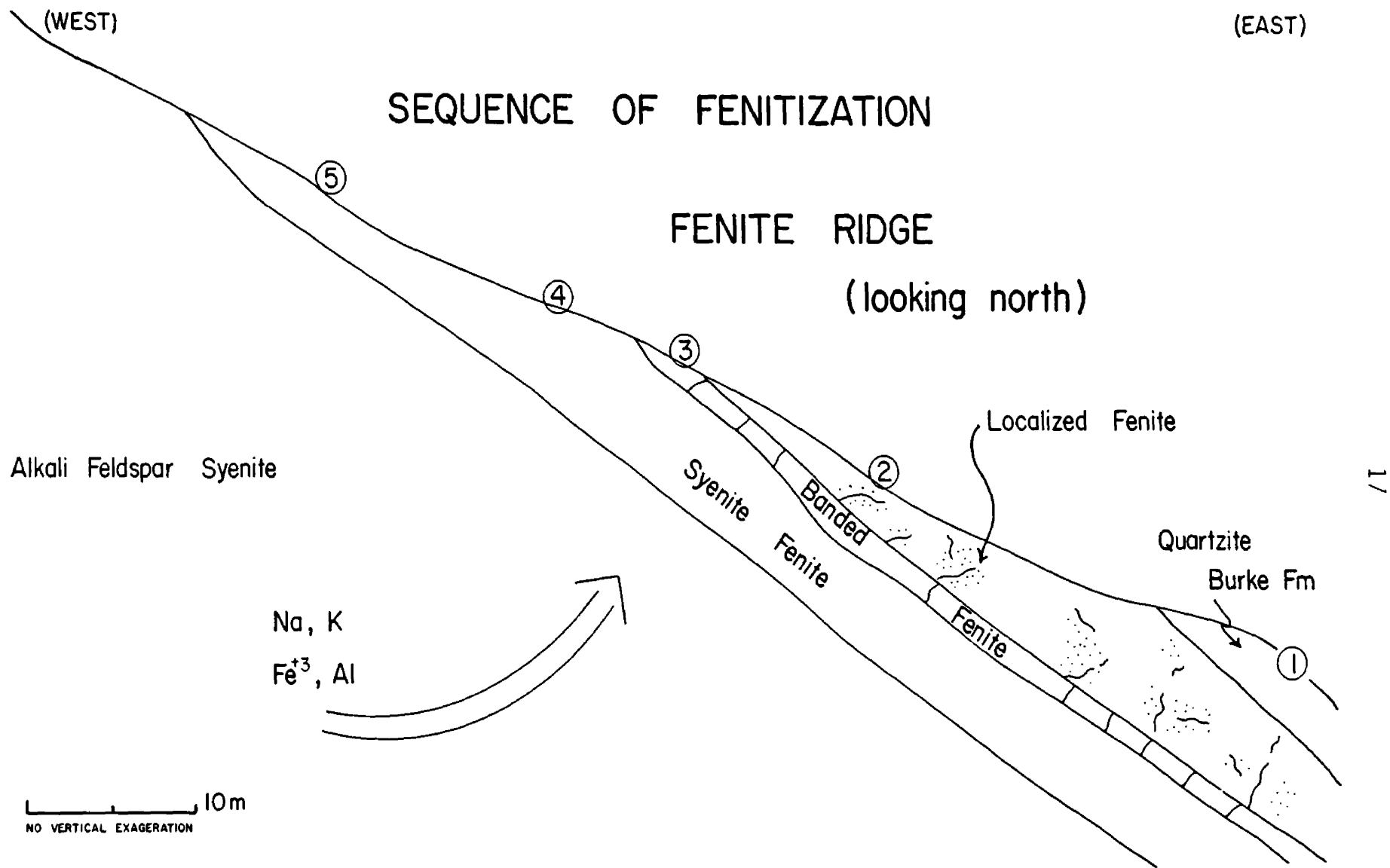


Figure 4. Sequences of fenitization with locations of whole rock chemical analyses circled.

### Invaded Host Rocks

In the Heather Ann complex, the upper Burke Formation of the Proterozoic (Precambrian Y) Belt Supergroup has been fenitized. This formation consists of gray quartzites with argillaceous quartzite laminae 5-20 cm thick. These quartzites have been burial metamorphosed to the biotite zone of the greenschist facies, and in some areas the laminae show minor deformation. In thin-section, the quartzites are cross-laminated and have regular graded-bedding.

The Burke quartzite consists of 65-75% quartz, 15-25% detrital potassium feldspar which is optically orthoclase, 2-5% plagioclase feldspar which is commonly oligoclase to andesine, tr-3% biotite, and traces of iron oxide, muscovite, and apatite. The quartzite is moderately well-sorted and the grains are sub-angular to sub-rounded, ranging in size from 0.1-0.5 mm. Quartzite has a mortar texture of quartz and potassium feldspar of equal grain size within a matrix of finer-grained and granulated quartz. The argillaceous quartzites consist of greater proportions of biotite (10-15%) and muscovite (2-5%) and are equigranular with a grain size of less than 0.06 mm.

The original host rock composition can have a considerable effect on the fenite mineral assemblage. Specifically, mafic host rocks react to fenitization differently than more siliceous rocks. Dawson (1961) stressed that the most important compositional parameter in determining the mineral modes in fenites is the amount of excess free silica in the host rock. Abundant quartz allows the fenitizing alkali and iron ions to react with silica and nucleate new alkali

silicates. The Heather Ann quartzites have abundant free quartz, and new alkali minerals are easily nucleated.

In general, existing minerals in mafic host rocks are replaced by alkaline varieties and few new phases are nucleated (Robins and Tysseland, 1979). Fenites formed from mafic host rocks may lack aegirine or soda-amphibole. Biotite remains stable throughout the fenitization of the amphibolites in the Firesand River complex of Ontario (Heinrich, 1966).

The most important compositional parameter in the host rocks of the Heather Ann complex is the presence of biotite-rich laminae. The growth of soda-amphibole is due to the sodium metasomatism of the relict biotite, and it is restricted to the biotite-rich areas of the host quartzites.

#### Localized Fenite Zone

Spotted quartz-fenites are associated locally with unmetasomatized Burke rocks in the outer metasomatic zone. The localized fenites are concentrated around green-mottled and comb-structure veins, which are usually 1-6 cm thick. The fenitizing veins follow bedding planes and fractures formed in a mild shatter zone around the intrusive syenite. The localized fenite zone is equivalent to the shatter zone of Heinrich (1966) and Woolley's outer quartz fenite zone (1969).

The fenite veins are more intensely fenitized than the surrounding quartz fenites and represent the infiltrating channelways of the fenitizing solutions from the source syenite. These solutions diffuse outwards from the infiltration veins for approximately 1 meter and

form the spotted localized fenites. Fenitization in this zone exhibits both infiltration and diffusion-type metasomatism (Korzhinskii, 1970).

The spotted quartz fenites consist of 30-40% potassium feldspar which is optically orthoclase, 25-40% plagioclase which is predominantly albite to oligoclase, 15-35% relict quartz, 1-8% aegirine, tr-3% soda-amphibole, and trace amounts of zircon, magnetite, rutile, sphene, biotite, and muscovite. The major changes mineralogically in the Burke quartzites due to fenitization are:

1. Alteration of quartz to untwinned albite
2. Growth of potassium feldspar
3. Sodium metasomatism of relict twinned plagioclase
4. Introduction of aegirine and soda-amphibole

The spotted texture of the quartz-fenites is characteristic of the localized fenite zone. It is due to rounded and randomly distributed clusters of minute aegirine crystals. These clusters range in size from 0.5-2 mm. The aegirine crystals commonly form small corona-structures around subhedral magnetite crystals. The potassium feldspar in the quartz-fenites forms turbid and ameboid crystals approximately 0.25-0.5 mm in size. The diffusion of the fenitizing solutions interstitially around the quartz grain boundaries causes the growth of these metasomatic minerals. Soda-amphibole and aegirine are intergrown sporadically in the quartzites with relict biotite laminae. The biotite appears metasomatized and has a peculiar olive-green pleochroism. With increasing fenitization, the biotite alters to soda-amphibole.



### Fenite Veins

A network of mottled-green fenite veins and veinlets occurs within the localized fenite zone. They consist of 40-60% microcline perthite and turbid potassium feldspar perthite, 20-30% untwinned and twinned albite, 5-15% aegirine, and trace amounts of sphene and acicular apatite. There is no relict quartz in the fenite veins. Some albite crystals display an intricate sodium zoning with inclusions of minute aegirine crystals aligned inside the feldspar grains. The fenite veins have a grain size of 1-2 mm and are coarser than the surrounding quartz-fenites. The fenite vein contact with the quartz-fenites can be very sharp, and the intensity of fenitization decreases markedly away from the solution channelways. The presence of perthite feldspar in the fenite veins suggests a higher temperature of formation than the surrounding quartz-fenites with two discrete feldspar phases. The higher temperature and increased metasomatism indicate that these veins were the infiltration channelways of the fenitizing solutions from the source syenite.

Comb-structure veins are also common in the localized fenite zone. LeBas (1977) describes comb-structure veins as veins in which aegirine and feldspar display a prismatic to acicular habit with their long axes perpendicular to the walls of the veins. LeBas notes that comb-structure veins are common throughout the East African province and represent the pathways of late-stage fenitizing solutions. In the Heather Ann complex, the comb-structure veins have little diffusion outwards from their contacts.

### Banded Fenite Zone

The banded-fenite zone is located inwards from the localized fenite. This zone is distinguished by a faint banded structure of the aegirine and amphibole. This zone is relatively narrow (1-3 m thick) and forms an outer transition zone around the inner syenite-fenite. The banding of the mafic minerals is due to the accentuation of the original sedimentary layering by the growth of the metasomatic minerals. This relict bedding and banding cannot be traced for more than 2 m. The most notable banding is due to the growth of soda-amphibole in the relict biotite-rich laminae. The banding and elongation of the aegirine crystals parallel to their C-crystallographic axes may be due to the growth of these crystals parallel to outward flow of the fenitizing solutions along original sedimentary bedding.

The banded fenites consist of 25-40% sodic plagioclase, 15-25% microcline and orthoclase, 15-25% aegirine, 5-10% soda-amphibole (Mg-arfvedsonite), and trace amounts of magnetite, zircon, rutile, biotite, muscovite, and apatite. Mineralogically, the banded-fenite zone is distinguished from the localized fenite zone by the disappearance of relict quartz and, for the most part, biotite. The aegirine and soda-amphibole occur as well-developed crystals, 1-2 mm in length, instead of small clusters of stubby prisms.

The banded-fenite zone is recognized by its diagnostic porphyroblastic texture. The aegirine, soda-amphibole, and sodic-plagioclase all occur as large porphyroblasts in a finer-grained crystalloblastic

matrix of feldspar, relict biotite and muscovite. The soda-amphibole is also poikiloblastic around biotite and feldspar. The plagioclase porphyroblasts generally occur in a decussate pattern of interlocking laths. Most of these textural characteristics strongly resemble thermal metamorphic rocks near igneous contacts, but in the fenites, there has been a rapid growth of metasomatic minerals from the influx of fenitizing solutions.

### Syenite-Fenite Zone

The syenite-fenite zone is the innermost zone in contact with the alkali-feldspar syenite, and consequently, the most intensely fenitized zone in the Heather Ann complex. Its greenish-white swirled appearance distinguishes this zone from the banded fenite and the gray intrusive alkali-feldspar syenite. Mineralogically, this zone is distinguished by the appearance of perthite and the disappearance of soda-amphibole. The inner syenite-fenite zone varies from 10-15 meters thick. The inner contact between the syenite-fenite and the intrusive syenite is gradational. Along this contact, apophyses of syenite and juxtaposed fragments of relict quartzite are included in the syenite-fenite. For the most part, any gross brecciated structure has been obscured by intensive fenitization; however, well-developed brecciation structures are preserved in the roof-zone of the complex.

The syenite-fenite consists of 30-70% perthite, 10-40% albite, 10-20% aegirine, and trace amounts of magnetite, sphene, rutile, zircon, and biotite. The aegirine occurs as bladed crystals and

radial aggregates 1-6 mm long. The albite forms random and decussate laths 1-2 mm long. The perthite occurs as both exsolution perthite and replacement perthite. The exsolution perthite consists of well-developed crystals which have exsolved 10-20% patch albite. The replacement perthites are more common and result from the continued metasomatism of the early-formed feldspar. Individual grain boundaries are ragged and are cut by braid and ribbon sodic plagioclase.

The syenite-fenite has a granoblastic texture, but relict-grained crystalloblastic patches are common. The aegirine crystals in the syenite-fenite commonly occur as radial aggregates in which individual crystals have grown from a common center. Radial crystallization is a distinctive metasomatic texture and indicates rapid crystallization of the aegirine around a limited number of available nuclei.

Rheomorphic fenites are present in the inner syenite-fenite zones of several alkalic intrusives. Brögger (Heinrich, 1966) recognized that the temperature in the fenite aureole at the Fen complex could be high enough (700°C) to partially melt and mobilize the country rocks during fenitization. A partially melted fenite is called a "rheomorphic" fenite or an "ultra-fenite". However, the syenite-fenite in the Heather Ann complex was not mobilized to any extent, because the temperature during fenitization was not high enough to partially melt the Burke quartzites.

### Alkali-Feldspar Syenite

The intrusive alkali-feldspar syenite is a gray and medium-grained rock. Its homogeneous texture distinguishes this syenite from the metasomatic syenite-fenite zone. In thin-section, the alkali-feldspar syenite consists of large microcline-perthite crystals surrounded by interstitial aegirine and plagioclase. This texture contrasts with the syenite-fenite which has a more-random distribution perthite, plagioclase, and aegirine.

The alkali-feldspar syenite is commonly albitized by auto-metasomatism near the syenite-fenite contact. This alteration appears as white rims of albite surrounding the larger perthite grains. This alteration occurs from late-stage fenitizing solutions moving through the crystallized syenite. In thin-section, the albite metasomatism occurs as albite-twinned plagioclase reaction rims surrounding the perthite and aegirine. This zone of albitization extends 10-20 meters into the alkali-feldspar syenite and provides good field evidence that the alkali-feldspar syenite was the source of the fenitizing solutions. Fenitization is a continuing process which extends from the initial stages of syenite intrusion and fracturing throughout the crystallization of the syenite.

### Feldspathization

The process of fenitization is complicated in many areas because investigators have tried to explain separate events by one process. The prevailing evidence from many alkalic provinces suggest that there

are at least three separate processes which are attributed to fenitization (LeBas, 1977):

1. Normal Na-K metasomatism (the main metasomatism in the Heather Ann complex)
2. Later potassic or feldspathic metasomatism
3. Hydrothermal silicification (probably unrelated to fenitization)

These separate processes are usually difficult to recognize, especially in provinces where successive intrusions have superimposed several "fenitization" episodes upon one another.

In Chilwa Island, Alnö, Rufunsa, and Amba Dongar, distinctive potassic metasomatic rocks have been recognized in association with carbonatite intrusions (Heinrich, 1966; Von Eckermann, 1948; Woolley, 1969). These monomineralic potash-feldspar rocks are bright red due to extensive hematite staining. Chemically, there is a sharp increase in the oxidation ratio and an increase in the  $K_2O:Na_2O$  ratio during this metasomatism. Mineralogically, feldspathization involves (Woolley, 1969):

1. A breakdown of sodic pyroxene and soda-amphibole to iron oxides and hematite.
2. Alteration of alkali feldspar to turbid and hematite-stained potassium feldspar

These feldspathic fenites are commonly radioactive, due to thorium, and contain concentrations of cerium rare-earth elements (Heinrich and Moore, 1970). These metasomatic rocks have a wide variety of names in the literature: red dikes, potash fenites, feldspathic fenites, and trachytes (Sutherland, 1965).

Feldspathic fenites occur as rings of feldspathic breccia, veins, dikes, or pipes (Heinrich and Moore, 1970). The field relations in various complexes indicate that feldspathization occurs after sodium-potassium fenitization and is characteristically related to carbonatite intrusion. In Chilwa Island in Africa, the central carbonatite core is surrounded by feldspathic fenite breccia, which is, in turn, ringed by sodium fenites. This zonation indicates that the early sodium-fenitization is followed by a "slower" or less-penetrating potash metasomatism (Sukheswala, Sethna, and Viladkar, 1972).

Feldspathization in the Heather Ann complex occurs as minor feldspathic fenite veins and patches which cross-cut the main fenite zones. These feldspathic fenites are red, due to hematite, and are usually 10-40 cm wide. They are radioactive and in part provide the fenite zone's above-background radioactivity. In thin-section, the potash fenite consists of turbid potash feldspar and iron-oxide. Iron-oxide occurs as both turbid patches and as replacement of the prismatic aegirine. Feldspathic alteration in the Heather Ann complex follows the same mineralogical trends as the feldspathization at other complexes.

The muscovite syenite unit in the Heather Ann complex is exposed on the west end of Emma Creek and in the central core of the complex (Fig. 3). This syenite consists of 70-80% perthitic potassium feldspar, 10-15% albite, 10-15% muscovite, and minor amounts of magnetite, hematite, zircon, allanite, rutile, zeolite, and uranoan thorite (Mejstrick, pers. comm.). This syenite is distinctive because of its

lack of pyroxene, amphibole, or biotite. The alkali feldspar is also clouded with hematite and is orange-red. All of these characteristics indicate that the muscovite syenite may be a product of feldspathization and potassic metasomatism. Similar muscovite syenite rocks have been noted in the Rainy Creek complex (Boettcher, 1966) and in the Rocky Boy stock in the Bearpaw Mountains (Pecora, 1962).



CHAPTER IV  
MINERALOGY OF FENITIZATION

The mineralogical changes exhibited with increasing fenitization of the Burke quartzites are schematically shown in Figure 5. Metasomatism involves the replacement of minerals with an accompanying change in the chemical composition of the rocks. Mineral replacement is primarily accomplished through the chemical action of pore solutions dissolving some minerals and immediately depositing others (Orville, 1962). The rock maintains its solid state during this mineral replacement. The mineral changes occurring in the Heather Ann quartzites are relatively simple; relict quartz is dissolved and aegirine, and sodic and potassic feldspars are recrystallized. Biotite also disappears and is replaced by soda-amphibole. The fenitizing solutions eventually reach equilibrium with the country rocks and mineral replacement ceases.

Aegirine

Aegirine ( $\text{NaFe}^{+3}\text{Si}_2\text{O}_6$ ) is a major constituent of the Heather Ann fenites; it is present throughout all three fenite zones. In the localized fenite zone, aegirine occurs as small stubby crystals in clusters. In the higher grade fenite zones, aegirine occurs as subhedral and euhedral prisms. The prisms are distributed as separate crystals and as radial masses.

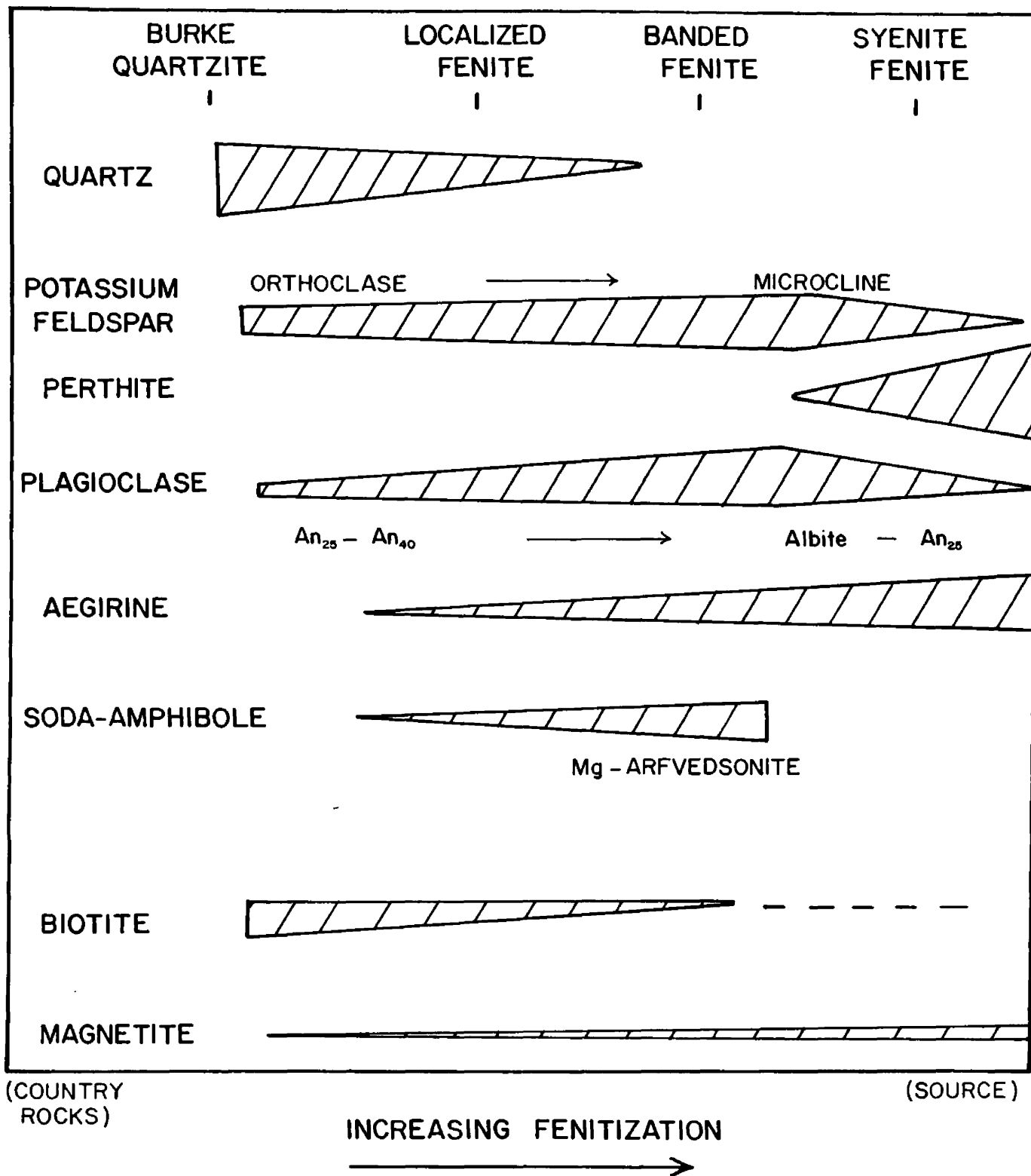


Figure 5. Mineralogical changes occurring in Burke quartzite with increasing fenitization.

The aegirine is characterized by its green pleochroism (x = green, y = yellowish-green, z = yellowish-brown). Some of the crystals are color-zoned with the lighter colors near the outer edge of the crystal. The prisms range in size from 0.5 to 8 mm. The aegirine has  $Z\Delta c$  of  $87-90^\circ$  and a  $2V$  of approximately  $70^\circ$ . It is biaxially negative and is length-fast. The length-fast character is useful in distinguishing the small aegirine crystals from the soda-amphibole.

Bailey (1969) has conducted the experimental studies of the aegirine system at 2-5 kb water pressure. His experiments show that aegirine's upper stability limit ranges from  $870-780^\circ\text{C}$  depending on the partial pressure of oxygen in the system. Aegirine melts incongruently to magnetite and liquid at  $780^\circ\text{C}$  with a quartz-fayalite-magnetite buffer. The presence of quartz and magnetite in the fenite zones indicates that the quartz-fayalite-magnetite buffer is a good approximation of the partial pressure of oxygen. Under more reducing conditions, aegirine will not form.

Aegirine crystallizes experimentally under oxidizing conditions and from a melt with excess sodium silicate, in which alkalis exceed alumina and iron oxide (Bailey, 1969). The formation of aegirine during fenitization indicates that the fenitizing solutions were alkaline and oxidized. The stability of aegirine in all three fenite zones indicates that the temperature of fenitization was below  $780^\circ\text{C}$ .

Aegirine decomposes to iron oxide during feldspathization. There is a marked increase in the K and Al content of the metasomatized rocks during this later metasomatism (Sukheswala, Sethna, and Viladkar,

1972). There is also a sharp increase in the oxidation ratio towards 100 (Woolley, 1969). Feldspathic fenites no longer contain excess sodium silicate, and aegirine becomes unstable, altering to iron oxide. Under these high oxidizing conditions, the iron oxide is usually hematite.

### Soda-Amphibole

Soda-amphibole, identified optically as Mg-arfvedsonite,  $\text{Na}_3(\text{Mg}, \text{Fe}^{+2})_4 \text{Al}(\text{Si}_8\text{O}_{22})(\text{OH})_2$ , occurs in the localized fenite zone and in the banded-fenite zone. It disappears in the syenite-fenite zone with increasing temperature. The soda-amphibole occurs as small clusters and acicular crystals which rim and replace biotite in the localized fenite zone. In the banded fenite zone, the soda-amphibole occurs as 1-2 mm euhedral and subhedral poikiloblastic crystals. The soda-amphibole is restricted to formation in the biotite-rich quartzites in all the occurrences studied. Aegirine is the only mafic mineral in the pure quartzites with no relict biotite.

The soda-amphibole is distinguished by its amphibole cleavage and pleochroism (x = blue-green, y = grey-blue, z = pale yellow-green). A  $Z\Delta c$  of  $60-70^\circ$  classifies this amphibole as Mg-arfvedsonite. The crystals are biaxially negative with a  $2V$  of approximately  $60^\circ$ . Some show strong dispersion with  $r < v$  and lack complete extinction. Zoning in the amphibole is variable. The texture of the grains is poikiloblastic, surrounding feldspar and biotite.

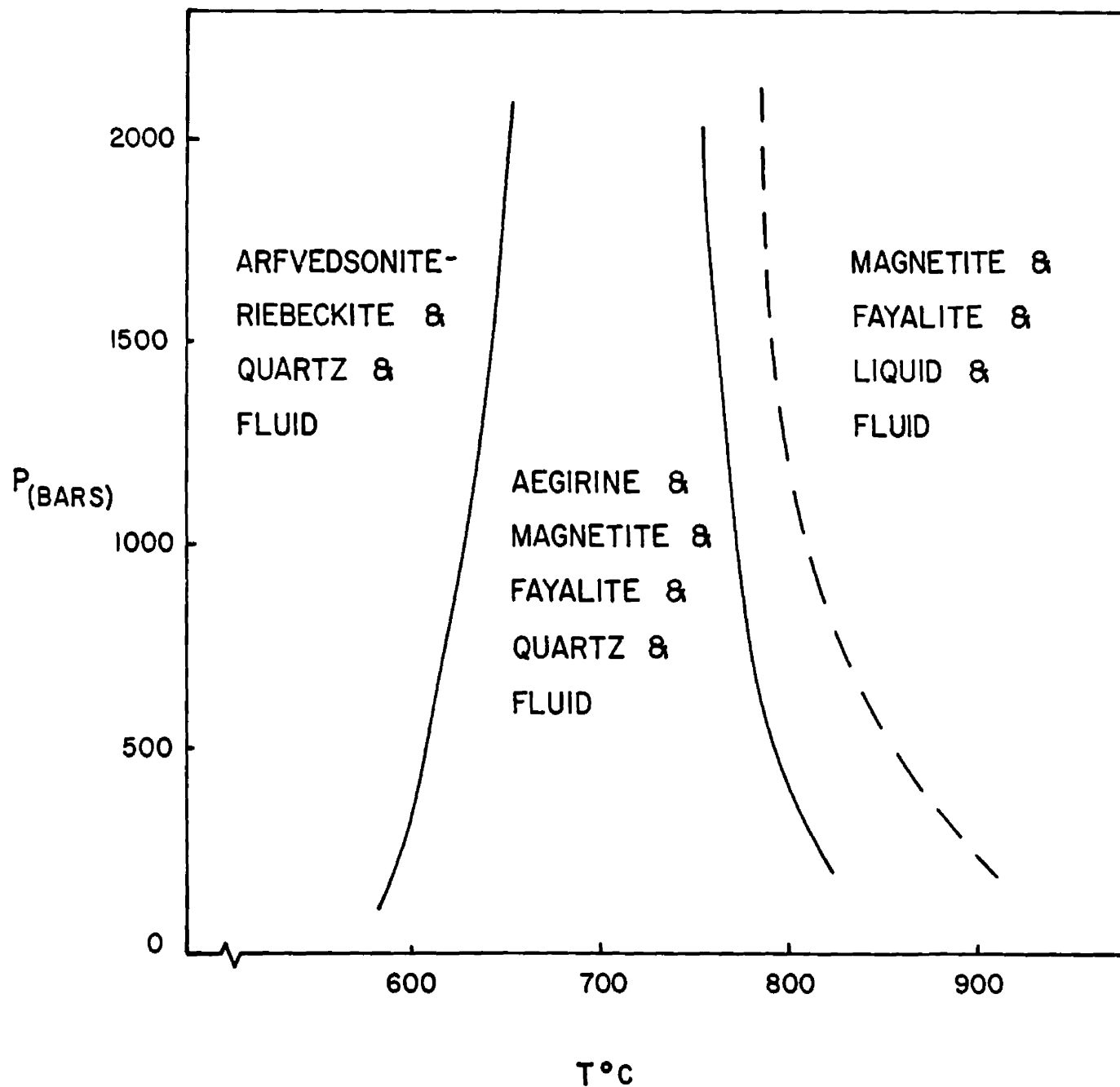


FIGURE 6. Phase relations of Riebeckite bulk composition ( $\text{Na}_2\text{O} + 5 \text{FeOx} + \text{SiO}_2$ ) with a magnetite, quartz, and fayalite buffer, from Ernst, 1968.

Ernst (1969) found experimentally that riebeckite-arfvedsonite is stable to 655°C under the quartz-fayalite-magnetite buffer. The amphibole decomposes to aegirine+magnetite+quartz+fluid above this temperature (Fig. 6).

Mg-arfvedsonite is the most common amphibole in the fenites of the East African province. Its crystallization is favored by high concentration of Mg, Fe<sup>+2</sup>, and OH<sup>-</sup> in the host-rock and slightly oxidizing conditions (Sutherland, 1969). In the Heather Ann fenites, Mg-arfvedsonite forms in the biotite-rich quartzites, which are rich in Mg, Fe<sup>+2</sup>, and OH<sup>-</sup>. A similar occurrence of Mg-arfvedsonite forming from the metasomatism of relict biotite is noted by McKie (1966) in the Oldonyo Dili fenites of East Africa. All of these situations indicate that the presence of soda-amphibole during fenitization is dependent on the original host-rock composition.

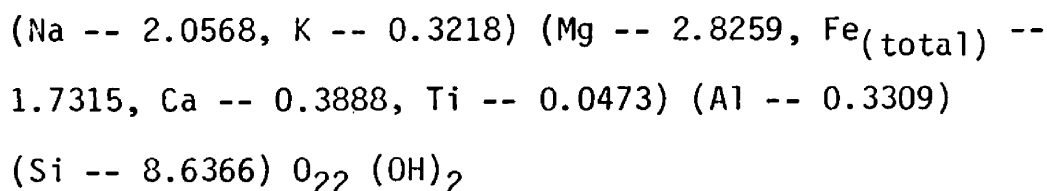
Soda-amphibole disappears in the high-grade syenite-fenite zone of the Heather Ann complex. The syenite-fenite zone is distinguished by exsolution perthite which indicates a temperature of formation of approximately 670°C, or above the two-feldspar solvus of Orville (1963). At this temperature, soda-amphibole is above its upper stability limit and decomposes to aegirine and iron oxide, which are both abundant in the syenite-fenite zone. Increased oxidizing conditions in the syenite fenite zone may also contribute to the soda-amphibole's instability.

Mg-arfvedsonite is a good zone mineral in the Heather Ann fenites because of its disappearance in the inner fenite zone. A

similar mineralogical zonation occurs in the Homa Mountain fenites of East Africa (Sutherland, 1969). Fenites exposed in the higher temperature zone near the contact with the intrusive ijolite consist of aegirine and orthoclase, but in the lower temperature outer zone, the fenites consist of aegirine, Mg-arfvedsonite and orthoclase.

### Electron Microprobe Analysis

The soda-amphibole was analyzed with an electron microprobe at the Idaho Bureau of Mines and Geology. This analysis (Table 3) confirmed the optical identification of this amphibole as Mg-arfvedsonite. ZAF effects were corrected by the Bence Albee method using a computer accessed by remote terminal to the probe. A structural formula for this amphibole based on 24 oxygens is:



This soda-amphibole is classified as Mg-arfvedsonite midway in composition between the eckermannite and arfvedsonite compositions of Deer, Howie, and Zussman (1966).

### Plagioclase

A trace to 3% detrital plagioclase occurs in the Burke Formation quartzites within the type section on Fenite Ridge. The plagioclase ranges in composition from oligoclase to andesine based on optical determination. With increasing fenitization, the modal percentage of

TABLE 3. Electron microprobe analysis of soda-amphibole

<u>Oxide</u>	<u>Concentration %</u>
SiO <sub>2</sub>	59.1
TiO <sub>2</sub>	0.4
Al <sub>2</sub> O <sub>3</sub>	1.9
FeO (total)	14.1
MgO	12.9
CaO	2.4
Na <sub>2</sub> O	7.2
K <sub>2</sub> O	<u>1.7</u>
	99.7

sodic plagioclase increases dramatically. Metasomatic plagioclase occurs in three characteristic habits:

1. As a direct replacement of relict quartz grains
2. As replacement of the detrital feldspar forming checker-board-twinned albite
3. As well-developed albite crystals occurring as porphyroblasts and locally in decussate aggregates.

Albite forming from quartz is clear, untwinned, and retains the anhedral outline of the original quartz grains. It is distinguished from quartz and orthoclase by its biaxial interference figure and its relief. This feldspar is assumed to be close to the albite end member in composition due to the abundant sodium metasomatism. Sodium metasomatism of the original feldspar has caused checker-board twinned albite. This type of albite is distinguished by its twinning on the



albite law resembling a checker-board. These twins consist of a complex pattern of stubby alternating twin lamellae which do not pass through the entire length of the crystal. Starkey (1959) has attributed such checker-board twinning to sodium metasomatism of potassium feldspar in which the exchange of the Na for K ions has disrupted the crystal lattice into separately twinned regions. In the Heather Ann fenites, the relict and introduced sodic plagioclase also display checker-board twinning suggesting that introduction of sodium into sodic plagioclase can also cause complex twinning patterns. The checker-board twinned feldspar ranges in composition from albite to oligoclase. These compositions were determined optically using the bisectrix method.

Albite plagioclase laths develop as porphyroblasts 1-2 mm long with increasing fenitization. These albite crystals are often Carlsbad twinned and nucleate in decussate aggregates in which contiguous crystals lie in a criss-cross pattern. This pattern minimizes internal stress and eases recrystallization of the larger feldspar crystals. Several spot microprobe analysis of these crystals indicate pure albite in which Ca content is below detection limits.

#### Potassium Feldspar

The Burke quartzites contain 15-25% detrital potassium feldspar which appears as subhedral and anhedral crystals devoid of twinning. Optically the feldspar appears to be orthoclase. This potassium feldspar increases in modal amounts and alters to well-developed tartan-twinned microcline crystals with increasing fenitization.

Spot microprobe analyses of the microcline indicate a very pure potassic feldspar with less than 0.55% Na<sub>2</sub>O. Pure microcline and pure albite represent an equilibrium pair in the presence of the fenitizing solutions. Exsolution perthite forms in the higher-temperature syenite-fenite zone because additional Na can be admitted into the microcline lattice.

Potassium feldspar occurs as ameboid crystals in the localized fenite zones. The crystals envelop and rim the relict quartz and grow from the metasomatism of the quartz. The potassium feldspar lacks twinning and appears turbid. Turbidity is one of the first signs of alteration in most fenite zones (Vartiainen and Woolley, 1976) The nature of turbidity in potassium feldspar is not well understood, but Laves (1950) has attributed it to the incipient conversion of the monoclinic orthoclase to triclinic microcline. This interpretation agrees with the transition of the potassium feldspar from orthoclase to microcline in the Heather Ann fenite zones.

#### Minor Minerals

Several minor minerals form during fenitization. Although rarely exceeding trace amounts, they are pervasive throughout the fenite zones and absent in the Burke quartzites.

Magnetite occurs in all the fenite zones as interstitial to euhedral grains. It is black and opaque in thin-section. The magnetite is magnetic and commonly forms corona structures with aegirine in the localized fenite zone.

Sphene is orange-brown in hand-specimen and occurs sporadically as euhedral crystals as large as 2 mm in the syenite-fenite zone. In thin-section, it is distinguished by its high relief, extreme birefringence, and cleavage. The sphene locally surrounds aegirine and is a late-forming mineral.

Rutile is reddish-brown and uniaxial positive in thin-section. It is commonly associated with aegirine as small prismatic crystals, and exhibits high relief.

Zircon is also uniaxial positive but is distinguished from rutile by its pleochroic haloes, lack of color, and length-slow crystals. It occurs predominantly as small aggregate masses in the localized fenite zone.

## CHAPTER V

### THE CHEMISTRY OF FENITIZATION

#### Major Elements

The increase in alkali minerals during fenitization is accompanied by changes in the bulk chemistry of the metasomatized quartzites. Major-element variations in the Heather Ann fenites define chiefly a sodic-potassic trend. Five samples for whole-rock chemical analyses were collected on Fenite Ridge. The circled numbers in Figure 4 indicate the locations of these samples. Sample #1 was collected in the unfenitized Burke Formation and the numbers increase with assumed increasing fenitization as the alkali feldspar syenite contact is approached. Table 4 summarizes the molecular weight-percent values of the major oxides in the Heather Ann samples. Bondar-Clegg, Inc., of Lakewood, Colorado, completed these whole-rock analyses by XRF with an accuracy of  $\pm 2\%$   $\text{SiO}_2$ ;  $\text{Al}_2\text{O}_3 \pm 0.5\%$ ;  $\text{FeO}$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{K}_2\text{O}$ , and  $\text{Na}_2\text{O}$  all  $\pm 0.1\%$ .

Weight percent variations do not truly reflect the changes in rock compositions with fenitization because they distort upwards the values for elements with relatively high atomic weights such as Fe. For this reason, the whole-rock analyses have been converted to cation proportions on the basis of a standard-cell of 100 oxygen anions. Barth (1948) first introduced this standard-cell method, and McKie (1966) argues that this method should be used to study chemical

variation during fenitization. This standard-cell method assumes that fenitization is a solid-fluid reaction in which the gross oxygen content of the metasomatized rock remains constant. However, this assumption of constant oxygen content does not imply that fenitization takes place at constant volume.

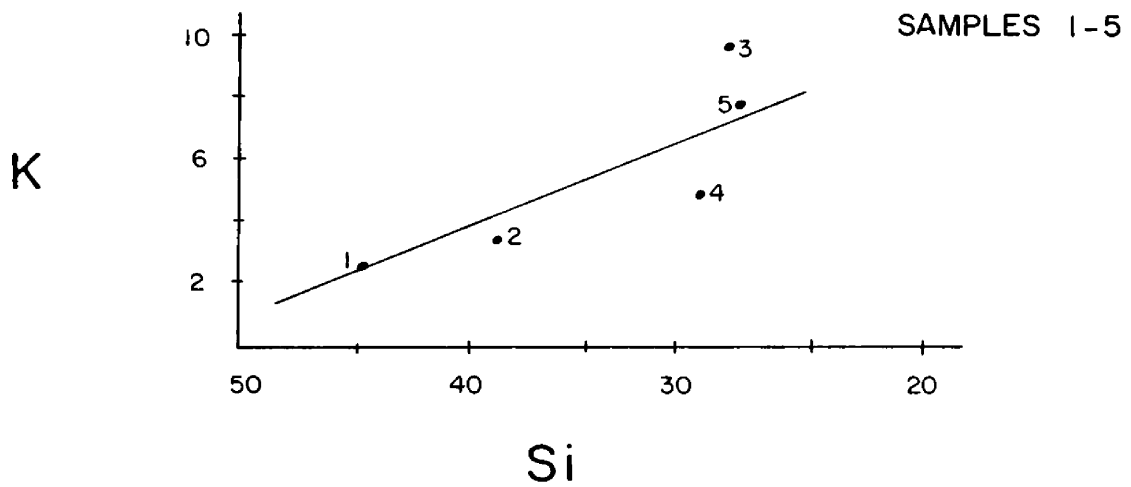
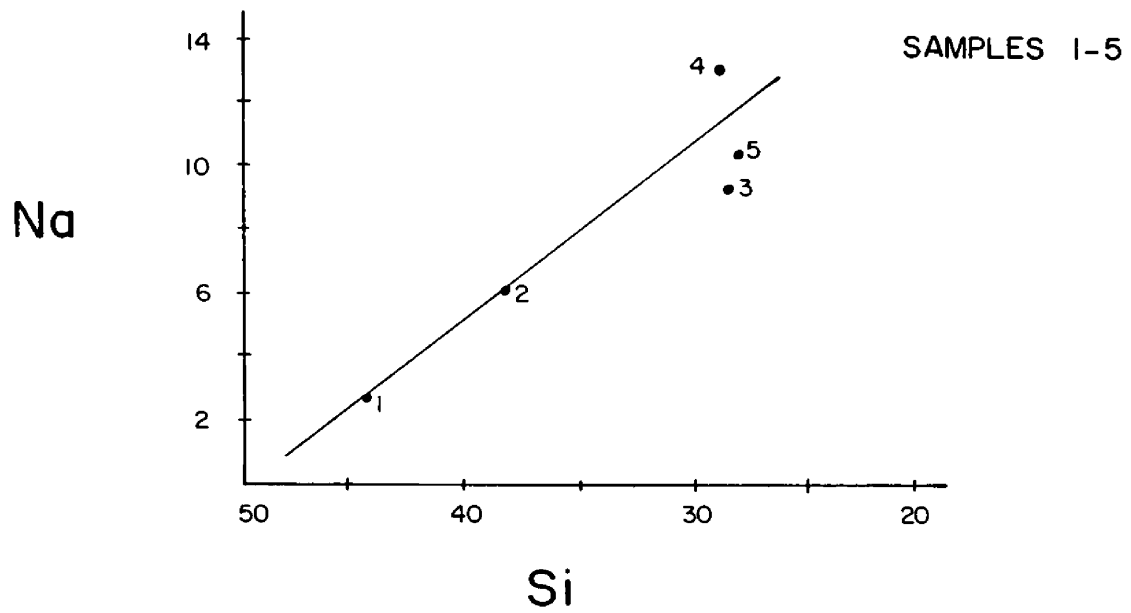
It is clear that the Burke Formation quartzites show a marked enrichment in Na, K, Al, and  $\text{Fe}^{+3}$  with increasing fenitization (Table 4). Si content decreases in relation to the increase in these major elements during fenitization. Chemically, the quartzites are transformed into a composition similar to the saturated alkali-feldspar syenite. McKie (1966), Woolley (1969) and many others have chosen variation diagrams of enriched elements plotted against Si content to display the chemical trends during fenitization. Figure 7 and Figure 8 follow this tradition with plots of Na, K, Al, and  $\text{Fe}^{+3}$ . The units in both graphs are in the number of cations per 100 anions, and the Si scale is enlarged to provide a wider spread.

These plots show nearly straight-line increases in Na, K, Al,  $\text{Fe}^{+3}$  with increasing fenitization towards the alkali-feldspar syenite contact. Na, K, and Al show the most marked increase, followed by a minor increase in  $\text{Fe}^{+3}$ . This sodic-potassic-alumina trend agrees with the modal mineralogy changes, which indicate an increase in alkali pyroxenes, soda-amphibole, and alkali feldspar.

TABLE 4. Chemical analyses of the Heather Ann fenites corrected to cations per 100 anions. Locations of samples shown on Figure 4.

Sample #	1	2	3	4	5
Location:	quartzite	local fenite	banded fenite	syenite fenite	syenite fenite
SiO <sub>2</sub>	90.80	81.30	62.2	64.00	61.00
TiO <sub>2</sub>	0.05	0.20	0.45	0.01	0.15
Al <sub>2</sub> O <sub>3</sub>	4.02	8.06	15.5	17.60	16.20
Fe <sub>2</sub> O <sub>3</sub>	1.15	3.05	4.80	5.35	6.80
FeO	0.25	0.50	0.65	0.25	0.90
MnO	0.03	0.05	0.14	0.09	0.09
MgO	0.05	0.45	1.35	0.15	0.45
CaO	0.15	0.30	1.05	0.65	1.35
Na <sub>2</sub> O	1.03	3.30	5.10	7.50	5.80
K <sub>2</sub> O	2.10	2.60	8.10	4.10	6.60
P <sub>2</sub> O <sub>5</sub>	0.01	0.01	0.01	0.03	0.01
Si	44.35	38.70	28.70	29.15	28.25
Ti	0.01	0.07	0.15	0.05	0.05
Al	1.60	3.20	5.60	6.30	5.90
Fe <sup>+3</sup>	0.27	0.73	1.10	1.23	1.57
Fe <sup>+2</sup>	0.20	0.39	0.50	0.20	0.70
Mn	0.02	0.04	0.10	0.10	0.10
Mg	0.07	0.65	1.90	0.20	0.60
Ca	0.15	0.31	1.00	0.60	1.30
Na	2.46	6.08	9.10	13.20	10.40
K	2.62	3.10	9.50	4.80	7.80
P	-	-	-	-	-

QUARTZITE → SYENITE FENITE



INCREASING FENITIZATION

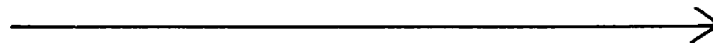


Figure 7.

Variations in cation concentrations per 100 anions for Na and K.

QUARTZITE —————> SYENITE FENITE

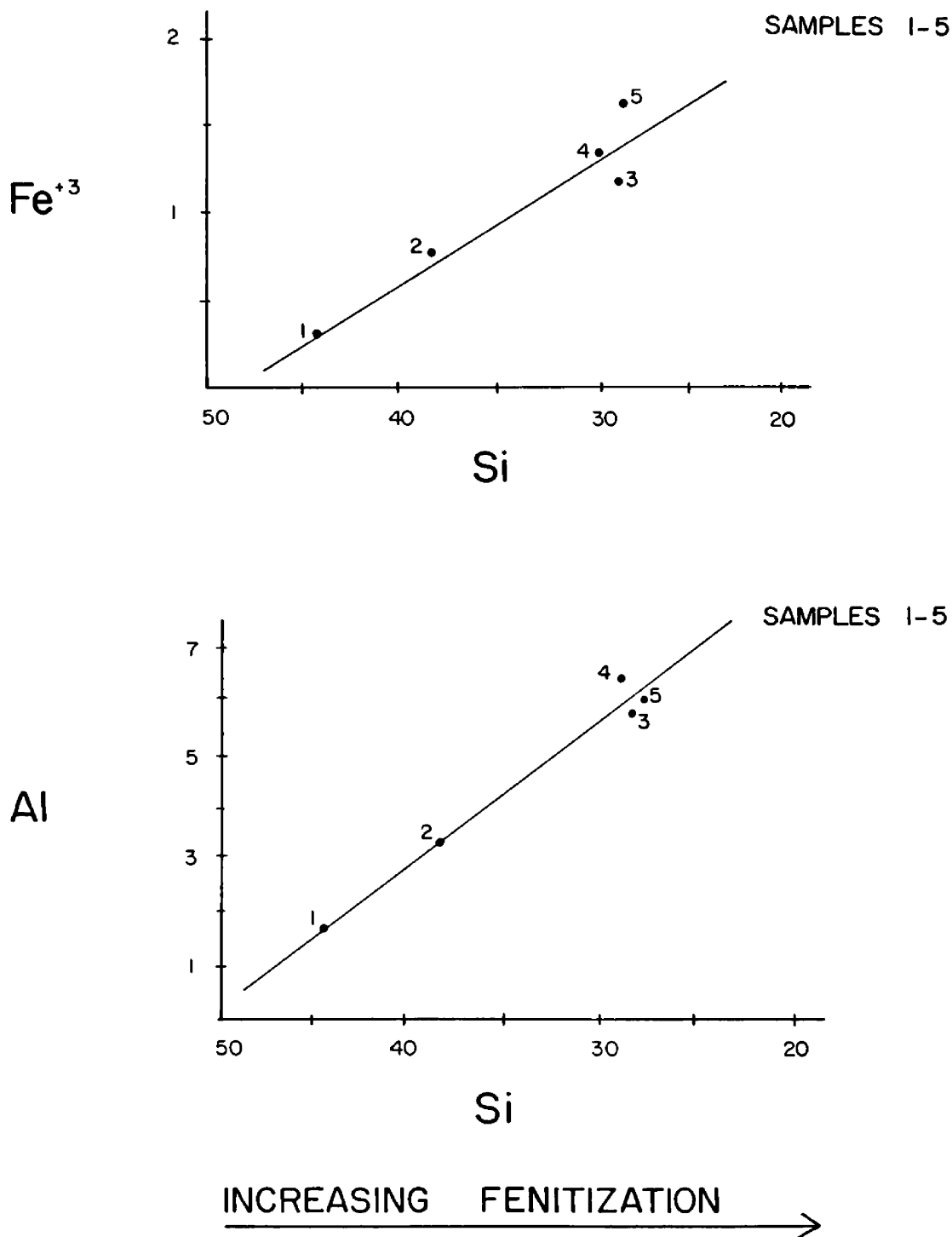


Figure 8.

Variations in cation concentrations per 100 anions for Fe<sup>3+</sup> and Al.



### Oxidation

In Chilwa Island, Spitzkop, Oldinyo Dili and several other alkalic complexes, the oxidation ratio increases during fenitization. McKie (1966) defines the oxidation ratio as:

$$\text{Oxidation Ratio (O.R.)} = 100 \frac{\text{Fe}^{+3}}{(\text{Fe}^{+3} + \text{Fe}^{+2})}$$

The oxidation ratio increases from 57 in the quartzites to a high of 87 in the banded fenite zone of the Heather Ann complex. The ferrous iron remains fairly constant throughout fenitization. Von Eckermann (1948) and others have described fenitization as an oxidizing process resulting from the high oxidizing capabilities of CO<sub>2</sub>, a major constituent of the fenitizing solutions. McKie (1966) disagrees with this interpretation and attributes the increase in the oxidation ratio to the large influx of already oxidized ferric iron from the source magma.

The evidence in the Heather Ann fenites supports McKie's interpretation. Ferric iron is added to the quartzites and the relict ferrous iron is not strongly oxidized during fenitization. Oxidation was a minor process during the Heather Ann fenitization.

### Minor Elements

Minor-element enrichment of the rare-earth elements (REE), Nb, and Zr have been recognized in the fenite zones surrounding several alkalic complexes. Among these are Nemegosenda Lake (Ontario), Seal Lake (Labrador), Manitou Island complex (Ontario), Ilmeno-Vishnevgorosk (Russia) (Heinrich, 1966), and most recently, the Seiland

province (Robbins and Tysseland, 1979) and Borralan complex in Scotland (Martin, Whitley, and Woolley, 1978).

In the Heather Ann fenites, there has been a minor enrichment of the REE, Nb, and Zr. The five samples collected for whole-rock analyses were also analyzed for several minor elements by XRF. Table 5 summarizes these results.

TABLE 5. Minor element concentrations (ppm) in the Heather Ann fenite zone.

Sample #	1 quartzite	2 local. fenite	3 banded fenite	4 syenite- fenite	5 syenite- fenite
La	6	18	38	5	5
Ce	5	21	69	5	5
Y	5	20	36	5	5
Nb	9	17	35	14	9
Zr	140	500	385	81	91
U	2	3	5	2	2

These minor-element trends have been plotted against Si in Figure 9. La, Ce, Nb, Y, and Zr all show anomalous concentrations in the localized and banded-fenite zones. There is little enrichment pattern in the inner syenite-fenite zone based on two samples. The rare-earth enrichment pattern in the distal fenite zones of the Heather Ann complex is similar in order and magnitude to the pattern observed in the fenitized quartzites of the Borralan complex, Scotland (Martin, Whitley, and Woolley, 1978).

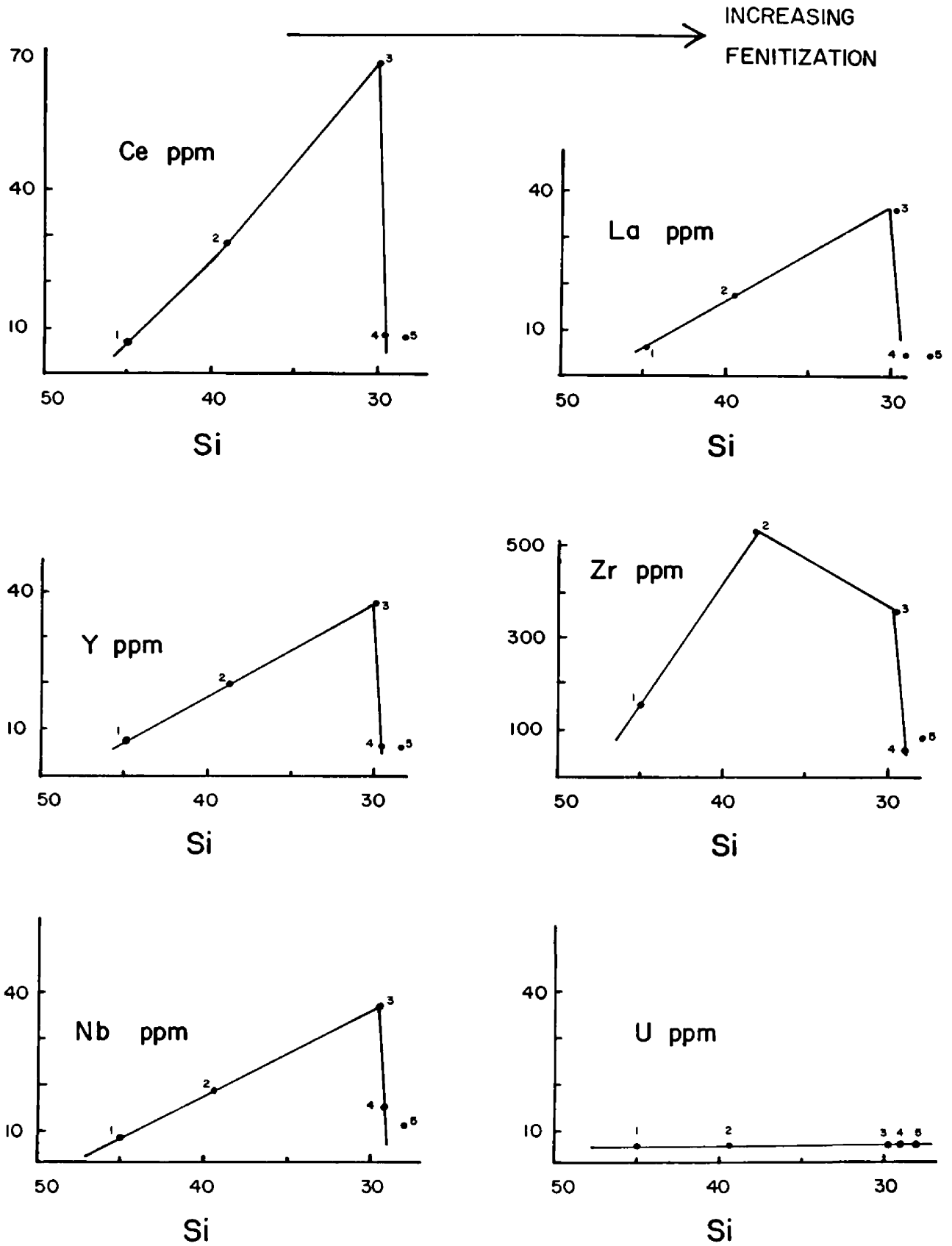


Figure 9. Plots of minor-element concentrations as a function of Si with increasing fenitization.

The mobility of these minor elements during fenitization is explained by their close affinity with a gas or fluid phase. Pneumatophilic elements form compounds which are much more soluble in the fluid phase than in the melt of a magma. The distribution of La, Ce, Y, Zr, and Nb is based on observations in nature and petrographic research and these elements are all classified as excellent pneumatophilic elements (Rittmann, 1975). Therefore, the separation of a fenitizing fluid phase from a carbonated magma would tend to concentrate these minor elements.

Kosterin (1959) considered the nature of the solubility of the rare-earth elements in solution. The REE could not be transported in solution as simple ions because they would be immediately precipitated, and complexing is necessary to explain REE solubility (Haskin, Frey, Schmitt, and Smith, 1966). Experimental studies show that rare-earth elements and probably Nb and Zr can form soluble and stable complexes with the  $\text{CO}_3^{-2}$  that is,  $\text{RE}(\text{CO}_3)_3^{-3}$ . Kosterin (1959) discovered that in the majority of economically valuable REE deposits the REE are associated with alkali metals and weak  $\text{H}_2\text{CO}_3$  acids. Therefore, alkaline carbonate complexing is evidently the most effective way to transport these minor elements in solution. The carbonate complexes can be broken and the rare-earths precipitated by a decrease in the alkalinity of the solution or by a decrease in the  $\text{CO}_2$  partial pressure.

The fenitizing solutions of the Heather Ann complex were both alkaline and probably rich in  $\text{CO}_3^{-2}$ , and La, Ce, Y, Nb, and Zr were

particularly soluble in these solutions. The concentration of these minor elements in the distal fenite zones of the Heather Ann complex is related to the transporting complexes. With decreasing fenitization in the outer zones, both alkalinity and CO<sub>2</sub> content of the fenitizing solutions decrease causing the dissociation of the carbonate complexes and precipitation of the minor elements.

## CHAPTER VI

### THE NATURE OF FENITIZATION

Fenitization is one of the most diagnostic and identifiable features of alkalic complexes. Fenite zones characteristically surround the alkalic rocks in the form of a dome, and Von Eckermann (1948) recognized that fenitization is more intensive at depth. This evidence suggests that fenitization begins at considerable depth and accompanies the intrusion of the alkalic magma (Heinrich, 1966). Field evidence indicates that fenitization is an "early" episode that accompanies both the initial intrusion of the alkalic complex and the shattering and doming of the wall-rocks by infilling the fractures with fenite veinlets. Fenitization of the country rocks can be quite intensive, causing active brecciation and even fluidization of the metasomatized wall rocks.

#### Petrogenesis

A major problem encountered in the study of fenitization is the mechanism responsible for the extensive wall-rock alteration. The process does not appear to be simple diffusion because fenitizing solutions actively infiltrate the country rocks for distances of 400 to 1,000 m from alkalic complexes. It is also not related to residual solutions or to a "second boiling" episode since field evidence implies that fenitization is an early event (Heinrich, 1966). Sorenson (1974) classifies fenitization as a progressive metasomatism

that occurs near magmatic temperatures. General consensus supports the concept that fenitization is an interaction of a magmatic fluid phase rich in  $\text{CO}_2$  and  $\text{H}_2\text{O}$  with the solid wall-rocks (Ferguson, McIver, and Danchin, 1978).

There are no experimental studies on the process of fenitization, but Robbins and Tysseland (1979) have suggested that the work of Mysen (1975) on the solubility of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  in alkaline silicate magmas has direct relation to fenitization. The  $\text{CO}_2$  solubility in separate studies of albite, nepheline, and jadeite melts is as high as 2-3 wt% at 20 kb pressure, but its solubility in these magmas drops to less than 1 wt% at less than 5 kb. Mysen (1975) reasons that intrusion of a  $\text{CO}_2$ -saturated magma from mantle depths would force the exsolution of a  $\text{CO}_2$ -rich fluid phase. This scenario is schematically shown in Figure 10. This separate fluid phase provides the mechanism to transport the fenitizing fluids from the alkalic magma. The  $\text{CO}_2$  fluid phase would separate early and approximate the magmatic temperatures observed during fenitization. This mechanism also explains why fenitization is associated only with alkalic rocks. Alkalic magmas are characteristically saturated in  $\text{CO}_2$  at depth, and  $\text{CO}_2$  plays an important role in their differentiation and petrogenesis (Rock, 1976).

#### Source of the Fenitizing Fluids

In the Heather Ann complex the source of the fenitizing fluids is the alkali-feldspar syenite. A recurrent and conformable sequence of fenite zones occurs along the southeast contact of the syenite with

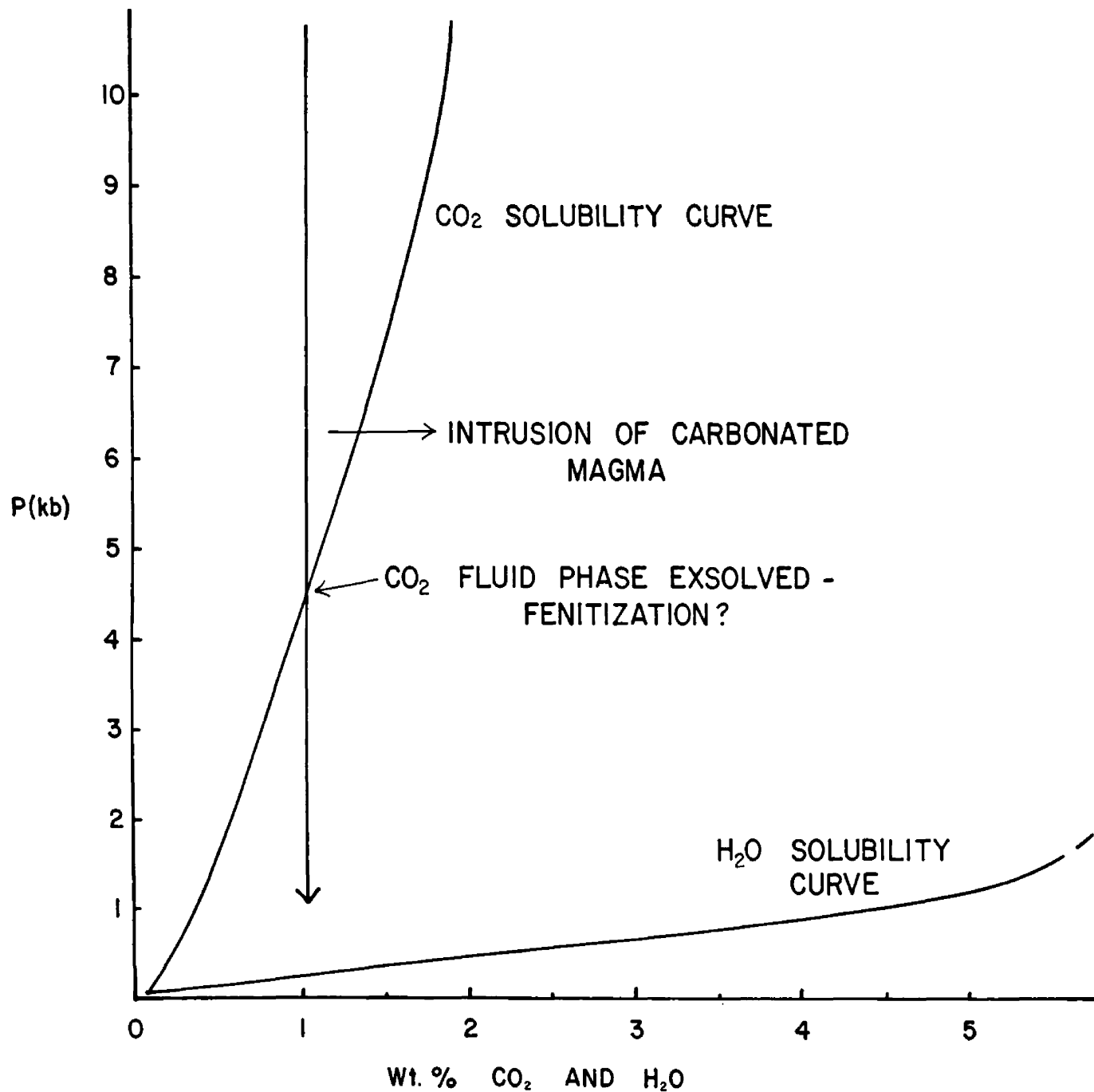


FIGURE 10. Weight percent solubility of CO<sub>2</sub> in albite melt at 1450° C (Mysen, 1975), contrasted with H<sub>2</sub>O solubility in albite melt at 1100° C (Burnham, 1975) showing exsolution of CO<sub>2</sub> fluid phase with pressure decrease.



the country rocks. The higher-grade syenite-fenite zone is everywhere in contact with the intrusive syenite and fenitization decreases outwards from the syenite contact. The chemical trends also show a direct relation between the degree of fenitization and distance from the intrusive contact. Figure 11 shows the abrupt decrease in Na, K, Al, and  $Fe^{+3}$  in the metasomatized quartzites with increased distance from the syenite contact. This chemical trend reinforces the close genetic link between the syenite and fenitization. Furthermore, the fenitized contact rocks are enriched in the same elements that are abundant in the alkali-feldspar syenite.

Much discussion in the literature concerns the ultimate source of the fenitizing solutions. Dawson (1964) and McKie (1966) argue that carbonatite magmas are the sole source of fenitizing solutions. Boettcher (1966) uses this argument in the Rainy Creek complex near Libby, Montana and concludes that the solutions from the exposed silicate rocks could not have formed the Rainy Creek fenites. Boettcher believes that the fenites are formed from a nearby carbonatite and that the mere presence of fenites provides the best field evidence for a carbonatite at depth.

The presence of fenites does not necessarily imply a carbonatite at depth since alkalic silicate rocks are equally capable of fenitization. At Fen, Brögger (1921) believes that the source of the fenitization was the alkaline silicate rocks, whereas Heinrich (1966) maintains that fenitization is associated with both carbonatites and alkaline silicate source rocks. Evidence from more recent studies

SYENITE CONTACT      FENITE ZONES      BURKE FM QUARTZITE

→      →

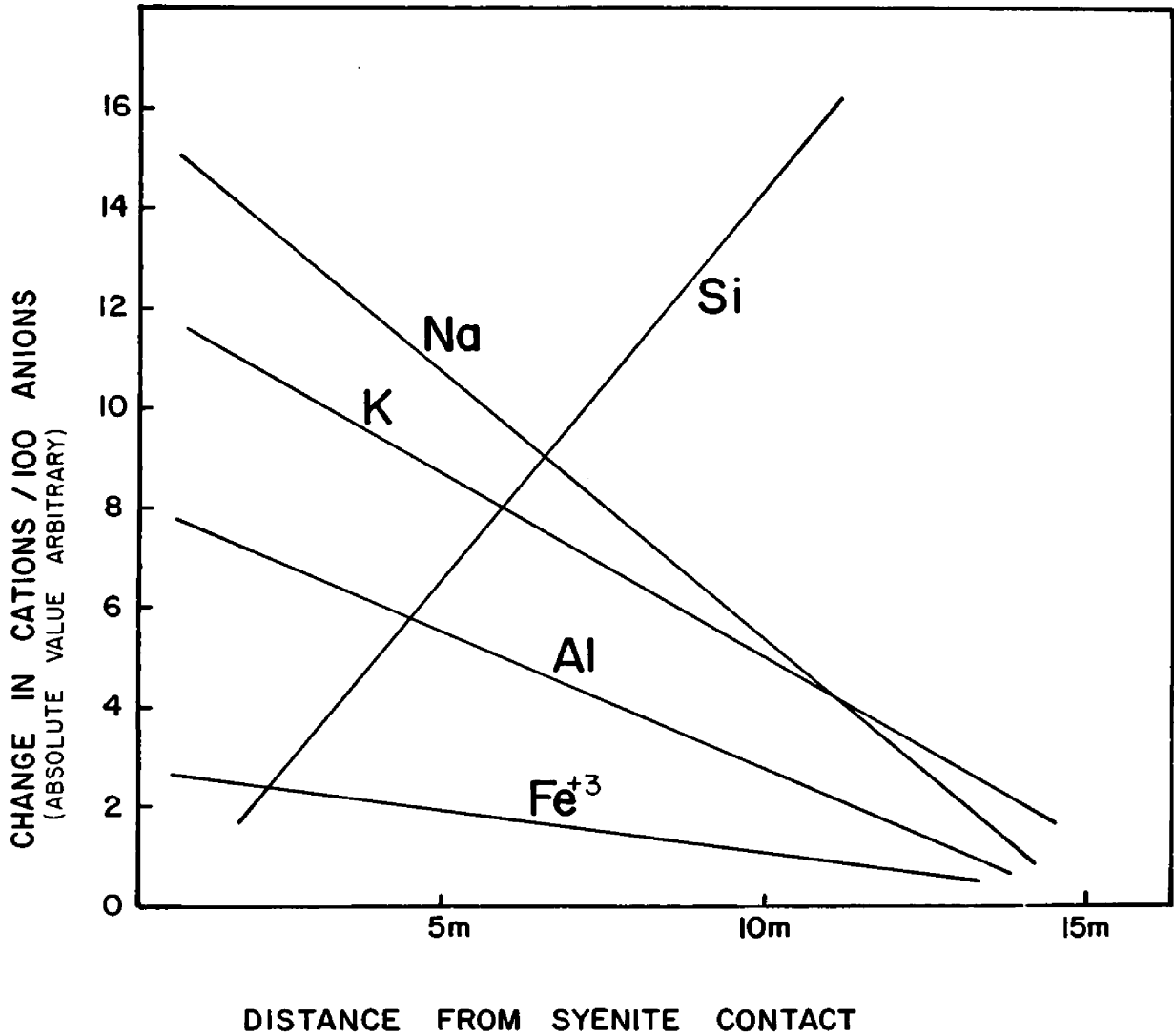


Figure II. Variation of major-element trends with distance from alkali-feldspar syenite contact.

indicates that fenitization is not solely restricted to carbonatites. Fenitization is associated with a nepheline syenite body at the Monchique alkalic complex in Portugal (Rock, 1976) and at Epembe, in South Africa (Ferguson, McIver, and Danchin, 1978). Woolley and others (1972) believe that fenitization at the Borralan complex is related to a pseudoleucite syenite, and Siemiatkowska and Martin (1975) argue that the fenitization source in the Mississagi quartzite was an alkaline silicate magma. Field evidence and chemical trends in the Heather Ann complex are further evidence that alkalic syenites can also have fenitized border zones.

The process of fenitization does not depend on the composition of the source magma, but rather, its CO<sub>2</sub> content. A magma saturated with respect to CO<sub>2</sub> at depth can produce fenitized border zones. Carbonatites, because of their high CO<sub>2</sub> content, usually provide the best evidence of fenitization, but any carbonated magma, regardless of composition, could cause fenitization of its surrounding country rocks.

#### Volume Increase

In the past, most geologists believed that metasomatic processes such as serpentinization and fenitization occur at constant volume. To retain its constant volume, a metasomatized rock had to lose constituents to balance the influx of additional elements. The alternative, to simply allow for a volume increase in the metasomatized rock, was practically ignored. Most of the literature supports the

concept that fenitization is a constant-volume process with an accompanying loss of silica. Recently, however, Appleyard and Woolley (1979) and LeBas (1977) have suggested that desilication may be a minor process and that fenitization may involve a volume increase. The strongest argument for constant-volume metasomatism has always been that relict sedimentary layering or metamorphic schistosity is preserved in the fenitized rocks. In the Heather Ann fenites, sedimentary layering is preserved in the mildly fenitized quartzites but is severely disrupted and brecciated in the higher-grade banded zone. Fenitization in the syenite-fenite zone obliterates all sedimentary structures. This field evidence directly negates constant volume metasomatism and supports volume increase with fenitization.

The most convincing field evidence for volume increases during fenitization is the brecciation structures in the fenite aureole. Fenitization has extensively brecciated the Mississagi quartzite near Sudbury, Ontario (Siemiatkowska and Martin, 1975). The breccia fragments vary in size from 1-16 cm and are replaced by aegirine, riebeckite, and alkali feldspar. Some of the fragments are subrounded and aligned in a "flow" matrix. These authors suggest that the breccia formed from an explosive process. This assumes that the fenitizing solutions were gas-driven and under sufficient pressure to cause flow-brecciation. This type of brecciation and fenitization in the Mississagi quartzite must have been accompanied by a volume increase.

Similar fenite breccias are found in the roof zone of the Heather Ann complex. Argillaceous quartzite fragments are displaced and surrounded by syenite-fenite. The fragments are angular and range in size from 1 cm to 0.5 m. Relict sedimentary layering exists in fragments surrounded by metasomatic reaction rims of aegirine and alkali feldspar. The fenite breccia of the Heather Ann complex displays no flow textures or evidence of explosive formation. Still, the disruption of the original layering and intense brecciation of the fenitized quartzites indicates that fenitization in the Heather Ann complex did not occur at constant volume.

Fenitization, by its very nature, accompanies the emplacement and doming of alkaline intrusive rocks. This doming generally causes a volume increase and fracturing in the surrounding country rocks. Von Eckermann (1948) and Heinrich (1966) both recognize the formation of shatter areas in many fenite zones due to intrusive doming. The fenitizing solutions actively migrate along these fracture zones. Such active tectonic fracturing is further evidence for volume expansion in the fenitized aureoles surrounding alkaline intrusions.

### Silicification

It is not necessary to remove silica from the metasomatized country rocks if there is a volume increase in the fenite aureole. However, fenitization is considered by many to be a desilication process (Heinrich, 1966; Woolley, 1969; McKie, 1966), since there is widespread silicification around certain alkalic complexes.

Silicification of the carbonatites at Alnö, Rufunsa, and Chilwa Island (Vartiainen and Woolley, 1976) is attributed to fugitive silica, derived from desilication during fenitization, migrating backwards into the carbonatites.

Sukheswala and others (1972) attribute the widespread silicification and fluorite mineralization of the carbonatites at Amba Dongar in India and Okorusu in South Africa to a hydrothermal event. This is a more reasonable explanation than the desilication theory. Fenitization involves the outward flow of fenitizing fluids from the source magma. Since it would be difficult to establish a reverse diffusion process of silica back into the alkalic rocks against this flow, it is more likely that silicification is a separate hydrothermal event unrelated to fenitization.

There is abundant silica veining throughout the fenite zone and the alkali-feldspar syenite in the Heather Ann complex. The Susie quartz body is also at the roof of the complex. Minor fluorite and copper-staining accompany the quartz veining. The veins range from 1 mm to 100 cm in width and commonly contain comb structures and cavities which are common to epithermal quartz veins. The silica veining cross-cuts the fenite zones and has no direct relationship to the metasomatism. It seems to be a later hydrothermal event unrelated to fenitization.

### Pressure

The presence of miarolitic cavities in the quartz syenite of the Heather Ann complex indicates shallow emplacement to a depth of approximately 3 km (Bakken, 1977). The alkali-feldspar syenite has been intruded to this same level of emplacement. The pressure conditions in the fenite aureole at this depth were 800-1,000 bars.

### Temperature

The formation of perthite in the syenite-fenite zone suggests a temperature of the fenitizing solutions above the alkali feldspar solvus. Orville (1963) found that the crest of the feldspar solvus was approximately 680°C. Orville's crest is at a higher temperature and more Ab-rich composition than the standard Bowen and Tuttle (1950) solvus crest because his experiments were designed to model metasomatism by using a starting material of crystallized feldspar instead of glasses, and a 2 $\mu$  alkali chloride fluid phase instead of pure water. For these reasons, Orville's higher temperature solvus is used in Figure 12 to estimate the temperature of fenitization.

An estimation of the composition of the alkali feldspar in the syenite-fenite was made by calculating the norm % of Or and Ab from the whole-rock analysis (sample #5). Mole percent of Or is estimated at 45.3% and of Ab at 54.6% in a homogeneous alkali feldspar formed in the syenite-fenite zone. The temperature of formation of a completely homogeneous alkali feldspar of this composition is estimated from Figure 12 at 670°C and a maximum temperature of 670-700°C

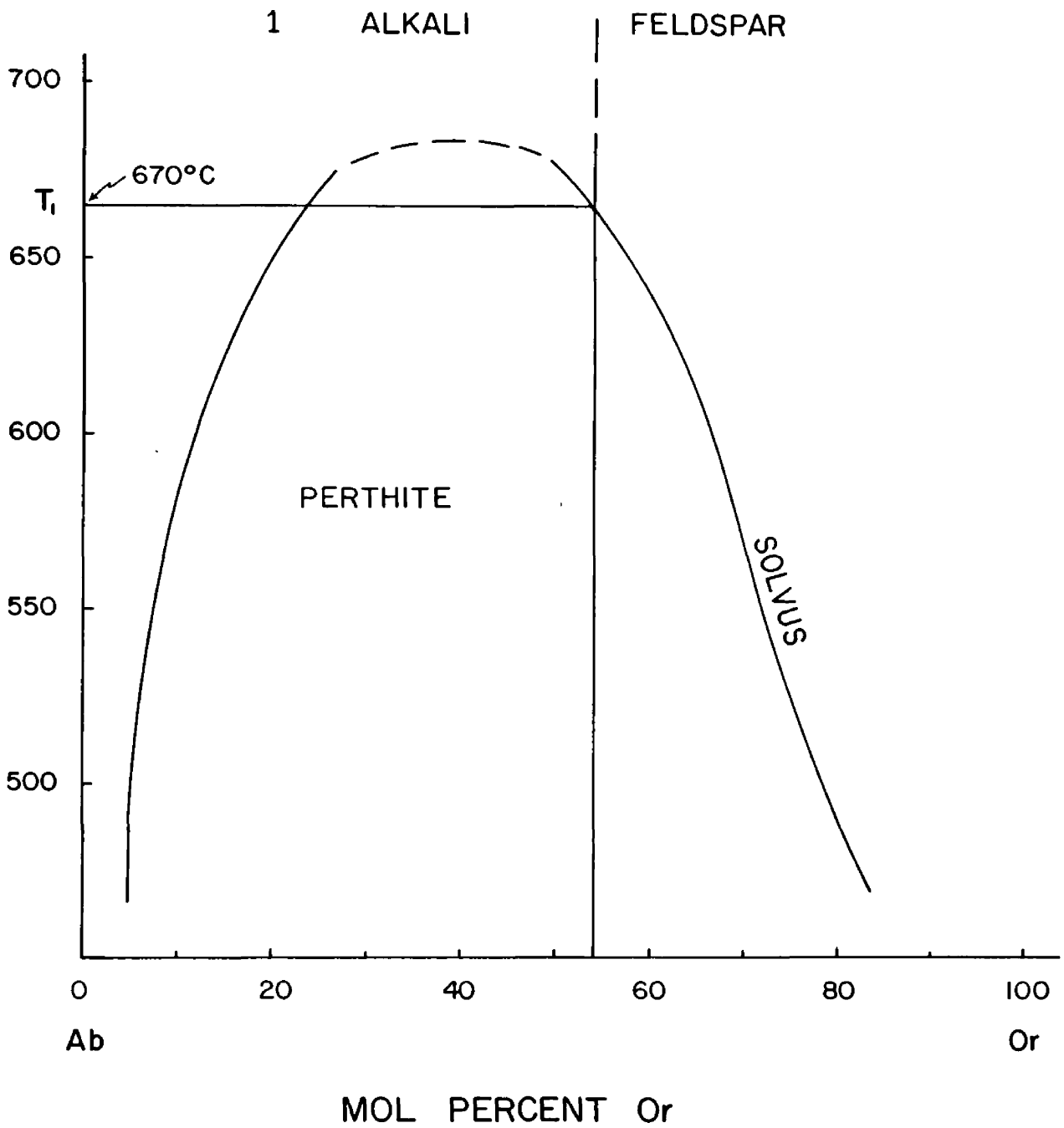


Figure 12. Alkali feldspar solvus (Orville, 1963) with estimation of temperature of formation of homogeneous feldspar.



TABLE 6. Molecular norm of syenite-fenite

Q	0.47
Or	39.00
Ab	46.59
Ac	2.20
Di	2.42
Wo	1.47
He	4.14
Mt	2.76
Il	0.28
Ap	0.02

seems reasonable in the highest-grade syenite-fenite zone of the Heather Ann complex.

The temperature drops to below 655°C in the outer fenite zones because of the stability of arfvedsonite in these zones. A minimum temperature of fenitization is difficult to assign. Both aegirine and soda-amphibole (riebeckite) form at near-surface temperatures and pressures in the Green River Formation of Wyoming (Milton and Eugster, 1959). Conceivably, alkaline replacement could occur at very low temperatures. Still, Orville (1963) discovered that metasomatic reactions between albite and alkali-chloride solutions occur rapidly only above 400°C. Therefore, a reasonable lower temperature range in the fenite aureole of the Heather Ann complex is approximately 400°C, based on the kinetics of the albite reaction. Overall, the temperature

of fenitization ranges from 700-400°C, decreasing gradually away from the alkali-feldspar syenite contact.

### Composition of the Fenitizing Solutions

The composition of fenitizing solutions is poorly understood (LeBas, 1977). The solutions must consist predominantly of CO<sub>2</sub> if fenitization is related to the early exsolution of CO<sub>2</sub>-rich fluid phase. The thermodynamics of CO<sub>2</sub> in silicate melts is not well known. CO<sub>2</sub> solubility in melts differs radically from H<sub>2</sub>O solubility but the reasons for these differences are not clear. Mysen (1975) studied CO<sub>2</sub>-saturated, quenched silicate melts with infrared spectrometry and determined that CO<sub>2</sub> enters the silicate melt both as discrete CO<sub>2</sub> molecules and also as carbonate anions, CO<sub>3</sub><sup>-2</sup>. The amount of CO<sub>3</sub><sup>-2</sup> ions increases in water-rich melts where polymerization is less. The exsolved fluid phase involved during fenitization is therefore presumed to consist of CO<sub>2</sub> and CO<sub>3</sub><sup>-2</sup> as well.

Such fenitizing solutions would be above their critical point at the temperatures and pressures inferred during fenitization in the Heather Ann complex. Supercritical fluids under high confining pressures (800-1,000 bars) have a density approaching that of a low-temperature liquid and have considerable solvent ability (Krauskopf, 1979).

Fenitizing solutions are enriched in Na, K, Al, and Fe<sup>+3</sup>, which are the elements added to the wall rocks during fenitization. The high solubility of these ions in the fenitizing solutions can be

explained by "complexing". The carbonate anion,  $\text{CO}_3^{-2}$ , is a bidentate ligand that forms soluble complexes with both  $\text{Al}^{+3}$  and  $\text{Fe}^{+3}$ . These carbonate complexes have a minus three charge,  $\text{Al}(\text{CO}_3)_3^{-3}$  or  $\text{Fe}(\text{CO}_3)_3^{-3}$ . Three  $\text{Na}^{+1}$  and  $\text{K}^{+1}$  ions move with the solutions to maintain the electrical neutrality of the solution. Carbonate complexing also mobilizes the REE, Zr, and Nb found in anomalous concentrations in the Heather Ann fenite aureole. The complexes dissociate in the Burke quartzites with decreasing  $\text{CO}_2$  pressure after the fenitizing solutions have exsolved out of the syenite magma. The carbonate anions do not form any carbonate minerals in the fenite zones because there is very little Ca or Mg in the quartzites. Most of the carbonate and  $\text{CO}_2$  probably diffuse into the rocks. In other fenite provinces, a marked increase in C in the whole-rock analyses has been documented (Robbins and Rysseiland, 1979), but C was not analyzed in the Heather Ann fenites.

Fenitizing solutions in the Heather Ann complex are not necessarily aqueous. Although minor water or bicarbonate may accompany the fluid phase, there is not a separation of a hydrous phase during fenitization. Figure 12 shows that water can remain soluble in the silicate magma. Most investigators have assumed that the fenitizing solutions were aqueous chloride brines (Currie, 1971; Robbins and Rysseiland, 1979; Martin, Whitley, and Woolley, 1978). These studies view fenitization as a desilication process which needs alkaline and aqueous solutions to remove silica from the fenite zones. Fenitization in the Heather Ann complex does not form hydrous minerals. Soda-amphibole is the only hydrous mineral phase, and it forms from the sodium metasomatism of the relict hydrous biotite.

In conclusion, fenitization of the Heather Ann complex is a volume increase metasomatism in which Na, K, Al, and  $\text{Fe}^{+3}$  are added to the wall-rocks around the alkali-feldspar syenite. These elements are added because they are particularly solvent in the  $\text{CO}_2$  and  $\text{CO}_3^{-2}$  fluid phase which exsolved from the alkali-feldspar syenite during intrusion and decompression. The constituents of the fenitizing solutions precipitate from solution and metasomatize the country rocks due to a decrease in  $\text{CO}_2$  pressure in the Burke quartzites.

## CHAPTER VII

### DISCUSSION

Ever since Brogger first introduced the term fenite for rocks in the Fen complex of Norway in 1921, the process of fenitization has gained widespread recognition and interest. The best explanation for this interest is that many geologists believe the fenites give some clue about the origin and petrogenesis of alkalic rocks and carbonatites.

The differentiation trend in the Heather Ann complex from nepheline-normative rocks to quartz oversaturated rocks is a good example of the thermal-divide problem in the Ne-Ks-Qtz system. Nepheline-normative liquids should not fractionate to form quartz-rich liquids, but in nature this process and its reverse seems to occur commonly in alkalic complexes. Differentiation by fractional crystallization fails to explain this thermal-divide problem, and more imaginative processes must be envisioned.

Fenitization offers some very useful insights into this differentiation problem. The extensive aureole of fenitization surrounding the Heather Ann complex is undeniable evidence that there has been a transfer of Na, K, Al, and  $Fe^{+3}$  from the alkali feldspar syenite. The chief effect of this element transfer has been to induce peralkalinity in the Belt quartzites. If Na, K, Al, and  $Fe^{+3}$  are mobile during fenitization, then one must conclude that they are also mobilized within the source magma itself. For example, movement of these

elements into a part of the magma chamber would induce peralkalinity in that melt phase. The nepheline syenite in the Heather Ann complex is slightly enriched in Na, Al, and perhaps Fe compared to the other oversaturated phases (Tables 2 and 3). Therefore, generation of nepheline normative rocks in the Heather Ann complex can be accomplished by an "alkali transfer" of the mobile elements into a separate part of the magma chamber and eventually into the country rocks to produce fenitization.

This concept of fluid transport of alkalis to produce a nepheline syenite is a very old concept. R. A. Daly in 1912 (Shand, 1947) argued that feldspathoidal rocks could be formed by escaping carbon dioxide carrying alkalis toward the top of the magma chamber. A magma would then become differentiated by Daly's process into a lower pyroxenite portion and a highly alkalic upper portion from which all types of alkali-rich rocks could form. Geologists in the past dismissed this theory because the crystallized magma does not bear any imprint of this process (Bailey, 1975). Still, fenitization around syenites and nepheline syenites offers excellent field evidence that alkali transfer is a viable differentiation process in alkalic rocks.

Experimental petrology has been primarily concerned with explaining magmatic differentiation by fractional crystallization and gravitational crystal settling and has relatively ignored alkali transfer as an important mechanism in differentiating magmas. Experimental studies modelling this process and fenitization have not yet been defined. New experiments should be undertaken to study alkali transfer in alkalic rocks.

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## APPENDIX 1



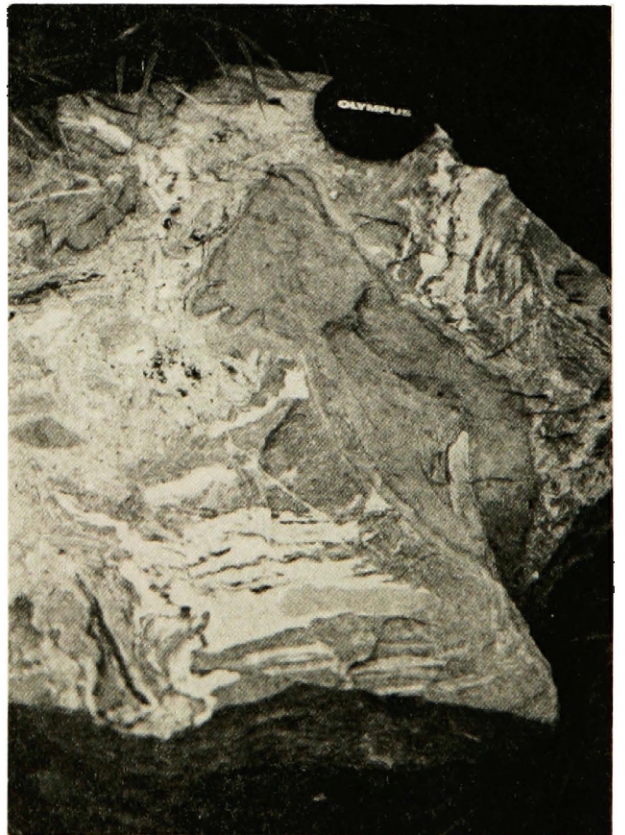
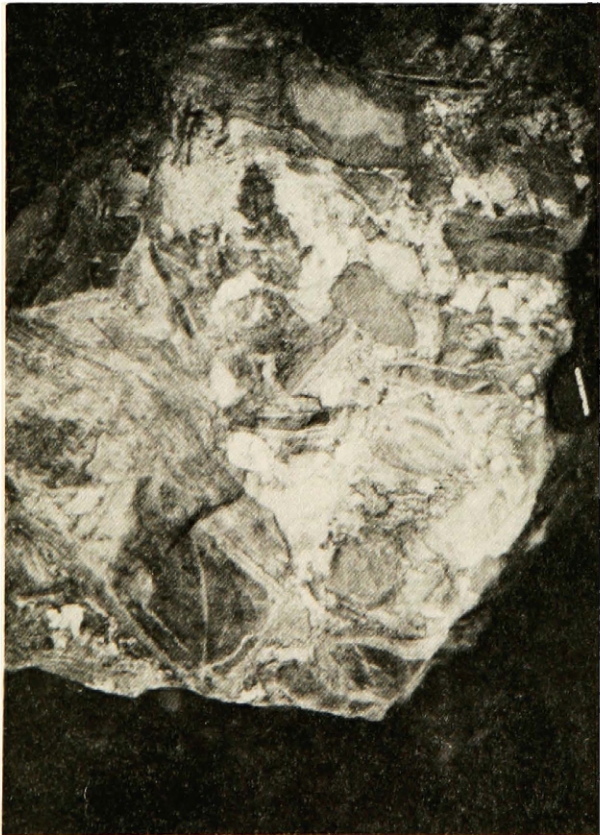
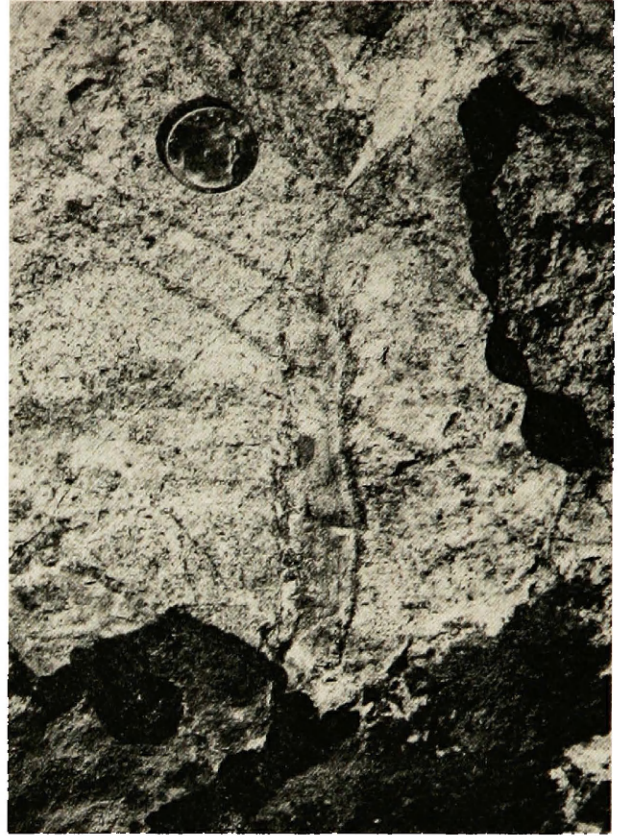
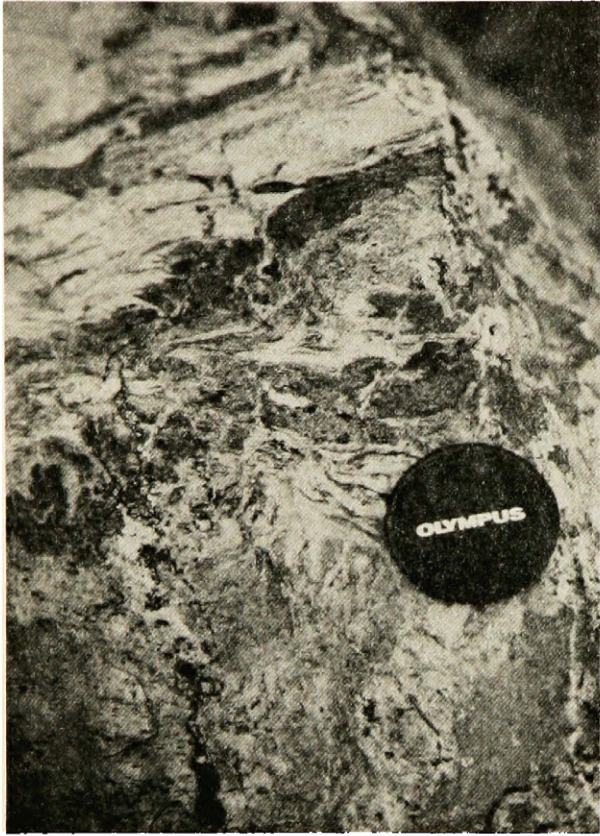


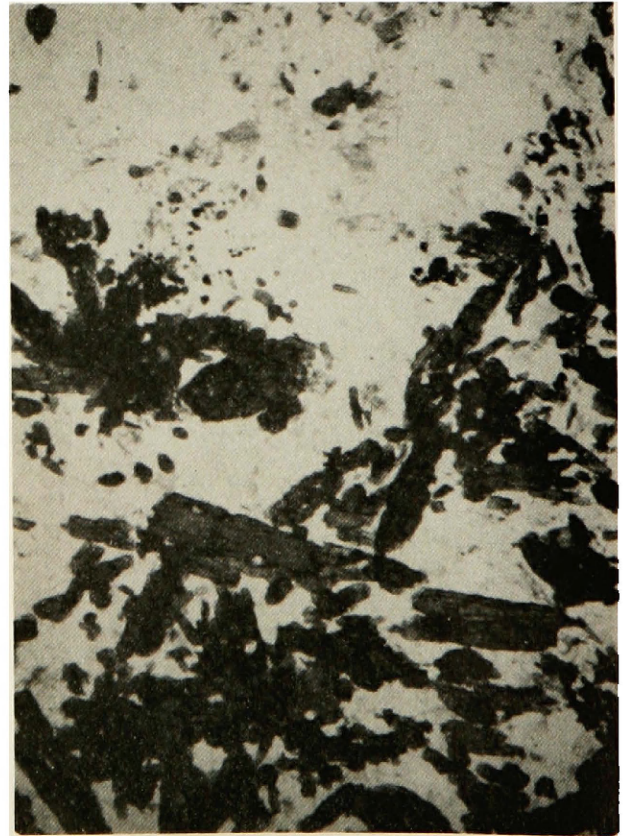
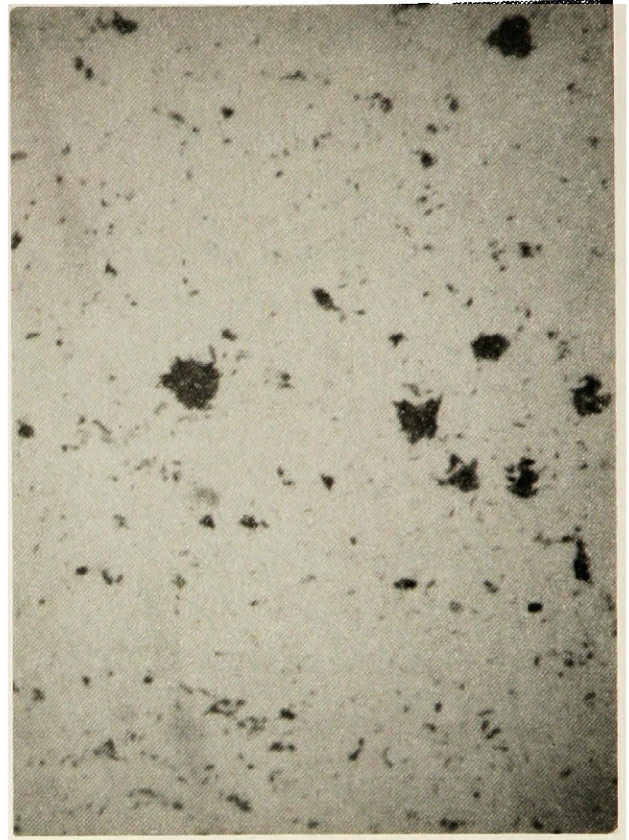
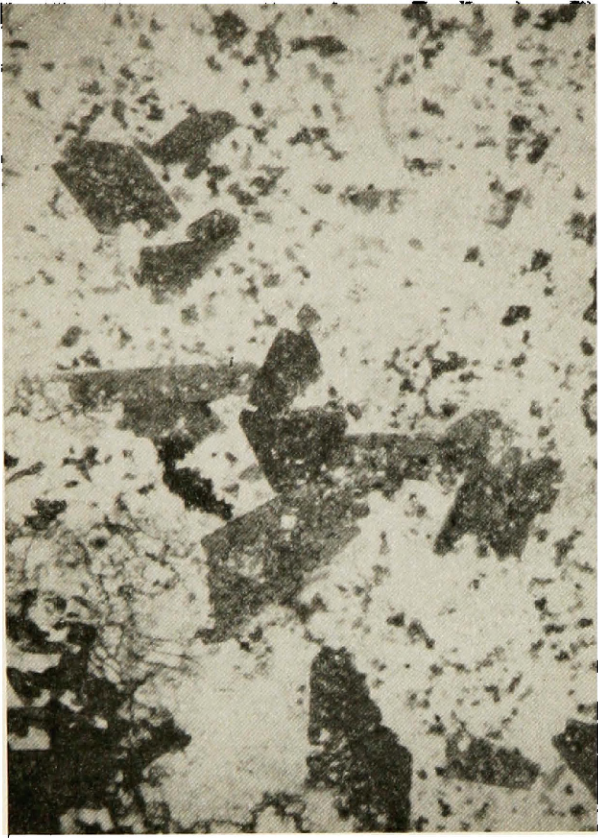
Plate 1. Fenite breccia, clasts of quartzite surrounded by syenite-fenite.

Plate 2. Green swirled texture of syenite-fenite zone.

Plate 3. Syenite-fenite with relict quartzite clasts.

Plate 4. Comb-structure fenite veins in syenite-fenite zone.





## Photomicrographs

Plate 5. Metasomatic sphene, 2 mm, microcline perthite in right bottom corner, syenite-fenite zone, X-nicols.

Plate 6. Poikiloblastic Mg-arfvedsonite, 1 mm, banded fenite zone.

Plate 7. Aegirine prisms, 2-4 mm, syenite-fenite zone.

Plate 8. Aegirine clusters in spotted quartz-fenite, localized fenite zone.



## APPENDIX 2

## Estimated Modal Mineralogy of Whole-rock Samples

Mineral	Sample #1 qtzite	Sample #2 loc. fenite	Sample #3 band. fenite	Sample #4 sy. fenite	Sample #5 sy. fenite
K-spar	15	40	25	25	15
Perthite	--	--	--	25	55
Plagioclase	3	15	45	35	10
Aegirine	--	5	15	15	20
Mg-Arfvedsonite	--	2	3	--	--
Quartz	80	30	--	--	--
Biotite	1	7	1	--	--
Magnetite	tr	tr	tr	tr	tr
Sphene	--	--	tr	tr	tr-1
Zircon	--	tr-1	tr	tr	tr
Muscovite	tr	tr	--	--	--
Apatite	tr	tr	tr	tr	tr
Rutile	--	--	--	--	tr