$^{40}Ar/^{39}Ar$ Thermochronology of the Britt Domain Grenville Province - Georgian Bay, Ontario

by

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Abstract

The $^{40}Ar/^{39}Ar$ thermochronology of a transect of the Britt domain, Central Gneiss Belt, Grenville Province has been examined in this study. In total, twelve argon gas analyses were obtained. These came from five locations within co-genetic, single-cycle plutonic bodies which were metamorphosed during the Grenville Orogeny. Argon gas spectra were obtained for the minerals hornblende, biotite and K-feldspar separated from the plutonic rock samples. Diffusion experiments were carried out on the K-feldspars. This data yielded a calculated closure temperature for K-feldspar of 221° C (+/- 14°). The presence of excess argon was implicated in most of the biotite analyses. A cooling history diagram was obtained for the Britt domain. The rate of cooling from hornblende closure temperatures to K-feldspar closure temperatures, subsequent to the Grenville Orogeny was calculated at 7.5° C/Ma. The corresponding rate of exhumation would be about 0.25 km/Ma. These values are two to three times higher than values obtained from neighbouring areas but are much lower than values for young, active thrust orogens such as the Swiss Alps. It is believed that this area of the Britt domain underwent uniform cooling and exhumation after its metamorphism during the Grenville Orogeny. The relatively high rates, compared to nearby regions, may be due to the proximity to the Grenville Front.

Acknowledgements

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Dr. N.G. Culshaw and Dr. P.H. Reynolds for suggesting the study and supervising the work - they provided enthusiastic guidance as well as financial support; K. Taylor for advice and assistance in the argon lab; J. Mooers for advice on mineral separation technique; D. Corrigan for discussion and assistance in collecting samples in the field; and K. MacKillop for handling the initial crushing and some separation of mineral samples.

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1.1 Introduction to Regional Geology and Study

The Grenville Province is the youngest structural province in the Canadian Precambrian shield. It is mainly composed of amphibolite and granulite facies gneisses which underwent their last major orogenic event about 1.0-1.2 billion years ago (the Grenville Orogeny) (Moore, 1986).

The rocks of the Grenville Province are made up of so-called parauthochthonous and allochthonous terranes (Rivers and Chown, 1986). The Grenville Front, a zone of mylonitic rocks, marks the boundary with the autochthonous rocks of the Superior Province to the north. The parauthochthonous rocks in the Grenville Province are thought to have been derived from the northern (Superior) authochthon. They show the structural and metamorphic effects of the north- west directed thrusting of the Grenville Orogeny, while the autochthonous rocks do not. Allochthonous terranes are presumed to have been tectonically emplaced, as nappes, by northwest thrusting during the Grenville collisional orogen, south of the Grenville Front (Rivers and Chown, 1986).

This thesis presents the first $^{40}Ar/^{39}Ar$ thermochronometric study of the Britt domain, Central Gneiss Belt northwest of Parry Sound, Ontario (see Figure 1). The study area covers a zone almost the full width of the Britt domain, perpendicular to the Grenville Front Tectonic Zone (GFTZ), a region of the southwest Grenville Province believed to be mainly parautochthonous (Culshaw,N.G. pers. comm. 1989). Amphibolite facies gneisses within the Britt domain structurally overlie the Grenville Front Tectonic Zone and they in

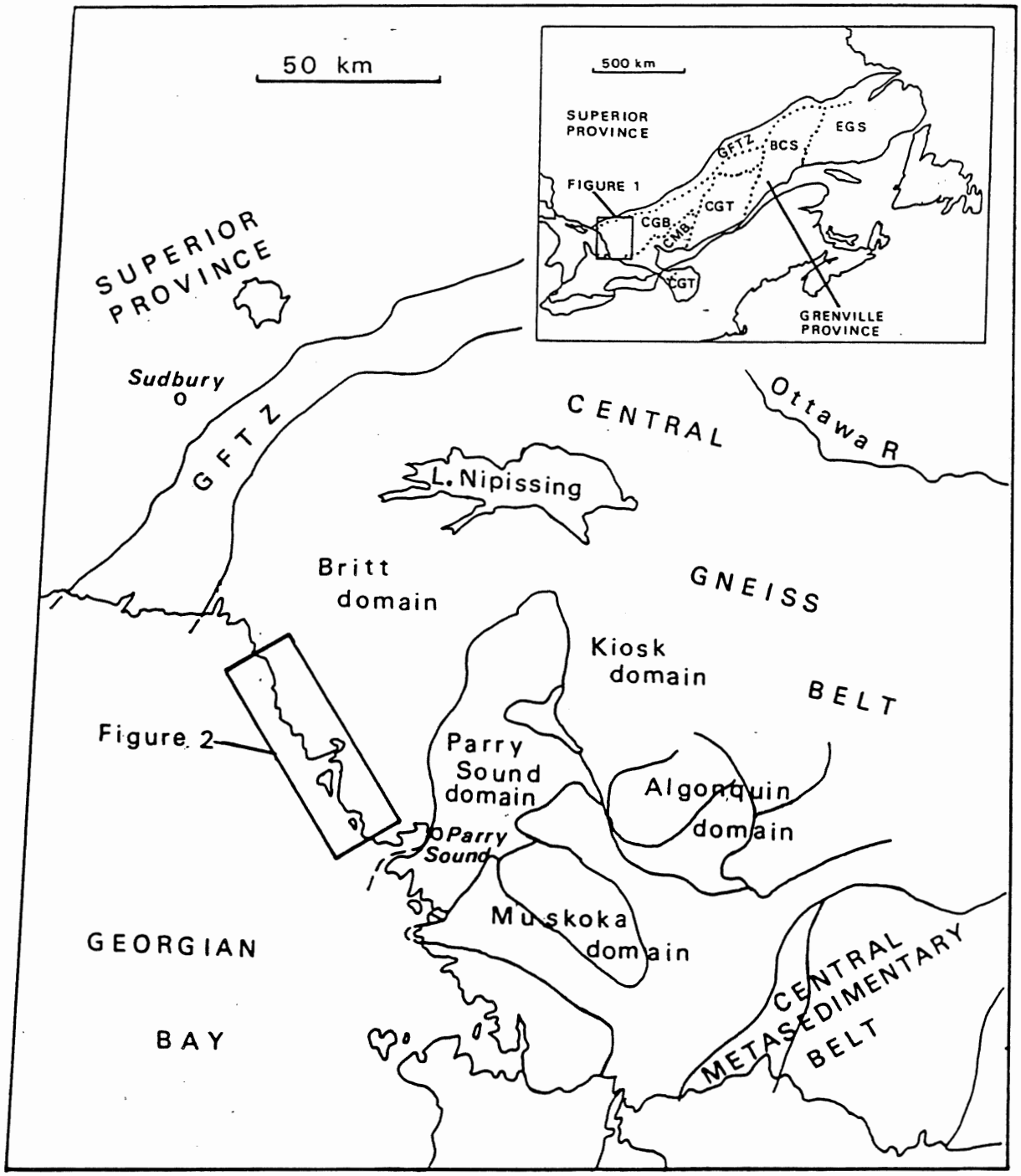


Figure 1 - Area of Study, Grenville Province

(adapted from Davidson, 1984)

turn are overlain by a major nappe - the Parry Sound domain in the south (Davidson, 1986).

Thermochronometry has been carried out on a suite of plutonic rocks intruded into the country rocks of the Britt domain. Some U-Pb dates from zircons have been obtained by others for this area. These are listed in Table 1. $^{40}Ar/^{39}Ar$ studies can obtain cooling histories for an area by dating co-existing minerals which have different closure temperatures for argon retention. Such studies have only been done in a few areas of the Grenville Province. These areas include:

1) S.W. Labrador (Dallmeyer and Rivers,1983)
2) Bancroft Terrane, Haliburton, Ontario (Berger and York, 1981)
3) Elzevir Terrane, Central Ontario (Hanes et al, 1988 and Lopez-Martinez and York, 1983) and
4) most recently a number of locations east and south from Parry Sound, Ontario within the Central Gneiss Belt and Central Metasedimentary Belt (Cosca et al,1988).

Table 1 - U-Pb Dates, Central Gneiss Belt

Event	Method	Age	Reference
Intrusion of the Britt pluton	U-Pb (zircon)	1456 Ma	van Breeman et al, 1986
Parry Sound Shear Zone ductile displacement	U-Pb (zircon)	1159 Ma	van Breeman et al, 1986
Peak Metamorphism Britt domain	U-Pb (zircon)	1015 Ma	D. Corrigan, pers. comm., 1989
Late pegmatite dykes Britt domain	U-Pb (zircon)	997 Ma	Corrigan et al, 1989

This study attempts to resolve the cooling history of a distinct system of plutonic rocks subsequent to their metamorphism in the Grenville Orogeny. This will be helpful in understanding processes of uplift and erosion related to the orogeny. It is a unique study for a number of reasons:

i) no $^{40}Ar/^{39}Ar$ data have been obtained for this area between Parry Sound and the Grenville Front

ii) the study spans a distance some 70 km long perpendicular to the Grenville Front, representing a cross-section of the Britt domain

iii) the rocks analyzed are compositionally all the same.

1.2 Geology of the Central Gneiss Belt and Plutonic Rocks

The Grenville Province has been divided into a number of zones based on tectonic style, metamorphic grade and rock assemblages. These zones are the Grenville Front Tectonic Zone (GFTZ) to the north, the Central Gneiss Belt (CGB), Central Meta-sedimentary Belt (CMB), Central Granulite Terrane (CGT), Baie Comeau Segment (BCS), and the Eastern Grenville Sub-province (EGS) (Wynne-Edwards,1972) (see inset Figure 1).

The Central Gneiss Belt lies southwest of the Grenville Front Tectonic Zone and extends parallel with it to the northeast. The CGB adjacent to Georgian Bay is divided into a number of domains consisting of different rock assemblages often with contrasting

structural and metamorphic features. These distinct domains are separated from each other by ductile shear zones (Davidson et al, 1982). Davidson and coworkers (1982) interpret the domains to be segments or slices stacked on top of each other by northwest directed thrusting. Of these domains the Britt domain is the lowermost in the stack and is structurally overlain by the Parry Sound domain immediately to the south. The area of this study is a north-south transect across the Britt domain.

The Britt domain has been divided into four distinct gneiss associations by Culshaw et al (1988). These associations are combinations of paragneisses or orthogneisses which show poly-metamorphic histories. Pelitic rocks throughout the Britt domain consistently contain the mineral assemblage kyanite-K-feldspar-migmatite (melt). This assemblage indicates high pressure and high temperature of formation (> 7 kb - Carmichael, 1978). The country gneisses have been intruded by mid-Proterozoic granitic rocks. These plutonic bodies are termed "single cycle" as they show the effects of only one metamorphic event (Culshaw et al, 1988). The largest of these, the Britt pluton, has been dated by U-Pb zircon methods as intruding at 1456 (+9/-6) Ma (van Breeman et al, 1986). An identical date has been obtained for a nearby pluton, 1456 (+/-12) Ma (D. Corrigan,pers. comm., 1989). The gneisses and intrusive granitic rocks were metamorphosed to amphibolite facies during the Grenville Orogeny. Deformation, partial migmatization and folding with N.W. trending fold axes occurred during this event. D. Corrigan (Msc. thesis in progress, pers. comm., 1989) estimates metamorphism in the northern Britt domain to have

attained peak values of ~ 700° C at 1015 (+/-18) Ma. Major ductile thrusting occurred earlier at the Parry Sound Shear Zone (PSSZ) and the Grenville Front Tectonic Zone (GFTZ). Van Breeman et al (1986) have dated syntectonic pegmatites within the PSSZ, which indicate displacement at 1159 (+5/-4) Ma. Minor late stage shearing is dated at 1121 (+/-5) Ma (van Breeman et al, 1986).

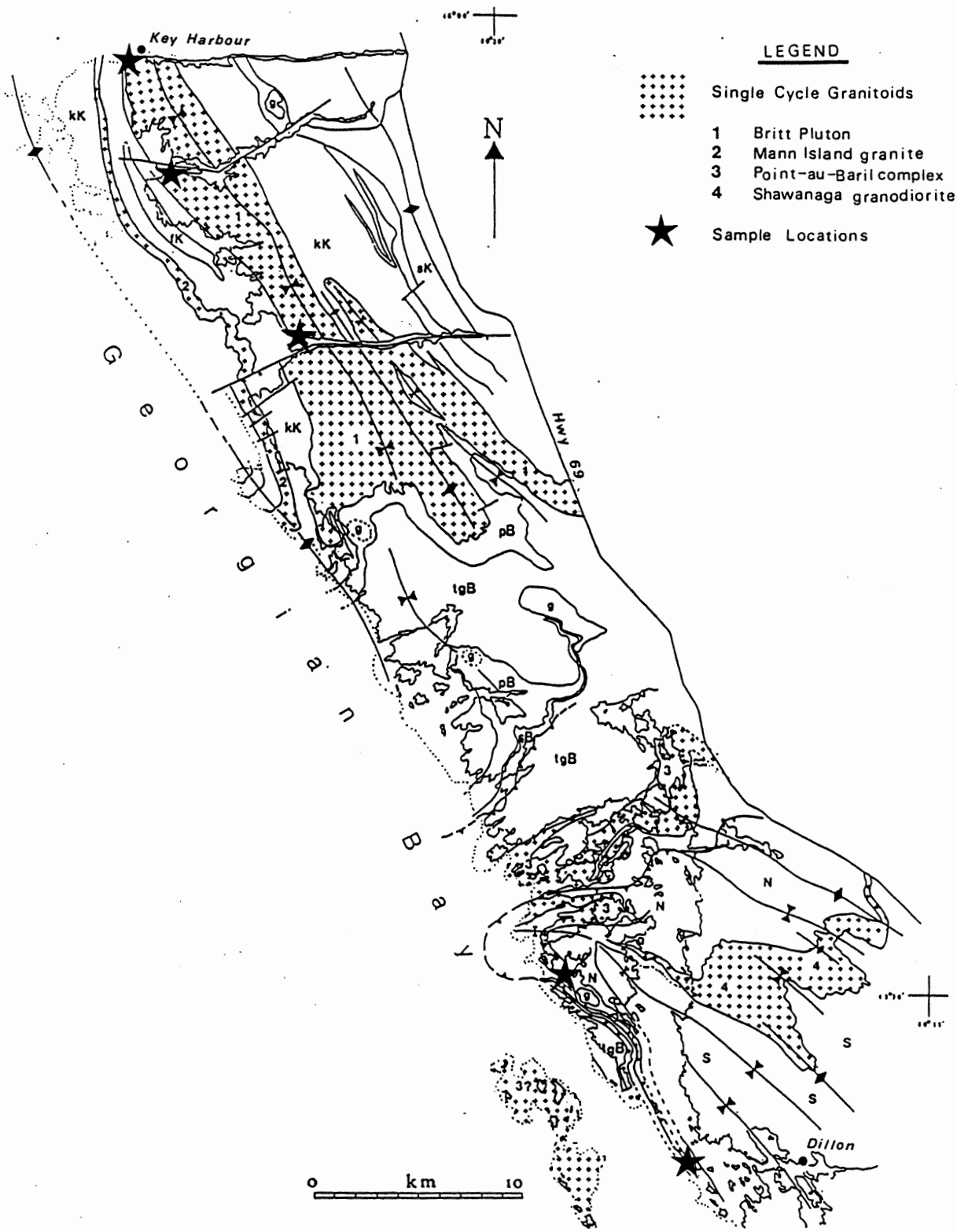
As mentioned previously much of the Britt domain is believed to be parauthochthonous. Field relations such as the presence of distinctive dykes and the similarities of Britt domain rocks to rocks close to the GFTZ support this (Culshaw,pers. comm.,1989).

A link may exist between rocks of the CGB, S.W. Grenville Province and Proterozoic rocks of the mid-North American continent. Van Breeman and Davidson (1988) suggest that both these areas are composed of similar crustal rocks. Some of their main evidence is that both areas have been intruded by granitic plutons (such as studied here) with similar ages. Comparisons of these areas (for example comparing $^{40}Ar/^{39}Ar$ cooling histories of the granites) should be useful in unravelling the larger-scale tectonic history.

1.3 Sampling

Samples were taken from plutons of the single cycle mid-Proterozoic granitic rocks including the Britt pluton and Pointe au Baril complex, in the region between Key Harbour and Sand Bay (Dillon) - see Figure 2. This is an approximately 70 km wide

Figure 2 - Sample Locations, Britt Domain (from Culshaw et al 1988)



transect and includes most of the Britt domain. Five samples were obtained, the two southern-most in 1987, the other three in 1988. A 10 km spacing for the sampling was originally envisaged and was kept to, except for an about 20 km gap where the single cycle granitoids of interest are not present.

The granitoid rocks sampled are metaplutonic rocks of either the Britt pluton (to the north) or Pointe au Baril complex (in the south). These bodies are believed to be related (Culshaw et al, 1988). These granitoid rocks were chosen for study because of their extensive nature and their consistent composition. This may be of help in argon dating studies. The granitoid rocks were commonly highly strained. Samples from low strain areas, representing a more pristine nature, were sought.

The single cycle plutonic rocks are megacrystic grano-dioritic orthogneisses with a mineral compostion of hornblende-biotite-quartz-feldspar-garnet. They show various states of strain and migmatization and have megacrystic feldspars where undeformed. One major event, the Grenville Orogeny, has affected them.

1.4 Methods and Aim of Study

From the five samples collected, a combined total of twelve mineral separates of hornblende, biotite and potassium feldspar were obtained. These minerals were irradiated and then analyzed by the $^{40}Ar/^{39}Ar$ method. Since these minerals have different closure temperatures for the retention of argon, a plot of closure temperatures versus age yields a cooling history curve. Hornblende

retains argon at the highest temperature, followed by biotite and then potassium feldspar. Isotopic resetting occurs when metamorphism raises temperatures above the mineral closure temperatures. In the Britt domain the latest resetting event of this kind occurred during the peak metamorphism of the Grenville Orogeny. A cooling curve, representing the cooling history subsequent to the Grenville Orogeny, is presented for the area examined. Rates of cooling can give indications of the processes by which exhumation has occurred. These processes may be those of active tectonic uplift, erosion or some combination of the two.

Chapter 2 - $^{40}Ar/^{39}Ar$ Dating

2.1 Theory

The ages of rocks can be determined by analytical methods based on the principles of radioactive decay of isotopes. Of particular interest in this study are the elements potassium K, and argon Ar, and their isotopes. The radioactive decay of the "parent" element ^{40}K over geologic time produces the so-called "daughter" or radiogenic isotope ^{40}Ar. The rate of decay of ^{40}K to ^{40}Ar is constant and by measuring the ratio of the two isotopes an age can be calculated for the time at which the system became closed to isotope diffusion. With two different elements, however, separate analytical techniques are required.

$^{40}Ar/^{39}Ar$ dating is an isotopic variation of conventional K/Ar dating. With the $^{40}Ar/^{39}Ar$ method the measurement of ^{40}K is achieved indirectly from the measurement of neutron activated ^{39}Ar, as these two are in proportion to each other. Rock or mineral samples are irradiated with fast neutrons in a nuclear reactor which causes a portion of the ^{39}K in the samples to be converted to ^{39}Ar. The $^{40}Ar/^{39}Ar$ ratio is then measured and an age can be calculated. This eliminates the need for a separate K analysis (Dallmeyer,1979).

An additional advantage to $^{40}Ar/^{39}Ar$ dating is that the technique allows a sample to be incrementally heated during analysis. This results in an age spectrum being produced, rather than just a total gas age (York, 1984).

The production of ^{39}Ar by irradiation is given by the following formula:

$$^{39}Ar_K = {}^{39}K \Delta T \int \varphi(\epsilon)\sigma(\epsilon)\, d\epsilon \qquad (1)$$

where $^{39}Ar_K$ = ^{39}Ar produced from ^{39}K
^{39}K = ^{39}K present in sample
ΔT = duration of irradiation
$\varphi(\epsilon)$ = irradiation parameters
$\sigma(\epsilon)$ = " "

The production of radiogenic ^{40}Ar from the spontaneous decay of ^{40}K is given by the following formula:

$$^{40}Ar^* = {}^{40}K \frac{\lambda_e}{\lambda} (e^{\lambda t} - 1) \qquad (2)$$

where $^{40}Ar^*$ = radiogenic ^{40}Ar produced in sample
^{40}K = ^{40}K present in sample
t = sample age
λ_e = decay constant for electron capture by ^{40}K
λ = total decay constant for ^{40}K

By combining equations 1 and 2 one obtains a formula expressing the $^{40}Ar/^{39}Ar$ ratio:

$$\frac{^{40}Ar^*}{^{39}Ar} = \frac{^{40}K\ \lambda_e\ (e^{\lambda t} - 1)}{^{39}K\ \lambda\ \Delta T \int \varphi(\epsilon)\, \sigma(\epsilon)} \qquad (3)$$

As some of the irradiation parameters and other values are difficult to evaluate, a quantity J is introduced.

$$J = \frac{^{39}K\ \lambda}{^{40}K\ \lambda_e}\ \Delta T \int \varphi(\epsilon)\, \sigma(\epsilon)\, d\epsilon \qquad (4)$$

Replacing the appropriate values in equation (3) by J yields:

$$\frac{^{40}Ar^*}{^{39}Ar} = \frac{e^{\lambda t} - 1}{J} \qquad \text{or } J = \frac{e^{\lambda t} - 1}{^{40}Ar^*/^{39}Ar} \qquad (5)$$

The factor J can be determined experimentally for an irradiation as long as a sample of known age is irradiated along with the unknowns. From equation (5) the ages of the unknowns are derived by solving for t :

$$t = \frac{1}{\lambda} \ln \left({}^{40}Ar^*/^{39}Ar\ J + 1 \right) \qquad (6)$$

The error in t is expressed as:

$$\sigma_t = \left[\frac{J^2 F^2 (\sigma_F^2 + \sigma_J^2)}{t^2 \lambda^2 (1 + FJ)^2} \right]^{1/2} \qquad (7)$$

where $F = {}^{40}Ar^*/^{39}Ar$
and σ_F^2 and σ_J^2 are percent variances of F and J.

(Faure,1977).

2.2 Closure Temperatures

It is very important when discussing isotopic age dates to understand the significance of the geologic conditions affecting dates. Since isotopic ages are a measure of the decay of parent to daughter isotopes it is clear that these ages represent the times

at which the various isotopes became immobile and began to accumulate in a mineral or rock. Prior to these times, isotopes were mobile (i.e. they could diffuse) and any daughter isotopes produced by radioactive decay may have migrated out of the system.

It was once thought that isotopic ages must represent either the time of crystallization of a rock from a melt, or the time of recrystallization during a metamorphic event - times when mobile elements obviously become immobile (Dodson, 1973). However, Dodson (1973) noted that some isotopes, particularly radiogenic argon and strontium, are mobile in minerals at temperatures below that of crystallization. Generally speaking, during cooling, the temperature at which an isotope becomes immobile and begins to accumulate in a system is its "closure" temperature. An apparent argon age (t_c) represents the time at which a rock unit cooled through a particular isotopic closure temperature. See Figure 3 below.

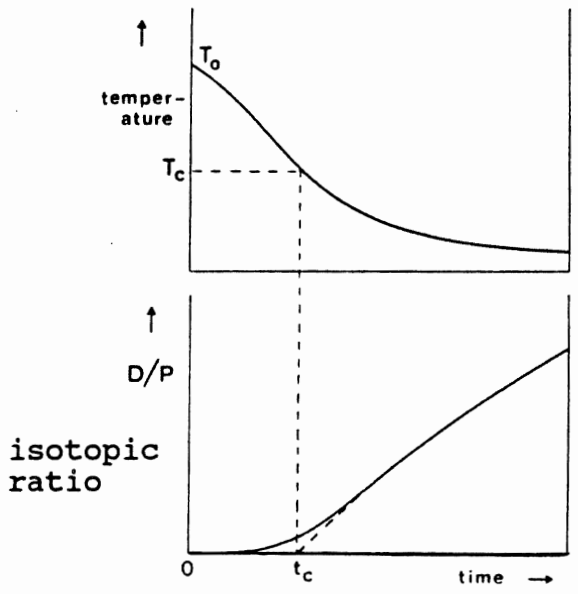


Figure 3 -

Closure temperature (T_c) related to age (t_c)

(after Dodson, 1973)

Since different minerals have different closure temperatures for argon retention, the cooling history of a sample can be obtained by plotting the $^{40}Ar/^{39}Ar$ ages for coexisting minerals on a temperature-time graph. Minerals commonly used in $^{40}Ar/^{39}Ar$ studies are hornblende, micas and feldspars. In this study hornblende, biotite and K-feldspar are used.

Dodson (1973) provides a method by which the closure temperature of a mineral can be calculated. In the Dodson equation the closure temperature is given by :

$$T_c = \frac{E/R}{\ln \frac{AR\,(T_c)^2\,(D_o/a^2)}{E\,(dT/dt)}}$$

where E = calculated activation energy
R = gas constant 1.987 cal/mol ^{o}K
A = diffusion geometry
dT/dt = cooling rate ^{o}C/sec
D_o = diffusion frequency factor
a = grain size parameter (effective diffusion distance)

The required factors can be derived from an Arrhenius plot of diffusion parameters obtained from the $^{40}Ar/^{39}Ar$ step heating analysis. The slope of such a plot is equal to - E/R and the y-intercept is equal to D_o/a^2 (see section 4.2). This method is only useful, however, for minerals which remain stable during heating. Minerals which undergo phase transitions during heating or that have H_2O in their structure will give erroneous results under ordinary (<u>in vacuo</u>) lab procedure, due to the associated change in diffusion parameters. Hornblende and biotite are two such problematic minerals. Feldspars are more stable and therefore more

reliable (York, 1984; P. Reynolds pers. comm. 1988).

Closure temperatures can be obtained by utilizing essentially the same data that were used for obtaining apparent argon ages. For feldspars only a slight change in analytical technique is required.

It is evident from the literature that the closure temperature of a mineral can vary slightly from region to region and even within the same outcrop. This is perhaps due to compositional differences (Onstott and Peacock, 1988). It is generally established, however, that hornblende has a relatively high closure temperature, biotite has a lower closure temperature and K-feldspar an even lower temperature of closure. General estimates for closure temperatures are listed below.

Table 2

Mineral	Closure Temperature
Hornblende	480-500 ° C
Biotite	280-300 ° C
K-feldspar	200 ° C

(Harrison, 1981; Harrison et al,1985; McDougall and Harrison, 1988)

After irradiation, a sample is analyzed in the lab by a step-heating process from which age spectra information is obtained. Age spectra signatures can often yield valuable information on the history of cooling and gas retention of a sample. Figure 4 shows age spectra for three minerals in a sample. The differences in

their ages reflects cooling through the three different closure temperatures.

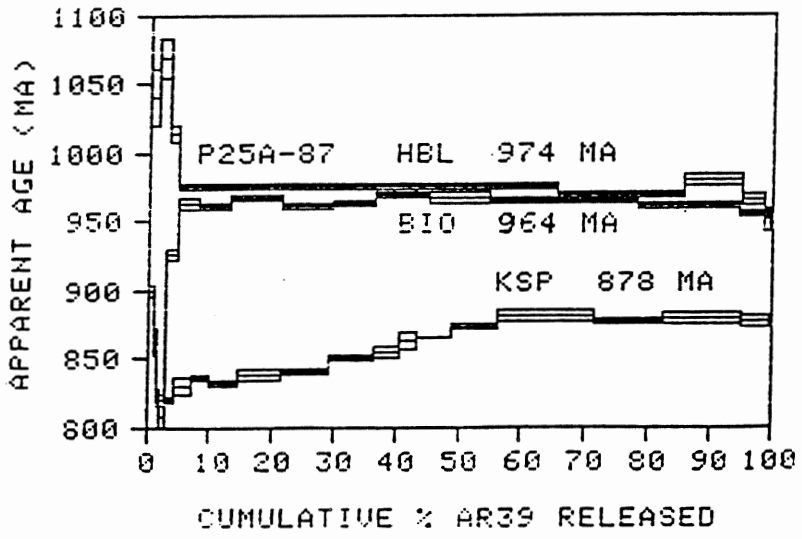


Figure 4 - Three mineral age spectra from one hand sample (P25A) of a granodioritic pluton, Britt domain, Central Gneiss Belt, S.W. Grenville Province

2.3 How To Read Age Spectra

Different methods exist by which argon spectra for minerals can be assigned an age. The first and most common is to use the total gas age which represents the weighted average of ages from all heating steps. When spectra are discordant (not flat) however, total gas ages can be erroneous or misleading. The second method,

preferred in this study, is that of using objectively assigned criteria to determine a "plateau age". The criteria used are those of Fleck et al (1977) which require that a plateau represents at least 50 % of the gas released in contiguous steps. In addition, no two of these steps can have age differences greater than the "critical value" (C.V.). The C.V. is calculated as follows:

$$C.V. = 1.960\ (\delta_1^2 + \delta_2^2)^{1/2}$$ with δ_1 and δ_2 being the standard deviation of the two steps used (Fleck et al, 1977).

If the above criteria are met, a weighted average of those steps used determines the plateau age.

An examination of the previous Figure 4 (three co-existing minerals) can clarify these points. Hornblende has a total gas age of 977 Ma but it is seen to have an anomalous "spike" in age in the initial steps. The plateau age, which excludes this anomaly, has a slightly lower age of 974 Ma. The biotite total gas age is 949 Ma but this includes the seemingly anomalous low initial ages. The plateau age is more representative at 964 Ma. The total gas age for K-Feldspar is 862 Ma. It can be seen that this spectra is not concordant (not flat). It has a staircase pattern rise in age for ~50 % of the gas released, then a plateau for the latter 50 %. The plateau age for K-Feldspar P25A is 878 Ma. This plateau is taken from the last 50 % of the gas released and passes the C.V. test.

2.4 Interpretation of Age Spectra

The interpretation of an age spectrum can in some cases be straightforward, in other cases it can be confusing. It is generally thought that the "plateau" age (the age from the flat, relatively concordant part of an age spectrum) represents the cooling age of a mineral through its closure temperature. It has been observed, however, that some concordant (or flat) spectra have yielded anomalously old ages. Biotite can often show this effect. This is believed to be due to the presence of excess argon. Excess argon is argon which was not present in a sample initially but which was subsequently incorporated into the sample. K.A. Foland (1983) has studied the effects of excess argon in biotite and finds it to be a problem which cannot be resolved from the interpretation of step-wise age spectra alone. He believes that excess argon in biotite is common in slowly cooled poly-metamorphic rocks.

S.L. Anderson (1988) notes the presence of excess argon in biotites from the Grenville Province but suggests that hornblendes are less likely to contain excess gas. With a co-existing biotite-hornblende pair then, biotite would show the presence of excess argon by yielding an apparent age older than that of hornblende. Such "anomalous pairs" are one way of recognizing the presence of excess argon. Other evidence can come from analyses which yield geologically unreasonable ages for samples (e.g. far too old). A third indicator of the presence of excess argon is found in the age spectra of some hornblendes, and K-feldspars, but generally not in the spectra of biotites. This occurs when a discordant spectrum

is produced yielding abnormally high ages (a "spike") in the first few heating steps which then level off to a plateau (Anderson, 1988).

Dallmeyer and Rivers (1983), working in the north-eastern Grenville Province, have observed all of the above indications of excess argon. Cosca, Sutter and Essene (1988), working in the south-west Grenville Province, have particularly noted the presence of excess argon in biotites. My work in the Britt domain indicates excess argon effects, to different degrees, in hornblende, biotite and K-feldspar.

The occurrence of discordant age spectra for some minerals can indicate a partial resetting of argon systems due to metamorphic events, may be due to slow cooling, or as discussed above may indicate the presence of excess argon. Partial resetting can be indicated by spectra which typically show low gas ages during low temperature steps. The apparent ages rise to a plateau level during the later, high temperature steps of an analysis. Discordant spectra of this type arise when metamorphic temperatures affect argon diffusion systems in minerals but do not rise high enough to totally reset the system. Minerals with lower closure temperatures (such as feldspars) will show the effects of reheating before minerals with higher closure temperatures (such as hornblendes). Slow cooling can also result in discordant spectra. This is mainly seen in feldspars. In these minerals low temperature, staircase, step-heating patterns indicate partial argon gas loss. At higher temperatures asymptotic values are usually reached. These plateau values likely correspond to the ages

at which minerals cooled through their closure temperatures.

If the cooling ages and temperatures of closure for various co-existing minerals in a sample are plotted, a thermal history cooling curve can be defined. It is useful to compare cooling curves calculated for different areas within an orogenic belt. This thesis presents cooling history data, for similar plutonic rocks, within the Britt domain, across strike south of the Grenville Front Tectonic Zone.

Chapter 3

3.1 Sample Description

All the samples obtained come from "single cycle" mid-Proterozoic granodioritic plutons. Of the five rocks sampled, two were obtained in 1987 by Dr. Nicholas Culshaw and Peter Wallace and three in 1988 by Gordon Check, all of Dalhousie University, N.S. Samples G5, G6, and G10 are from the Britt Pluton in the north. Samples N406 and P25A are from a similar pluton in the south.

Hand specimens are generally quite similar megacrystic hornblende-garnet-biotite-potassium feldspar-quartz gneisses with varying degrees of strain from strong lineation and foliation to virtually none. Potassium feldspars form the megacrysts and are often quite deformed by strain.

Thin section observations yielded a few interesting features including:

- inclusions of potassium feldspar, quartz and biotite in hornblende and biotite and occasional minor intergrowth of hornblende/biotite.
- hornblende is generally moderately embayed and not zoned, but one slide (N406) contains hornblende that is extremely embayed and has very many inclusions.
- biotite and hornblende define a foliation in all the thin sections except N406 which shows no fabric.
- undulose extinction in quartz.
- microperthitic texture of nearly all potassium feldspars.

- the presence of significant proportions of plagioclase feldspar, generally not noticed in hand samples.
- slight alteration of most feldspars to sericite.
- lack of garnet in G6 and G10.
- the presence of epidote and sphene as discrete grains or as rims surrounding opaque minerals.
- small apatite grains observed in all slides.

On the following page, Table 3 lists a summary of the properties of the minerals used in this study for argon dating.

3.2 Sample Preparation

From the five rock samples examined twelve mineral separates were obtained (five biotite, four hornblende and three potassium feldspar). The fist-sized rocks were first crushed in a tungsten-carbide shatterbox by hydraulic press and then sieved and washed, yielding a 60 - 120 mesh fraction (.25-.125 mm). This size fraction was then used to obtain hornblende, biotite and K-feldspar separates by the following methods.

The samples were run through a Frantz magnetic separator which separated them into felsic and mafic fractions by their magnetic susceptibilities (quartz/feldspar less magnetic than biotite/hornblende/garnet). Nearly pure biotite samples could then be obtained by the technique of paper-panning the mafic fraction on an inclined sheet of paper. Thin, flat biotite adhered to the sheet while other minerals rolled off. From the

Table 3 - Summary of Mineral Properties

Sample	Mineral	Grain size	%	Properties
G5	- Hornblende	< 5 mm Avg. 1 mm	10%	- Anhedral, embayed edges - Inclusions - Some biotite intergrowth
	- Biotite	< 1 mm	10%	- Subhedral laths - Minor inclusions
	- K-feldspar	< 5 mm Avg. 1 mm	30%	- Anhedral - Slight sericitization - Microperthitic texture
G6	- Biotite	< 1 mm	5-10%	- Subhedral
G10	- Hornblende	< 5 mm Avg. 1.5 mm	25%	- Anhedral - Some inclusions - Slight biotite intergrowth
	- Biotite	< 1.5 mm	5%	- Subhedral - Smaller secondary phase as inclusions
	- K-feldspar	.5-1 mm	30%	- Anhedral - Moderate sericitization - Microperthitic texture
N406	- Hornblende	.5-3mm	15-20%	- Anhedral, embayed - Many inclusions - Slight intergrowth with biotite and garnet
	- Biotite	< .5 mm	2%	- Subhedral laths or wider pieces
P25A	- Hornblende	< 4 mm Avg. 1 mm	5-10%	- Anhedral - Few inclusions - Minor biotite intergrowth
	- Biotite	< 1 mm	5-10%	- Subhedral laths
	- K-feldspar	Avg. 1 mm	20%	- Anhedral - Slight sericitization - Microperthitic texture

fraction rolling off the sheet, hornblende was separated from the other minerals by heavy-liquid immersion. A solution of methylene-iodide (density ~2.9 g/cc) was used to first separate out any remaining light, unwanted minerals (quartz, feldspar,biotite). The remaining heavy garnet/hornblende mixture was then separated by carefully drawing off the garnet-rich portion from the bottom of the heavy methylene-iodide solution, leaving a relatively pure hornblende separate behind.

The non-magnetic, felsic fraction was similarly immersed in a heavy liquid solution (sodium polytungstate- density ~2.6g/cc) to separate out the less dense K-feldspar from quartz, plagioclase feldspar and other denser non-magnetic minerals.

The relatively pure mineral separates obtained were then placed in acetone and carefully handpicked using an optical microscope. Using this method very high sample purities resulted (>99%). Aliquots of biotite (~200mg), hornblende (~500mg) and K-feldspar (~100mg) were wrapped in foil and placed inside a cannister. The cannister was irradiated at McMaster University by bombardment with fast neutrons for approximately ten hours. It was returned to Dalhousie University and the samples were allowed to "cool" for nearly two months before analysis began.

3.3 Argon Lab Procedure

Argon gas was extracted from micas and amphiboles by placing them in a quartz tube which was externally resistance-heated by an enclosing Lindberg furnace. Feldspars were heated separately in a

higher temperature, internally resistance-heated, tantalum furnace. The glass tubing was then pumped to obtain vacuum conditions. Gas released from the sample upon heating was admitted to the A.E.I. MS-10 mass spectrometer after the following conditions had been met:

1) The sample had been outgassed for at least fifty minutes at each temperature increment (generally 25-50° C) which increased to a maximum of 1140° C (1300° C in the higher temperature furnace).
2) The gas impurities had been separated by cleaning the gas with the titanium "getter" which traps impurities.
3) Remaining impurities (volatiles) had been removed by condensation in a "cold" finger.

The gas sample was moved around the <u>in vacuo</u> system aided by the process of activated charcoal adsorption at liquid nitrogen temperatures (-196° C) and a system of valves (see diagram Figure 5).

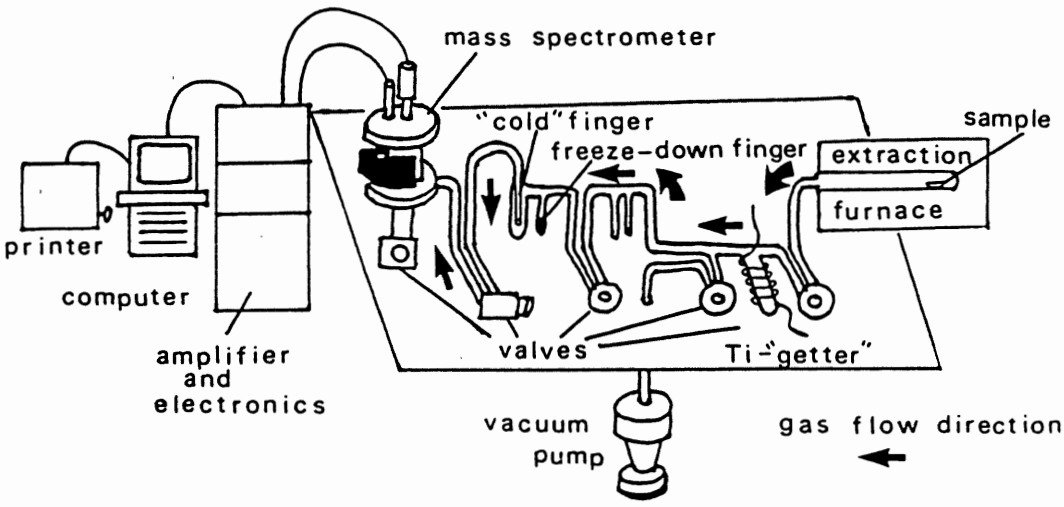


Figure 5 - Dalhousie University Argon Gas Analysis System

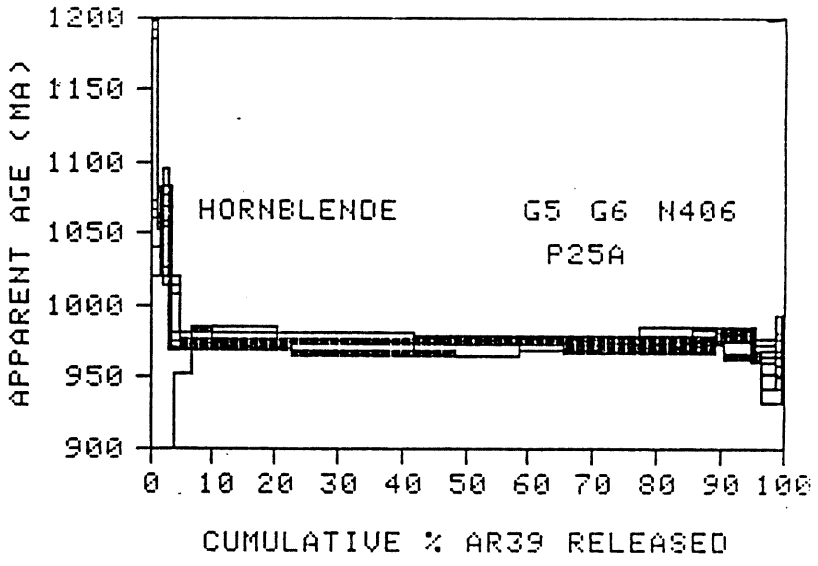
Gas admitted to the mass spectrometer was analyzed for the following isotopes of argon: ^{40}Ar, ^{39}Ar, ^{37}Ar, ^{36}Ar. Measurements of ^{36}Ar and ^{37}Ar were used for atmospheric and elemental contamination corrections. The mass spectrometer signals were amplified and then sent to an Apple IIE computer which has programs for the data handling. For each mineral sample the gas released from approximately ten incremental heating steps was analyzed. The gas released from each step had its Ar ratios measured fifteen times, requiring about fifty minutes total analysis time. An immediate printout of isotope ratios, correction factors and age for the step was obtained. All the gas release steps for a sample were later plotted together on an apparent age versus $\%^{39}Ar$ diagram yielding an age spectrum.

Chapter 4 - Results

Hornblende:

Hornblende dates were obtained for four samples G5, G6, N406 and P25A. Their plateau ages, respectively, are 968, 975, 975 and 974 Ma. All four are plotted on one graph in Figure 6 showing their close similarities in age and spectral pattern. Of interest is the elevation or "spike" in age of the initial gas release, in three of the four spectra. Dallmeyer and Rivers (1983) attribute this effect to loosely bound excess argon concentrated on the rims of hornblende crystals. Alternatively, as suggested by Dallmeyer and Sutter (1980), ^{39}Ar loss due to the effects of irradiation recoil may be occurring. The plateau ages defined by the remaining concordant steps represent geologically reasonable ages for cooling through the temperature of closure (T_c) for hornblende.

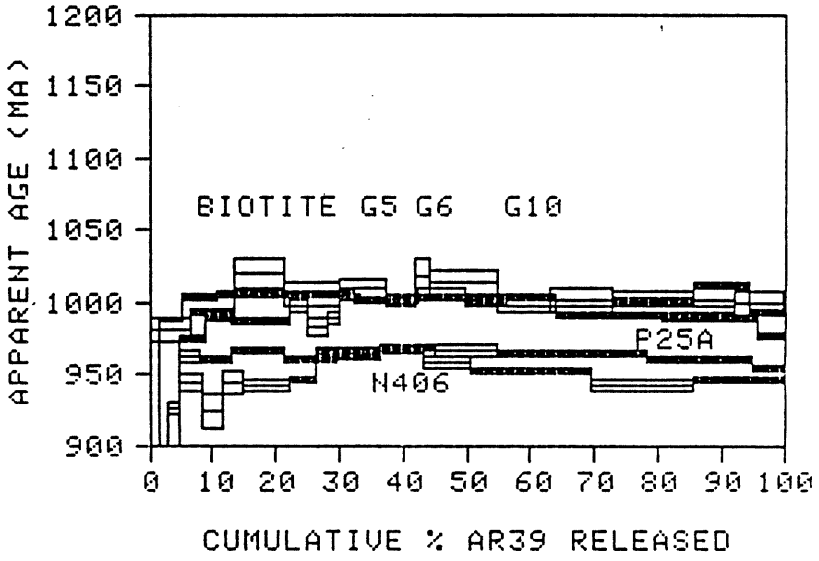
Figure 6 - Hornblende Spectra



Biotite:

Biotite ages were obtained for five samples G5, G6, G10, N406 and P25A. Their spectra are plotted together for comparison in Figure 7. Plateau ages are defined for all of the spectra except G6 (its age is given as a weighted average, not meeting the C.V. plateau criteria). The ages respectively are 1003, 990, 1003, 947 and 964. From Figure 7 it is seen that the spectra plot in roughly two groupings, the upper (G5, G6, G10) around 1000 Ma and the lower (N406, P25A) around 955 Ma. When each sample is compared with its co-existing hornblende, it is seen that the upper grouping of biotites gives dates which are above those of the hornblendes. This is contrary to what would be expected. These samples are thought to give anomalously old ages due to the presence of excess argon.

Figure 7 - Biotite Spectra

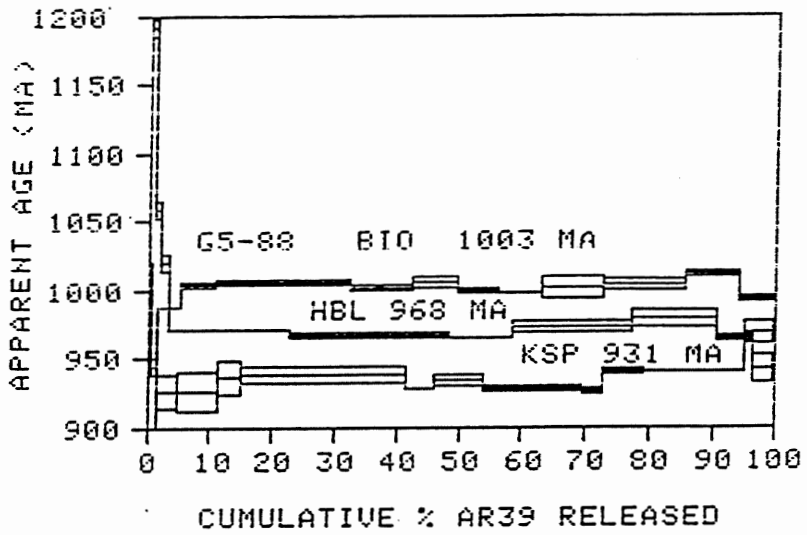


A clear example of the presence of excess argon is seen below in Figure 8 (sample G5) where an anomalous biotite spectrum is plotted with its co-existing hornblende and K-feldspar.

Figure 8 -

G5 Co-existing Minerals

Anomalous Biotite

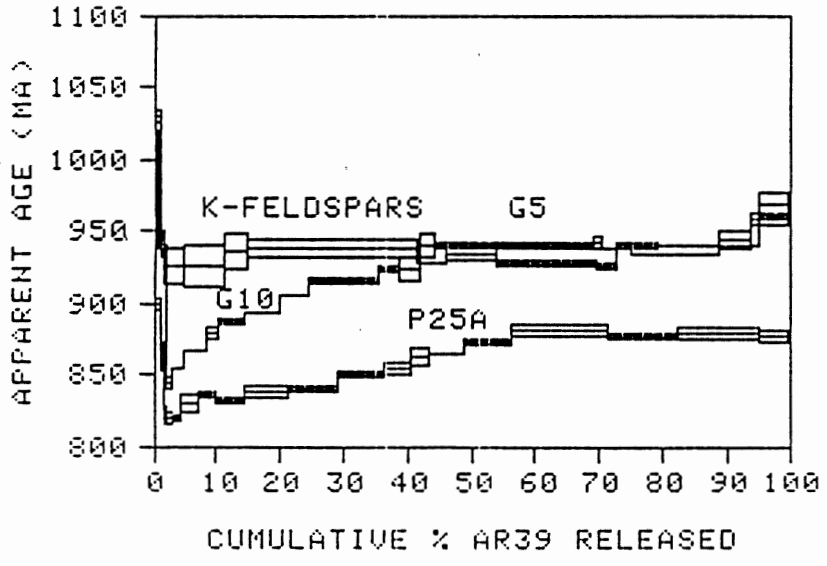


Only the southern two samples (N406 and P25A) yielded biotite spectra which plot below their respective hornblendes. This, however, cannot be the sole criteria for judging reliability. Their ages may still be slightly elevated due to the presence of excess argon. As mentioned earlier concordant biotite spectra, giving anomalously old ages, occur frequently.

K-Feldspar:

K-feldspar dates have been obtained from samples G5, G10 and P25A. Plateau ages determined are, respectively, 931, 938 and 878 Ma. These are correlated with closure temperatures calculated from diffusion plots (see section 4.2). Figure 9 shows the K-feldspar spectra plotted together. The plateau ages for G5 and G10 are seen to merge while P25A is lower. All three spectra show an initial spike in age probably due either to excess argon or ^{39}Ar recoil loss during irradiation. G5 displays an otherwise concordant spectrum, unusual for slowly cooled feldspars which usually have staircase spectra. G10 and P25A display the more usual staircase pattern ascending to a plateau level.All K-feldspars plot below their co-existing hornblendes and biotites as expected and are believed to give reliable dates. Thus G5 and G10 belong to one grouping and P25A to another. The reasons for two feldspars yielding staircase patterns and one a concordant plateau are unknown but are likely to be related to diffusion properties of the minerals.

Figure 9 - K-Feldspar Spectra



4.2 Argon Diffusion Data For K-Feldspar

As mentioned earlier (chapter 3) it is important to know the closure temperature of a mineral as this relates to the age resulting from analysis. An Arrhenius diffusion plot is used to assist in calculating the T_c. During the step-heating of a sample the argon gas release (i.e. diffusion) can be carefully monitored with respect to time and temperature. These data allow one to solve diffusion equations yielding the diffusion parameter D_o/a^2 which is then plotted (as a logarithmic function) against temperature on the Arrhenius plot.

Biotite and hornblende, which contain structural water, are thermodynamically unstable while being heated in a vacuum. This results in argon gas release by methods other than diffusion (McDougall and Harrison,1988). The uncertainty of argon release by such hydrous minerals during <u>in vacuo</u> heating makes them unsuitable for this type of diffusion plot (Cosca et al, 1988). Early determinations of closure temperatures for these minerals by diffusion plots from <u>in vacuo</u> analyses (Berger and York, 1981), resulted in closure temperatures much higher than those calculated for data obtained during controlled hydrothermal experiments (conditions under which biotite/hornblende should be relatively stable) (Cosca et al, 1988). Thus for this study, closure temperatures for biotite and hornblende are taken from controlled hydrothermal studies reported in the literature. For hornblende this is 480-500° C (Harrison, 1981) and for biotite this is ~ 280° C (Harrison and McDougall, 1985).

K-feldspar, however, is a stable anhydrous mineral which does undergo diffusive argon loss during the step heating process (in vacuo or hydrothermally). Since in this study step heating was done in vacuo it was reasonable to plot K-feldspar diffusion data on the Arrhenius diagram and determine the temperatures of closure. Calculations using the argon step heating data yield the diffusion parameters $\log_{10} D/a^2$. These are plotted against 1000/T (° K). Figure 10 a) shows an Arrhenius plot for a K-feldspar from sample P25A. This is an excellent example showing how a straight line can be fitted to the lower temperature steps (< 750° C). The jog in the line at 750° C (~ 0.95) is likely to be due to perthite lamellae homogenization beyond this temperature as predicted by McDougall and Harrison (1988). Figures 10 b) and 10 c) show the plots of the two other K-feldspars analyzed. The slope of the line corresponds to the activation energy E and the y-intercept gives the diffusion parameter D_o/a^2. These values along with some constant values are put into Dodson's (1973) equation (see chapter 2) to determine the closure temperature Tc.

$$Tc = \frac{E/R}{\ln \frac{AR\,(T_c)^2\,(D_o/a^2)}{E\,(dT/dt)}}$$

where:

E = calculated activation energy derived from slope (-E/R)
R = gas constant 1.987 cal/mol °K
A = diffusion geometry 55 (sphere)
dT/dt = cooling rate 3.16 x 10^{-14} °C/sec (1° C/Ma)
D_o = frequency factor
a = grain size parameter (effective diffusion distance)

P25A has a calculated T_c of 221° C (+/- 14°).

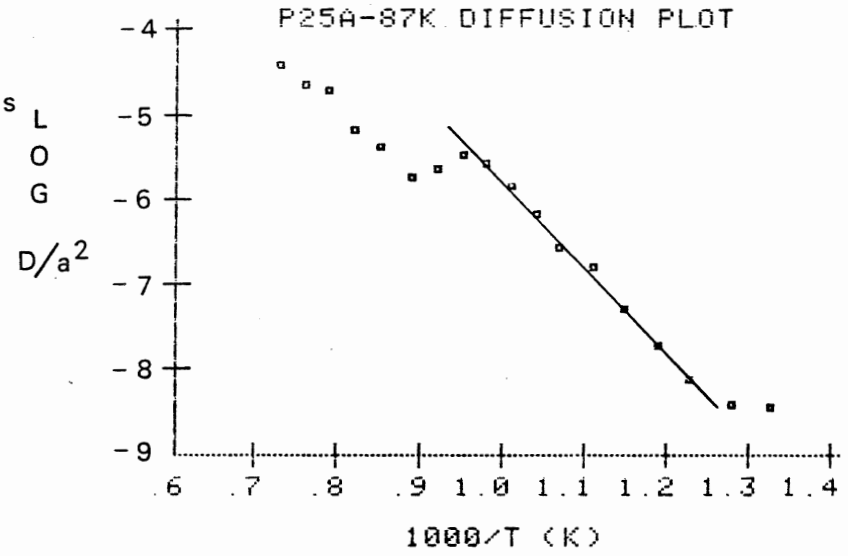
G5 has a slightly higher T_c = 231° C (+/-27°).

G10 has a lower T_c = 186° C (+/- ~60°).

Figure 10 –
Arrhenius Diffusion Plots

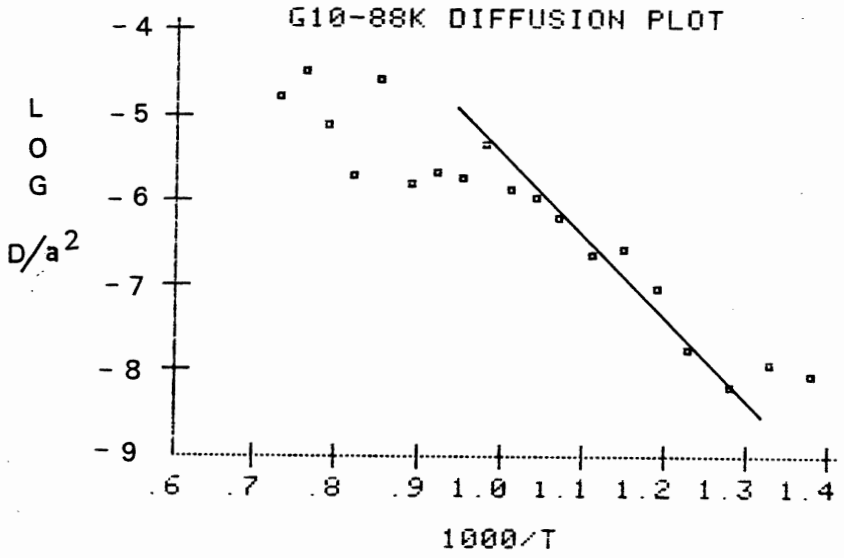
a) $E/R = 23553$

$D_o/a^2 = 27863$



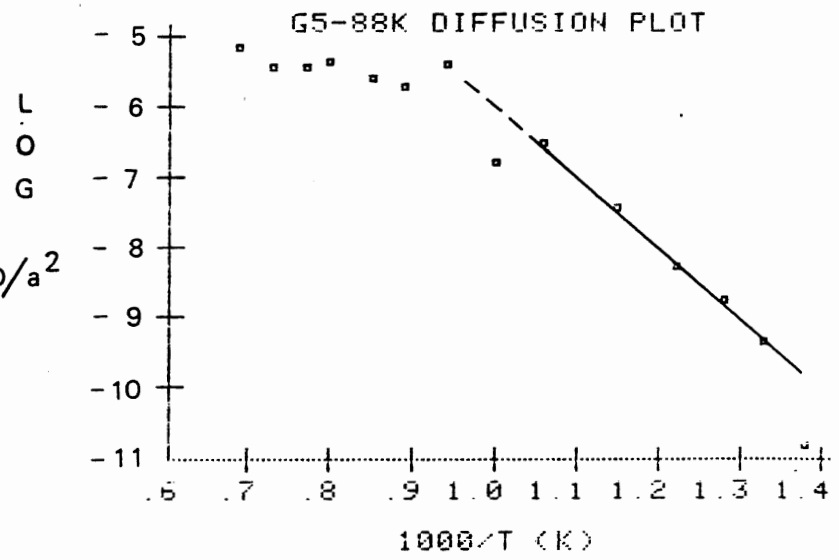
b) $E/R = 21074$

$D_o/a^2 = 4756$



c) $E/R = 24219$

$D_o/a^2 = 40710$



Although the method of argon gas analysis for the diffusion plots proceeds in the same manner as for ordinary argon analysis, it is important to use many incremental temperature steps (especially at the lower temperatures) and to accurately record heating time during a diffusion experiment. P25A appears to have yielded the best result and its T_c of 221° C (+/- 14°) will be taken to represent the T_c for all the K-feldspars in this study. The other calculated T_c's have errors within its range. This T_c (221° C) is slightly higher than some others reported (130-200° C McDougall and Harrison, 1988).It is noted, however, that a T_c of 230 ° C (+/- 18°)(using dT/dt = 0.5° C/Ma) was calculated by Berger and York (1981) for a K-feldspar a few hundred kilometres southeast from this study, within the Central Metasedimentary Belt.

It is noted that it may be possible to obtain segments of cooling curves from feldspar diffusion data rather than just one temperature/time point. The method assumes that the spectral profile is related to slow cooling and mineral diffusion gradients. McDougall and Harrison (1988) outline how calculations yielding a closure temperature profile from a mineral proceed. The useful result is that the cooling rate for the duration of mineral closure could be obtained (P. Reynolds, pers.comm.,1989).

4.3 - Discussion of Spectra Results

It has been seen that the hornblende spectra all yield similar apparent ages (within errors). As was shown, the biotite spectra can be separated into those obviously influenced by excess argon

and those not.

The apparent age difference of the two feldspar groupings has a number of possible explanations:

1) Different thermal histories for the sites - Although this is possible there is no apparent reason for different thermal conditions of this sort. The consistency of hornblende dates across the area constrains such a theory. Any thermal difference would have had to arise subsequent to regional cooling through hornblende closure temperatures. A complex structural explanation for this does not seem likely.

2) Turner's model for diffusive gas loss due to reheating events - Turner (1969) has modeled diffusive argon loss in samples that have undergone a degassing event. His model curves (Figure 11) show the style of spectra expected for varying degrees of gas loss, by simple volume diffusion from spheres, due to a specific event. The calculated curves diverge from the age of a reheating event and rise to plateaus representing varying percentages of the true mineral age. At first glance, the K-feldspar spectra from this study appear to be approximated by Turner's model (refer back to Figure 9). With such a model G5 represents no gas loss, G10 shows slight gas loss and P25A shows greater gas loss. Two problems with this are seen. First, G10 has a plateau age slightly above G5 when it should be slightly below (although this falls within errors). Second, and most important, the Turner model necessitates a degassing (reheating) event at an age from which the spectra initially diverge. As seen in Figure 9 this would be sometime between 800 and 850 Ma. No such event is known, within hundreds of

millions of years of this time, for this area of the Grenville Province.

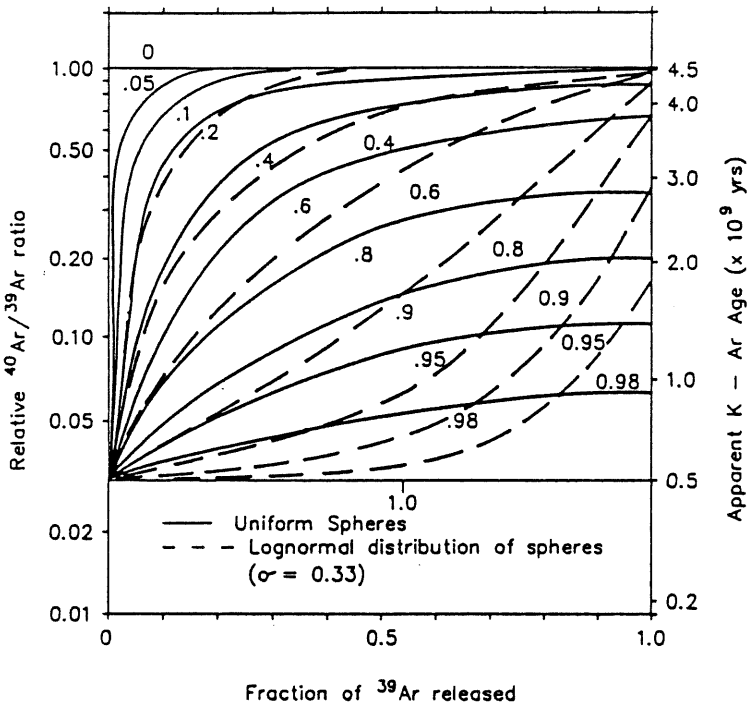


Figure 11 - Turner diffusion model for uniform spheres. Reheating event at 0.5 Ga of a 4.5 Ga old sample (from McDougall and Harrison, 1988 after Turner, 1969)

3) Differences based on varying diffusive characteristics of the K-Feldspars - If the crystallographic structures of the feldspars differ, this could affect diffusive gas loss during slow cooling which would result in apparent age differences (Harrison and McDougall, 1982). X-ray diffraction methods which could reveal crystallographic structure were not attempted in this study.

Varying diffusive properties have also been explained as due to preferential argon gas loss along incoherent perthitic lamellae (McDougall and Harrison, 1988; Harrison and McDougall, 1982).

Parsons et al (1988) recently have suggested an opposing theory in which argon gas is retained most completely in minerals with a large number of perthitic lamellae (i.e. microperthites). They suggest that diffusive argon gas loss in K-feldspars is directly related to the presence of micropore structures and inversely related to the amount of perthitic lamellae. Micropore frequency in perthitic K-feldspars is believed to be lower than in K-feldspars with fewer lamellae. Thus, at the two ends of the scale, concordant spectra (low gas loss) could be expected from microperthitic K-feldspars with many lamellae and discordant spectra with rising staircase patterns (indicating gas loss) could be expected from low or non-perthitic K-feldspars. This explanation of Parsons et al (1988) may indicate the reasons for the differences in K-feldspar ages and spectral styles seen in this study. Differential gas loss, related to micropore frequency and reflected in varying degrees of microperthitization, may be the cause. A reheating event (Turner's model) is not necessary here, only slow cooling.

Other than the observation that in thin section most of the K-feldspars from this study appear to be microperthitic, at present little is known about how the diffusion properties of the samples analyzed relate to such features. Further studies of these features may be of use.

4) Excess argon - The possibility exists that the plateau age difference in the K-feldspars is due to the presence of excess argon. Originally it appeared that only the high ages in the initial gas release steps were possibly due to excess argon (refer

to section 4.1 K-feldspars). These high ages quickly drop off and are followed by the spectra assuming a slow cooling profile. The plateau age taken from the latter part of the spectra should be free from the influence of excess argon. Recent evidence, however, suggests that the K-feldspar data should be looked at more closely (P. Reynolds, pers. comm., 1989).

Of the above four possibilities, I believe that, at present, the theories for slow-cooling diffusive gas loss of Parsons et al (1988) (see 3)) best explain the apparent age difference and differences in spectral style for the Britt domain feldspars. Excess argon effects may, in fact, be superimposed upon the spectra, explaining at least the high ages of the low-temperature initial gas release steps.

4.4 - Summary of Results:

Figure 12 displays all $^{40}Ar/^{39}Ar$ spectra obtained. Each graph represents co-existing minerals in a sample. The sample locations are also indicated. To briefly summarize:

i) all hornblende dates are similar (~ 975 Ma) and are considered to be reliable
ii) three biotite dates are anomalously old (990-1003 Ma) and are considered to be unreliable
iii) two biotite dates are reasonable (964, 947 Ma) but an extraneous argon component is possible

iv) K-feldspar dates are somewhat ambiguous with two samples giving dates significantly different from the third (by ~ 60 Ma) at a calculated T_c of 221° C (+/-14°)

v) The above age difference in K-feldspars, as well as differences in spectral style, may reflect differential diffusive gas loss from the samples analyzed during slow cooling.

vi) The elevated plateau levels in the three anomalous biotites and possibly the high ages ("spikes") in the initial gas release steps of most of the hornblendes and K-feldspars indicate the presence of excess argon.

Table 4 presents the dates obtained from the analysis of the 12 minerals in this study.

Table 4

$^{40}Ar/^{39}Ar$ Dates - Georgian Bay, S.W. Grenville Province

Sample	Mineral	Total Gas * Age (Ma)	Plateau * Age (Ma)	Assumed Excess Argon
G5	Hornblende	973	968	
	Biotite	998	1003	yes
	K-feldspar	936	931	
G6	Biotite	990	(non-plateau)	yes
G10	Hornblende	977	975	
	Biotite	1002	1003	yes
	K-feldspar	925	938	
N406	Hornblende	969	975	
	Biotite	922	947	
P25A	Hornblende	977	974	
	Biotite	949	964	
	K-feldspar	862	878	

* All dates analytical error ~ +/- 1 %
Total gas age includes all temperature steps
Plateau age from weighted average of contiguous steps comprising > 50 % gas released and passing the Critical Value test (95 % confidence level)

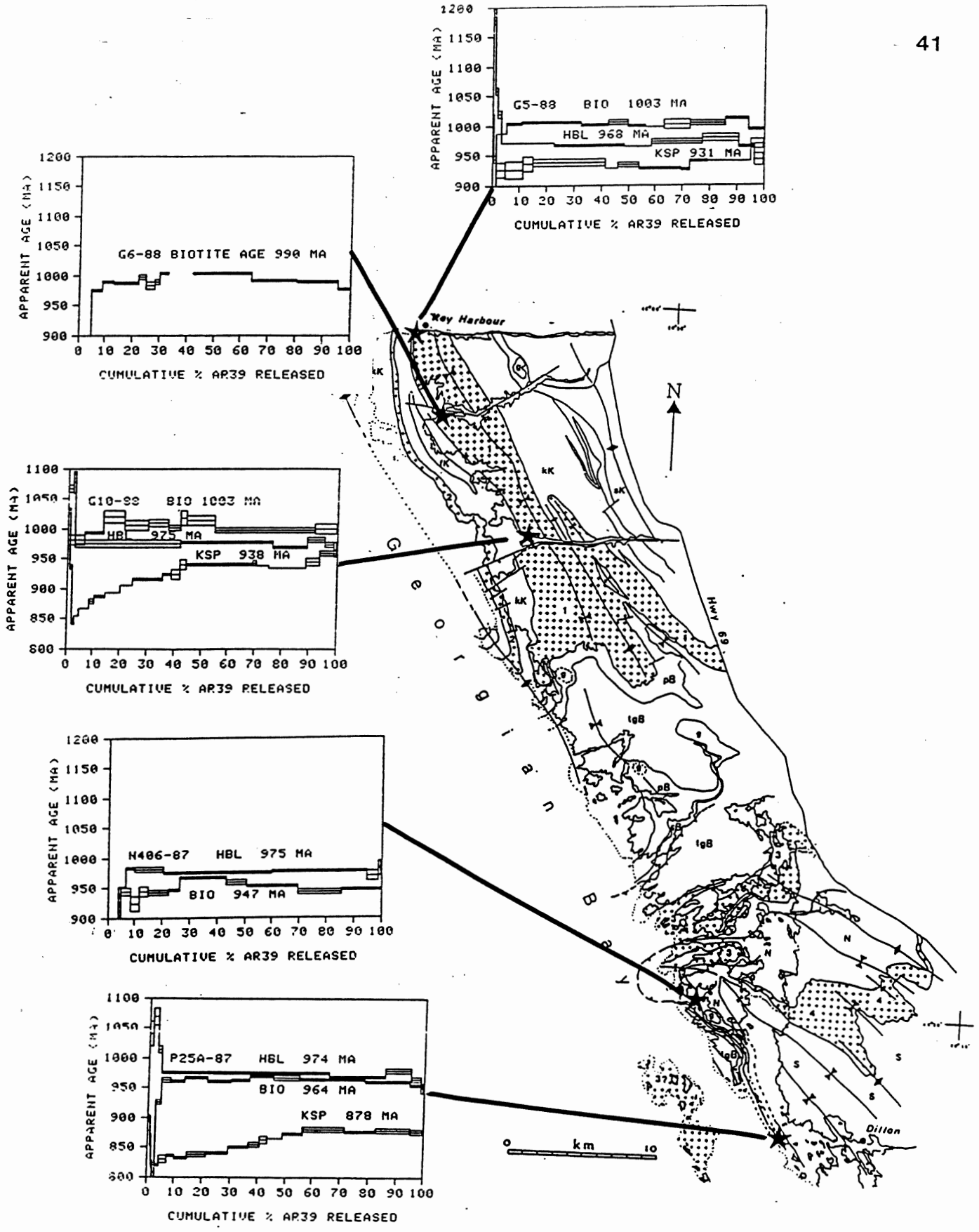


Figure 12 - Co-existing Mineral Spectra and Locations
(map adapted from Culshaw et al, 1988)

Chapter 5 - Geological Interpretation

5.1 Excess Argon

The geological explanations for excess argon are in general not well understood. Foland (1983) suggests that excess argon may result from a reheating event. Anderson (1988) has noted the prominence of excess argon effects in biotite close to the Grenville Front. A metamorphic event, such as that accompanying the Grenville Orogeny, may allow previously accumulated argon to diffuse to the grain boundaries of those minerals whose closure temperature is exceeded. If trapped in the rock, this argon could be incorporated into other minerals by differences in partial argon pressure and diffusion or by crystallization of new minerals. Apparently, in biotites slow cooling allows the extraneous argon to equilibrate throughout the grain (Foland, 1983). In hornblende the excess gas concentrates on the grain boundary (Dallmeyer and Rivers, 1983; McDougall and Harrison, 1988).

It appears that excess argon in this study may be attributable to the reheating resulting from the Grenville Orogeny.

5.2 Cooling and Exhumation History

Cooling History -

From the mineral ages resulting from this study it was possible to construct a basic cooling history diagram. In Figure 13 mineral ages are plotted versus closure temperatures. It is quickly seen that the biotites with assumed excess argon plot in a position far from the postulated curve. Similarly, the youngest feldspar is also away from the main trend.

Cooling rates from an estimated peak metamorphism of ~ 700° C at 1015 Ma (D. Corrigan, Msc. thesis in progress, pers. comm. 1989) to hornblende closure temperatures of ~ 500° C are consistent across the area at ~ 5° C/Ma (4.2-5.0° C/Ma). From 500° C to the calculated closure temperature of K-feldspar (221° C) the cooling rate increased to an average value of around 7.5° C/Ma. From 221° C to surface temperature of 20° C the cooling rate became 0.6° C/Ma (assuming that the rocks were exhumed by 600 Ma - as suggested by Cosca et al, 1988).

Two similar cooling histories using $^{40}Ar/^{39}Ar$ methods have been obtained by others in nearby areas of the Grenville Province. For comparison Figure 14 shows the work of Berger and York (1981), near Haliburton in the Central Metasedimentary Belt, replotted by McDougall and Harrison (1988). It was replotted in order to use more widely accepted T_c's for hornblende and biotite. Berger and York's original calculated values are several hundreds of degrees higher, probably due to errors introduced because of the instability of these minerals during <u>in vacuo</u> heating as mentioned

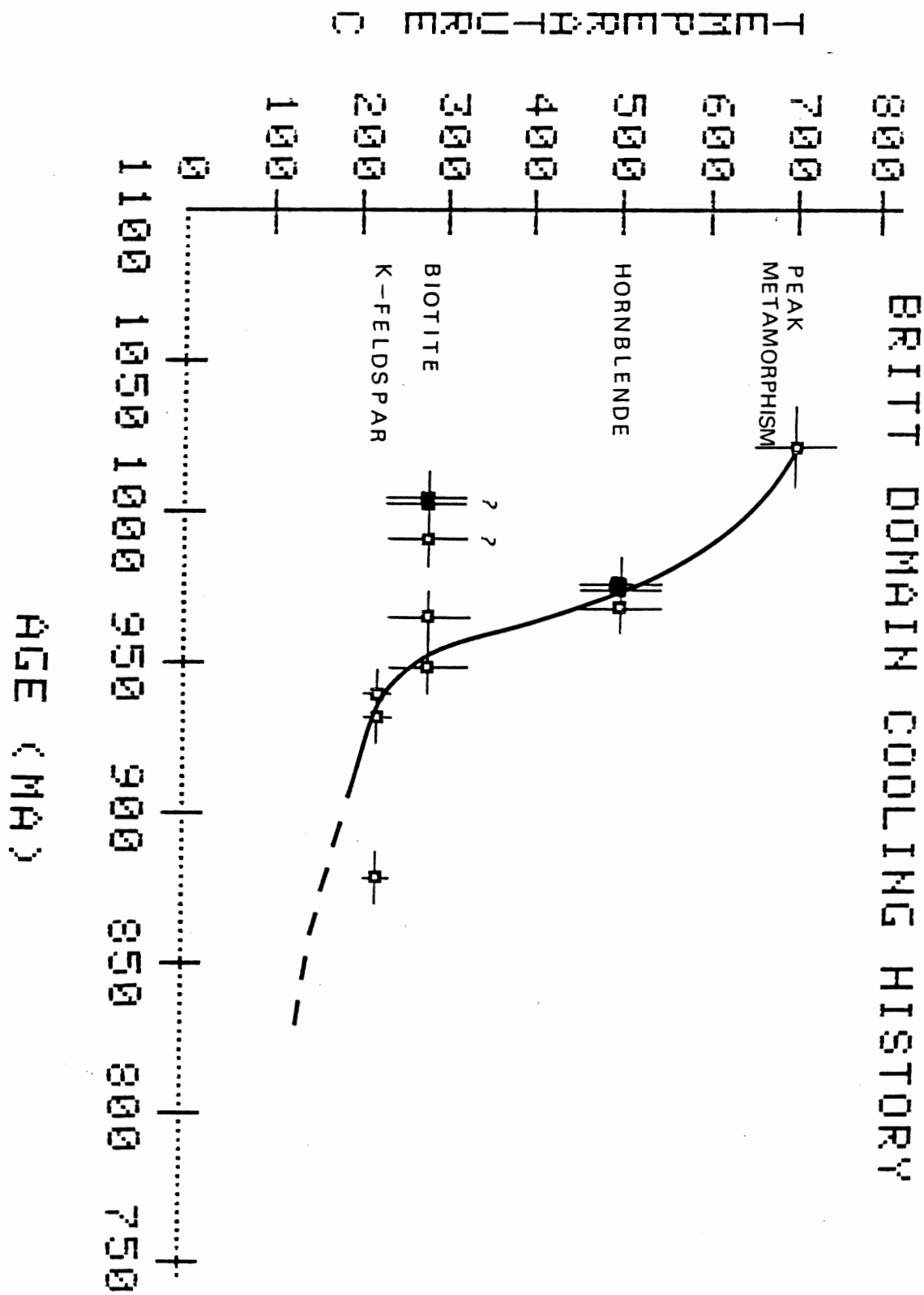


Figure 13 - Britt Domain Cooling History
Length of bars equals errors. Open squares represent one sample, filled squares represent two to three samples
? indicates excess argon.

in section 4.2.

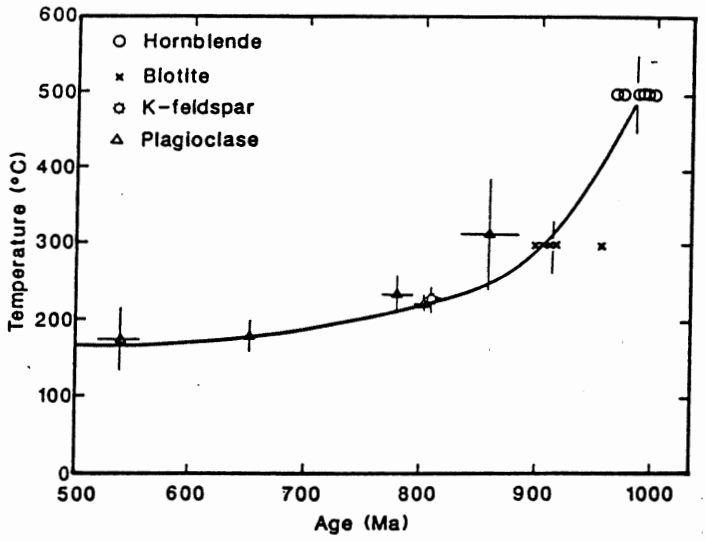


Figure 14 - Cooling History of Haliburton Area, C.M.B. (from McDougall and Harrison (1988) replot of Berger and York, 1981)

The replotted data seem reasonable and a cooling rate from hornblende to K-feldspar closure of about 2° C/Ma results. The hornblende dates are similar to those from this study but the feldspar and biotite ages are younger.

In the Central Gneiss Belt, east of this study, recent work by Cosca et al (1988) has resulted in estimates of cooling rates of between 1 and 4° C/Ma. Their hornblende dates are similar, although more variable, to those from this study and most of their K-feldspar dates are younger.

Compared to these two nearby studies, the results from this thesis give cooling rates 2 - 3 times as great.

Exhumation History -

Depth at which the samples retained argon can be calculated by using the mineral closure temperature divided by an average geothermal gradient. This has been done using a gradient of 30° C/km - typical for many orogenic terranes. The depths calculated range from 17 km for hornblende to 7 km for K-feldspar. These depths, divided by the age difference of co-existing mineral pairs allow rates of exhumation to be determined.

Approximate rates of exhumation are:

0.17 km/Ma from peak metamorphism to hornblende closure

0.25 km/Ma from hornblende to K-feldspar

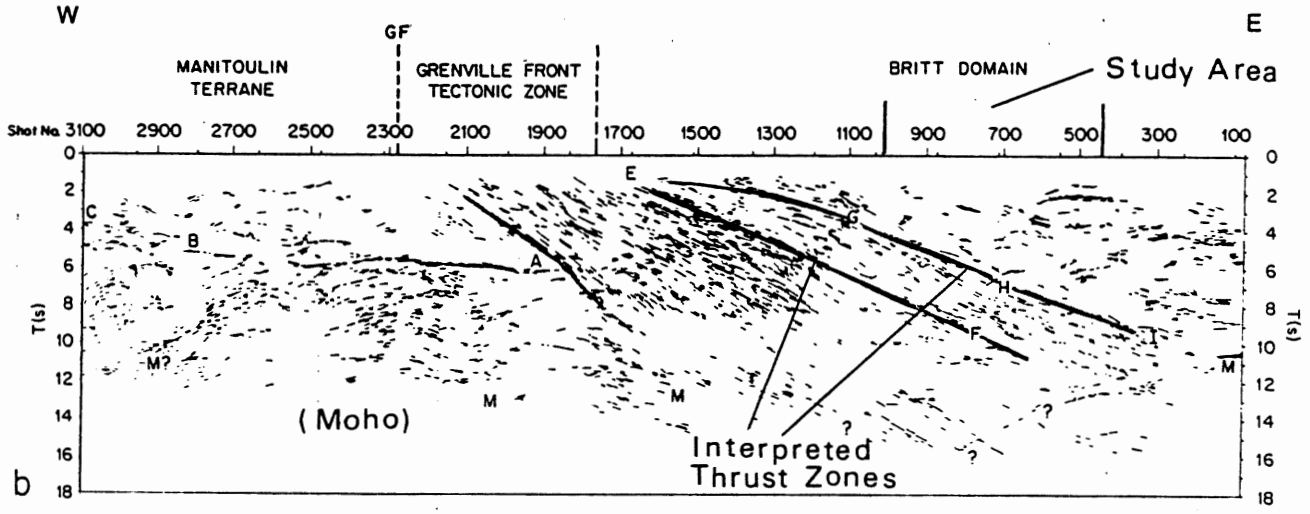
0.02 km/Ma from K-feldspar closure to the surface (assuming the rocks reached the surface by 600 Ma - Cosca et al, 1988)

Although these estimates contain large errors (due to combined errors in age and closure temperatures) they still indicate slow exhumation when compared to calculated exhumation rates for young active mountain belts such as the Alps. Hurford (1986) gives exhumation values for the Alps varying from about 0.5 km/Ma, immediately preceding and following major tectonism, to 2.2 km/Ma during maximum tectonic activity. Values from the Britt domain are at greatest half as fast as the lower Alpine values. However, compared to estimates of exhumation rates from nearby areas (Cosca et al, 1988 calculate rates of erosional uplift of 0.07-0.14 km/Ma), the rates from this study are nearly twice as fast.

5.3 Tectonic Model

This area of the Grenville Province is generally thought to have undergone north-west directed thrusting during the Grenville Orogeny (Davidson et al, 1982). This is now commonly thought to result from continental collision (Dewey and Burke, 1973). An imbricate structure has been postulated for the region in which southern domains are stacked on top of northern rocks. This results in the Parry Sound domain overlying the Britt domain which in turn overlies the Grenville Front Tectonic Zone (Davidson et al, 1982). Davidson (1984) has constructed a cross-section perpendicular to the Grenville Front, across the zone of this study, revealing the structure. Recent research (Green et al 1988 - GLIMPCE crustal profiles) has resulted in deep seismic reflection data for a line, nearly equivalent to Davidson's, off-shore in Georgian Bay (see Figure 15).

Figure 15 - Seismic Cross-Section From Georgian Bay (after Green et al, 1988)



The seismic data support much of Davidson's cross-section. Of interest here is the portion corresponding to the area of the Britt domain studied. This zone is seen to be at a distance away from the more steeply inclined Front Zone. In the Britt domain reflectors appear to be nearly horizontal, although many discontinuities occur with sub-horizontal expressions (Green et al, 1988). A more detailed representation of structure within the area of study does not appear possible with the current seismic data. In general it appears that the zone should not be affected by the type of exhumation to be expected at the Grenville Front.

Peak metamorphism in the area (1015 Ma - Britt domain - D. Corrigan,pers. comm., 1989; 1030 Ma - nearby Algonquin domain - van Breeman et al, 1986) appears to occur much later than thrusting at the Parry Sound Shear Zone (1159 - 1121 Ma, van Breeman et al, 1986). This again discounts any active thrusting element in the cooling and exhumation history of the study area.

From the above indications, it appears likely that the study area has been affected by relatively slow, regional exhumation due to erosion. The calculated rates of cooling and uplift concur although indicating rates up to twice those obtained from studies to the south and east.

Green et al (1988) observe a thicker crust underneath the Grenville Front Tectonic Zone, perhaps attributable to stacking of thrust sheets or terranes. They suggest that this thick crustal mass may have caused the flexural downwarping of adjacent regions. Is it possible that the relatively higher cooling rates for the

area of this study can be partly explained as the result of the (local) residual rebound of such downwarped regions ?

Chapter 6 - Conclusions

In this study, $^{40}Ar/^{39}Ar$ analyses have been done on five plutonic rock samples coming from the Britt domain, Grenville Province. A total of twelve age spectra were obtained for minerals separated from the rock samples, resulting in twelve cooling ages. From the mineral ages, a cooling history was derived.

Diffusion experiments carried out during the argon gas analysis of the K-feldspars resulted in Arrhenius plots which yielded a temperature of closure for K-feldspar of 221° C (+/- 14° C).

Excess argon is found to be present in at least 60 % of the biotites resulting in anomalously old, yet otherwise indistinguishable, concordant spectra. Its presence may also be indicated in some of the hornblendes and K-feldspars as an initial elevated age for the first few per cent of argon gas release during step heating. This age quickly levels off to plateau values.

Although hornblende and biotite dates are similar to those of other workers in neighbouring areas, most K-feldspar dates from this study are older. The linear rate of cooling from hornblende to K-feldspar closure temperatures is estimated to be 7.5° C/Ma with a corresponding rate of exhumation of 0.25 km/Ma. These values are about two times those from studies to the east and south, still within the Grenville Province. A uniform cooling and exhumation history is postulated for the length of the study area.

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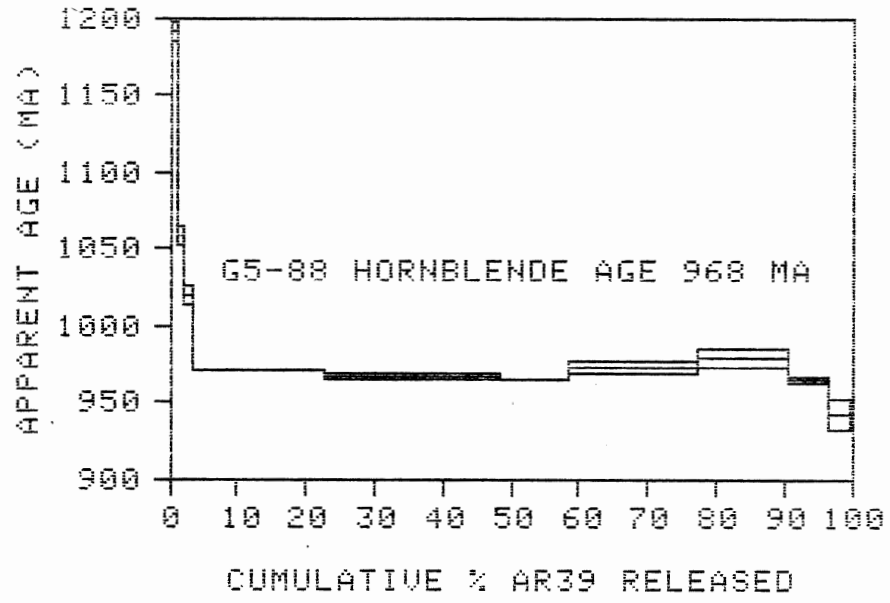
Appendix - Mineral Spectra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1000
950
900
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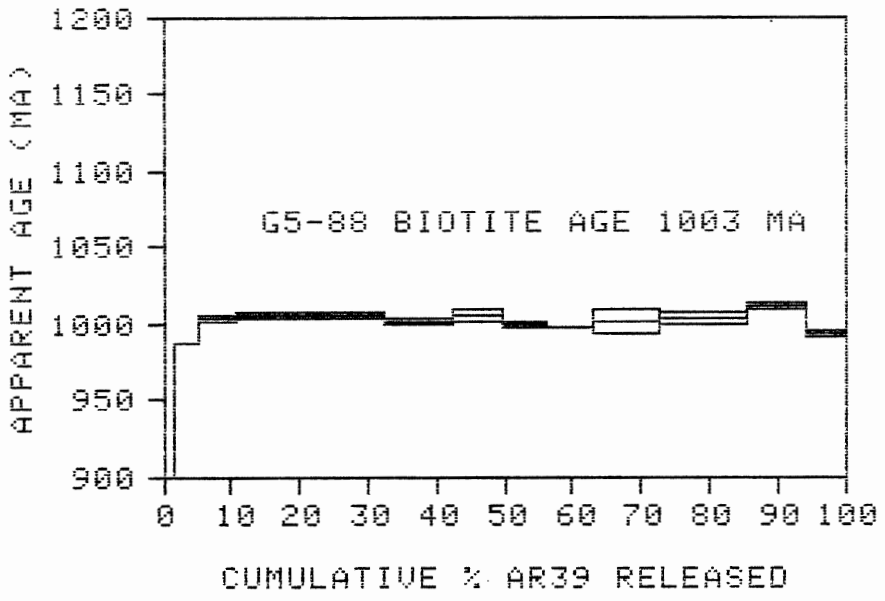
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900
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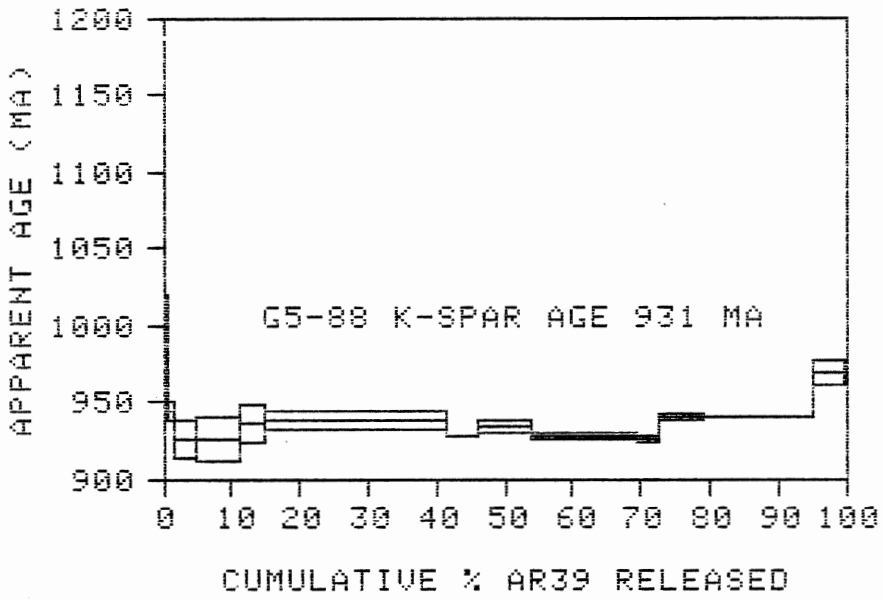
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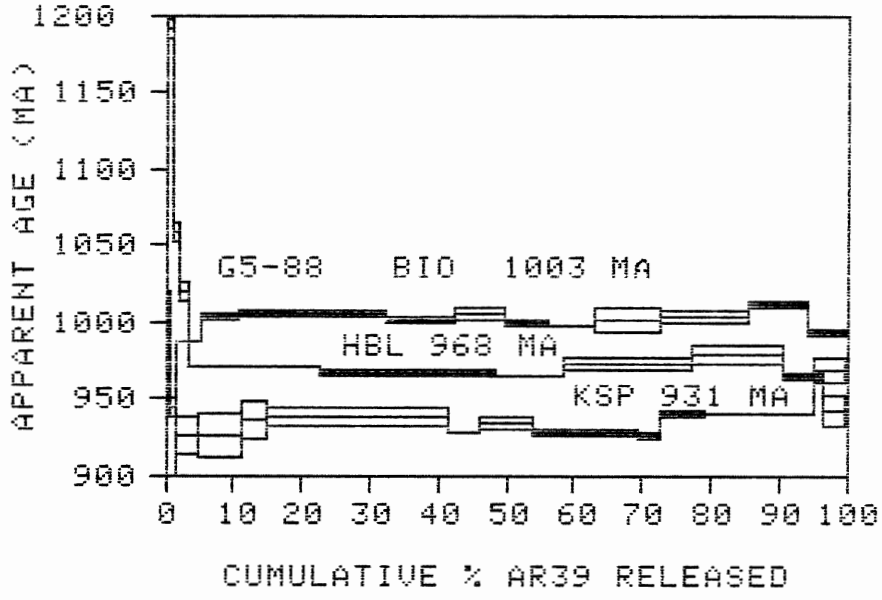
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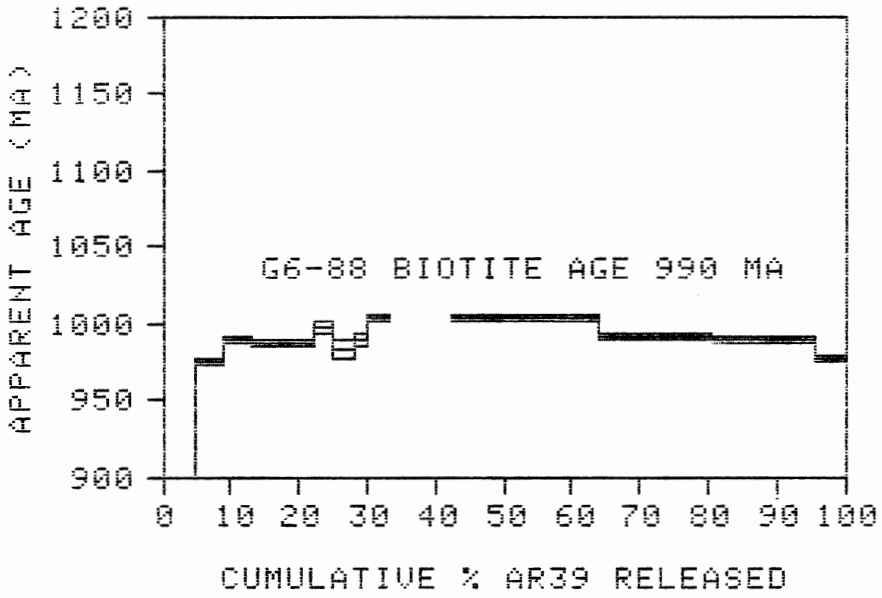
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1000
950
900
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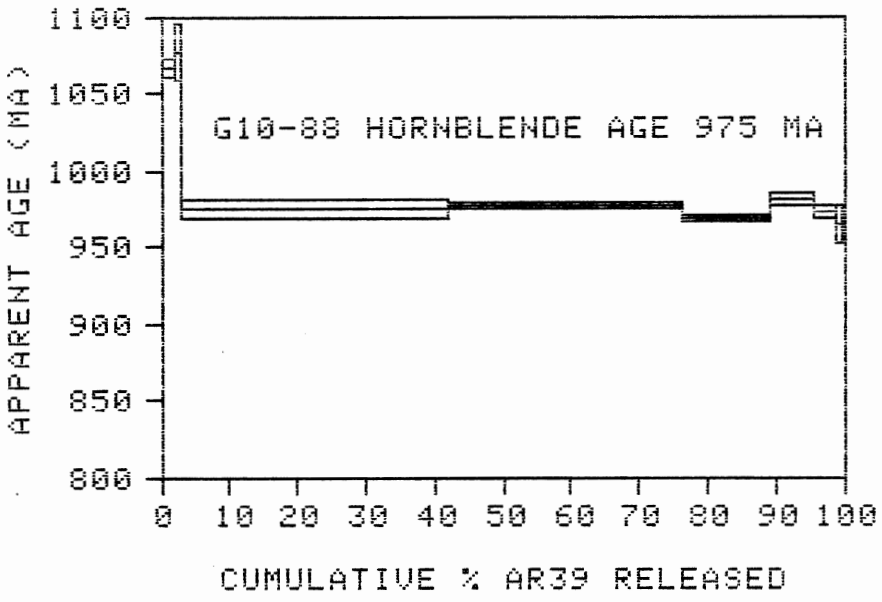
30
40
50
60
70
80
90
100
CUMULATIVE % AR39 RELEASED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950
900
850
800
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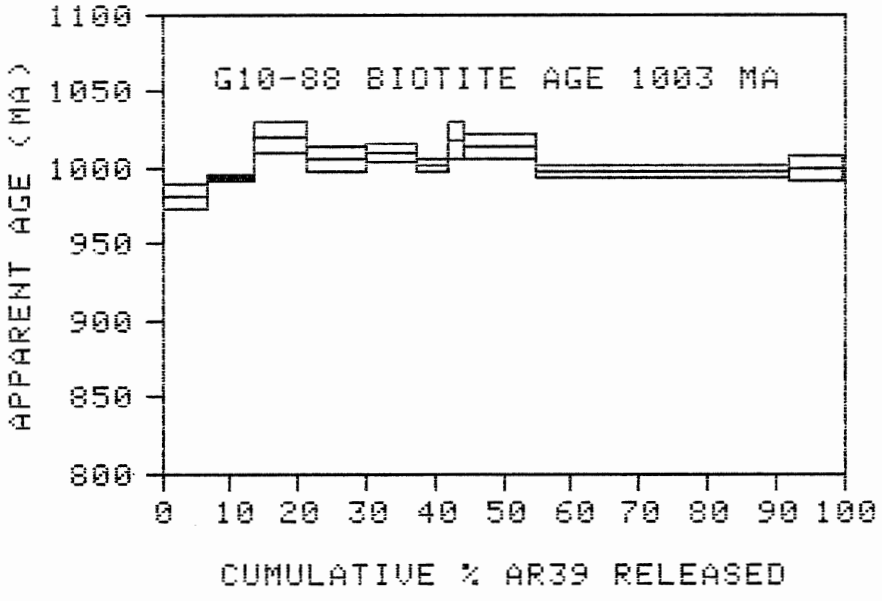
CUMULATIVE % AR39 RELEASED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APPARENT AGE (MA)
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1050
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900
850
800
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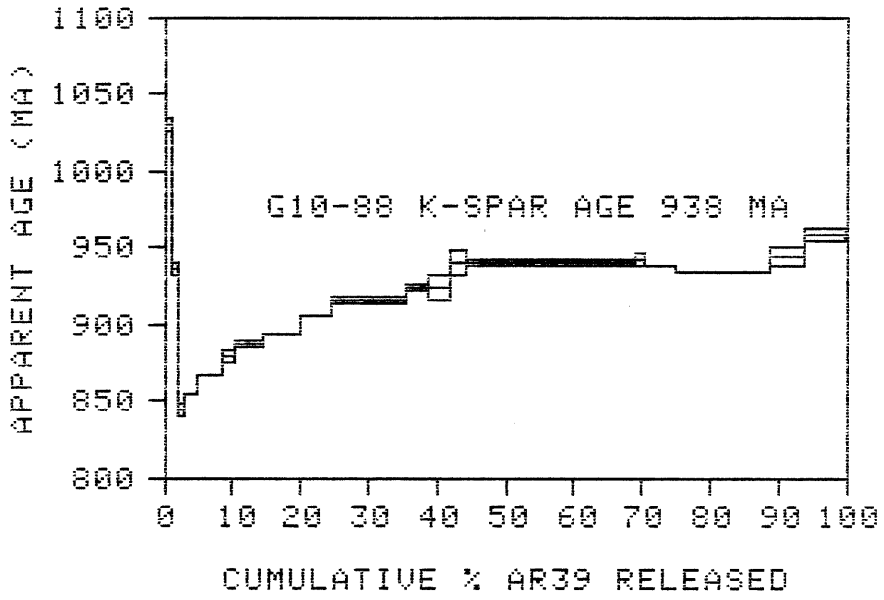
CUMULATIVE % AR39 RELEASED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850
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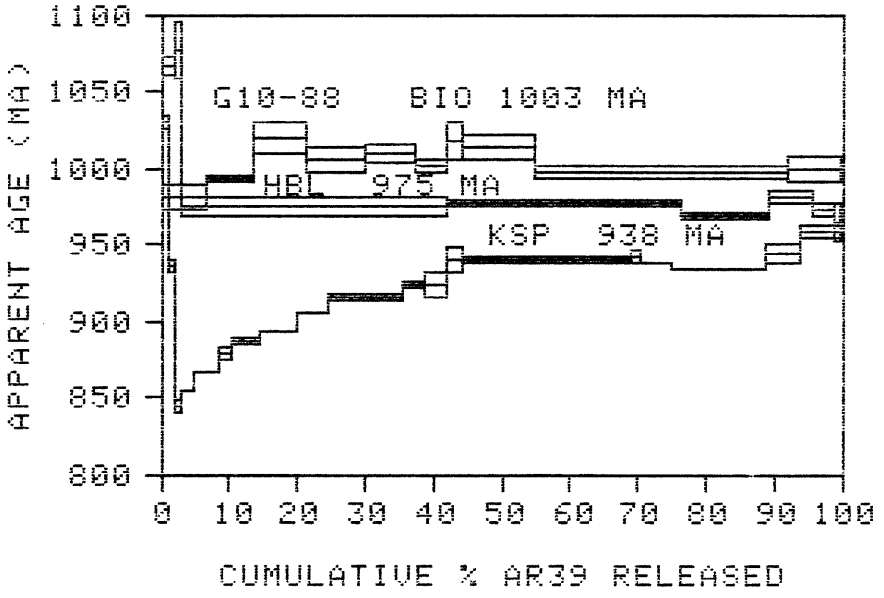
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HBL 975 MA
KSP 938 MA
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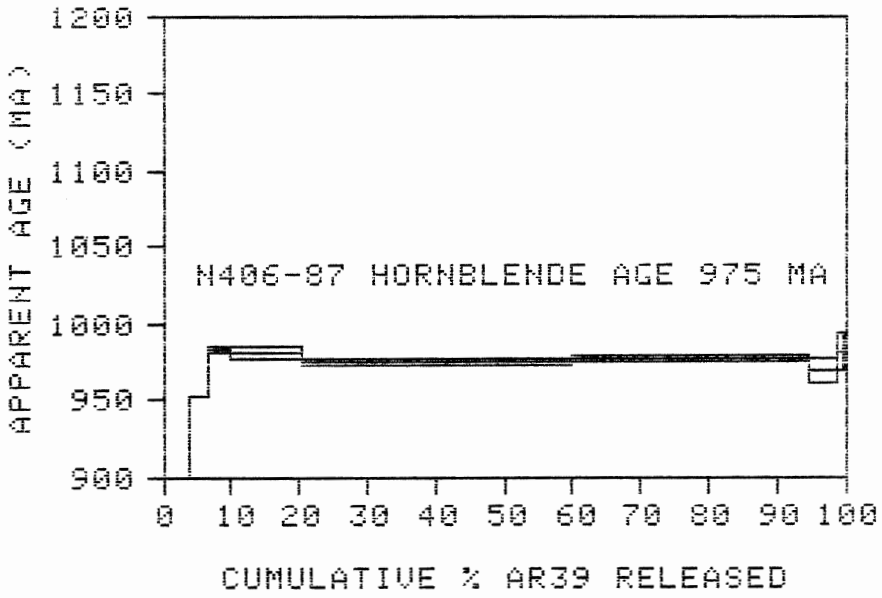
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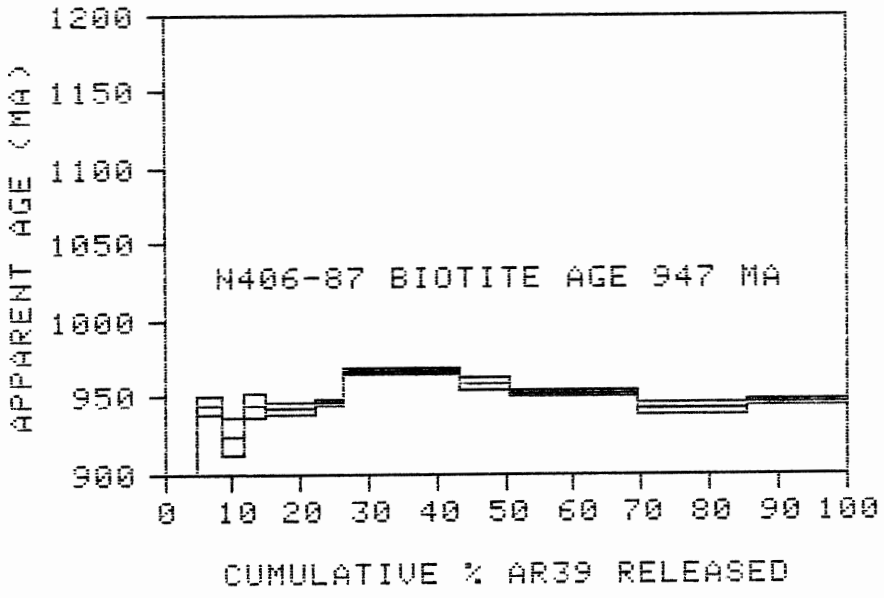
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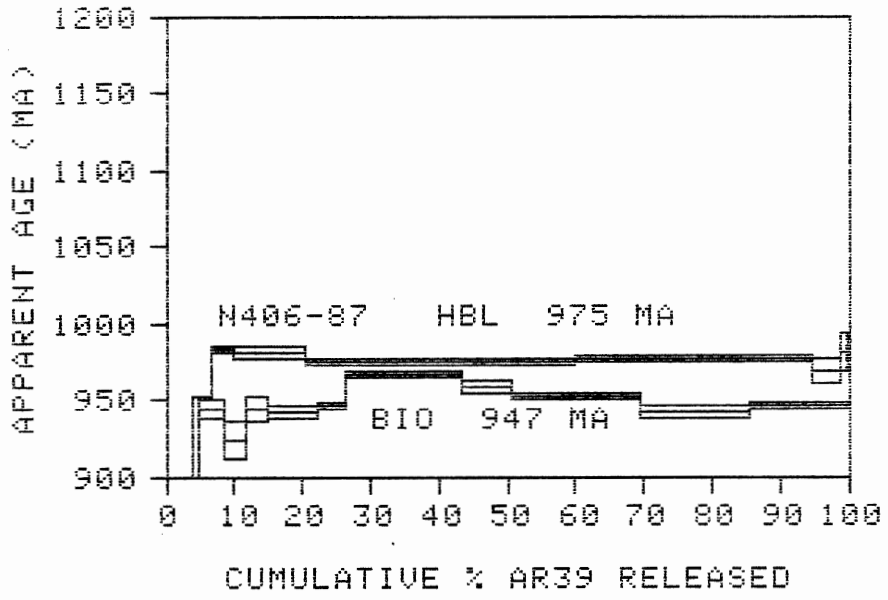
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1100
1050
1000
950
900
N406-87 HBL 975 MA
BIO 947 MA
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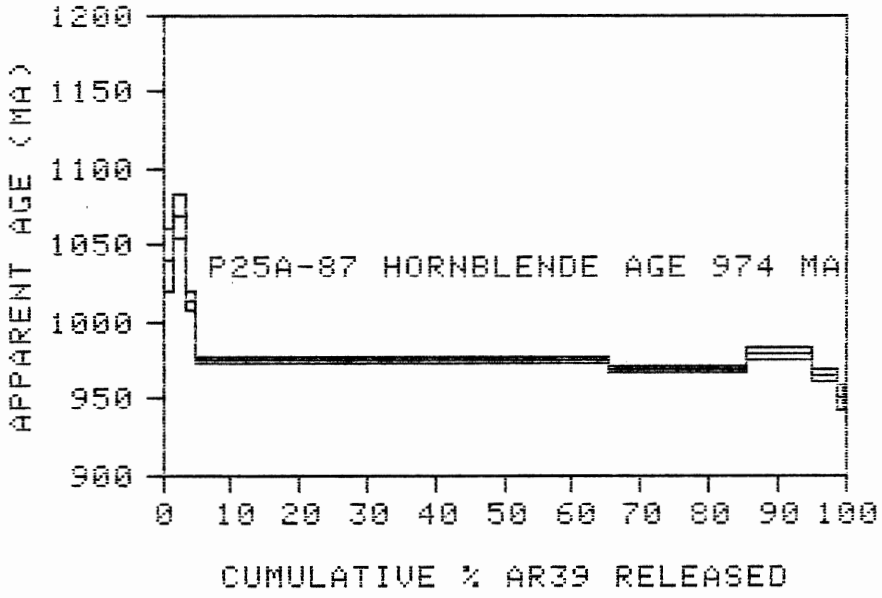
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P25A-87 HORNBLENDE AGE 974 MA
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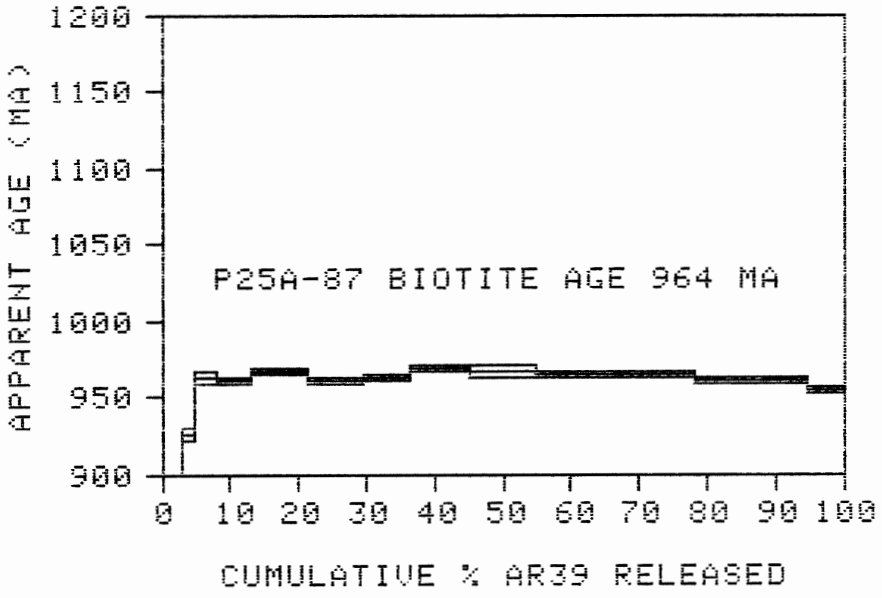
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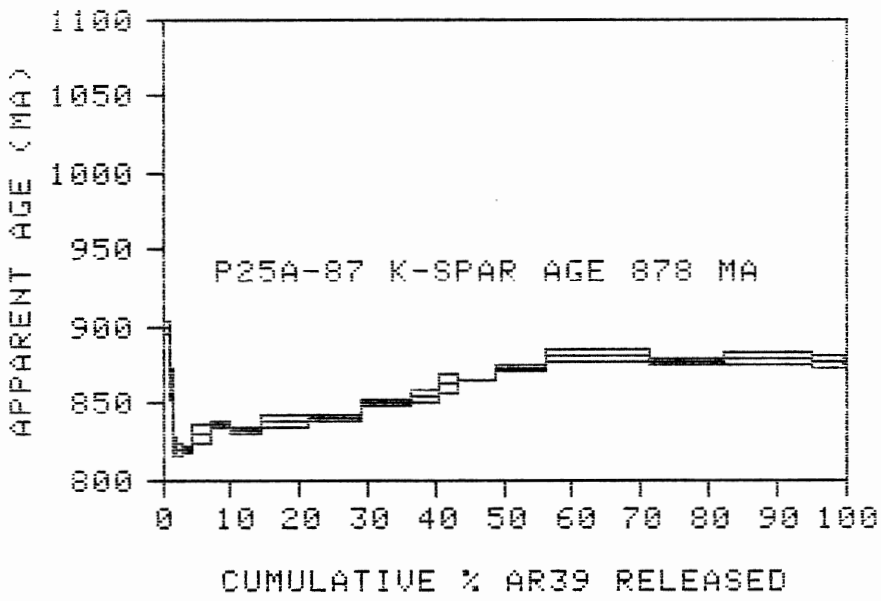
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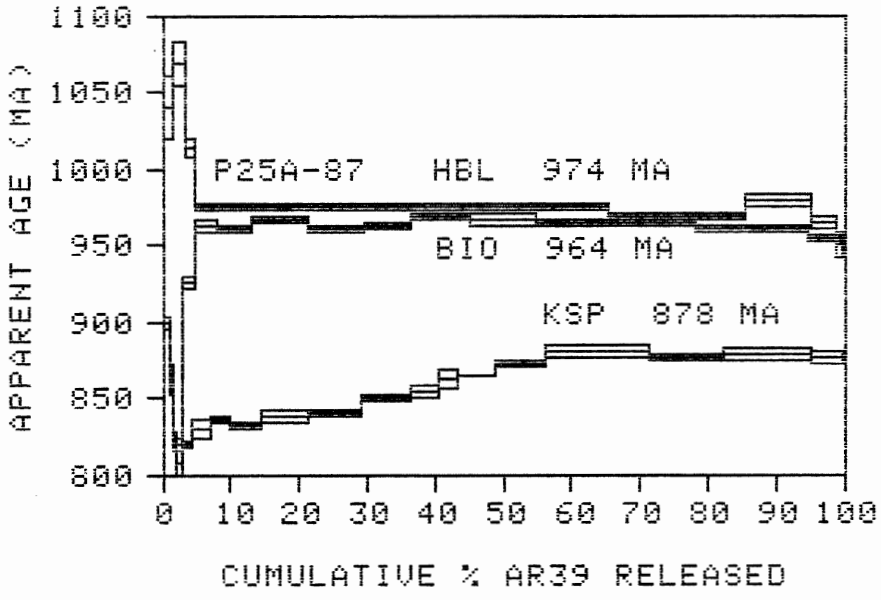
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850
800
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BIO 964 MA
KSP 878 MA
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CUMULATIVE % AR39 RELEASED

Appendix - Analysis Summary Sheets

G5-88H HORNBLENDE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
750	4	1	1190 +/- 7	28	1.9	1037	1.7	0
850	3	<1	1058 +/- 7	21	1.1	1377	2.9	0
900	4	1	1020 +/- 8	22	2.3	1365	3	0
925	58	20	971 +/- 1	4	2.9	7216	21.3	0
950	76	26	967 +/- 3	5	3	6390	18.9	0
975	29	10	964 +/- 2	5	2.9	5424	15.9	0
1000	57	19	972 +/- 5	5	3	5640	16.4	0
1025	39	13	979 +/- 7	15	2.9	1956	5	0
1050	18	6	964 +/- 3	24	3	1242	2.9	0
1075	10	3	941 +/- 10	60	3.7	494	.6	0

TOTAL GAS AGE = 973 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

G5-88B BIOTITE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
550	6	1	712 +/- 6	30	-	1001	3.2	-
600	16	4	987 +/- 2	3	-	11434	33.6	-
650	21	5	1003 +/- 2	1	-	29070	85	-
700	85	22	1005 +/- 3	<1	-	59361	174.3	-
750	40	10	1001 +/- 3	<1	-	53388	157.3	-
800	28	7	1006 +/- 4	<1	-	35002	102.2	-
825	25	6	1000 +/- 2	1	-	21001	61.4	-
850	27	7	998 +/- 2	2	-	16314	47.7	-
900	39	10	1000 +/- 9	1	-	22665	66.3	-
950	50	13	1003 +/- 5	1	-	20483	59.6	-
1000	36	9	1010 +/- 3	2	-	15306	43.9	-
1050	22	6	993 +/- 3	12	-	2556	6.7	-

TOTAL GAS AGE = 998 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

G5-88K K FELDSPAR SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
450	<1	<1	994 +/- 217	75	-	395	.2	-
480	2	<1	1054 +/- 29	54	-	548	.7	-
510	3	<1	1002 +/- 19	35	-	839	1.6	-
550	4	<1	944 +/- 7	27	-	1115	2.6	-
600	22	3	926 +/- 13	7	-	4485	13.7	-
670	42	6	926 +/- 16	5	-	6495	20.3	-
730	25	4	935 +/- 13	5	-	6524	20.1	-
790	173	26	938 +/- 8	3	-	10098	31.6	-
850	31	5	928 +/- 2	4	-	7635	24	-
910	52	8	933 +/- 6	4	-	6763	21	-
970	53	8	927 +/- 4	6	-	5363	16.5	-
1030	49	7	928 +/- 3	5	-	5819	18	-
1100	22	3	925 +/- 2	5	-	6462	20.2	-
1170	40	6	940 +/- 3	3	-	9887	30.8	-
1230	107	16	940 +/- 1	4	-	8342	25.8	-
1300	31	5	968 +/- 9	6	-	4877	14.1	-

TOTAL GAS AGE = 936 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

G6-88B BIOTITE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
550	24	5	540 +/- 2	27	-	1108	5.1	-
600	18	4	974 +/- 3	2	-	12340	37	-
650	21	4	988 +/- 3	<1	-	33927	101.3	-
700	29	6	986 +/- 2	<1	-	38655	116	-
725	14	3	986 +/- 3	2	-	13461	39.8	-
750	14	3	997 +/- 6	1	-	28330	83.5	-
775	15	3	982 +/- 7	1	-	19926	59.6	-
800	9	2	989 +/- 5	2	-	16130	47.6	-
825	15	3	1003 +/- 3	3	-	10681	30.7	-
850	45	9	-	-	-	-	-	-
900	102	21	1003 +/- 2	<1	-	29725	87	-
950	79	17	991 +/- 3	<1	-	32794	97.6	-
1000	73	15	988 +/- 4	2	-	16104	47.6	-
1050	20	4	977 +/- 3	9	-	3238	9	-

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

G10-88H HORNBLENDE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
750	6	2	1067 +/- 8	29	.7	1007	1.8	0
850	3	1	1077 +/- 20	18	1.5	1610	3.5	0
900	112	39	975 +/- 6	2	2.8	15586	46.9	0
950	101	35	976 +/- 3	3	2.8	9968	29.6	0
975	37	13	968 +/- 4	5	2.8	6057	17.8	0
1000	18	6	981 +/- 5	9	2.8	3248	8.9	0
1025	10	3	972 +/- 5	23	2.9	1294	3	0
1050	3	1	964 +/- 13	45	3.3	655	1.1	0

TOTAL GAS AGE = 977 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

G10-88B BIOTITE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
630	27	7	981 +/- 9	37	-	801	1.5	-
660	26	7	993 +/- 3	2	-	13274	38.9	-
700	32	8	1020 +/- 11	2	-	16129	45.8	-
750	34	8	1004 +/- 9	2	-	13509	39	-
800	29	7	1010 +/- 6	3	-	11338	32.3	-
825	19	5	1000 +/- 6	6	-	5351	15	-
850	8	2	1017 +/- 13	10	-	2887	7.5	-
900	43	11	1013 +/- 8	8	-	3709	9.9	-
950	146	37	998 +/- 5	6	0	4777	13.3	0
1000	33	8	1000 +/- 9	25	-	1170	2.5	-

TOTAL GAS AGE = 1002 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

G10-88K K FELDSPAR SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
450	8	1	1030 +/- 5	8	-	3521	9.2	-
480	4	<1	936 +/- 5	1	-	22771	72.7	-
510	2	<1	861 +/- 14	3	-	8494	29.4	-
540	4	<1	845 +/- 6	2	-	18091	65.5	-
570	13	2	853 +/- 2	<1	-	32360	116.6	-
600	22	4	865 +/- 2	<1	-	63504	225.8	-
630	13	2	878 +/- 4	<1	-	74129	258.8	-
660	26	4	887 +/- 3	<1	-	60420	208.1	-
690	32	5	893 +/- 1	<1	-	88607	303.2	-
720	30	5	906 +/- 2	<1	-	58598	196.5	-
750	68	11	916 +/- 3	<1	-	50981	168.4	-
780	20	3	924 +/- 4	<1	-	55935	183	-
810	22	3	923 +/- 9	<1	-	53412	174.9	-
850	15	2	939 +/- 9	<1	-	76951	246.8	-
900	155	25	939 +/- 4	1	-	25066	79.8	-
950	8	1	943 +/- 6	2	-	18694	58.9	-
1000	28	4	939 +/- 2	2	-	16205	51.2	-
1050	87	14	934 +/- 2	4	-	7321	22.7	-
1100	31	5	943 +/- 8	10	-	2903	8.3	-
1140	40	6	958 +/- 5	15	-	1926	5.1	-

TOTAL GAS AGE = 925 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

N406-87H HORNBLENDE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
750	12	4	806 +/- 8	32	1.1	931	2.4	0
850	10	3	952 +/- 1	12	.7	2432	6.7	0
900	11	3	984 +/- 4	9	2.3	3351	9.2	0
925	35	11	980 +/- 5	3	2.9	10467	31	0
950	131	39	975 +/- 2	1	3.1	22382	67.8	0
975	92	28	976 +/- 3	2	3	16049	48.2	0
1000	24	7	977 +/- 4	3	3	9283	27.5	0
1025	14	4	969 +/- 9	12	3.1	2371	6.4	0
1050	4	1	981 +/- 14	40	3.7	741	1.3	0

TOTAL GAS AGE = 969 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

N406-87B BIOTITE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
550	23	5	308 +/- 5	20	-	1461	13.7	-
600	16	4	943 +/- 6	2	-	13088	40.9	-
650	14	3	924 +/- 13	1	-	25113	81.6	-
700	15	3	944 +/- 9	<1	-	29660	93.9	-
750	34	7	942 +/- 5	<1	-	50428	160.8	-
800	19	4	946 +/- 3	<1	-	31402	99.2	-
850	76	17	967 +/- 3	3	-	9257	27.7	-
8	34	7	958 +/- 4	4	-	8376	25.2	-
950	87	19	952 +/- 4	3	-	10975	33.8	-
1000	72	16	941 +/- 6	3	-	10328	32.2	-
1050	67	15	946 +/- 3	3	-	11127	34.5	-

TOTAL GAS AGE = 922 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

P25A-87H HORNBLENDE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
750	6	2	1039 +/- 22	21	1.9	1393	3	0
850	6	2	1069 +/- 15	12	1.2	2449	5.8	0
900	6	2	1012 +/- 7	11	2.2	2763	7.2	0
925	130	34	976 +/- 3	2	2.7	14192	42.6	0
950	102	27	975 +/- 3	1	2.8	19763	59.7	0
975	77	20	968 +/- 3	2	2.7	17766	54.1	0
1000	36	9	978 +/- 5	4	2.7	7710	22.6	0
1025	14	4	964 +/- 5	12	2.8	2459	6.7	0
1050	5	1	950 +/- 9	32	2.7	928	2	0

TOTAL GAS AGE = 977 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

P25A-87B BIOTITE SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
500	8	2	297 +/- 5	58	-	510	2.6	-
550	3	<1	808 +/- 9	14	-	2088	6.9	-
600	7	2	926 +/- 5	6	-	5212	16.1	-
650	12	3	961 +/- 5	2	-	12864	39.2	-
700	18	5	961 +/- 3	2	-	15475	47.4	-
750	33	8	967 +/- 4	1	-	20010	61.1	-
800	32	8	960 +/- 3	2	-	13356	40.8	-
850	26	7	961 +/- 3	4	-	8401	25.3	-
900	33	9	968 +/- 3	6	-	5264	15.3	-
950	37	10	965 +/- 5	5	-	5758	16.9	-
1000	91	24	964 +/- 3	3	-	9489	28.6	-
1050	62	16	960 +/- 3	5	-	5383	15.9	-
1100	21	5	954 +/- 3	18	-	1661	4.3	-

TOTAL GAS AGE = 949 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION

P25A-87K K FELDSPAR SUMMARY

°C	mV 39	% 39	AGE(Ma)	% ATMOS	37/39	40/36	39/36	% IIC
480	4	<1	899 +/- 5	17	-	1786	5	-
510	2	<1	863 +/- 11	3	-	9709	33.7	-
540	2	<1	822 +/- 8	2	-	11885	44.1	-
570	4	1	820 +/- 4	<1	-	53095	201.7	-
600	5	1	819 +/- 3	<1	-	47502	180.8	-
630	10	3	830 +/- 8	<1	-	52794	197.5	-
660	11	3	836 +/- 3	<1	-	150848	561.4	-
690	18	5	831 +/- 4	<1	-	41407	154.6	-
720	25	7	838 +/- 4	<1	-	72029	266.7	-
750	31	8	840 +/- 2	<1	-	64220	237	-
780	27	7	850 +/- 4	<1	-	33844	122.6	-
810	15	4	855 +/- 5	<1	-	32970	118.5	-
850	11	3	862 +/- 8	3	-	11694	40.9	-
900	21	6	865 +/- 2	3	-	11811	41.1	-
950	28	7	873 +/- 3	1	-	24264	84.6	-
1000	57	15	880 +/- 5	2	-	11908	40.6	-
1050	43	11	876 +/- 4	6	-	5211	17.2	-
1100	48	13	879 +/- 5	9	-	3266	10.4	-
1140	19	5	876 +/- 5	13	-	2319	7.1	-

TOTAL GAS AGE = 862 Ma

J = 2.2E-03

ERROR ESTIMATES AT ONE SIGMA LEVEL

37/39,40/36 AND 39/36 Ar RATIOS ARE CORRECTED FOR INTERFERING ISOTOPES

% IIC - INTERFERING ISOTOPES CORRECTION