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PETROLOGY AND GEOCHEMISTRY OF AN ARCHEAN MIGMATITE TERRAIN, FAVOURABLE LAKE AREA, NORTHWEST ONTARIO

PETROLOGY AND GEOCHEMISTRY OF AN ARCHEAN MIGMATITE TERRAIN, FAVOURABLE LAKE AREA, NORTHWEST ONTARIO

By

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SCOPE AND CONTENTS:

The "F-Zone" is part of a migmatitic, radiometrically anomalous belt which forms the contact between a large granitic batholith and a region of homogeneous diatexite. Petrographic and geochemical analysis (including whole rock and rare-earth element analyses) of these three units has been carried out. Results indicate that the batholith was formed by partial fusion of sedimentary and volcanic material; the homogeneous diatexite arose in a similar way although fusion was less complete and; the migmatite incorporates material from both of these units. Late stage metasomatic-hydrothermal activity has concentrated uranium from the country rock in the migmatite zone.

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CHAPTER I

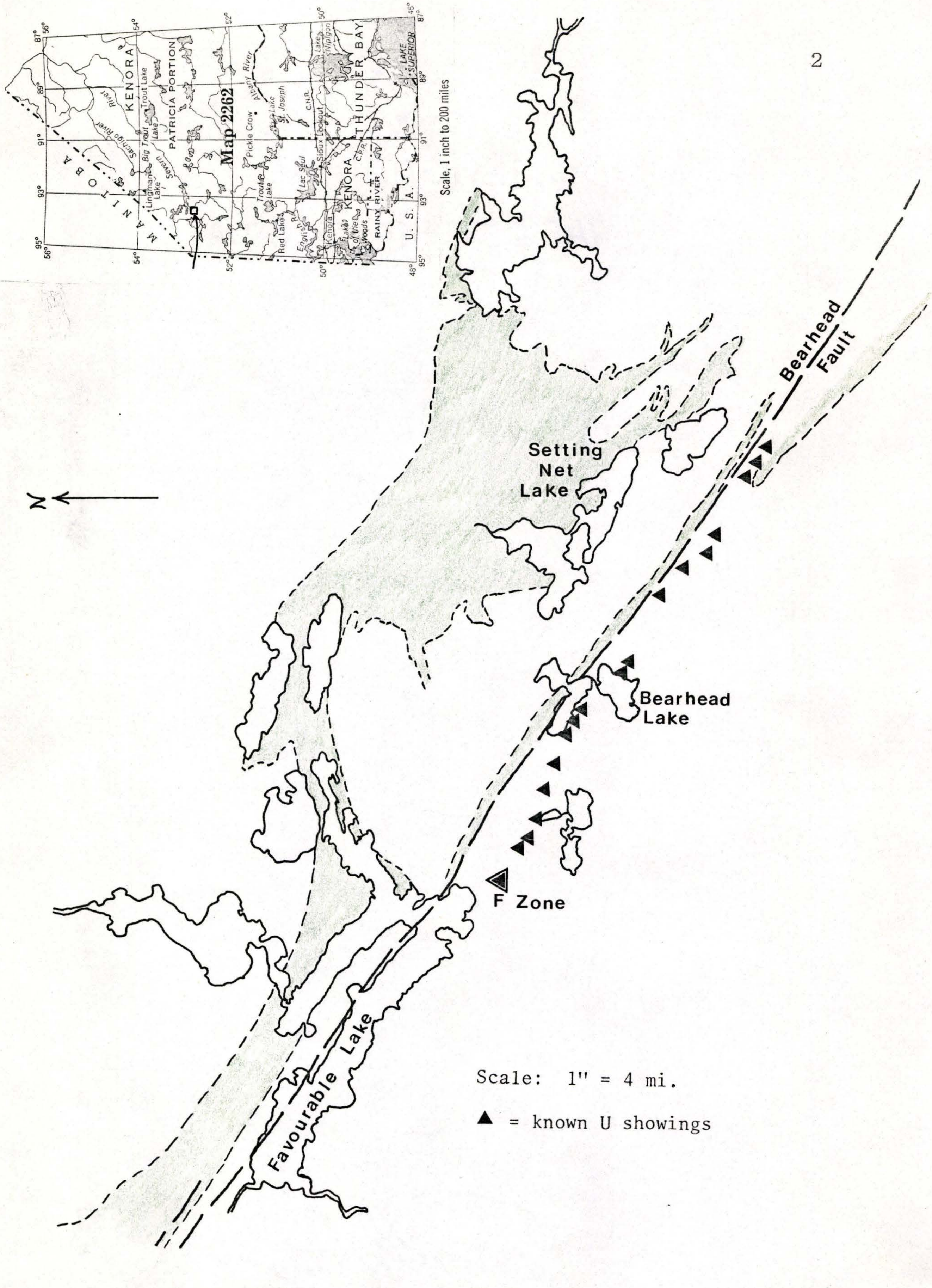
INTRODUCTION

1. Location and Accessibility:

The study area lies along a radiometrically anomalous migmatite belt situated within the Beren's River Block of the Superior Province, northwestern Ontario. This belt trends roughly S-SE between Favourable Lake and Bearhead Lake (see Map 2262, Favourable Lake - Beren's Lake Sheet, Geological Compilation Series, Ayres, et. al., 1968-1972).
A location and index map is given in this report (see Fig. 1).

The portion of this belt of interest in this thesis was named the "F-Zone" by Tudale Explorations Limited during earlier work and this terminology has been retained. The "F-Zone" is roughly 30m wide by 300m long and may be pinpointed at latitude $52^{\circ}49'$, longitude $93^{\circ}54'$.

At present the only access to the "F-Zone" is by float equipped, fixed wing aircraft into Favourable Lake from Red Lake, a distance of 190 km to the south. From the south end of Favourable Lake it is necessary to traverse by canoe approximately 1 km up the Bearhead River followed by a short traverse on foot into the study area.



Scale: 1" = 4 mi.

▲ = known U showings

Fig. 1 : Location map and regional geology

2. Previous Work:

The belt of anomalous uranium mineralization between Favourable and Bearhead Lakes has been known since the mid 1950's. However, not until the late 1960's was any significant mapping or exploration carried out.

The most extensive work done in the area has been by Tudale Explorations Limited. This group carried out extensive geological bedrock mapping, trenching and drilling operations along the belt's entire length during the period 1969-1971 in order to determine any economic potential. Tudale presently holds 14 claims along the belt with the "F-Zone" lying within claim # KRL58526 (Claim Map Area Sheet #M.2881). Details of Tudale's work are available from open file #63.2487, Assessment Files Research Office, 77 Grenville St., 8th Floor, Toronto.

Reconnaissance geological mapping at scale of 1:125,000 and 1:15,840 has been carried out in the area by the Ontario Geological Survey (Ayres, 1968, 1969, 1972). As well, this area was covered as part of a reconnaissance programme involving ground evaluation of airborne radiometric anomalies over roughly 140,000 km^2 of northwestern Ontario by the Ontario Geological Survey during the 1978 field season (Breaks & Bond, 1978).

3. Statement of Problem:

During the 1978 field season, while under the employ of the Ontario Geological Survey, the author was granted several days in which to carry out field studies of the "F-Zone".

Previous work by Tudale Exploration Limited had identified the anomalous belt as a pegmatitic uranium-bearing contact zone between a large mass of gneissic red granite to the south and a granite migmatite complex to the north. The gneissic red granite was believed to be a metasomatic granite derived by deep-seated regional metamorphism and granitization of metasedimentary rocks similar to those found to the north of the contact. Uranium would thus be concentrated in fluids during granitization and then further concentrated and redistributed by late stage hydrothermal activity.

The aim of this investigation was to map and sample, in detail, a small part of the contact zone and the units on either side of it to determine: (a) any relationships (petrologic and chemical) between the contact zone rocks and the country rock; (b) the source of the granite batholith, and; (c) possible sources for the uranium mineralization. The "F-Zone" was selected as the best section for this purpose because it showed the highest radiation levels and the most interesting petrographic assemblage.

Some 75 samples were collected from the batholith, contact zone and outcrops to the north (see Fig. 2). Of these

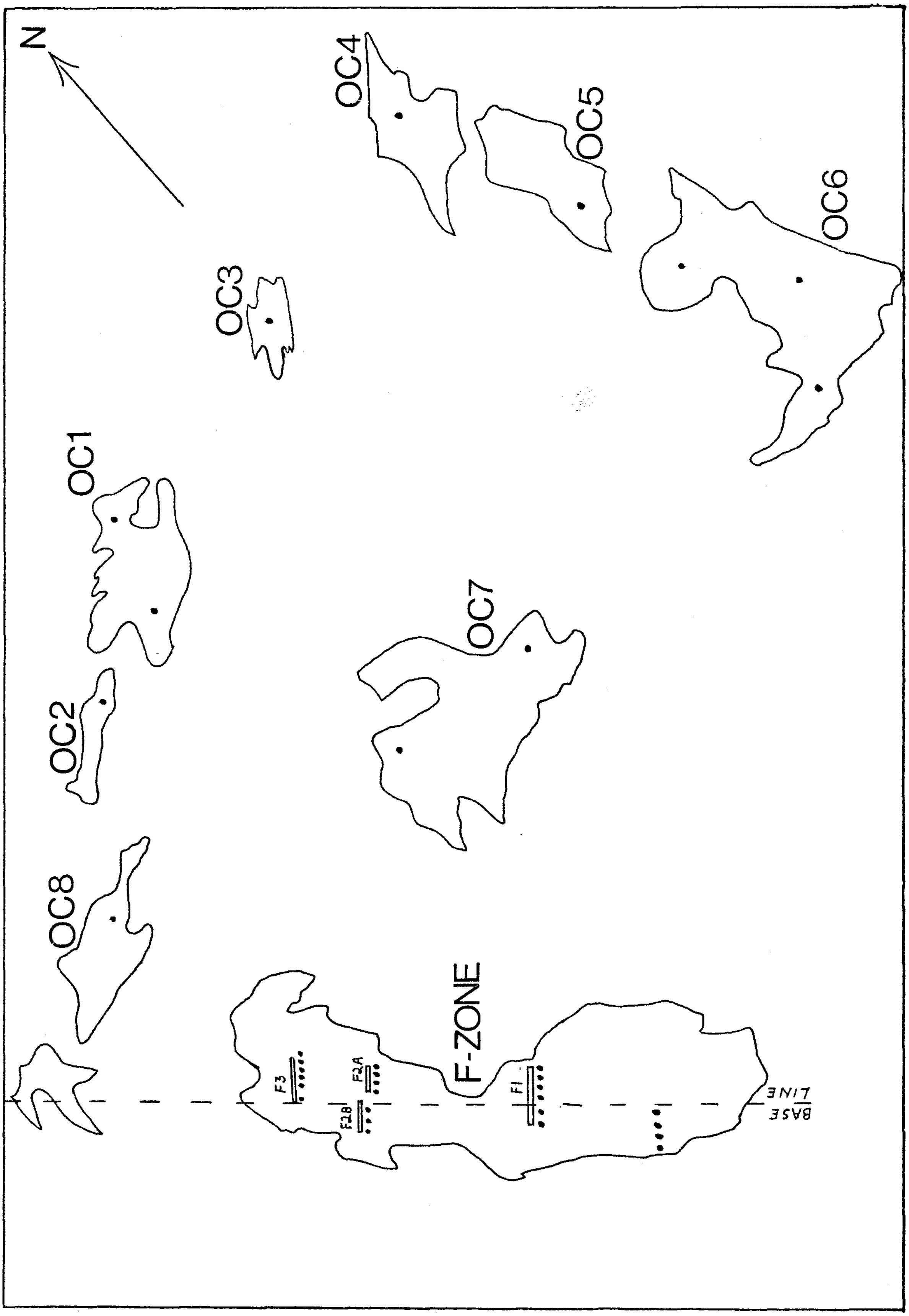


Fig. 2 : Sample location map.

30 representative samples were selected for thin section analysis, 25 were prepared for chemical analysis by X-ray fluorescence and 20 were analysed for rare earth elements by instrumental neutron activation analysis at McMaster University.

4. Method of Mapping and Sampling:

In order to allow for mapping on a very detailed scale (1" = 5 m) it was necessary to spend two days setting up a grid system at 10 m spacing over most of the study area. This grid system was based on tape and compass measurements.

A total of four trenches had been excavated previously by Tudale and these aided in providing a detailed three-dimensional view of parts of the contact zone. Sampling of the contact zone was carried out primarily along these trenches which allowed large, relatively fresh samples to be taken.

Samples of the Setting Net Batholith were taken at 10 m intervals along a line running perpendicular to the contact. Poor exposure limited further sampling of the batholith in this area. The unit to the north of the contact zone was sampled at various random outcrops.

5. Geophysical Survey:

A detailed scintillometer survey was conducted over the same grid system used for mapping. In general, readings were not taken over trenches since any such readings would be expected to give higher values compared to readings taken over weathered surfaces.

A McPhar Spectra 44-D scintillation counter was used to determine K, U and Th. Scintillometer readings were then processed by the OGS to give ppm U and Th and K in weight percent. The U concentrations have been plotted and contoured on a base map of the "F-Zone" (see Uranium contour map in back pocket).

CHAPTER II

GENERAL GEOLOGY

1. Regional Geology:

The Favourable Lake - Bearhead Lake area is characterized by a south-southeast trending metavolcanic-metasedimentary belt extending from Northwind Lake to the Ontario-Manitoba border and outcropping along the north shores of Favourable and Setting Net Lakes (Ayres, 1968, 1969) (see Fig. 1).

As exposed in the vicinity of Setting Net Lake this belt consists of a 7.5 km thick, isoclinally folded sequence of Early Precambrian metavolcanics and derived metasediments representing five progressive stages (cycles) in the development of the greenstone complex (Ayres, 1977). This complex has attracted a good deal of attention in the past as a result of the presence of economic deposits of gold, silver, nickel, molybdenum and others. However, the remoteness of the area has hindered exploitation of these resources.

The greenstone belt is bounded to the north and south by younger granitic batholiths. The batholith to the south is known as the Setting Net Lake Batholith. This is a large (∿ 2700 sq km) granitic to granodioritic rock mass which is multiphase in nature.

The position of the northern contact of this batholith is uncertain. Ayres (1969) believed the batholith was in direct contact with the greenstone complex and that the migmatite belt lay within the batholith. However, recent mapping (Breaks & Bond; this author, 1978) has placed the contact of the batholith to correspond to the migmatite belt. The rocks to the north of this belt have been termed "homogeneous diatexites" (Brown, 1973) based on textures and characteristics observed in field and may or may not be genetically related to the batholith.

A large fault known as the Bearhead Fault runs roughly parallel to the greenstone belt over its entire length. According to Ayres (1969) this fault is a roughly vertical dip-slip fault with an upthrust southern block. In the Favourable Lake - Bearhead Lake area the fault runs parallel to, and 2 km to the north of, the migmatite belt. The fault is believed to postdate all other features in the area.

2. The "F-Zone":

Based on mineralogical and textural criteria (see Chapter III) the migmatite zone and surrounding outcrops have been subdivided into several phases. These phases are as follows:

1. Granite (Setting Net Batholith)
2. Homogeneous diatexite
3. Pegmatitic Pyroxene Granite
4. Pegmatitic Biotite Granite
5. Pegmatitic Pyroxene Syenite
6. Quartz-rich biotite granitoid
7. Metasediments and metavolcanics

A map showing the distribution of these phases can be found in the back folder of this text.

(a) Migmatite Zone:

Within the migmatite zone itself phases tend to be very coarse-grained to pegmatitic. Contacts between phases are gradational and were mapped in the field on the basis of grain size and mafic minerals present (biotite, pyroxene).

The distribution of phases is very irregular with no one phase persisting along the entire strike length of the zone. There is however a crude zonation present within the zone. Adjacent to the batholith pyroxene syenite and pyroxene granite are dominant rock types. Progressing away from the contact pyroxene wanes in abundance and becomes subordinate to biotite as the common mafic mineral. Sphene is also abundant along the contact and becomes less abundant moving away from it.

All units within the pegmatite zone show a moderately well developed lineation or gneissosity trending parallel to the batholith contact. This gneissosity results from a preferred orientation of mafic minerals, predominantly biotite.

Relict rafts of metasediments (biotite gneiss) and metavolcanics (hornblende gneiss) are common in the migmatite zone. The contacts of these rafts range from sharp to gradational and the rafts themselves appear to have undergone various degrees of recrystallization. The surrounding granitic phases are usually coarser grained where in contact with the rafts.

(b) Setting Net Lake Batholith:

The Setting Net Lake Batholith, as exposed south of the "F-Zone", is a homogeneous, medium grained, granitic rock mass. As with many batholithic intrusions a weak gneissosity is evident due to the alignment of mafic minerals. The contact between the batholith and the migmatite zone is gradational and was established in the field as the point of appearance of visible sphene and pyroxene.

Again small rafts of hornblende and biotite gneiss are present. They have a random orientation and show sharp contacts with the batholith rocks. Where in contact with these rafts the batholith tends to be finer grained suggesting a chilled relationship.

(c) Homogeneous Diatexite:

According to Brown (1973) diatexis is "high grade anatexis in which fusion may be complete" and, therefore, a diatexite is "a rock produced by diatexis in which there is no continuous magmatic banding". This rock possesses a plutonic, granitoid appearance and so is almost invariably mapped as a plutonic, igneous rock.

According to Breaks and Bond (1977) diatexites possess several features which allow them to be distinguished from common plutonic rocks in the field:

(1) remnants of paleosome are nearly always present,

(2) a "turbulent" character with abundant contorted, plastically deformed inclusions is often notable,

(3) wide range in grain size even within one hand specimen.

A medium- to coarse-grained average grain size is most prevalent, although pegmatitic equivalents are common.

(4) distinctive earthy-white weathered surface,

(5) characteristic accessory minerals such as almandine and/or cordierite and/or sillimanite may be present.

The composition of diatexites ranges between granite and trondhjemite. A homogeneous diatexite is, as the name suggests, homogeneous in composition with less than 10% inclusions.

The units to the north of the "F-Zone" fit all of these criteria being granitic in composition, variable in grain size and texture and containing 10-15% contorted biotite and hornblende gneiss inclusions. Cordierite, sphene and allanite were all noted in the field as accessory minerals.

CHAPTER III

PETROGRAPHY

1. Modal Analyses:

Due to the coarse-grained nature of most units it was possible to do visual point counting of stained slabs. Some of the finer grained units required point counting of thin sections. In both cases the specimens were stained for potassium feldspar and a total of 500 counts were counted for each.

The modal proportions of plagioclase, alkali feldspar and quartz (see Table I) were plotted according to Streckeisen (1976) (See Fig. 3). This diagram, when supplemented with field and textural evidence helped to classify the various phases.

2. Phase Descriptions:

(i) Granite-Setting Net Batholith:

Modally this unit plots within the granite field in the Streckeisen classification scheme (Streckeisen, 1976, see Fig. 3). The rock is medium-grained, holocrystalline and hypidiomorphic granular in texture with potassium feldspar, plagioclase and quartz making up the essential minerals. Orthoclase and microcline are present in approximately equal

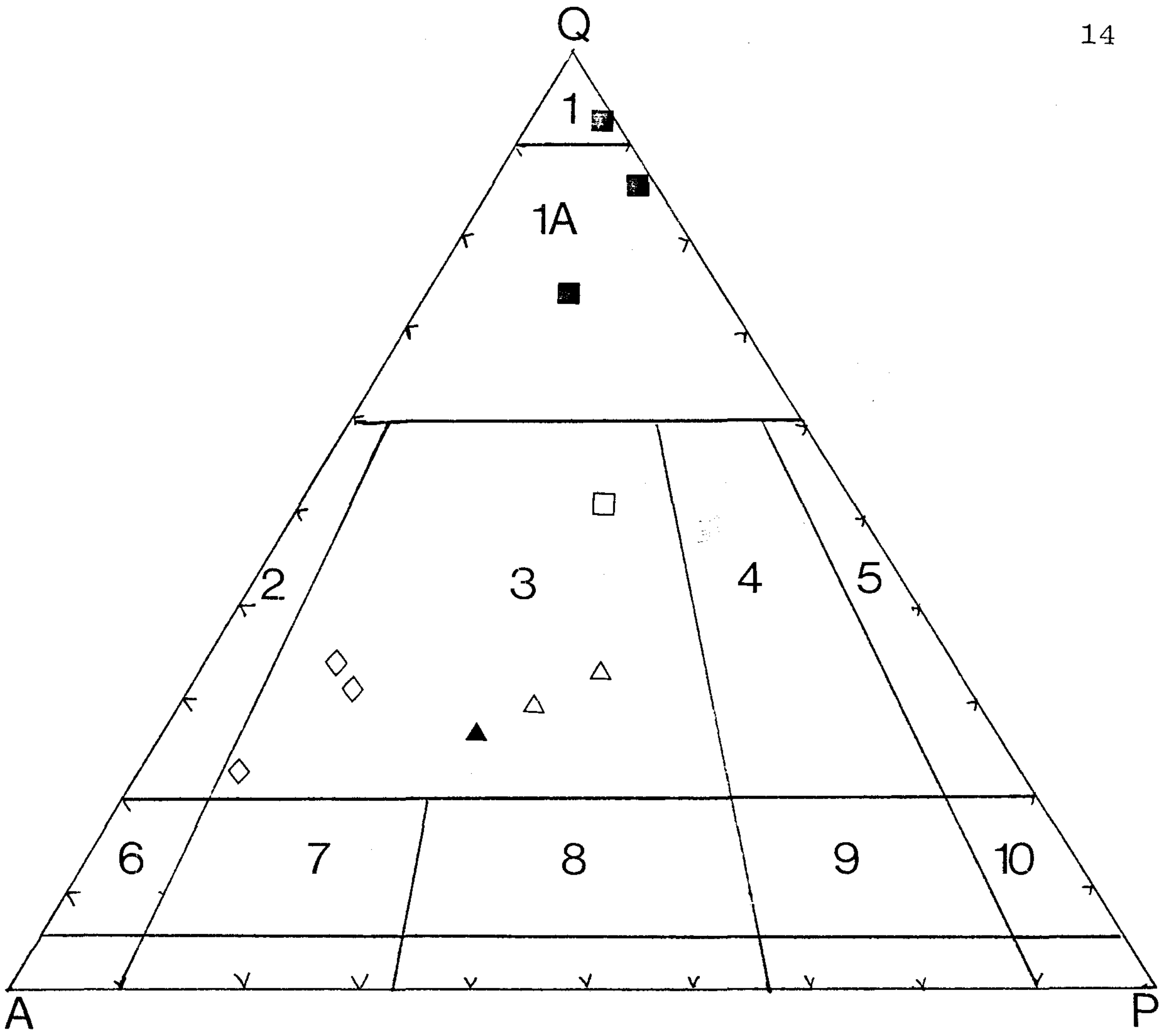


Fig. 3: Qtz-Alkali Feldspar -- Plagioclase Diagram (IUGS, 1973)

1. Quartzolite
1A. Quartz-rich granitoid
2. Alkali feldspar granite
3. Granite
4. Granodiorite
5. Tonalite
6. Alkali-feldspar quartz syenite
7. Quartz syenite
8. Quartz monzonite
9. Quartz monzodiorite
10. Quartz diorite

Legend:
■= Quartz-Biotite Granite
◇= Pegmatitic Pyroxene Granite
▲= Setting Net Batholith
△= Homogeneous Diatexite
◆= metased-metavolc
□= Pegmatitic Biotite granite

proportions. Both tend to be anhedral. No perthite was observed.

Plagioclase averages 25% of the unit. In a few instances it is observed to be subhedral in habit. Generally, however it is anhedral due to alteration and the formation of myrmekite between it and the potassium feldspars. Invariably the plagioclase is partially altered to sericite.

Quartz fills interstices between the feldspars. It comprises roughly 20% of the unit and is characterized by anhedral, lobate habit, sutured boundaries between grains and undulose extinction.

Biotite is the prominent mafic mineral and it too fills interstices making up less than 5% of the unit.

Common accessories are epidote, allanite and anhedral sphene. All are present in trace amounts only (< 1%).

(ii) Homogeneous diatexite:

This unit also plots as a granite in the Streckeisen scheme. As will be seen later it is also very similar to the granite batholith in chemical composition. Therefore, the classification of homogeneous diatexite has been used to otherwise distinguish it from the granite batholith.

Although this unit shows little compositional difference from the batholith it does exhibit a marked variation in grain

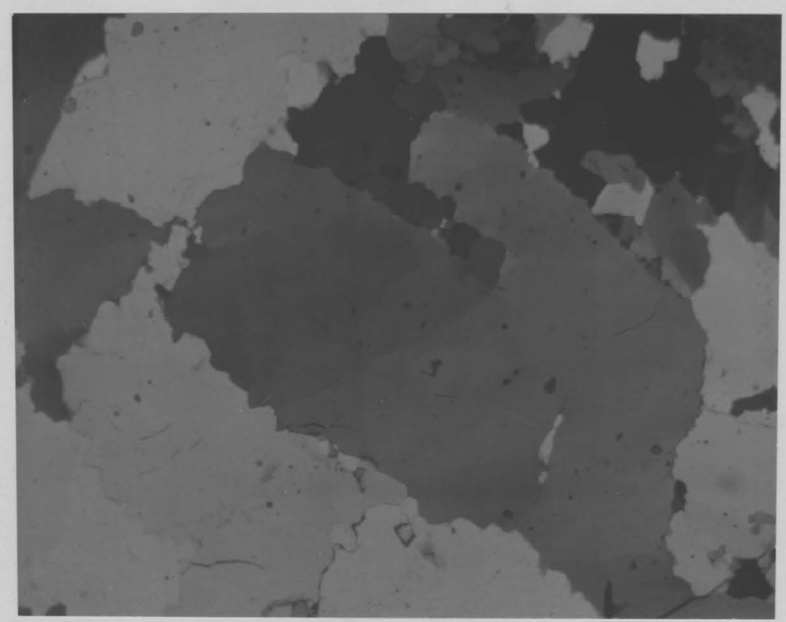


Plate 1: Typical undulose quartz with sutured boundaries. 40 x Magnification.

Plate 2: Subhedral sphene surrounded by microcline, plagioclase and quartz (x-nicols) 10 x Magnification.

size and texture ranging from medium- to coarse-grained and from massive to porphyritic. This behaviour is typical of diatexites.

The phenocrysts in the porphyritic phases are potassium feldspar of subhedral to euhedral habit.

Accessory minerals in the diatexite include allanite, epidote/clinozoisite and sphene. Cordierite was observed in the field but not detected in thin section.

(iii) Pegmatitic Pyroxene Granite:

This unit plots in the granite region of Streckeisen's (1976) classification diagram. It is characterized by a generally coarse-grained to pegmatitic (1 - 3 cm) texture as well as the presence of up to 10% aegirine-augite.

In hand specimen the pyroxene appears as large (∿ 2 cm), hypidiomorphic crystals with a spongy texture. Under the microscope the pyroxene is poikilitic, commonly with inclusions of euhedral apatite and rimmed by hornblende and actinolite. The pyroxene wraps around euhedral sphene suggesting that it crystallized later than the sphene. The amphibole rims are indicative of either retrograde autometasomatism, late stage hydrothermal activity or a combination of both.

Potassium feldspar, plagioclase and quartz show the same textural relationships as in the above two units. Hints of

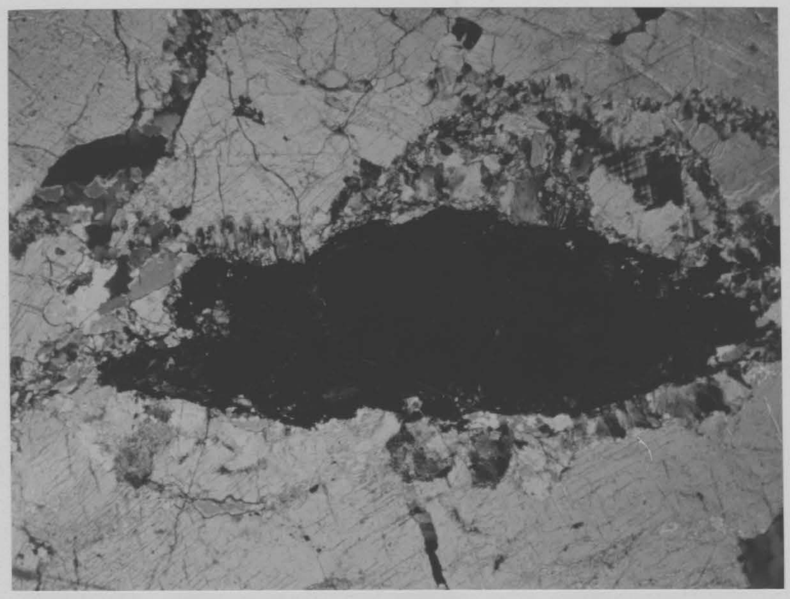


Plate 3: Pyroxene rimmed by myrmekitic intergrowth. 10 x Magnification.

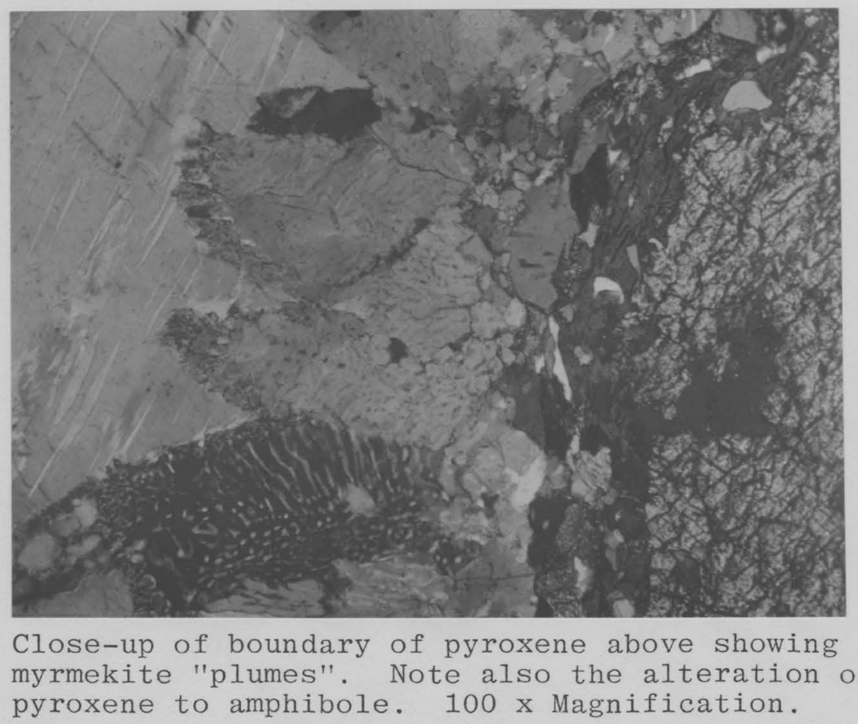


Plate 4: Close-up of boundary of pyroxene above showing myrmekite "plumes". Note also the alteration of pyroxene to amphibole. 100 x Magnification.

flame perthite are evident. Myrmekitic intergrowth is slightly more common in the pegmatitic pyroxene granite and is particularly well developed around the pyroxenes.

The most prominent accessory mineral is sphene. It is generally euhedral and may comprise up to 5% of the rock locally. Other accessories include epidote, biotite and trace molybdenite (< 1%).

(iv) Pegmatitic Biotite Granite:

This unit plots as a granite in the Streckeisen scheme but is distinguished from the pyroxene granite by the presence of biotite as the major mafic constituent. The unit is coarse-grained to pegmatitic, holocrystalline and hypidiomorphic granular. Potassium feldspar is the main felsic constituent making up roughly 50% of the rock. The development of flame and patch perthite is very common. The perthite quite often encloses anhedral grains of plagioclase. These grains are distinctive in that they commonly possess a sericitized core surrounded by clean, well twinned albite. The source of the albite is most likely exsolution from the potassium feldspar during the formation of perthite.

Anhedral quartz with sutured boundaries and undulose extinction is interstitial to the feldspars.

As stated earlier biotite is the major mafic mineral.

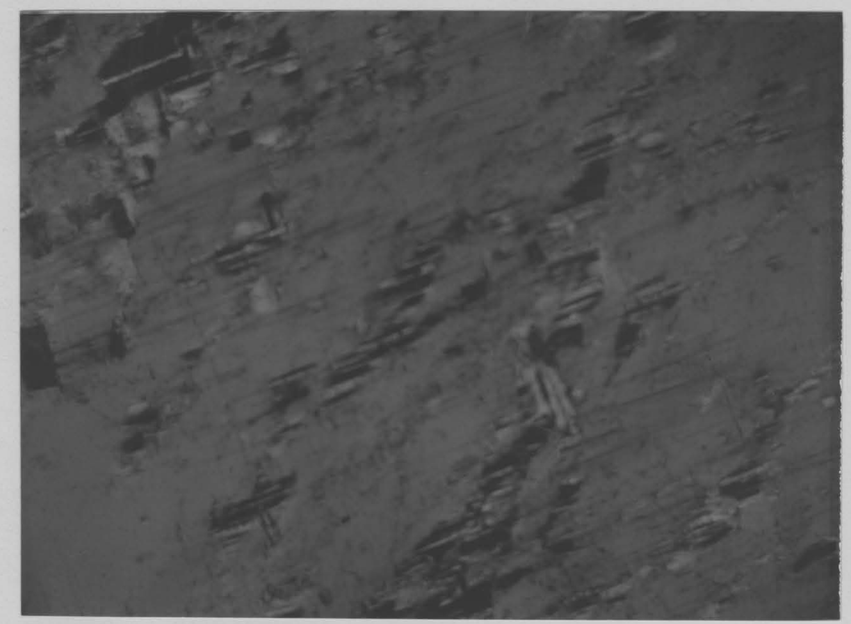


Plate 5: Patch perthite. 40 x Magnification.

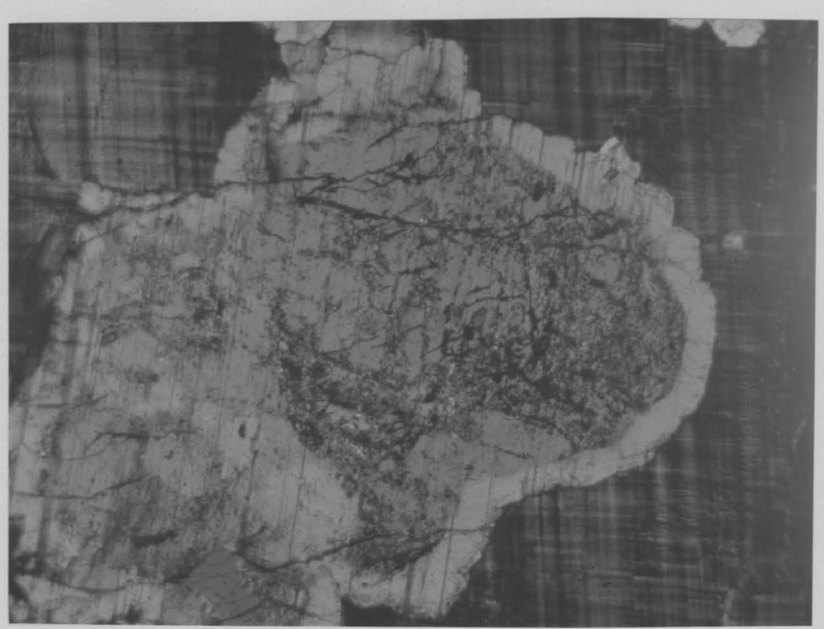


Plate 6: Sericitized plagioclase with clean albite rim enclosed in microcline. 40 x Magnification.

Quite often it is found in clots or "books" and always shows a preferred orientation lending a gneissic fabric to the rock. The biotite is characterized by pleochroic haloes and in one thin section it was observed to be distinctly twinned.

Accessory minerals present are sphene, hornblende and pyroxene.

(v) Quartz-rich Biotite Granitoid:

A very quartz-rich unit, this rock type plots in the quartz-rich granitoid and quartzolite fields in the Streckeisen scheme. Biotite is common and occurs as clots or well developed "books". Orthoclase, microcline and plagioclase are also present in amounts varying from 0 - 30% of the total rock. All three are allotriomorphic granular. The plagioclase is highly sericitized.

Quartz varies in habit from coarse-grained with interlobate boundaries to fine-grained and "sugary". In all cases it shows undulose extinction. Small fracture zones running throughout the quartz are common.

Accessory phases of note are epidote and chlorite.

(vi) Pegmatitic Pyroxene Syenite:

Although this unit makes up only a small part of the migmatite zone it is definitely the most interesting from a petrographic standpoint. Compositionally it consists of roughly equal proportions of pyroxene, potassium feldspar and sphene along with up to 3% molybdenite. Grain size averages 2 - 3 cm with the sphenes commonly being 1 - 2 cm long. Quartz and plagioclase make up less than 10% of the unit.

The sphene is invariably euhedral although, in many cases, individual crystals have been broken. All other constituents are anhedral.

Molybdenite occurs as flakes or "leafs" ranging from .5 - 1 cm across and is found along boundaries between grains.

Another common accessory mineral is allanite. In thin section it appears surrounded by distinctive radiating fractures and this, combined with its reddy-brown colour makes it easily identifiable.

(vii) Metasediments and Metavolcanics:

Remnants or "rafts" of metasedimentary and metavolcanic material are common in the migmatite zone and homogeneous diatexite and to a lesser extent in the batholith. These rafts generally appear highly deformed with internal folding

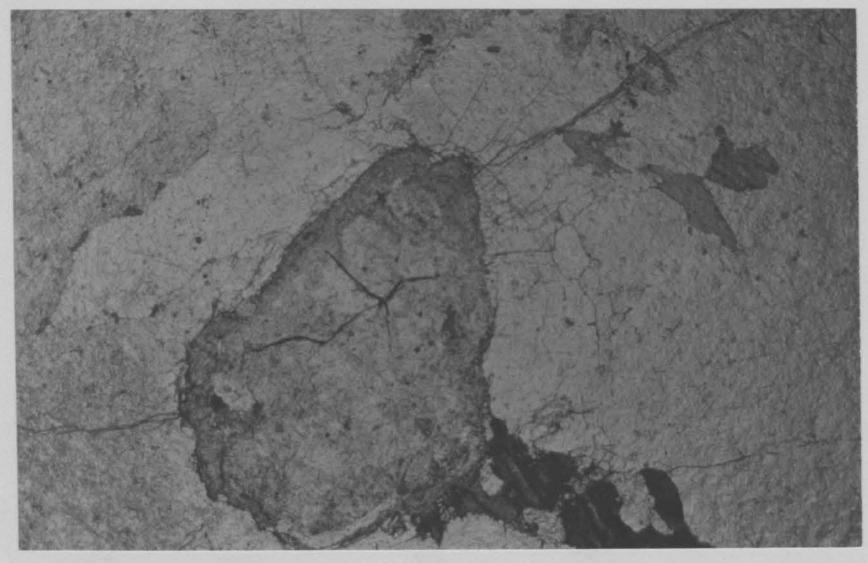


Plate 7: Allanite (medium grey) showing characteristic radiating fractures. 40 x Magnification.

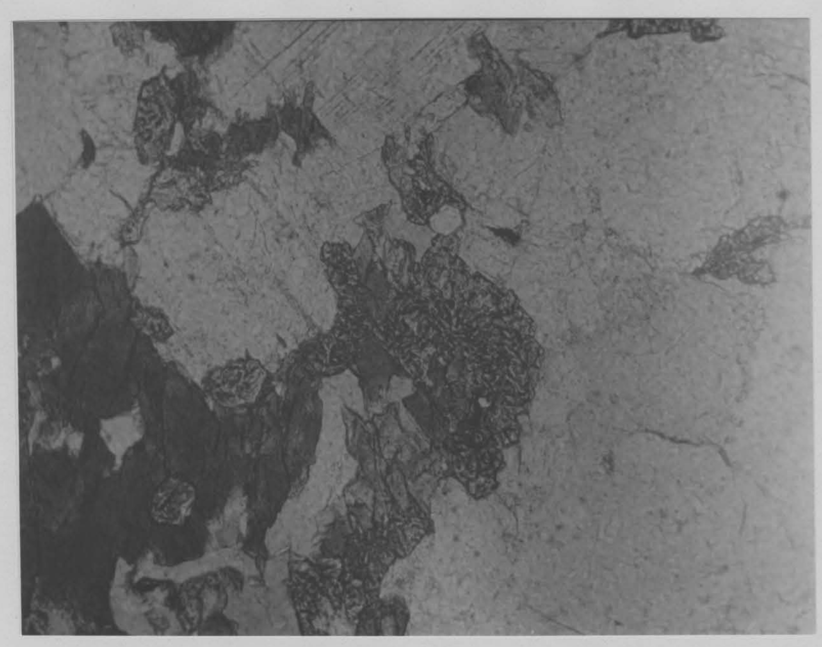


Plate 8: Vermicular clinozoisite associated with amphibole. Note also the euhedral grain of apatite near center of photo. 40 x Magnification.

of the foliation being evident in many cases.

The metasedimentary material is most common. Compositionally this material is a well banded biotite gneiss. The melanosome consists primarily of biotite plus hornblende. Vermicular clinozoisite is also common and most likely arises through retrograde autometasomatism involving hornblende and biotite. As the rocks cooled following diatexis the clinozoisite would form via the reaction:

$$\text{hornblende} + \text{biotite} \rightarrow \text{clinozoisite} + SiO_2$$

Of note within the migmatite zone were two rafts of meta-iron formation. These rocks, when studied in thin section, turned out to be composed of 70% quartz, 20% grunerite and 10% disseminated opaque blebs. The grunerite was polysynthetically twinned and very distinctive.

Metavolcanic rafts consisted of hornblende of unknown composition plus equant laths of unaltered labradorite.

One feature of note is that pyroxene and sphene are almost always found around the contacts of the metasediments. This type of a relationship could be explained by the reaction:

$$\text{Anorthite} + \text{Biotite} + \text{Qtz} \rightarrow \text{sphene} + \text{cpx} + \text{K - spar} + \text{water}$$

This reaction would only be expected to occur under water-poor conditions.

3. Petrographic Summary:

The following mineralogical and textural characteristics are of note:

(1) presence of K-feldspar as the predominant feldspar.

(2) the presence of clinopyroxene and sphene along the batholith contact and around metasedimentary rafts within the migmatite zone suggests initially very dry conditions. In being dry it is implied that conditions were also very hot since granitic material will melt at higher temperatures if insufficient water is available (Tuttle & Bowen, 1958).

(3) an increase in the abundance of perthite in the migmatite zone. This fact, coupled with replacement of pyroxene by hornblende and sericitization of the plagioclase suggests late-stage metasomatism by alkaline-water rich fluids.

(4) the formation of clinozoisite in metasedimentary remnants via autometasomatism as the rocks cooled following diatexis.

CHAPTER IV

ELEMENTAL GEOCHEMISTRY

1. Major and Trace Element Variations:

(a) Analytical Methods:

Both major and trace element concentrations were obtained using a Philips Model PW 1450 AHP automatic sequential X-ray fluorescence spectrometer at McMaster University. The elements Si, Al, Fe, Mg, Ca, K, Ti, Mn and P were analysed using a Cr X-ray tube while Rb, Sr, Y, Zr, Nb, S, Ni, Cr, Co, Pb, Cu, Zn and As were analysed with a Mo X-ray tube.

Both powder pellets and fusion pellets were prepared. Powder pellets prepared by the procedure outlined by Marchand (1973) were used for the measurement of trace element concentrations. Major element concentrations were obtained on fusion pellets which were made following the procedure outlined by Hutchinson (1974).

In order to check the accuracy of XRF analyses, several standards were run with the samples and compared to recommended values (Abbey 1977). Standards used include GSP-1, W-1, BCR-1, NlM-G, NlM-L, JR-1, JG-1, NlM-D, SY-1, SY-2 and SY-3. As well, one standard remained in the machine through the entire time and acted as a drift monitor.

Normative values were obtained using a Barth mesonorm program (Birk, 1975).

Major and trace element data as well as normative data have been tabulated in Appendix A.

(b) Major Element Trends:

Several petro-chemical variation diagrams have been employed to discern any relationships or trends which may have bearing on petrogenesis of the various units.

Two variation diagrams concerned with the Qtz-Ab-Or-An system have been used. Fig. 4 is a plot of this system projected onto the Q-Ab-Or plane. It shows that samples from the Setting Net Batholith and homogeneous diatexite cluster in a tight group within Winkler and Van Platen's (1961) area for granitic rocks. The samples of various units from the migmatite zone however tend to plot closer to the Or and Qtz apices of the diagram.

Preliminary interpretation of these trends would suggest that the batholith and diatexite represent crystallization from a granitic magma while the migmatites reflect the effects of residual SiO_2 and K_2O - rich fluids.

Kleeman (1965) urges caution in the use of Q-Ab-Or diagrams. He claims that rocks plotted on this type of diagram tend to plot closer to the Or apex than they should. He suggests that the use of an Or-Ab-An diagram is more representative of the Q-Or-Ab-An system in the case of granitic melts produced from partial fusion of sedimentary material. The

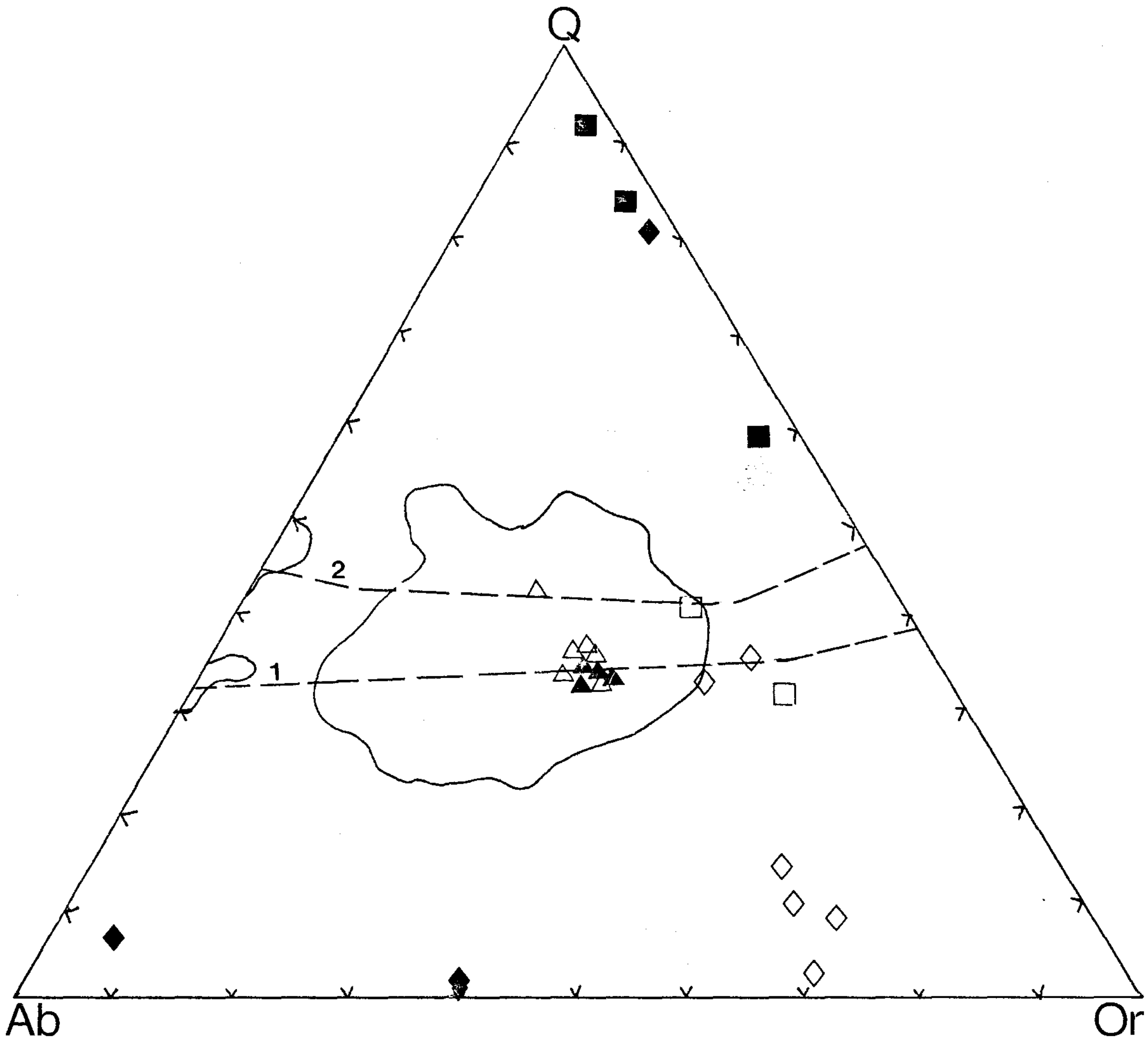


Fig. 4 : Normative Q-Ab-Or ternary plot. Solid irregular line is Winkler and Van Platen's (1961) area for granitic rocks. Dashed lines are cotectics in the Q-Ab-Or-H_2O system at P_{H_2O}500 atm (1) and 5000 atm (2) (Condie, 1969).

Legend as in Fig. 3

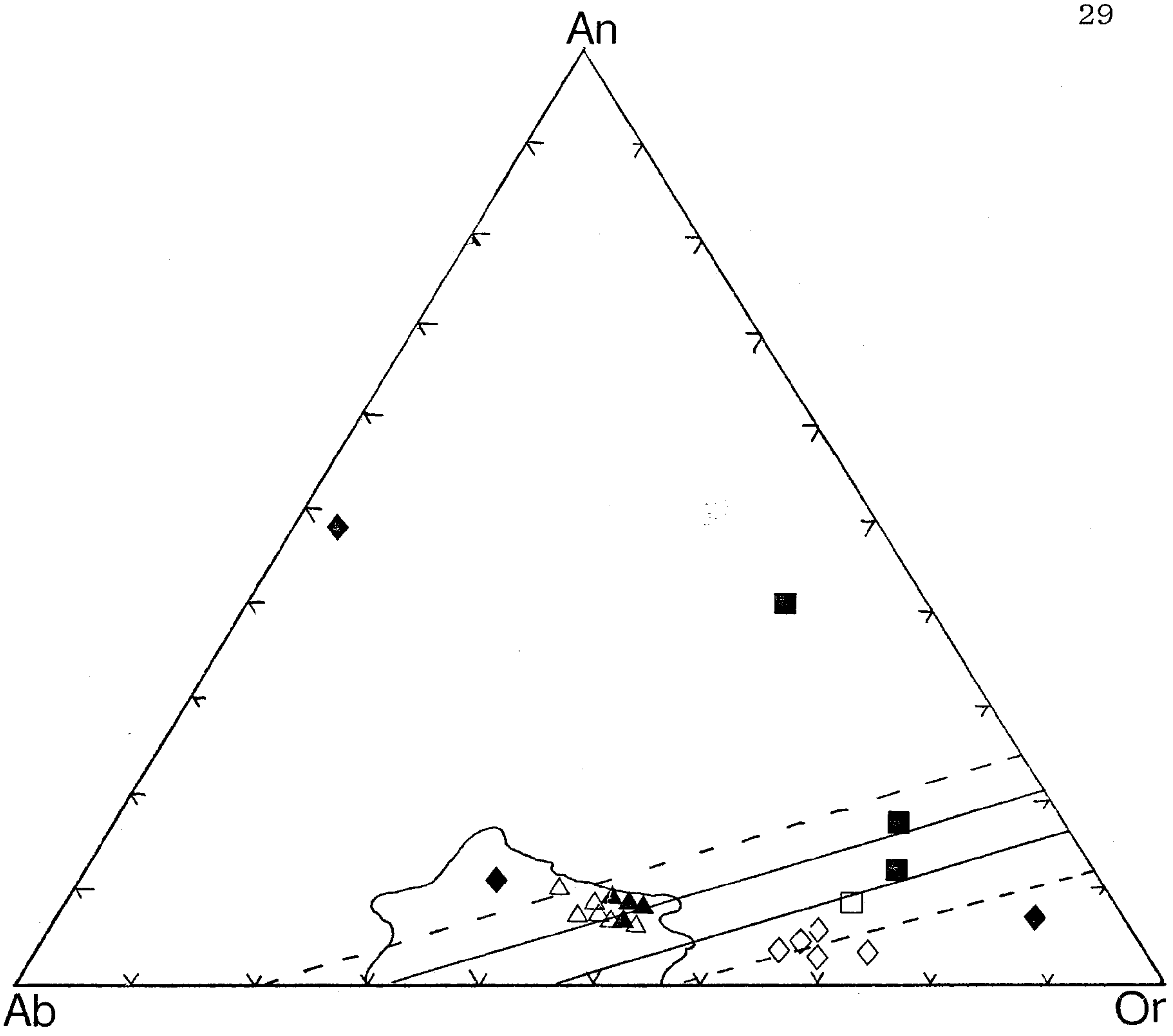


Fig. 5 : Normative An-Ab-Or ternary projection from the quartz apex. Solid straight lines represent the low temperature trough and dashed lines show the uncertainty due to analytical error (Kleeman, 1965). The solid, irregular line represents the "average granites" of Tuttle and Bowen (1958) that contain 80% or more normative Ab+An+Or.

Legend as in Fig. 3

reason for this is that most clastic sedimentary rocks have an excess of silica and hence quartz will be present as a phase up until the final stages of melting.

A plot of An-Ab-Or is given in Fig. 5 showing the low temperature trough of Kleeman (1965) into which the composition of granitic liquids should fall irrespective of pressure. The area for Tuttle and Bowen's (1958) "average granites" is also shown.

Again the batholith and homogeneous diatexite plot in a tight group within the "average granite" field and slightly off the plagioclase side of the low temperature trough. The migmatites plot, on the average, on the orthoclase side of the trough. Thus, all evidence seems to suggest that the batholith and diatexite have arisen from crystallization of a granitic magma produced by the melting of sedimentary rocks while the migmatitic phases show strong evidence for late-stage, hydrothermal activity.

Another feature of note on Fig. 4 is the position of the cotectics for the Q-Ab-Or-An-H_2O system at P_{H_2O} = 500 and 5000 atm. (after Condie 1969). As can be seen the 5000 atm. cotectic passes through the middle of the batholith-diatexite group. Such a high P_{H_2O} suggests crystallization at fair depth rather than close to the surface.

Figure 6 is a plot of the data on an AFM ternary diagram with the "igneous trend" of Green & Poldervaart (1958) superimposed on it. This data shows a strong trend towards enrichment in alkalies.

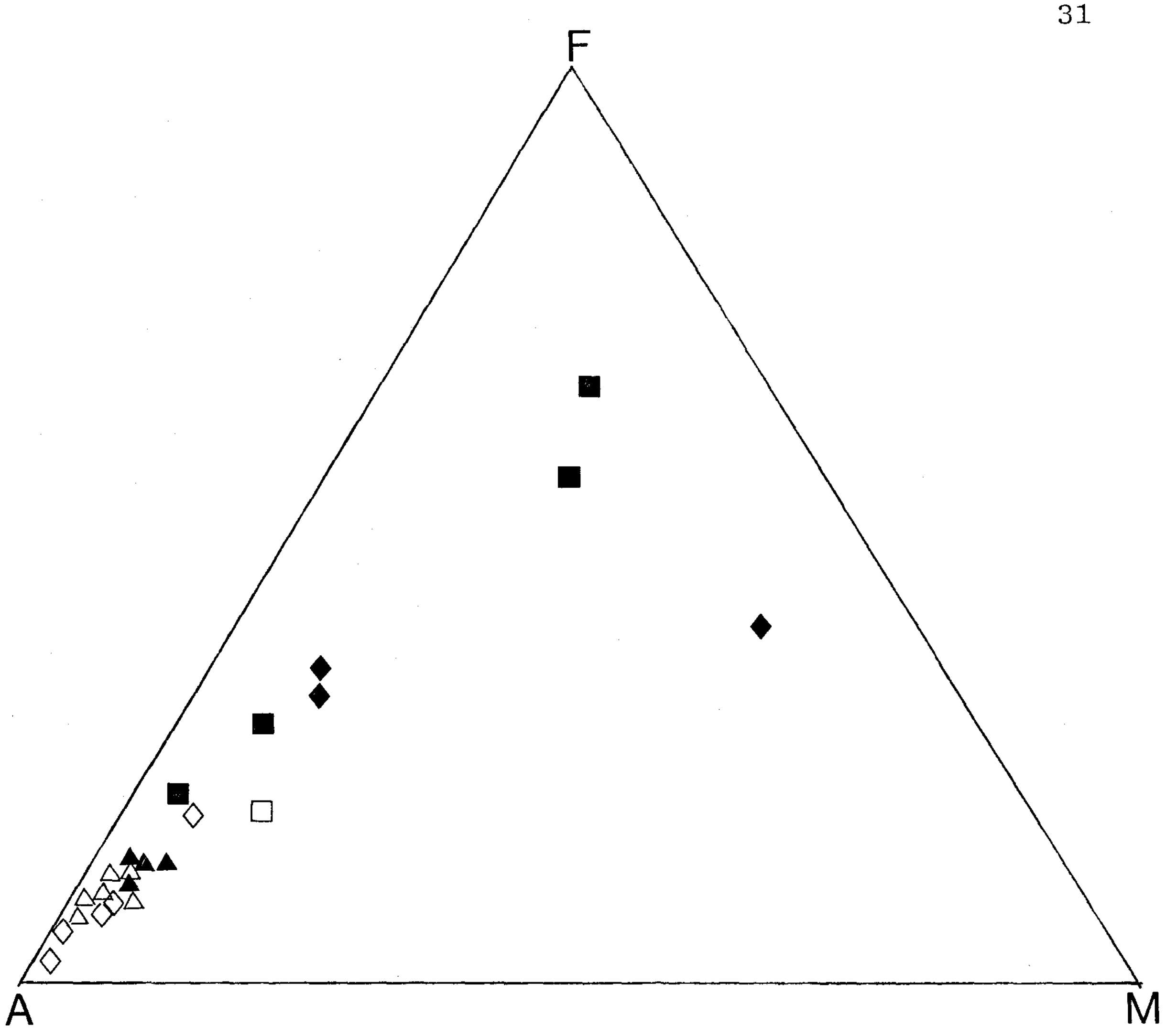


Fig. 6 : AFM

A = Total alkalies

F = Total Fe as Fe_2O_3

M = Total Mg

in cation wt% summed to 100, Legend as in Fig. 3

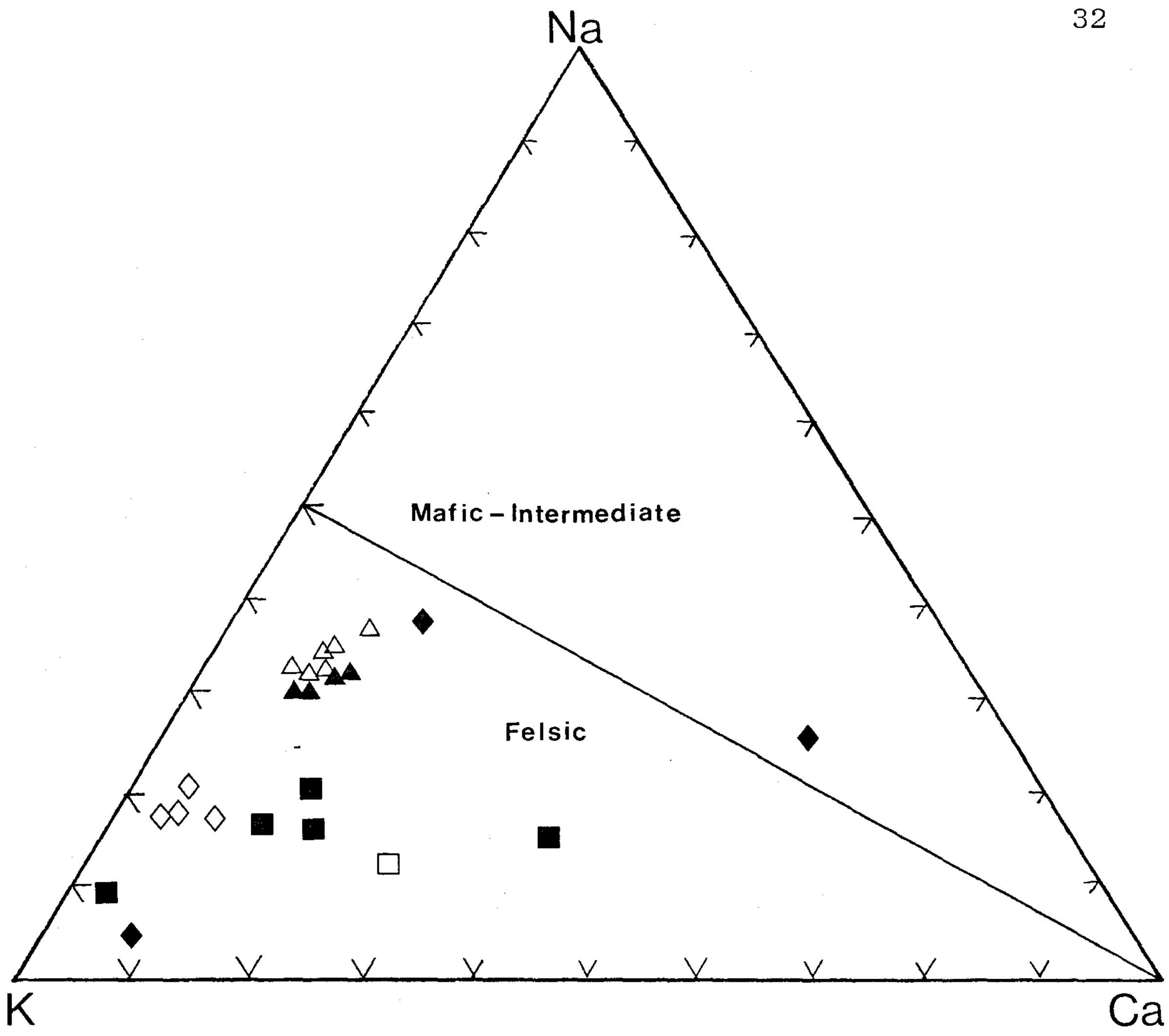


Fig. 7 : Na - Ca - K diagram with mafic-intermediate and felsic regions of Green and Poldervaart (1958).

Figure 7 shows the Ca-Na-K petro-chemical diagram of Green & Poldervaart (1958) with their meridian line for fractionation of mafic to felsic assemblages. As can be seen all units (except for a metavolcanic raft) plot in the felsic area with the migmatite zone rocks plotting closer to the K apex. Green & Poldervaart suggest that the production of potassic rocks indicates that locally operative processes dominate over those of fractionation.

(c) Trace Element Trends:

The application of trace element data to problems in petrology has become an increasingly more powerful tool over the past 10-15 years with the development of more accurate analytical techniques. The behaviour of many trace elements during crystallization of magmas is now well understood and several of these trends have been considered with regards to the "F-Zone".

(i) K-Rb Trends:

Rubidium is very similar in size and chemical character to potassium and so the two show a close association or "coherence" in igneous processes. Shaw (1968) suggested that the most likely mechanism for fractionation of K and Rb is partitioning between silicate melt and one of (a) biotite, (b) aqueous phase (decrease in K/Rb) or (c) amphibole (increase in K/Rb). During anatexis of a biotite gneiss the expected phases would be aqueous fluid (low K/Rb), silicate melt (normal K/Rb) and residual gneiss (higher K/Rb).

Applying this to the "F-Zone" then, it would be expected that the batholith and diatexite should have normal K/Rb since they crystallized from anatectic melts (average crustal K/Rb = 230, Shaw, 1968). The migmatites should have low K/Rb and the metasedimentary remnants higher K/Rb.

Figure 8 shows a plot of K vs Rb. It can be seen that the batholith and diatexite do show normal ratios and that the quartz-rich granitoids from the migmatite zone have very much lower ratios. However, the pegmatitic units show normal or even slightly elevated ratios. This trend is most likely due to the high proportion of K-feldspar and biotite in these units which would tend to concentrate potassium and keep the K/Rb ratio high. Condie (1969) noted in studies of the Laramie batholith that pegmatitic and aplitic veins showed normal K/Rb ratios when they should have been lower. He offered no explanation for this.

In conclusion, K/Rb ratios indicate that the quartz-rich phases in the migmatite zone represent the most fractionated material while the batholith and diatexite are the least fractionated.

Fig. 8 : K(wt%) vs Rb (ppm). Legend as in Fig.3

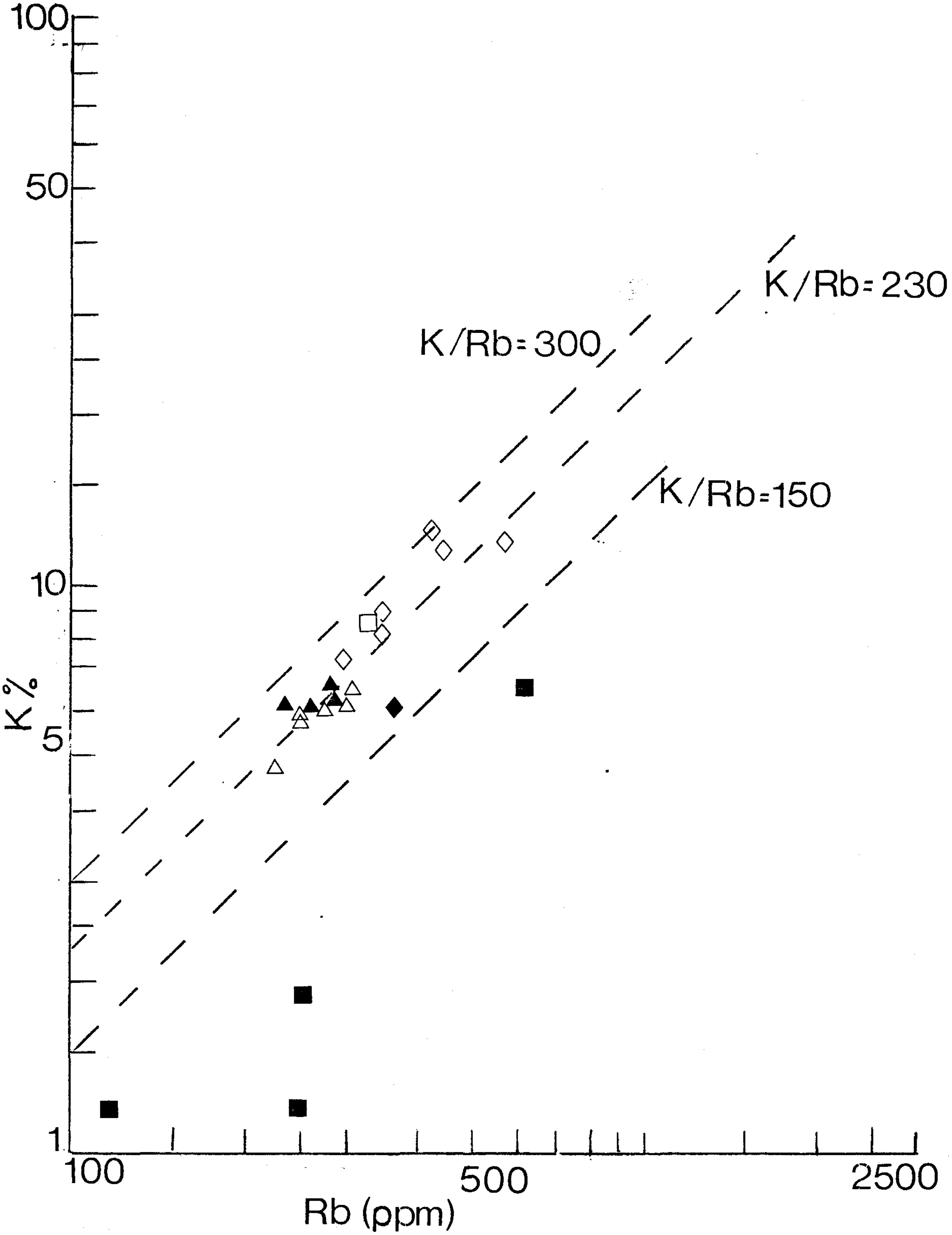


TABLE 1 AVERAGE Rb, Sr, Rb/Sr and K/Rb

	Setting Net Batholith	Homogeneous Diatexite	Pyroxene Granite	Biotite Granite	Quartz-Biotite Granitoid	Metavolcanic Raft	Metasediment Raft
Rb ppm (average)	267	268	331	395	425	11	365
Sr ppm (average)	199	163	169	157	29	166	246
Rb/Sr (average)	1.34	1.64	1.96	2.52	14.66	.07	1.48
K/Rb (average)	238	223	263	276	33	3323	169
Addendum:							
*Cs	6.7	6.0		1.2	1.1	-	.9

*Analysed by neutron activation at McMaster University.

(ii) Rubidium-Strontium Trends:

Data from the Setting Net Batholith and homogeneous diatexite have been plotted on a Rb-Sr grid after Condie (1973), (see Figure 9). The various fields on this grid indicate crustal thickness and have been constructed from detailed Rb/Sr geochemistry and geophysical studies of modern volcanic environments. This plot shows that the batholith and diatexite again cluster in a tight group, have Rb/Sr ratios of > 1 and lie in the > 30 km crustal thickness field. This depth must be taken with a grain of salt since the behaviour of Rb and Sr under anatectic processes could be expected to differ from their behaviour in volcanic processes, the data from which has been used to construct the grid.

Of possible significance is the fact that the batholith and diatexite do plot together which would seem to indicate that they both formed at roughly the same depth, whatever that depth may have been.

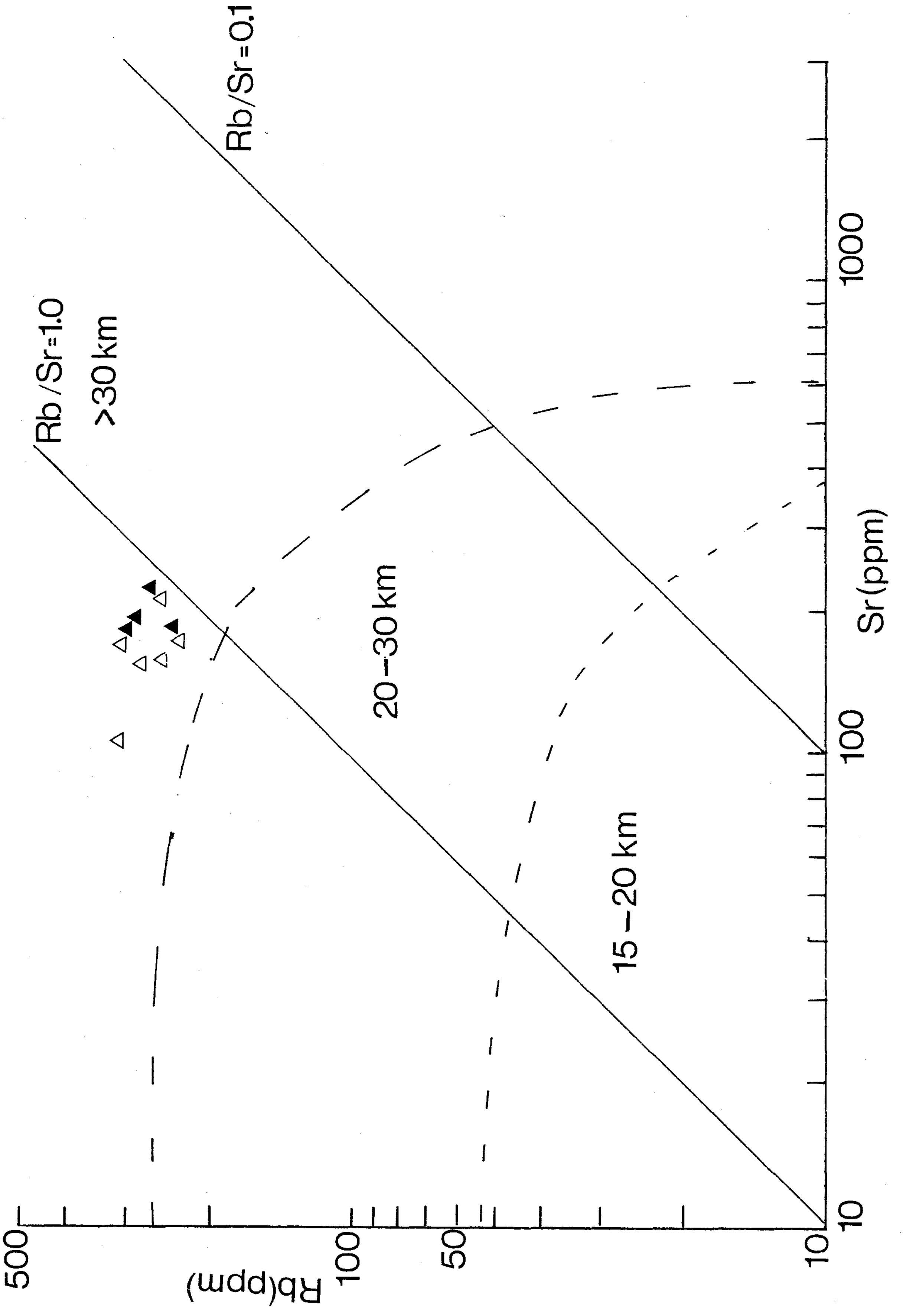
(iii) Uranium and Thorium:

Geochemistry of Uranium:

Uranium occurs in six valence states of which +1, +2, +3 and +5 are unimportant in nature. U^{+4} ion is the most abundant species in nature and is only stable under reducing conditions such as in magmas. Calcium ion (.99 Angstroms)

Fig. 9 : Rb *vs* Sr thickness grid (after Condie, 1973).

Legend as in Fig. 3



substitutes for it in some calcium minerals, most notably sphene and apatite. The only 4-valent cation similar to U^{+4} is Th^{+4} and the similarities between the two leads to extensive isomorphism. The most common means of separating the two is to oxidize U^{+4} to $U^{+6}O_2$ which may then be carried away in solution from the unoxidizable Th. This leads to low Th/U ratios in hydrothermal vein-type deposits.

Uranium in Granitic Rocks:

In high silica magmas uranium tends to be concentrated in late-stage residues and commonly is taken into accessory minerals such as sphene and apatite. This does not seem to be the case in the "F-Zone" since XRD analysis of sphene separates supplied by the OGS showed only minor radiation levels. This may result in part from the fact that the sphene, based on textural relationships, is believed to be an early phase.

Alternately, the uranium may stay in solution until the very last stages of solidification and be deposited as a film on grain surfaces of major minerals. Uranium in the granites of Haliburton County, Ontario appears to occur in this manner (McKelvey, et. al., 1955).

McKelvey, et. al. (1955) also report uranium in migmatitic granitic rocks which contain numerous altered inclusions of biotite gneiss. In these rocks the uranium occurs as very finely disseminated uraninite intimately associated with biotite. Molybdenite, zircon and disseminated sulfides are also common in these rocks. At the "F-Zone" yellowcake (uranium oxide) is common in biotite clots in the quartz-rich phases, especially where exposed in trenches. This yellowcake represents oxidation of exposed uraninite. Molybdenum and disseminated sulfides are also common.

A plot of Th vs. U is given in Figure 10. The data points can be seen to fall in the range Th/U = 7 - 10 which is slightly above the average Th/U of 5 in granitic rocks. However, no significant separation of country rocks from the migmatites is evident suggesting that hydrothermal activity has not been severe enough to separate the U from the Th.

Conclusions:

Uranium appears to have been concentrated in the "F-Zone" via three possible mechanisms:

(1) in accessory minerals such as sphene and allanite,
(2) as a film on grain surfaces of major minerals,
(3) as finely disseminated uraninite associated with biotite.

The latter two most likely represent the dominant processes. What appears to have happened is that the uranium has been concentrated in the migmatite zone by metamorphic/metasomatic processes with the source of the uranium being the country rocks which already contain well above the crustal

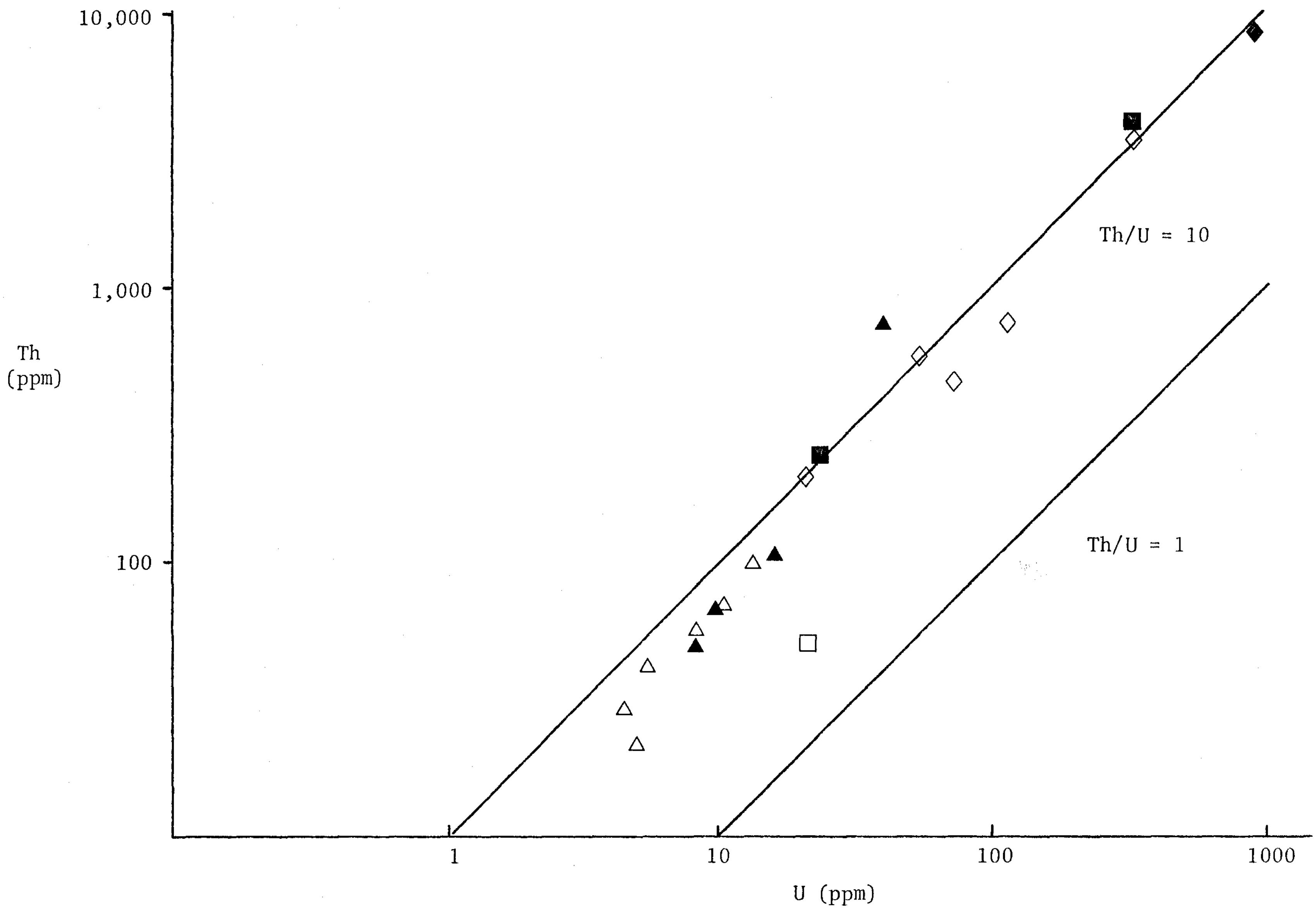


Fig. 10: U vs Th (ppm)

TABLE 2 THORIUM, URANIUM AND Th/U

SAMPLE	CONC. U (ppm)*	CONC. Th (ppm)+	Th/U
OC1	4.4	28	6.4
OC2	8.7	56	6.4
OC3	11.2	69	6.2
OC4	5.5	41	7.5
OC6	4.9	22	4.5
OC8	13.5	99	7.3
23 + 13	39.5	172	4.4
23 + 20	11.4	68	6.0
23 + 30	8.1	48	5.9
23 + 40	16.6	105	6.3
F1-1A	22.9	50	2.2
F1-1B	5.7	-	-
F1-9	23.2	200	8.6
F2A-O	26.6	230	8.6
F2A-7	331.0	3374	10.2
F2B-4	1494.0	-	-
F2B-7	1573.0	-	-
F3-2	918.0	8542	9.3
F3-35	57.4	554	9.7
F3-40	377.0	3686	9.8
F3-45	116.0	701	6.0
F3-50	70.0	432	6.2
F3-53	68.3	-	-
F3-55	120.0	-	-

*Analyses provided by Ontario Geological Survey.

+Analyses done by neutron activation at McMaster University.

average of 4 ppm.

(iv) Rare Earth Elements:

Until recently (1968) the analysis of individual rare earth elements (REE) was, at best, a difficult task. However, the development of high resolution gamma-ray spectrometers now allows separate REE concentrations in whole rock powders to be reasonably accurately determined by neutron-activation techniques (Gordon, et. al. 1967).

The close similarities in chemical behaviour of this group led early geochemists to expect that no relative fractionation among them would be observed. It is now known that this assumption is incorrect and that fractionation among the REE is very common in igneous rocks. This fractionation may serve as a useful guide to the geochemical history of the rocks containing the REE.

With this in mind samples from the batholith, diatexite and migmatite zone were analysed for REE content.

Sample Preparation and Irradiation:

In preparation for irradiation in the McMaster Nuclear Reactor weathered surfaces were trimmed off and samples were crushed to a powder of less than 200 mesh using a porcelain-lined shatterbox. Powders were then loaded into 3 mm O.D. x 2 mm I.D. fused silica ampoules and weighed to an accuracy of .01 mg. The silica ampoules had previously been thoroughly cleaned by boiling in aqua regia followed by rinsing with distilled water. After loading the powders the ampoules were heat sealed.

Ten samples plus 3 standards (2 USGS - GSP - 1 and 1 USGS - BCR - 1, Abbey 1977) were then taped together and loaded as a package into aluminium cannisters for irradiation.

Irradiation periods varied from 12 - 24 megawatt-hours in the high flux position in the reactor (neutron flux of 4.5×10^{13} neutrons cm^{-2} sec^{-1}) and cooling times varied as well depending upon the elements of interest. The elements Sm, Nd and Lu were analysed after a 10 day cooling period while Ce, Eu, Tb and Yb were analysed after 40 days.

The gamma spectrometer system used for analysing samples consisted of:

(1) Ortec Ge-Li Gamma-ray detector Model 6001
(2) Canberra Model 1400 BIN and Power supply
(3) Ortec Model 120-4 Low Noise Preamplifier
(4) Ortec Model 452 Spectroscopy Amplifier
(5) Ortec Model 459 Bias supply
(6) Nuclear Data ND 812 Data Processor
(7) Nuclear Data, ADC/ND-560
(8) Nuclear Data Control Module
(9) Hewlett-Packard display oscilloscope and Telex teletype terminal

TABLE 3 ENERGIES OF γ-RAYS EMITTED BY OBSERVED NEUTRON-ACTIVATION PRODUCTS

ELEMENT	$T_{1/2}$	ENERGY (Gordon, 1968)	INTERFERENCE PEAKS
La^{140}	40.22h		
Ce^{141}	33d	145.43 ± .02	Fe^{59} 143
Nd^{147}	11.1d	91.1 ± .01	Th^{160} 87, Pa^{233} 87
Sm^{153}	47h	103.18 ± .02	Pa^{233} 94 - 98
Eu^{152}	12y	121.79 ± .03	Ba^{131} 124, Eu^{154} 123
		778.9 ± .7*	----
Tb^{160}	72.1d	298.5 ± .1	Pa^{233} 300
Tm^{170}	130d	84.26 ± .01	Tb^{160} 87, Ta^{182} 85
Yb^{169}	32d	177.23 ± .02	Ta^{182} 179
		197.97 ± .03*	Tb^{160} 197, Fe^{59} 192
Lu^{177}	6.7d	208.36 ± .01	Ba^{131} 216, Tb^{169} 216

*Energy used for calculations.

Results:

REE concentrations for various samples from the "F-Zone" are tabulated in Table 4. The photopeak energies from which the values of specific elements were calculated are listed in Table 3.

In order to compensate for the Oddo-Harkins effect in the abundances of REE it is common to "normalize" the observed values by dividing them by values found in some standard material. The abundances in chondrites (stoney meteorites) are generally used for this purpose since it is believed that these represent undifferentiated, primitive material.

Chondrite normalized values for samples from the Setting Net Batholith and diatexite are plotted in Figures 11 and 12 respectively.

The ranges in values and average values from the batholith and diatexite are plotted on Figure 13 to allow for easy comparison of the two units. As well, in Figure 14 the average Ce, Eu and Yb values from the migmatite zone are plotted along with the average batholith and diatexite values.

Discussion:

The chondrite normalized REE patterns for the batholith and diatexite both show a marked enrichment in light REE over heavy REE. This is a common pattern which has been

TABLE 4 RARE EARTH ABUNDANCES (ppm)

SAMPLE	La	Ce	Nd	Sm	Eu	Tb	Tm	Yb	Lu	Eu/Eu*[1]	(Ce/Lu)[2]	ΣREE[3]
C1		-	-	-	-	-	-	-	-	-	-	-
C2		44.4	5.3	1.6	.33	.42	.27	.60	.08	.42	555	53
C3		91.2	30.4	5.5	.54	.92	.64	1.2	.11	.33	829	131
C4		74.6	-	-	.38	.38	.27	.74	.08	-	933	76
C6		21	5.3	1.6	.53	.19	.17	.57	.05	-	420	29
C8		74.7	48.6	2.8	.55	.69	.49	1.6	.09	.57	830	130
23-13		36.7	-	11.1	.56	2.1	.8	2.05	.22	.17	167	54
23-20		158.4	-	-	.7	.78	.64	2.01	.13	-	1218	163
23-30		80.4	-	2.2	.59	.65	.48	1.8	.06	.64	1340	86
23-40		150.2	61.4	13.1	.98	1.6	.97	4.1	.31	.23	485	233
1-1A		6.8			-			-				
1-9		-			-			-				
2A-O		23.4			.14			-				
2A-7		55.7			.42			-				
2B-4		97			.51			1.2				
3-2		58			.40			.5				
3-35		38.5			.41			2.2				
3-40		152			-			1.1				
3-45		74			-			1.1				
3-50		171			.81			4.2				

Notes:
1. Eu/Eu* is the ratio of Eu concentration in the sample to the interpolated value, Eu*, from the chondrite-normalized RE fractionation pattern.
2. (Ce/Lu) is the chondrite-normalized ratio of Ce to Lu.
3. ΣREE is the sum of Ce + Nd + Sm + Eu + Tb + Tm + Yb + Lu in ppm.

Fig. 11 : Chondrite normalized REE concentrations for Setting Net Batholith.

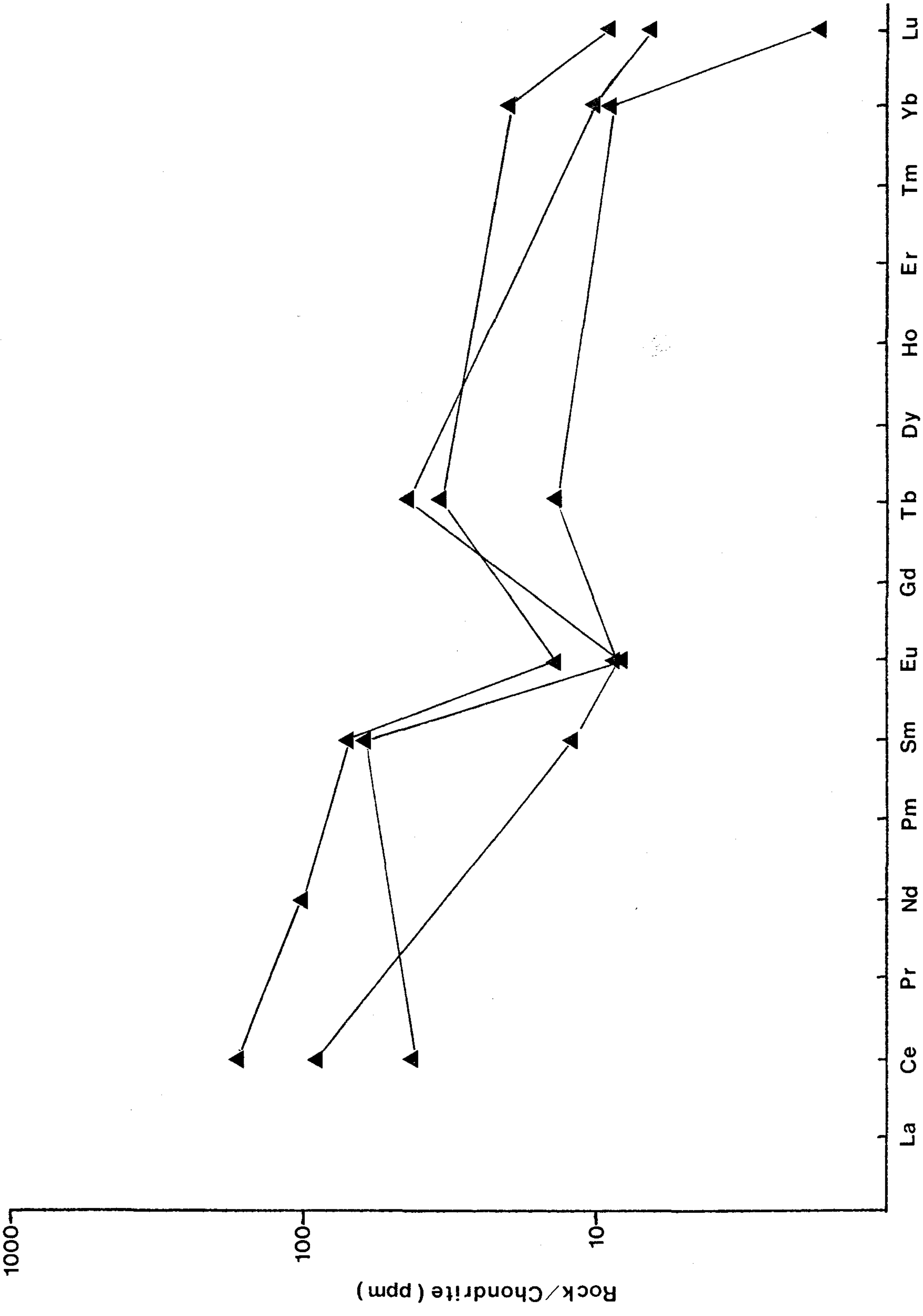
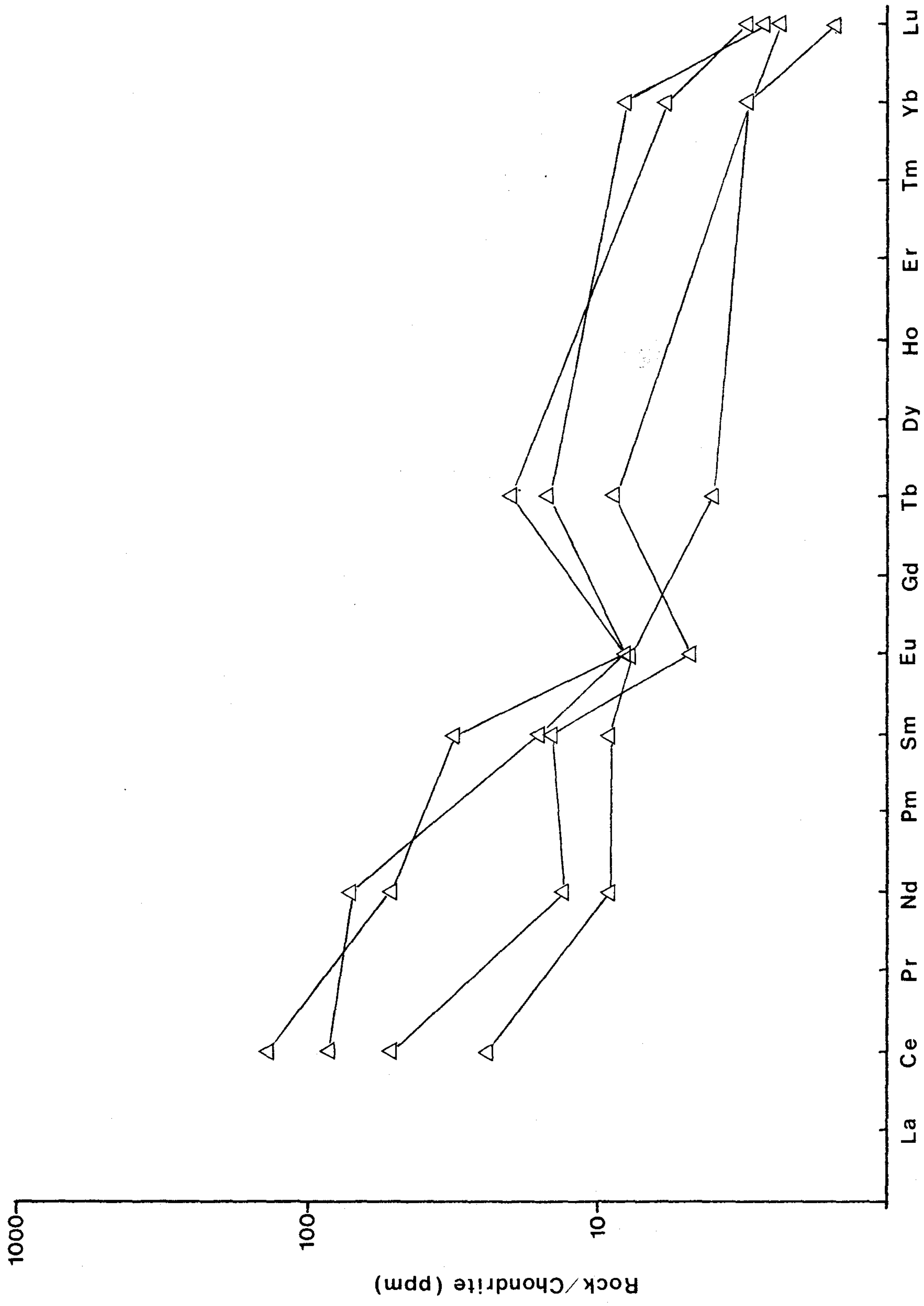


Fig. 12 : Chondrite normalized REE concentrations for homogeneous diatexite.



observed in virtually all igneous and sedimentary material (Goles, 1968). As suggested by Goles (1968) this enrichment of light REE in crustal material may be interpreted in two ways:

(1) systematic enrichment in light REE due to selective fusion of a mineral in the upper mantle which preferentially concentrates these elements.

(2) the light REE may be more mobile and thus more readily concentrated in differentiation processes (e.g. partial fusion).

Both processes are considered by Goles to be viable; however, the second one presents a problem since theory and observation suggest that heavy REE are preferentially transported by hydrothermal solutions (Haskin, et. al., 1966). Goles suggests different complexing agents in magmatic and hydrothermal environments as a way around this problem.

Of note in the rare earth patterns of the batholith and diatexite are marked negative europium anomalies. Eu anomalies are well documented in the literature (Goles 1968, Philpotts and Schnetzler 1968) with negative anomalies being characteristic of granitic rocks. Europium appears to be the only REE that occurs in the divalent state in nature and can therefore be separated from the rest of the trivalent REE in natural systems. The chemical properties of divalent Eu are more like those of calcium, strontium and lead and this results in its concentration in minerals

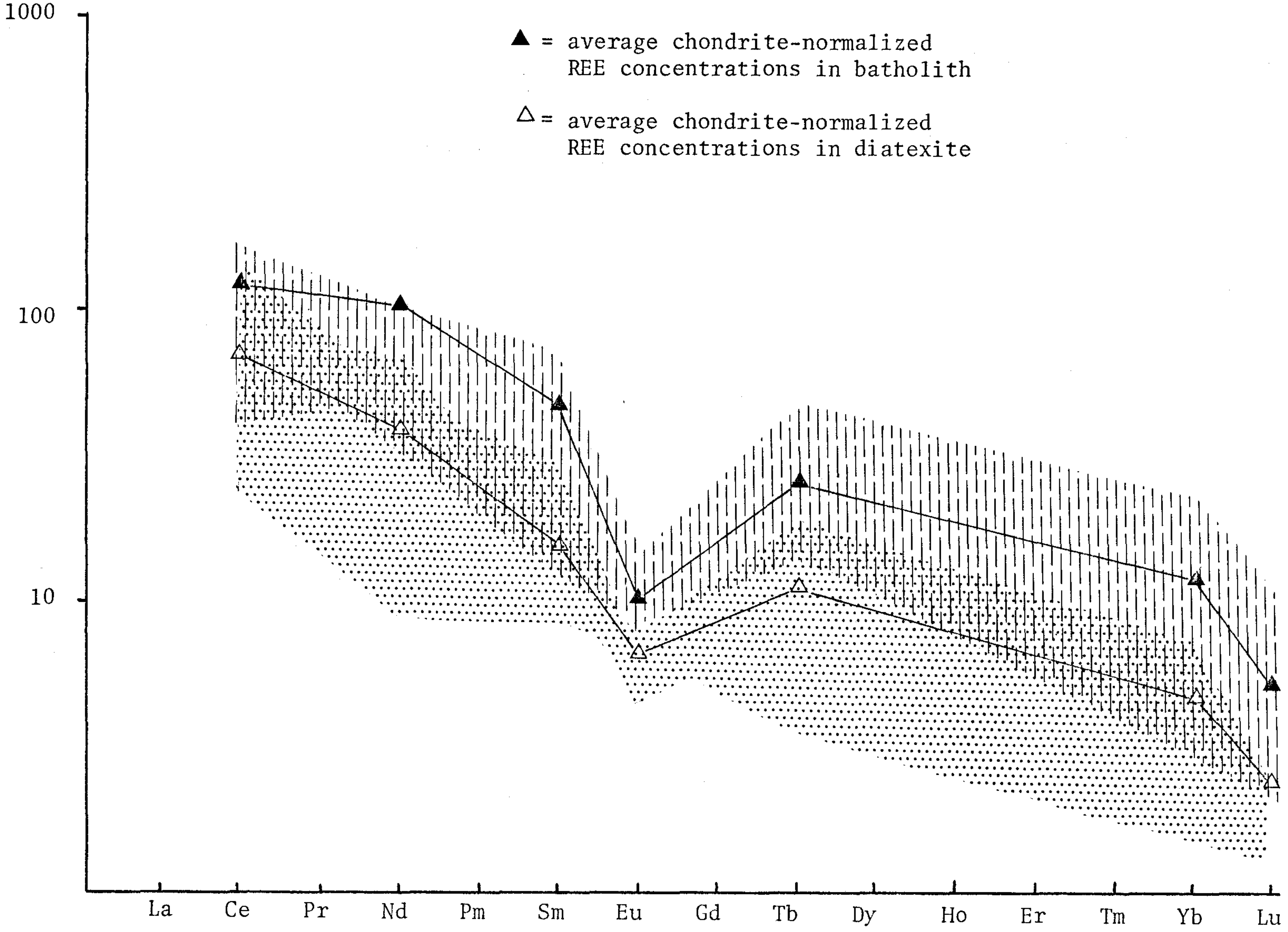


Fig. 13: Comparison of REE from Setting Net Batholith and Homogeneous diatexite. Dashed area represents range for batholith, dotted area is range for diatexite.

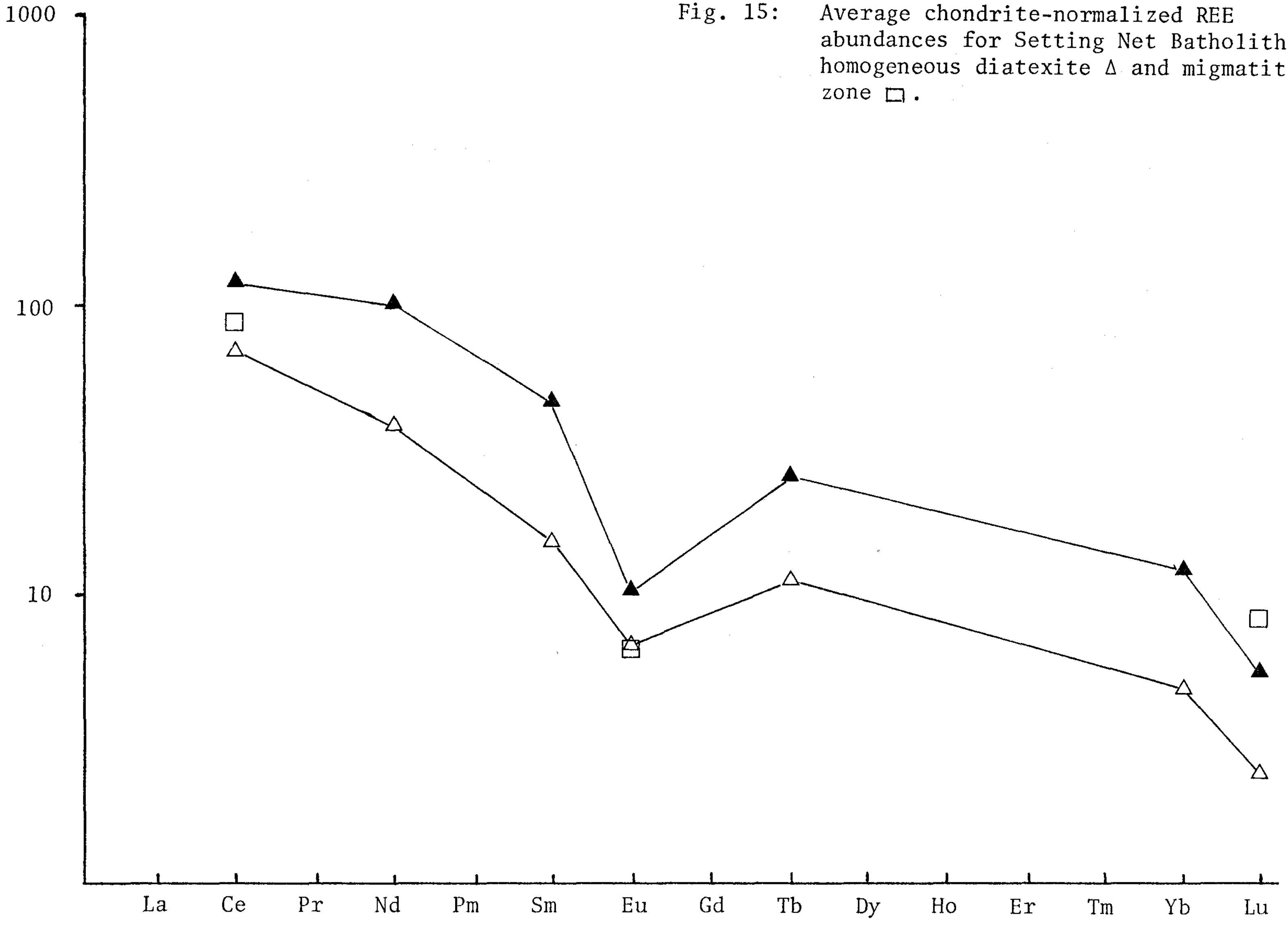


Fig. 15: Average chondrite-normalized REE abundances for Setting Net Batholith ▲, homogeneous diatexite △ and migmatite zone □.

of these elements (most notably plagioclase) (Philpotts and Schnetzler, 1968). Thus, it is suggested by Philpotts and Schnetzler (1968) that negative Eu anomalies in granitic rocks can be interpreted in terms of Eu depletion in granitic melts due to crystallization of feldspar.

Based on this argument the more pronounced Eu anomaly for the batholith samples compared to the diatexite would suggest that the batholith represents more fractionated material. The slightly higher REE content of the batholith lends support to this conclusion since REE (especially the light REE) tend to be concentrated in differentiation processes (Goles, 1968).

Unfortunately, many of the REE abundances for samples from the migmatite zone were not obtained due to analytical problems. Because of this proper comparison of the migmatite with the batholith and diatexite cannot be made. However values for Ce, Eu and Yb obtained for the migmatite show only minor differences from the other two units.

CHAPTER V

CONCLUSIONS

(1) The Setting Net Lake Batholith represents material crystallized from a granitic melt produced by partial fusion of sedimentary and volcanic material.

(2) Chemical considerations suggest that the batholith and homogeneous diatexite were formed by the same process. However, the higher proportions of metasedimentary and metavolcanic remnants in the diatexite coupled with the slightly higher REE content of the batholith indicate that the batholith represents more well differentiated material.

(3) The migmatite zone resulted from the intrusion of the batholith into the homogeneous diatexite, probably at slightly shallower depths.

(4) At the time of intrusion conditions were very hot and dry which allowed for the formation of pyroxene rather than biotite or hornblende along the contact.

(5) Based on preliminary REE results the material in the migmatite zone appears to be a mixture of material from the batholith and diatexite.

(6) Uranium has been concentrated in the migmatite zone from the surrounding country rock by metasomatic and late-stage hydrothermal mechanisms.

Suggestions for further work:

(1) XRD and REE analysis of individual minerals as a further aid to petrogenesis.

(2) Rb/Sr whole rock geochronology and initial $^{87}Sr/^{86}Sr$ of batholith, diatexite and migmatite zone.

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APPENDIX A

TABLE 5 MODAL ANALYSES

SAMPLES	OC2	OC6	23-20	F1-1A	F1-13	F2A-0	F2A-4	F2A-7	F2B-1	F2B-7	F3-58
Quartz	27.8	30.2	25.4	17.2	32.6	48.2	51.2	70.2	72.4	73.8	29.6
K-feldspar	37.6	28.2	39.6	55.2	53.6	35.0	22.0	1.6	13.0	-	50.8
Plagioclase	28.8	32.4	27.7	7.2	12.4	6.8	26.6	10.6	11.6	6.2	13.6
Biotite	5.8	9.2	7.3	-	1.0	10.0	.20	17.8	3.0	19.8	5.0
Hornblende	-	-	-	-	-	-	-	-	-	-	-
Pyroxene	-	-	tr	20.4	.6	-	-	-	-	.40	-
Epidote	-	-	-	-	-	-	-	-	-	-	-
Sphene	-	-	tr	-	-	-	-	-	-	-	1.0
Opaques	tr	tr	-	tr	-	tr	-	-	-	-	tr
Points Covered	500	500	500	500	500	500	500	500	500	500	500

TABLE 6 WHOLE ROCK ANALYSES (NORMALIZED) IN WEIGHT PERCENT OXIDES

SAMPLE	OC1	OC2	OC3	OC4	OC6	OC8	23-13	23-20	23-30	23-40	F3-2	F3-35
SiO_2	75.86	75.89	76.17	74.73	77.21	75.65	74.06	74.41	74.98	74.84	86.88	67.18
Al_2O_3	13.28	13.05	12.71	13.92	13.01	13.25	13.60	13.58	13.70	13.19	6.70	16.96
Fe_2O_3*	.62	1.11	1.01	.84	.78	.88	1.39	1.36	1.05	1.28	1.55	1.24
MgO	.23	.26	.37	.20	.25	.53	.69	.41	.29	.47	.47	.51
CaO	1.03	1.00	.93	.99	1.19	1.03	.95	.97	1.08	1.20	.23	.74
Na_2O	3.46	3.26	3.08	3.15	3.15	3.04	3.09	3.07	3.14	3.23	.16	2.87
K_2O	5.14	5.06	5.14	5.55	4.00	5.01	5.30	5.55	5.16	5.16	2.48	9.97
TiO_2	.09	.08	.20	.16	.15	.13	.25	.14	.13	.20	.87	.10
MnO	.05	.06	.07	.07	.07	.06	.06	.07	.07	.07	.08	.08
P_2O_5	-	-	.03	-	-	-	.05	.02	.02	.04	-	-

*Total Fe as Fe_2O_3

TABLE 6 WHOLE ROCK ANALYSES (con't)

SAMPLE	F3-40	F3-45	F3-50	F3-53	F3-55	F1-1A	F1-1B	F1-9	F2A-O	F2A-7	F2B-4	F2B-7	MV-19
SiO_2	63.64	63.17	68.34	76.66	75.86	70.76	58.51	79.49	82.01	79.32	92.68	89.50	51.36
Al_2O_3	16.88	17.88	16.50	12.51	12.25	12.39	19.36	11.46	9.44	6.51	4.94	4.26	13.09
Fe_2O_3	3.18	1.36	.81	.56	1.02	2.46	5.77	.25	1.62	7.61	.49	2.74	9.38
MgO	1.20	.42	.18	.25	.50	1.54	2.09	.11	.40	2.06	.13	1.00	11.23
CaO	.58	1.39	.60	.27	.46	3.44	2.08	.24	.13	1.46	.27	.19	10.92
Na_2O	2.39	2.88	2.67	1.83	2.17	1.61	5.20	1.99	.42	.29	.15	.15	2.59
K_2O	10.32	10.62	9.74	7.43	6.85	7.22	5.25	6.24	5.44	1.46	.95	.91	.31
TiO_2	.96	1.65	.68	.23	.39	.20	.67	.03	.17	.45	.05	.60	.38
MnO	.08	.05	.06	.04	.06	.16	.11	.04	.08	.20	.06	.10	.15
P_2O_5	.08	.16	.03	-	.04	.03	.08	-	-	-	-	-	.06

TABLE 7 TRACE ELEMENT ANALYSES IN PPM

SAMPLE	OC1	OC2	OC3	OC4	OC6	OC8	23-13	23-20	23-30	23-40	F3-2	F3-35
Rb	273	250	300	307	227	250	287	282	262	237	135	446
Sr	155	213	171	107	173	159	195	194	224	184	38	226
Y	11	14	18	0	9	32	25	26	21	34	24	29
Zr	190	207	260	151	131	200	123	229	196	207	606	102
Nb	14	11	31	23	20	16	34	15	19	26	88	20
S	109	116	106	171	131	116	258	176	134	185	2450	407
Ni	17	20	20	21	17	21	23	25	20	23	28	19
Cr	15	28	25	20	32	16	20	31	28	25	29	21
Co	0	4	0	0	4	0	4	0	2	7	6	0
Pb	28	31	44	25	25	23	101	24	34	49	991	104
Cu	3	6	4	4	5	5	16	4	4	9	13	6
Zn	23	24	33	22	18	24	19	25	24	27	49	26
As	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 7 TRACE ELEMENT ANALYSES IN PPM (con't)

SAMPLE	F3-40	F3-45	F3-50	F3-53	F3-55	F1-1A	F1-1B	F1-9	F2A-O	F2A-7	F2B-4	F2B-7	MV-19
Rb	568	425	413	347	346	331	365	298	603	253	116	246	11
Sr	186	179	160	128	131	169	246	158	49	22	26	13	166
Y	112	485	125	69	46	18	36	13	13	17	32	57	12
Zr	97	104	90	88	80	-	173	95	85	48	271	757	72
Nb	122	146	81	33	57	31	25	7	40	50	47	102	12
S	371	410	200	133	249	267	4808	137	209	860	381	1564	673
Ni	27	28	24	19	24	21	85	19	17	26	21	27	102
Cr	25	18	24	12	25	17	202	18	26	33	15	25	510
Co	12	5	0	0	3	10	12	5	0	13	3	4	33
Pb	528	93	42	62	84	66	37	34	305	993	1542	1851	11
Cu	11	4	4	5	11	5	48	5	4	12	6	9	58
Zu	53	21	17	17	20	48	187	6	23	144	14	68	70
As	-	-	-	-	-	-	-	-	-	-	-	-	6

TABLE 8 RARE EARTH CONCENTRATIONS (ppm) IN CHONDRITES USED IN SAMPLE NORMALIZATIONS (after Haskin, 1968)

La	Ce	Nd	Sm	Eu	Tb	Tm	Yb	Lu
0.330	0.88	0.60	0.181	0.069	0.047	0.030	0.200	0.034