THE AGE, ORIGIN, AND RARE-EARTH-ELEMENT DISTRIBUTIONS OF GRENVILLE PROVINCE URANIFEROUS GRANITES AND PEGMATITES

by

© A.D. Fowler

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

Department of Geological Sciences
McGill University
Montreal, Quebec

January 1980

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

Age determinations of various Grenville Province uraniferous granitic rocks from the Bancroft, Mt-Laurier and Johan Beetz areas have shown that these rocks are younger than the ages normally associated with the widespread Grenville orogeny ca. 1150 Ma ago. Previous studies have attributed the origin of many of these occurrences to in situ anatexis of uraniferous protoliths which may be related to the base of the Grenville supracrustal sequence.

An Rb-Sr whole rock isochron made up of pegmatitic granite samples from the now defunct Canadian Dyno, Greyhawk and Bicroft mines in the Bancroft area yields an age of 959 Ma. This contrasts with the age of 1181 Ma determined for the adjacent Cheddar granite. The radioactive granites and associated pegmatites of Mt-Laurier are about 930 Ma in age whereas the area's barren granites are 1083 Ma old. An age of 928 Ma was obtained from a pegmatite in the Johan Beetz area, where field evidence suggests that there are also older granites. The low strontium initial isotopic ratios of the various granites and pegmatites requires their having been generated from primitive sources.

The rare earth element data which were compiled after first having devised a method for correcting the analyses for unusual interferences associated with uranium-enriched samples during analysis by the neutron activation technique show that these elements display differential mobility during late stage alteration processes. The fluid phase considered responsible for the distribution of the uranium and thorium produced negative and positive europium anomalies in certain of the granites and pegmatites, respectively.

Some of these uraniferous granites are spatially and in part temporally related to abundant alkalic rocks which occur from Bancroft, to Mt-Laurier. Considerable control over the location of these rocks has been exerted by large fractures within the crust. A model relying upon the onset of tensional forces due to relaxation of compression, partial lithospheric melting in response to adiabatic decompression, heat focusing and volatile fluxing at the end of the Grenville Orogeny has been postulated to account for the origin and distribution of these "late Grenville" igneous rocks.

SOMMAIRE

Des déterminations d'âges de plusieurs granites uranifères de la province du Grenville, et plus particulièrement des régions de Bancroft, Mt-Laurier et Johan Beetz, démontrent que ceux-ci sont plus jeunes que l'orogénèse grenvillienne de 1150 Ma. Plusieurs études antérieures avaient attribué l'origine de ces roches à une anatexie in situ d'un protolithe uranifère, probablement à la base de la séquence supracrustale du Grenville.

Un isochrone Rb-Sr determiné sur roches globales, d'aspect pegmatitique provenant des gisements maintenant épuisés de la Canadian Dyno, Greyhawk et Bicroft, tous de la région de Bancroft, donne un âge de 959 Ma. Ceci contraste avec l'âge de 1181 Ma obtenu pour le granite de Cheddar voisin. Les granites radioactifs de la même région ont 1083 Ma. Un âge de 928 Ma a été obtenu pour une pegmatite de la région Johan Beetz, où les relations de terrain semblent suggérer la présence de granites plus anciens.

Les concentrations en terres rares ont été determinées par activation neutronique, après l'application d'une nouvelle méthode de correction visant à supprimer les interférences dues aux fortes teneurs en uranium. Les résultats démontrent la mobilité différentielle de ces éléments lors d'une altération tardive dans les pegmatites. La phase fluide responsable pour la distribution de l'uranium et du thorium est aussi la cause des anomalies en europium, négatives dans certains granites et positives dans les pegmatites.

Certains de ces granites uranifères sont reliés, dans l'espace et dans le temps, aux roches alcalines qui abondent dans les régions de Bancroft et de Mt-Laurier. En plus, ils semblent avoir cristallisé de liquides produits après l'épisode principale de l'orogénèse grenvillienne plutôt que par des processus d'anatexie in situ ou de métasomatisme. Les importants diaclases

dans la croûte ont exercé un contrôle important de la mise en place de ces roches.

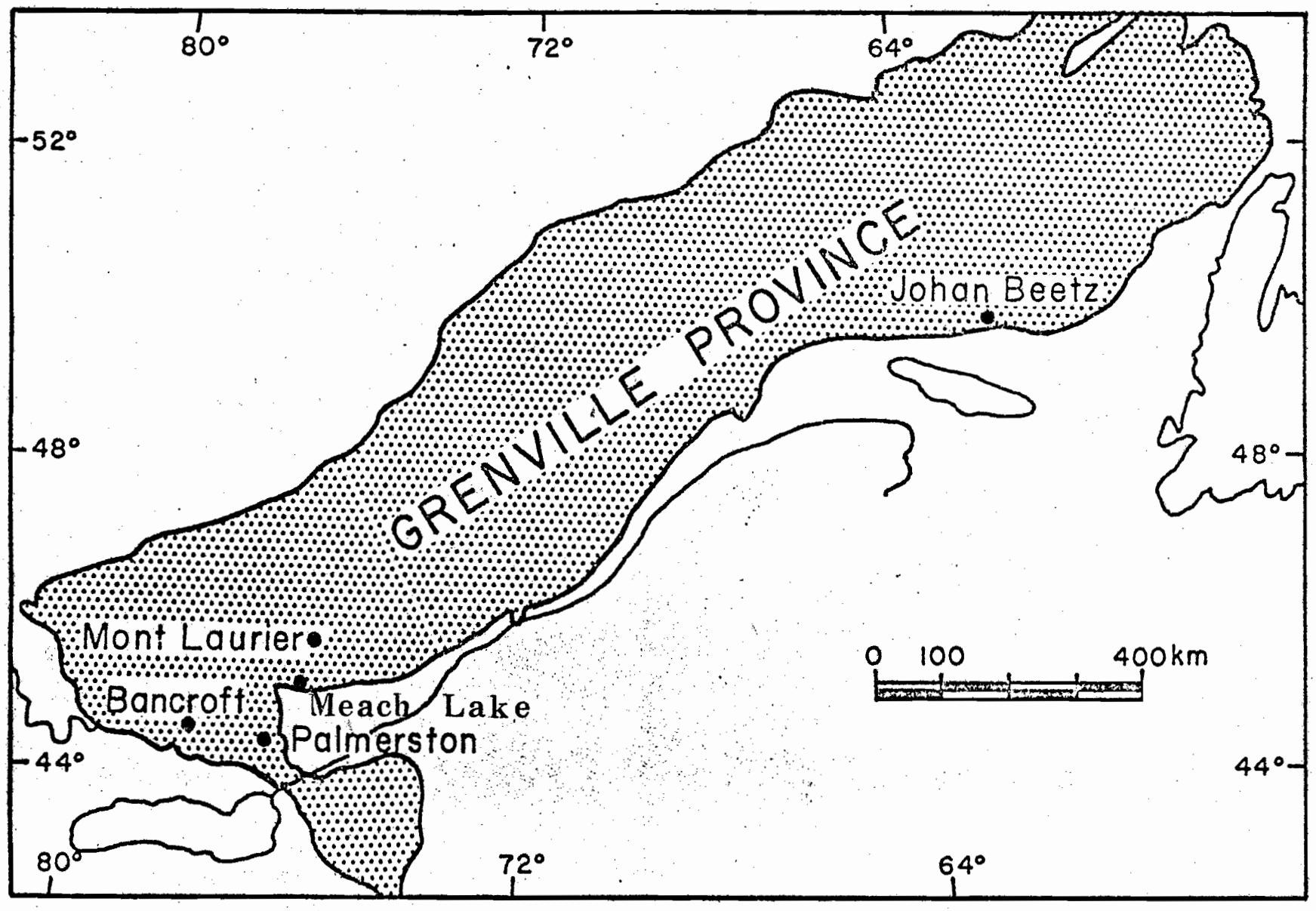
L'origine et la distribution de ces roches ignées d'âges tardi-grenvilliennes reflèteraient (1) le début d'une tectonique d'extension associée à une relaxation de la compression, (2) la fusion partielle de la lithosphère résultant d'une décompression adiabatique, (3) la convergence de flux de chaleur et de phases volatiles vers la fin de l'orogénèse.

CHAPTER I - INTRODUCTION

Uraniferous pegmatites can be found in many parts of the Grenville Province but especially in the zones shown in Figure I-1. The most notable of these, the Bancroft, Mt-Laurier and Johan Beetz areas, have been subjected to close scrutiny by mining companies over the past few decades. Uraninite was first discovered in Bancroft in 1922. During the uranium boom of the 1950s, and perhaps a little earlier for more dedicated military purposes, intense prospecting led to the opening of three mines; the Canadian Dyno, Bicroft and Faraday, which were all closed during the mid-sixties. As a result of the renewed interest in uranium in the 1970s the Faraday was reopened as the Madawaska mine in 1976.

To date neither the Mt-Laurier nor the St. Lawrence North Shore regions proven to possess uranium in economic concentrations despite intense exploration dating back to the 1950s.

The uraniferous pegmatites of the various regions are very similar in terms of their mineralogy, texture, alteration and mode of occurrence. They are granitic in composition, vary in texture from aplitic to pegmatitic and, with a few exceptions at Bancroft they are unzoned. Thorium is almost always associated with the uranium and is frequently found to be more abundant than the latter. The dominant primary radioactive minerals are uranoan thorite, thorian uraninite, allanite and zircon. Magnetite and a conspicuous brick-red hematite alteration are found in the large majority of the radioactive pegmatites. They occur in a variety of different host rocks such as marble, quartzite and quartzofeldspathic gneiss, that are metamorphosed to either medium or high grade. The radioactive pegmatites may conform to the hosts' foliation or cross it. In many of the areas the pegmatites are clearly



Figurel-1. Outline map of the Grenville Province showing the distribution of the major zones where uraniferous granites occur.

related to anomalously radioactive granites that lack a pronounced metamorphic fabric.

Elucidation of the origin of the uranium mineralization and its host rock is made difficult by the scarcity of outcrops in the area and the fact that the pegmatites intrude a migmatitic terrain, the leucosomes of which superficially resemble some of the uraniferous pegmatites. Field relationships can be ambiguous: for example, single pegmatites may display both cross-cutting and conformable relationships to host rocks.

Many of these occurrences appear to have a geological setting very similar to the Rossing uranium deposit, Namibia, which is a deposit of major significance. Therefore, this study on the origin of the uraniferous pegmatites, aside from being of scientific interest, may also have economic significance, as an understanding of the pegmatites' genesis would help to develop new exploration criteria and at the same time aid in an evaluation of the potential of the region.

Many authors have worked upon individual radioactive pegmatites or groups within a single area, but with the exception of Allen (1971) and Robinson (1961), have not recognized the similarity of these occurrences throughout the Grenville Province, nor speculated upon a common origin. Both the investigators mentioned above proposed that the deposits were formed by remobilization of a uraniferous supracrustal protolith. Surprisingly, with the exception of Charbonneau (1972) no other author has observed the radioactive nature of the late tectonic granites in the Mt-Laurier area. Also, in spite of the cross-cutting nature and youthful appearance of many of the radioactive granitic rocks, no one had attempted to measure the absolute age of these rocks. It was thought, therefore, that an understanding of the

precise timing of the pegmatite generation with respect to the development of the metamorphic rocks would be a promising approach.

In conjunction with the isotopic work an examination of the distribution of several trace elements was carried out, particularly the rare-earth-elements (REE). This work included devising a method for correcting REE analyses from fission product build-up and other interferences encountered during instrumental neutron activation work on uranium-enriched samples.

The present study shows that in rocks which have suffered post-crystallization alterations the REE may owe their present distribution to differential solubility of REE in a fluid phase. Europium anomalies which are considered by many to be the result of crystal liquid partitioning and as a consequence of great petrogenetic significance, may in fact, be formed by other means.

Finally, the results of field investigations, isotopic and chemical data reported in this thesis, clearly discount several possible modes of origin and provide a fairly unequivocal tectonic and geochemical framework for the pegmatites and their contained uranium.

CHAPTER II - RADIOELEMENT-ENRICHED GRANITES

Granites are in general more radioactive than most igneous rocks because they are relatively enriched in ^{40}K, U and Th as a result of their fractionated nature. There is, however, a wide range in the level of radioactivity in granites themselves, which reflects large variations in the abundances of the radioelements uranium and thorium and their daughter isotopes. Certain granites contain significantly more uranium and thorium than the values of 4 and 16 ppm, respectively, given by Larsen and Phair (1954) for an average granite. Well-known examples outside the Grenville Province are the Rossing granite (Namibia), the Conway granite (New Hampshire), the Bokan Mountain granite (southeastern Alaska), and certain granites located in the Massif Central (France).

The Rossing Deposit

The Rossing uranium deposit occurs on the flank of a major domal structure in a series of high-grade metamorphic rocks within the Damarran orogenic belt. Alaskite and pegmatite, the major uranium-bearing units, have invaded a mixed assemblage of schists, gneisses and marbles (Berning et al. 1976). The granitic rocks were developed and emplaced during the Damarran orogeny ca. 510 m.y. ago. Uraninite, betafite and secondary uranium minerals are disseminated through a large volume of granitic rock in proportions sufficient to constitute a "porphyry uranium deposit" (Armstrong 1974). The South African Atomic Energy Act forbids one from divulging the average ore grade of the deposit. However, Wyllie (1979) does quote a figure of 400 ppm U_3O_8. For similar reasons the thorium content of the deposit is not readily available but Berning et al. (1976) do give two U/Th ratios for

uraninite: one value is 9.0, the other 13.05. This, coupled with the average uraninite content of the uranium-bearing species of 55% and the presence of other thorium minerals such as thorogummite (Von Backstrom 1970), would suggest a minimum thorium content of approximately 20-30 ppm. This implies a minimum enrichment factor of perhaps 1 or 2 in thorium over that of the average granite, i.e., virtually none in comparison to the large uranium enrichment. The origin of this deposit seems somewhat obscure. However, on the basis of field relationships, Berning et al. (1976) suggested that the alaskite originated from either juvenile sources or by anatectic processes and that it experienced "passive nonviolent metasomatic emplacement". They imply that the uranium is derived from a uraniferous Precambrian formation which was subjected to syntexis by the alaskite melt:

> "The ultimate source of the uranium could thus be the early Precambrian basement that was heavily eroded during a major time-hiatus to provide spoil for redeposition in late Precambrian times as the Etusis formation. This assemblage was then subjected to syntexis in the core of the developing Damarran geosyncline with resultant emplacement of alaskite into stratigraphically higher strata."

The Conway Granite

The Conway granite (New Hampshire), is part of the White Mountain magma series, which is a mildly alkaline igneous suite ranging from gabbro to granite in composition. It contains on average 55 ppm thorium and 15 ppm uranium (Richardson 1964), mostly concentrated in the minerals allanite, huttonite, thorite and zircon. According to Richardson, 9% of the granite's thorium and 58% of its uranium is either dispersed or in an unknown phase. Foland et al. (1971) have reported a whole-rock Rb-Sr isochron age of 110 ± 7 m.y. and $^{87}Sr/^{86}Sr$ initial isotopic ratio of 0.705 ± 0.0007.[1]

---

[1] $\lambda = 1.47 \times 10^{-11} a^{-1}$

Foland and Faul (1977) have reported similar ages for this and other igneous bodies in New England and have shown that the granites are not the result of an orogenic (compressional) event. Furthermore they rejected the mantle-plume hypothesis expounded by Morgan (1971) and suggested that the locus of these intrusions was controlled by a major lithospheric fracture.

Two-Mica Granites in the Massif Central

Uranium deposits of the French Massif Central are associated with granites containing about 15-20 ppm uranium (Gangloff 1970). The economic deposits are pitchblende-bearing veins that postdate the granite host, and tend to be associated with lamprophyre dykes.

The host two-mica granites are peraluminous in character with peripheral tin-tungsten veins. The uranium is dispersed in the form of uraninite which is deuteric in character (Moreau and Ranchin 1973). These authors show that some of the two-mica granites are clearly intrusive and suggest that these may come from deep-rooted sources. Most authors, however, consider that these granites have formed by local anatexis and migmatization (see for example, Boudette 1977).

Ross Adams Deposit

The Ross Adams mine is situated in the Bokan Mountain albite-riebeckite granite of southeastern Alaska. The granite, which produced about 94,000 tons of 1% U_3O_8 ore, is Devonian in age and intrudes Ordovician plutonic rocks that are themselves albitized within a zone up to 2.4 km wide around the Bokan Mountain granite (Thompson 1979; Staatz 1978). The uranium content of chip samples taken from radioactive quartz and alkali feldspar

veins ranges from 0.005% to 1.8%. Thorium contents range from 0.0033% to greater than 10% (Staatz 1978). The radioactive minerals include uraninite, brannerite, thorite, allanite, and many species enriched in REE. Magnetite, limonite and hematite are relatively abundant. MacKevett (1963) considers that the deposit "originated in part from a primary segregation of uranium-thorium minerals in a late stage of the (evolution of the) peralkaline granite magma, but to a greater extent from subsequent hydrothermal alteration".

Distribution of Uranium and Thorium in Granites

The major differences between radioactive and normal granites are the content and nature of their accessory minerals, the abundance of certain trace elements, and to a lesser extent, their major element compositions. Uranium and thorium, elements of large ionic radii and high valence, do not fit easily into the structures of common rock-forming silicate minerals. As a consequence the elements are "magmatophile", ultimately forced into complex silicates, phosphates, niobates, tantalates or oxides, as their concentration during the evolution of granitic liquids increases. As seen from the data of Table 1, in an average granite the uranium and thorium tends to be dispersed in quartz, feldspar and mica or concentrated in discrete crystals of accessory minerals. In common silicate minerals these elements may occur to a limited extent as isomorphous substitutions, concentrations along structural defects, adsorptions at crystal imperfections or grain boundaries or inclusions as microcrystals of uranium minerals (Rogers and Adams 1974).

Smith (1974) reports that two-thirds of the uranium in K-feldspar is in the form of physical impurities which are acid-soluble. As the uranium and

Table I

Mineral	ppm U	ppm Th	Mineral	ppm U	ppm Th
Quartz	1.7 0.1-10	0.5-10	Garnet	6-30	-
Feldspar	2.7 0.1-10	0.5-10	Huttonite	$3x10^3$-$7x10^4$	nearly pure $ThSiO_4$
Biotite	8.1 1-60	0.5-50	Magnetite and other opaques	1-30	0.3-20
Musc	2-8		Monazite	3000 500-3000	125,000 $2x10^4$ $2x10^5$
Hornblende	7.9 0.2-60	5-50	Sphene	280 100-700	510 100-1,000
Pyroxene	3.6 0.1-50	-	Thorianite, Uraninite, Thorite, Uranothorite	Variable	Variable
Olivine from dunite	~0.05	0.02	Xenotime	$300-4x10^4$	-
Allanite	200 30-1000	9100 $1x10^3$-$2x10^4$	Zircon	1330 100-6000	560 $100-10^4$
Apatite	65 10-100	70 50-250			
Edidote	43 20-200	200 50-500			

Table I. The range of concentration (in ppm) of uranium and thorium and the average values in minerals from various North American granitic rocks. (After Rogers and Adams, 1969.)

thorium content of a granite increases above the average levels so does their concentration in accessory minerals such as zircon, monazite and apatite. Further concentration will result in the formation of uranium and thorium minerals. In general, because this degree of enrichment of incompatible elements involves a concommitant increase in the fluid content of the system, pegmatitic textures and a departure from a strictly granitic composition result.

The most conspicuous difference in the major-element concentrations between radioactive and common granites involve Fe, Na, K and Si. Radioactive granites are commonly enriched in magnetite or have been hematized or both. Those that show alkaline tendencies generally have a higher Na/K ratio and a lower SiO_2 content. This results in the appearance of riebeckite, intense albitization and, in certain French deposits, the total

corrosion of quartz resulting in the formation of episyenite.

Formation of Pegmatites

Cameron et al. (1949) reviewed the various hypotheses of pegmatite formation and classified them into three main groups. These authors were primarily concerned with explaining the zonation of pegmatites. They showed that early workers championed fractional crystallization of a pegmatitic magma in situ while others preferred an origin in which pegmatitic solutions crystallized along a fracture and progressively changed their composition. The third hypothesis requires initial crystallization of massive pegmatite and subsequent hydrothermal replacement.

Jahns and Burnham's (1969) model of pegmatite genesis consists of three stages. The first is the crystallization of granitic or pegmatitic anhydrous silicate with or without hydrous phases from a hydrous silicate melt. While this process continues a coexisting exsolved aqueous fluid separates and promotes the formation of large crystals. The final stage requires the cessation of crystallization from the silicate melt but the continued exchange of constituents with the fluid. The authors show that the crystallization of granitic melts with small amounts of initial H_2O can lead to an eventual enormous enrichment in H_2O even where crystallization of considerable amounts of OH-bearing phases is involved.

Furthermore Burnham (1967) has demonstrated that "continuous solubility between natural aqueous fluids and felsic magmas is precluded". He argues that CO_2 will enhance this effect as well as chlorides "in the amounts found in most crustal rocks". Fluorine would appear to have the opposite effect but Burnham feels that fluorine would have to be present in

very large concentrations to maintain complete solubility between fluid and melt. Jahns and Tuttle (1963) have shown that pegmatite and aplite may be formed contemporaneously from the same parent by varying the fluid pressure. It seems, therefore, that an essential ingredient in the formation of pegmatite-aplite complexes is an aqueous fluid.

CHAPTER III - GEOLOGY OF GRENVILLE PROVINCE RADIOACTIVE GRANITES

Summary of Grenville Province Geology

The Grenville Province is the youngest of the major divisions of the Canadian Shield. In contrast to most other structural provinces the overall metamorphic grade is high, there being only a few areas where greenschist facies rocks occur. The province consists of two main contrasting geologic elements (Doig 1977). To the northwest of a line from west of Bancroft to Mt-Laurier and beyond the rocks are essentially quartzofeldspathic gneisses with minor crosscutting granitic rocks, whereas to the southeast metamorphosed supracrustal rocks of the Grenville Supergroup and plutonic bodies predominate. The rocks of the Grenville Supergroup are composed dominantly of marbles, quartzites and metapelites which at least in southern Québec overlie a granulite-facies basement. The gneiss terrain is in large part composed of overprinted Archean and Aphebian rocks that in certain instances have been directly correlated with rocks northwest of the Grenville Front. In southern Ontario the metasedimentary rocks are associated with and intruded by igneous rocks ranging from granite to gabbro whereas in southern Quebec the most prominent intrusive rocks are monzonite and anorthosite. The anomalously radioactive granitic rocks studied in this project are a minor component of the intrusive rocks of the southern Grenville Province.

Bancroft Area

Regional Geology

The Bancroft area (Figure III-1), long known to geologists for its abundant alkaline rocks, is situated at the junction of the Madawaska Highlands, a large

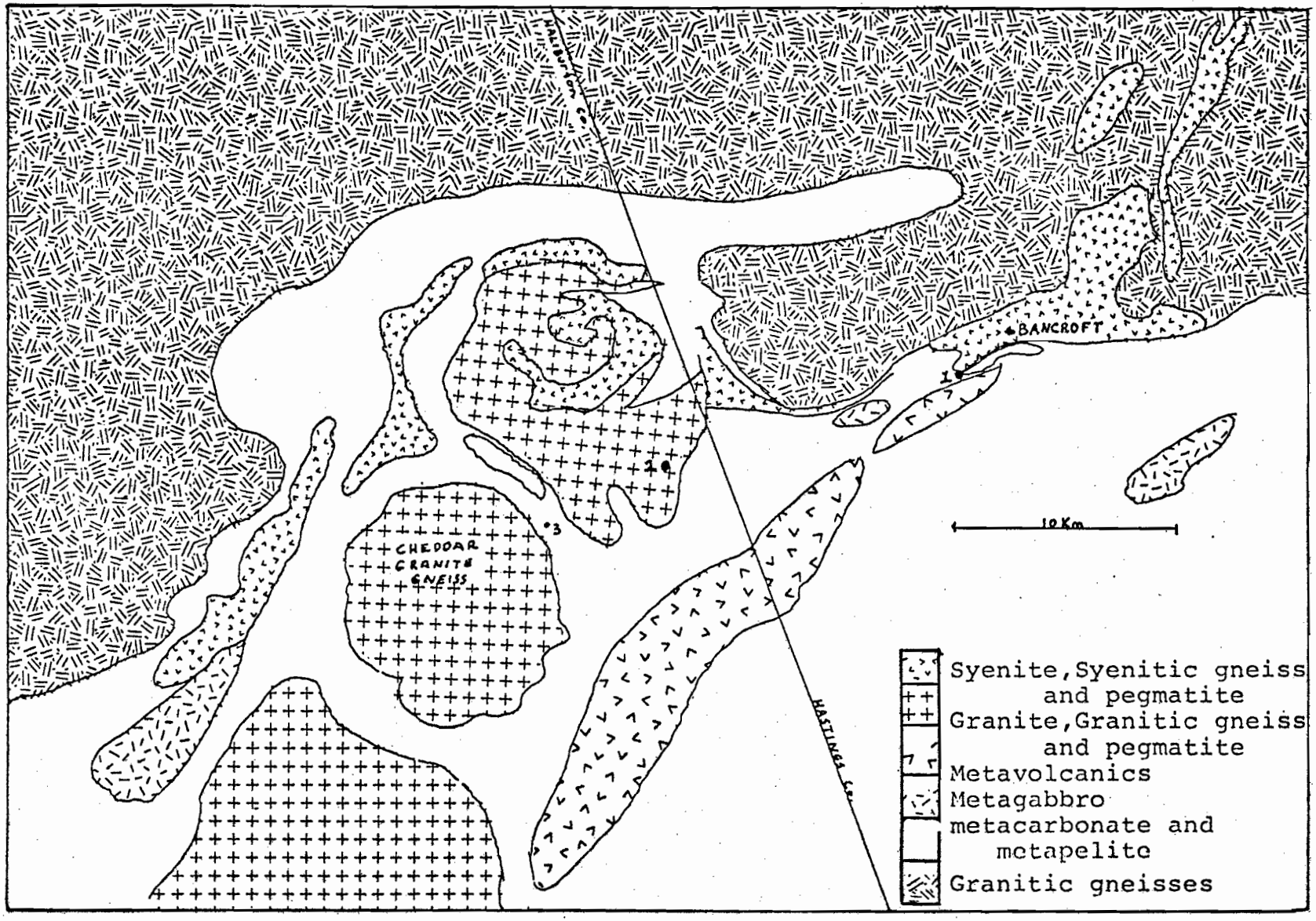


Figure III-1. Geology map of the Bancroft area showing the location of (1)the Greyhawk mine (2)the Bicroft mine and (3)the Canadian Dyno Mine. From Ontario Dep't of Mines map 1957b.

region of high-grade reworked early Proterozoic rocks to the north, and the Bancroft-Madoc area consisting of low to medium-grade Grenville supracrustal and other rocks. According to Lumbers (1967) the Bancroft-Madoc area is composed largely of a metasedimentary and metavolcanic sequence approximately 9,000 m thick. These rocks consist of pelitic schist, marbles and metamorphosed silicic, intermediate and basic volcanic rocks. Zircons from volcanic rocks near the base of this sequence yielded a U-Pb age of 1310 ± 15 Ma (Silver and Lumbers 1965). The supracrustal rocks were first intruded by albite granite, diorite, gabbro and nepheline syenite, were then metamorphosed to low and medium grade, at which time (1125 ± 25 Ma, Silver and Lumbers 1965) syntectonic quartz monzonites and potassic granites were emplaced. Typical of these is the Cheddar gneissic granite which has a penetrative gneissic fabric. Following the culmination of metamorphism a generation of pegmatite, pegmatitic granite, syenite dykes and calcite-fluorite-apatite veins were emplaced. These are the rocks with which the uranium deposits appear to be associated. Silver and Lumbers (1965) have reported a U-Pb zircon mineral age of 1050 ± 20 Ma for them.

The Radioactive Rocks

Satterly (1956) classified the uranium deposits of the area into three main groups, granitic and syenitic pegmatites, skarns, and hydrothermal deposits. Although all three types of deposit were investigated during the course of this study, primary attention was given to the pegmatites because of their dominant economic importance and because they presumably are somewhat less contaminated and thus more amenable to isotopic study. The radioactive pegmatites occur in a large assortment of rock types: granites, syenites, ortho and paragneisses, amphibolites and marble. Robinson (1961)

stated that the pegmatite dykes, which range in length from less than 10 m to over 100 m, are emplaced en échelon. In general they grossly parallel the foliation, but in detail truncate it. The contacts are sharp laterally but fade out into granitized zones longitudinally. Satterly (1956) recognizes two types of pegmatite at Bancroft, (1) a zoned type and (2) a complex type whose members are texturally and compositionally variable and not regularly zoned. The latter range in composition from granite to syenite.

The radioactive pegmatites of the area are composed of perthitic microcline, microcline, albite, peristerite, quartz-albite graphic intergrowths and quartz. Some of the albite is secondary as it rims and fills fractures in microcline crystals. Green biotite and hornblende and diopside are observed locally, the latter evidently having formed by syntexis as it is commonly associated with carbonate. In some samples both the diopside and carbonate completely encapsulate grains of quartz and feldspar. Although not seen in the course of this study, aegerine-augite has been observed in the pegmatites by Chayes (1942). Magnetite associated with zircon, which may be zoned, carbonate, fluorite and brown or red ferrugenous material are found in most specimens. In some cases the magnetite has been corroded by the carbonate and fluorite. Hematite is often abundant, coating grains and filling fractures. Ferruginous material is commonly associated with high radioactivity or with magnetite or hematite or both. The brown variety is slightly translucent and amorphous. The other variety is orange-red, also translucent and typically occurs as wispy thin filaments and again shows no diagnostic optical properties. It is suspected that this material contains anomalous quantities of uranium and thorium as some rocks containing the substance are radioactive yet do not appear to

contain distinct uranium and/or thorium bearing phases. Unfortunately the material volatilizes instantaneously under the microprobe beam.

The crystal size of the pegmatites is variable, but most crystals are in the 2-5 cm range. Some have obviously suffered post crystallization deformation. These have patches of quartz and feldspar which are reduced to grains much less than 0.1 mm in diameter whereas adjacent grains, in particular quartz, have been stretched out into lensoid strained forms imparting a cataclastic texture to the rock.

Aside from the ubiquitous hematization, the feldspars commonly show sericite and carbonate alteration. The common primary radioactive minerals found in the Bancroft pegmatites are zircon, allanite, uranothorite, uraninite, thorite, and more rarely such species as pyrochlore $(Na,Ca)_2Nb_2O_6F$, betafite $(U,Ca)(Nb,Ta,Ti)_3O_9 \cdot nH_2O$, fergusonite $(Y,ER)NbO_4$ and euxenite $(Y,Ce)(Ti,Nb,Ta)_2O_6$ (Satterly 1956). High concentrations of uranium may occur in conjunction with high concentrations of magnetite, intense hematization, areas of cataclasis or at pegmatite-country rock contacts.

It was decided early in this study to confine the examination to the radioactive pegmatites, which are known to be among the youngest rocks in the area. They will be compared to the Cheddar granite which, on the basis of textural and other field evidence, appears to be representative of many granites in the area that have the characteristics of syntectonic granite. Samples were taken for Rb-Sr dating from both this granite and the Canadian Dyno mine which outcrops within 1 km of it.

The Cheddar Granite

The granite has a prominent metamorphic fabric manifested by the alignment of biotite flakes which occur in thin films between layers of flattened

quartz and feldspar which are approximately 1 cm in width. This imparts a crude gneissosity to the rock. The rock is composed of microcline (some of which is perthitic), sodic oligoclase, quartz, biotite and rarely, hornblende. The crystal size is dominantly about 1 mm but ranges from less than 0.1 mm to greater than 2 mm. There is slight hematization along fractures in quartz and feldspar, and also a chloritization of the hornblende.

Mont Laurier Area

Regional Geology

There are two areas north of the town of Mt-Laurier (the Mitchinamecus-Lac Montagne, and Lac Patibre areas, Fig. III-2) where uranium occurs in economically significant concentrations. Near Mt-Laurier radioactive granite is quarried for building stone. This granite, however, is enriched in uranium and thorium only to the extent that it is a petrologic curiosity. Reconnaissance mapping of the region or segments thereof has been carried out by Wynne-Edwards et al. (1966), Aubert de la Rue (1948) and Osborne (1934). Rive (1976) has published a detailed description of the St-Véronique area just southeast of Mt-Laurier (Fig. III-3). Recently, Rimsaite (1978), Kish (1977, 1975), Tremblay (1974) and Allen (1971) have studied the uranium occurrences of the district. The rocks of the area can be divided into several units. The supracrustal Grenville Group is generally characterized by quartzite, marble, calc-silicate or pelitic lithologies. These were deposited approximately 1400-1200 Ma ago and were metamorphosed ca. 1100 Ma ago during the so-called Grenville event (Doig 1977). Basement to these rocks is a suite of gneisses which locally may be of either Archean or Aphebian age. They are metamorphosed to either the amphibolite or granulite facies and

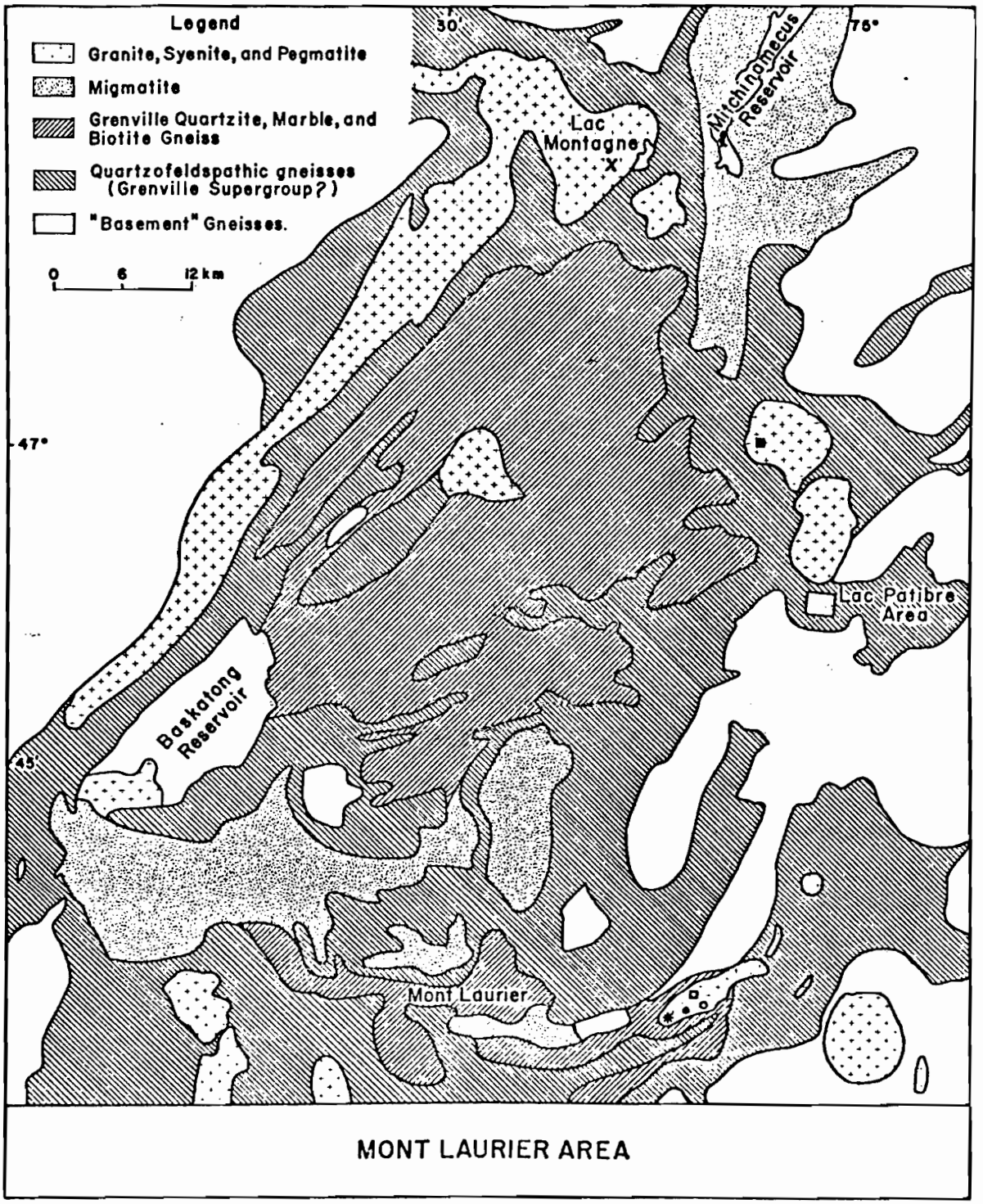


Figure III-2. Geology map of the Mt-Laurier area. After Wynne-Edwards et al. (1966).

typically are quartzofeldspathic gneisses. In certain localities they are intruded by gabbro, syenite, granite, alkali granite, pegmatite and rarely mica peridotite (Wynne Edwards et al. 1966). The granites and pegmatites appear to have been emplaced at the same time as the alkaline rocks and peridotite.

The Mitchinamecus Reservoir-Lac Montagne Area

The oldest rocks of the Mitchinamecus-Lac Montagne area are a group of migmatized biotite and hornblende gneisses. The leucosomes are commonly conformable, deformed and attenuated, and frequently have nebulous contacts with the melanosomes. Amphibolites are not uncommon in the area. Outcrops of granite gneiss and porphyroblastic granite gneiss which are considered coeval with the early metamorphism of the quartzofeldspathic gneiss occur sporadically. Owing to the paucity of outcrop, contact relations between the two are rarely observed. These granitic gneisses have a foliation parallel to that of the host gneisses, but on occasion show minor apophyses cross-cutting the quartzofeldspathic gneiss.

The quartzofeldspathic gneisses of the region vary in composition but on average contain 30-40% quartz, 15-25% plagioclase ($\sim An_{25}$), and variable amounts of biotite (5-25%) and hornblende (5-15%), with accessory sphene, magnetite, apatite and zircon. The leucocratic portions contain more plagioclase and the sum of the hornblende and biotite concentrations is about 10%. The average grain size is approximately 1 mm and the overall texture is granoblastic. Quartz and plagioclase are often polygonalized indicating that equilibrium conditions were obtained during metamorphism. Occasionally the plagioclase is mildly sericitized and the hornblende has been partly retrograded to biotite. These rocks belong to the amphibolite

facies.

The granite gneisses which cut the quartzofeldspathic gneisses have bands of quartz and feldspar about 0.5 cm in width alternating with wispy ~1 mm thin streaks of biotite. The rock is composed of about 15-20% quartz, rarely as graphic intergrowths, 20% albite, 40-50% microcline, up to 15% biotite, 5% sphene and accessory magnetite and allanite. In places the rock lacks the hypidiomorphic granular texture of a granite but has polygonized quartz and oligoclase. Some samples have sericitized feldspars and albitized oligoclase and in certain instances the biotite has been converted to epidote. This reaction and the albitization are interpreted as being prograde metamorphic reactions. Therefore, the granite gneiss belong to the greenschist facies of metamorphism. However, this prograde metamorphic "event" is probably retrograde with respect to the quartzofeldspathic gneiss. The author considers that the quartzofeldspathic gneiss obtained its typomorphic assemblage and metamorphic textures during the peak of metamorphism before being intruded by the granite. The milder metamorphic conditions existing at this later time were responsible for both the lower facies of the granite and the retrograde effects upon the gneiss. There are no lithologies exposed in the vicinity of the southwestern side of the Mitchinamecus Reservoir that could be considered diagnostic of the Grenville Supergroup. However, on the northeast side of the Reservoir there are outcrops of Grenville-group andalusite-bearing rusty weathering gneiss, marbles, and calc-silicate rocks.

All the above units and particularly the rocks on the southwest side of the reservoir are cut by pink granite, aplite and pegmatite which constitute the uraniferous rocks in the area. The aplite normally occurs as veins

and has either conformable or cross-cutting relationships with the gneiss, and in places it occurs as discontinuous masses of very irregular geometry. Oriented biotite imparts a slight planar fabric to the aplite which locally has been folded. The pegmatite, which is the youngest unit in the area, is composed of potassium feldspar, plagioclase, biotite and quartz, ranging in grain size from 2 cm to 0.5 m. Smaller veins (less than 0.1 m) may show signs of deformation (e.g., boudinage structure). Both the pegmatite and aplite have sharp contacts with the gneiss relative to those displayed by the previously mentioned leucosomes. The pegmatites and aplites appear intimately related to numerous intrusive masses of medium-grained pink granite and alaskite. These granites, which dominate the airborne radioactivity patterns in the area (Darnley et al. 1977) occur sporadically over several thousand km^2; they are interpreted to be syn- or late-tectonic granites by Wynne-Edwards et al. (1966). All of the rocks are cut by small (1 mm) fractures which are filled with epidote or hematite or both. The radioactive pegmatites are generally pink and unzoned. They have been strongly hematized and contain alkali feldspars, biotite, magnetite, zircon, allanite, uraninite, uranothorite and rarely, molybdenite. Texture, grain size and mineralogy vary widely throughout the pegmatites. They can be subdivided into two broad categories: (1) those that have sharply defined contacts and clearly cross-cut the gneisses, and (2) those that have tortuous contacts and are essentially conformable with the gneisses. Both often show minor phases of the other type and locally contain blocks of bleached metasomatically altered gneisses that exhibit a ghost stratigraphy. However, enclaves or islands of quartzofeldspathic gneiss within the cross-cutting pegmatites have for the most part survived unscathed. Large

remnants of quartzofeldspathic gneiss within the conformable pegmatites remain in pristine condition, whereas the smaller ones (4-5 cm in width) are quite often thoroughly granitized. Some of the pegmatites occupy the axial planes of late open folds within the gneisses. As at Bancroft highly radioactive zones have a tendency to be accompanied by cataclastic textures or abundant magnetite or hematite or both.

The granite-textured portions of the pegmatites are composed dominantly of approximately 50% microcline, some of which is perthitic, 25% oligoclase, 15-20% quartz and 0-20% brown-green pleochroic biotite. In some cases hematization and accompanying sericitization completely obscure the identity of the feldspars. Locally chess board albite is observed. Albitization has been operative as plagioclase-plagioclase or more particularly plagioclase-microcline grain boundaries have thin (<0.1 mm) rims of newly formed albite. This newly formed albite is neither sericitized nor hematized yet there is often a concentration of hematite at the boundary between the albite and older feldspar. This suggests that albitization post-dates sericitization and hematization. These processes are attributed to metasomatism during the final stages of crystallization.

The radioactive minerals seem concentrated at random in any given pegmatite but the following associations were observed. There is a definite tendency for the concentration of zircon, thorite, allanite and thorian uraninite to increase with hematization. Zircon, thorite and possibly uraninite also tend to be associated with concentrations of magnetite-ilmenite or biotite or both.

The magnetite embays and truncates previously formed crystals of feldspar and quartz. In some highly radioactive samples up to 90% of the rock

is composed of magnetite with heavily hematized vestigial quartz and feldspar. It is apparent that the radioactivity is associated with the magnetite and both are related to the hematization which itself is allied with the sericitization and albitization. Therefore the uranium and thorium mineralization is considered to be the product of late-stage metasomatism.

As mentioned above ilmenite occurs with the magnetite. Initially these minerals were believed to have formed through the sub-solidus oxidation of ulvöspinel-magnetite; as such they might have been used for geothermometry and geobarometry (Buddington and Lindsley 1964). However it soon became apparent that the ilmenite crystallized from a fluid phase after magnetite and not through "exsolution", as veins of ilmenite frequently cut the magnetite.

The Lac Patibre Area

The geology of the uranium occurrences in the vicinity of Lac Patibre (Axe Lake or Mekoos area) has been described in detail by Allen (1971). In essence he described units of migmatized biotite gneisses, calc-silicate rocks, metabasites and quartzites which are all cut by a massive pink monzonite. Aplite which may or may not be related to the monzonite (shown as granite on Figure III-2) occurs with either white or pink pegmatite. This colour difference is ascribed to the absence of ferric iron in the white varieties. Allen shows that these white pegmatites are restricted in occurrence to areas of calc-silicate rock where the partial pressure of CO_2 would have been high, preventing the formation of ferric iron compounds.

The pink pegmatites of this area appear similar to those described from the Mitchinamecus-Lac Montagne area, the white pegmatites differing in

that they contain pyrite rather than magnetite and are not hematized. One uranium showing is composed of both white and pink pegmatite heavily contaminated with metasediments that have biotite selvages containing highly radioactive material. In thin-section the white pegmatites are the same as the red varieties except that they contain minor amounts of carbonate, muscovite and pyrite. Samples of the contaminated pegmatite mentioned above show patches of impure quartzite surrounded by coarse pegmatitic-textured quartz and alkali feldspar. The quartzite is in part heavily sericitized and in part replaced by newly formed quartz. There are also areas where quartzite, close by but not intimately associated with the pegmatites, has four to five times the background radioactivity. Tremblay (1974) has reported that the radioactive minerals of this area are uraninite, uranothorite, allanite and zircon. Aside from the abundance of rocks which belong to the Grenville Supergroup in the vicinity of Lac Patibre and the white colouration of the pegmatites no gross disparities between this region and the Mitchinamecus-Lac Montagne area appear to exist.

The Guénette-Type Granite

The late tectonic granite that occurs throughout the Mt-Laurier area is best exposed in the quarries along highway 117 near the town of Guénette. These granites outcrop sporadically throughout the region. Those which occur just east of the town of Mt-Laurier are enriched in uranium and thorium in comparison to the average granite of Larsen and Phair (1954); as stated earlier, they stand out prominently on the airborne radioactivity map of the area (Darnley et al. 1977). Also in the vicinity of the town of Guénette are a group of grey syenites that seem to be related, at least temporally, to the granites. They also are unaffected by regional

metamorphism; however, they lack radioelement enrichment. Wynne-Edwards et al. (1966) considered the granites to be younger than the syenites, which they related to alkaline granites to the north. Rive (1976) described a pink medium-grained allanite and magnetite-bearing granite, dykes of which intrude the undeformed Ste-Véronique pyroxenite ring complex and its associated syenite. Furthermore, he states that, "It is identical to the extensive Guênette granite", and that a magnetite-bearing, "pegmatite is genetically associated with the pink granite".

In general, the rock is a very homogeneous pink granite having a grain size varying from 0.5 to 1.0 mm. Locally a weak fabric, here interpreted as primary, is discernible. Late stage fracture fillings of quartz, smokey quartz, muscovite, pyrite and fluorite (rarely) were observed. Several zones of grey granite were noted within the larger masses of pink granite. Occasionally they appear symmetrically disposed about fractures or occur at the periphery of enclaves; elsewhere they are apparently unrelated to any structure. These grey zones contain accessory pyrite rather than magnetite. Enclaves of quartzofeldspathic gneiss within the granite commonly have borders of pegmatite approximately 1 cm wide. Where the enclave has been nearly totally digested it does in fact become pegmatite. The pink granite consists of approximately 30% quartz, 35-55% microcline, 15-25% albite, 2-5% muscovite, fluorite from trace amounts up to 1%, 1% allanite, and accessory magnetite, zircon and apatite. The microcline and the plagioclase are commonly mildly sericitized. Green and brown biotite often has pleochroic haloes enveloping a highly birefringent material, presumably zircon. Zircon also occurs as individual crystals not associated with biotite. Strong hematization and the red filamentous material described

earlier often accompanies the allanite. The muscovite appears to have formed late as it embays microcline and often forms discontinuous irregular masses, not interlocking grains as part of a crystal network. The fluorite, either mauve or colourless, is often associated with magnetite and allanite in hematized zones. Samples of "grey granite" from areas approximately 5 cm wide near the boundary of pink granite and quartzofeldspathic gneiss are coarser grained than the pink granite and are primarily composed of quartz and plagioclase with biotite, sphene, and carbonate. Adjacent to this "grey granite" the metasedimentary rocks are particularly enriched in hornblende, biotite and sphene. Much of this biotite poikilitically encloses sphene, quartz and feldspar; it seems to have formed after these minerals. The sphene obviously contains significant amounts of uranium or thorium as the biotite around it is often damaged by radiation. Grey granite not obviously associated with enclaves is identical to the pink granite except that it is not hematized and contains pyrite.

Before describing the radioactive pegmatites of the Baie Johann Beetz region two relevant pegmatite occurrences (Meach Lake and Palmerston areas) located between Mt-Laurier and Bancroft will be briefly described. Although numerous other radioactive pegmatites were examined in southwestern Québec and southeastern Ontario, the majority were not scrutinized as they are either poorly exposed, of insufficient size or are isolated occurrences difficult to relate to local geology.

Meach Lake Area

Hogarth (1966) described an area near Meach Lake (Québec), just north of Ottawa which contains aplite and granite pegmatite. This material is

associated with what Hogarth terms "intrusive carbonate rock" shown to be closely allied to carbonatite. There are numerous coarse-grained carbonate rocks in the Grenville Province which are simply metamorphosed limestones. The Meach Lake carbonate body, however, contains fluorite, soda pyroxene, magnetite, zircon and betafite, and is associated with breccias having phlogopite-apatite-carbonate matrices, and zones of fenitization. Hogarth (1966) reported values of 0.8% SrO in calcite from a breccia, 1.1% from a dolomitic carbonate rock and 1.9% from vein calcite; these values are very much greater than 0.07% reported for three marbles of the Ottawa region away from this particular area. Almost all the "intrusive carbonate" is in what Hogarth terms aplite. The aplite is emplaced in a foliated syenite and is associated with pegmatite which is both younger and older than the aplite. Where the pegmatite is associated with marble it is grey. The aplite is radioactive and similar to the late tectonic granite described from Mt-Laurier. It is pink due to hematization, contains less than 10% plagioclase (An_8), and about 1% biotite which is invariably chloritized. Microcline, which accounts for about 50%-70% of the rock, is sometimes graphically intergrown with quartz, which comprises 25% of the aplite.

In places small veins of carbonate which are sometimes associated with riebeckite cut the rock. Elsewhere calcite, riebeckite and aegerine-augite form granular aggregates where they have replaced quartz in the aplite.

Palmerston Area

Pegmatites of variable radioelement content can be found throughout most of Palmerston and Canoto Townships (Fig.I-1) in granite, granite gneiss, paragneiss, amphibolite and marble (Smith 1956). The metamorphic grade of

the rocks varies from the greenschist to the amphibolite facies. Pegmatites cutting the marbles immediately northwest of Canoto Lake are well exposed. Once more the pegmatites are intrusive, both conformable and cross-cutting, unzoned, and vary abruptly in texture from graphic to granitic to pegmatitic. Contact metamorphic effects upon the marble are not pronounced. Thin selvages of diopside and a coarse recrystallization of the marbles are discernible at certain localities.

The pegmatites consist dominantly of quartz (50%) and microcline (30%) with lesser amounts of sodic plagioclase (10%). There is evidence of albitization. Crystals of sphene up to 3 mm in size form 10% of the rock in one exceptionally radioactive area. Here, apatite is present with the radioactive minerals monazite and thorite. Some of these crystals and their peripheries show extensive radiation shattering and are abundantly hematized.

Johann Beetz Area

The geology of the Johann Beetz area was first described in detail by Cooper (1953). In more recent years several authors have focused their attention on the granites and associated uranium mineralization (Baldwin 1970; Hauseux 1977; Mackie 1977). The oldest rocks in the area are muscovite-bearing metasedimentary units ranging in composition from pure quartzite to biotite schist. These have been intruded by sill-like gabbro bodies that are themselves truncated by younger granites. The youngest rocks are a series of pegmatites that cut all of the above units.

The Lac-Turgeon granite is the major anomalously radioactive feature on airborne radiometric maps in the Johann Beetz area (Darnley *et al.* 1977).

Although the granite mass in in places heterogeneous in terms of texture, composition and contained enclaves, it is also remarkably uniform in many areas. It is composed of equant crystals of clear to smokey quartz (20%), pink potassium feldspar (50%) and plagioclase (25%) approximately 3-4 mm in diameter. Biotite can be conspicuously lacking but in general accounts for 3% of the rock, and where present defines a faint yet pervasive fabric. Departures from this simple granite composition are both abrupt and manifold. The texture may change from aplitic to granitic to pegmatitic, to graphic or porphyritic, within meters. This can be accompanied by dramatic changes in colour and mineralogy, such as the appearance or disappearance of magnetite, pyrite, biotite, muscovite, smokey quartz, tourmaline and radioactive species.

The pegmatites are inequigranular and generally have shattered grains of plagioclase. This shattering tends to amplify the cleavage yet leaves the grain boundaries undisturbed. This resembles textures illustrated and described by Short (1968) known to be due to shock metamorphism. It is suggested by the author that this texture may have resulted from shock metamorphism owing to the sudden release of volatiles. The microcline appears strained and often embays and envelops previously formed quartz and plagioclase. Both feldspars and in particular the oligoclase are altered to sericite. In some cases distinct secondary muscovite and carbonate occur in the plagioclase. Biotite and zircon, which may show zoning, are ubiquitous whereas sphene and allanite are not seen in every thin section. The main radioactive species are uraninite and thorite.

Hauseux (1977) pointed out that on the basis of texture many of the metasedimentary rocks could be classified as granulites. It must be

emphasized, however, that typomorphic assemblages such as the hornblende-oligoclase-epidote of the amphibolites and the quartz-microcline-plagioclase-biotite-muscovite of the quartzites relegate these rocks to the almandine amphibolite facies as defined by Fyfe et al. (1958, p. 229). Contact relationships between the granite and the metasedimentary rocks are contradictory: in certain localities the granite definitely can be seen to cut the original bedding whereas elsewhere the two have conformable contacts and are sometimes observed to be folded together. Apophyses of granite and pegmatite cut the quartzite which in places is found in the granite as enclaves of at least 15 m in length.

Two other areas on the North Shore of the St. Lawrence River known for their radioactive mineralization in pegmatites and described by Baldwin (1970) were visited. The St. Augustine area (Fig.I-1) has pink granite and pegmatites outcropping in amphibolite facies quartzofeldspathic gneiss. The pegmatites which are either conformable with or cross-cut the gneisses are composed mainly of hematized microcline, plagioclase and quartz. Most of the radioactivity is caused by thorium and appears in many cases related to metasomatism. In the second area strongly hematized and highly radioactive uraniferous pegmatites of granitic composition cut the Grenville paragneisses in the vicinity of Sept Iles.

Summary

The uranium and thorium mineralization discussed occurs over a large portion of the Grenville Province in very similar granitoid rocks. Pink pegmatites occur in and cut across a diversity of different host rocks, quartzofeldspathic gneiss, quartzite, marble, amphibolite and syenite, all

of which have been metamorphosed to the amphibolite facies. In addition, the Bancroft, Mt-Laurier and Meach Lake occurrences are at least spatially associated with alkaline rocks. Temporal relationships between host and pegmatites in any given area may be obscure owing to the ambiguities in the field relationships.

Radioactive pegmatites commonly have sharp contacts and cross-cutting relationships with their host or somewhat diffuse contacts and conformable relationships. Large pegmatites may exhibit both modes of occurrence. Pegmatites found in carbonate terrain are frequently white or grey. In some regions they are associated with granite masses that are themselves anomalously radioactive.

As mentioned the pegmatites may vary in texture from aplitic to granitic to pegmatitic over short distances. Microcline, on occasion perthitic, plagioclase and quartz (which may be graphically intergrown with either of the feldspars), make up the essential minerals. Biotite, muscovite, sphene and magnetite are widespread as well. The common uranium and thorium-bearing minerals found in the various occurrences are uraninite, thorite, zircon and allanite. The uranium-thorium mineralization tends to be associated with intense hematization, sericitization or an enrichment in biotite, magnetite or sphene. There is evidence that some features related to the U-Th mineralization are post-crystallization effects related to late-fluid movement. The fact that the potassium feldspar of all these deposits is microcline is significant. Martin (1974) has shown that the presence of an aqueous fluid and in particular an alkaline aqueous fluid greatly enhances the formation of triclinic K-feldspar. The widespread sericitization of the feldspar indicates that a fluid was introduced after

crystallization. The process of albitization described at some localities would also require a fluid as a means of ion transport (Marmo 1971, p. 158) and perhaps also the introduction of sodium. The presence of chessboard albite is claimed by many to reflect sodium metasomatism (Smith 1974, V.2, p. 287). The zoned zircon described could be due to repeated overgrowths in response to pulses of fluid discharge after the main episode of pegmatite formation. Furthermore, the development of grey granite along fractures in pink granite must undoubtedly be due to the action of late-stage fluids.

It is therefore concluded that a fluid phase or phases played a major role in the generation, subsequent alteration and mineralization of the various pegmatites described.

The Grenville Province pegmatites discussed thus far have some characteristics in common with the Rossing deposit of Namibia. Both are composed of aplites and pegmatites which invade metasedimentary rocks. The Rossing, however, appears much larger, has lower thorium contents and is not related to syenitic rocks. On the other hand, some Grenville deposits are similar to the Conway granite of New Hampshire which is enriched principally in thorium, contains allanite, huttonite, thorite, and zircon, and is related to a suite of slightly alkaline igneous rocks.

CHAPTER IV - ISOTOPE GEOLOGY

Choice of Methodology

Much of the early geochronology done in the Grenville Province employed the K-Ar technique on single minerals such as biotite (Stockwell 1962). Most minerals have ^{40}Ar blocking temperatures that do not exceed about 250°C (York and Farquhar 1972, p. 108). Therefore, mineral samples dated by K-Ar means from any terrain that has been subjected to post-crystallization thermal events will usually yield the age of this latter event. In many cases this age is not the one desired and has been confused with the age of metamorphism. Therefore K-Ar ages from minerals of metamorphic terrains should be interpreted as either minimum ages of metamorphism (i.e., cooling) or dates of a discrete thermal event not necessarily related to primary metamorphism.

The $^{40}Ar/^{39}Ar$ incremental-heating technique was devised as a means of obtaining truer ages. It does give older dates and some insight into the thermal history of a particular sample. However, ages associated with this technique are also characteristically low in terms of significant metamorphic events.

Krogh and Davis (1972) have shown that the U-Pb systems in zircons from granite and nearby paragneisses of the French River area south of Sudbury were severely disturbed by metamorphism. Zircons from a single sample which may have been disturbed twice yield U/Pb ratios that occupy an area rather than defining a line on a concordia diagram. The Rb-Sr whole-rock isotope systematics were investigated for the same granite and paragneiss. Although Sr had equilibrated on a mineral-to-mineral scale during

the younger event the whole-rock technique was capable of "seeing through" this younger event, giving an age interpreted to be that of the original metamorphism. They concluded that the Rb-Sr whole-rock technique is superior to the U-Pb zircon method for many applications in regionally metamorphosed terrains. For the above reasons and because the $^{87}Sr/^{86}Sr$ ratio is a versatile isotopic tracer it was decided to use Rb-Sr isotopes in preference to the other isotopic systems mentioned.

Summary of Grenville Province Geochronology

Doig (1977) has shown that a large part of the Grenville Province gneiss terrain in proximity to the Grenville Front in Western Québec is in fact overprinted Archean material. Rb-Sr whole-rock ages in this section of the province range from 2,450 to 2,850 Ma. In Ontario, Krogh (1966) reported Rb-Sr whole-rock ages of 1,750 Ma in a broad region adjacent to the Front. Undoubtedly large portions of the Grenville Province, particularly to the west, consist of reworked Archean and Aphebian rocks. More to the southeast, supracrustal rocks of the Grenville Supergroup have been deposited in part upon this basement approximately 1300 Ma ago (Silver and Lumbers 1966). According to Doig (1977) "the metamorphism of the Grenville Supergroup in Québec (so-called Grenville orogeny) culminated about 1,100 Ma ago".

In the southern part of the province near Bancroft, Ontario, two periods of granite plutonism, 1250 ± 25 Ma and 1125 ± 25 Ma have been recognized by Silver and Lumbers (1965). More to the east, north of Montréal and in the Lac St-Jean region, Québec, Frith and Doig (1973), Barton and Doig (1974) and Doig (1977) have reported on the abundant

granitic and monzonitic plutonism as well as the metamorphic ages of peli tic gneisses ca. 1100 - 1150 Ma ago. A rather sparse but widespread and locally abundant series of granites and pegmatites, including those of this study, intrude the pre-existing metamorphic rocks in numerous localities.

The history of the Grenville Province is long and complex. The main period of metamorphism, the Grenville Orogeny, seems to have affected Aphebian and Helikian (Grenville) supracrustal rocks ca. 1100 Ma ago. It appears that plutonic rocks were emplaced before, during and after this event and that the province as a whole was closed to Ar diffusion ca. 950 Ma ago.

Analytical Procedures

Rb/Sr ratios were measured on powder pellets by X.R.F. spectrometry after approximately 5 kg of rock had been crushed, pulverized and split. The peaks and corresponding backgrounds were counted five times each for 100 s for each sample, and a maximum of twenty times for the standards. The data were corrected for curvature of the background after the method outlined by Barton (1971) and dead-time corrections were applied. A conversion factor relating the measured Rb/Sr ratios for the U.S.G.S. standards to those determined by isotope-dilution mass spectrometry was then calculated and applied to the samples. Error is estimated to be less than 1%. The $^{87}Sr/^{86}Sr$ ratios were measured using a six-inch Nier-type single filament mass spectrometer with the sample loaded in chloride form. Twenty double scans were measured per sample; this typically yielded standard deviations of the mean $^{87}Sr/^{86}Sr$ isotopic ratio of approximately 0.0004. The results of five runs of the Eimer and Amend standard $SrCO_3$ during the

study yielded a mean value of 0.7076 and standard deviation of 0.0003. The least-squares isochron lines were computed using the method of York (1966).

All errors are reported at the 68% confidence level. The new ^{87}Rb decay constant of 1.42×10^{-11} yrs^{-1} was employed (Steiger and Jager 1977) both for new results, and data reported from the literature.

Rb-Sr Age Relationships of the Radioelement-Enriched Granites to their Hosts

After having determined that the radioelement-enriched granites do structurally postdate the metamorphic rocks of each area it was decided to try and relate their time of emplacement to that of Grenville metamorphism. As mentioned, Barton and Doig (1974) and Doig (1977) have obtained Rb-Sr whole-rock isochrons from pelitic rocks which yield ages (ca. 1100 Ma) interpreted to be those of Sr-isotope equilibration during the Grenville event. In view of the absence of suitable pelitic rocks close to the radioactive pegmatites dated in this study it was decided to try and date what appeared to be the youngest granites showing a penetrative fabric in each area which appear to be syntectonic in nature. Although this method runs the risk of determining pretectonic ages, the ages obtained are comparable to and certainly do not refute the ages of metamorphism obtained from pelites elsewhere in the province.

Bancroft Area

As mentioned in Chapter III, two isochrons were prepared from rock suites sampled in the Bancroft area, the gneissic Cheddar granite and a composite group of samples from three radioactive pegmatites. Figure IV-1, the pegmatite isochron, yields an age of 959 ± 16 Ma and an $^{87}Sr/^{86}Sr$

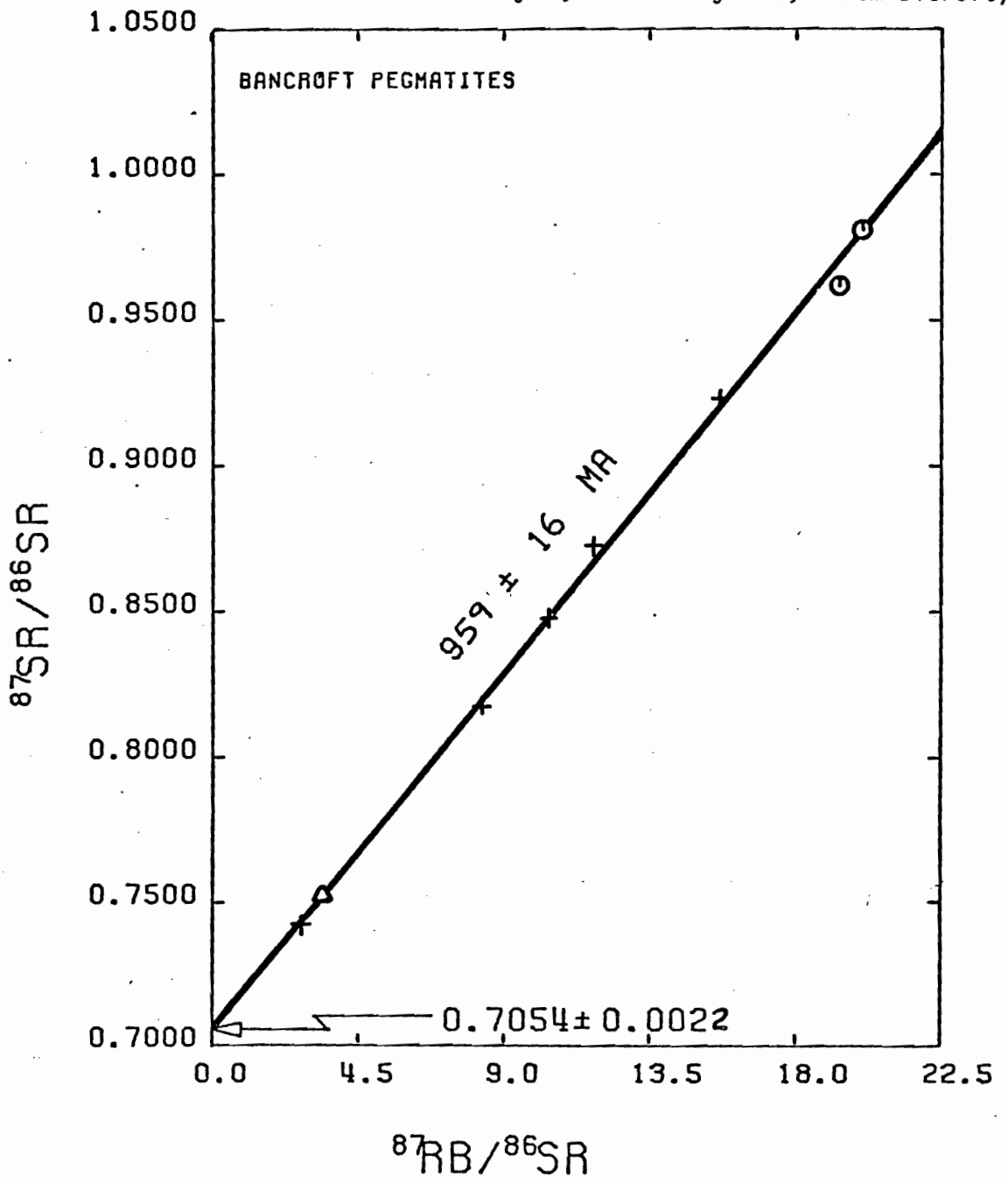
initial ratio of 0.7054 ± 0.0022. The five samples depicted by (X) marks are from the former Canadian Dyno mine, the two depicted by (⓪) marks are from the defunct Greyhawk mine 17 km to the NE and the single sample marked by a (Δ) is from the former Bicroft mine 7 km NE of the Canadian Dyno mine (see Fig. III-1).

The fact that the samples from all three mines fit the isochron well shows that there are no gross dissimilarities in age or $^{87}Sr/^{86}Sr$ initial isotopic ratios, that they have remained undisturbed in terms of Sr isotope geochemistry since that time and suggests a common parent material.

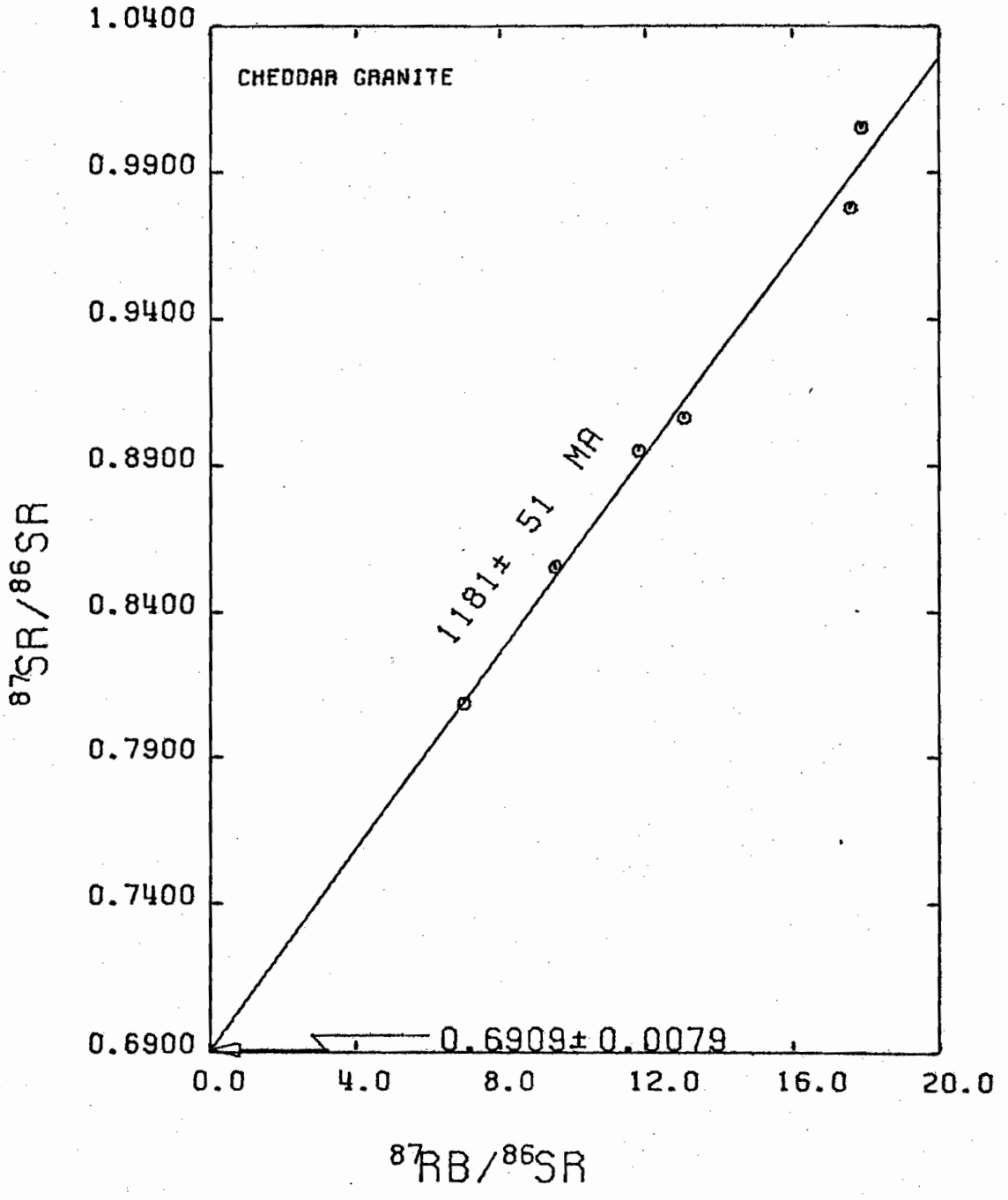
The age of 959 ± 16 Ma shown for these rocks is considerably lower than the age of 1100 Ma usually assumed to be the culmination of Grenville Province metamorphism. The age is different from 1050 ± 20 Ma U-Pb zircon date obtained by Silver and Lumbers (1965) from veins and pegmatites of the area but not directly comparable owing to uncertainty in the decay constants. An average age of 1036 Ma computed from 7 dates ranging from 990 to 1090 Ma (data summarized by Macintyre et al. 1967) based on U-Pb dates, of uraninites and thorianites from skarns and pegmatites of the area, is also similar to that obtained in this study. The large range (100 m.y.) exhibited by these analyses indicates the possibility that the U-Pb systems have been disturbed; they are therefore a less reliable indication of age than the Rb-Sr whole-rock isochron of this study.

The $^{87}Sr/^{86}Sr$ initial ratio of 0.7054 has a relatively high associated error of 0.002. This ratio, although slightly higher than the mantle ratio of 0.703 at that time, is certainly not indicative of rocks formed by anatexis. Specifically, it is highly unlikely that these rocks would have formed by anatexis of a pelitic or greywacke-type protolith without an

Figure IV-1. Rb-Sr whole rock isochron of Bancroft area uraniferous pegmatites (X from Canadian Dyno, ⊙ From Greyhawk, △ from Bicroft).



FigurelV-2. Rb-Sr whole rock isochron of the Cheddar Granite Gneiss, Bancroft area.



extraordinary enrichment in Rb.

In contrast to this is the isochron (Fig. IV-2) derived from the adjacent Cheddar granite, which yields an age of 1181 ± 51 Ma. This age, interpreted to be that of early syntectonic granite emplacement, suggests that the pegmatites are late or post tectonic.

The $^{87}Sr/^{86}Sr$ initial ratio of 0.6909 is at face value unreasonably low but has a high error of 0.0079 owing to the lack of points close to the ordinate and the scatter that exceeds experimental error. In summary, the radioactive pegmatites at Bancroft are clearly much younger than the syntectonically emplaced Cheddar gneissic granite and are interpreted as being late or post tectonic in age.

Mt-Laurier Area

Mitchinamecus-Lac Montagne Area

Figure II-2 shows the location of sample suites taken from the Mt-Laurier area for Rb-Sr studies. Samples were selected from the pegmatites of the Lac Patibre area but then rejected as thin section study showed that many contain a high proportion of included metasedimentary material. Figures IV-3 and IV-4 are two whole-rock isochrons obtained from cross-cutting pegmatites approximately 75 m long by 10 m wide which are situated on the southeastern side of the Mitchinamecus Reservoir. The isochron shown in Figure IV-5 refers to a pegmatite outcropping near Lac Montagne about 5 km to the west of the Mitchinamecus Reservoir, in the area mapped as granite by Wynne-Edwards *et al.* (1966). The dates for the three pegmatites, 928 ± 38, 938 ± 36, and 917 ± 33 Ma, resemble those reported for the Bancroft-area pegmatites. They are in a similar way much younger

Figure IV-3. Rb-Sr whole rock isochron of the Lac Montagne Pegmatite,Mt-Laurier.

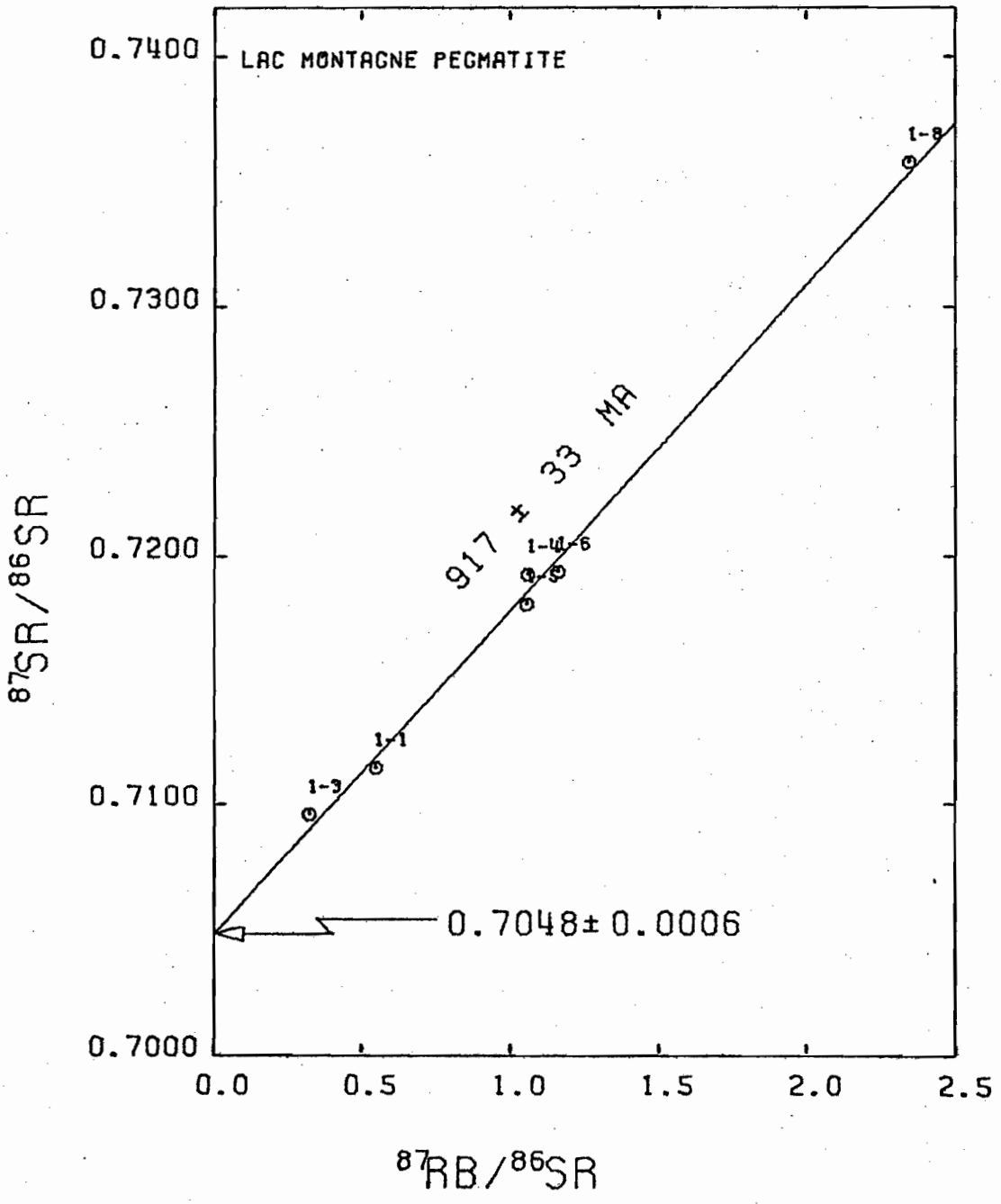


Figure IV-4. Rb-Sr whole rock isochron of the Mitchinamecus Pegmatite #1, Mt-Laurier area.

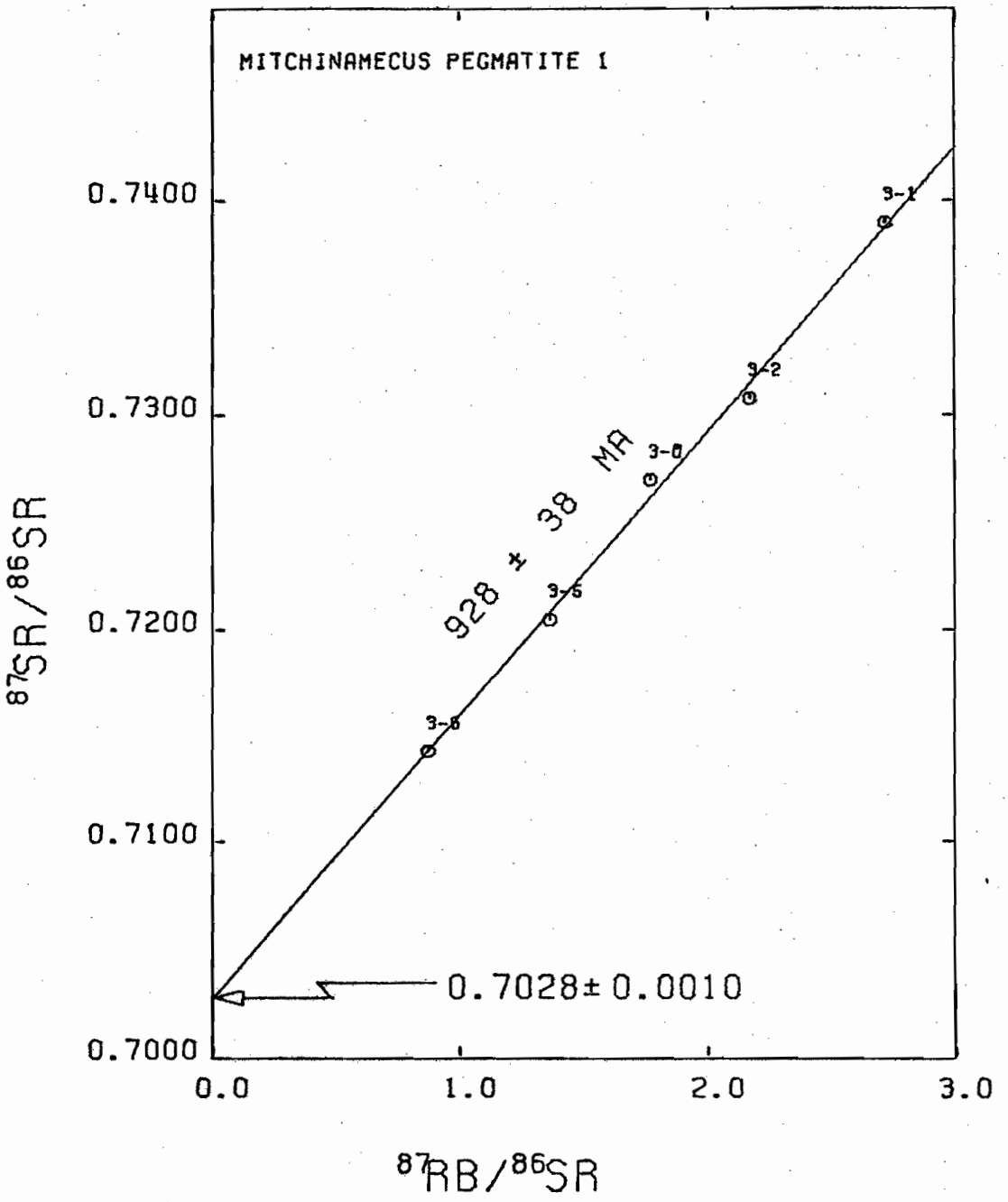
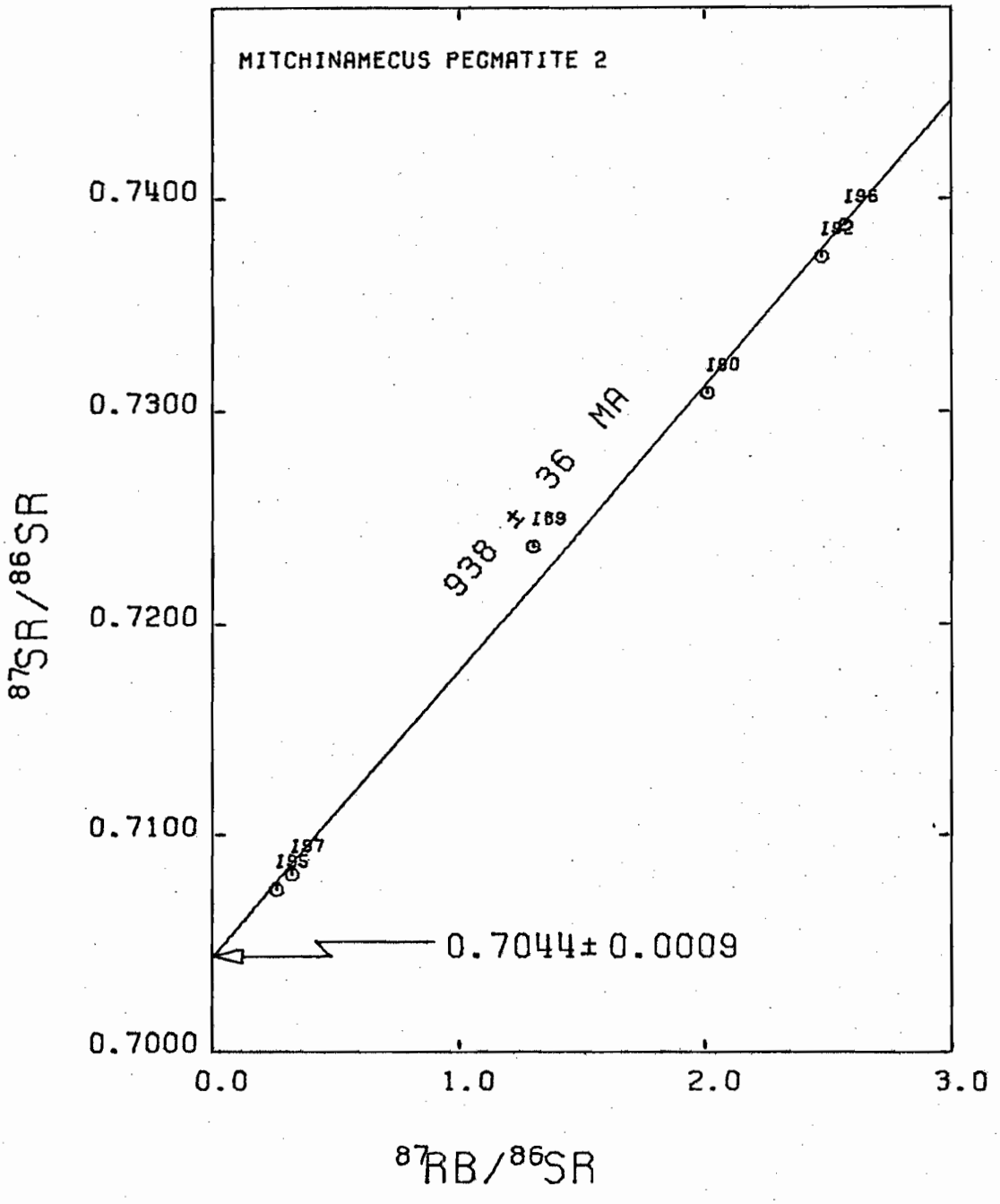


Figure IV-5. Rb-Sr whole rock isochron of the Mitchinamecus Pegmatite #2, Mt-Laurier area.



than the dates commonly reported for the peak of Grenville metamorphism.

A somewhat older date was obtained from the aplite described in Chapter III which has a slight planar fabric in places but lacks the distinct layering of the gneissic granite. This aplite, which is enriched to some extent in uranium, was sampled within 2 km of the Mitchinamecus pegmatites. It yields an age of 988 ± 24 Ma. This date (Fig. IV-6) confirms the textural evidence and shows that the rock is younger than the main period of metamorphism. However, it also shows that this particular aplite is somewhat older than the pegmatites of the area.

Figure IV-7 is composed of samples from a pegmatitic granite just to the east of the reservoir. The large scatter and clustering of the data points make the error large (~13%) and as a consequence yields an "age" of 924 Ma, uninterpretable except to say that it does not refute the age data from the pegmatites.

An attempt was made to date the age of metamorphism by means of the quartzofeldspathic gneiss in the vicinity of the Mitchinamecus Reservoir. Figure IV-8 shows that the data do not define an isochron and results in the high error of 274 Ma associated with the 980 Ma "age". However, there is at least the suggestion that the gneiss is not a reworked Archean or Aphebian rock.

In contrast to the above the granitic gneiss described earlier yielded an isochron age of 1083 ± 40 Ma (Fig. IV-9) approximately 150 Ma greater than that of the pegmatites. The $^{87}Sr/^{86}Sr$ initial ratio of 0.7039 ± 0.0004 coupled with the fact that the granite has a gneissic texture, polygonized grains and is only greenschist facies indicates that this granite is late syntectonic.

Figure IV-6. Rb-Sr whole rock isochron of the Mitchinamecus Aplite, Mt-Laurier area.

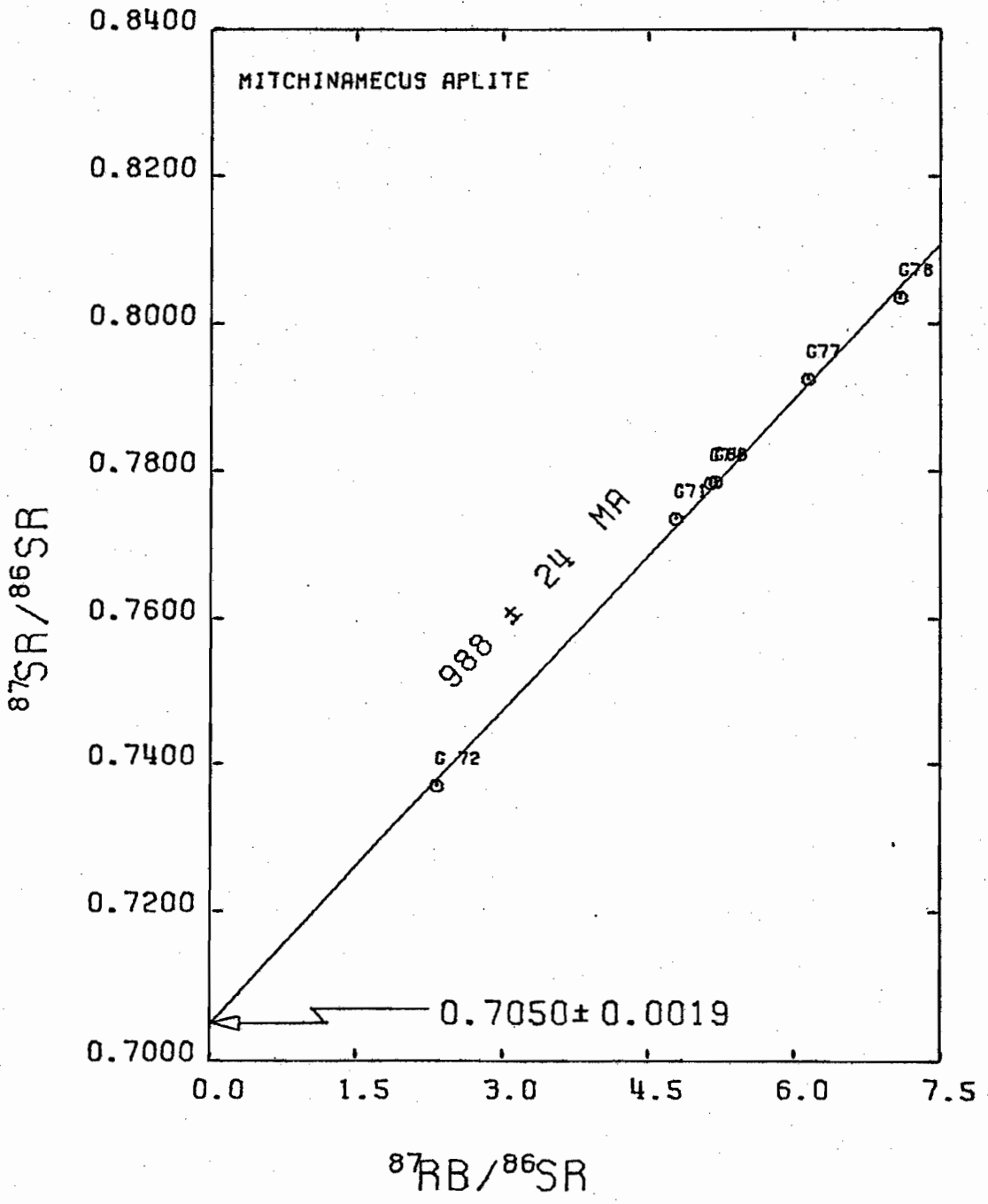


Figure IV-7. Rb-Sr whole rock isochron of the pegmatitic granite Lac Edmond, Mt-Laurier area.

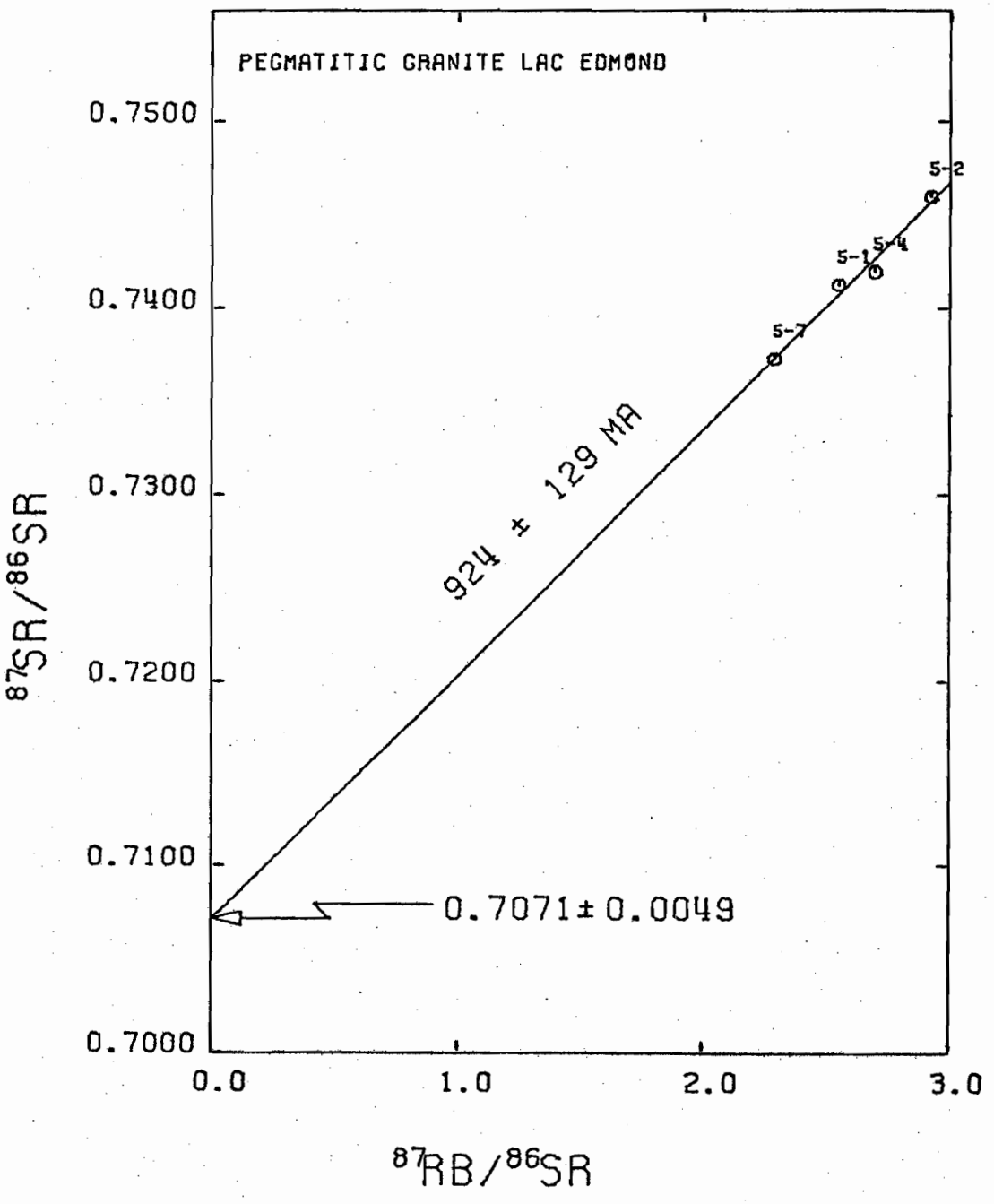
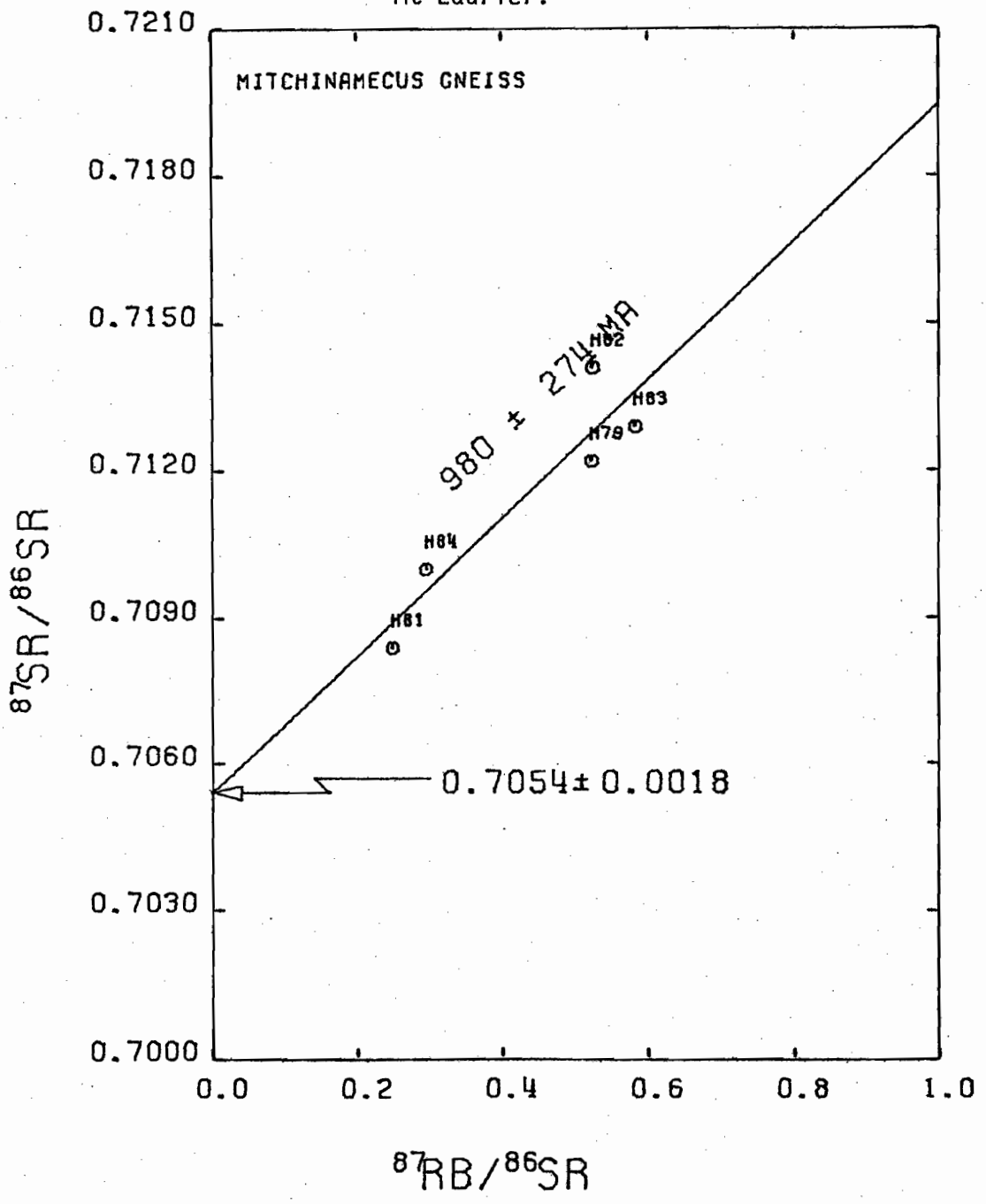
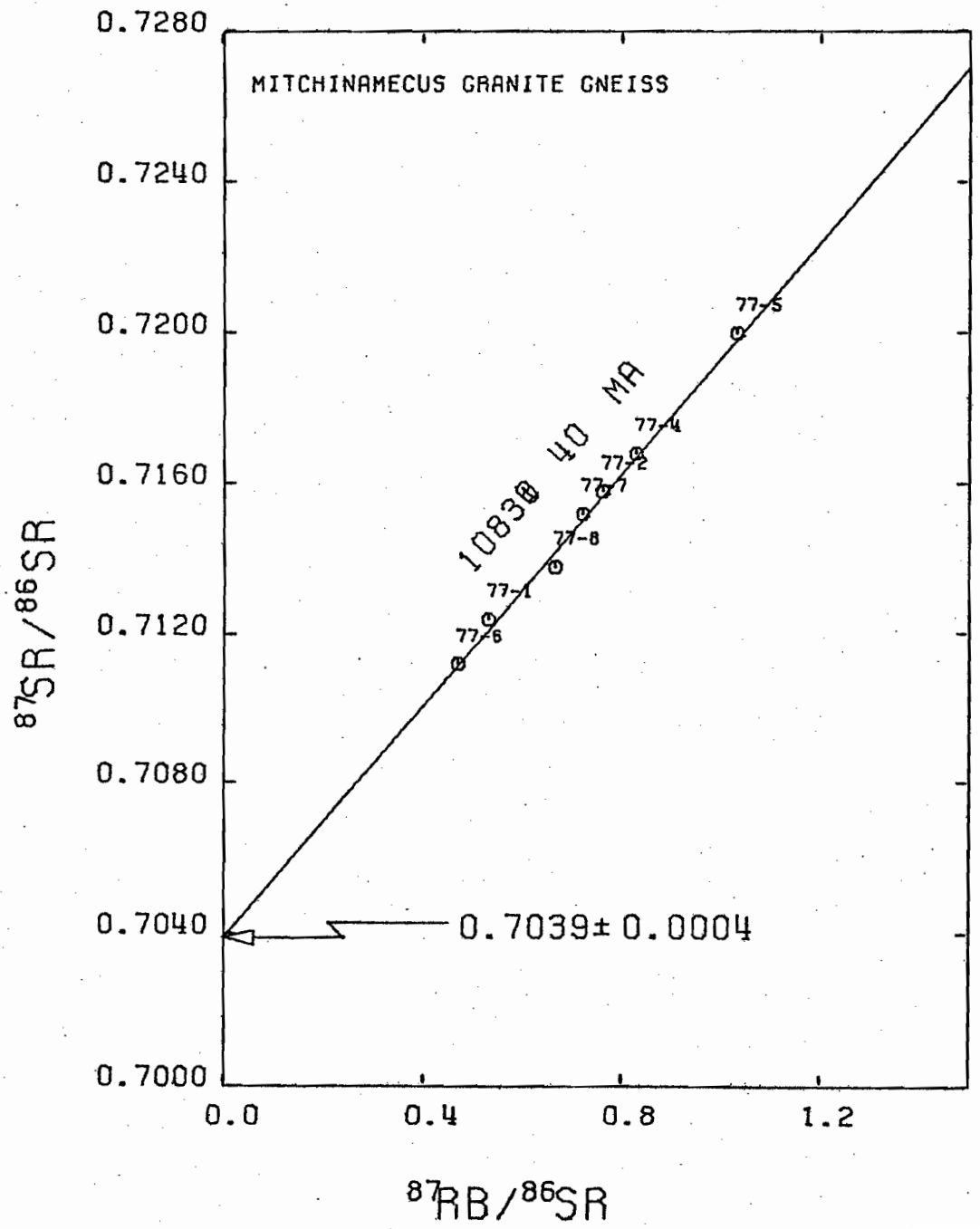


Figure IV-8. Rb-Sr "isochron" of the quartzofeldspathic gneiss in the Mitchinamecus Resevoir area, Mt-Laurier.



FigurelV-9. Rb-Sr whole rock isochron of the Mitchinamecus granite gneiss, Mt-Laurier area.



The $^{87}Sr/^{86}Sr$ initial ratios and associated errors of the two Mitchinamecus pegmatites and the Lac Montagne pegmatite are 0.7028 ± 0.001 0.7044 ± 0.0009 and 0.7048 ± 0.0006. These ratios fall within the upper part of the "basalt field" on the $^{87}Sr/^{86}Sr$ versus time diagram of Faure and Powell (1965), demonstrating that they are in fact primitive. Furthermore it can be demonstrated that representative Aphebian and Archean rocks occurring within the Grenville Province would yield very much higher $^{87}Sr/^{86}Sr$ initial ratios in response to a 930 Ma event than those reported here. Calculations using the data of Doig (1977) show that typical Archean and Aphebian gneisses within this part of the Grenville Province would yield $^{87}Sr/^{86}Sr$ initial ratios of 0.7106 - 0.7146 and 0.707 - 0.719 respectively, in response to a 950 m.y. event. These ranges correspond to $^{87}Rb/^{86}Sr$ ratios for isochrons of Archean and Aphebian gneisses of 0.35 - 0.38 and 0.22 - 1.2 respectively (see Doig 1977, Figures 5,8,9 and 14). This would preclude formation of the pegmatites from the quartzofeldspathic gneiss found in the vicinity of the Mitchinamecus Reservoir be they Kenoran or Aphebian as the average $^{87}Rb/^{86}Sr$ of these rocks is about 0.4.

Undoubtedly the anatexis of exceedingly Rb-deficient rocks shortly after deposition could cause the observed low $^{87}Sr/^{86}Sr$ initial ratios. However the pegmatites postdate the deposition of Grenville Province sediments by about 350 m.y.

Therefore, in view of the fact that the pegmatites postdate Grenville metamorphism by 150 Ma and have Sr-isotope geochemistry indicating they have formed from a low-Rb source and not the abundant supracrustal rocks, it is concluded that they must not have formed through in situ anatexis during the Grenville orogeny.

Guénette Granite

Figure IV-10 is an isochron based on samples taken from the radioactive granite at the Guénette quarries, granites in its vicinity, and also from outcrops of similar granite as much as 40 km away (Fig. II-2). The age of 977 ± 53 Ma is indistinguishable from those of the Mitchinamecus pegmatites and granite presented earlier. The $^{87}Sr/^{86}Sr$ initial ratio of 0.7043 ± 0.0025 is again typical of juvenile material. In spite of the slight scatter of points about the line of best fit, this isochron demonstrates that the source material of these widely distributed granites was isotopically relatively homogeneous with respect to Sr.

Baie Johan Beetz

The isochron of Figure IV-11 is made up of data from samples of graphic granite from the Turgeon Lake granite mass which hosts the Johan Beetz uranium mineralization. The age of 928 ± 30 Ma is again younger than that normally associated with Grenville metamorphism. Unfortunately most of the rocks in the area that show evidence of having experienced this metamorphism (quartzite and gabbro) are Rb-deficient. Therefore, first-hand knowledge of the age of metamorphism is lacking. However, 1100 Ma dates have recently been produced for the youngest foliated granites in an area 60 km to the west (R. Doig, unpublished data). Hence, there is no reason to believe that the age of metamorphism here deviates markedly from that determined elsewhere in the Grenville Province. The age of the Turgeon Lake granite (928 Ma) is distinctly younger than this and confirms the field interpretation that this granite is late or post kinematic with respect to the Grenville event. Unfortunately, the error associated with the

Figure IV-10. Rb-Sr whole rock isochron of the Guénette granite, Mt-Laurier area.

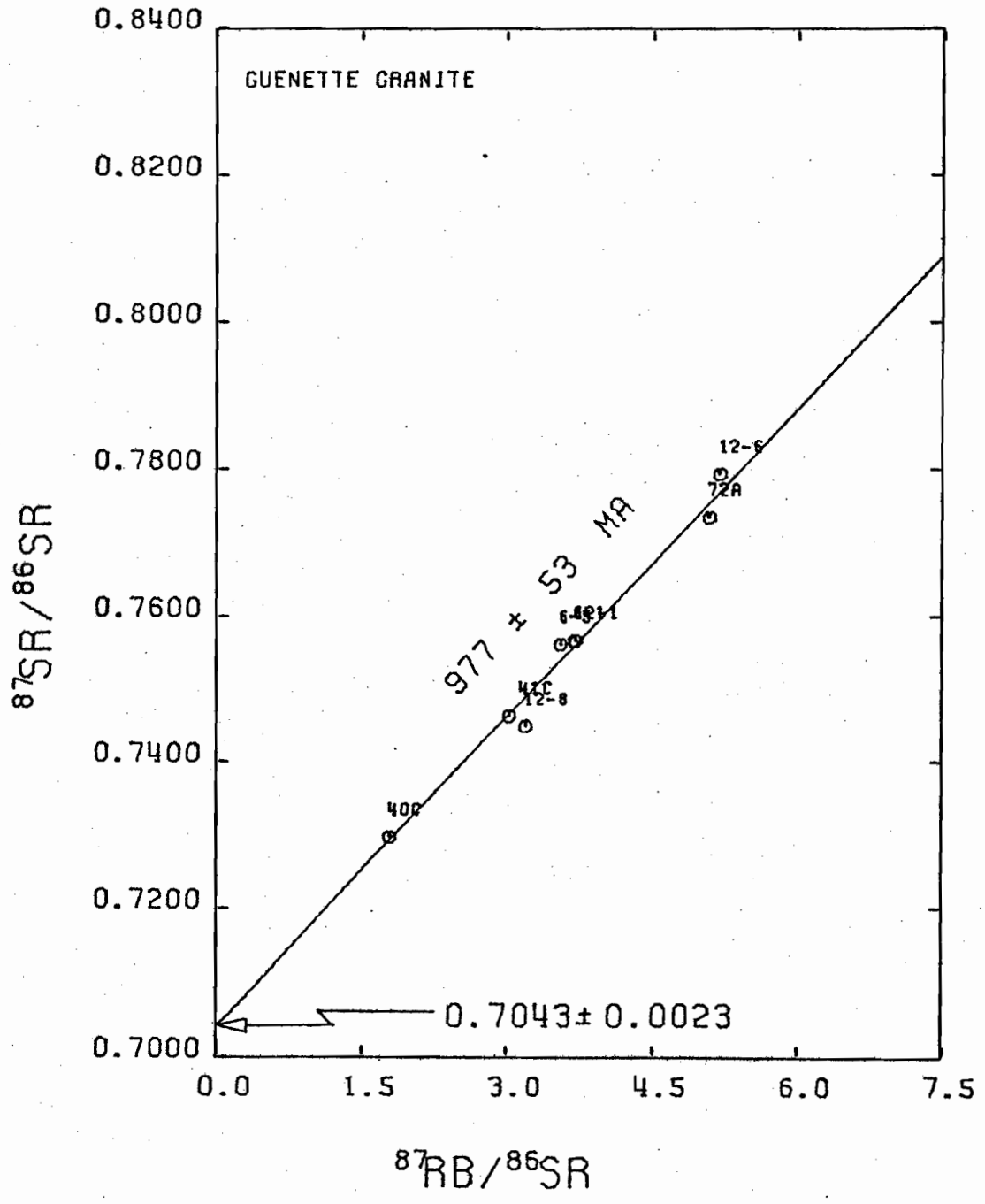
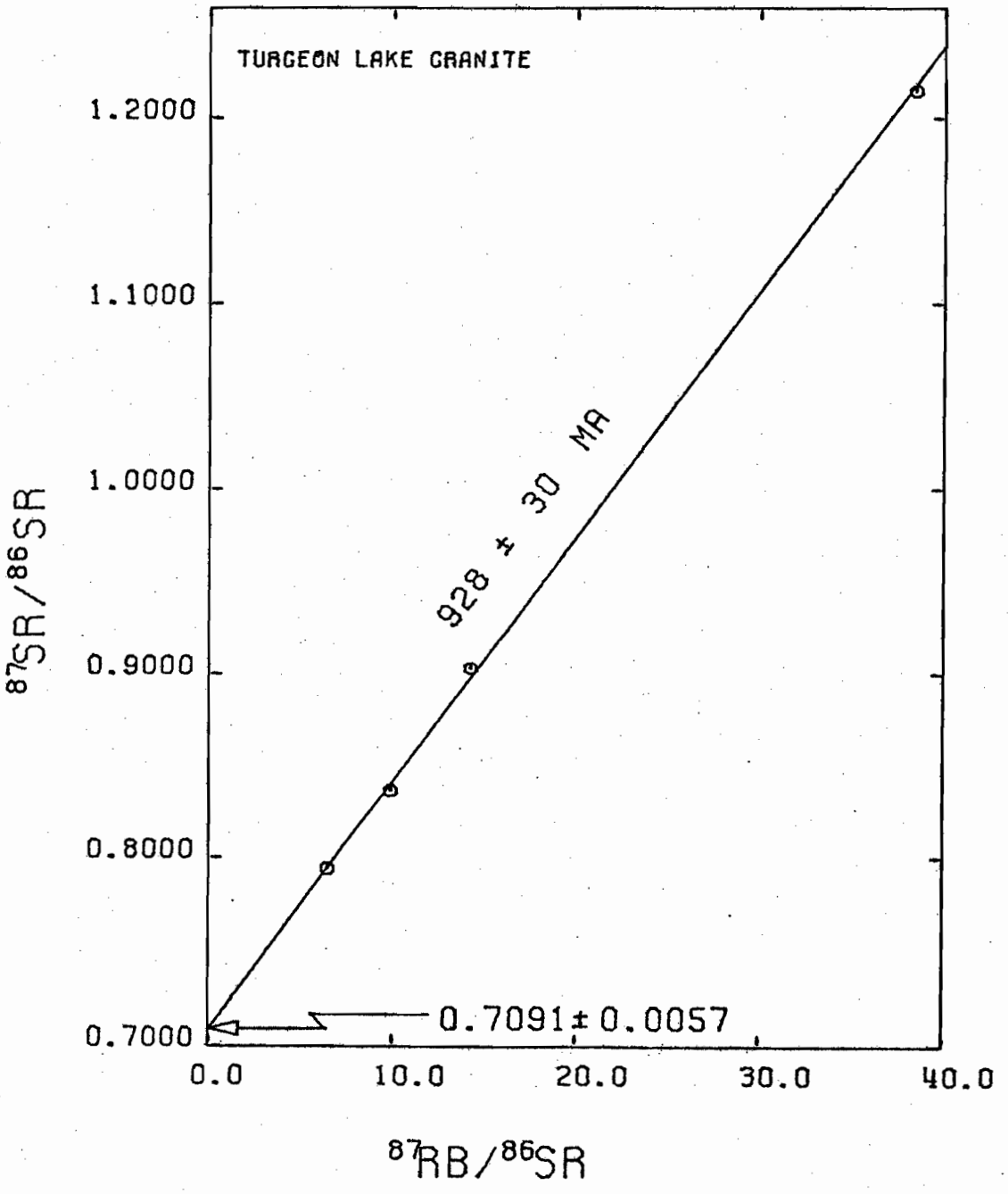


Figure IV-11. Rb-Sr whole rock isochron of the Turgeon Lake Granite, Johan Beetz area.



$^{87}Sr/^{86}Sr$ initial ratio (0.7091 ± 0.0053) is an order of magnitude greater than that normally attributable to experimental error. This arises because of the high $^{87}Rb/^{86}Sr$ values obtained from this particular rock-suite and the lack of values close to the ordinate. This error makes the range of possible values for the $^{87}Sr/^{86}Sr$ initial ratio large (0.704 - 0.714) and consequently, renders it uninterpretable. The limited number of data points is due to unfortunate duplication in terms of Rb/Sr ratio in samples collected from this somewhat remote area.

Summary

To recapitulate, the most striking feature of the data presented in this chapter is the young and similar age of the uraniferous pegmatites sampled over some 2,000 km of the Grenville Province. The ages of the pegmatites ranging from 917 to 960 Ma are significantly younger than the age of Grenville metamorphism. These data coupled with the primitive nature of the $^{87}Sr/^{86}Sr$ initial ratios constrains the radioactive pegmatites to having formed by means other than *in situ* anatexis of metasedimentary rocks during the Grenville Orogeny.

CHAPTER V - TRACE AND MAJOR ELEMENT GEOCHEMISTRY

The purpose of this chapter is to present and interpret geochemical data. However it is first necessary to discuss the merits and/or limitations of such data when dealing with granitic rocks and in particular those which have been subjected to post-crystallization alteration. Because much of the work was done by instrumental neutron activation analysis and a method was devised to circumvent the unusual problems posed by uranium-enriched samples, this technical contribution will be outlined first.

Neutron Activation Analysis

Analyses of certain rare earth elements (REE) and trace elements were performed at the Nuclear Engineering Laboratories, Ecole Polytechnique, Montreal, employing the general technique of Gordon et al. (1968). Approximately two grams of sample were placed into polyethylene containers which were sealed and loaded into the reactor via a rabbit in a pneumatic tube. The capsules were irradiated 58 seconds with a thermal neutron flux of either 0.5 or 1.0 x 10^{11} n $cm^{-2}sec^{-1}$ and both cooled and counted approximately ½ hour for the analyses of Dy, Ba, U and Mn. They were then irradiated for 2 hours at a flux of 10^{12} n $cm^{-2}s^{-1}$ and after cooling one week the γ-ray peaks of La, Sm, Yb and Lu were measured for counting times of 1.3 to 5 hours. The remaining elements, Ce, Eu, Tb and Th were counted for similar times after a further week of cooling. The counting was performed on a Canberra model 8180 4096 - channel analyzer coupled to a 37 cm^3 Ge(Li) crystal with 2.0 KeV resolution (FWHM at 1332 KeV). The U.S.G.S. standard granite G_2 was run as a calibration check. The results of this sample run are given in Appendix B. Elemental concentration is related to experimental

variables and constants by the following equation:

$$P = \frac{N\gamma\ \lambda}{\beta\ \phi}\ \frac{1}{(1-e^{-\lambda ti})(e^{-\lambda ta})(1-e^{-\lambda tc})}$$

where $N\gamma$ = number of γ-rays counted

P = mass of element in micrograms

ti = irradiation time

ta = cooling time

tc = counting time

ϕ = neutron flux

The parameter β which relates detector efficiency, γ-ray intensity and thermal neutron cross-section to the above was determined experimentally for each element in various media.

With the exception of certain uranium and thorium-rich samples the overall precision based on replicate analyses of U.S.G.S. standards is estimated to be 5 to 10%.[1] The presence of high uranium and to a lesser extent thorium, concentrations relative to REE or other trace elements may contribute to a higher overall error.

High uranium concentrations produce three different interferences: (1) an interference from γ-rays produced by elements formed from ^{238}U, (2) an interference from χ-rays of these elements and lastly (3) in certain cases the actual production of a particular trace element of interest through ^{235}U fission. The first two effects have been mentioned by some authors in studies of silicate rocks, for example Gordon et al. (1968) and Jacobs et al. (1977). Erdtman (1972) has calculated the level of interference for various fission products but to the author's knowledge this

---

[1] Personal communication, G. Kennedy, Department of Nuclear Engineering, Ecole Polytechnique, Montreal.

topic has not been considered in the literature pertaining to INAA of silicate rocks. As a consequence of this, routines for correcting the various interferences were devised. The general technique requires irradiation and subsequent analysis of a known amount of natural uranium in an otherwise blank sample. Appropriate conversions are then made to the actual samples on the basis of their uranium concentration. Peaks for all the elements discussed were plotted for many different uranium and thorium concentrations in order to assess the magnitude of the interferences. All peak and background integrations were performed manually and corrections were applied depending upon the relative amount of uranium to the element interfered with. The sample data are given in Appendix B. The following are examples of the correction procedures used in calculating the abundance of each element.

La La is conveniently measured using the 1596 KeV ^{140}La peak produced by ^{139}La $(N\gamma)^{140}La$. Jacobs et al. (1977) state that the 1596 KeV peak is free from interference and lies in an area of low background allowing precise La determination. This is not strictly true as ^{140}La also lies in a fission chain (Chart of the Nuclides, General Electric Company) and is produced in uranium-enriched samples. ^{140}La is produced from ^{140}Ba which can be assumed to form instantaneously as its precursors (I,Xe,Cs) have very short half lives. ^{140}Ba, however, has a half life of 12.79 days so that the amount of ^{140}La produced will depend upon the time the actual counting is done after irradiation. A uranium spiked blank was analyzed approximately one week after irradiation and its ^{140}La activity at 1596 KeV, A_2 was recorded. The activity of ^{140}Ba at time of formation A°, i.e. irradiation was calculated from the ^{140}La activity, A_2^t: measured at time t after irradiation.

$$A_2{}^t = \frac{\lambda_2}{\lambda_2-\lambda_1} A_1{}^\circ(e^{-\lambda_1 t} - e^{-\lambda_2 t}) \qquad (5\text{-}1)$$

Solving for $A_1{}^\circ$ under standard run conditions of thermal neutron flux = 10^{12}, irradiation time = 2 hours and counting time of 18,000 sec yields an activity of $\frac{63.7 \text{ counts}}{\mu g \text{ U}}$ ^{140}Ba. As an example, the sample MLC II which has 68 μg U and was counted 362,104 seconds after irradiation yielded a ^{140}La activity due to ^{235}U fission products of 3061 counts corresponding to 0.67 μg La or 17% of the actual La content of 4.6 μg. Admittedly the sample is depleted in La (1.9 ppm) but this does show that this effect can be appreciable even in cases where the uranium concentration is low, in this case 32.7 ppm.

Ce — Ce is measured from the gamma activity at 145.4 KeV associated with the reaction $^{140}Ce(N\gamma)^{141}Ce$. ^{141}Ce also lies in a fission chain but because its half life is relatively long (32.5 d) in comparison to its precursors and because it is normally counted several weeks after irradiation, it may be assumed to have formed instantaneously from its precursors at the time of irradiation. An analysis of the irradiated uranium-spiked blank showed that 3.37 μg uranium will produce 1 μg of Ce. Sample CD I from the Canadian Dyno mine contains 420 μg Ce and 106 μg uranium. The amount of fission-produced ^{141}Ce was calculated to be 31.4 μg or 7.5% of the net Ce content of 420 μg.

Sm — ^{153}Sm, which has a photopeak of 103.2 KeV is produced from the activation of ^{152}Sm. ^{153}Gd also has a photopeak of 103.2 KeV. However, the longer half life of this element (241.6 d) reduces its interference effect to a minor level (Jacobs et al. 1977). Figure V-1 shows a spectrum of G_2 and a uranium-enriched sample in the vicinity of the

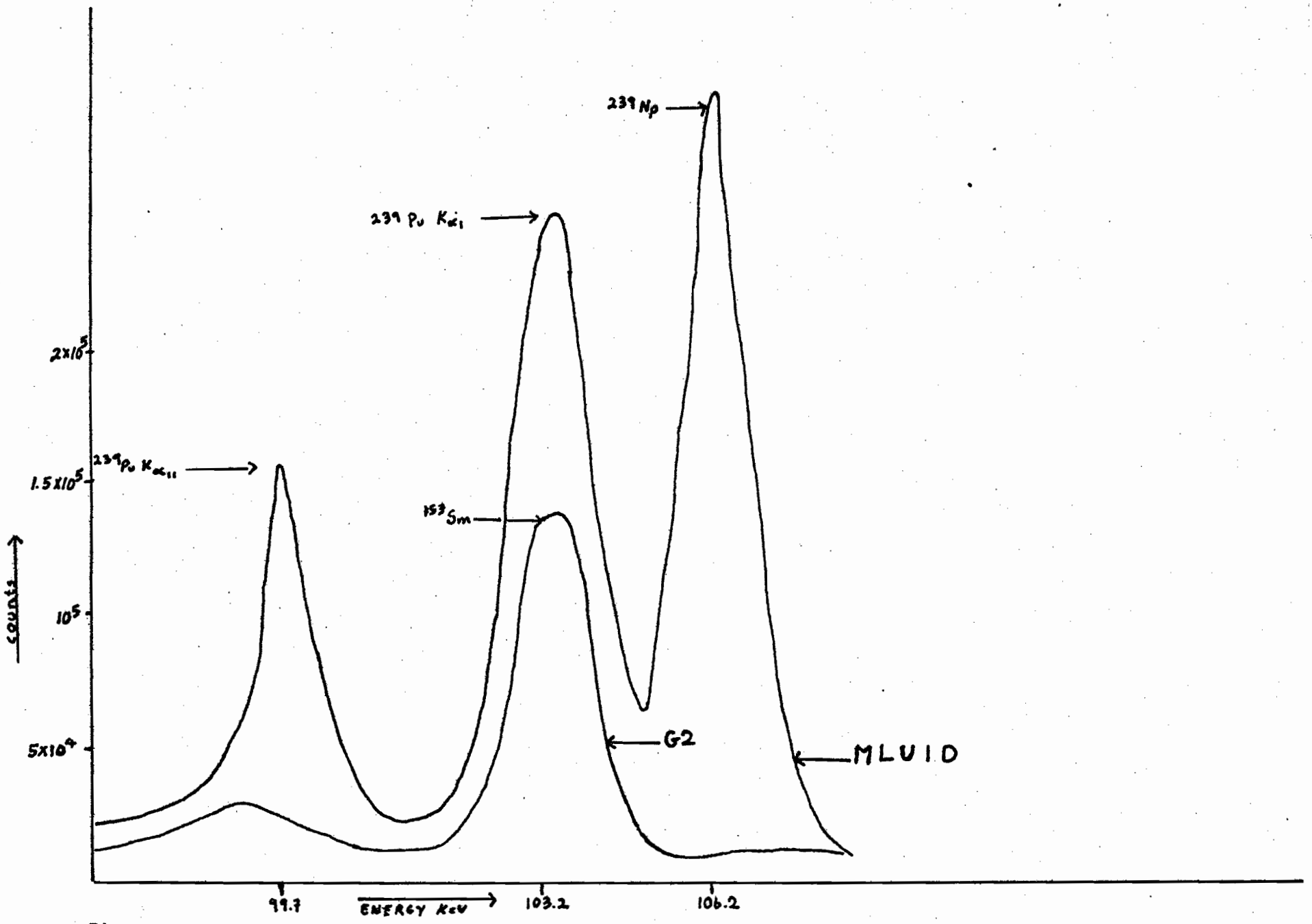


Figure V-1. A gamma-ray spectrogram in the vicinity of 100 KeV illustrating the effect of high uranium concentration upon the 103.2 KeV peak of ^{153}Sm.

103.2 KeV peak. The background is rather high at this low energy for peaks of both samples and the MLU ID sample peak background is very poorly resolved, particularly on the high energy side. This is due to a ^{239}Np γ-ray at 106.1 KeV produced by $^{238}U(^{N}N\gamma\beta^{-})^{239}Np$. The Sm peak height of sample MLU ID is approximately twice that of G2 yet the samples contain 2.15 and 7.3 ppm of Sm respectively. This is due to ^{139}Pu $K\alpha_1$ X-radiation of 103.76 KeV which is associated with a $K\alpha_2$ X-radiation shown at 99.55 KeV which interferes with the background on the low energy side of the ^{153}Sm peak.

In high uranium samples the 103 KeV peak was measured by assuming that the background of the high energy side is symmetrical with that of the low energy side as it is in low uranium samples, and adjusting the peak area accordingly. The effect of the Pu $K\alpha_1$ X-radiation was corrected by relating its activity to the uranium concentration of a uranium-spiked blank and compensating for its 56.4 hour half life. One µg of uranium irradiated for 2 hours at $\phi = 10^{12}$ N $cm^{-2}s^{-1}$, cooled for 7 days and counted for one hour, yields the equivalent of 0.11 µg Sm at 103 KeV. For sample CD I which has over 11.6 µg Sm and 106 µg uranium this amounts to 15.6 µg of fission-produced Sm being present after a cooling time of 10.45 d. Further interference may be produced by X-rays in the region 94 to 98 KeV (Gordon et al. 1968), due to ^{233}Np formed from thorium. A 104 KeV X-ray is also produced by the decay of Np.

Eu ^{152}Eu produced through the activation of ^{151}Eu was determined from its 1408 KeV peak. This peak appears to be free of interferences in the rocks studied.

Tb The 879 KeV ^{160}Tb gamma peak was found to be free of interference.

However, Gordon et al. (1968) observed an interference from ^{44}Sc at 889 KeV, and ^{154}Eu at 873 KeV due presumably to the poorer resolution of their detector.

Dy ^{165}Dy was measured using the 94.7 KeV peak. The analysis can suffer from an interference from the 233 Pa $K\alpha_2$ X-ray at 92.29 KeV and the $K\alpha_1$ X-ray at 95.87 KeV produced by $^{232}Th(n\ \beta^-)^{233}Pa$. However, because the thermal neutron capture cross section is much greater for ^{164}Dy than for ^{232}Th, and the activity of ^{165}Dy is far greater than that of ^{233}Pa, this interference was not significant for short irradiations (~1 min) and short cooling times of 2-3 hours.

Yb ^{175}Yb was determined from the 282.5 KeV peak. The presence of the 285 KeV ^{239}Np peak produced by the $^{238}U\ (n\ \beta^-)^{239}Np$ reaction may add a significant contribution to the background of the Yb peak. In analyses of samples where this peak was appreciable the background was computed from the 280.5 KeV channels only, which were found to be free from interferences caused by the 277.5 KeV ^{239}Np peak.

Lu ^{177}Lu has a 208 KeV peak which is interfered with by 210 KeV ^{239}Np and an unidentified (summation?) peak at 205.8 KeV. Samples containing a ratio of $\frac{U}{Lu}$ in excess of about 3 have their Lu peak almost totally masked by this interference. Because of this Lu contents are not reported in many cases. Another possible interference is the 210 KeV ^{233}Th peak.

Ba Ba was measured using the 165.8 KeV peak of ^{139}Ba which lies in a fission chain. A similar method to the ^{140}La correction was used. Equation (5-1) may be rearranged to yield

$$A_1^\circ = \frac{\lambda 2 - \lambda 1}{\lambda_2}\ A_2 t(e^{\lambda_1 t} - e^{\lambda_2 t}) \qquad (5\text{-}2)$$

where in this case A_1° = parent ^{139}Cs at t°

A_2 = ^{139}Ba at t.

One can easily devise a method of computing A_1°/µg U using a spiked blank. However in this decay scheme $T_{\frac{1}{2}}{}^{139}Cs << T_{\frac{1}{2}}{}^{139}Ba$ which creates additional problems for samples counted shortly after irradiation (less than 1 hour). In this situation equation (5-1) only gives ^{139}Ba counted at the instant t, whereas in fact the counts will have accumulated from ta (start of counting) to ti (end of counting) during which time significant ^{139}Ba will have formed. This may be corrected by integrating equation (5-1) between ta and ti.

$$\int_{ta}^{ti} A_2{}^t dt = \frac{\lambda_2}{\lambda_2-\lambda_1} A_1^\circ \int_{ta}^{ti} e^{-\lambda_1 t} dt - \int_{ta}^{ti} e^{-\lambda_2 t} dt$$

$$= \frac{\lambda_2}{\lambda_2-\lambda_1} A_1^\circ \left[\left(\frac{-e^{-\lambda_1 ti}}{\lambda_1} - \frac{-e^{-\lambda_1 ta}}{\lambda_1} \right) - \left(\frac{-e^{-\lambda_2 ti}}{\lambda_2} - \frac{-e^{-\lambda_2 ta}}{\lambda_2} \right) \right] \quad (5\text{-}3)$$

which combined with (5-1) yields:

$$A_2{}^t = \frac{\lambda_2}{\lambda_2-\lambda_1} A_1^\circ \left[\left(e^{-\lambda_1 ta} - e^{-\lambda_2 ta} \right) - \left(\left(\frac{e^{-\lambda_1 ti}}{\lambda_1} - \frac{e^{-\lambda_1 ta}}{\lambda_1} \right) - \left(\frac{e^{-\lambda_2 ti}}{\lambda_2} - \frac{e^{-\lambda_2 ta}}{\lambda_2} \right) \right) \right]$$

The ^{139}Ba activity determined for a 555 µg uranium-spiked blank irradiated for 58 s at $\phi = 10^{12}$ n $cm^{-2}s^{-1}$ and counted for 15 min after a 47 min delay time was 7539 counts, equivalent to 153 µg Ba. This corresponds to an activity of ^{139}Cs at t = 0 of 3.287×10^7 counts or 59764 counts/µg uranium. Sample Bi I from the Bicroft mine has 96.5 µg uranium or an activity of ^{139}Cs of 5.77×10^6 counts at t = 0. This corresponds to a ^{139}Ba activity after ta = 1320 s and ti = 1800 s of

620 counts produced through fission. This amounts to approximately 15% of the total ^{139}Ba activity observed in this sample.

Uranium and Thorium Content of the Mont Laurier Rocks

Uranium and thorium analyses were performed *in situ* using a portable gamma-ray spectrometer with a 3"x3" (7.6 cm x 7.6 cm) NaI(Tl) crystal. The sensitivities and stripping ratios were calculated from measurements done at the Geological Survey of Canada's calibration facilities at Upland's Airport, Ottawa, using the method of Grasty and Darnley (1971). Szöghy and Kish (1978) have shown that the ^{214}Bi content of a sample from a highly radioactive area (approximately 300 times natural background) is out of equilibrium with respect to ^{238}U by 25%. This effect would be much smaller or nonexistent for the analyses of the less radioactive material reported here because (a) the effect would diminish with radioactivity and (b) the effective sample volume for *in situ* measurements is far larger than the sample volumes taken for laboratory analyses and as a result there will be less differential migration of individual daughters of the ^{238}U decay series out of or into the larger sample. Figure V-2 shows the results of 90 determinations of eU and eTh for these rocks. Although the plot as a whole seems to be random it does reveal several trends if the data are separated by rock type. Almost all the granites contain less than 25 ppm eU but the majority contain approximately 80 ppm eTh.[1] In fact, an analysis of the data from thirty γ-ray spectrometric stations in the homogeneous pink granite yielded a mean of 8.9 ± 5.7 and 92.7 ± 19.5 for eU and eTh respectively and a ratio

[1]The terms eU and eTh are contractions of equivalent uranium and equivalent thorium respectively, meaning that U and Th have been estimated from their ^{214}Bi and ^{208}Tl activities.

eTh/eU of 10.4 ± 7. Notable exceptions are the white granites' higher eU. However, it should be noted that the white granite is exceedingly rare in comparison to the pink.

Uranium and thorium are distributed in a heterogeneous manner in the pink pegmatites. In general, the pegmatites contain more of these elements than the granites. In contrast with the white pegmatites whose eTh/eU ratio is characteristically less than one, this ratio is almost invariably greater than one in the pink pegmatites. With one exception analyses of over 30 quartzofeldspathic gneisses, marbles and quartzites fall in the area near the origin (15 ppm eTh, 5 ppm eU). The very high ratio of eTh/eU in the granites which tends to decrease in the pegmatites would seem to indicate that the late-stage fluids preferentially carried uranium relative to thorium out from the granite to the pegmatites. This process is probably related to oxidation of uranium which is more mobile in the hexavalent state in comparison to the tetravalent state. The white pyritiferous pegmatites have very much lower Th/U ratios indicating that U^{+6} was precipitated from solution owing to reducing conditions.

Uranium and Thorium Contents of the Rocks of the Johan Beetz Area

Figure V-3 shows the distribution of uranium relative to thorium for radioactive rocks of the Johan Beetz region. Mean values and standard deviations for 16 γ-ray spectrometric stations from pink granite are 48.6 ± 16.7 ppm eTh and 21.7 ± 11.8 for eU, and yield a eTh/eU ratio of 2.3 ± 1.4. This indicates that the Turgeon Lake granite is more enriched in uranium relative to thorium than both the Mont Laurier granites and the average granite of Larsen and Phair (1954). The pegmatites occupy a broad area but

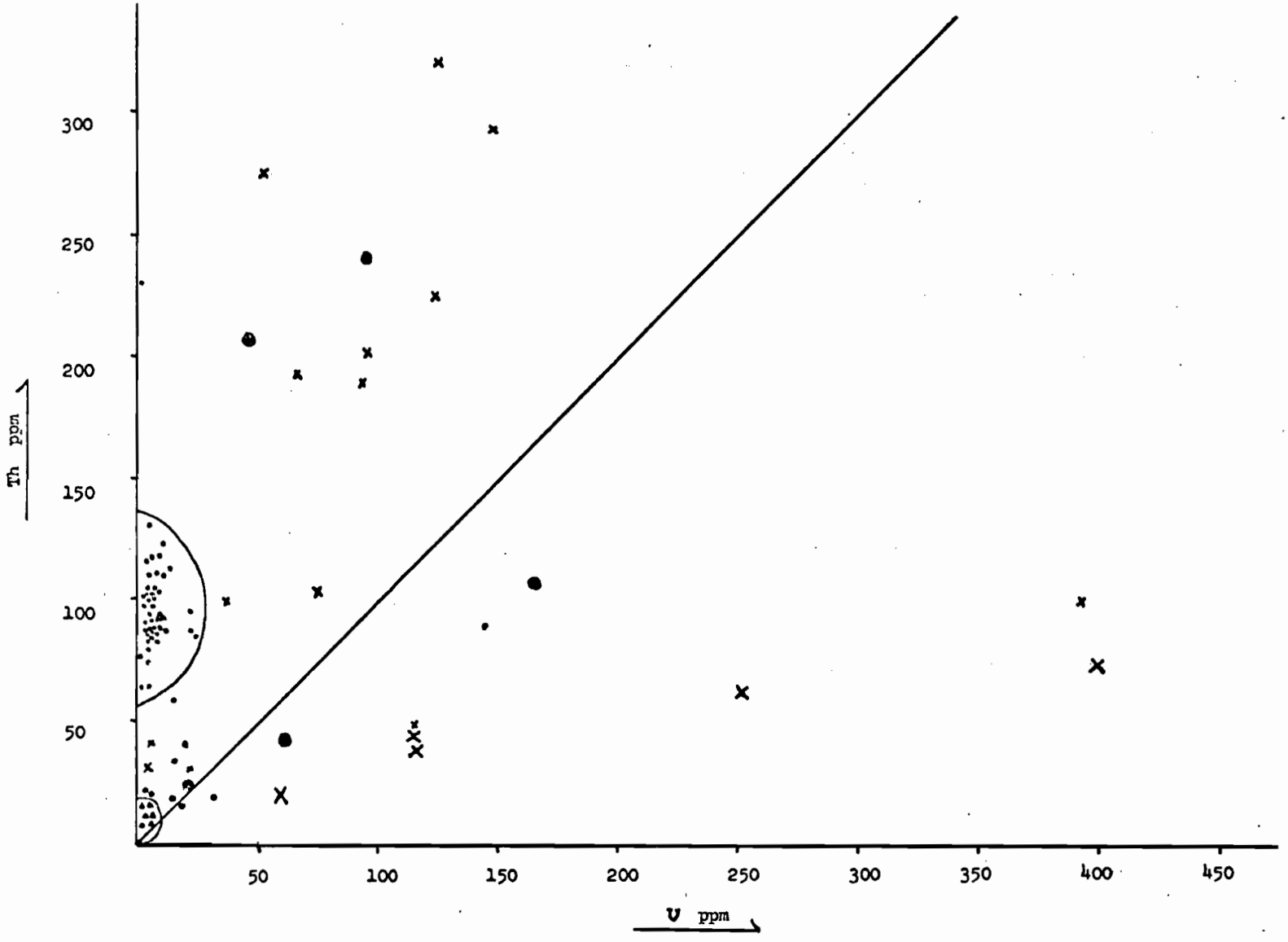


Figure V-2. A plot of uranium versus thorium for the Mt-Laurier area rocks. The large dots and X's denote white granite and pegmatite respectively and the small dots and x's pink granite and pegmatite. The small triangles represent quartzofeldspathic gneisses. The reference line shows where Th/U 1.

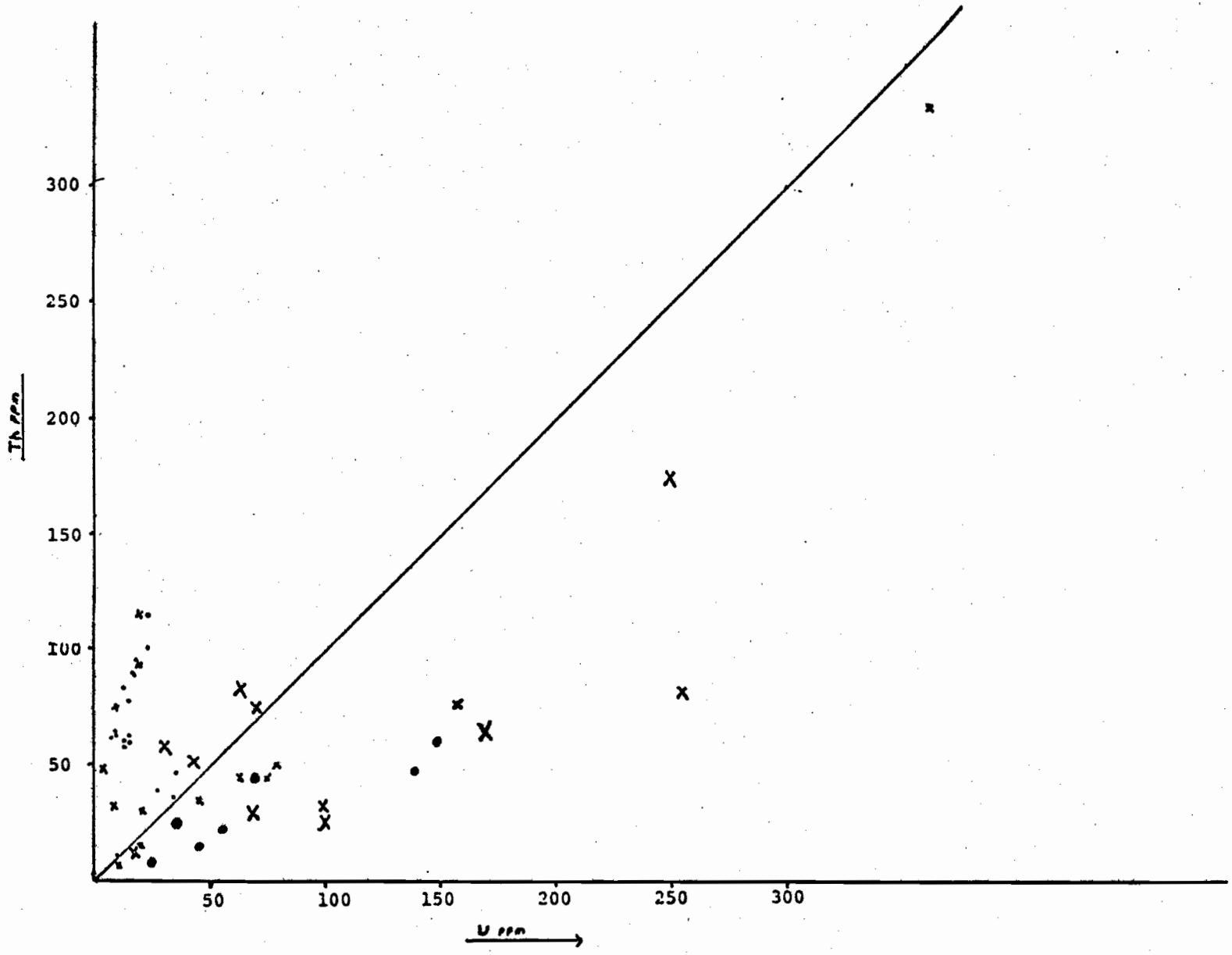


Figure V-3. A plot of uranium versus thorium for the Johan Beetz area rocks. The symbols are the same as those of figure V-2.

the white or pyritiferous pegmatites tend to have low Th/U ratios in comparison to the pink ones. A limited number of stations from the Bancroft area are also plotted on Figure V-3. The data set is too small to be usable in terms of radioelement distribution, except to say the pegmatites are enriched relative to the Cheddar granite.

Comparative Geochemistry of the Rare Earth Elements

The Lanthanide series elements or rare earth elements (REE) are unique in the degree to which they possess similar chemical properties. The reason for this and other factors which control their occurrence in nature will be discussed first before reviewing their distribution in granites. The isochemical behaviour of these elements is due to the fact that when progressing through the series it is energetically more feasible to fill the 4f electron subshell rather than the 5d. These new electrons are shielded from the valence region by the 5s, 5p and 6s subshells' electrons (Moeller 1963). By contrast, in the actinide series the added 5f electrons project into the valence region (Sinha 1966). The filling of the 4f shell thus produces no systematic changes in chemistry (i.e. valence) except a contraction of the radius (the so-called lanthanide contraction) due to the increased nuclear charge.

Schilling and Winchester (1967) have shown that this contraction results in the heavy rare earth elements (HREE) being depleted in more differentiated rocks relative to the light rare earth elements (LREE). The contraction allows the REE to form progressively stronger coordination complexes in solution with increasing z. Table V-1 shows the electronic configuration of neutral, divalent, trivalent and tetravalent lanthanides,

Table 11: Characteristic Electron Configurations and Radii for Y, REE, Th and U.*

Electron configuration 4f and higher.
Actinides 5f and higher.

Element	Z	REE^{o}	REE^{2+}	REE^{3+}	REE^{4+}	AC^{6+}	Characteristic Valence	Ionic Radius A^{o} REE^{2+}	REE^{3+}	REE^{4+}	AC^{6+}
Y	39	$4d^{1}5S^{2}$					3	0.93	0.88		
La	57	$5d^{1}6S^{2}$		$5S^{2}5P^{6}$			3		1.061		
Ce	58	$4f^{1}5d^{1}6s^{2}$		$4f^{1}$	$5S^{2}5P^{6}$		3,4		1.034	0.92	
Pr	59	$4t^{3}6S^{2}$		$4f^{2}$			3		1.013		
Nd	60	$4f^{4}6S^{2}$		$4f^{3}$			3		0.995		
Pm	61	$4f^{5}6S^{2}$		$4f^{4}$			3		0.979		
Sm	62	$4f^{6}6S^{2}$	$4f^{6}$	$4f^{5}$			2,3	-	0.964		
Eu	63	$4f^{7}6S^{2}$	$4f^{7}$	$4f^{6}$			2,3	1.09	0.950		
Gd	64	$4f^{7}5d^{1}6S^{2}$		$4f^{7}$			3		0.938		
Tb	65	$4f^{9}6S^{2}$		$4f^{8}$	$4f^{7}$		3,4		0.923	0.84	
Dy	66	$4f^{10}6S^{2}$		$4f^{9}$			3		0.908		
Ha	67	$4f^{11}6S^{2}$		$4f^{10}$			3		0.894		
Er	68	$4f^{12}6S^{2}$		$4f^{11}$			3		0.881		
Tm	69	$4f^{13}6S^{2}$		$4f^{12}$			3		0.869		
Yb	70	$4f^{14}6S^{2}$	$4f^{14}$	$4f^{13}$			2,3	0.93	0.858		
Lu		$4f^{14}5d6S^{2}$		$4f^{14}$			3		0.848		
Th	90	$6d^{2}7S^{2}$			$6S^{2}6P^{6}$		4			1.02	
U	92	$5f^{3}6d^{1}7S^{2}$			$5f^{2}6S^{2}6P^{6}$	$6S^{2}6P^{6}$	4,6		0.97		0.80

*From Ryabchikov and Ryabukhin (1970), Bagnall (1972) and The Handbook of Chemistry and Physics.

actinides, Y and corresponding ionic radii. Note that trivalent Y has an almost identical radius to Er^{3+}, explaining the common occurrence of Y with HREE. According to Ryabchikov and Ryabushkin (1970), on the basis of observation and quantum mechanical considerations, there are three trivalent electronic configurations which lead to stable ions in the REE. These are the La^{3+} which are isoelectric with xenon, $Gd^{+3}(4f^7)$ and $Lu^{3+}(4f^{14})$. As a consequence of this, those rare earths with "anomalous" valences tend to form stable ionic configurations. They show that Ce^{4+} may assume the La^{3+} electronic configuration, that in strongly reducing media Yb^{+3} may gain an electron to achieve the Lu^{+3} stable form, and that Sm and Eu may be divalent and Tb tetravalent to achieve the Gd^{+3} stable electronic configuration. Therefore, changes in redox conditions will produce non-uniform chemical responses and consequently produce variations in the (relative) REE abundances in the geological environment. For example, Eu^{2+} which has an ionic radius similar to Ca^{2+} is commonly enriched or impoverished relative to neighbouring REE as it substitutes for calcium in plagioclase-rich rocks. To facilitate comparison of patterns between samples the abundance of each element is divided by the abundance in chondritic meteorites. This compensates for the effects of the Oddo-Harkins rule of elemental abundances. In this thesis the values of Schmitt et al. (1963) were used for normalization.

Significance of REE Patterns from Granites

In general the REE distribution patterns of granites show more fine structure, i.e., departures from linearity, than more mafic rocks. La, Lu, Ce and Eu often deviate markedly from the pattern established by the other lanthanides (Kiljonen and Rosenberg 1974). It has been shown that the REE

patterns of granitic rocks derived from a melt which had crystallized anorthosite or some other plagioclase-rich rock have prominent negative Eu anomalies, high LREE abundances relative to HREE and high ΣREE (for example, Hedge et al. 1979). Kiljonen and Rosenberg (1974) and McCarthy and Kable (1978) have shown that very similar Eu depleted distributions may be expected of granites derived from metasedimentary rocks during anatexis. As a result of such a process, the REE patterns of the restite are relatively enriched in Eu. Furthermore, as McCarthy and Kable (1978) pointed out, the bulk of the REE partition coefficient data available pertain to the common silicate minerals and has been obtained through phenocryst-matrix studies. They demonstrate that the distribution of incompatible trace elements in granites is largely governed by zircon, apatite and other unspecified minor minerals rather than by the common silicates. Therefore, these authors consider that the use of REE in granitic rocks as a petrogenetic tracer is severely restricted. Despite the restrictions this puts on the REE of granites for modelling purposes, it was decided to investigate them for two reasons: (a) to compare the radioelement content to certain REE in order to evaluate the relative mobility of uranium, thorium and various REE under different conditions; (b) to compare the chondrite normalized patterns of the REE from the radioactive rocks in order to interpret similarities and/or differences in terms of origin.

High-temperature REE Complexes

In view of the fact that the uranium and thorium enrichments of the granites and pegmatites in this study are related to the movement of late-stage fluids and that the REE tend to share the same host minerals as uranium

and thorium, it is appropriate at this point to discuss the behaviour of REE and uranium and thorium in hydrothermal systems.

In pegmatites the REE are to a large extent concentrated in minerals such as fluorite, apatite, sphene and zircon (Vlasov 1966), whereas in hydrothermal deposits they are concentrated in distinct REE-forming minerals. The REE content of the former group of minerals in hydrothermal deposits is enormously impoverished in comparison to these same minerals in pegmatites. Also, owing to the greater solubility of the HREE relative to the LREE, Ce-group minerals are normally formed before Y-group minerals in a given paragenetic sequence. This effect has been demonstrated in pegmatites, as Murata et al. (1959) have shown that there is a systematic decrease in the monazite/xenotime ratios going from wall to core of pegmatites in eastern Minas Gerais, Brazil. Kosterin (1959) has shown that the REE may be transported in hydrothermal solutions in fluoride and sulphate complexes but most effectively in carbonate complexes. He states that a considerable excess of Fe^{3+}, Zr and Al are needed over REE for transport in the fluoride form and suggests that $REFeF_6$ might be a likely complex. A possible example of this is the Scrub Oaks iron mine, New Jersey, which contains abundant magnetite and hematite associated with fluorapatite, uranium, thorium and REE (Klemic et al. 1959). Mineyev (1966) has shown that under experimental conditions REE complexes with fluorine and are soluble in aqueous solutions in the 500-550°C range. Also, Bandurkin (1961) stated that the fluoride form of transport at elevated temperatures was much more likely than the carbonate form in the greisens he studied. He also shows that simple fluoride complexes $(MeF)(MeF_2)$ are unstable whereas more intricate complexes, MeF_4, MeF_5 and MeF_6 are stable in alkaline solutions.

Mobility of the REE in the Mt-Laurier Granitic Rocks

In an attempt to test the hypothesis that the REE were transported as fluoride complexes and draw some conclusions about the relative solubility of the species, several graphs of element abundances were plotted. Only data from the Mt-Laurier area is used as there is greater variation in the types of radioactive rocks present. That is to say, samples were available for several radioactive granites and both white and pink pegmatites, whereas the Bancroft and Johan Beetz samples dominantly consist of pink pegmatite only. Figure V-4 shows that there is a direct positive linear correlation between ΣREE (sum of REE analyzed) and fluorine for relatively low uranium samples which would support the hypothesis that the REE were complexed in the fluoride form. This does not rule out the possibility that the REE may also have been complexed to some degree as other species eg. carbonate or sulphate. Although there is no proof that uranium migrated as UF_6 (i.e. a plot of U vs F for low REE samples) it is well documented in the literature that this is the case at elevated temperatures (e.g. Bohse et al. 1974).

Figure V-5 shows that there is a hyperbolic relationship (i.e. inverse) between U and ΣREE eliminating the possibility of auto-correlation arising from the two groups competing for limited mineral sites which would yield a straight line of negative slope. It is suggested therefore that solutions that were oxidizing and mildly alkaline carried out U^{6+} in preference to Th^{4+} and REE in the fluoride complexes from the granite to form pegmatites.

The Mt-Laurier pegmatites (Figure V-6) show positive europium anomalies which in view of the earlier discussion of the REE chemistry of granites and hydrothermal systems most likely reflects the chemistry of the pegmatitic fluid and that of its host rock rather than an earlier period of fractional

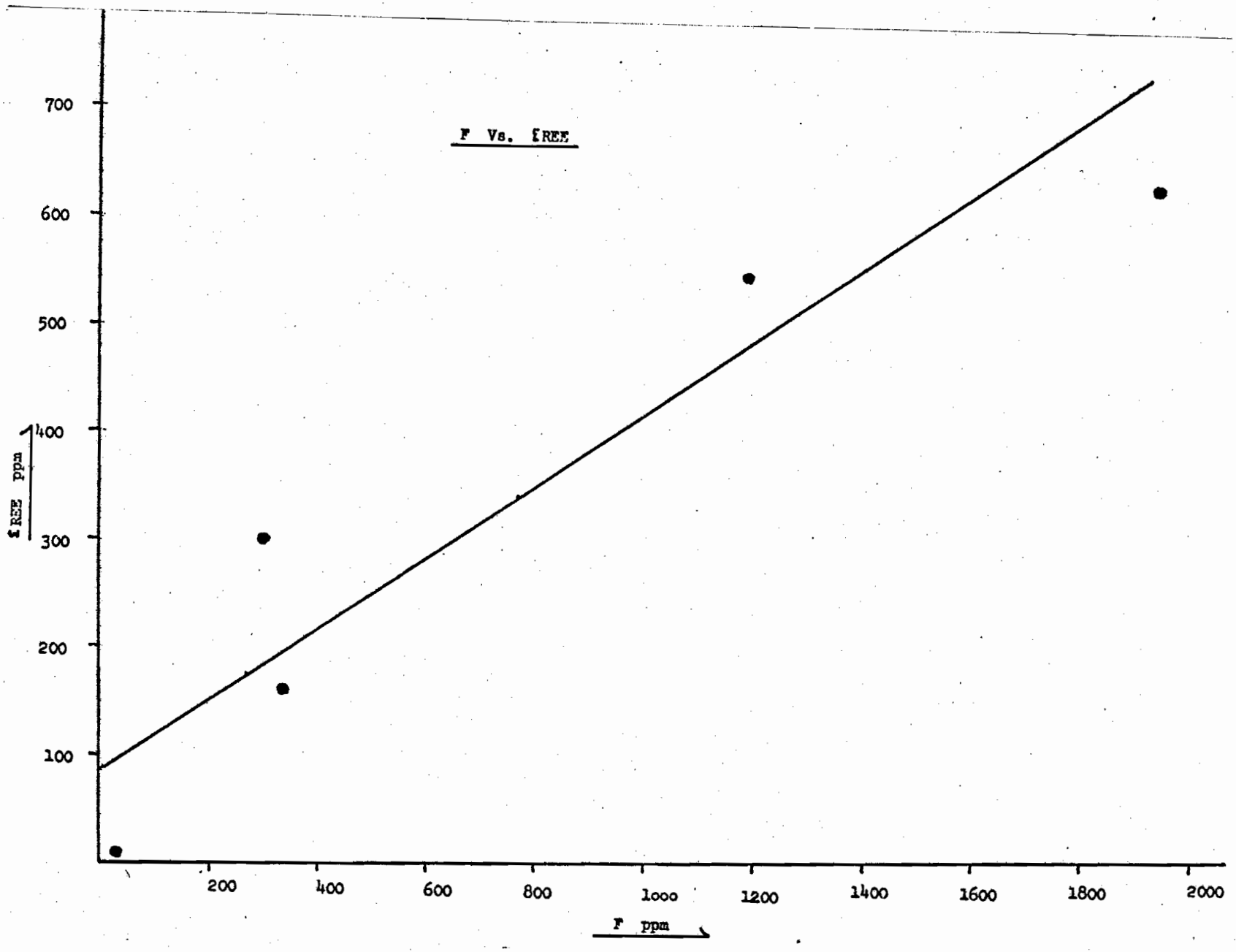


Figure V-4.A plot of fluorine versus total REE analyzed for Mt-Laurier pegmatites and Guénette type granites.

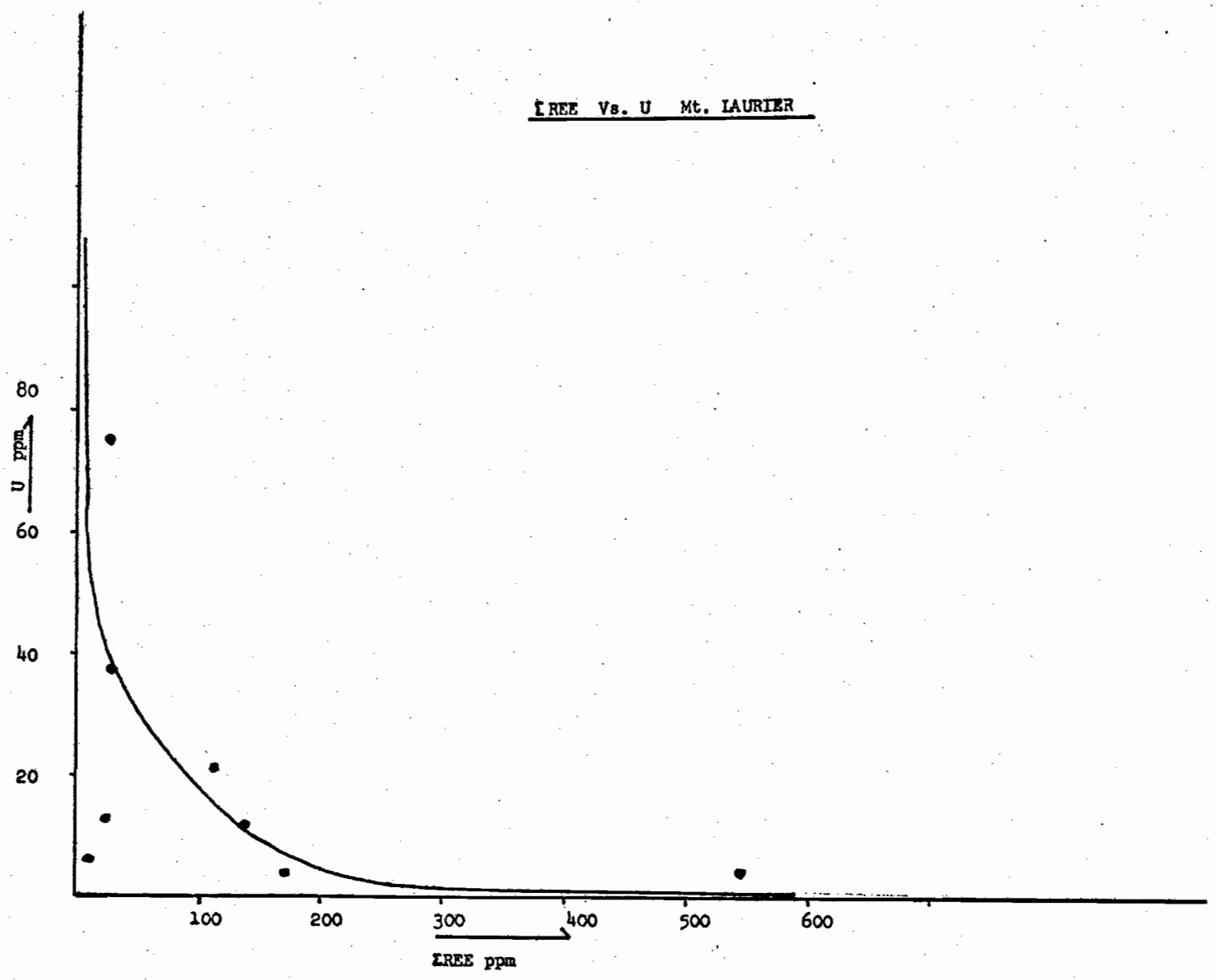


Figure V-5. A plot of uranium versus total REE analyzed for Mt-Laurier area pegmatites.

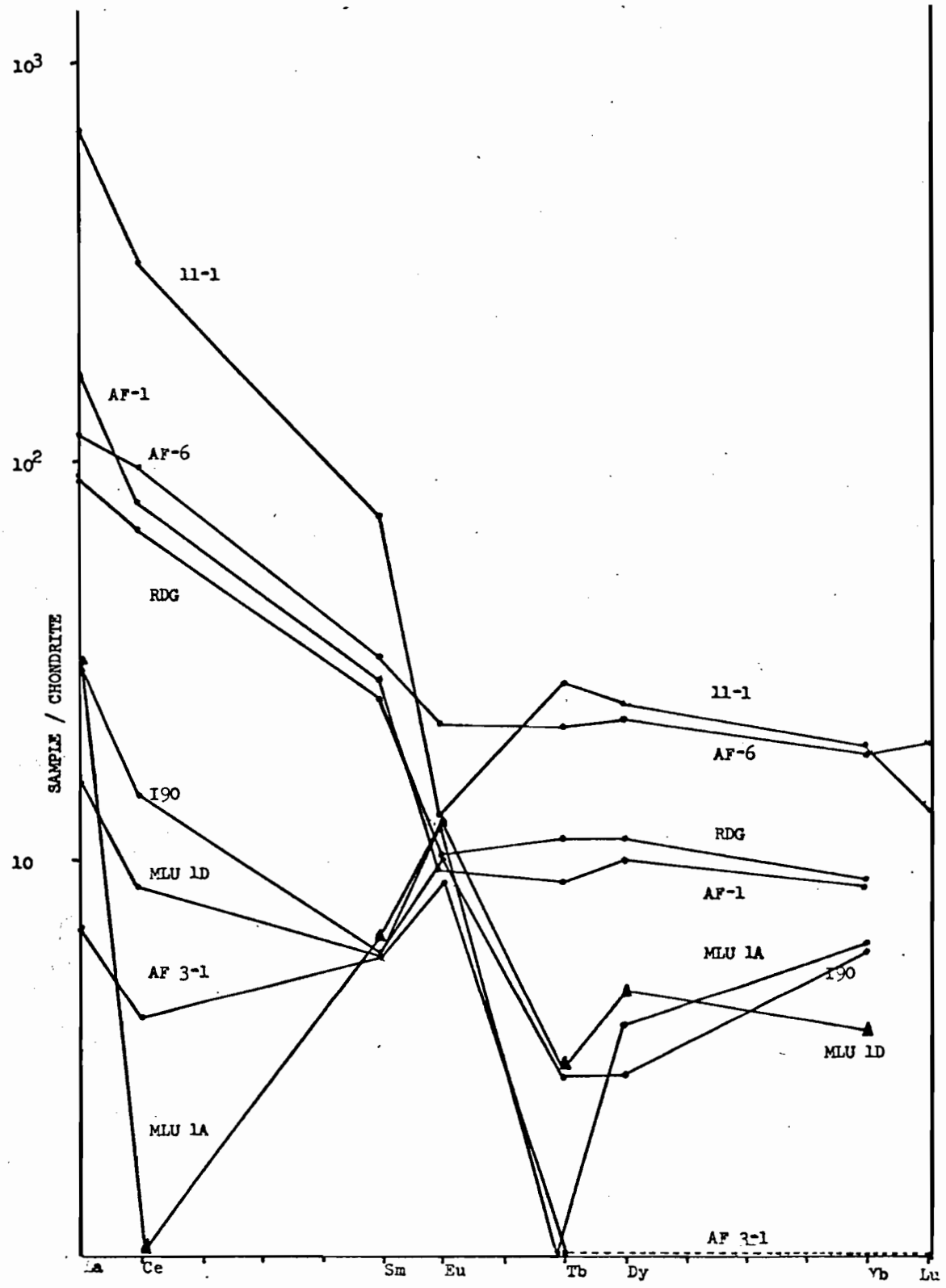


Figure V-6. The REE spectra for the Mt-Laurier area radioelement enriched rocks. Samples MLU 1A and 1D are white pegmatites, I90 and AF 3-1 are pink pegmatites and RDG,AF-1, AF-6 and 11-1 are granites.

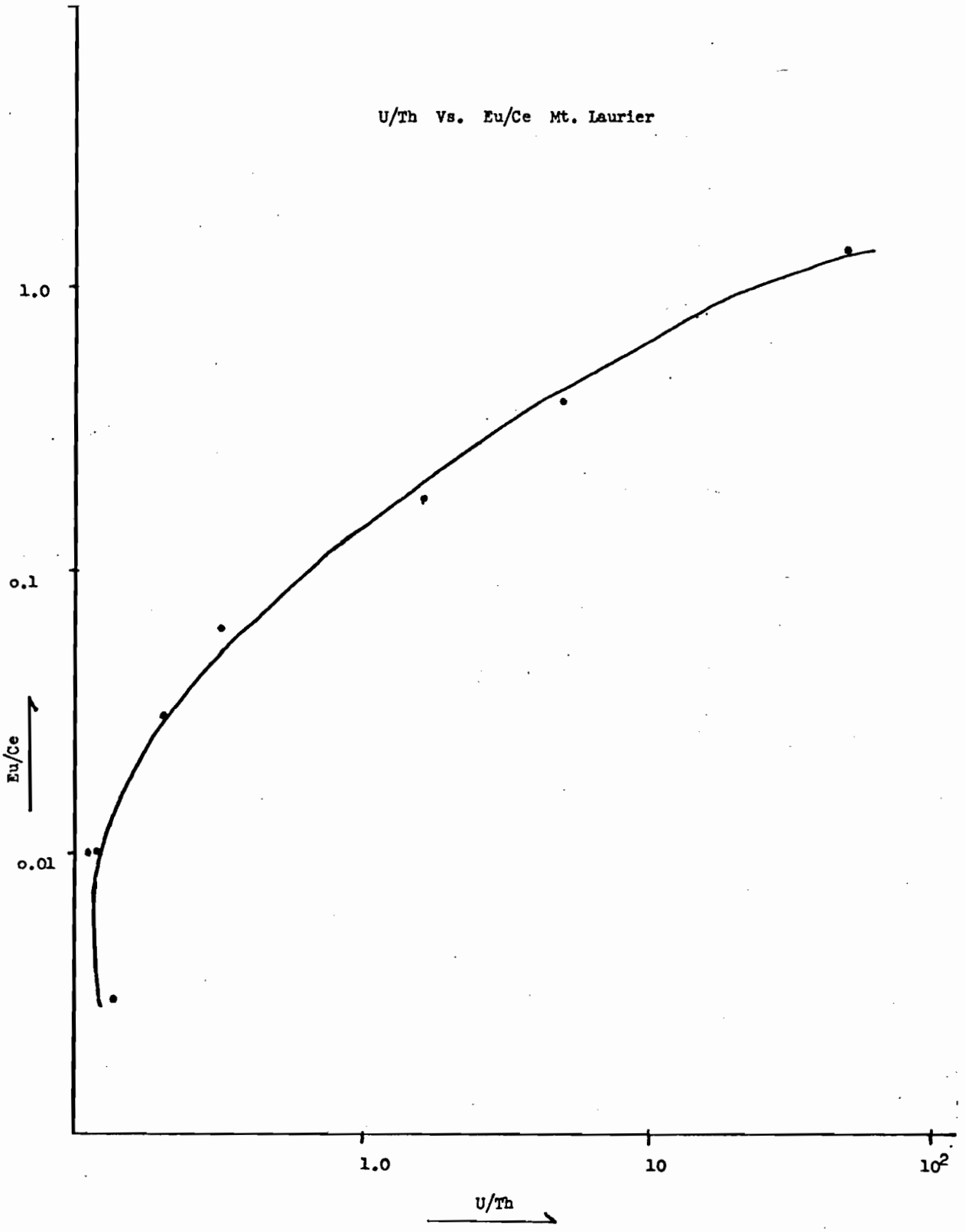


Figure V-7. The ratio U/Th versus Eu/Ce for the Mt-Laurier area pegmatites.

crystallization or melting. These particular samples are also those which have low ΣREE, high uranium and tend to have low cerium and thorium contents. There is a direct correlation between europium and uranium in the pegmatites. Although the chemical similarity of cerium and thorium is less evident from the patterns, thorium is directly subjacent to cerium on the periodic chart, tetravalent cerium and thorium have similar ionic radii (0.92 and 1.02 A respectively) and both take on inert gas type electronic structure in the tetravalent form (Ce is analogous to Xe and Th to Rn). These similarities are an indication of a possible geochemical affinity. This is substantiated to some degree by the fact that the minerals allanite and monazite, which are commonly enriched in thorium are also enriched in cerium (Deer, et al. 1963: V. 1, p. 213, v. 5, p. 340). Therefore, because the U/Th ratio can be controlled to some extent by redox conditions in a melt and because there were large differences in the redox state of the various Mt-Laurier area pegmatites, a correlation between U/Th and Eu/Ce was attempted. Figure V-7 indicates a strong positive correlation and demonstrates that anomalies in individual REE may be a consequence of differential solubility of those particular elements in response to changes in valence. In addition, terbium, which may also be tetravalent, appears to vary in the same manner as cerium and Ytterbium which can be divalent and may show anomalous behaviour. Because of the poor INAA resolution from neighbouring lutecium owing to interferences in uranium-enriched samples it is not known from this study whether or not this latter correlation exists in the Mt-Laurier samples.

The REE Patterns of the Mt-Laurier Rock Units

In general the chondrite normalized patterns of the pegmatites have low ΣREE (10-30 ppm) and have distinct positive Eu anomalies (Fig. V-6, MLU 1D,

MLU 1a, AFIII-1, I90). Sample XI-1 from the pink granite has high ΣREE (540 ppm) shows a negative Eu anomaly, and samples AF VI, AF I and RDG, with intermediate ΣREE values (160, 135 and 110 ppm respectively) are slightly LREE enriched relative to HREE and show little or no Eu anomalies. Also, samples MLU 10, MLU 19, and AFIII-1 are pyrite bearing, whereas the remainder are magnetite bearing. There is, therefore a tendency for low ΣREE to be associated with the pegmatites, particularly those which are pyrite bearing. In contrast to these, sample MR77-1 (Figure V-8) from the older gneissic granite has high ΣREE (380 ppm) and shows a smoothly decreasing pattern with no Eu anomaly.

The author proposes the following sequence of events to explain the observed REE, uranium and thorium distributions in the granites and pegmatites. In the final stages of granite crystallization calcium bearing plagioclase broke down in the presence of an alkaline silica-rich fluid to form epidote and albite by the following reaction:

$$2NaCaAl_3Si_5O_{16} + 2SiO_2 + NaOH \rightarrow Ca_2Al_3Si_3O_{12}(OH) + 3NaAlSi_3O_8 \quad (5\text{-}4)$$

(andesine) (clinozoisite) (albite)

This could explain the late stage albite and with the introduction of Th, Ce and Fe the mineral allanite. The observation that the granite has undergone pervasive hematization suggests that the fluids were oxidizing in nature. These alkaline oxidizing fluids preferentially scavenged uranium relative to thorium and to a lesser extent REE as fluoride complexes from the granites to the pegmatites. Furthermore it is suggested that an earlier-formed plagioclase of the granite had Eu^{2+} substituting for Ca. The reaction above (5-4) liberated the Eu^{2+} which was immediately oxidized and became enriched in the fluid relative to the other REE. This would explain the low ΣREE of the

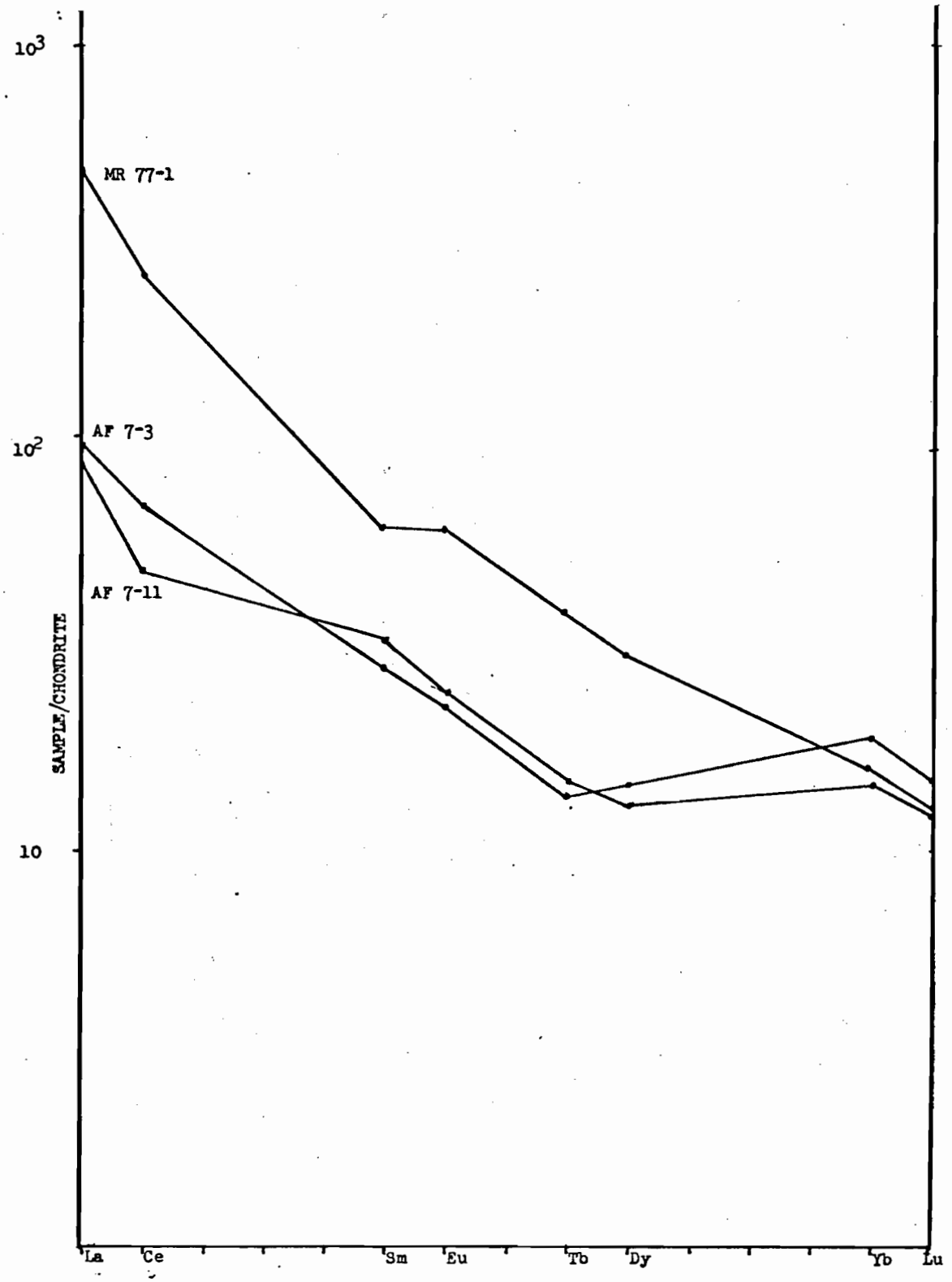


Figure V-8. The REE spectra for the Mt-Laurier area quartzofeldspathic gneisses.

pegmatites as the lanthanides are not as easily complexed in alkaline as they are in acid media (Bandurkin, 1961). It is further postulated that the above effects may have been amplified where the white-pyritiferous pegmatites crystallized. That is, the REE as a whole with the exception of Eu were mobile in the lower pH more reducing conditions which led to the formation of the high U/Th pyritiferous pegmatites.

From the foregoing discussion it is evident that the relative distribution of the REE is no panacea for determining the source material and previous history of granitic rocks, particularly those in which there is evidence of late-stage migration of incompatible elements.

Similarly it would seem inappropriate to rely solely upon the REE pattern of a suspected restite remaining after granite formation by partial melting to test whether in fact the material is a residuum. During dry melting one would expect the LREE, which are more incompatible than HREE owing to their larger ionic radius, to fractionate into the melt phase. Eu would tend to remain with Ca. Therefore one might anticipate a restite that may or may not have a positive Eu anomaly and may be smooth or relatively HREE-enriched depending upon the starting material and the amount of melt abstracted. Kiljonen and Rosenberg (1974) have observed that some Norwegian gneisses do have positive Eu anomalies. The gneisses appear, however, for the most part to be HREE-enriched. They "tentatively attribute" the former to metamorphic differentiation. During wet melting ($pH_2O = P_{tot}$), a LREE-enriched pattern may result relative to the original parent because of the increasing solubility with Z. Variations in the content of F, CO_2, and the T and pH might drastically affect this simplistic view. The REE patterns of the Mitchinamecus quartzofeldspathic gneiss are LREE-enriched and show no Eu anomalies (Fig. V-8, 7-11 and 7-3). Without a detailed knowledge of the premetamorphic REE

concentration of the rock and appropriate rock-fluid or rock-melt partition coefficients it is impossible to determine whether these patterns are those of a restite or not.

Bancroft, Johan Beetz and Meach Lake REE Patterns

Figures V-9, V-10 show the REE patterns from the Bancroft, Johan Beetz and Meach Lake areas. Samples CH 3 and 9 are from the Cheddar gneissic granite, CD1 and 4 are from the Canadian Dyno mine, Bi I is from the Bicroft mine and 14-4 is from the Turgeon Lake granite, Johan Beetz. All the Bancroft samples with the exception of GKI which has very low ΣREE (~15 ppm) display prominent negative Eu anomalies. Classical interpretation would lead one to suggest that the rocks were derived from a source that had precipitated large amounts of Ca plagioclase. This might in fact be the case for the older and non-mineralized Cheddar gneissic granite, but the pegmatites which have been mineralized after crystallization may owe their patterns to the late stage fluids from which they formed. This cannot be substantiated as the Bancroft sample suites collected do not have the chemical variability of the Mt-Laurier samples. To illustrate this the U/Th ratio of the five samples only ranges from 0.30 to 1.15 whereas for the Mt-Laurier rocks the ratio ranges from 0.11 to 52.9. Thus pegmatites with positive europium anomalies might exist.

The pattern from pegmatitic granite sample 14-4 from Turgeon Lake is erratic and appears to be LREE enriched. Sample 14-1 is HREE-enriched relative to LREE indicating that it may have inherited its REE signatures late in the alteration stage. One sample from the Meach Lake aplite (MLC 2) is shown in Figure V-10). It is possible that the REE did not complex in a fluoride form in this case as the late-stage fluid must have been peralkaline in nature as shown by the veins of riebeckite and corrosion of quartz. Kogarko (1974) has

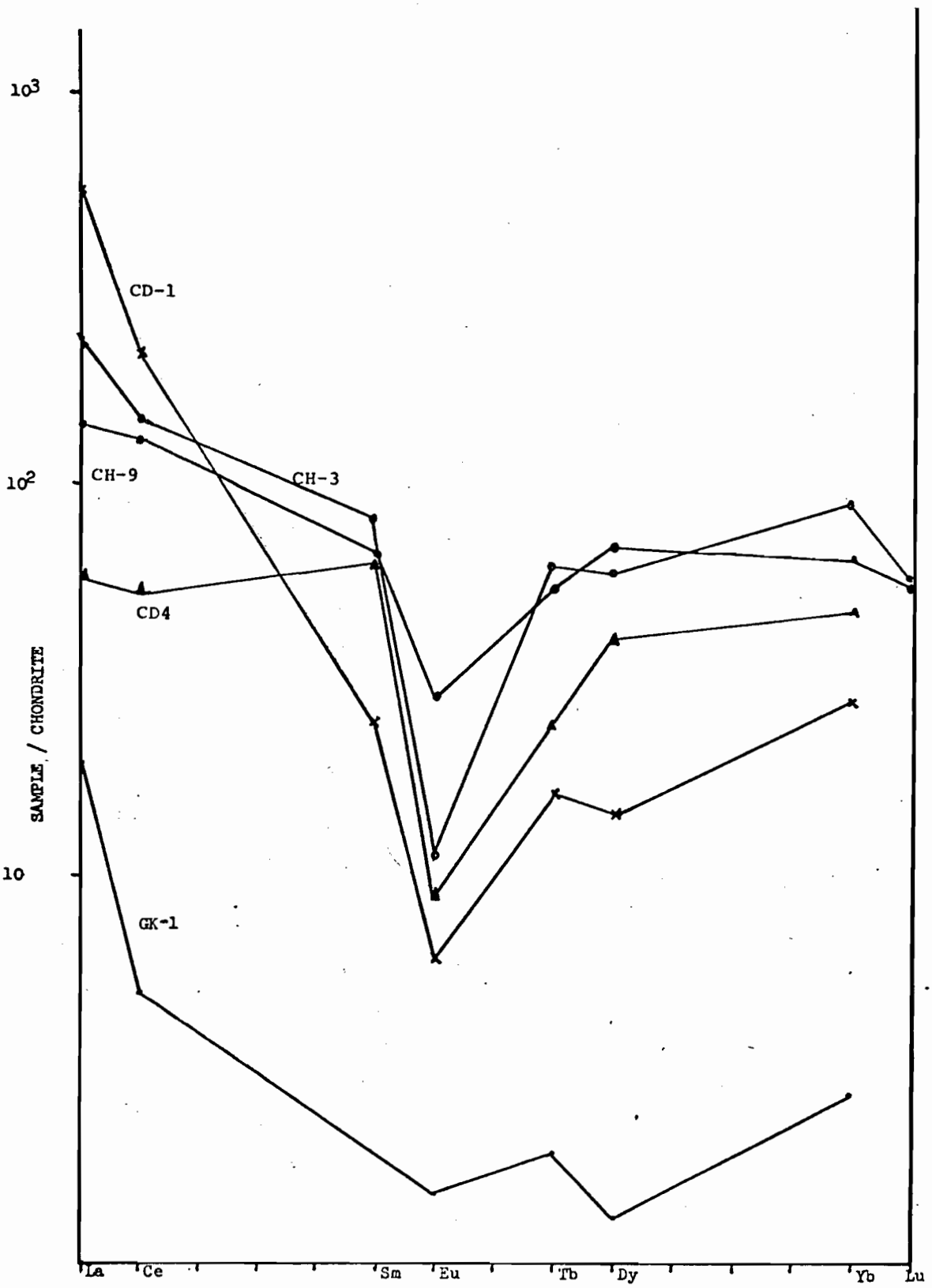


Figure V-9. The REE spectra for the Bancroft area rocks. The patterns designated CH are from samples of the Cheddar granite gneiss. The remainder are from the radioactive pegmatites of the Canadian Dyno and Greyhawk mines.

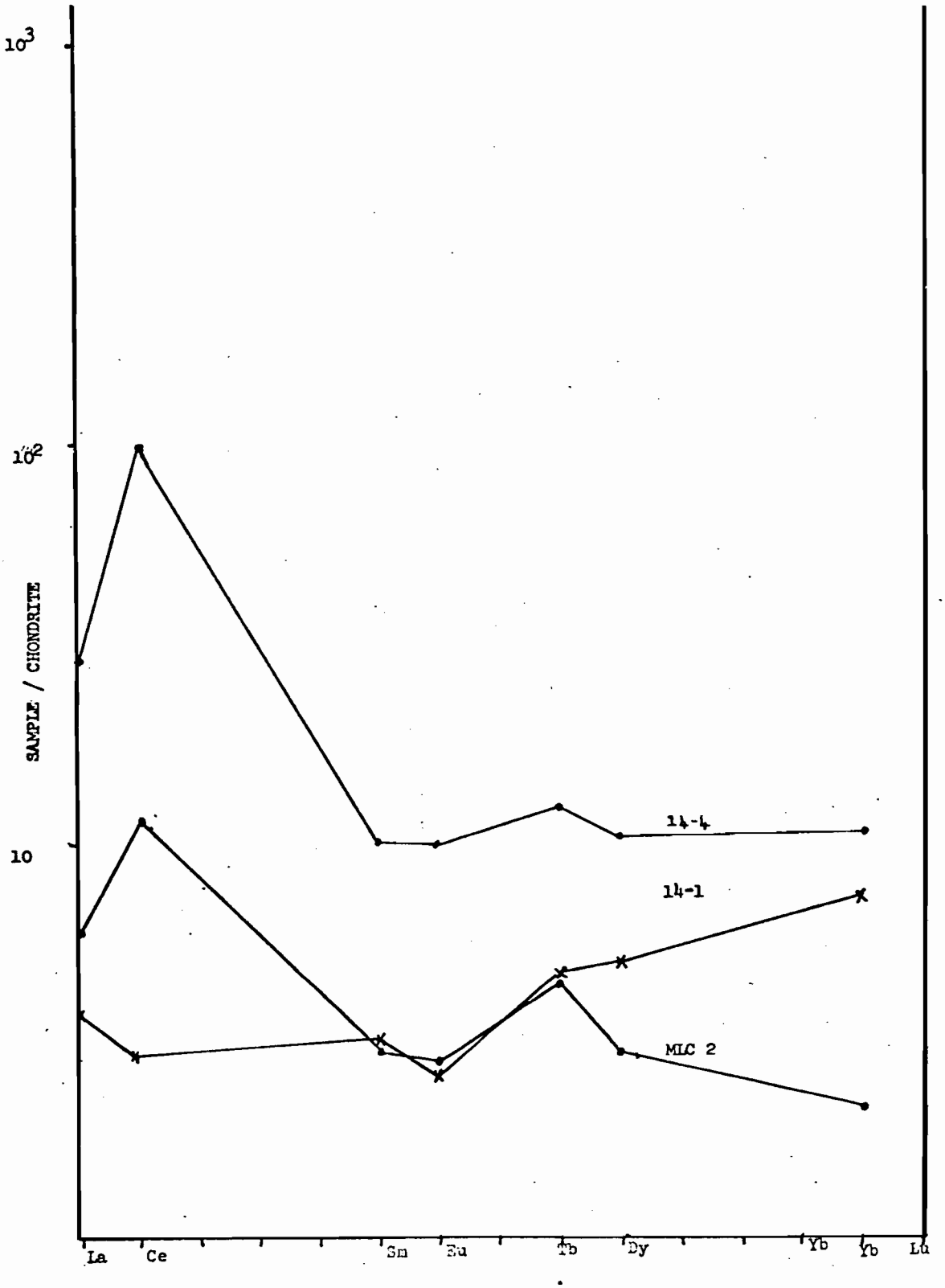


Figure V-10. The REE spectra of the Turgeon Lake Granite (14-1 and 4) and aplite from Meach Lake (MLC 2).

demonstrated that fluorine is soluble in peralkaline undersaturated melts. Therefore it is possible that the fluorine remained in the melt and did not complex REE in solution, thus making a relatively REE-depleted fluid. Martin et al. (1978) have shown that LREE-enriched patterns similar to that of MLC 2 may result from metasomatism of a quartzite by a peralkaline fluid. However, the ΣREE of the Meach Lake aplite is ~14 ppm whereas ΣREE of the same elements for the fenitized rocks of Martin et al. (1979) ranges from about 40 ppm to greater than 300 ppm. This suggests that the Meach Lake REE pattern is due to only a slight degree of metasomatism.

Finally it should be noted here that a very recent paper by McLennan and Taylor (1979) also discusses extreme REE mobilization associated with uranium mineralization. They show that the REE spectra of uranium-enriched samples associated with the low temperature hydrothermal mineralization of the Cahill Formation are LREE-depleted and HREE-enriched. They show a strong correlation between REE and U and suggest both were complexed as carbonate complexes. They demonstrate that there is no coherence between uranium and thorium as shown by their negative correlation between U and U/Th. Their REE patterns show none of the Eu, Ce or Tb anomalies demonstrated in this study.

Major and Minor Element Geochemistry

Figure V-11 is a plot showing the molar proportions of quartz, potassium feldspar and albite in various granites, pegmatites and gneisses of the Mt-Laurier, Bancroft and Johan Beetz areas. Note that for the most part the granites and pegmatites fall within the field of granites as defined by Tuttle and Bowen (1958), but they tend to be dispersed in a direction away from the thermal minimum. Rocks that have crystallized from a melt are expected to cluster about the thermal minimum regardless of the origin of

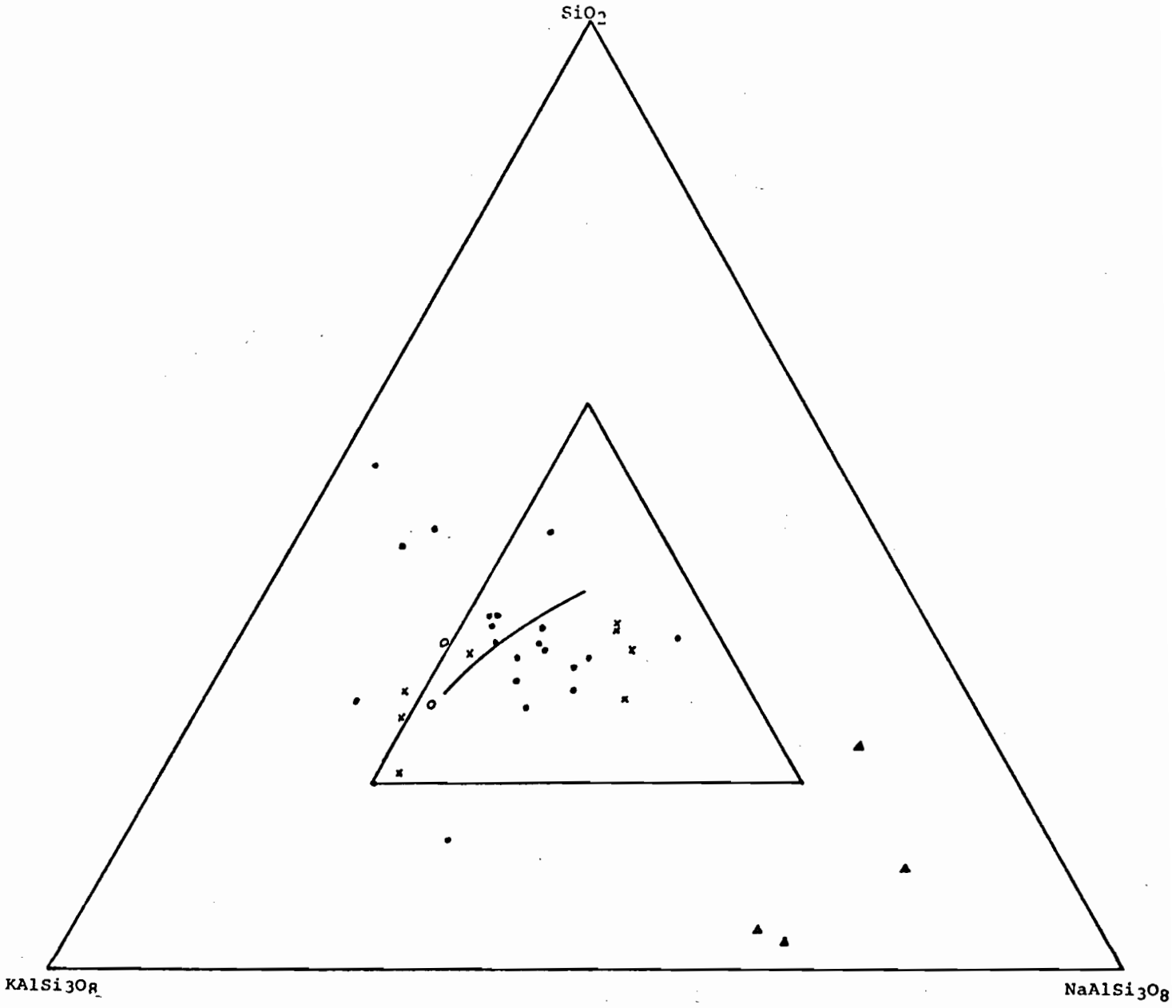


Figure V-11, The molar proportions of quartz, potassium feldspar and albite of various rocks of this work. The field of granites as defined by Tuttle and Bowen (1958) and the ternary minimum from 500 to 10,000 bars pH_2O are also shown. The dots are analyses of Mt-Laurier radioactive rocks, x's are analyses of Bancroft radioactive rocks, open circles are analyses of Turgeon Lake Granite, and the triangles are analyses of the Mitchinamecus quartzofeldspathic gneiss.

TABLE III

Agpaitic Indices		$CaO + Na_2O + K_2O/Al_2O_3$	K_2O/Na_2O
AFI	0.59	0.85	1.38
AFII	0.70	0.89	1.97
AFII-1	0.47	0.75	0.56
AFIII	0.55	0.77	6.98
AFIV	0.42	0.56	17.8
AFV	0.41	0.67	4.51
RDG	0.61	0.89	1.01
AFIII-1	0.62	0.85	1.69
AFIII-6	0.48	0.94	0.53
AFV-1	0.65	0.69	1.35
AFV-7	0.59	0.87	1.25
AFVI-1	0.62	0.68	1.23
AFVI-6	0.64	0.95	1.16
*AFVII-2	0.36	1.12	0.2
* VII-8	0.39	1.00	0.2
AFXI-5	0.63	0.73	2.02
XI-9	0.50	0.75	3.37
XII-1	0.64	0.96	2.05
AFXII-7	0.64	1.03	1.88
*Ch 3	0.7	0.77	1.19
*Ch 7	0.69	0.73	1.22
ML40a	0.63	1.03	1.56
ML71	0.66	1.00	1.04
I 90	0.85	0.95	2.04
AFIII-2	0.82	0.83	3.86
AFII	0.65	0.75	1.97
*Ch 9	0.71	0.84	1.2
AF14-1	0.88	0.89	3.4
AF14-4	0.91	0.92	2.31
*MR77-1	0.58	0.71	0.47
*MR77-4	0.86	1.10	0.43
MLU1a	0.69	0.75	1.78
MLU1D	0.62	0.86	1.65
ML C	0.93	1.15	6.12
BiI	0.95	1.06	1.12
GKI	0.98	1.00	2.74
GK2	0.99	1.00	2.58
CDI	0.96	1.02	1.84
CD4	0.96	1.06	3.77

Variations in K_2O, Na_2O, CaO, with respect to Al_2O_3 in the radioactive rocks.

*denotes a gneiss or non-radioactive granite.

the melt. Hauseux (1976) interpreted the large dispersion from the minimum in her granites from Johan Beetz as due to their formation through metasomatism of a sedimentary protolith. Undoubtedly, metasomatism has disturbed the original distribution of the alkalis. However, in such texturally diverse rocks as these, considerable scatter about the thermal minimum is to be expected, as Jahns and Tuttle (1963) have shown that co-existing aplite and pegmatite frequently do not plot in the thermal valley, but the combined bulk composition of these co-existing rocks does. Therefore the distribution of major elements is not considered to be a reliable petrogenetic indicator. Owing to the complex manner in which the pegmatites and aplites outcrop in the areas discussed, it would be seemingly impossible to compute the average bulk composition of the parent granite. Consequently the calculation of a pressure of formation from the thermal minimum is precluded.

Table V-2 shows the agpaitic indices, the ratio $Na_2O + K_2O + CaO/Al_2O_3$ and the ratio K_2O/Na_2O for 32 radioactive granites, pegmatites and aplites from the areas studied in this thesis. The mean value of the agpaitic index and ratio $Na_2O + K_2O + CaO/Al_2O_3$ of 0.7 ± 0.17 and 0.88 ± 0.14, respectively, shows that the rocks as a group are metaluminous in nature. The Bancroft pegmatites and some of those from Mt-Laurier show peralkaline tendencies. The ratio K_2O/Na_2O is quite variable and apparently unrelated to the agpaitic index, suggesting that fluctuations in the latter are not exclusively controlled by either Na_2O or K_2O content.

Rb, Ba and Sr

El
∧ Bouseily and El Sokkary (1975) have recently reviewed the geochemistry of Rb, Ba and Sr and proposed a discriminant relationship among them which could be useful for tracing differentiation trends in silicic rocks. In

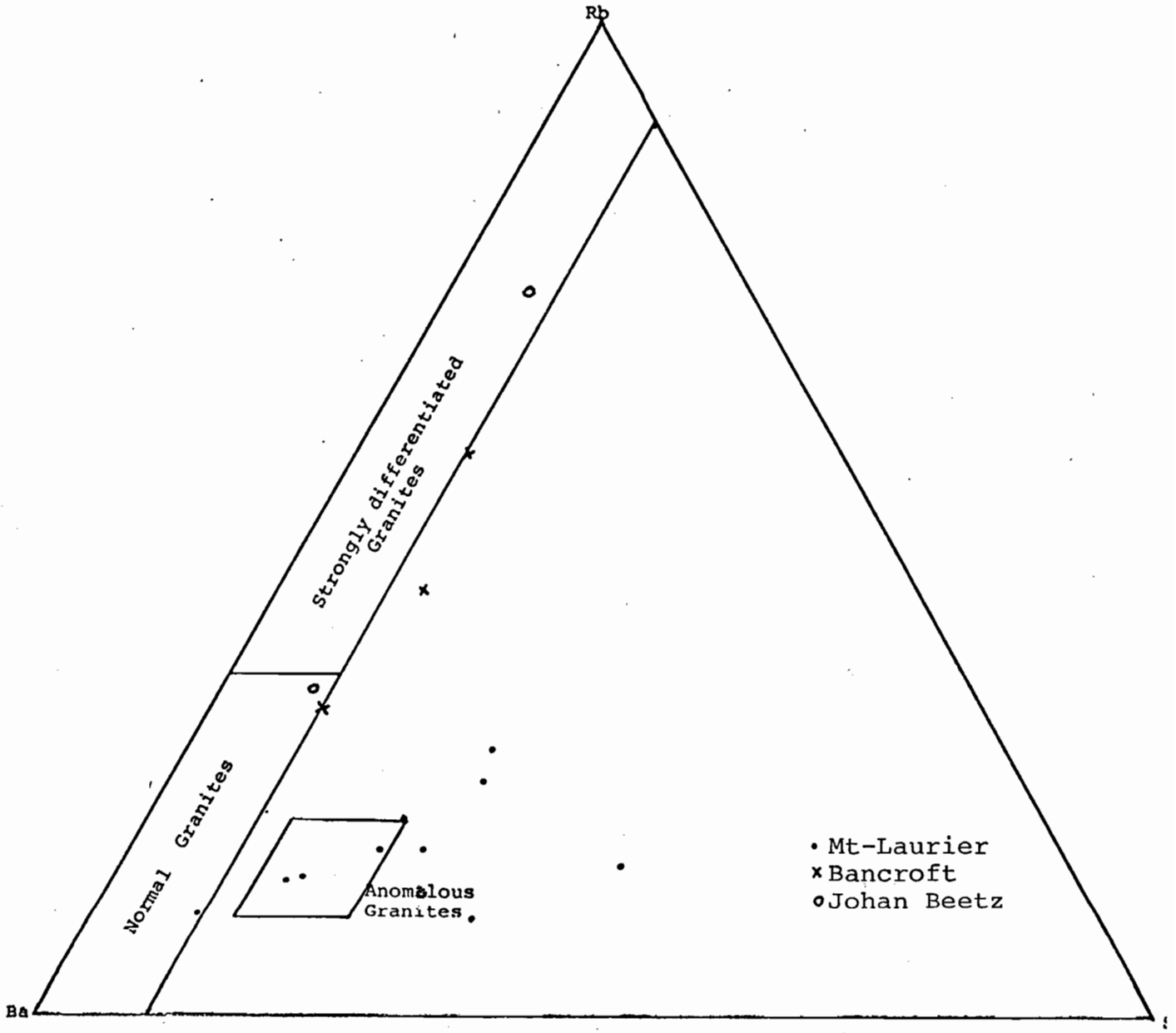


Figure V-12. Relationship between Rb,Ba, and Sr for the radioactive granites and pegmatites.

essence, the concentration of Ba tends to increase with differentiation, then declines sharply at the extreme acid end, whereas the concentration of Rb remains relatively constant, though increasing in late-stage processes. Sr tends to decrease rapidly with differentiation.

Figure V-12 shows that most of the radioelement-enriched granitic rocks from Mt-Laurier fall in or adjacent to the field of anomalous granites on the Rb/Sr/Ba plot of El Bouseily and El Sokkary (1975). They considered that rocks in this field have suffered Rb fractionation (i.e., loss) during metasomatism. The Bancroft and Johan Beetz radioactive pegmatite samples plot within the field of strongly differentiated granites, indicating extreme Rb enrichment at a late stage of crystallization.

Summary

Aside from presenting a technique which is capable of correcting errors involved in REE analyses by INAA when high U concentrations are encountered, it was shown that anomalous behaviour of individual REE may be correlated with variation in U and Th concentrations. Specifically, Eu appears to vary as U does whereas Ce and Tb vary in a similar manner to Th. The REE that were apparently transported in solution as fluoride complexes were subject to differential solubility depending upon pH and eH. The large scatter in the data plotted within petrogeny's residua does not support the contention that the radioactive granites were formed through the metasomatism of a sedimentary protolith. The scatter is consistent with that shown by Jahns and Tuttle (1963) for co-existing aplites and pegmatites. The relationship between Rb, Sr and Ba demonstrates that the radioactive granitic rocks are highly evolved or metasomatized.

CHAPTER VI

ORIGIN OF THE URANIFEROUS GRANITES AND PEGMATITES

In this chapter the data presented thus far will be reviewed prior to discussing popular theories of formation for the Grenville Province radioelement-enriched granitic rocks. Other hypotheses more consistent with the data of this thesis will then be discussed including a model for producing granites and their uranium mineralization which is compatible with present concepts of tectonic evolution of the Grenville Province.

The radioelement-enriched granites and pegmatites may truncate or be conformable with the gneissosity of their host rocks. They do not possess the penetrative metamorphic fabric of their hosts. In at least two regions (Bancroft and Mt-Laurier) they are temporally related to syenites and undersaturated rocks. The Rb/Sr whole-rock ages of the granites and pegmatites demonstrate that they did not develop during the peak of the Grenville event but some 150-200 Ma later. The similar age dates and $^{87}Sr/^{86}Sr$ initial ratios support the concept that the spatially associated and mineralogically similar granites and pegmatites are consanguinous.

For the Mt-Laurier area, Kish (1977) has suggested that there are genetically separate pegmatitic units (grey and pink types). However, field relationships, geochemical evidence and the existence of consanguinous pink and grey facies in the related granites make such a distinction inconsequential.

Several authors have recognized the similarities between the uranium deposits of the Grenville Province and have advanced various theories to account for their origin and widespread distribution.

Bancroft Area

Robinson (1961), considering the Bancroft deposits, stated that the "distribution of deposits around and similarity of age to granite intrusions suggest a genetic relationship". However, due to the fact that these deposits are found over a large area he further suggested that "the source of the rarer elements (i.e., uranium and thorium) may have been some co-extensive early sediment" and that "migration and concentration of those elements was supplied by heat from intruding granitic rocks".

Evans (1966) in a study of what he termed lit-par-lit gneiss at the Bicroft mine concluded that much of the material for the granitic layers of the gneiss was derived from pelitic layers. Furthermore, he stated that both these granitic portions and aegirine-augite bearing pegmatite dykes which transect them were produced by extreme metasomatism during regional metamorphism. More recently Gordon and Masson (1978, 1977) and Bright (1975) presented a similar model for the Bancroft-area radioelement-enriched pegmatites. They proposed a tenuous hypothesis involving derivation of granite through anatexis of basal arkoses or other units at the base of the Grenville Supergroup as it was suggested that these arkoses "might contain economic concentrations of heavy minerals such as uranium-rich minerals" and that, "this portion of the sequence appears to have a higher concentration of granite pegmatites than is found elsewhere ... (Lumbers, 1975)". Bright (1975) suggested that the pegmatites which he erroneously claims are restricted to the carbonate section of the Grenville Supergroup gained further uranium from the uraniferous horizons of the metasediments or transformed them into calc-silicate deposits. Gordon and Masson (1978) noted that the "York River G zone" cuts syenite and syenitic gneiss which

areinterlayered with one meter-thick layers of apatite and marble; this suggested to them sedimentary phosphate deposits and hence a possible source for the uranium.

Most of these theories of origin do not consider the fact that the radioactive pegmatites are demonstrably non-metamorphic in character. Furthermore, the fact that they are approximately 150 Ma younger than the peak of Grenville Province metamorphism and that their ages coincide with that of K-Ar blocking dates (ca 250°C) preclude the possibility that they were formed by in situ anatexis. Also, the author is unaware of any co-extensive early uranium-rich sediment. There undoubtedly are sporadic occurrences of clastic rocks enriched to some degree in uranium in the Grenville Province. These, however, are commonly found in proximity to pegmatites, suggesting that their uranium may be epigenetic in origin. The proposal that uranium may have come from phosphatic sources, although inventive, requires a separate source for the thorium as phosphate rocks typically have low thorium contents (Rogers and Adams, 1969, p. 90-K-3). In addition, McKelvey (1956) and McKelvey et al. (1955) have shown that uranium, which substitutes for calcium in the apatite structure in phosphates, is generally not abundant in phosphates formed in the presence of excess calcium. They showed that phosphatic nodules in limestones are generally non-uraniferous. Finally, the low $^{87}Sr/^{86}Sr$ initial ratios preclude such high-Rb sources as arkoses or pelites.

Mt-Laurier Area

Kish (1977, 1975), Tremblay (1974) and Allen (1971) have studied the pegmatites of the Mt-Laurier area. Tremblay (1974), whose work is entirely

restricted to the Lac Patibre area, observed that the only difference between the white and pink pegmatites was in the iron mineralogy, distribution of uranium, and the U/Th ratio. She noted that the white pegmatites are more common in carbonate terrain, whereas the pink pegmatites tend to be concentrated in quartzo-feldspathic gneiss, and all are near the supposedly unconformable contact between the lower Grenville Group and the gneiss. Surprisingly, she did not comment on or consider the co-existence of the two types. It is her contention that the uranium distribution was controlled by the stratigraphy of the original sediments and that the uranium deposits are genetically related to the unconformity. A number of pegmatites which do not occur near the contact apparently posed a dilemma. One of these has cross-cutting relationships with its host, and according to Tremblay (1974) "The magma from which the pegmatite crystallized was probably developed at a deeper level and injected into its present location". She also noted a regional trend in the Th/U ratio in which thorium increases to the south. This may be correct in the limited area she examined but it is certainly not a regional trend, as shown by the results of the Geological Survey of Canada airborne radiometric survey (Darnley et al., 1977).

Allen's (1971) field study was also restricted to the Lac Patibre area; he recognized an aplitic phase associated with the late-tectonic granite (monzonite in his work). He also noted that the granite, which he considered to be clearly intrusive tends to be white where it intrudes carbonate-rich rocks. However, he considers that the pegmatites of the area were formed <u>in situ</u> through anatexis of the biotite gneiss. He reasoned that because (1) the pegmatites are largely conformable, (2) their

enclaves are unrotated, the foliation in the pegmatites is parallel to that of the metasediments, (3) the amount of pegmatite present is apparently a function of the amount of biotite gneiss present, they were derived from the biotite gneiss by anatexis. These features could arise if the pegmatites were intruded along foliation planes with concomitant metasomatism causing relict foliation. The sympathetic relationship between the amounts of biotite gneiss and of pegmatite developed could simply be due to the relative fissility of the rocks intruded. Allen estimated the amount of pegmatite in each of the host rock units as follows: in biotite gneiss 20-80%, mean 46%; in calc silicate and marble containing variable amounts of biotite gneiss 6-24%; in quartzite 16%; and metabasite containing variable amounts of biotite gneiss 8-30%. Certainly the more massive rocks have less pegmatite and there is a tendency for metabasites, quartzites and marbles to contain increasing amounts of pegmatite with increasing biotite gneiss. Allen also considers that the uraniferous pegmatites are in close proximity to the "inferred base of the Grenville" and therefore unconformity-related.

Kish (1977) in a study of the Lac Patibre area concluded that the homogeneous pink granite "may not be related to the pink granitic pegmatite". Furthermore, he states on the basis of scanty evidence that: "Both pegmatites (pink and white) have been generated locally by partial melting of the gneisses and are thus different from complex pegmatites which are genetically related to large granitic masses, have intrusive contacts and are zoned." He also noted a great lithological change in the Lac Patibre area ascending from the quartzofeldspathic gneisses of the Patibre formation to the more pelitic and carbonate-bearing gneisses of the La Force formation.

He considers the Patibre formation to be Pre-Grenville. Although possible, there is no concrete evidence of this as the formation may well represent a greywacke deposited just prior to the deposition of more pelitic and calcareous assemblages, to be metamorphosed with them ca. 1150 Ma ago. Although many Aphebian uranium deposits are associated with unconformities lying between rocks developed during Archean and Proterozoic times (Roscoe, 1968), this is obviously not the case in Mt-Laurier as the pelites and marbles are clearly not Aphebian. Even though an unconformity may be present within the sedimentary sequence at this level there is no evidence that it marks a major break in time (i.e., Helikian-Aphebian).

Johan Beetz Area

In her study of the Johan Beetz area, Hauseux (1977), concluded that the granites and uraniferous pegmatites were metasomatic in origin. She based this conclusion to a large extent upon many observations of granitized sedimentary rocks with demonstrable sedimentary structures, zoned zircons, aligned enclaves in the granite, and the heterogeneity of the granitic rocks. She concluded that autometasomatism by fluids released during high-grade Grenville metamorphism caused the granitization. She did not recognize the Turgeon Lake granite body as being an intrusive mass as did Cooper (1953). Mackie (1977) considered the uranium deposits to be hydrothermal in nature, the granite having originated by anatexis during the Grenville Orogeny. The field relationships described earlier in this thesis are not at variance with the possibility that the Turgeon Lake Granite was intruded after the Grenville Orogeny and that release of volatiles caused metasomatism and hybridization. The age of this unit, in any event, is not consistent with metamorphic events elsewhere in the Grenville Province.

Many proponents of in situ anatexis consider that systematic orientations between enclaves within a granite and metasedimentary rocks at the periphery is substantial proof of a metasomatic origin for the granite. However, Pitcher (1970) has shown that (1) enclave orientations can be produced when blocks of country rock are spalled into a viscous magma, retaining their original orientations in the roof zone of the intrusion as it consolidates, or (2) stresses that accompany intrusion may orient both the enclaves and surrounding rocks. He concluded that ghost stratigraphy and structure are themselves rarely adequate to prove a metasomatic replacement origin.

The fact that zircons exhibit overgrowths in some granites is often cited as being evidence that the overgrowths were formed during anatexis by coating pre-existing detrital zircons. I suggest that such overgrowths are to be expected in igneous environments where fluids rich in incompatible elements are present. Presumably each zone would represent the passage of fluids with slightly different amounts of U, Th and Zr.

In summary, most of the authors cited have failed to realize that the late-tectonic granites are radioelement-enriched and related to the pegmatites. They attempted to relate the deposits to intangible uranium-rich sedimentary units which have yet to be observed. The cogenetic granites and pegmatites are obviously not the result of in situ anatexis, as shown by their partly cross-cutting nature, non-metamorphic textures, young Rb-Sr whole-rock ages and low $^{87}Sr/^{86}Sr$ initial ratios. Several methods of producing granite from deeper, more Rb-depleted levels in the lithosphere will now be examined.

Ultrametamorphism as described by Brown and Fyfe (1970) might well yield granitic melts of composition over a wide area. They considered that progressive breakdown of hydrous minerals would evolve sufficient

water to effectively flux granitic material from the continental crust to produce granitic melts. This could have been a valid method for generating the granites under discussion provided a suitable energy source was available long after the peak of the Grenville Orogeny.

It is proposed here that isothermal decompression may have initiated melting. The mechanism for this, crustal unloading, will be discussed more fully in a later section of this chapter. These processes, operating from 150 to 200 Ma years after the main pulse of the Grenville Orogeny, could conceivably produce granites with low $^{87}Sr/^{86}Sr$ initial ratios. One could argue that deep crustal material metamorphosed during the Grenville Orogeny ca. 1150 Ma ago would have liberated its radiogenic ^{87}Sr in preference to common Sr during a partial melting event at that time. This would yield anomalous $^{87}Sr/^{86}Sr$ ratios in both the melt and restite (Peterson and Pederson 1978; Heier and Compton 1969; Heier 1964). The restite would therefore be depleted in ^{87}Sr and elements necessary for granite formation, that is, silica and alkalis. As a consequence, the restite would have a low $^{87}Sr/^{86}Sr$ ratio and low Rb content making it a suitable source for the production of low $^{87}Sr/^{86}Sr$ initial ratio granitic material by ultrametamorphism some 150 Ma after the "main event". Although this model may explain the Sr isotope data it is difficult to rationalize the concomitant uranium and thorium enrichments. The event that purged the system of ^{87}Sr and Rb would also remove uranium and thorium very effectively, as they are incompatible in the restite. Fahrig et al. (1967) have shown that large tracts of amphibolite and granulite-facies rocks of the Canadian Shield are depleted in uranium relative to thorium. It is conceivable that a model involving ultrametamorphism may fit the data. However, the author finds loss of Rb and ^{87}Sr and retention of uranium and thorium rather contradictory trends.

Granites formed through igneous processes can be broadly categorized as being either anorogenic or orogenic in nature (Martin and Piwinskii 1974). The rocks of the anorogenic group, such as those documented in this thesis tend to have low Ca, Mg and Al contents, low $^{87}Sr/^{86}Sr$ initial ratios (depending upon degree of crustal contamination), high K, K/Na, Fe/Fe+Mn); and are enriched in compatible trace elements (Loiselle and Wones 1979; Martin and Piwinski 1974). The latter authors have shown that granitoid rocks associated with large volumes of mafic rocks may be derived through (1) crystal fractionation aided by (2) volatile transfer in the magma resevoir. Although such a mechanism could produce granites with similar chemical and isotopic abundances to the radioelement-enriched granites of this thesis the source of the water in a continental environment may at first seem somewhat problematical.

Bailey (1970, 1964) has shown that "residual" magmas (i.e. those that occupy the thermal valley of petrogeny's residua system) are localized in the crust in areas of pressure release such as the East African Rift System. He stated that juvenile gases in the mantle may well migrate to zones of lower pressure. Furthermore he (Bailey, 1970) stated that addition of water into the crust from the mantle would cause an increase in temperature as the adiabatic cooling of the water would be less than the temperature drop along the geothermal gradient.

Many recent authors consider that juvenile volatiles in the mantle play a significant role in petrogenesis (Eggler 1976; Eggler et al. 1976; Huang and Wyllie 1975; Kushiro 1975; Wendlandt 1977a, 1977b; Bailey 1964, 1970). Therefore a process involving a tensional environment would be capable of placing primitive mafic rocks in a field of wet melting (Bailey

1970). Depending upon the depth, composition of the fluid and parent rock, a variety of igneous rocks could be produced by volatile fluxing.

Before presenting my suggested model, modern theories for the tectonic evolution of the Grenville Province will be examined. Wynne-Edwards (1976) in an attempt to explain his division of the Grenville Province into various zones (Wynne-Edwards 1972) based upon perceived major North-South trending discontinuities in lithology, structure, or metamorphism proposed the "Millipede Model of Ductile Plate Tectonics". In essence, his model requires that a plate moved over an active spreading center and was deformed in a ductile manner. Anorthosites were produced as the plate crept northward "like a millipede over a relatively fixed series of igneous centers in the mantle".

However, the lithologic discontinuities including the suggested North-South alignment of anorthosites are highly subjective and the required systematic variation in ages of anorthosites is not supported by geochronological evidence. Finally, no mechanism is proposed for such extensive overriding of a spreading ridge by continental lithosphere.

Few attempts have been made to fit modern plate-tectonic models to the Grenville Province. Reasons for this are that diagnostic petrotectonic suites (eg. mélange, blueschist, ophiolites, arc volcanic rocks) were never formed, have been metamorphosed beyond recognition, eroded away, or overlooked. One exception is the hypothesis of Condie & Moore (1977) which suggests on geochemical grounds that the volcanic rocks of the Bishop Corners area, southern Ontario are in fact arc-type tholeiites related to a subduction zone. Dewey and Burke (1973) have proposed a basement reactivation model involving continental collision for the Grenville Province. They envisaged a collision

between Andean and Atlantic type margins after all intervening oceanic lithosphere had been consumed. Owing to the buoyancy of continental crust, continued convergence produced crustal thickening in the warmer, less dense, Andean mass which they concluded resulted in the development of a crust similar to that of the present-day Himalayas, 60 to 80 km thick. They postulated that the Grenville-age structural overprinting of Archean and Proterozoic terrain was produced by an event of this type and that the suture zone lies to the southeast of the Grenville Front, which they consider to be analogous to the northern edge of the Tibetan Plateau.

Dewey and Burke's (1973) model, although difficult to substantiate in detail does involve considerable crustal thickening, basement reactivation and subsequent denudation, a concept which most authors seem to accept (e.g. Doig 1977; Baer 1976; Wynne-Edwards 1972; Dëland 1956).

The Model

The proposed model for the generation of the uraniferous granitic rocks relies to a large extent upon uplift due to isostatic adjustment as a result of a thickened crust developed during the Grenville Orogeny ca 1150 Ma ago. The fact that most K-Ar ages on biotites of the Grenville Province yield 900 to 950 Ma ages indicative of biotite argon-blocking temperatures of about 250°C, demonstrates that the material exposed at present cooled rather rapidly. This rapid uplift which was most likely accompanied by a release of horizontal compression or perhaps a change to a tensional environment is probably in itself sufficient to promote partial melting of lithosphere. England (1979, 1978) has shown that uplift accompanying erosion may steepen geotherms and that material buried over 30 km may undergo isothermal decompression. He shows that rocks at 900°C exhumed to the surface at a

linear rate over 50 or 200 Ma only cool by 10% or 20%, respectively, of the total temperature during the first 30 km of ascent if initially buried 60 km, and 15% or 30% during the first 20 km of a 40 km exhumation. The rate of exhumation appears large but this is compensated to some extent by the fact that radiogenic heat production was not considered in the calculations. His work does show that there is a tendency for isothermal conditions to be approximated during decompression of material from depths of 30 km or more.

The postulate that the granites and associated rocks were generated during a tensional episode cannot be unequivocally proven. However, certain supplementary evidence supports this idea. Figure VI-1 shows the distribution of the various radioelement-enriched granites and pegmatites of the Grenville Province and major lithospheric fractures and lithologic discontinuities in the region. Note that the Sept-Isles, Johan Beetz, and St. Augustine occurrences all coincide with the edge of the St. Lawrence Rift System as defined by Kumarapeli and Saull (1966). Undoubtedly the major periods of plutonism associated with this feature are Phanerozoic in age (565 and 100 Ma ago; Doig & Barton, 1968; Doig 1970). However, early movement is known to have occurred as Phillpotts and Miller (1963) obtained a K-Ar age date of 975 ± 45 Ma from a pseudo-tachylite sample of an associated fault. Furthermore many authors consider that large fractures similar to the St.-Lawrence Rift System have histories extending back into the Precambrian (Zamarayev, S.M. and Ruzhich 1977). In fact, Dufresne (1948, pp. 209-211) showed that faults in the Paleozoic sedimentary rocks of the St. Lawrence valley tend to be controlled by those in the adjacent Precambrian rocks.

Similarly, many of the uraniferous pegmatites and granites of Renfrew County (i.e. Palmerston Area) are spatially related to the Ottawa-Bonnechere Graben which is part of the St. Lawrence Rift System. As shown earlier the

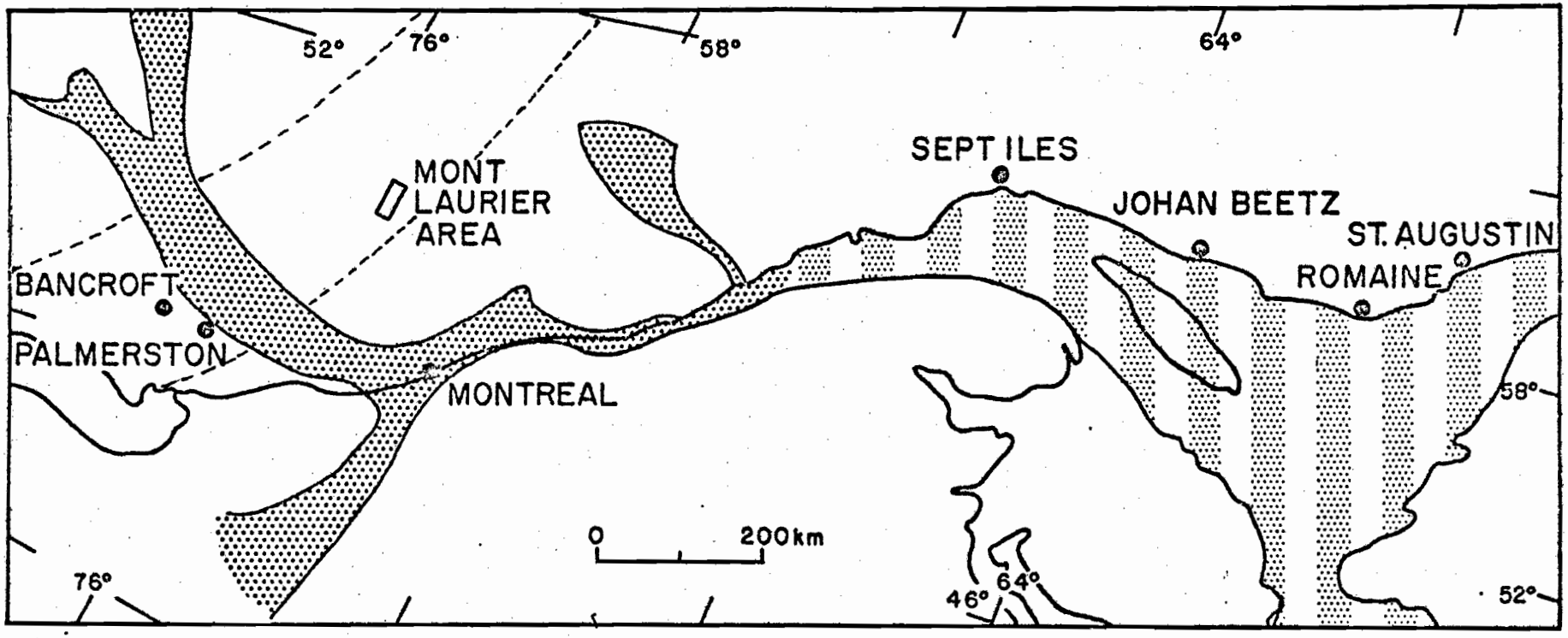


Figure VI-1. The Saint Lawrence Rift System as defined by Kumarapeli and Saull (1966). The continuous stipple is defined whereas the discontinuous is assumed. The dashed lineis the approxiamate border of the Grenville Alkaline Province as defined by Currie (1976).

Bancroft region lies at a major discontinuity in structure and lithology. This discontinuity which coincides with the locus of occurrences of alkaline rocks of the area, represents an ancient major crustal fracture in this area. The rocks of the Mt-Laurier region show no obvious spatial relationship to the St. Lawrence Rift System, but the nearby Gatineau River valley is considered to be a tributary to the main system.[1] In addition, the older inferred Bancroft rift zone can readily be traced to the northeast to Mt-Laurier and beyond (Fig. III-2). As the following quotation demonstrates, Osborne (1934) was perhaps the first to consider relating the Mt-Laurier area syenitic rocks to those at Bancroft.

> "Lithologically similar pulaskites and nepheline syenites are known in the Monteregian hills which rise above the St. Lawrence lowland 130 miles south of this locality. Although the Monteregian intrusives cut the flat-lying lower Palaeozoic limestones, they must have penetrated the underlying basement of pre-Cambrian. Such a relationship can be actually demonstrated in the Laurentian outlier at Oka. Is the stock described here a representative of that series? On lithological grounds alone, one would say it is, but one important difference is seen under the microscope: the Monteregian intrusives lack pleochroic haloes about the radioactive minerals, whereas such haloes are well developed in the stock here described and have an 'over-exposed' look, which is taken to indicate geological antiquity. The stock is for this reason believed to be older than the Monteregian intrusive and may be co-magmatic with the alkaline syenite of the Haliburton-Bancroft region previously mentioned. The Ontario rocks are thought to be of pre-Cambrian age but may be younger."

The data presented in this thesis combined with the above spatial and petrotectonic associations make a strong case for emplacement of the granitic rocks in a tensional environment. The present author suggests that partial

---

[1] Personal Communication, P.S. Kumarapeli, 1977

fusion of peridotite within the mantle during decompression led to the production of basaltic magma which then rose into magma reservoirs in the crust or surfaced as plateau basalt. Juvenile water leached granitic melts from either crystals differentiated in the magma chamber or gabbro formed from it (Martin and Piwinski 1974; Bailey 1970). Wyllie et al. (1976) showed that liquid produced by melting of mafic material much above 10 kb. were not granitic in composition but tended to be enriched in plagioclase. Similarly, Piwinski (1973) reported that granitic magmas produced at water pressures of 10 kb. or more are granodioritic to dioritic in composition. This suggests that the maximum depth at which the granite melts could have been produced was 30 km. It is considered that water-rich fluids leached silica and alkalies in granitic proportions and incompatible elements from hot gabbroic crystal mushes to form the radioelement-enriched granite melts. A granite melt produced in such a manner would be water saturated and thus incapable of reaching the surface (Harris et al. 1970). The contained water would be driven off as crystallization proceeded and ultimately be responsible for the distribution of incompatible elements in the granites and pegmatites. The fact that the granites are enriched in uranium and thorium is a result of the efficaceous leaching of these incompatible elements from relatively undepleted mafic rock.

The magma reservoir from which the granites were derived would today be largely composed of gabbro or anorthosite. The latter are very abundant in the Grenville Province and at least one is known to be associated with rifting, albeit 565 Ma ago (Higgins and Doig 1976).

This model can also account for the associated alkaline rocks. They can be produced by partial melting under CO_2 saturation of mantle peridotite

at approximately 40 km depth (Wendlandt 1977a). In fact one Mt-Laurier area syenite is associated with mica peridotite (Wynne-Edwards et al. 1966). Also carbonatites may be formed through partial fusion of carbonated peridotite at 90 km depth (Eggler 1976). It is suggested that carbonatites which are also enriched in thorium and uranium gain their enrichment in a similar manner to the granites but with a CO_2-rich fluid. This model can explain the presence of high uranium and thorium contents in isotopically primitive rocks outcropping in small volumes over large distances in relatively linear belts.

The relationship proposed by some authors, e.g. Allen (1971) and Kish (1977), suggesting that many of the uranium deposits of the Grenville Province are related to the edge of the Grenville Group, is to some extent confirmed by this thesis. However, they are not unconformity-related but are related to large features such as the Bancroft-Renfrew lineament of Baer (1976) which controlled the distribution of Grenville Group sediments, and in this author's opinion, later acted as zones of weakness for the uraniferous rocks to ascend along. Therefore, the relationship between the edge of the Grenville sediments and the uranium deposits in granites of the Grenville Province is fortuitous in terms of genesis. It is also suggested that the syenites and carbonatites temporally or spatially related to the granites formed in a similar fashion from a relatively CO_2-rich fluid phase.

Exploration Significance

There has been much recent interest in "porphyry" uranium deposits (Armstrong 1974). The Rossing uranium deposit of Southwest Africa is considered by many people to be closely analogous to those of the Grenville Province. The origins of the two types of deposit are, however, apparently

quite distinct. Berning et al. (1976) ascribed the Rossing deposit to syntexis involving juvenile material interacting with supracrustal rocks. They speculate that the uranium was originally contained within early Precambrian rocks which were eroded and reconstituted in later Precambrian times and finally subjected to syntexis during orogenesis. The Rossing granite does have a high $^{87}Sr/^{86}Sr$ initial isotopic ratio typical of rocks which have been subjected to crustal reworking.[1] It seems, therefore, that the Rossing type may have formed in part from supracrustal rocks and might be restricted in its occurrence on the basis of stratigraphy. Therefore, on a more pessimistic note one should perhaps reflect upon the possibility of finding rocks containing disseminated extractable uranium in large enough tonnages to constitute a "porphyry" uranium deposit in the Grenville Province. A detailed field and laboratory investigation of the various rocks of the Rossing deposit could help resolve its origin. This would then enable one to formulate more specific exploration programs with regard to "porphyry" uranium in the Grenville Province. The author suggests that the Grenville uraniferous granites may in fact be more akin to the Conway, New Hampshire (Richardson 1964), the Bokan Mountain Alaska (MacKevett 1963) and the Kaffo Valley, Nigeria (Mackey et al. 1952), granites which are anorogenic, and not the result of crustal anatexis. On this basis it would be worthwhile to explore the younger granites within the Grenville Province, especially those associated with large lineaments or alkaline rocks.

So far most uranium explorationists in the Grenville Province have focused primarily upon pegmatites and granites. Unfortunately these rocks

---

[1] Personal communication; C. Hawkesworth, Department of Earth Sciences, University of Leeds, Leeds, England, December 1977.

make poor mining prospects: the granites rarely make the grade and the pegmatites rarely make the tonnage requirements.

The author would like to suggest that there may be two additional types of granite-related deposits in or near the Grenville Province. The first possibility is that hydrothermal solutions laden in uranium may have discharged from granite into a suitably reactive host rock such as marble and formed vein-type or skarn deposits. Not only would a carbonate host tend to exert a strong chemical control and cause precipitation of various species from solution but it may also have selectively enriched uranium relative to thorium. The second possible additional type of deposit would be a low-temperature type in which suitable younger sedimentary host rocks might become mineralized with uranium from these labile granites. One possible example, although by no means economic, is the copper-uranium-hydrocarbon mineralization in the dolomitic sandstones of the South March formation near Ottawa (Grasty et al. 1973).

CHAPTER VII - SUMMARY AND CONCLUSIONS

Fieldwork suggests that the uraniferous pegmatites are late in the sense that they display partly cross-cutting relationships to their host and are themselves not metamorphosed. The Rb-Sr age data confirm their youthful nature and show that they are at least 150 Ma younger than the peak of metamorphism in the area. This and the primitive $^{87}Sr/^{86}Sr$ initial ratios preclude their having formed by *in situ* anatexis. Metasomatism of pre-existing uraniferous protoliths is also ruled out unless intrusion of post-tectonic granite is the mechanism invoked for reconstituting the sedimentary rocks. Large tracts of Grenville clastic sedimentary rocks containing syngenetic uranium are, however, unknown. Evaporites could not have been the source of the mineralization as they tend to have low thorium contents, and in the presence of high calcium, little uranium.

A model involving ultrametamorphism of crustal material below the present level of exposure would require the source terrain to have suffered a pre-existing partial melting episode (*ca.* 1150 Ma ago) to reduce Rb and radiogenic ^{87}Sr so that a 930 Ma event could produce rocks with low $^{87}Sr/^{86}Sr$ initial ratios. Although feasible, the author does not favour this model as uranium and thorium would be lost to a large degree in the first event (*ca.* 1150 Ma). Furthermore, it cannot explain the association of certain of these granites with alkaline rocks.

A model more consistent with the field relationships, isotopic evidence, age and widespread distribution of the granites does emerge. Erosion of the Grenville terrain and consequent isostatic uplift and relaxation of horizontal compressive forces provided areas of relatively low pressure for juvenile gases to migrate to. This combined with "isothermal" decompression produced

basaltic magma by partial fusion of mantle peridotite. These magmas filled reservoirs at depths of 30 km or less in the crust and proceeded to undergo differentiation. Primitive fluids interacting with crystal differentiates produced granite which then intruded into the crust along pre-existing zones of weakness. The water-saturated nature of the melt prevented it from reaching the surface before crystallization. Fluids rich in incompatible elements which escaped from the crystallizing granite formed the pegmatites. By varying the CO_2 content of the juvenile gases, composition of the parent, and depth of formation, the observed alkaline rocks and even carbonatite can be generated. It is therefore suggested that the radioelement-enriched granites are anorogenic in character and perhaps similar in origin to the Conway granite and Ross Adams deposit.

Where the pegmatites intrude carbonate-rich terrain there is a strong tendency for them to be white in colour, pyrite-bearing and to have high U/Th ratios relative to those developed in quartzofeldspathic terrains where they are normally pink, magnetite- and hematite-bearing and have lower U/Th ratios. These pegmatites which are interpreted to have come from very similar granite sources owe their differences to the fact that the white pegmatites were formed in a relatively reducing environment. The REE of the pegmatites, which appear to have been complexed as fluorides, show anomalous behaviour.

It is suggested that the late stage fluids which were responsible to a large degree for the pegmatites' formation caused the breakdown of a calcium-bearing plagioclase and the subsequent formation of allanite and albite. Because these fluids were oxidizing Eu^{2+} which was substituting for Ca^{2+} in the plagioclase became incompatible Eu^{3+}. Therefore the fluid, which then

migrated to the pegmatites, was enriched in Eu relative to other REE and U/Th owing to its oxidizing nature. The ΣREE of the white pegmatites is low and their REE patterns display positive europium anomalies. There is a tendency for the ΣREE of the pink pegmatites and granites to be high and for their patterns to show negative europium anomalies. Cerium and gadolinium appear to show opposite, and ytterbium similar, behaviour to europium. This may be due to pH changes in the fluid at the site of deposition. In forming the white pegmatites the fluid preferentially deposited uranium relative to thorium and europium relative to other REE. This demonstrates that the REE do not behave in the isochemical manner proposed by previous authors. Great care should be exercised in interpreting REE patterns from granitic rocks which have formed in a fluid-rich environment.

Contributions to Knowledge

The Faculty of Graduate Studies requires that "contributions to knowledge" be listed clearly in a separate section of this thesis. The following is my perception of such a contribution.

1) This work represents the first comprehensive study on the origin of Grenville Province uraniferous granitic rocks. In contrast to other studies this work has led to the conclusion that the granites are significantly younger than the peak of Grenville metamorphism and that they were formed from juvenile material.

2) The work represents the first application of precise whole rock Rb-Sr isochron geochronology to the various radioelement-enriched pegmatites and granites of the province.

3) A temporal and genetic relationship between the pegmatites and radioelement-enriched granites has been shown to exist. The age data, primitive Sr isotopic initial ratios and the association of these rocks with alkaline rocks has led to the suggestion that they are rift-related.

4) A model relying upon the onset of tensional forces due to relaxation of compression, partial lithospheric melting in response to adiabatic decompression, heat focusing and volatile fluxing at the end of the Grenville Orogeny has been postulated to account for the origin and distribution of these "late Grenville" igneous rocks.

5) A method for correcting rare earth element analyses from fission product build-up and other interferences encountered during instrumental neutron activation analysis of samples with high uranium concentrations was devised.

6) In the Mt-Laurier area, it was shown that REE were transported in part as fluorine complexes and that the character of the REE spectra of the granites are due to late-stage alterations. Uranium was preferentially scavenged relative to the thorium and REE by late-stage oxidizing alkaline solutions and carried out to the pegmatites.

7) The negative europium anomalies of the Guenette granites and the positive europium anomalies of the associated pegmatites are ascribed to late stage alterations. This is the first time that europium anomalies have been shown to be a result of such late-stage processes. Traditional interpretations ascribe these anomalies to crystal-melt interactions in the primary magmas.

8) It was shown that a positive correlation between the U/Th ratio and Eu/Ce ratio of the pegmatites exists, which suggests that the latter ratio may also be a sensitive indicator of redox conditions in igneous environments.

Acknowledgements

Special thanks are due to Professor R. Doig, supervisor of this thesis, for his advice, assistance and guidance given throughout every stage of the project. The author is also appreciative of the assistance rendered to him by Profs. D. Francis, A.E. Williams-Jones, and R. Martin through discussion of various topics and constructive criticism of the early drafts. Thanks are extended to Professor D. Hogarth of Ottawa University and J. Packard, the former for introducing him to the Meach Lake area and the latter for his aid with the field work; and to Prof. S. Kumarapeli of Concordia University for discussion of the geology of the St. Lawrence Graben System. The author also benefitted from discussion with many fellow graduate students at McGill. Field assistance was able provided by I. Falconner and T. Payne during the summer of 1977 during which time the author was in the employ of the Geological Survey of Canada. The help given by numerous members of this organization, in particular B. Charbonneau and K. Ford, is much appreciated. Geologists of various mining companies are thanked for having allowed access to properties and for providing interesting discussion.

The staff of the Nuclear Engineering Department of Ecole Polytechnique provided reactor and spectrometer time free of charge. The author is particularly grateful for the help given to him by Dr. G. Kennedy at Ecole Polytechnique. A brief discussion on the chemistry of Lanthanides with Prof. Harrod of the Chemistry department of McGill proved be to most useful. Thanks are also extended to G. Aislin of the Geological Survey of Canada for performing the fluorine analyses and to J. Bouvier for some of the major element analyses. Financial assistance in the form of a National Research Council Post Graduate Student Scholarship during 1976 and 1977, and support

from National Research Council and Geological Survey of Canada grants held by Professor Doig are gratefully acknowledged. L. Forrest, K. Rivett and V. Trimarchi typed the manuscript and R. Yates helped with the drafting. Finally, the continued support and encouragement given to me by my family, in particular my parents, Graham, Virginia and Terry, is particularly appreciated.

REFERENCES

Allen, J.M., 1971. The genesis of Precambrian uranium deposits in eastern Canada, and the uraniferous pegmatites at Mont Laurier, Quebec. Unpublished M.Sc. thesis, Queen's University, Kingston, Ontario, 83 p.

Armstrong, F.C., 1974. Uranium resources of the future - "porphyry" uranium deposits. In Formation of Uranium Ore Deposits. Proceedings of a Symposium, Athens, I.A.E.A., pp. 625-635.

Baer, A.J., 1976. The Grenville Province in Helikian times: a possible model of evolution. Phil. Trans. Roy. Soc. London 280, pp. 499-515.

Bailey, D.K., 1964. Crustal warping - a possible tectonic control of alkaline magmatism. J. Geophys. Res. 69, pp. 1103-1111.

Bailey, D.K., 1970. Volatile flux heat focusing and the generation of magma. In Mechanisms of Igneous Intrusion, ed. by Newall, N., and Rast, N., Gallery Press, Liverpool, pp. 177-186.

Baldwin, A.B., 1970. Uranium and thorium occurrences on the North shore of the St. Lawrence. Can. Mining Met. Bull. 63, pp. 699-707.

Banderkin, G.A., 1961. Behaviour of the rare earths in fluorine-bearing media. Geochemistry, pp. 159-166.

Barton, J.M., Jr., 1971. A geochronologic and stratigraphic study of the Precambrian rocks north of Montreal. Unpubl. Ph.D. thesis, McGill University, Montreal.

Barton, J.M., and Doig, Ronald, 1974. Temporal relationships of rock units in the Shawinigan area, Grenville Province, Quebec. Canadian J. Earth Sciences 11, pp. 686-690.

Berning, J., Cooke, R., Hiemstra, S.A., and Hoffman, V., 1976. The Rossing uranium deposit, South West Africa. Econ. Geol. 71, pp. 351-368.

Bohse, H., Rose-Hansen, J., Sørenson, H., Steerfelt, A., Løvborg, L., Kunzendorf, H., 1974. On the behaviour of uranium during the crystallization of magmas - with special emphasis on alkaline magmas. In Formation of uranium ore deposits. IAEA-SM-183/26, pp. 49-60.

Boudette, E.L., 1977. Two mica granite and uranium potential in the Northern Appalachian orogen of New England. Short papers of the U.S.G.S. Uranium - Thorium Symposium, Golden, Colorado. Ed. by Campbell, J.A., pp. 23-24.

Buddington, A.F.,and Lindsley, D.H., 1964. Iron-titanium oxide minerals and synthetic equivalents. J. Petrology 5, pt. 2, pp. 310-357.

*Aubert de la Rue, E., 1948. Les régions de Nominique et de Sicotte, comtés de Labelle et de Gatineau. Ministère des Mines, Québec, Rapport Géologiques 23, 74p.

Burnham, C.W., 1967. Hydrothermal fluids at the magmatic stage. In Geochemistry of hydrothermal ore deposits, ed. by Barnes, H.L. Holt, Rinehart and Winston, Inc., pp. 34-76.

Bright, E.G., 1976. Cavendish and Anstruther townships, Peterborough County. In Summary of field work 1976, ed. by Milne, O.G., Cowan, W.R., Card, K.D., and Robertson, J.A. Ontario Div. Mines, MP67, pp. 122-126.

Brown, G.C., and Fyfe, W.S., 1970. The production of granitic melts during ultrametamorphism. Contrib. Mineral. and Petrol. 28, pp. 310-318.

Cameron, E.N., Jahns, R.H., McNair, A.H., and Page, L.R., 1949. Internal structure of granite pegmatite. Econ. Geol. Monograph #2, 115 p.

Charbonneau, B.W., 1973. Ground investigation of the Mont Laurier Airborne Radioactivity Survey. In Report of Activities, Part A, Geol. Surv. Can. Paper 73-1, pp. 67-80.

Chayes, F., 1942. Alkaline and carbonate intrusives near Bancroft, Ontario. Bull. Geol. Soc. Amer. 53, pp. 449-512.

Condie, K.C., and Moore, J.M., 1977. Geochemistry of Proterozoic volcanic rocks from the Grenville Province, Eastern Ontario. Geol. Assoc. Canada, special paper No. 16, pp. 149-168.

Cooper, G.E., 1953. Geology of the Johan Beetz area. Unpublished Ph.D. thesis, McGill University, Montreal, 137 p.

Currie, K.L., 1976. The alkaline rocks of Canada. Geol. Surv. Can. Bull 239, 228 p.

Darnley, A.G., Charbonneau, B.W., and Richardson, K.A., 1977. The distribution of uranium in rocks as a guide to the recognition of uraniferous regions. Symposium on Recognition and Evaluation of Uraniferous Areas, I.A.E.A. Vienna, Austria, 1975. IAEA TC 15/9, pp. 55-86.

Deland, A.N., 1956. The boundary between the Timiskaming and Grenville Subprovinces in the Surprise Lake area, Quebec. Proc. Geol. Assoc. Can. 8, pp. 127-141.

Deer, W.A., Howie, R.A., Zussman, J., 1963. Rock forming minerals. Longmans, Green and Co., London.

Dewey, J.F., and Burke, K.C.A., 1973. Tibetan Variscan and Pre-Cambrian basement reactivation: Products of continental collision. J. Geology 81, pp. 683-692.

Doig, R., and Barton, J.M., Jr., 1968. Ages of carbonatites and other alkaline rocks in Quebec. Canadian J. Earth Sciences 5, pp. 1401-1407.

Doig, R., 1970. An alkaline rock province linking Europe and North America. Canadian J. Earth Sciences 7, pp. 22-28.

Doig, R., 1977. Rb-Sr geochronology and evolution of the Grenville Province in Northwestern Quebec, Canada. Geol. Soc. Amer. Bull. 88, p. 1843-1856.

Dufresne, C., 1948. Faulting in the St. Lawrence plain. Unpublished M.Sc. thesis, McGill University, Montreal, 216 p.

Eggler, D.H., 1976. Composition of the partial melt of carbonated peridotite in the system CaO-MgO-SiO_2-CO_2. Annual report of the Director of the Geophysical Laboratory, Carnegie Institution, pp. 623-626.

England, P.C., 1978. Some thermal considerations of the alpine metamorphism - past, present and future. Tectonophysics 46, pp. 21-40.

England, P.C., 1979. Continental geotherms during the Archean. Nature 277, pp. 556-558.

El Bouseily, A.M., and El Sokkary, A.A., 1975. The relation between Rb, Ba and Sr in granitic rocks. Chemical Geology 16, pp. 207-219.

Erdtmann, G., 1972. Interference in neutron activation analytical determinations by uranium fission. J. Radioanal. Chem. 10, pp. 137-138.

Evans, A.M., 1966. The development of lit par lit gneiss at the Bicroft Uranium Mine, Ontario. Canadian Mineralogist 8, pp. 593-609.

Fahrig, W.F., Eade, K.E., and Adams, J.A.S., 1967. Abundance of radioactive elements in crystalline shield rocks. Nature 214, pp. 1002.

Faure, G., and Powell, J.L., 1972. Strontium Isotope Geology. Springer-Verlag, New York, 188 p.

Foland, K.A., Quinn, A.W., and Giletti, B.J., 1971. K-Ar and Rb-Sr Jurassic and Cretaceous ages for intrusives of the White Mountain Magma Series, northern New England. Amer. J. of Science 270, pp. 321-330.

Foland, L.A., Faul, H., 1977. Ages of the White Mountain Intrusive - New Hampshire, Vermont, and Maine, U.S.A. Amer. J. Science 277, pp. 888-904.

Frith, R.A., and Doig, Ronald, 1973. Rb-Sr isotopic ages and petrologic studies of the rocks in the Lac St. Jean area, Quebec. Can. J. Earth Sciences 10, pp. 881-899.

Fyfe, W.S., Turner, F.J., and Verhoogen, J., 1958. Metamorphic reactions and metamorphic facies. Geol. Soc. Amer., Mem. 73, 258 p.

Gangloff, A., 1970. Notes sommaires sur la géologie des principaux districts uraniferes etudiés par la C.E.A. Uranium Exploration Geology, I.A.E.A. Pl - 391/16, pp. 77-106.

Gordon, G.E., Randle, L., Goles, G.G., Corliss, J.B., Beeson, M.H., and Oxley, S.S., 1968. Instrumental activation analysis of standard rocks with high-resolution γ-ray detector. Geochim. Cosmochim. Acta 32, pp. 369-396.

Gordon, J.B., and Masson, S., 1977. Uranium and thorium deposits in Ontario. Ontario Geological Survey Misc. Paper 75. Ed. by Milne, et al., pp. 192-194.

Gordon, J.B., and Masson, S., 1978. Mineral resource studies in the Pembrooke-Renfrew area, Southeastern Ontario. Ontario Geological Survey Misc. Paper 82, pp. 180-185.

Grasty, R.L., and Darnley, A.D., 1971. The calibration of gamma-ray spectrometers for ground and airborne use. Geol. Surv. Canada Paper 71-17, 27 p.

Grasty, R.L., Charbonneau, B.W., and Steacy, H.R., 1973. Uranium occurrence in paleozoic rocks west of Ottawa. Geol. Surv. Can. Paper 73-1A, pp. 286-289.

Green, D.H., and Ringwood, A.E., 1972. A comparison of recent experimental data on the gabbro-garnet granulite-eclogite transition. J. Geology 80, pp. 277.

Harris, P.G., Kennedy, W.Q., and Scarfe, C.M., 1969. Volcanism versus Plutonism - the effect of chemical composition. Liverpool Geo. Soc. Symposium on Mechanism of Igneous Intrusion, Jan. 1969.

Hauseux, M.A., 1977. Mode of uranium occurrence in a migmatitic granite terrain, Baie Johan Beetz, Quebec. Can. Mining Met. Bull. 70, pp. 110-116.

Hedge, C.E., Kujoti, F., Celerte, G.E., and Fuler, R.L., 1979. Rare earth abundances and Rb-Sr syrlematics of basalts, gabbros, anorthosites and minor granitic rocks from the Indian Ocean Ridge System, Western Indian Ocean. Contrib. Mineral. Petrol. 68, pp. 373-376.

Heier, K.S., 1964. Rubidium/strontium and strontium-87/strontium-86 ratios in deep crustal materials. Nature 202, pp. 477-478.

Heier, K.S., and Compston, W., 1969. Interpretation of Rb-Sr age patterns in high-grade metamorphic rocks, North Norway. Norsk. Geologisk Tidsskrift 49, pp. 257-283.

Higgins, M.D., and Doig, R., 1977. 540 Myr-old anorthosite complex in the Grenville province of Quebec, Canada. Nature 267, No. 5606, pp. 40-41.

Hogarth, D.D., 1966. Intrusive carbonate rock near Ottawa, Canada. In International Mineralogical Association, fourth general meeting Mineralogical Society of India, pp. 45-53.

Huang, W.L., and Wyllie, P.J., 1975. Influence of mantle CO_2 in the generation of carbonatites and kimberlites. Nature 257, pp. 297-299

Jacobs, J.W., Koroter, R.L., Blanchard, D.A., and Hashin, L.A., 1977. A well-tested procedure for instrumental neutron activation analysis of silicate rocks and minerals. J. of Radioanalytical Chem. 40, pp. 93-114.

Jahns, R.H., and Tuttle, F., 1963. Layered pegmatite aplite intrusives. Mineralogical Society of America Special Paper, pp. 78-92.

Jahns, R.H., and Burnham, C.W., 1969. Experimental studies of pegmatite genesis. - I. A model for the derivation and crystallization of granitic pegmatites. Econ. Geol. 64, pp. 843-864.

Kish, L., 1975. Radioactive occurrences in the Grenville of Quebec, Mont Laurier Cabonga district. Quebec Department of Natural Resources, Preliminary Report 310, pp. 27.

Kish, L., 1977. Patibre (Axe) Lake Area. Ministère des Richesses Naturelles, Preliminary Report DPV-487, 15 p.

Klemic, H., Heyl, A.V., Taylor, A.R., and Store, J., 1959. Radioactive rare earth deposits at Scrub Oaks mine, Morris Count, New Jersey. U.S.G.S. Bull 1082-B, 59 p.

Koljonen, T., and Rosenberg, R.J., 1974. Rare earth elements in granitic rocks. Lithos 7, pp. 249-261.

Kogarko, L.N., 1974. Role of volatiles. In The Alkaline Rocks, ed. by Sorensen, H., John Wiley and Sons, London, pp. 474-487.

Kosterin, A.V., 1959. The possible mode of transport of the rare earths by hydrothermal solutions. Geochemistry, pp. 381-387.

Krogh, T.E., Davis, G.L., Aldrich, L.T., Hart, S.R., and Stueber, A., 1966. Geological history of the Grenville Province. Carnegie Institution, Annual Report of the Director of the Geophysical Laboratory, pp. 528-536.

Krogh, T.E., and Davis, G.L., 1972. The effect of regional metamorphism on U-Pb systems in zircons and a comparison with Rb-Sr systems in the same whole rock. Carnegie Institution, Annual Report of the Director of the Geophysical Laboratory, pp. 564-571.

Kumarapeli, P.S., and Saull, V.A., 1966. The St. Lawrence Valley system: a North American equivalent of the East African rift valley system. Can. J. Earth Sciences 5, pp. 683-692.

Kurhiro, I., Satake, H., and Akimoto, S., 1975. Carbonate-silicate reactions at high pressures and possible presence of dolomite and magnesite in the upper mantle. Earth and Planetary Science Letters 28, pp. 116-120.

Larsen, E.S. Jr., and Phair, G., 1954. The distribution of uranium and thorium in igneous rocks. In Nuclear Geology, ed. by Faul, H. John Wiley and Sons Inc., 414 p.

Lumbers, S.B., 1967. Geology and mineral deposits of the Bancroft-Madoc area. In Guidebook geology of parts of eastern Ontario and western Quebec, ed. by Jenness, S.E. Geol. Assoc. Can. Annual Meeting, Kingston, pp. 13-29.

Lumbers, S.B., 1975. Pembroke area, District of Nipissing and County of Renfrew. In Summary of field work, ed. by Milne, V.G., Hewitt, D.F., Card, K.D. Ontario Div. Mines MP63, 158 p.

Loiselle, M.C., and Wones, D.R., 1979. Characteristics and origin of anorogenic granites. Abstracts, Geol. Soc. Amer. 92nd annual meeting, p. 468.

Macintyre, R.M., York, D., and Moorhouse, W.W., 1967. Potassium-argon age determinations in the Madoc-Bancroft area in the Grenville Province of the Canadian Shield. Can. J. Earth Sciences 4, pp. 815-828.

Mackie, B., 1977. Petrogenesis of the Lac Turgeon granite and associated uranium occurrences near Baie Johan Beetz, Quebec. Geol. Soc. Amer., abstracts, vol. 9, no. 7, p. 1080.

MacKay, R.A., Beer, K.E., and Rockingham, J.E., 1952. The albite-riebickite-granites of Nigeria. Dept. of Scientific and Industrial Research, Geol. Survey and Museum, Atomic Energy Division, Report GSM/AED. 95, Her Majesty's Stationary Office, London, 25 p.

MacKevett, E.K., Sr., 1963. Geology and ore deposits of the Bokan Mountain uranium-thorium area, Southeastern Alaska. U.S.G.S. Bull., 1154, pp. 1-125.

Marmo, V., 1971. Granite petrology and the granite problem. Elsevier, 244 p.

Martin, R.F., 1974. Controls of ordering and subsolidus phase relations in the alkali feldspars. In The Feldspars, ed. by Mackenzie, W.S., and Zussman, J., Manchester University Press, 706 p.

Martin, R.F., and Piwinskii, A.J., 1974. The contrasting origin of orogenic and non-orogenic granitoid rocks. In Andean and Antarctic volcanology problems, International Assoc. of Volcanology and Chemistry of the Earth's Interior, Francesco Gianni and Figli Publishers, Napoli Italy, pp. 482-496.

McCarthy, T.S., and Kable, E.J.D., 1978. On the behaviour of rare-earth elements during partial melting of granitic rock. Chemical Geology 22, pp. 21-29.

McKelvey, V.E., Everhart, D.L., and Garrels, R.M., 1955. Origin of uranium deposits. Econ. Geol. Fiftieth Anniversary Volume, ed. by Bateman, A.M., Part I, pp. 464-533.

McKelvey, V.E., 1956. Uranium in phosphate rock. U.S. Geol. Surv. Prof. Paper 300, pp. 477-482.

McLennan, S.M., and Taylor, S.R., 1979. Rare earth element mobility associated with uranium mineralization. Nature 282, pp. 247-250.

Mineyev, D.A., 1963. Geochemical differentiation of the Rare Earths. Geochemistry, pp. 1129-1149.

Mineyev, D.A., Dikov, Yu.P., Sobolev, B.P., and Borutskaya, V.L., 1966. Differentiation of rare-earth elements under super-critical conditions. Geochemistry International, pp. 357-359.

Murata, K.J., Dutra, C.V., daCorta, M.T., and Branco, J.J.K., 1959. Composition of monazites from pegmatites in eastern Minas Gerais, Brazil. Geochim. Cosmochim. Acta. 16, pp. 1-14.

Moeller, T., 1963. The chemistry of the lanthenides. Reinhold Publishing Corporation, New York, 117 p.

Moreau, M., and Ranchin, G., 1973. Hydrothermal changes and tectonic controls in the intragranitic uranium in deposits in the French Central Massif. Translation of pp. 77-100 of Colloque Scientifiques International, Paris, 46 p.

Morgan, W.J., 1971. Convection plumes in the lower mantle. Nature 230, pp. 42-43.

Osborne, F.F., 1934. Labelle - L'Annoncialion map-area. Quebec Bureau of Mines, Annual Report, Part E, 52 p.

Petersen, J.S., and Pedersen, S., 1978. Strontium-isotope study of the Kleivan granite, Southern Norway. Norsk Geologisk Tidsskrift 58, pp. 97-102.

Pitcher, W.S., 1970. Ghost stratigraphy in intrusive granites - a review. In Mechanisms of Igneous Intrusion, ed. by Newall, N., and Rast, N., Liverpool Geological Soc., pp. 123-140.

Piwinski, A.J., 1973. Experimental studies of igneous rock suites, central Sierra Nevada batholith, California: Part II. N. Jb. Miner. Mn., 4.5, pp. 193-213.

Phillpotts, A.R.,and Miller, J.A., 1963. A Precambrian glass from St. Alexis Des Monts, Quebec. Geol. Mag. 100, pp. 337-344.

Richardson, K.A., 1964. Thorium, uranium and potassium in the Conway granite, New Hampshire, U.S.A. In The Natural Radiation Environment, ed. by Adams, J.A.S., and Lowder, W.M., University of Chicago Press, pp. 39-50.

Rimsaite, J., 1978. Mineralogy of radioactive occurrences in the Grenville Structural Province Ontario and Quebec: a preliminary report. Geol. Surv. Canada Paper 78-1B, pp. 49-58.

Rive, M., 1976. Région de Sainte-Véronique. Ministère des Richesses Naturelles, Rapport Géologique 182, 68 p.

Robinson, S.C., 1961. Economic uranium deposits in granitic dykes, Bancroft District, Ontario. Canadian Mineralogist 6, pp. 513-521.

Rogers, J.J.W., and Adams, J.A.S., 1974. Uranium. Handbook of Geochemistry, vol. II/4 sec. 92, ed. by Wedepohl, K.H., Springer-Verlag, Berlin.

Roscoe, S.M., 1968. Huronian rocks and uraniferous conglomerates in the Canadian Shield. Geol. Surv. Can., Paper 68-40, 205 p.

Ryabchikov, D.I., and Ryabukhin, V.A., 1970. Analytical chemistry of yttrium and the lanthanide elements. A. Aladyem, translator. Humphrey Science Publishers, Ann-Arbor, 365 p.

Satterly, J., 1956. Radioactive mineral occurrences in the Bancroft area. Ont. Dept. Mines, Ann. Rep. 65, Pt. 6, 181 p.

Schilling, J.G., and Winchester, J.W., 1967. Rare-earth fractionation and magmatic processes. In Runcorn, S.K., ed., Mantles of the Earth and Terrestrial Planets. Interscience, pp. 267-283.

Schmitt, R.A., Smith, R.H., Lasch, J.E., Mosen, A.W., Olehy, D.A., and Vasilevskis, J., 1963. Abundances of the fourteen rare-earth elements, scandium and yttrium in meteoric and terrestrial matter. Geochim. Cosmochim. Acta. 27, pp. 577-622.

Short, N.M., 1968. Experimental microdeformation of rock materials by shock pressure from laboratory-scale impact and explosions. In Shock Metamorphism of Natural Materials, ed. by French, B.M., and Short, N.M., Mono Book Corp., Baltimore, 644 p.

Silver, L.T., and Lumbers, S.B., 1965. Geochronologic studies in the Bancroft-Madoc area of the Grenville Province, Ontario, Canada. Geol. Soc. Amer. Spec. Publ. 87, P. 156.

Sinha, S.P., 1966. Complexes of the rare earths. Pergamon Press, New York, 205 p.

Smith, B.L., 1956. Geology of the Clarendon-Dalhousie area. Ont. Dept. of Mines, Vol. 65, part 7, pp. 1-46.

Smith, J.V., 1974. Feldspar minerals. Springer-Verlag, three volumes.

Staatz, M.H., 1978. I and L uranium and thorium vein system, Bokan Mountain, Southeastern Alaska. Econ. Geol. 73, pp. 512-523.

Steiger, R.H., and Jager, E., 1977. Subcommission of Geochronology: convention on the use of decay constants in Geo- and Cosmochronology. Earth and Planetary Science Letters 36, pp. 359-362.

Stockwell, C.H., 1962. Second report on structural provinces, orogenesis, and time classification of rocks of the Canadian Precambrian Shield. In Geol. Surv. Can. Paper 62-17, Age determinations and geological studies, ed. by Lowdon, J.A., et al., pp. 123-133.

Szoghy, I.M., and Kish, L., 1978. Determination of radioactive dis-equilibrium in uranium-bearing rocks. Canadian Jour. Earth Sciences 15, pp. 33-44.

Thompson, T.B., 1979. Genesis of the Bokan Mountain U-Th deposits southeastern Alaska. Geol. Soc. Amer. Abstracts, 92nd annual meeting, pp. 527.

Tremblay, D., 1974. Mineralogy and geochemistry of the radioactive pegmatite of the Mont Laurier area, Québec. Unpublished M.Sc. thesis, Queen's University, Kingston, Ontario, 133 p.

Tuttle, O.F., and Bowen, N.L., 1958. Origin of granite in light of experimental studies in the system $NaAlSi_3O_8$ - $KAlSi_3O_8$ - SiO_2-H_2O. Geol. Soc. Amer., Mem. 74, 153 p.

Vlasov, K.A., 1966. Geochemistry of rare elements, Vol. 1. Israeli Program for Scientific Translations Ltd., Jerusalem, 688 p.

Von Backstrom, J.W., 1970. The Rossing Uranium Deposit near Swakopmund, Southwest Africa. In Uranium Exploration Geology, I.A.E.A. - P1-391/12, pp. 143-150.

Wendlandt, R.F., 1977a. The system $KAlSiO_4$ - Mg_2SiO_4 - SiO_2 - CO_2: Phase relations involving forsterite, enstatite, sanidine, kalsilite, leucite, vapour and liquid to 30 K bar. Report of the director of the Geophysical laboratory, Carnegie Insititution, pp. 435-441.

Wendlandt, R.F., 1977b. The system K_2O - MgO - Al_2O_3 - SiO_2 - H_2O - CO_2: Stability of phlogopite as a function of vapour composition at high pressures and temperatures. Report of the director of the Geophysical laboratory, Carnegie Institution, pp. 441-448.

Wyllie, P.J., Huang, W.L., Stern, C.R., and Maaløe, S., 1976. Granitic magmas: possible and impossible sources, water contents, and crystallization sequences. Can. Jour. Earth Sciences 13, pp. 1007-1019.

Wyllie, R.J.M., 1979. Rossing Uranium reaches rated production. World Mining 32, No. 1, pp. 42-52, No. 2, pp. 52-58.

Wynne-Edwards, H.R., Gregory, A.F., Hay, P.W., Giovanella, C.A., and Reinhardt, E.W., 1966. Mont Laurier and Kempt Lake map areas, Quebec. Geol. Surv. Can., Paper 66-32, 32 p.

Wynne-Edwards, H.R., 1972. The Grenville Province. In Price, R.A., and Douglas, R.J.W., eds., Variations in tectonic styles in Canada. Geol. Assoc. Canada Spec. Paper 11, p. 263-334.

Wynne-Edwards, H.R., 1976. Proterozoic ensialic orogenesis: the millipede model of ductile plate tectonics. Amer. 5 Sci. 276, pp. 927-953.

York, D., 1966. Least squares fitting of a straight line. Can. J. Physics 44, pp. 1079-1086.

York, D., and Farquhar, R.M., 1972. The Earth's age and geochronology. Pergamon Press, New York, 178 p.

Zamarega, S.M., and Ruzhich, V.V., 1978. On relationships between the Baikal rift and ancient structures. Tectonophysics 45, pp. 41-47.

APPENDIX A

Rb-Sr Isochron Data

Bancroft Pegmatites

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
GHAWK 1	6.51700	19.34442	0.96180
GHAWK 2	6.74320	20.05380	0.98150
BICROFT 1	1.17250	3.41024	0.75250
CDYNO 1	3.99810	11.76569	0.87260
CDYNO 3	2.83600	8.30130	0.81760
CDYNO 4	3.54140	10.39713	0.84830
CDYNO 8	0.94680	2.75105	0.74240
CDYNO 10	5.29420	15.65656	0.92330

Cheddar Granite

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
CH1	4.00730	11.81852	0.89510
CH2	3.28090	9.63834	0.85470
CH3	4.42580	13.06695	0.90630
CH6	5.91360	17.58070	0.97800
CH8	6.00250	17.89198	1.00540
CH9	2.38280	6.96853	0.80850

Mitchinamecus Pegmatite 1

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
AF3-1	0.93620	2.71935	0.73900
AF3-2	0.74580	2.16455	0.73080
AF3-3	0.60820	1.76453	0.72700
AF3-5	0.46880	1.35923	0.72050
AF3-6	0.29970	0.86841	0.71430

Mitchinamecus Pegmatite 2

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
I89	0.44820	1.29991	0.72370
I90	0.69300	2.01133	0.73090
I92	0.85380	2.47959	0.73730
I95	0.08960	0.25945	0.70750
I96	0.88540	2.57464	0.73880
I97	0.11110	0.32173	0.70820

Lac Montagne Pegmatite

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
AF1-1	0.18850	0.54605	0.71150
AF1-3	0.11110	0.32178	0.70960
AF1-4	0.36560	1.05985	0.71930
AF1-5	0.36420	1.05570	0.71810
AF1-6	0.40010	1.15991	0.71940
AF1-8	0.80760	2.34507	0.73580

Mitchinamecus Granite Gneiss

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
G68	1.77910	5.18776	0.77850
G71	1.63890	4.77660	0.77350
G72	0.80110	2.32647	0.73700
G74	1.76150	5.13639	0.77840
G77	2.10500	6.14648	0.79250
G78	2.42590	7.09119	0.80360

Pegmatitic Granite Lac Edmond

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
5-1	0.87700	2.54796	0.74130
5-2	1.00560	2.92294	0.74600
5-4	0.92710	2.69371	0.74200
5-7	0.78740	2.28675	0.73730

Mitchinamecus Gneiss

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
H79	0.18070	0.52349	0.71220
H81	0.08600	0.24905	0.70840
H82	0.18130	0.52533	0.71410
H83	0.20140	0.58350	0.71290
H84	0.10190	0.29514	0.71000

Mitchinamecus Aplite

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
77-1	0.18340	0.53132	0.71240
77-2	0.26310	0.76247	0.71580
77-4	0.28630	0.82979	0.71680
77-5	0.35640	1.03329	0.72000
77-6	0.16210	0.46956	0.71120
77-7	0.24920	0.72215	0.71520
77-8	0.23000	0.66642	0.71380

Guenette Granite

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
12-1	1.27390	3.70673	0.75680
12-6	1.78210	5.19696	0.77940
12-8	1.09590	3.18507	0.74490
6-1	1.27070	3.69742	0.75680
6-5	1.22040	3.55088	0.75630
72A	1.74520	5.08642	0.77350
40C	0.61370	1.78096	0.72970
41C	1.03890	3.01985	0.74640

Turgeon Lake Granite

SAMPLE	RB/SR	RB-87/SR-86	SR-87/SR-86
14-1	12.63560	38.42050	1.21510
14-3	3.36990	9.88276	0.83700
14-4	4.82940	14.25470	0.90350
14-8	2.20840	6.44973	0.79460

APPENDIX B

Trace Element Concentration
(in PPM)
INAA Analysis

	AF-6	AF11-1	RDG	AF1	AF3-1	I90	MLU1A	MLU1D	77-1	AF7-3	AF7-
La	57.4	214.0	31.2	50.5	02.2	10.0	10.1	05.5	154.0	32.0	30.1
Ce	86.2	289.0	65.0	71.8	03.0	13.2	--	07.7	243.0	63.0	46.2
Sm	06.9	015.1	05.6	05.0	01.2	01.8	01.4	01.8	013.6	06.6	06.7
Eu	00.9	001.0	00.8	00.7	00.6	00.8	01.0	01.0	005.2	01.6	01.9
Tb	00.6	001.4	00.6	00.5	--	00.1	--	00.1	001.9	00.7	00.8
Dy	04.1	007.6	03.5	03.0	--	00.8	01.1	01.5	008.9	04.3	04.2
Yb	01.5	003.6	01.4	01.6	--	01.1	01.1	00.7	003.1	03.4	02.9
Lu	00.3	000.5	--	--	--	--	--	--	000.9	00.5	00.3
Ba	647.0	440.0	305.	950.	740.	520.	940.	780.	2190.	380.	280.
U	04.3	008.5	09.3	10.6	06.0	37.0	12.7	75.0	--	--	02.1
Th	38.1	061.5	38.0	88.6	08.3	115.	00.2	14.7	--	--	02.1

	Ched3	Ched9	CD4	Bi-1	Gk-1	14-1	14-4	MLC-2	AF12	AF5	U.S.G.S. G2
La	078.3	045.8	14.1	059.8	06.4	01.2	08.8	01.9	257.0	111.0	094.2
Ce	133.9	130.1	47.2	147.0	04.6	02.7	92.4	10.6	339.0	177.0	167.0
Sm	016.9	014.5	13.8	--	--	00.7	00.6	00.6	017.0	010.5	007.2
Eu	000.8	002.2	00.7	001.4	00.1	00.2	00.5	00.2			001.2
Tb	003.1	002.8	01.2	002.9	00.1	00.2	00.8	00.2			000.5
Dy	017.4	021.7	12.1	012.5	00.4	01.5	03.2	00.9			002.6
Yb	016.9	012.1	08.8	008.4	00.5	01.3	01.7	00.4			000.7
Lu	001.8	001.8	--	--	--	--	--	--			000.1
Ba	021.0	033.2	588.	152.0	363.	173.	1060	610.			1800.
U	006.9	003.1	128.	042.1	32.4	05.4	12.4	32.7			001.7
Th	009.7	005.3	110.	139.6	57.6	02.7	21.0	25.3			024.0

APPENDIX C

Major Element Data

Mt-Laurier Area

sample	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	FeO	Fe_2O_3	MnO	TiO_2	P_2O_5
AF 1	69.0	14.0	0.5	0.4	3.5	4.8	7.7		--	0.05	0.05
AF3-1	73.3	13.4	0.1	.05	1.6	9.4	.66		.01	.02	0.01
AF3-3	73.0	14.5	0.9	o.1	2.5	6.4	0.3	0.6	.01	.03	--
AF3-6	74.6	13.1	1.9	0.2	3.5	2.8	0.8	1.6	.02	.06	--
I90	73.4	13.2	0.8	0.1	2.2	6.9	1.3		.02	.06	0.01
AF5-1	70.7	14.2	0.7	0.7	3.0	6.2	0.9	1.6	.03	.38	0.12
AF5-7	71.1	14.2	0.9	0.5	2.9	5.5	1.1	1.2	.02	.19	0.06
RDG	73.6	14.7	0.7	0.3	3.6	5.4	1.5		--	.14	0.03
AF 6	72.8	14.4	1.2	0.2	3.2	5.9	2.1		--	.20	0.03
AF6-1	73.4	13.5	0.9	0.2	2.9	5.4	1.6	0.2	.05	.20	0.03
AF6-5	72.3	13.4	1.0	0.3	3.1	5.5	0.9	0.7	.05	.20	0.02
AF7-2	58.9	17.8	5.8	2.8	5.0	1.5	4.8	1.4	.15	.72	0.35
AF7-3	60.2	17.1	4.6	2.4	4.8	2.0	6.0		.11	.80	0.41
AF7-8	64.6	17.3	3.8	1.4	5.3	1.6	2.3	1.8	.06	.60	0.18
AF7-11	58.2	17.5	5.1	2.7	4.8	1.9	6.4		.13	.83	0.36
AF11-1	70.9	14.1	0.8	0.4	3.1	6.0	2.6		.03	.39	0.08
AF11-5	70.3	13.5	1.2	0.4	2.8	5.7	2.1	0.2	.04	.40	0.07
AF11-9	70.3	13.5	1.2	0.4	1.1	5.6	2.8	1.4	.04	.38	0.06
AF12-1	71.2	13.4	1.2	0.3	2.8	5.7	1.4	0.5	.02	.31	0.04
AF12-7	72.8	13.5	1.0	0.2	3.0	5.7	1.0	0.8	.03	.26	0.01
ML40a	70.7	13.9	1.6	0.3	3.4	5.3	i.9	0.5	.04	.35	0.06
ML71	71.4	13.6	1.0	0.2	3.5	5.5	1.0	1.3	.04	.22	0.02
77-1	58.9	17.0	2.3	1.6	4.1	5.7	2.8	2.4	.09	1.4	0.41
77-9	59.7	16.9	2.4	1.6	4.0	6.2	1.9	3.1	.09	1.2	0.40
MLU1a	66.0	16.9	1.0	0.6	3.1	8.4	0.4	3.1	.03	.27	--
MLU1d	74.0	14.3	1.0	0.1	2.5	6.3	-	0.2	-	.02	--

Major Element Data
Bancroft Area

sample	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	FeO	Fe_2O_3	MnO	TiO_2	P_2O_5
Ched 3	75.3	11.7	o.6	0.1	3.8	4.5	1.8	0.8	.04	.24	--
Ched 7	75.8	12.2	0.4	0.1	3.8	4.6	1.5	1.0	.05	.21	--
Bi 1	74.5	12.3	0.8	0.2	4.1	4.6	1.3		.02	.03	0.01
GK1	72.9	12.7	0.1	0.1	2.0	8.4	0.6		.01	.01	0.01
GK2	73.2	13.5	0.1	-	2.3	8.9	0.5		.01	.01	0.02
CD1	74.0	12.2	0.4	0.1	2.5	7.0	0.5		.01	.09	0.01
CD4	70.5	14.5	0.8	0.3	2.4	9.1	0.9		.03	.21	0.04
					Turgeon Lake						
14-1	73.4	14.6	0.2	0.2	2.4	8.2	0.2		-	.04	0.07
14-4	73.9	12.6	0.1	0.4	2.1	7.4	0.3	0.5	.02	.20	0.03

Rb and Sr Concentration
XRF Analysis
PPM

	AF3-1	AF3-3	AF3-6	AF5-1	AF5-7	AF6-6	AF11-5	MLU1a	MLU1d	77-1
Rb	143	220	70	280	240	110	350	191	307	116
Sr	158	360	230	321	307	108	402	260	825	666

	CH3	CH7	Gk1	CD1	CD4	BI1	AF14-1	AF14-4
Rb	141	221	773	312	301	108	615	600
Sr	37	31	117	77	89	89	49	125

F Analyses
NA_2CO_3/ZnO flux fusion
PPM

	AF3-1	AF5	AF6	AF11	AF12
F	33	310	340	1200	1785

Appendix D

Sample Location Index

Universal Transverse Mercator Grid

in meters

Sample Name	Abbreviation	Zone	Easting	Northing
Lac Montagne Pegmatite	AF1	18	475500	5229500
Mitchinamecus Pegmatite 1	AF3	18	483450	5233600
Mitchinamecus Pegmatite 2	I90	18	483400	5233700
Pegmatitic Granite L. Edmond	AF5	18	483150	5232350
Mitchinamecus Granite	RDG	18	482600	5235800
Guenette Granite	AF6	18	488500	5205500
Mitchinamecus Gneiss	H	18	482750	5233900
Quartzofeldspathic Gneiss	AF7	18	484050	5231800
Guenette Granite	AF11	18	440200	5158700
Guenette Granite	AF12	18	481700	5155800
Guenette Granite	ML40	18	480700	5155000
Guenette Granite	ML71	18	483250	5154900
Guenette Granite	ML41	18	483050	5155800
Guenette Granite	ML72	18	483750	5155500
Mitchinamecus Gneissic Granite	77	18	485850	5236250
Lac Patibre	MLU	18	493600	5195350
Cheddar Granite	Ched	17	723800	4985500
Bicroft Mine	Bi	17	733750	4986600
Canadian Dyno Mine	CD	17	728850	4981400
Greyhawk Mine	Gk	18	272100	4990750
Turgeon Lake	14	20	504800	5581050
Meach Lake	MLC	18	429500	5042000