THE UNIVERSITY OF ALBERTA

ZIRCON GEOCHRONOLOGY
OF
NORTHEASTERN ALBERTA

by

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A THESIS
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ABSTRACT

Zircons from several suites of Precambrian rocks of Northeastern Alberta were studied using conventional U - Th - Pb dating techniques. It was found that the zircon dating confirmed the emplacement of the younger Colin - Andrew Lakes granites at approximately 1900 m.y. and gave some support to the proposition that their formation involved anatexis. However, the zircons from the older Charles Lake granites and the migmatite - gneiss complex have been considerably updated, with the 2500 m.y. ages for these rocks (derived from Rb - Sr and whole rock U - Pb) being partially to completely obliterated in the zircons by the high grade metamorphism accompanying the Hudsonian orogeny. The thorium dates are widely discordant, reflecting the effect of metamorphism, and the differences between the thorium and uranium data indicate migration of these elements as well as lead in the discordancy of these zircons. The Colin - Andrew Lakes zircons show higher uranium and thorium contents than do the other groups of zircons, providing an explanation for their more metamict appearance and slightly greater discordancies. The results reflect the need for applying several dating techniques to gain the greatest amount of understanding of a complex geologic region.

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CHAPTER I INTRODUCTION

A. Preamble

Over the last few decades, isotopic geochronologic studies have assumed major importance in the study of historical Precambrian geology. In an effort to understand the time relationships of geological materials and the sequence of geologic activities, geologists first looked to fossils to provide a time frame of reference. However, if the age of the earth is approximately 4500 million years, reasonable fossil correlation is only possible for about 15 per cent of geologic time. As understanding of radioactive processes and isotopic variations increased, tools were evolved which gave access to dating the remaining 85 per cent of geologic time and which in fact were instrumental in setting the generally accepted figure of 4.5 billion years for the age of the earth. Not only do these nuclear clocks extend the useful range of geochronology, but they are applicable to a wide range of geological materials including many extensive areas of unfossiliferous rocks.

To be used as a nuclear clock, a system composed of the combination of a particular radioactive species and a particular mineral should meet several criteria. Ideally, all the parent species originally present should still be accounted for either as parent nuclide or as decay daughter and the only daughter present should be that formed through radioactive decay or as a measurable initial amount. To meet this requirement there should be no gain or loss of parent or daughter from the time of formation to the present, i.e., the system should be closed. The radioactive decay rate must be of a favorable magnitude and be accurately determined. The system should be amenable to accurate chemical and isotopic analyses of both parent and daughter nuclides.

Although no parent - daughter combination exemplifies the ideal completely, there are three major pairs that approach it closely enough in various degrees to be useful to the geologist. These are the potassium - argon, the rubidium - strontium, and the uranium - thorium - lead pairs. The latter group is really a family of three parent - daughter combinations and is the one with which this study is concerned. The three which compose this family are the U^{238} - Pb^{206}, U^{235} - Pb^{207}, and Th^{232} - Pb^{208} nuclide pairs and we will be concerned with their behavior in the mineral zircon.

The fact that many minerals are not ideally closed systems during geological time increases, rather than decreases, interest in their study. Since the various parent - daughter pairs are different elements, they demonstrate differing behaviour, both from other pairs and in different rocks and minerals, and numerous factors in the geologic setting and history of the analysed minerals will have a bearing on the age interpretation made. Cogenetic minerals often show significant differences in age and it is the elucidation of the factors leading to these age differences which provides more information about the geology and history of the rock than just its age since crystallization. All the factors affecting the age interpretations derived from an isotopic analysis of a particular rock or mineral are not yet known and the ongoing study of these factors remains a major concern of geochronology. Some of the principal examples of effects on nuclear clocks being studied are the episodic and/or diffusive loss or gain of parent and/or daughter nuclide from a mineral after its formation. The presence of these various effects permits the utilization of the nuclear clocks in differing ways. For example, the age and history of one particular rock may be studied in detail, or a larger region or group of rocks may be more generally surveyed. The present study could be said to come under the latter category. In the present study an attempt is made to interpret the behaviour of a large suite of zircons from a fairly complex, closely studied area (the Precambrian exposure in Northeastern Alberta), in the light of presently available geochronologic and geologic information.

B. U - Th - Pb Systematics in Zircons

A form of the law of radioactive [illegible]cay, $N_D = N_P(e^{\lambda t}-1)$, describes four ways of lead isotopic variation in the case of a U and Th bearing phase:

$$Pb^{206} = U^{238}(e^{\lambda 238t}-1)$$

$$Pb^{207} = U^{235}(e^{\lambda 235t}-1)$$

$$Pb^{208} = Th^{232}(e^{\lambda 232t}-1)$$

and $$\frac{Pb^{207}}{Pb^{206}} = \frac{U^{238}(e^{\lambda 235t}-1)}{137.9U^{238}(e^{\lambda 238t}-1)}$$

where: $N_D(Pb^{206}$ etc.) = number of atoms of daughter nuclide

$N_P(U^{238}$ etc.) = number of atoms of parent nuclide

λ(238 etc.) = decay constant for a particular parent nuclide

t = time since formation of the mineral

If a U - Th - Pb bearing phase has remained a closed system throughout its existence then one semi-independent and three independent identical values for the time it has existed may be obtained after solution of the above equations for "t".

Uranium - thorium minerals usually depart from this ideal closed system behaviour however, giving discordant ages. The pattern of age discordancy most often found in zircons is $t_{206} < t_{207} < t_{207/206}$. This pattern is interpreted as being due to some mechanism of lead loss (Baadsgaard, 1965). The value of t_{208} in zircons may lie anywhere in relation to the above pattern, but occurs most commonly as $t_{208} \leq t_{206}$.

The problem of the lead - loss mechanism has drawn much attention in geochronological work. Wetherill (1956) proposed an episodic loss of lead. Using a "concordia" or "$r_{238} - r_{235}$" diagram (a plot of Pb^{206}/U^{238} versus Pb^{207}/U^{235} on which the locus of points for which $t_{206} = t_{207}$ is a curve known as the concordia) he showed that the measured ratios of episodically altered cogenetic zircons lay on a chord of the concordia. He recognized the upper intercept of chord and concordia to be the "true" age of the system and the lower intercept to mark the age of an episode of lead loss. This model fits some situations in which an event corresponding to the time of the proposed lead - loss episode can be determined by other means such as K - Ar dating.

Nicolaysen (1957) and Tilton (1960) show that the continuous diffusion of lead will result in a similar pattern. They worked with a ratio of diffusion constant to radius of diffusion (D/a^2) that is constant over time ($D(t) = D_0$) and showed that the line joining points of different D/a^2 for a particular age on a concordia diagram approximates linearity over most of its length but curves more sharply down to the origin for small values of r_{238} and r_{235}, rather than intercepting the concordia and requiring a later episode. In this way Tilton (1960) was able to show that a world - wide event at 500 million years was not required to explain lead loss from widely distributed Archean zircons (as it is for an episodic model).

Wasserburg (1963), in a further mathematical treatment of diffusion, assumed the diffusion coefficient to be a time dependent function of the integrated radiation damage done to a crystal by uranium and thorium decay $(D(t) = D_1t)$ rather than a constant as in Tilton's treatment. The diffusion trajectory traced on the $r_{238} - r_{235}$ diagram in Wasserburg's model also is linear over the majority of its length and is not very different from that developed from Tilton's model, giving a slightly lower intercept (younger age) when the linear part is extrapolated to meet the concordia.

Wetherill (1963) looked at cases where diffusion loss of both parent and daughter occurred, based on Tilton's model. He showed that uranium loss will also lead to a straight line pattern on a concordia diagram, but one with a different slope than that for lead loss. Thus the U - Pb ages may be high or low depending on whether uranium or lead is lost or will remain concordant if both parent and daughter are lost at compensating rates. Combining a pulse of metamorphic lead loss with uranium and lead diffusion may so complicate matters that no regular pattern can be determined.

Steiger and Wasserburg (1966) and Allègre (1967), using $r_{232} - r_{235}$ diagrams (concordia diagrams with Pb^{208}/Th^{232} plotted against Pb^{207}/U^{235}), discussed discordancies in thorium dates. These papers point out that while thorium generally is present in conjunction with uranium and produces a lead isotope as the end product of its radioactive decay, it is a distinct chemical species and the differences in its behaviour can produce differing geochronologic information. Steiger and Wasserburg point out that data on a $r_{232} - r_{235}$ diagram are not restricted to the region representing nonfractionating daughter loss in a single phase system and in fact indicate that zircon should be looked at as a multiphase system. The importance of such factors as a varying Th/U ratio and possible displacements of Th from U within the crystal is noted. Allègre points out the direction of movement on a $r_{232} - r_{235}$ diagram of a point representing a U - Th - Pb phase which would be produced by gain or loss of uranium, thorium, and lead and various combinations of the three. Both papers emphasize the need for more study involving thorium because of the added information it should supply to the interpretation of geologic ages and histories.

It has been established that continuous diffusion processes have operated to produce discordant ages. In other cases an appropriately timed event (generally thermal in nature) would seem to be responsible. However, in a great many cases it is difficult to distinguish between episodic lead loss and one of the diffusion models as a basis for the observed discordancy.

C. Geology and Geochronology of N.E. Alberta Shield Rocks

The Charles - Andrew - Colin Lakes area is part of the Precambrian Shield exposed in Alberta. The area lies in the northeastern corner of the Province south and west of the junction of the Alberta, Saskatchewan, and Northwest Territories borders, north of Lake Athabasca (fig. 1).

As mentioned by John D. Godfrey in his reports (1961, 1963, 1963, 1964, 1966), only sporadic geologic work had been carried out in the area until the start of his detailed (2 inches to the mile) mapping project in 1957. This work, done for the Research Council of Alberta, involved pace and compass traverses spaced at one-quarter to one-third mile intervals. During this work, samples for petrologic and later geochronologic work were collected.

The exposed Precambrian igneous and metamorphic rocks of Alberta lie within the Churchill Province of the Canadian Shield. The study area comprises a metamorphosed fold belt between two cratonic blocks and therefore presents a fairly complex situation for geological and geochronological study (fig. 2).

The basement of the area consists of a migmatitic - gneissic complex formed by at least two cycles of sedimentation, metamorphism, and intrusion. This is overlain sporadically by metasedimentary rocks which appear to have been laid down in later stages of the last of the two orogenic cycles identifiable in the area (Baadsgaard and Godfrey, 1972). The basement is intruded by two groups of granitic - granodioritic rocks. The older of these groups, which consists mainly of foliated hornblende granites in the Allan fault zone of the Charles Lake area, is cut by pegma-

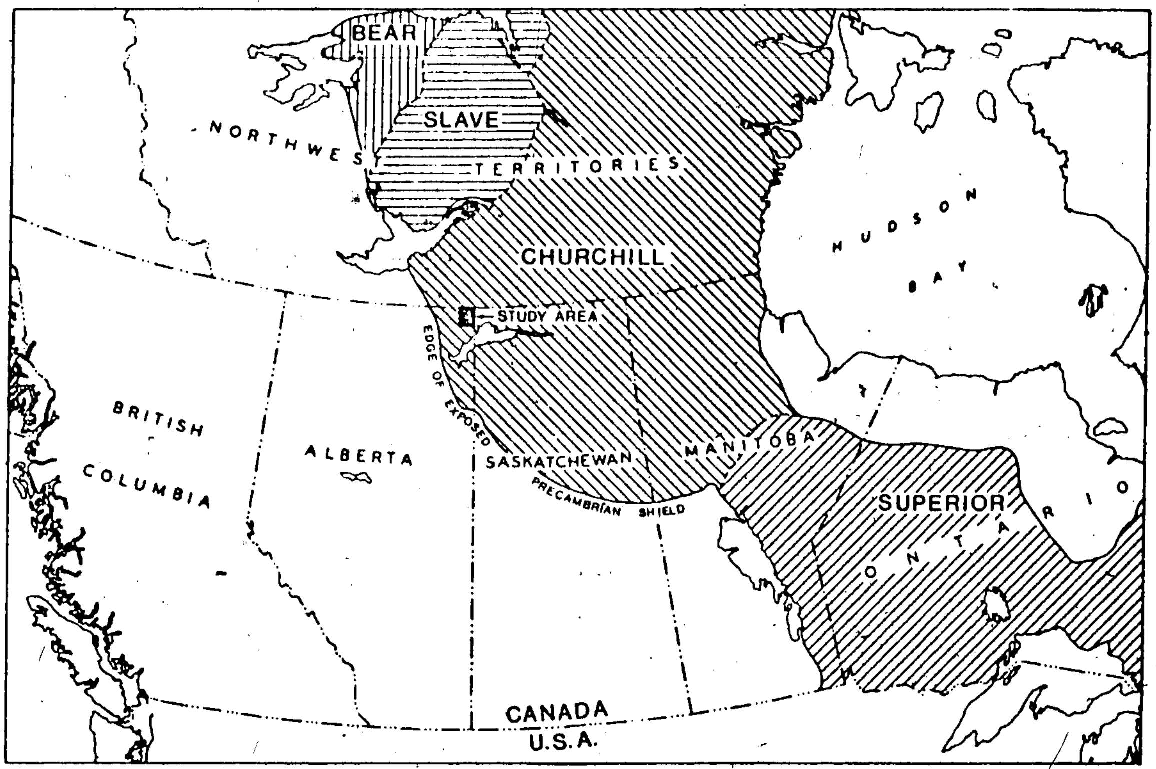
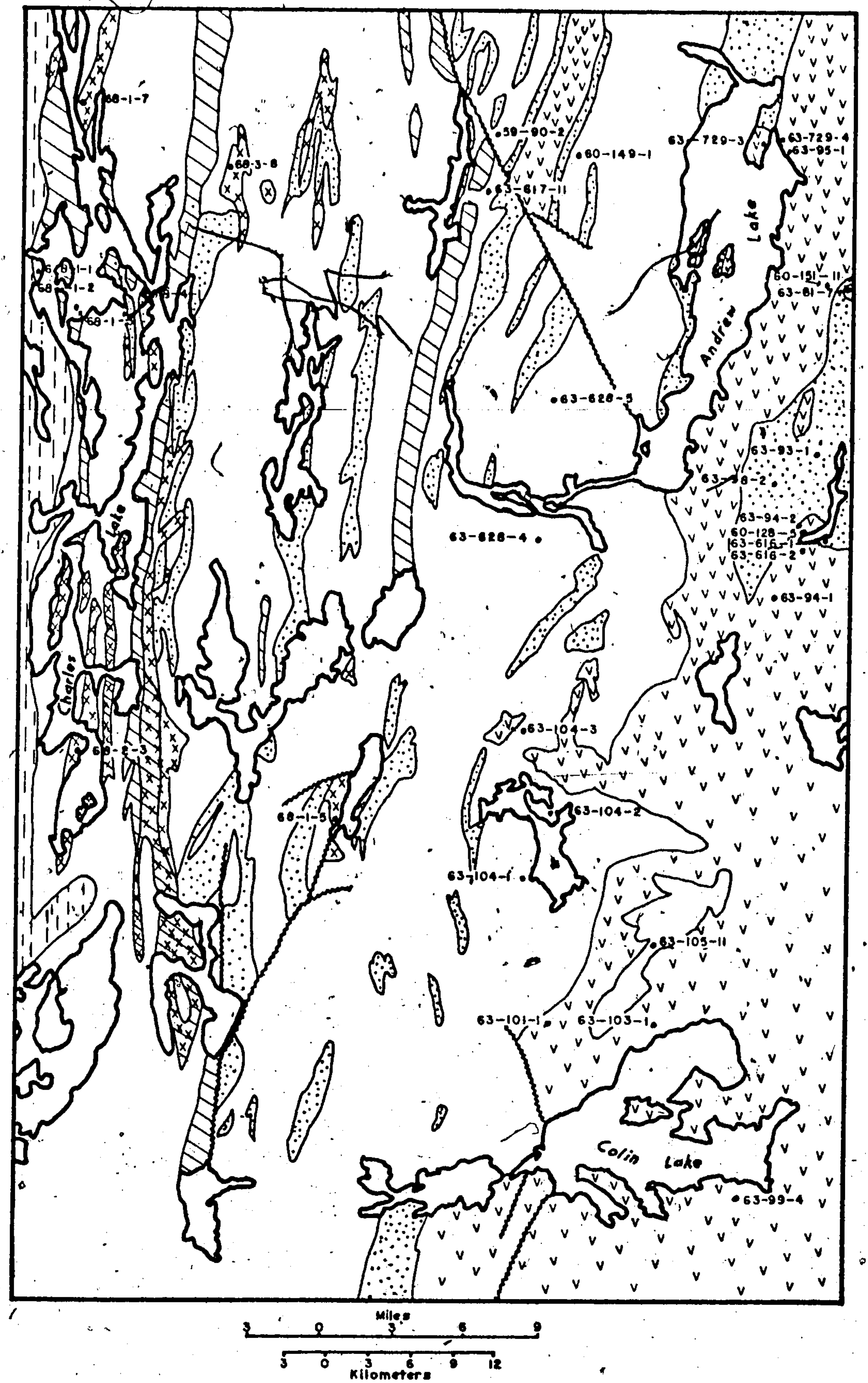


Fig. 1. Location map of the study area in the Canadian Precambrian Shield (After Baadsgaard and Godfrey, 1972).

LEGEND

Migmatitic Gneiss	☐
Other Metasedimentary Rock (Quartzite, Schist, Amphibolite)	▒
Colin - Andrew Lakes Granites	∨
Charles Lake Granites	×
Arch Lake and Raisin Granites	▥
Mylonitic Bands	▨
Major Faults	〰
Sample Locations	•60-149-1

FIGURE 2. Regional geology of the Charles - Colin - Andrew Lakes area of the Precambrian Shield, Northeastern Alberta. (after Baadsgaard and Godfrey, 1972)


68-1-7
68-3-8
59-90-2
60-149-1
63-729-3
63-729-4
63-95-1
63-617-11
68-1-1
68-1-2
68-3-4
68-1-3
Andrew
Lake
60-151-11
63-81-7
63-628-5
63-93-1
63-98-2
63-94-2
60-128-5
63-616-1
63-616-2
63-94-1
63-628-4
Charles
Lake
68-2-3
63-104-3
63-104-2
68-1-5
63-104-1
63-105-11
63-101-1
63-103-1
Colin
Lake
63-99-4
Miles
3 0 3 6 9
3 0 3 6 9 12
Kilometers

tites giving Rb - Sr dates of 2524 ± 27 m.y. (Baadsgaard and Godfrey, 1972) and represents material emplaced during the Kenoran orogeny. The other granitic material, consisting mainly of porphyroblastic biotite granites (such as the Colin Lake granite - granodiorite complex) as well as massive to foliated biotite and leucocratic granites, appears to have been remobilized during the Hudsonian orogeny with the migmatitic - gneissic complex possibly providing the parent material. Amphibolites occur in fairly small bodies throughout the map area but appear to concentrate in the granite gneisses and metasedimentary regions.

The characteristic northerly and vertical orientation of structural features of the area such as foliation; gneissosity; and elongate outline of metasedimentary, amphibolite, and granitic bodies all point towards a deep seated plastic deformation with maximum stress on an east - west axis. The cataclastic deformation producing mylonite most likely accompanied this plastic deformation in its later stages. The mylonite bands show thermal recrystallization and rewelding, probably due to later thermal activity. Younger breccias within the mylonite zones and northeast and northwest transverse faults which offset and truncate contacts of all groups including the mylonites, indicate later fault movement at a higher crustal level. Glacial scouring during the recent ice age has left relatively fresh exposed outcrops which greatly facilitates geologic study in the area.

Earlier geochronological work has involved mineral K - Ar, whole rock and mineral Rb - Sr, and whole rock and mineral U - Pb dating. The K - Ar mica dates give a very sharp distribution around 1790 m.y. which Baadsgaard and Godfrey (1972) attribute to a late orogenic thermal pulse with rapid uplift rather than a slow uplift and cooling which would produce a tailing of dates down from the Hudsonian peak at 1900 m.y. The hornblende K - Ar dates show a mean of 1880 m.y. but the number of samples is too small to determine whether this is statistically different from the mica dates.

The Rb - Sr determinations can be arranged into three groups. In the Andrew - Colin Lakes area an excellent fit to an isochron of t = 1893 ± 6 m.y. is obtained for whole rock determinations on the granites and intrusives. The data points representing the gneisses and metasediments scatter above this line. The initial ratio of Sr^{87}/Sr^{86} of 0.7083 is too high for a granite derived from a source region of basalts but fits quite well a model proposed for anatectic origin (Baadsgaard and Godfrey, 1972). Apatite - whole rock isochrons for both granites and gneisses give an average date of 1760 ± 60 m.y., comparing well with the K - Ar date of 1790 ± 40 m.y. and indicating thermal metamorphic conditions strong enough to affect strontium in apatite occurred about 100 m.y. after emplacement of the granites. In the Charles Lake district whole rock determinations were obtained on pegmatites cutting the granitic and metasedimentary rocks. The pegmatites in the granites yield a firm isochron with t = 2524 ± 27 m.y. The pegmatites in metasedimentary rocks scatter above this line in a manner similar to the scatter of the easterly gneisses above the younger granite line. This date (2524 m.y.) is the first evidence obtained for rocks of Archean age in N.E. Alberta.

Whole rock U - Th - Pb determinations were carried out on six of the younger intrusives of the Andrew - Colin Lakes area. The points on a Pb^{207}/Pb^{204} versus U^{235}/Pb^{204} diagram give a fairly good fit to a 1890 m.y. isochron. The points on a Pb^{206}/Pb^{204} versus U^{238}/Pb^{204} diagram give a poorer fit to a 1960 m.y. isochron. The points on a Th - Pb isochron plot scatter widely between a maximum isochron of 1900 m.y. and a minimum of 960 m.y. Thus a close agreement in dates (1900 m.y.) with the Rb - Sr data on the same samples is obtained but with a greater scatter in the data points for the U - Pb data. All the above geochronologic data is derived from Baadsgaard and Godfrey (1966 and 1972).

Lee (1972) looked at the whole rock behaviour of five of the intrusives of the Charles Lake area. He determined a date of 2500 m.y. for these materials, which gives fairly close agreement with the above mentioned Rb - Sr date of 2524 m.y. for pegmatites cutting these rocks as well as others in the area.

Both Lee and Baadsgaard did some work on zircons in the rocks utilized for whole rock U - Pb studies. This data will be re-examined in conjunction with the more extensive zircon work done for the present study.

CHAPTER II SAMPLES

A. Coverage of Rock Types

The samples represented in this study might be termed "second generation" samples because they were collected on the basis of previous mapping and examination of hand specimens collected during that mapping. The size of rock samples required for multiple mineral dating (50 pounds or more) precludes their collection during the original pace and compass traverse mapping. All the recognized individual rock types were covered in the sample collection. The basement gneisses were sampled a number of times at various points so as to provide a somewhat representative coverage of this rock type over the whole study area. Other rock types were sampled at points at which they appeared to be most "typical" of the rock. As completely as possible, "fresh" unweathered samples were collected. Sample locations are given on the map in fig. 2 and the rock from which each sample was taken is listed with the zircon descriptions in the Appendix.

B. Separation and Purification of Zircons

Rock samples from which any weathered surfaces had been removed were broken in a jaw crusher and the resultant crush put through a rotary plate mill and reduced to -100 mesh. The heavy mineral concentrates were separated from this rock powder on a Wilfley table. The zircon was separated from this concentrate using standard techniques of magnetic separation; tetrabromoethane, methylene iodide, and hot clerici float - sink separation; and nitric acid cleaning to remove sulphides. Where possible, zircon populations were split on the basis of magnetic or gravity variations. Final separates were treated with hot 1:1 nitric acid for one hour and then washed with lead free distilled water immediately before analysis. A small portion of each separate was reserved for microscopic examination.

C. Description

When examining the appearance of the bulk zircon separates, some variation is noticeable. The zircon separates from the Charles Lake granites show a fairly uniform hyacinth color. In contrast, the zircon separates from the Colin - Andrew Lakes granites show a range of color in the tan to beige tones. The metasedimentary zircons show a wide variety, ranging in color of the bulk separate from quite a dark tan to beige and even a greyish color. A very few approach a hyacinth color but do not show the same clarity and uniformity of color as do the older granites.

Under microscopic examination, the zircons from all the study area tend to be poorly shaped, yellowish to brownish in color, zoned and have inclusions but with a great deal of variety away from this generalization. The Charles

Lake granite zircons appear as a group to be larger in grain size than the other zircons. Although a few separates in the other two groups are as coarse or coarser than representatives of the Charles Lake group, the Charles Lake granitic zircons are more uniformly of larger grain size and include no separates of very small zircons as do the other groups. In the Charles Lake group the zircons within a separate also seem to be more uniformly sized. In the other groups the same separate often has zircons ranging from approximately 100 mesh to -250 mesh. On the whole, both the groups of granitic zircons show better crystal form than do those of the metasedimentary group. The Charles Lake group especially would be termed euhedral to subhedral (although there are still some rounded zircons included in these separates) while the migmatite - gneiss zircons are generally much more rounded.

The Charles Lake granitic zircons are in general much clearer and more transparent than those of the other groups. The faint hyacinth color of the bulk separates is reduced in intensity upon magnification and many of these zircons appear colorless when examined microscopically. In particular the Colin - Andrew Lakes zircons are more clouded and darker than those of the other two groups. The metasedimentary group are intermediate in appearance with zircons ranging from near transparent to very dark. Dark spots of inclusions occur in zircons within every group but lighter acicular inclusions (most probably growth cavities) appear to be most common in the Charles Lake zircons, perhaps only because they show up better in these more transparent zircons. Although zoning is noticeable as surfaces of optical discontinuity in the zircons of all three groups, there appears to be a lower incidence of it in the Charles Lake zircons and where it does occur in this group, it is more often regular and follows the euhedral crystal outline than in the other groups. A more complete description of the zircon separates is given in the Appendix.

A. Methods

The zircon samples (generally between 0.1 and 0.5 gms.) were fused with purified sodium tetraborate (Merck 'Suprapur' anhydrous sodium tetraborate was found to be of adequate purity) in a platinum dish at 950°C. to 1000°C. until the zircons were seen to be dissolved in the borax. Several hours of heating were generally required. The fusions were done using an amount of borax that was approximately six times the weight of zircon. The solidified melts were dissolved in redistilled dilute HCl with constant rapid stirring (in order to keep silica in solution). The solution was transferred to volumetric flasks for dilution and storage.

Lead was extracted from an aliquot of the sample solution using a double extraction with 0.01% diphenylthiocarbazone (dithizone), first in the presence of citrate and then in the presence of cyanide. The lead was finally recovered by precipitation as lead sulphide which was loaded on a single tantalum filament for running on the mass spectrometer. Two lead isotopic analyses were done on each sample -- one "unspiked" (for determining isotopic composition) and the other "spiked" by adding Pb^{208} as isotopic dilutant prior to the first dithizone extraction (for determining lead concentration).

The lead isotopic composition was determined on a 12 inch radius of curvature, 90° sector, single focussing, solid source mass spectrometer. The instrument is equipped with a Keithley vibrating reed amplifier, digital voltmeter with printed tape output, and facilities for "peak switching" between pre-set magnet current positions. The usual operating conditions for lead was 4.5 KV accelerating voltage and a 10^{10} ohm resistor on the amplifier. Usually lead emission began at a filament current of about 1.8 amps at which point the greater portion of the potassium in the load had been burned off. Ratios of Pb^{207}/Pb^{206} and Pb^{208}/Pb^{206} were measured from the digital output obtained by alternately switching between the pre-set magnet current positions for masses 206, 207, and 208. The ratio Pb^{206}/Pb^{204} was measured from chart output obtained by scanning the magnet current across the mass positions. On some samples from which only a small amount of lead was produced, the emission was not high enough for digital output to be effective so all ratios were measured from chart scans. The 206, 207, and 208 masses were resolved and little tail correction was found to be necessary. Measurement precision of the Pb^{207}/Pb^{206} and Pb^{208}/Pb^{206} ratios was generally ±0.1% (one standard deviation) and the Pb^{206}/Pb^{204} ratio about ±2% (quite adequate since only small common lead corrections were generally necessary).

Uranium and thorium were determined by isotope dilution. An aliquot of the sample solution was double - spiked with U^{235} and Th^{230} in proportion to produce U^{238}/U^{235} and

Th^{232}/Th^{230} ratios approximating unity. Uranium and thorium were precipitated from this aliquot with the R_2O_3 elements using ammonium hydroxide. The uranium and thorium were then separated out using an anion exchange method. The precipitate was dissolved in a minimum amount of redistilled 6M HNO_3 and added to 14 X 1.2 cm. column of Dowex 1-X8 anion exchange resin converted to the nitrate form. Uranium was then eluted with 6M HNO_3 and the thorium stripped off with 0.5M HNO_3. These nitrates were loaded on a single Ta filament for isotopic analysis in the mass spectrometer. Some of the early analyses had the uranium and thorium nitrates combined on the same filament with H_3BO_3 as activator. Generally, however, the uranium and thorium isotopic analyses were run separately using H_3PO_4 as activator for uranium and $HClO_4$ as activator for thorium.

Isotopic composition of uranium and thorium were measured on a 6 inch radius of curvature, 60° sector, single focussing solid source mass spectrometer equipped with a Cary vibrating reed amplifier with a 10^{11} ohm resistor. This instrument also is equipped with digital tape output and "peak switching" facilities. Emission of UO_2^+ appeared at about 2.7 amps filament current and 1.7 KV accelerating voltage. Emission of ThO_2^+ appeared at about 3.0 amps filament current and 2.0 KV accelerating voltage. In either case isotope ratios were measured from the digital output. A measurement precision for uranium of about 0.5% to 1.0% and for thorium of 1% to 2% was generally obtained. A more complete discussion of methods used in the University of Alberta Department of Geology geochronology laboratory may be found in O'Nions (1969).

Two sets of spikes were used in the course of this work. All were prepared and calibrated by Dr. H. Baadsgaard. Compositions of these spikes are presented in Table 1. During the course of this work the author ran two blank determinations on the lead analyses. The results of these along with another done by Dr. H. Baadsgaard are presented in Table 1. Uranium and thorium blanks used are those determined by O'Nions and which are 0.005 μg. for uranium and no detectable blank for thorium.

TABLE 1. "Spike" lead and blank compositions

Spike # Lead	Pb^{208}, μg.	Pb^{207}, μg.	Pb^{206}, μg.
#2	20.152	0.0101	0.0456
#3	18.284	0.009	0.040

U + Th	U^{235}, μg.	U^{238}, μg.	Th^{230}, μg.	Th^{232}, μg.
#2	20.4252	0.0266	12.217	1.066
#3	16.252	0.021	8.937	0.7796

TABLE 1. (cont'd)

Blank determined by	Total Pb Blank, µg.	Lead Ratios 204:206:207:208
H. Baadsgaard	0.3896	1:17.52:14.81:37.43
L. W. Day	0.3200	1:14.83:12.53:30.62
L. W. Day	0.4095	1:17.77:15.02:37.27

B. Results

Analytical results and the ages and concordia plot ratios calculated from them are presented in Tables 2 and 3. Ages and ratios are calculated with the aid of an APL computer program written by Dr. H. Baadsgaard. This program selects and corrects for contaminant lead based on the 207/206 ratios. This program was revised by the present author to incorporate the recently redetermined decay constants $\lambda_U 238 = 1.5513 \times 10^{-10}$ yr.$^{-1}$ and $\lambda_U 235 = 9.8485 \times 10^{-10}$ yr.$^{-1}$ from Jaffey et al (1971) and $\lambda_{Th} 232 = 0.4948 \times 10^{-10}$ yr.$^{-1}$ from Tatsumoto et al (1973). Errors assigned to the U - Pb ratios are about ±1.5% based on the above mentioned measurement precisions and this is the size of the error boxes used on the concordia diagrams. Errors on the Th - Pb ratios would be slightly larger and more variable than this. Error boxes are not presented on the thorium concordia diagram.

TABLE 2. U - Th - Pb isotopic analytical data

Sample No.	U^{238}, ppm	U^{235}, ppm	Th^{232}, ppm	Pb^{206}, ppm	Pb^{207}, ppm	Pb^{208}, ppm	Measured atomic ratios, Pb 206/204	207/206	208/206
59-90-2[1,2]	554.5	3.97	256	159.1	21.42	22.91	605 ±16	0.1550 ±.0005	0.1959 ±.0014
60-128-5[2]	724.2	5.19	642	167.1	18.82	45.56	1380 ±0.4	0.1217 ±.0003	0.2927 ±.0003
60-149-1[2]	831.5	5.96	352	191.7	26.04	24.01	335 ±5	0.1730 ±.0005	0.2209 ±.0007
60-151-11[2]	1225	8.78	347	238.3	28.30	21.53	406 ±6	0.1520 ±.0005	0.1732 ±.0006
60-729-3[2]	1450	10.38	231	299.3	33.38	16.04	646 ±11	0.1324 ±.0004	0.1065 ±.0033
60-729-4[2]	1607	11.51		289.3	30.61		816 ±5	0.1223 ±.0006	0.1444 ±.0008
63-81-7	982.5	7.09		233.7	29.60	31.80	2[illegible]8 ±2	0.18134 ±.00014	0.27087 ±.00040
63-93-1	993.7	7.12	348.4	244.7	30.86	32.64	551 ±2	0.15040 ±.00013	0.19227 ±.00017
63-94-1	1583	11.33	533.0	340.6	37.85	69.04	280 ±1	0.16050 ±.00011	0.31639 ±.00023
63-94-2	733.5	5.25	274.4	188.1	22.46	24.76	1063 ±4	0.1316 ±.0008	0.1621 ±.0010
63-95-1	1611	11.54	587.2	306.9	33.01	37.55	1080 ±6	0.1200 ±.0001	0.15354 ±.00007
63-98-2	1011	7.24	329.6	224.6	25.45	25.27	567 ±3	0.13270 ±.00008	0.17130 ±.00007
63-99-4	1574	11.27	569.8	261.9	27.72	24.20	1387 ±13	0.11540 ±.00008	0.11630 ±.00007

TABLE 2. (continued)

Sample No.	U^{238}, ppm	U^{235}, ppm	Th^{232}, ppm	Pb^{206}, ppm	Pb^{207}, ppm	Pb^{208}, ppm	Measured atomic ratios, Pb 206/204	207/206	208/206
63-101-1	793.5	5.68	441.3	193.8	21.30	21.54	1045 ±15	0.1227 ±.0001	0.1426 ±.0001
63-103-1	1289	9.23	878.7	261.0	29.12	31.32	938 ±9	0.12470 ±.00006	0.15486 ±.00015
63-104-1	178.6	1.28	107.7	61.44	9.14	11.50	1179 ±12	0.15639 ±.00010	0.21902 ±.00004
63-104-2	1328	9.51	311.3	306.5	34.48	28.45	726 ±5	0.13112 ±.00010	0.13898 ±.00013
63-104-3	763.9	5.47		182.8	24.84	22.28	4250 ±87	0.13834 ±.00003	0.12873 ±.00005
63-105-11	500.0	4.22	186.5	190.1	26.86	16.47	2640 ±36	0.1449 ±.0001	0.10017 ±.00006
63-616-1,A	1212	8.68	1041	247.8	26.21	71.20	376 ±3	0.14270 ±.00008	0.36772 ±.00018
63-616-1,B	868.5	6.22	735.8	232.4	26.36	64.16	532 ±4	0.13904 ±.00011	0.33227 ±.00015
63-616-2,A	1942	13.91	936.2	281.7	31.75	35.16	493 ±2	0.14033 ±.00010	0.19195 ±.00009
63-616-2,B	2869	20.55	2628	183.2	18.72	28.53	122 ±0.7	0.21761 ±.00015	0.42774 ±.00028
63-617-11	895.6	6.41		280.8	32.32	28.31	644 ±14	0.1361 ±.0001	0.15250 ±.00015
63-628-4,A	483.9	3.46		149.2	21.42	14.99	1050 ±50	0.1554 ±.0003	0.1315 ±.0007
63-628-4,B	1164	8.33		302.7	39.11	25.54	638 ±4	0.14988 ±.00009	0.13654 ±.00008

TABLE 2. (continued)

Sample No.	U^{238}, ppm	U^{235}, ppm	Th^{232}, ppm	Pb^{206}, ppm	Pb^{207}, ppm	Pb^{208}, ppm	Measured atomic ratios, Pb 206/204	207/206	208/206
63-628-5,A+B	1167	8.36	1790	247.1	27.80	68.55	327.7 ±0.5	0.15440 ±.00009	0.37075 ±.00010
63-628-5,C+D	946.3	6.78	239.7	222.5	26.91	28.54	450 ±4	0.15078 ±.00017	0.20261 ±.00004
63-628-5,F	432.6	3.10	182.2	132.0	17.04	17.48	843 ±36	0.14450 ±.00019	0.17060 ±.00039
63-628-5,G	314.3	2.25		102.0	14.17	12.79	1908 ±40	0.14495 ±.00006	0.14492 ±.00007
68-1-1,B	1223	8.76	511.9	288.6	39.68	40.54	507 ±3	0.16336 ±.00013	0.20388 ±.00015
68-1-3	636.3	4.56	210.9	177.4	22.53	20.78	754 ±3	0.16040 ±.00008	0.14440 ±.00009
68-1-5[3]	421.1		220.6	120.0			1250 ±50	0.1343 ±.0001	0.1679 ±.0003
68-1-7,A[3]	230.3		114.8	72.44			805 ±7	0.1445 ±.0001	0.1933 ±.0004
68-1-7,B	485.8	3.48	238.0	136.7	16.68	20.73	847 ±16	0.1377 ±.0007	0.1891 ±.0007
68-2-3[3]	697.4		221.1	162.8			572 ±8	0.1483 ±.0001	0.1428 ±.0001
68-3-8,A[3]	373.9		191.0	98.76			2143 ±20	0.12101 ±.00006	0.1766 ±.0002
68-3-8,B	1963	14.06		137.0	15.39	20.83	2055 ±8	0.11840 ±.00014	0.16700 ±.00019
68-3-8,C	379.9	2.72	216.7	99.51	11.21	16.94	1095 ±19	0.12474 ±.00051	0.19875 ±.00115
68-4-1[3]	1567		512.1	315.0			645 ±18	0.1292 ±.0003	0.1584 ±.0002

[1] Field designation of these samples was of the form JG-59-90-2 but since all samples in this study come under the JG group, this suffix has been dropped.

[2] Analyses by H. Baadsgaard.

[3] Analyses by K.S. Lee.

TABLE 5. Calculated dates and ratios

Sample No.	DATE[1], m.y.				ATOMIC RATIOS		
	206/238	207/235	207/206	208/232	206/238	207/235	208/232
59-90-2	1845	1995	2150	1890	0.331	6.13	0.0981
60-128-5	1525	1655	1830	1500	0.2666	4.106	0.0770
60-149-1	1530	1800	2170	1520	0.2671	4.900	0.0782
60-151-11	1310	1560	1930	1350	0.2247	3.660	0.0692
60-729-3	1375	1560	1820	1500	0.2379	3.643	0.0770
60-729-4	1220	1410	1720		0.2077	3.017	
63-81-7	1560	1780	2050		0.2747	4.767	
63-93-1	1614	1806	2040	2009	0.2844	4.924	0.1045
63-94-1	1432	1591	1810	2727	0.2487	3.792	0.1445
63-94-2	1673	1794	1940	1938	0.2963	4.854	0.1006
63-95-1	1282	1469	1750	1392	0.2201	3.249	0.0713
63-98-2	1472	1632	1840	1658	0.2566	3.990	0.0855
63-99-4	1134	1353	1720	936	0.1923	2.792	0.0474
63-101-1	1602	1685	1790	1071	0.2821	4.255	0.0544
63-103-1	1355	1546	1820	788	0.2340	3.582	0.0398
63-104-1	2158	2240	2320	2275	0.3975	8.116	0.1191
63-104-2	1524	1658	1830	1962	0.2667	4.117	0.1020
63-104-3	1573	1845	2170		0.2764	5.155	
63-105-11	2040	2139	2230	1898	0.3723	7.217	0.0985
63-616-1,A	1367	1511	1720	1486	0.2362	3.429	0.0763
63-616-1,B	1736	1787	1850	1876	0.3091	4.811	0.0973
63-616-2,A	999	1298	1830	829	0.1676	2.591	0.0419

TABLE 3. (continued)

Sample No.	DATE[1], m.y. 206/238	207/235	207/206	208/232	ATOMIC RATIOS 206/238	207/235	208/232
63-616-2,B	459	721	[illegible]50	243	0.0738	1.034	0.0121
63-617-11	1993	1935	1870		0.3623	5.721	
63-628-4,A	1965	2114	2260		0.3563	7.018	
63-628-4,B	1694	1873	2080		0.3006	5.328	
63-628-5,A B	1411	1588	1830	845	0.2446	3.776	0.0427
63-628-5,C D	1549	1733	1960	2520	0.2717	4.508	0.1328
63-628-5,F	1947	2011	2080	2054	0.3526	6.245	0.1070
63-628-5,G	2052	2130	2210		0.3748	7.148	
68-1-1,B	1554	1843	2190	1711	0.2726	5.143	0.0883
68-1-3	1800	1918	2050	2107	0.3222	5.612	0.1099
68-1-5	1835	1940	2000	1665	0.3292	5.578	0.8584
68-1-7,A	2000	2040	2080	2080	0.3634	6.447	0.1085
68-1-7,B	1814	1892	1980	1873	0.3251	5.445	0.0971
68-2-3	1540	1770	2050	1330	0.2697	4.694	0.0678
68-3-8,A	1720	1790	1875	1820	0.3052	4.820	0.0940
68-3-8,B	500	820	1830		0.0806	1.243	
68-3-8,C	1704	1763	1830	1689	0.3026	4.676	0.0872
68-4-1	1350	1515	1760	1405	0.2322	3.444	0.0720

[1] Constants used in calculating these dates are given in the text.

CHAPTER IV INTERPRETATION

A. U - Pb Concordia Diagrams

The zircon results are grouped in r_{238} - r_{235} diagrams (figs. 3 to 5) on the basis of the previous work (mainly Rb - Sr) in the area. The grouping used is that evolved from the geologic and geochronologic work by Baadsgaard and Godfrey (1972), and the terminology used in referring to these groups generally follows that used by them. Thus the groups are the Charles Lake or older granites from the western part of the region, the Colin - Andrew Lakes or younger granites from the eastern part of the region, and the migmatite - gneisses and other metasedimentary rocks present throughout the region. On the concordia diagrams the 1900 m.y. and 2500 m.y. diffusion curves (approximate ages of the two granitic groups from the previous work) are given for reference.

It can be noted from the r_{238} - r_{235} diagrams that the concordia patterns for these groups are not as definitive as would have been expected if the zircon data closely reflected the Rb - Sr data. This loss of definition appears as a narrowing of the separation between the younger and older groups. The data for the Charles Lake granite group (fig. 4) and the migmatite - gneiss group (fig. 5) have moved considerably from the 2500 m.y. diffusion line while that for the Colin - Andrew Lakes granitic group (fig. 3) has stayed at the 1900 m.y. diffusion line. The data points

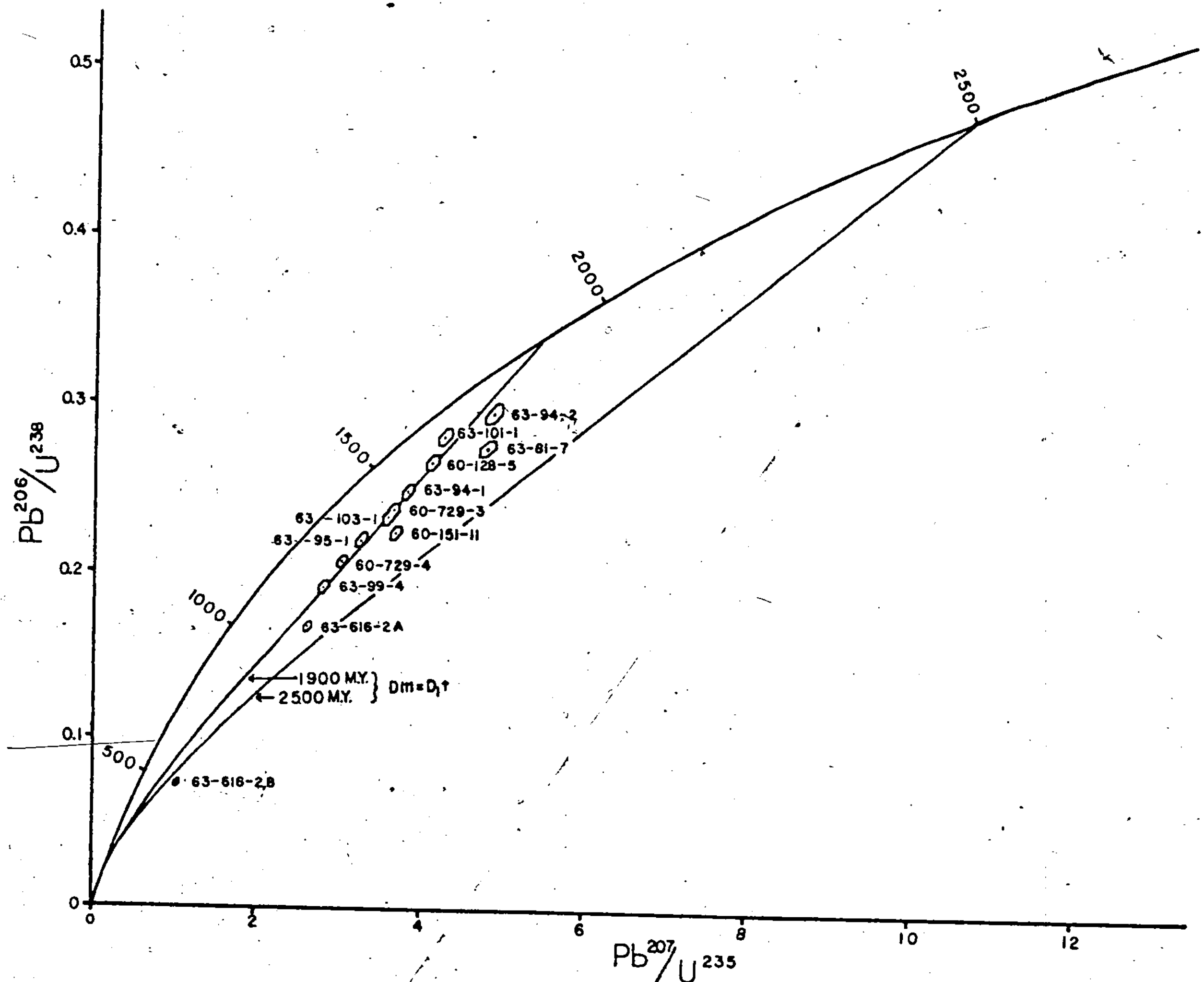


Fig. 3. Concordia diagram (r_{238} vs r_{235}) for zircons from the Colin - Andrew Lakes "Younger" Granites. Continuous Pb-diffusion lines of the type $D(t) = D_1t$ (D_1 a constant) (Wasserburg, 1963) are shown as references.

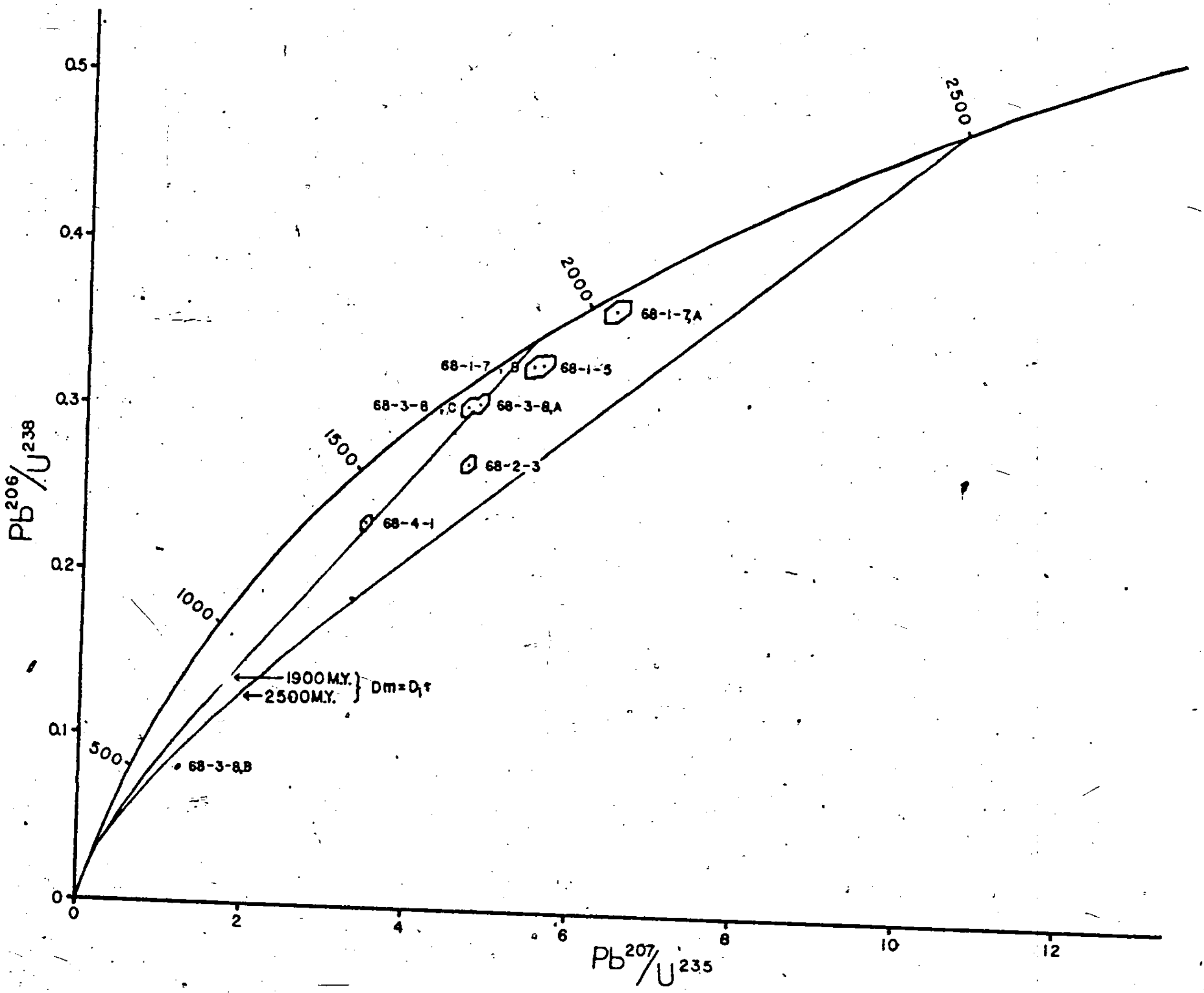


Fig. 4. Concordia diagram (r_{238} vs r_{235}) for zircons from the Charles Lake "Older" Granites. Continuous Pb-diffusion lines of the type $D(t) = D_1 t$ (D_1 a constant) (Wasserburg, 1963) are shown as references.

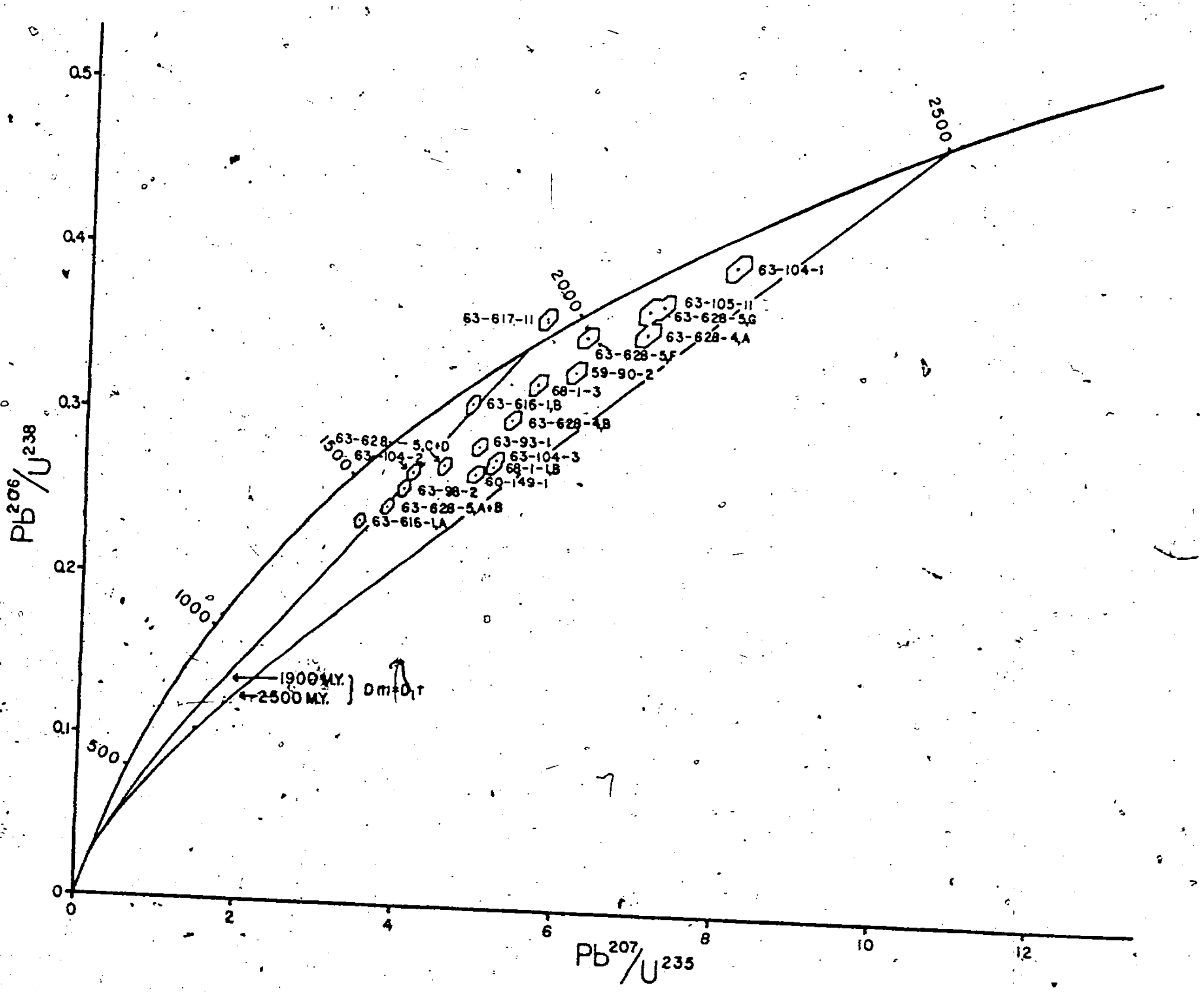


Fig. 5. Concordia diagram (r_{238} vs r_{235}) for zircons from the Migmatitic - Gneisses and Other Metasedimentary rocks. Continuous Pb-diffusion lines of the type $D(t) = D_1 t$ (D_1 a constant) (Wasserburg, 1963) are shown as references.

for the older groups have been shifted so strongly that in no case do any points go as high as the 2500 m.y. diffusion curve and in fact a number of points in each of these older groups now lie on the 1900 m.y. diffusion curve. As might be expected from the greater diversity of rocks included in this group, the data points in the migmatite - gneiss group show a wider spread than the points representing samples in the other groups and thus show the closest approach to the 2500 m.y. diffusion curve. The occurrence of a couple of points in the Colin - Andrew Lakes group above the 1900 m.y. diffusion curve is noted.

As well as a variation of dates within the groupings there is also a variation in apparent discordancy. Within each group there is a range from very discordant (distant from the concordia curve) to fairly concordant points (near the concordia curve) on the concordia diagrams. Some general trends in variation in discordancy between groups may be noted. The zircons from the granites of the Colin - Andrew Lakes area (nominally younger than the rocks in the other groups) do appear to be slightly more discordant than zircons from these other groups. There are no points on the corresponding $r_{238} - r_{235}$ diagram (fig. 3) which appear as close to the concordia line as do points on the diagrams for either of the older groups (figs. 4 and 5).

B. Geochronologic Correlation

A study of the above mentioned patterns of points on the concordia diagrams indicates that the correlation in dating between this zircon work and previous geochronologic work is not an outstanding one. The 1900 m.y. event does show up in the zircon work, but it shows up indiscriminantly in all groups, even those Charles Lake granites which are cut by pegmatites dated at 2524 m.y. by Rb - Sr work. The 2524 m.y. or older ages do not show up in the zircon work at all. There are dates present that range up to about 2300 m.y. but no particular date or event is indicated so it is assumed that these dates are produced by diffusive and/or episodic degeneration of the 2500 m.y. dates indicated in other work and thus a considerable updating of zircons in the Charles Lake and migmatite - gneiss groups has occurred. This would appear to signify that the event dated at roughly 1900 m.y. (1893 m.y. by Rb - Sr work) had a more extensive effect on the zircon dates than on the whole rock U - Pb and Rb - Sr dates. It has apparently reset some zircons to a 1900 m.y. date and also added an episodic complication to the diffusion pattern of some older zircons. The lack of any points below the 1900 m.y. diffusion line would appear to indicate that the processes setting the K - Ar dates down to 1790 m.y. were not of sufficient magnitude to reset zircon dates down to 1790 m.y. The above notes lead to the proposition that these zircon results support the possible emplacement of the Colin - Andrew Lakes granites at 1900 m.y. but do not confirm nor disprove the emplacement of the Charles Lake granites at or before 2500 m.y.

It is possible to propose reasons for the lack of correlation between this zircon work and the previous work with regard to the older ages for the migmatite - gneiss complex and the Charles Lake granites. Metamorphism must have reached a fairly high grade in this area in order to produce migmatitic rocks and so it is not unreasonable to expect extensive effects on the minerals in these rocks. The fact that the granites have been made semi-conformable with the loss of sharp contacts in many places would indicate their involvement in the metamorphic processes and the attendant possibilities for mineral disturbances are present in these rocks also. Thus episodic effects can be expected in all the zircons from these older rocks. If, as Baadsgaard and Godfrey (1972) propose, the Colin - Andrew Lakes granites are anatectically derived, the few dates older than 1900 m.y. within this group would most likely represent the effects of remnants from the older parent material. A disturbance strong enough to produce such anatexis could certainly produce or contribute to the updating effects noted in the zircons from the older rocks. Since these effects have been strong enough to move some of the data points for these zircons right over to the 1900 m.y. line it is not surprising that all have been affected to the extent that the 2500 m.y. ages have been obliterated.

The possibilities for these strong effects are supported by the microscopic appearance of these zircons. The migmatite - gneiss zircons definitely show the effects of metamictization. Although the Charles Lake zircons are more transparent and euhedral, it must be remembered that this is stated as a comparison with the other groups within this study. When compared with zircons from other areas, the possibilities of radiation damage are apparent. Although less frequent than among zircons of other groups, cracks and cloudy or dark areas are present. It is felt that the older zircons from the area have been opened up to episodic effects during strong metamorphism.

C. Th - Pb Dating in Zircons

It must be emphasized that the study of the Th - Pb nuclear clock should be carried forward along with U - Pb studies. Understanding the behaviour of the third, independent nuclide in zircons (and whole rock and other minerals) will provide valuable comparison and contrast with the behaviour of the two uranium nuclides. As Steiger and Wasserburg (1966) state, end member behaviour in a series of uranium - lead phases may give an apparent straight line which masks the intermediate behaviour but a thorium analysis provides an added dimension which may give a more complete picture of the overall systematic isotope behaviour.

Since thorium is an independent element from uranium it does not automatically come along through an analytical procedure designed for uranium. Geochronologic workers often disregard thorium rather than design and use analytical procedures especially for it and thus much useful information is not developed. In the present study, thorium procedures were carried along with those for uranium and lead but in some cases a satisfactory analysis was not obtained.

Those zircons for which thorium analyses were obtained are presented in a r_{232} - r_{235} diagram (fig. 6). The differences between groups noted on the U - Pb concordia diagrams hold, in a general way, on the Th - Pb concordia diagram. As in the uranium diagrams, the members of the Colin - Andrew Lakes group are generally more discordant than those of either of the other groups and tend to cluster more towards the younger end of the concordia line. The members of the Charles Lake and migmatite - gneiss groups are intermingled with respect to age but those of the Charles Lake group do seem to be more concordant, the data points representing them (with the exception of 68-1-5 and 68-2-3) lying fairly close to the concordia line. It is also noted that in most cases of samples that have separate magnetic or gravimetric fractions analyzed these fractions follow the same order of discordancy on both the r_{238} - r_{235} and r_{232} - r_{235} diagrams. A similar sort of parallel order was noted by Steiger and Wasserburg (1966) for the Sandia granite zircons. It must be emphasized that these are only general patterns, and that there are obvious individual exceptions which can be readily noted from an inspection of the concordia diagrams.

The scattering on the r_{232} - r_{235} diagram (fig. 6),

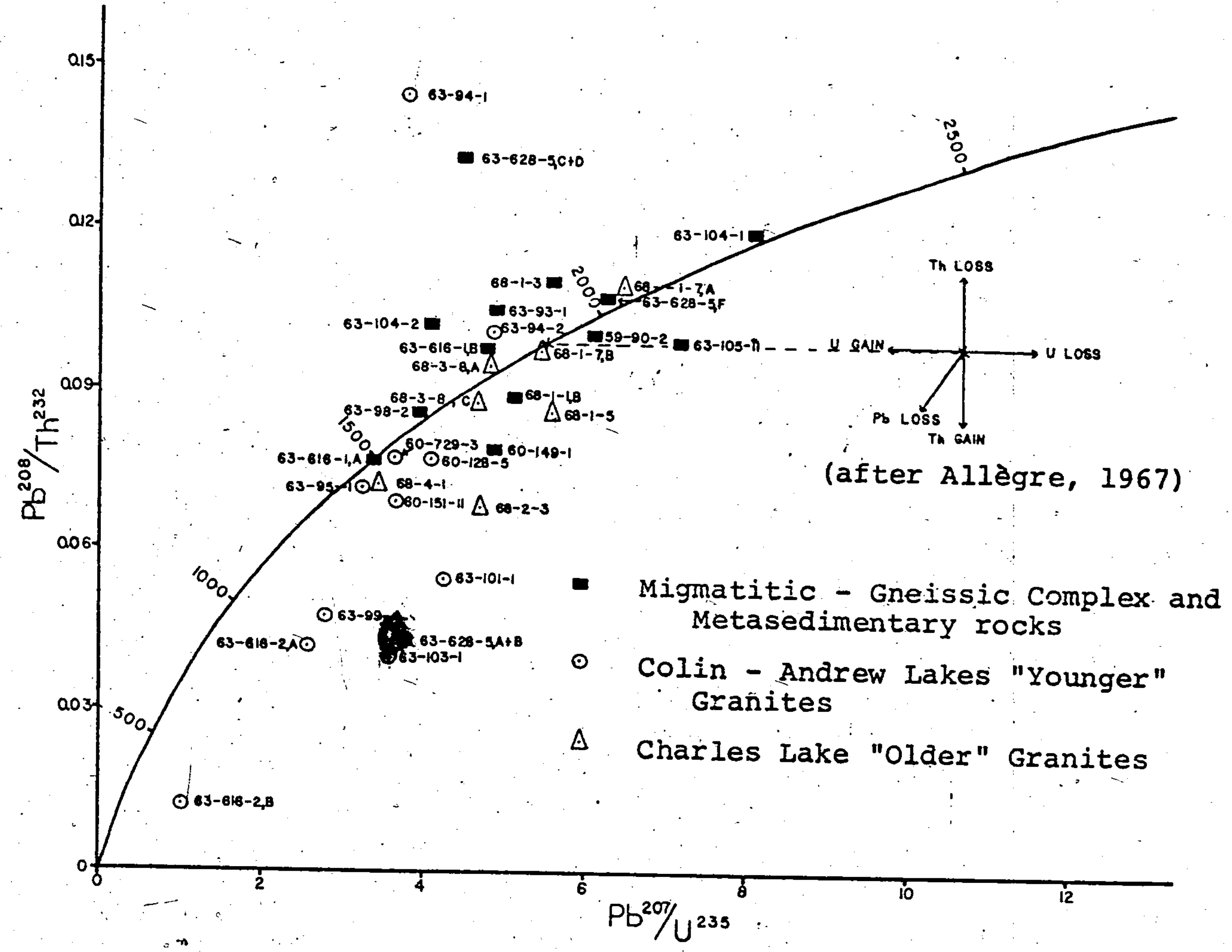


Fig. 6. Concordia diagram (r_{232} vs r_{235}) for zircons from the entire study area.

especially as contrasted with the r_{238} - r_{235} diagrams, would seem to be indicative of the involvement of parent nuclide mobility in the discordancy of many of these samples (as well as lead mobility). If lead loss alone accounts for the discordancy of these samples, then points on the U - Pb and Th - Pb concordia diagrams should show a constant relationship to each other. The data point for a particular sample need not be in exactly the same position on each diagram (due to differences between thorium and uranium) but it would have held the same position relative to the other data points. With the current data no such relationship exists and so the mobility of one, and most probably both, parent nuclides is indicated as contributing to the discordancy of these zircons.

Although it is impossible to trace the history of the generation of each point of the current data, it is possible to envisage a manipulation of the vectors for gain or loss of uranium thorium, and lead (shown by Allègre (1967) and given on figure 6 for reference) so that each data point could be reached starting from the appropriate 1900 m.y. or 2500 m.y. point on the concordia. It would not be possible to arrive at many of the points by invoking lead loss alone so that parental element movement is implicated. If the 2524 m.y. Rb - Sr age for the Charles Lake granites and the migmatite - gneisses is accepted, their placement on the r_{232} - r_{235} diagram (fig. 6) would appear to indicate considerable disturbance by the 1900 m.y. event involving loss of lead and both gain and loss of uranium and thorium with respect to each other. There is no evident general trend towards the enrichment of uranium with respect to thorium (or the reverse) having occurred during this disturbance. A striking example of probable parent nuclide mobility is sample 63-94-1 which lies on the 1900 m.y. diffusion line on the $r_{238} - r_{235}$ diagram (fig. 3) but must have lost considerable thorium (relatively) to reach its present position on the $r_{232} - r_{235}$ diagram (fig. 6).

The wide scattering on the $r_{232} - r_{235}$ diagram and the divergent behaviour of the thorium and uranium nuclear clocks demonstrated by most zircons also indicates the strength of the metamorphic effects in the area. Under less severe conditions a closer correspondence of the thorium and uranium concordia diagrams might have been expected. If a very liberal interpretation is made of the pattern of data points on the $r_{232} - r_{235}$ diagram (fig. 6) taken en masse, a line could be drawn through the data which would intersect the concordia at approximately 1900 m.y., and cut the x-axis in a manner similar to that noted by Steiger and Wasserburg (1966) for other thorium data. Since a similar line at 2500 m.y. would not contact any data points, the 1900 m.y. line is loosely indicative of updating of the thorium ages analogous to that of the uranium ages.

As stated previously, the errors encountered in thorium analyses are somewhat larger than those encountered in uranium analyses. This may affect the placement of an indivdual point on the r_{232} - r_{235} diagram, but only to a fairly limited degree, and so should not influence greatly the overall pattern or the degree of scattering obtained. All points presented have no known or obvious sources of error great enough to make suspect their placement on the concordia diagram.

With further study of the behaviour of the thorium nuclear clock more information with greater reliability should be obtained. New analytical procedures are required to match the procedures that are evolving for lead and uranium analyses allowing accurate isotopic analyses down to very low levels. As well as supplying further dates to compare with those derived from uranium work, a better grasp of thorium behaviour may help provide a better understanding of the problem of discordancy in zircons. The potential of thorium - lead in zircon geochronology is far from completely realized.

D. Geochemical and Mineralogic Factors

Uranium and thorium contents of the zircons from the various rock groups are presented in histograms (figs. 7 and 8). There is a trend for the Colin - Andrew Lakes granites to have slightly higher uranium and thorium contents, the Charles Lake granites to have the lowest contents, and the migmatite - gneisses to spread across the intermediate area of the graph. This would agree with the trend to slightly greater discordancy of the Colin - Andrew Lakes zircons as

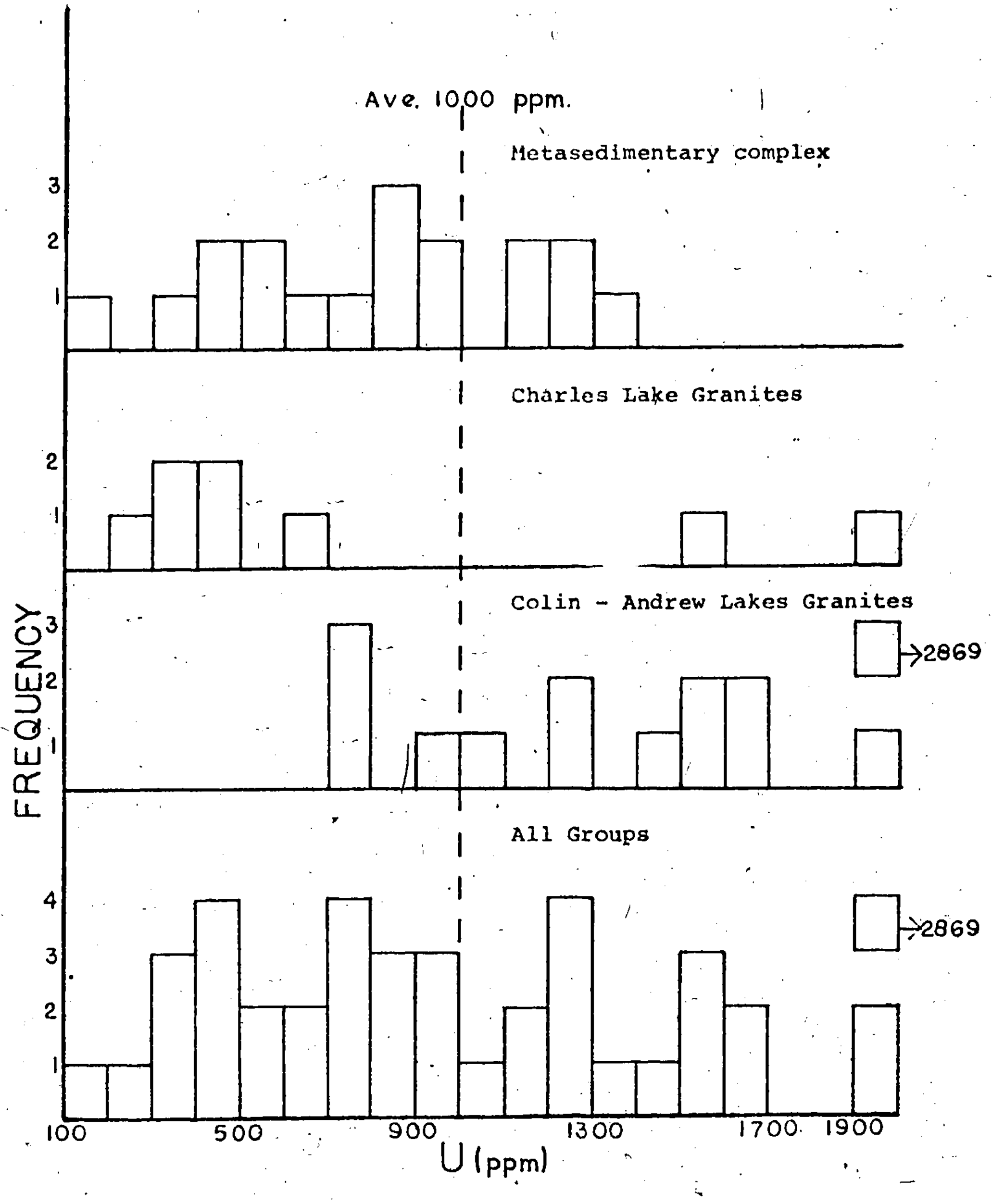


Fig. 7. Frequency distribution diagram of ~~uranium~~ content of zircons.

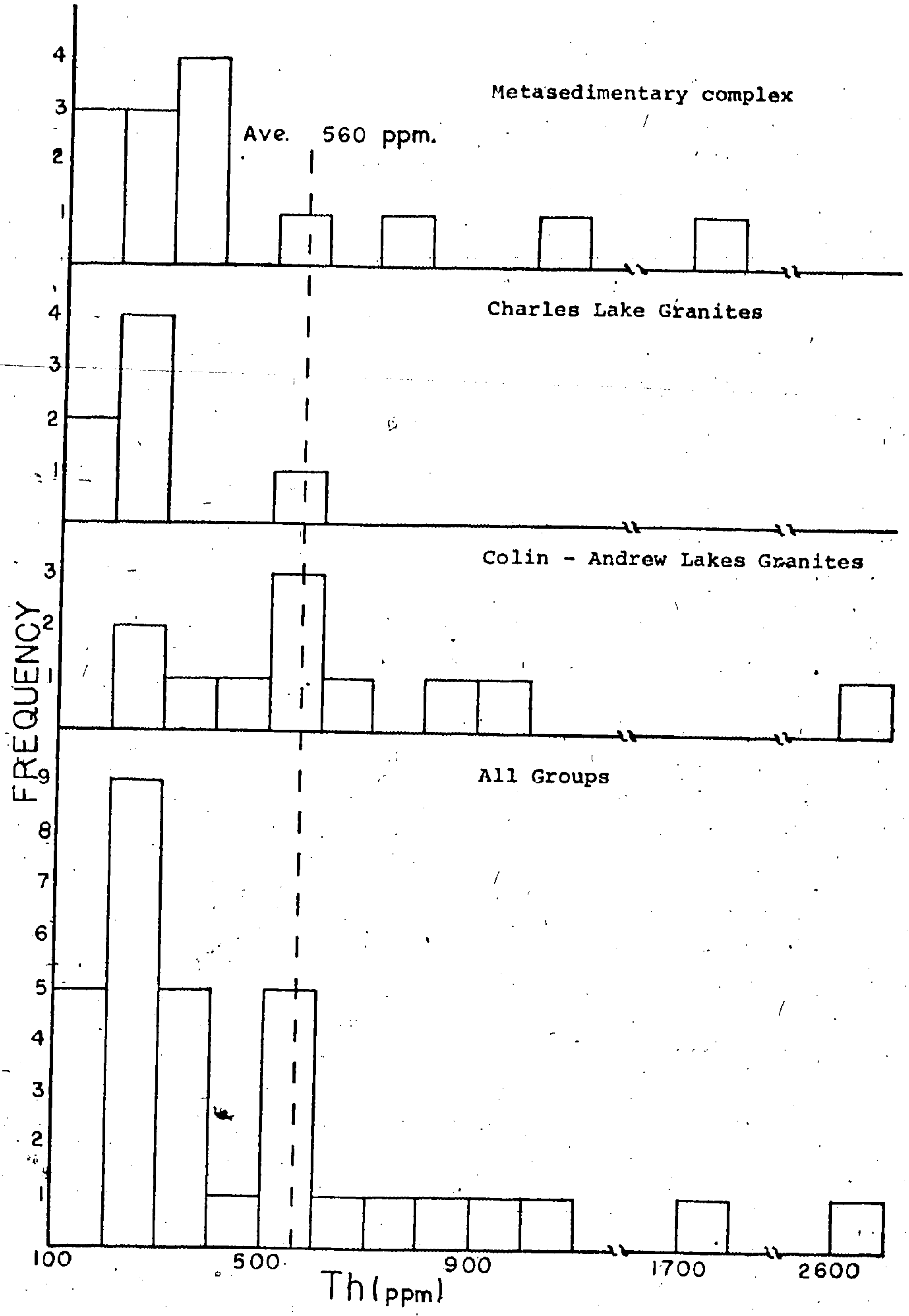


Fig. 8. Frequency distribution diagram of thorium content of zircons.

Silver and Duetsch (1963) found greater discordancy with higher uranium contents. The presence of increased abundances of uranium and thorium in the Colin - Andrew Lakes zircons compared with the Charles Lake zircons is supported by the parallel increased whole rock abundances to be noted in an examination of the whole rock data for these granites as reported by Baadsgaard and Godfrey (1972) and Lee (1972). This would follow from the geochemical behaviour found for uranium and thorium in that they increase in abundance in the later differentiates (in this case, the Colin - Andrew Lakes granites) during petrological evolution. The separation appears most noticeably in the graph of combined uranium and thorium contents (fig. 9). It is not so noticeable in the graph of uranium to thorium ratio (fig. 10). This would probably indicate that both parents are involved in any process together and that uranium is not enriched in relation to thorium to any great extent in any group. As noted previously, there have been individual cases where both enrichment and depletion of uranium in relation to thorium has occurred since the formation of the zircon but no group appears to be characterized by either process. This is supported by looking at a plot of uranium content versus thorium content (fig. 11) on which it can be seen that the data points for the various groups are interspersed and no definite segregation is seen as would be expected if uranium were enriched (or depleted) over thorium differentially in the groups. It should be noted that the number of

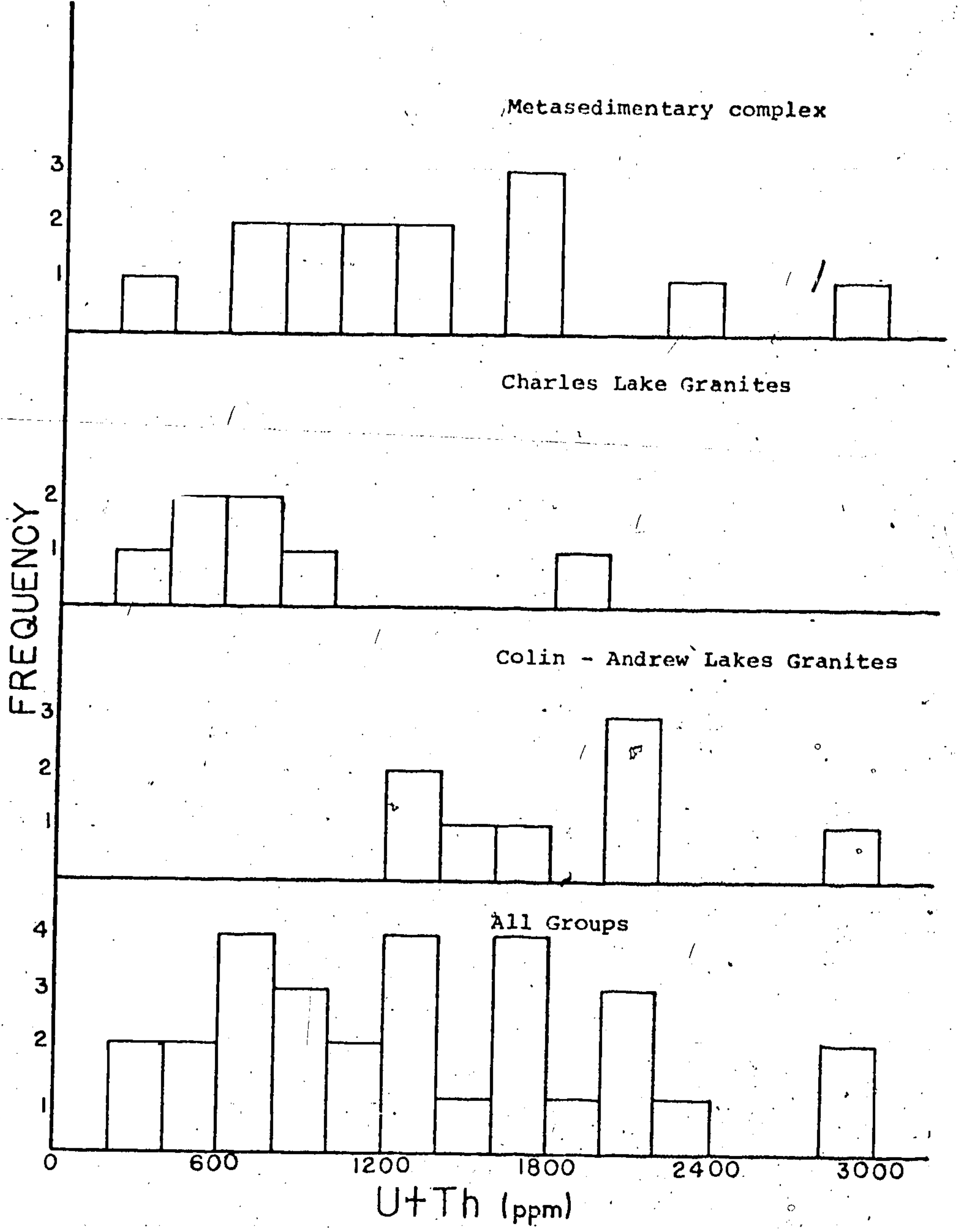


Fig. 9. Frequency distribution diagram of combined uranium and thorium content of zircons.

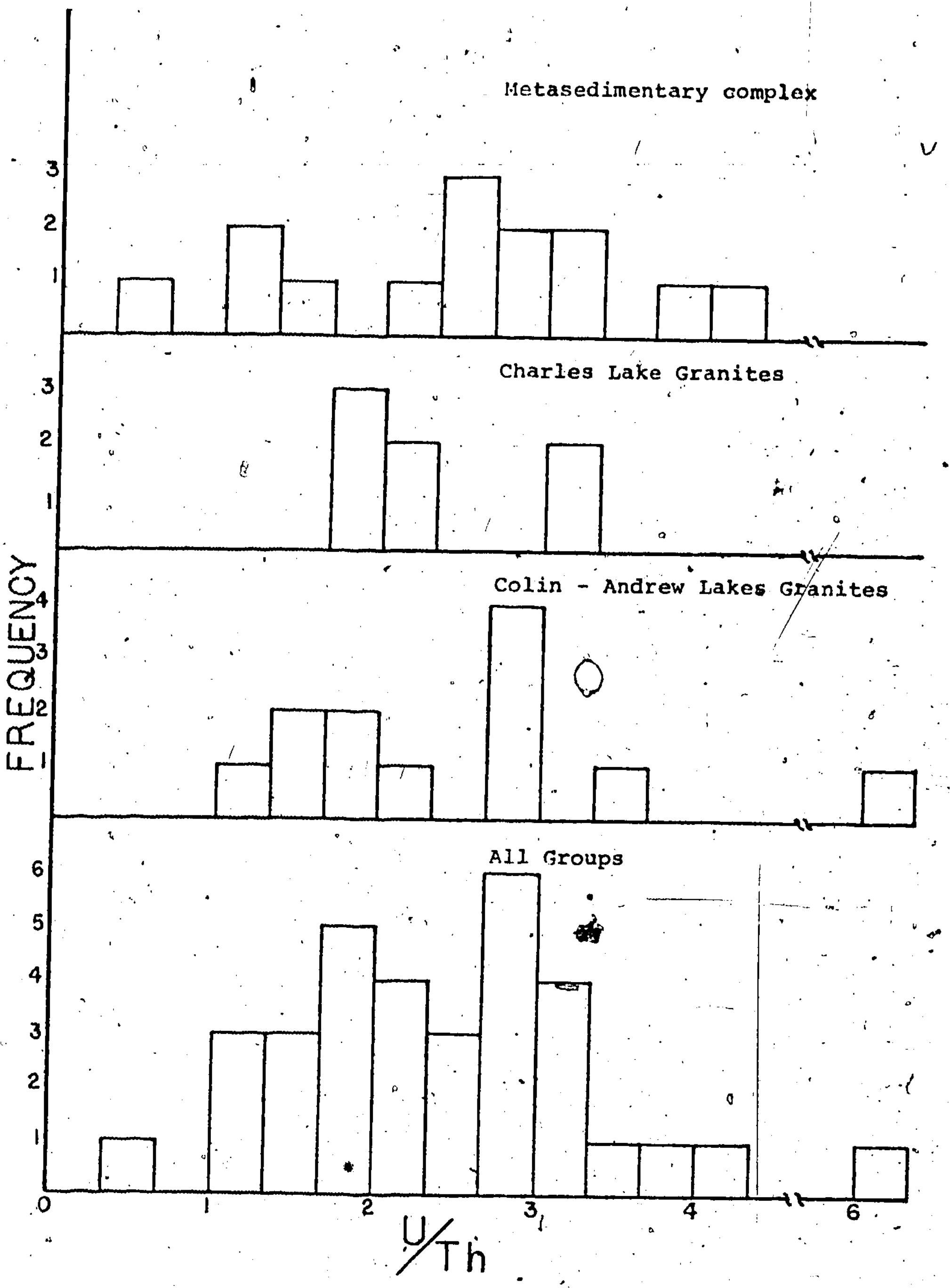


Fig. 10. Frequency distribution diagram of the uranium to thorium ratio of zircons.

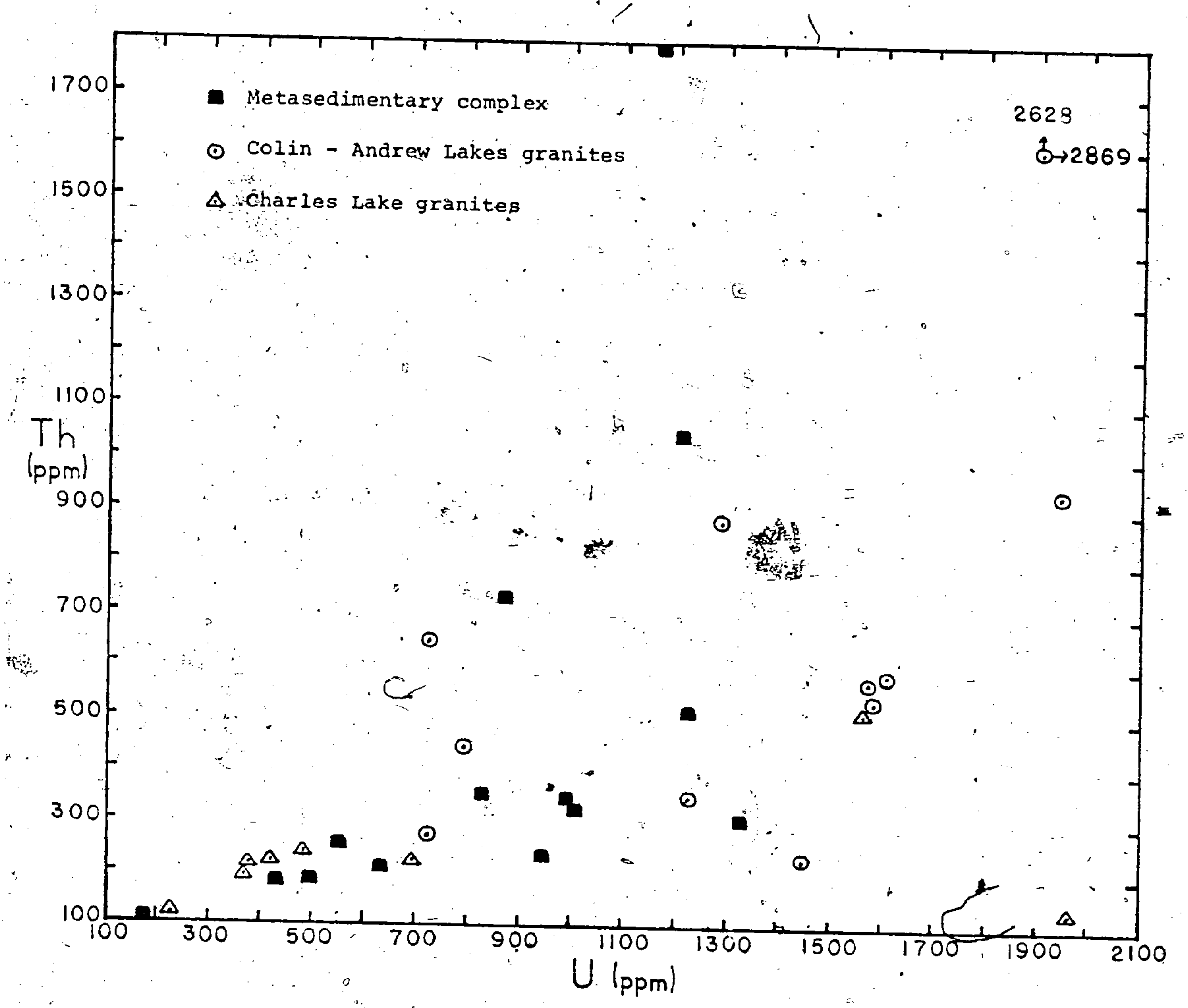


Fig. 11: The relationship between uranium and thorium contents of zircons.

samples included in these histograms is statistically somewhat low and that a greater number of results may enhance or decrease the separation of peaks on the histograms. It is believed, however, that the trends noted are real and a greater number of analyses would sharpen the peaks and show the differences between groups more clearly. The fact that Godfrey reports radioactive anomalies and even some evidences of uranium mineralization from the Colin - Andrew Lakes district supports the view that this part of the study area at least is somewhat enriched in uranium. This would be in agreement with the higher uranium and thorium contents found in the zircons from this district.

In comparing these present results with those obtained by Ahrens (1965) it would seem that any process affecting the enrichment or depletion of the parent elements has not been exceptional because the contents of uranium and thorium fall easily in to the high frequency range of his histograms and the average thorium to uranium ratio lies very close to that reported by him (0.42 this data versus 0.47 by Ahrens). Even the same positive skewness is present to some extent, although because of the smaller number of samples it is not developed as strongly. There is some disagreement in the literature, however, because Tilton and Silver (discussion in Silver, 1962) agree on 700 ppm. as the average uranium content of zircons from granitic rocks while Ahrens gives an average of 1330 ppm. The average derived from the analyses of this study is 1000 ppm.

There does not appear to be a general correspondence between placement on the concordia diagram and any particular characteristic chosen from microscopic examination. Some samples which appeared to be particularly discordant were especially noted. Sample 68-3-8,B which is far down towards the origin on the concordia diagram for the Charles Lake granites (fig. 4) does not appear significantly different from fractions A and C which appear close together fairly near the concordia. There is thus no obvious visible reasons for the anomalous placement of fraction B. The analytical results on this fraction appear to be good and the lead content does not seem to be particularly low (no loss of lead compared with the other fractions). The lead content of fraction B is the highest of the three fractions, but the measured Pb^{206}/Pb^{204} ratio is in agreement with that of fractions A and C (table 2) and is in fact one of the highest ratios obtained in these analyses, indicating low presence of common or contaminant lead. Thus exceptional lead loss from fraction B can be ruled out. However, the analysis does show a very much higher uranium content in fraction B (on the order of five times that of fractions A and C). The origin of this excess uranium is not known. One might suspect a contaminant uranothorite grain except for the fact that all zircon separates were subjected to the same hot nitric acid wash before analysis which has apparently eliminated this contamination in the other zircon separates analyzed and which has been shown to be effective in eliminating uranothorite in previous studies (Silver and Deutsch, 1963). The presence of a grain or two of zircon with large internal inclusions of uranothorite (which would be untouched by acid washing) would be another possible source of uranium contamination but this cannot now be checked. A generally higher uranium content in zircon from this rock can be ruled out because it is not found in fractions A and C of the separate. Finally, although the analysis of this fraction does not appear anomalous, the possibility of analytical error must be considered. The high uranium content compared to fractions A and C would especially appear to be suspect. Although nothing untoward was noticed during this analysis, contamination during analysis is a possibility; but again, this cannot now be checked. Thus, while the placement of this data point is an excellent demonstration of parental element involvement in discordancy, the reason for the anomalous placement of this fraction on the concordia diagram (compared to fractions A and C) remains speculative.

Samples 63-616-2,A and B (which also show fairly large discordancy) in the Colin - Andrew Lakes granite group (fig. 3) appear (under microscopic examination) to be the darkest, cloudiest zircons within this group. A case may thus be made for their being the most metamict and therefore having suffered the largest discordance. Again, while lead content may be slightly lower than the average found in this study, uranium content is higher than average and this appears to be the basis of the discordancy in this case.

The placement of the data point for sample 63-617-11 in the migmatite - gneiss group (fig. 5) is also noted as being anomalous, but neither its appearance nor its analysis provide a reason. In appearance it resembles many of the zircon separates from the other gneisses. The uranium content is slightly below the average of all the zircons analyzed, but not so low as to permit one to say that it has lost uranium more than other zircons (which its placement on the concordia diagram would tend to indicate). The only notable fact is that while the uranium content is slightly below average, the lead content is somewhat above average. This may indicate that uranium loss has occurred, but there is no indication why this has occurred in this sample and not in other similar samples. With this sample also, analytical error cannot be ruled out even though there is nothing in the analysis to indicate that this would be the reason for its anomalous placement on the concordia diagram.

When the results for magnetic and gravimetric splits of some of the zircon separates are considered, a definite correlation between the relative density of a split and its discordancy can be seen for the Colin - Andrew Lakes and migmatite - gneiss groups. The heavier a zircon separate, (less magnetic on the Franz Isodynamic separator) the more concordant it is. This result is related to the work by Silver (1962) in which he reports increasing magnetic susceptibility (or decreasing density) with increasing uranium content. This relationship between uranium content, density, and concordancy would be expected because the greater the uranium content, the greater the degree of metamictization (which lowers the density of the crystal). The greater the degree of metamictization of a crystal, the greater are the possibilities for element mobility and therefore the greater the discordancy found. The similarity in behaviour of the current data to that reported by Silver can be seen from table 4.

The anomalous behaviour of sample 68-3-8 has already been discussed; and, as mentioned, may be due to some sort of contamination of fraction B or to analytical error. Sample 68-1-7 can be seen to also be anomalous in the order of its magnetic susceptibility but the relationship between uranium content and order of discordancy is upheld. This leads to the speculation that the fractions of sample 68-1-7 were mislabelled as to magnetic susceptibility at the time of separation. It would appear from the above results that the least magnetic (heaviest) fraction should be employed to obtain the most concordant ages.

TABLE 4. The relationship between magnetic susceptibility, uranium content, and discordance in fractionated zircon samples.

Sample	Direction of increasing magnetic susceptibility of fractions within a sample	Fraction	Uranium content (ppm)	Direction of increasing discordancy of fractions within a sample
63-616-1	↓	B	868.5	↓
		A	1212	
63-616-2	↓	A	1942	↓
		B	2869	
63-628-4	↓	A	483.9	↓
		B	1164	
63-628-5	↓	G	314.3	↓
		F	432.6	
		C+D	946.3	
		A+B	1167	
68-1-7	↑	A	230.3	↓
		B	485.8	
68-3-8	↓	A	373.9	↓
		B	1963	↑
		C	379.9	

CHAPTER V CONCLUSIONS

The data derived in this study provides another example of the increased amount of information developed through the use of concordia plots as opposed to just calculating an age for a mineral. Since in each group of zircons studied there are points which lie on or near the 1900 m.y. diffusion curve, no zircon in this age range (up to a 207/206 age of about 2000 m.y.) could be placed in the younger or older group by concordia plot position alone. However, when the patterns of data points on the concordia diagrams are examined, the separation between the younger and older groups becomes more apparent.

The pattern on the Colin - Andrew Lakes granite concordia diagram (grouped fairly closely around the 1900 m.y. diffusion curve) supports the Rb - Sr and whole rock U - Pb derived age of 1900 m.y. for these granites. From their Rb - Sr studies of the intrusives and granites of the Colin - Andrew Lakes district, Baadsgaard and Godfrey (1972) state that the formation and emplacement of these rocks involved either extensive contamination from, or partial anatexis of, the metasedimentary terrain. The high initial ratio of Sr^{87}/Sr^{86} in the Colin - Andrew Lakes granites leads them to favor anatexis. The present data does not provide proof for either process, but would also appear to support anatexis. There is no obvious contamination (such as two distinct zircon populations) to be seen in the zircon separates from these rocks and the few ages older than 1900 m.y. observed in the zircon data from these granites may represent remnants from the parent material which have survived the anatectic processes.

An examination of the concordia plots for the Charles Lake granites and the migmatite - gneisses leads to the conclusion that there has been considerable updating of the zircons from these older rocks. These plots show a spread of data points from the 1900 m.y. diffusion curve (which appears to be the limiting line concerning disturbance of zircons over the whole study area) up to only approximately 2300 m.y. When this is compared with the Rb - Sr and whole rock U - Pb data showing ages of 2500 m.y. or greater, the updating of the zircons is obvious. An episodic disturbance of zircon ages to this extent is compatible with the high temperature metamorphism which has been experienced by most of this area. In view of this, metamorphic annealing has likely played a part in producing the somewhat clearer colors and lower incidence of zoning noticed on the Charles Lake zircons. There are no indications of an anatectic origin for these granites comparable to those noted for the Colin - Andrew Lakes granites.

The thorium data derived in this study produces no clear pattern for any of the groups of rocks investigated since data points for each group are well scattered and interspersed with one another. It is felt that this scatter is due to, and indicative of, the complex high temperature metamorphism the whole study area has undergone. If the thorium data points for all three groups of rock are considered together, a reference line may be drawn through them which intersects the concordia at approximately 1900 m.y. and the x-axis in a manner similar to that reported by Steiger and Wasserburg (1966) for other thorium data. A similar line at 2500 m.y. does not come near any of the data points and so an updating of the thorium ages comparable to that of the uranium ages may be postulated. However, the scatter of the thorium data makes the placement of such a line and the resultant correlation between thorium and uranium updating somewhat speculative.

The zircons from the Colin - Andrew Lakes granites generally have higher uranium and thorium contents than those from the Charles Lake granites or the migmatite - gneisses. This explains their slightly greater discordancy and also the more metamict appearance of these zircons compared to some others encountered in this study. The Colin - Andrew Lakes granites are the youngest rocks to come under scrutiny in the study area, and this fact combined with the geochemical tendency for uranium and thorium to be relatively abundant in lower temperature melting rocks would appear to explain the higher uranium and thorium contents in the zircons from these rocks.

There is some evidence for the discordance in the zircons in this study being due to parental element loss or gain, rather than only daughter diffusion. The anomalous uranium and thorium contents of widely discordant samples and the differing behaviour of some samples on the uranium and thorium concordia diagrams points to involvement of uranium and thorium in the discordancy producing processes in these zircons. The fact that uranium appears to have been both gained and lost with respect to thorium and the fact that there appears to be no difference between the three zircon groups in this respect would seem to indicate that the processes accounting for the mobility of these elements is not weathering or hydrothermal alteration. Under weathering conditions uranium is oxidized to the hexavalent state which is fairly mobile while thorium remains in its quadravalent form which is quite immobile. Therefore a definite preferential uranium loss might have been expected.

A salient point derived from this study is that it reemphasizes the need for applying several dating methods, where possible, to an area in order to most satisfactorily help delineate its geological history through isotopic studies. Taken out of the context of the other geochronological work done on the area, the data derived in this study would not have near the meaning it has when considered in such context. Such information as the updating of the older zircons would not have been obvious without the background of the older dates provided by Rb - Sr and whole rock U - Pb work. Zircon dating (or other dating) may stand alone where conditions such as those accompanying one sharp plutonic event are involved, but in a regionally metamorphosed complex terrain, a combination of several approaches provides the most reliable and informative isotopic representation of the geological history and processes being studied.

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APPENDIX

Descriptions of Zircons from Microscopic Examination

Note: Although each zircon separate shows quite a variable range of color and (especially) size, the indications given for each of these properties refers to the majority of the sample examined. The terminology used in referring to these properties is explained below. Each term refers to a slight range of the appropriate property, as indicated, and are thus somewhat approximate.

Size:

Large is 100 to 170 mesh.

Intermediate is 170 to 230 mesh.

Small is less than 230 mesh.

Color: (Based on standard colors)

Yellowish gray is yellowish gray (5Y8/4) to grayish yellow (5Y7/2).

Moderate yellow is moderate yellow (5Y7/6) to dusky yellow (5Y6/4).

Light olive brown is light olive brown (5Y5/6) to moderate olive brown (5Y4/4).

59-90-2	Quartz Monzonite Gneiss
60-128-5	Hybrid Granite
60-149-1	Quartz Monzonite Gneiss

60-151-11 Quartz Monzonite

60-[illegible]29-3 Granodiorite

60-729-4 Porphyroblastic Quartz Monzonite

No portions for microscopic examination were saved from these early samples.

63-81-7 Granite Boss

Very small size. Either euhedral or rounded with very few subhedral; some broken grains present. Yellowish gray. Elongation ratio varies from 1/1 to 1/4. Zoning present in some grains, some inclusions present. Few cracks are apparent.

63-93-1 Metasediments

Shows great size range from small to large but with small grains predominating. Habit also ranges from euhedral to rounded in all size ranges with some broken fragments, particularly in the larger sizes. Yellowish gray to moderate yellow. Elongation ratio varies from 1/1 to 1/3. Zoning and cracking very common but few inclusions are obvious because of the dark color of some grains. Rounded cores can be seen in some grains.

63-94-1 Granite C

Some range in size with intermediate sizes predominating. Generally euhedral to subrounded with a few broken fragments. Moderate yellow in color. Elongation ratio varies from 1/1 to 1/3. Zoning and inclusions present but extent hard to determine due to dark color. Some cracking and dark cores can be seen.

63-94-2 Biotite Microgranite

Small to intermediate in size. Crystals are mainly euhedral with some subhedral. Yellowish gray in color. Elongation ratio varies from 1/1 to 1/3. Zoning and inclusions present but few cracks noted.

63-95-1 Granite A

Small to intermediate in size. The smaller crystals are generally rounded while the larger ones are more commonly euhedral with some being broken. Yellowish gray in color. Elongation ratio varies from 1/1 to 1/2 but some longer grains were probably present before being broken. Zoning is common. A few cracks and dark round inclusions are present.

63-98-2 Lava Flow

Generally intermediate in size. Sharply euhedral to subhedral. Color is yellowish gray but some red areas are present. Elongation ratio is 1/1 to 1/3. Zoning and cracks are very common and many dark inclusions are present.

63-99-4 Granite B

Small in size with the occasional larger grain present. Generally rounded but some may be termed subhedral. Almost colorless to yellowish gray in color. Elongation ratio 1/1 to 1/4. Cracks are quite common. Some zoning and inclusions present.

63-101-1 Quartz Diorite

Generally of an intermediate size but a good representation of both larger and smaller grains are present. Subhedral to rounded in habit. Yellowish gray in color with some reddish areas present. Elongation ratio 1/1 to 1/3. Cracks and zoning quite common but inclusions less so. Quite a few broken grains are present.

63-103-1 Granite D

Both large and small grains present but few intermediate in size. Many grains, especially the larger ones, are broken. Yellowish gray with reddish areas present. Elongation ratio 1/1 to 1/3. Zoning, cracks, and dark inclusions are all quite common.

63-104-1 Granite Gneiss

Large grains. Rounded to subhedral with many broken grains. Moderate yellow with some reddish areas. Elongation ratio 1/1 to 1/4. Zoning fairly uncommon but cracks and large inclusions less so.

63-104-2 Granite Gneiss

Very small rounded grains. Yellowish gray. Elongation ratio 1/1 to 1/3. Zoning not very apparent because of the small grain size but some cracks and inclusions can be seen.

63-104-3 Granite Gneiss

Intermediate in size. Rounded to subhedral with many irregular and broken fragments. Nearly colorless to yellowish gray. Elongation ratio 1/1 to 1/3. Zoning and inclusions present and cracks are fairly common but some grains are clear of all imperfections.

63-105-11 Granite Gneiss

Grains are large. Rounded to subhedral with a few euhedral present. Many grains are broken. Moderate yellow with some reddish tinge. Zoning is quite noticeable. Cracks and inclusions are widely present. Elongation ratio 1/1 to 1/3 but because of broken grains, many may have been longer than this would indicate. Rounded cores are fairly common.

63-616-1,A Amphibolite Plug

Intermediate in size. Grains appear to be mainly broken fragments and any which show terminations are subhedral. Yellowish gray to moderate yellow. Some zoning apparent. Few inclusions but many cracks are present. Elongation ratio is 1/1 to 1/5, but again this is probably exceeded in the complete grains.

63-616-1,B

Intermediate to small. As above, grains are practically all broken fragments with subhedral terminations when present. Elongation ratio 1/1 to 1/5 but probably exceeded in whole grains. Yellowish gray in color. Few inclusions, more zoning, and many cracks.

63-616-2,A Massive Biotite P Granite

Intermediate in size. Some euhedral grains present but most are very irregular in shape. Moderate yellow but many show red, especially in the rounded cores which are quite prevalent. Elongation ratio 1/1 to 1/3. Some zoning is present and cracks and inclusions are quite common.

63-616-2,B

Intermediate to small. More euhedral grains than in the above fraction but still primarily very irregular. The color is generally somewhat darker than above, moderate yellow to light olive brown, and not so many grains show red staining. Elongation ratio 1/1 to 1/2. Zoning, cracks, and inclusions similar to above but the incidence of rounded cores seems to be less.

63-617-11 Granite Gneiss

A range of sizes is present but the majority are small to intermediate. Generally subhedral to rounded but with a few of both euhedral and very irregular grains present.

Moderate yellow to yellowish gray in color. Zoning and cracks common with inclusions being less so. A few rounded cores present.

63-628-4,A Granite Gneiss

Intermediate to small. Generally rounded with some subhedral. Almost colorless to yellowish gray. Elongation ratio 1/1 to 1/3. Zoning is fairly common but crack and inclusions are less so. Some very noticeable rounded cores are present.

63-628-4,B

Small in size. Rounded to irregular. Near colorless to yellowish gray. Elongation ratio 1/1 to 1/3. Zoning, inclusions, and cracks similar to above fraction.

63-628-5,A Granite Gneiss

Small to intermediate. Subhedral to rounded and irregular. Near transparent to yellowish gray in color. Elongation ratio 1/1 to 1/4. Cracks and light inclusions fairly common, but little zoning and incidence of dark inclusions.

63-628-5,B

Grains are very similar to those of the above fraction in size, color, zoning, and cracking. Dark inclusions more common than with above. Elongation ratio 1/1 to 1/3.

63-628-5,C

Smaller than above and more irregular in form. Color is about the same. Elongation ratio 1/1 to 1/4. Zoning, cracking, and inclusions similar to above.

63-628-5,D

Larger than above -- in the intermediate range with very small grains. Grains tend to be more subhedral than irregular. Color, zoning, cracking, and inclusions similar to above. Elongation ratio 1/1 to 1/3. Rounded cores are visible in some of the better shaped grains and these cores tend to be darker than the surrounding crystal.

63-628-5,F

Smaller than above and more rounded. Color, zoning, and inclusions similar to D, but cracks do not appear as commonly. Elongation ratio 1/1 to 1/3.

63-628-5,G

Intermediate to large in size. Subhedral. Color, zoning, and inclusions similar. Cracks more common in this fraction. Elongation ratio 1/1 to 1/5.

68-1-1,B Biotite Granite Gneiss

Intermediate to large in size. Rounded in form. Almost colorless but cloudy. Some zoning and inclusions can be seen but their extent is masked by the cloudiness.

Not many fractures. What appear to be rounded cores can be observed in a few instances.

68-1-3 Hornblende Granite Gneiss

Intermediate to large. Subhedral to euhedral. Broken and irregular grains fairly common. Near colorless but with some red staining present. Elongation ratio 1/1 to 1/3. Zoning, inclusions, and cracking all indicated but masked by the overall dark color.

68-1-5 Biotite Q Granite

Intermediate in size. Generally broken and irregular in shape. Some euhedral terminations noted. Near colorless to yellowish gray. Elongation ratio 1/1 to 1/4 but probably extended beyond this in whole grains. Fracturing and zoning quite common but inclusions less so.

68-1-7,A Foliated Hornblende Granite

Intermediate to large. Subhedral in form. Near colorless, but some red stains are present. Elongation ratio 1/1 to 1/4. Zoning and cracks are present and inclusions are common, often in the form of clear acicular bodies as well as the dark round inclusions noted in other separates.

68-1-7,B

Very similar in all aspects to fraction A.

68-2-3 Grey Hornblende Granite

Intermediate to large in size. Subhedral to rounded but with a noticeable incidence of irregularly shaped grains. Near colorless to yellowish gray. Elongation ratio 1/1 to 1/3. Zoning and inclusions are well masked by the dark color but some cracks can be seen, as can some apparent rounded cores.

68-3-8,A Biotite Q Granite

Intermediate in size. Euhedral to subhedral. Some irregularly shaped grains are present. Near colorless to yellowish gray. Elongation ratio 1/1 to 1/5. Zoning and inclusions are common and most grains show fracturing.

68-3-8,B

Similar to above in size, zoning, inclusions, and fracturing. Somewhat lighter in color and more tendency towards subhedral in shape.

68-3-8,C

Slightly smaller generally than the other fractions with more small grains present. More rounded in shape, similar in color. Elongation ratio 1/1 to 1/6. Zoning, inclusions, and fracturing similar to above.

68-4-1 Biotite Granite F

Intermediate to small in size. Subhedral to rounded in shape with many long thin grains. Elongation ratio 1/1 to 1/6 and possibly greater because of some broken grains being present. Yellowish gray in color. Zoning and fracturing common but inclusions are slightly less so. A few cores can be seen.