$^{40}Ar/^{39}Ar$ DATING OF SILURIAN-DEVONIAN ROCKS FROM THE GANDER AND BOTWOOD ZONES OF NEWFOUNDLAND AND THEIR PALEOMAGNETIC IMPLICATIONS.

by

WILLIAM REEVES MORGAN

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DEPARTMENT OF GEOLOGY
DALHOUSIE UNIVERSITY
HALIFAX, NOVA SCOTIA
CANADA
B3H 4J1

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Author: William Reeves MORGAN

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ABSTRACT

Paleomagnetic poles recently reported by Lapointe, Murthy, and others are widely divergent from poles of similar age from cratonic North America. Two of the units from Newfoundland have each yielded two widely separated paleopoles. These units are the Mount Peyton Batholith (Botwood Zone) and a suite of diabase dikes from the Wesleyville area (Gander Zone).

Detailed $^{40}Ar/^{39}Ar$ stepwise outgassing measurements were made on a number of biotite and hornblende samples from these two units in an attempt to determine if age differences accounted for the observed variance in paleopoles. Results from the Wesleyville dikes yielded age spectra with plateaus at about 390 Ma. This is consistent with previously reported ages of 332 ± 42 Ma for the younger Newport Pluton (Bell et al., 1979). However, it conflicts with the reported 300 ± 18 Ma age for the Locker's Bay Pluton which is cut by the dikes. The freshest hornblendes and biotites from the Mount Peyton diorite yield an age plateau of about 425 Ma. Diorite inclusions from within the late granite phase yield distinctly younger ages corresponding to a 390 Ma age reported by Bell (personal communication). Similarity with the granites in age and pole location for the inclusions, suggests the ages and magnetizations have been reset during the granite emplacement.

Paleomagnetic data for the Northern Appalachians during the Silurian-Devonian yield two spatially distinct groups. From the paleomagnetic data, it would appear that the Botwood and Gander Zones of Newfoundland may have moved relative to the rest of Appalachia during these times.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

1.1 Statement of the Problem

Paleomagnetic studies on the Silurian-Devonian rocks of the Northern Appalachians have become increasingly more important for reconstruction of the paleocontinental margin. Until recently, data for Northern Appalachia has been sorely lacking. Recently, however, there has been a rapid increase in the number of paleopole determinations for the area. To date, a comprehensive study of paleomagnetic data related specifically to Northern Appalachia has not been made. This study is an attempt to clarify this situation with respect to the Silurian-Devonian.

The paleopoles recently reported for Newfoundland by Lapointe (1979) and Murthy (personal communication) are widely divergent from the APW path defined from rocks of similar ages from cratonic North America. Two of these poles were obtained from the Mount Peyton granite-diorite batholith (Botwood Zone), and two were from a suite of diabase dikes from the Wesleyville area (Gander Zone).

Paleopoles for the early diorite and late granite phases from Mount Peyton are widely separated from each other. Similar results are obtained for the paleopoles from the

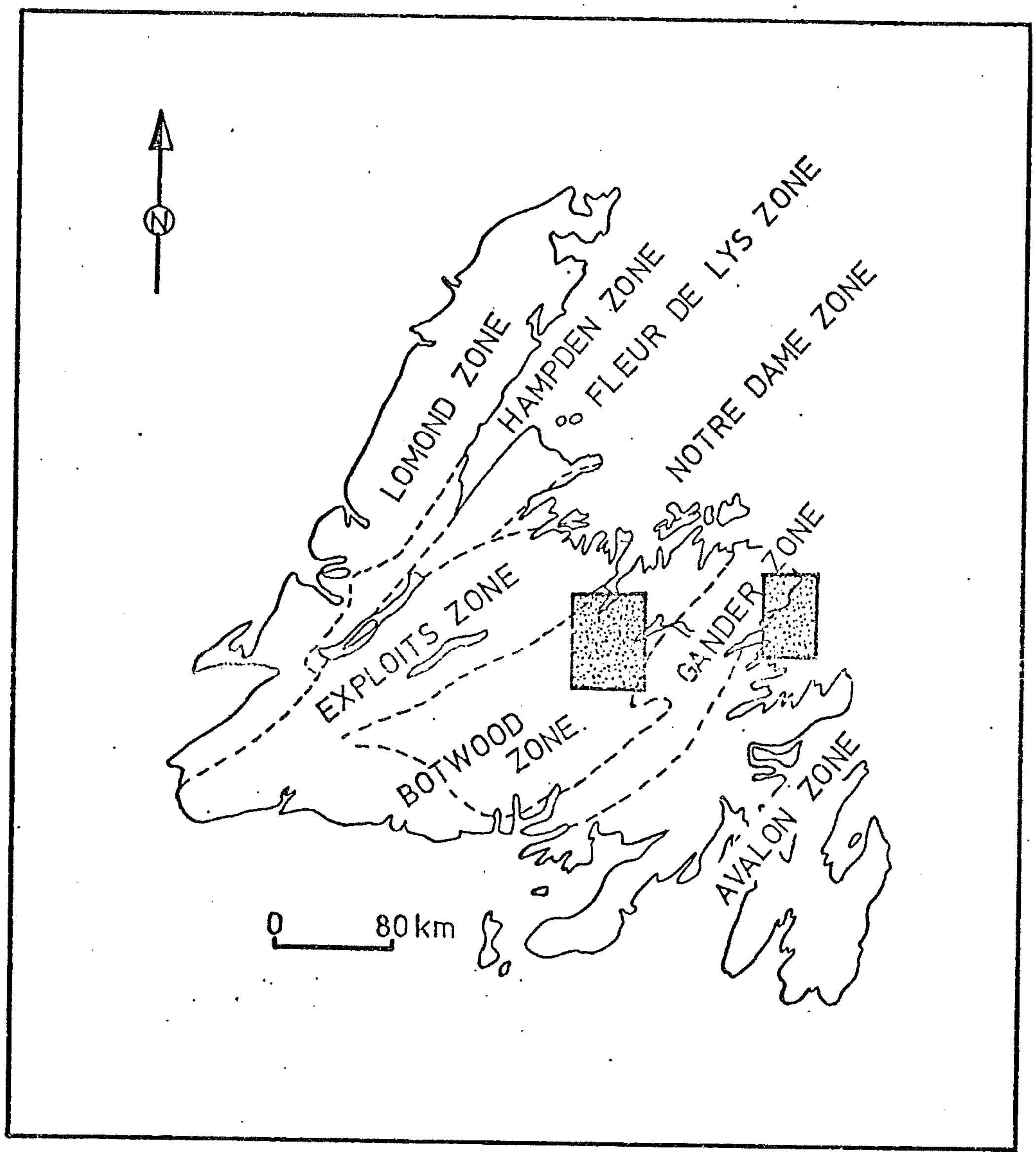


Figure 1

Locations of the study areas. The map shows the tectonographic zones of the Newfoundland Appalachians according to Williams et al. (1974).

dikes in Wesleyville.

At the present, reliable ages for the diorites and dikes in these two areas are lacking. $^{40}Ar/^{39}Ar$ dating of these units may serve to clear up the confusion surrounding their anomalous poles. Dating the dikes from Wesleyville may also serve to place some age constraints on the paleopoles recently reported by Murthy.

1.2 Scope of the Study

Several studies have pointed to the success of dating magnetizations based on the similarities between magnetic blocking temperatures and isotopic blocking temperatures. This paper will attempt to date the magnetizations of the rocks yielding divergent paleopoles by the $^{40}Ar/^{39}Ar$ method.

Samples for the study were provided by P.L. Lapointe (Mount Peyton) and by A.R. Berger (Wesleyville). Petrographic study of the samples was limited to thin section descriptions.

Special attention was given to the Wesleyville samples as the present confusion surrounding the ages of plutons yielding dispersed poles makes interpretation of such data difficult.

Actual paleomagnetic analysis and methods lie outside the scope of the present thesis and can be found in the related references. Paleomagnetic data was collected from presently published studies or made available to the author by outside sources. Correlation and discussion of paleopoles were limited to the Silurian-Devonian of Northern Appalachia.

CHAPTER 2

ARGON DATING

2.1 Introduction

Radioactivity is defined as the spontaneous breakdown or decay of an unstable nucleus. Radioactivity was first discovered by Becquerel in 1896. It was this discovery which has made possible the development of isotopic dating methods.

Potassium-argon age dating has been known and widely accepted for a number of years. Dalrymple and Lanphere (1969) provide a useful general reference. The $^{40}Ar/^{39}Ar$ method of K-Ar dating was first suggested by Sigurgeirson (1962) and later Merrihue (1965). Earliest published results were on meteorite samples by Merrihue and Turner (1966). The first terrestrial results appeared later (Mitchell, 1968).

2.2 Behavior of Argon

The primary assumption behind the theory of dating with isotopes of argon is that there has been no introduction of radiogenic ^{40}Ar in the rock other than that produced by the decay of ^{40}K. The rock is assumed to have behaved as a closed system. The validity of this assumption depends upon the geologic history and nature of the sample to be dated.

It is assumed that the rock studied was free of argon at the time of cooling. This however is not always the case. Excess argon can be present in the rock in one of two ways; incorporated at time of crystallization or inherited from older rocks.

The formation of igneous rocks has long been thought to involve partial or complete melting. According to Dalrymple and Lanphere (1969), this process can release radiogenic ^{40}Ar. Chemical and physical reconstitution as a result of metamorphism will also release ^{40}Ar. Thus ^{40}Ar may be available to a mineral phase at crystallization or recrystallization and be incorporated in it. Fumarole studies have shown that such argon may be available in amounts one hundred times greater than the normal quantity of atmospheric argon contained in rocks. This will result in 'older' ages for a rock.

Argon can also be inherited from older rocks by the outgassing of xenoliths of such rocks picked up during magmatic emplacement. The younger rock will acquire the ^{40}Ar released from the older xenoliths.

Loss of argon from a mineral will result in the apparent age being younger than its true age. If the loss is only partial, the resulting age will be difficult to interpret as it may have resulted from a number of losses and accumulations. If loss is total, then the reset age will reflect the event initiating the loss. According to Dalrymple and Lanphere (1969), seven geologic factors can result in argon being lost from a mineral:

1. Inability of the mineral to retain argon.
2. Complete or partial melting.
3. Chemical or physical reconstitution following metamorphism.
4. Weathering and alteration may disrupt the lattice causing complete or partial loss.
5. Recrystallization.
6. Reheating
7. Actual physical damage to the crystal lattice.

Handling and treatment of the sample may also contribute to argon loss. Such factors include grain size and irradiation problems. In the latter, for example, an atom can recoil to a position substantially removed from its normal lattice position during irradiation. Conservation of momentum requires that decay reactions involve kinetic energy. The greater that energy, the farther the atom will travel, and the greater the lattice damage. Mitchell (1968) sets an upper limit of 0.1 μm for the range of ^{39}Ar atoms in a mica lattice (in Parrot, 1976). Thus, loss of argon due to dispersion by recoil should not be a factor except where the sample is fine-grained. Horn et al. (1975) came to a similar conclusion using pyroxenes and plagioclases from lunar rocks.

The transport mechanism which appears to account for the movement of argon is diffusion. Diffusion is the process by which materials move by random molecular motion from one place to another. This movement takes place from areas of high concentration to those of low concentration. Diffusion studies by Musset (1969) indicate that diffusion parameters can be altered by heating, perhaps as a result of induced lattice defects. Such defects may include vacancies, dislocations, fracturing, impurities, laboratory grinding, and strain. Diffusion is thought to be anisotropic and as a result, atoms will travel either parallel or perpendicular to mica sheets. Musset (1969) indicates that in micas, the space between the sheets is too small to allow the passage of argon unless they are disrupted.

2.3 Potassium-40 Decay

Potassium is made up of three natural isotopes of mass numbers: 39 (93.08%); 40 (0.12%); and 41 (6.91%). Potassium-40 has a half life of about 1,250 million years. It decays to two daughter products: calcium-40 and argon-40.

^{40}K has an unusual decay. About 89.5% of the time it decays by beta-decay (by losing an electron from its nucleus) to ^{40}Ca:

$$^{40}K \longrightarrow {}^{40}Ca + \beta^{+}$$

The remainder of decays (10.5%) produce ^{40}Ar by electron capture and the emission of a gamma ray:

$$^{40}K + e^- \longrightarrow {}^{40}Ar + \gamma$$

As Calcium is a common element and ^{40}Ca comprises the majority of all calcium (96.67%), the amount produced by beta-decay of ^{40}K is minimal, and difficult to detect. However, as argon is a rarer element, and even though ^{40}Ar is the most abundant argon isotope (99.60%) in the Earth's atmosphere, it is not hard to detect ^{40}Ar derived from ^{40}K (as we assume rocks outgas and begin with no ^{40}Ar).

Rutherford showed in the early 1900's that radioactive decay followed an exponential law. This fundamental equation is:

$$\frac{dP}{dt} = -P\lambda \qquad (2\text{-}1)$$

Where P equals the number of parent atoms and λ equals the decay constant. By integration of equation (2.1), one can arrive at:

$$P = P_o e^{-\lambda t} \qquad (2\text{-}2)$$

Where P_o equals the number of parent atoms at time zero, and P is the number of atoms at time t.

By further rearrangement and substitution, one can arrive at the basic age equation:

$$t = 1/\lambda \ \ln(1+\lambda/\lambda e \ \frac{^{40}Ar^*}{^{40}K}) \qquad (2\text{-}3)$$

Where t is the time since cooling to argon retention temperatures, λ is the ^{40}K decay constant ($\lambda = \lambda_e + \lambda_\beta$), λ_e and λ_β equal the partial decay constants for the ^{40}Ca and ^{40}Ar branches, and $^{40}Ar^*/^{40}K$ is the observed ratio of radiogenic argon to parent potassium.

2.4 $^{40}Ar/^{39}Ar$ Method

When a rock or mineral with potassium is irradiated with fast neutrons, a number of reactions produce isotopes of argon. The reaction of interest is the conversion of a proportion of ^{39}K in a sample to ^{39}Ar. The sample is irradiated along with a standard sample of known age which acts as a monitor of the dose of neutrons received by the unknown. After irradiation the argon is extracted and isotopically analyzed. The amount of radiogenic ^{40}Ar derived from ^{40}K decay through time can be determined relative to the amount of ^{39}Ar generated from ^{39}K during irradiation. By comparing the ratios determined for the unknown and the standard, one can determine the age of the unknown.

After a sample has been irradiated, the amount of ^{39}Ar produced by fast neutrons is:

$$^{39}Ar = {}^{39}K \Delta T \int \phi(E) \sigma(E) dE \qquad (2\text{-}4)$$

where ^{39}K is the number of potassium-39 atoms present, ^{39}Ar is the number of Argon-39 atoms produced, $\phi(E)$ is the neutron flux at energy E, $\sigma(E)$ is the neutron capture cross-section of the reaction producing ^{39}Ar from ^{39}K, and ΔT is the irradiation time. Rearranging equation (2-3) yields:

$$^{40}Ar^* = R/1+R \; ^{40}K \; (e^{\lambda t-1}) \qquad (2\text{-}5)$$

where $R = \lambda e/\lambda\beta$. By dividing equation (2-5) by (2-4) one obtains:

$$\frac{^{40}Ar}{^{39}Ar} = \frac{^{40}K}{^{39}K} \; \frac{R}{1+R} \; \frac{1}{\Delta T} \; \frac{(e^{\lambda t-1})}{\phi(E)\sigma(E)dE} \qquad (2\text{-}6)$$

If we define the irradiation parameter, J, to be:

$$J = \frac{^{39}K}{^{40}K} \; \frac{1+R}{R} \; \Delta T \; \phi(E)\sigma(E)dE \qquad (2\text{-}7)$$

Then from equation (2-6) it follows that:

$$J = \frac{e^{\lambda t-1}}{^{40}Ar/^{39}Ar} \qquad (2\text{-}8)$$

If the standard of known age t_s and the sample of unknown age t_u are irradiated with the same neutron flux, equation (2-5) becomes:

$$^{40}Ar^*_s = \frac{R}{1+R} \; ^{40}K_s \; (e^{\lambda t_s-1}) \qquad (2\text{-}9)$$

$$^{40}Ar^*_u = \frac{R}{1+R} \; ^{40}K_u \; (e^{\lambda t_u}-1) \qquad (2\text{-}10)$$

Equations (2-9) and (2-10) can be written similarly to equation (2-8) following the method outlined above:

$$J_s = \frac{e^{\lambda t_s-1}}{^{40}Ar^*_s \,/\, ^{39}Ar_s} \qquad (2\text{-}11)$$

$$J_u = \frac{e^{\lambda t_u}-1}{{}^{40}Ar_u^* / {}^{39}Ar_u} \qquad (2\text{-}12)$$

Equation (2-12) can be rearranged such that:

$$t_u = \frac{1}{\lambda} \ln(1+J_u \frac{{}^{40}Ar_u^*}{{}^{39}Ar_u}) \qquad (2\text{-}13)$$

In Equation (2-7) J is dependent only upon the neutron flux, which is constant by design. Therefore, $J_s = J_u$ and equation (2-13) can be written as:

$$t_u = \frac{1}{\lambda} \ln(1+J_s \frac{{}^{40}Ar_u^*}{{}^{39}Ar_u}) \qquad (2\text{-}14)$$

$$\text{or, } t_u = \frac{1}{\lambda} \ln(1+ \frac{({}^{40}Ar^*/{}^{39}Ar)_u}{({}^{40}Ar^*/{}^{39}Ar)_s} (e^{\lambda t_s}-1) \qquad (2\text{-}15)$$

Equation (2-15) is the equation for apparent age.

In order to obtain a valid age estimate, certain assumptions must first be met:

1. At the time of formation of the rock, all the pre-existing radiogenic argon must have been outgassed. Obviously, if the rock incorporates radiogenic argon at crystallization, its apparent age will be too old.

2. The rock must have remained a closed system since crystallization. There must have been no loss or gain of potassium or argon except by natural radioactive decay. Loss of radiogenic argon by diffusion is common.

3. Any non-radiogenic argon present must have the composition of atmospheric argon. Ideally the total ^{40}Ar is the sum of the atmospheric and radiogenic ^{40}Ar. The amount of atmospheric argon is calculated by monitoring ^{36}Ar. This is on the assumption that all ^{36}Ar is atmospheric in origin and that all ^{40}Ar is either radiogenic or atmospheric.

The major advantage of the $^{40}Ar/^{39}Ar$ method is that the argon can be released in stages to obtain a series of apparent ages. This is the stepwise-outgassing technique. If the sample has remained a closed system since formation, the $^{40}Ar/^{39}Ar$ ages of all temperature steps will be identical. If the sample has in some way been disturbed after cooling, then a complex age spectrum will in general result.

CHAPTER 3

PROCEDURE

3.1 Description of the Extraction System

A schematic diagram of the argon extraction system is shown in Figure 2. The system can be divided into three components based on function. Each of these sections can be isolated by high vacuum valves. The first section consists of the extraction furnace in which the sample is placed inside a tantalum crucible (melting point = 2977°C). The crucible is placed within a heating coil and the whole assembly surrounded by a water jacket. A charcoal trap (C_1) is attached to the furnace to collect the gases released by the sample. The trap consists of activated charcoal which is cooled by liquid nitrogen.

Most of the reactive gases are removed in the second section consisting of a titanium furnace. The titanium furnace is heated to temperature and then allowed to cool in stages after exposure to the gas. This should remove the majority of gases other than argon. This section is attached to the furnace by the E.F. valve (a). It is connected by the isolation valve (b) to the pump and by the 'cow-line' valve (c) to the third section.

In the third section, or 'cow-line', the sample is collected by means of a second charcoal trap (C_2). To

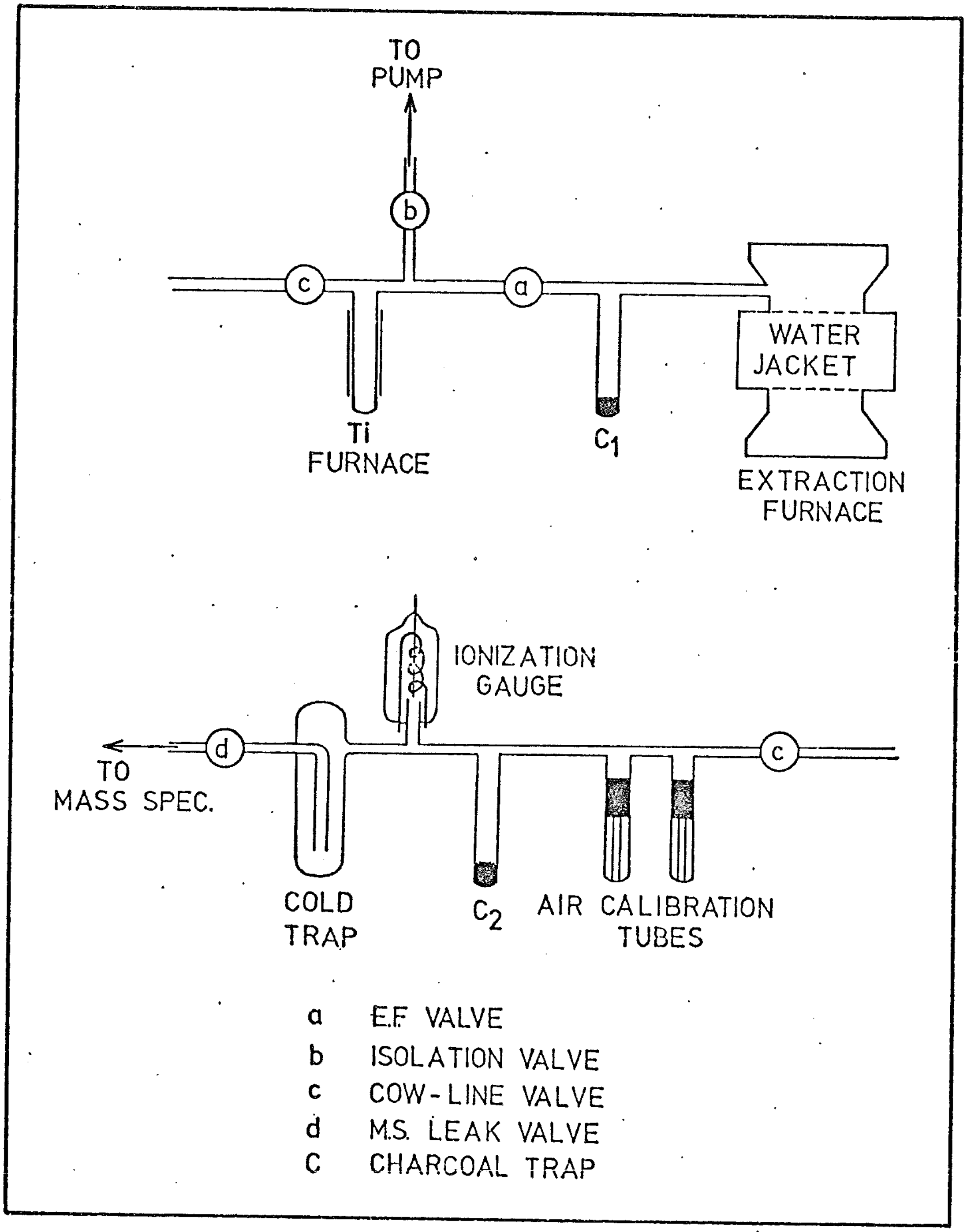


Figure 2

Schematic diagram of the Argon Extraction System.

further purify the sample, it passes through a liquid nitrogen cold trap before it reaches the mass spectrometer. This should trap any remaining condensable gases. The sample is then let into the mass spectrometer (a modified AEI MS10 Model) by a calibrated leak valve (d). Pressure is continually monitored in the cow-line by an ionization gauge. Mass discrimination is determined by periodically analyzing atmospheric argon using air samples contained in breakable glass tubes within the cow line.

3.2 Sample Preparation

Preparation of the samples was relatively straightforward. The samples were first crushed and then sieved to retain the 45 to 100 mesh fraction. To obtain the mineral separates, the sample was first put through tetrabromomethane to separate the heavy and light minerals. From the heavy fraction, biotites and hornblendes were separated using the Frantz Isodynamic Separator. The samples were then cleaned in distilled water and acetone.

The prepared samples were then wrapped in aluminum foil and packed along with known standards in aluminum sample cans. The cans were sent to the reactor at McMaster University for irradiation with fast neutrons. Time of irradiation averaged two and a half days.

3.3 Age Spectrum Diagrams

As mentioned earlier, the major advantage to this technique is that the gas is released in a series of steps and provides a number of apparent ages on the one sample. The accepted method of presenting the data is on an age spectrum diagram. Here, the apparent ages measured on gas fractions released at various temperatures are plotted against the percent of ^{39}Ar released. By plotting against percent ^{39}Ar released, one can readily tell which apparent ages are significant in light of the amount of gas they represent.

In the ideal case, where a sample has remained as a closed system since cooling, the ages for each step will be identical and yield a perfect plateau. The term 'plateau' designates that part of an age spectrum plot composed of consecutive gas fractions which represent greater than 50% of the total ^{39}Ar released. The ages in these fractions must lie within the 95% confidence limits of its neighbors (Reynolds et al., 1978).

Hanson et al. (1975), Berger (1975), and Dallmeyer (1975) have all commented upon using the shapes of spectra for determining thermal processes. Berger (1975) was able to show that as a contact zone is approached, the biotite spectra take on a 'saddle'-shape. Comparison with co-existing hornblendes would indicate if the samples have been thermally affected.

3.4 Dating of Biotite and Hornblende

Because of their different retention properties, co-existing biotites and hornblendes are a useful indicator of thermal events. Biotites are ideal for argon studies as they commonly contain greater than 9% K_2O. Under normal conditions, argon will be retained rather well. However, the argon will be lost easily at temperatures above a few hundred degrees. Hornblendes commonly contain from 0.2 to one percent K_2O. Hanson and Gast (1967) dated samples at intervals away from a granitic body. Biotites fifty feet away from the contact had ages similar to hornblendes one hundred feet away. On studies near a dike contact, they showed that hornblendes were affected only near the dike; biotite showed much greater loss further away. Thus biotite is less retentive at higher temperatures than hornblende.

Co-existing biotites and hornblendes will therefore act as sensitive indicators of thermal reheating. Agreement in ages will usually indicate that they have not been seriously disturbed since cooling below argon retention temperatures.

Incremental heating studies in the laboratory have shown that biotites will normally outgas their argon between 600 and 900°C (Berger, 1975). Hornblendes release argon between 950 and 1100°C (Berger, 1975). However, Harrison et al. (1979) have suggested that in natural systems, hornblende will outgas its argon between 400-550°C. They were able to show that in a cooling body the retention temperature for biotites is approximately 180°C. Dallmeyer (1978) indicated an upper limit of 300-345°C for biotite.

As the temperature in a rock falls below these temperatures, diffusion will slow and effectively cease; hence, the mineral in question will become a closed system. Because of the dependance of the diffusion coefficient on temperature (Musset, 1969), the transition to a closed system occurs over a narrow temperature range. This temperature range is usually so small that it is referred to as a single blocking temperature (York, 1978).

A similar phenomenon occurs in rock magnetism with the magnetic moment of a cooling body. The magnetic moment of a rock is able to assume the direction of the surrounding magnetic field if the temperature is high. As the temperature drops, thermal fluctuations become weak so that the magnetic moments are unable to assume the lower temperature directions (York, 1978). As cooling continues, the magnetic moments become fixed. As this effect is related exponentially to temperature, the freezing of the magnetic direction also occurs over a narrow temperature range (York, 1978). This is referred to as the magnetic blocking temperature. This magnetic blocking temperature is variable but is usually in the range of 300°C to 600°C.

The similarity between isotopic and magnetic blocking temperatures has been noted for some time (York, 1978 and Berger, 1979). Thermal events which affect the magnetism should similarly affect the isotopic age. It is this assumption which allows us to date remnant magnetizations by the $^{40}Ar/^{39}Ar$ method.

CHAPTER 4

REGIONAL GEOLOGY AND PREVIOUS STUDIES

4.1 Mount Peyton Batholith

Botwood Group: The Botwood Group is Silurian in age (Williams, 1964) and consists primarily of red and grey micaceous sandstones (Wig-Wam Formation) with other siltstone, conglomerate, and limestone rocks. This formation overlies the other member of the Botwood Group, the Lawrenceton Formation. The latter consists of purple to red mafic and silicic volcanics. Generally, the contact between the two formations is sharp.

The sandstones are light red to brown, fine-grained and micaceous in nature and generally exhibit cross-laminations. Malpas and Kennedy, 1974, were able to show that the cross-bedding and ripple marks indicate shallow water deposition (Lapointe, 1979). The sandstones strike northeast and dip from 45°-90°. The Botwood Group is thought to represent deposition in intermontane basins after the closing of the proto-Atlantic (Williams et al., 1974,and Strong, 1979).

Most of the rocks within the study area have been affected by low grade regional (greenschist) metamorphism (Anderson and Williams, 1970). A narrow contact aureole superimposed on the regional metamorphism around the Mount Peyton batholith has been described (Williams, 1962, Anderson and Williams, 1970, and Strong, 1979). The aureole shows a change within 10 metres from shale to slatey schist to hornfels to diorite. The rocks exhibit dissolution of quartz and the growth of platey minerals parallel to the contact (Strong, 1979).

Mount Peyton Batholith: The Mount Peyton Batholith has been classified as a bimodal intrusion by Strong, 1979. The intrusion is composite in nature. The early phase is dioritic in composition and the later phase ranges from granitic to monzonitic. A mixture of the two phases can be seen around the edges of the intrusion. These consist of diorite inclusions floating in a granite matrix.

Geometrically, the pluton is an oval-shaped body approximately 60 by 30 kilometres and is located in the centre of Newfoundland (Figure 3). The centre of the pluton consists of medium to coarse-grained hornblende syenite, granite, monzonite, and quartz monzonite. The outer ring consists of diorite and quartz diorite.

The Mount Peyton intrudes the Botwood Group and has a fault bound contact to the southeast with greywackes of the Davidsville Group. Previous radiometric dating has yielded ages for the pluton ranging from 264 ± 52 Ma to 410 ± 21 Ma for a granite and hornblende-diorite respectively (see Table 1). Bell et al., 1977 reported Rb/Sr ages of 375 ± 15 Ma for a

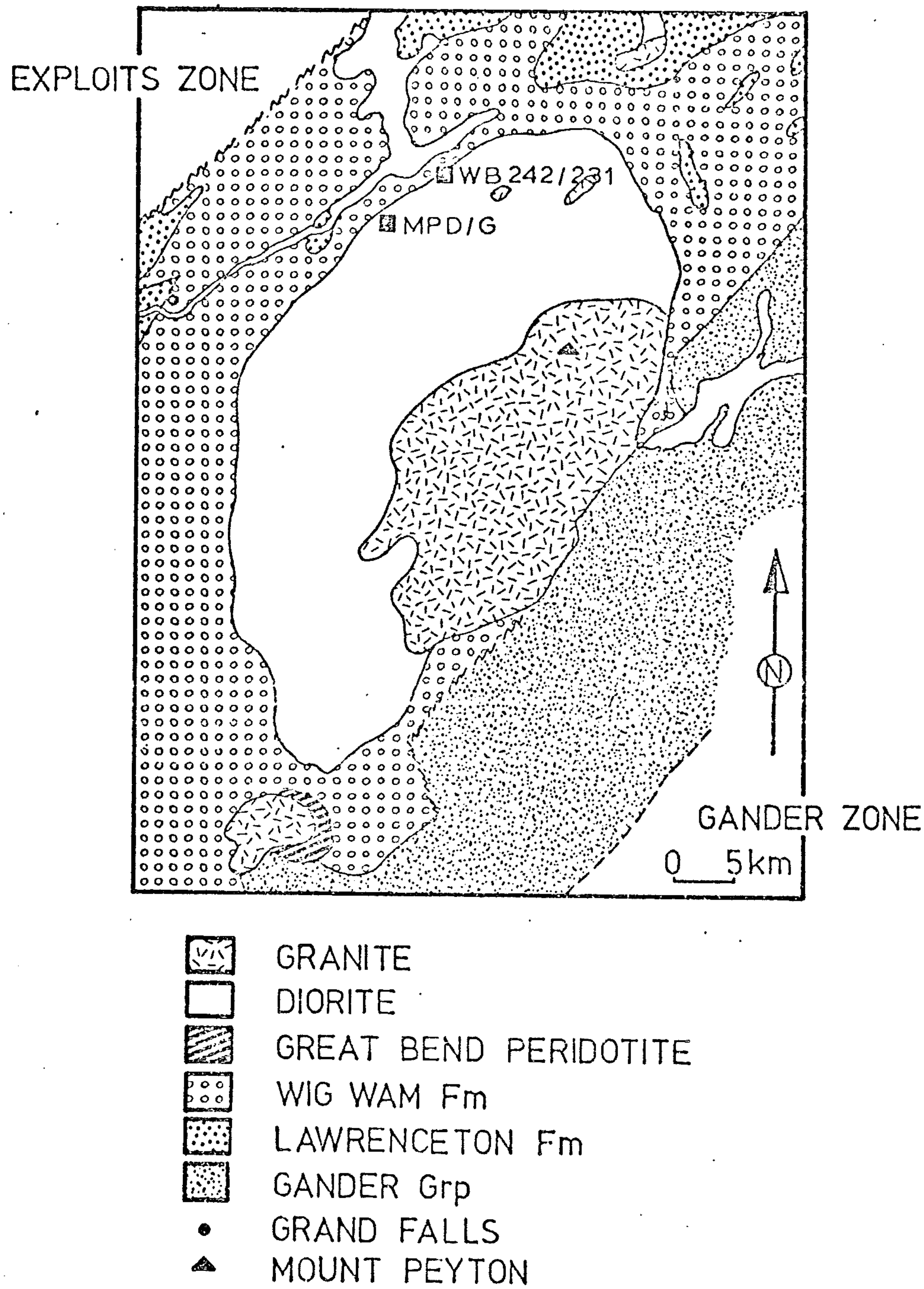


Figure 3

Geologic setting of the Mount Peyton Batholith showing sample locations (after Strong, 1979).

TABLE 1

Radiometric Data Previously Available

For the Botwood Area

Locality/Unit	Lithology	Radiometric Method K/Ar (Ma)	Rb/Sr (Ma)
Mt. Peyton Batholith	Bio - Granite	380 ± 50[1]	---
Mt. Peyton Batholith	Granite	264 ± 52[1]	---
Mt. Peyton Batholith	Hbl-bio-qtz diorite	410 ± 21[1]	---
Mt. Peyton Batholith	Granite-granodiorite	---	375 ± 15[2]
Mt. Peyton Batholith	Granite-granodiorite	---	380 ± 30[3]
Mt. Peyton Batholith	Granite-granodiorite	---	390 ± ?[4]
Botwood Group			
(Wigwam Formation)	Sandstone	423,422 ± 17[1]	---
(Lawrencton Formation)	Rhyolite	None available	

1. Williams, 1964
2. Bell et al., 1975
3. Bell et al., 1977
4. Bell, 1980 - personal communication

late phase granite-granodiorite. Bell (personal communication) confirms an age of approximately 390 Ma for this phase.

Geochemical studies by Strong (1974 and 1979) indicate that the Mount Peyton Batholith is a bimodal calc-alkaline suite. The Mount Peyton Suite exhibits a discontinuous variation along the calc-alkaline trend from high-alumina basalt to granite compositions (Strong, 1979). Strong's studies show that the batholith has exceptionally low Sr values with high CaO, Zr, Al_2O_3, Fe_2O_3, and MgO values. These higher values may be a function of the complex lithologic relationships within the pluton. There is also a strong K_2O enrichment (with respect to higher SiO_2 values) which is paralleled by Rb.

The narrow contact aureole (one kilometre wide) around the pluton suggests a shallow level of intrusion. Geophysical data indicates the pluton is shaped like an inverted cone extending to a depth of ten kilometres (Weaver, 1967).

4.2 Wesleyville

The Wesleyville area lies within the northeastern part of the Gander Zone (Williams et al., 1974). The region consists of gneisses, migmatites, and metasediments cut by a number of granitic intrusions and diabase dikes. The migmatites and gneisses of the Gander Zone are thought to be sedimentary in origin (Jayasinghe and Berger, 1976). The Wesleyville area shown in Figure 4 consists of granitic rocks belonging to five major plutons: the Powder Hill leucogranite, and the Deadman's Bay, Cape Freels, Locker's Bay, and Newport megacrystic granites.

The Precambrian gneisses belong to the upper amphibolite metamorphic facies and contain biotite, hornblende, quartz, oligoclase, garnet, and potash-feldspar. The gneisses to the west of the Newport pluton and to the east of the leucogranite are highly migmatitic. The migmatites often contain inclusions which exhibit tightly folded gneissic banding.

The plutons in the area are all composed of coarse-grained granite characterized by megacrysts of potash-feldspar. The Powder Hill pluton is a leucogranite containing garnet-muscovite-biotite. The megacrystic granites are normally massive, but can be highly foliated. The leucogranites are always deformed. Rb/Sr ages for three of the plutons have been reported: 400±5 Ma for the Cape Freels, 332±42 Ma for the Newport, and 300±18 Ma for the Locker's Bay pluton (see Table 3).

The dikes occur in a ten kilometre strip between Deadman's Bay and Trinity Bay. They trend north-south and dip vertically or nearly vertically. Widths range from one

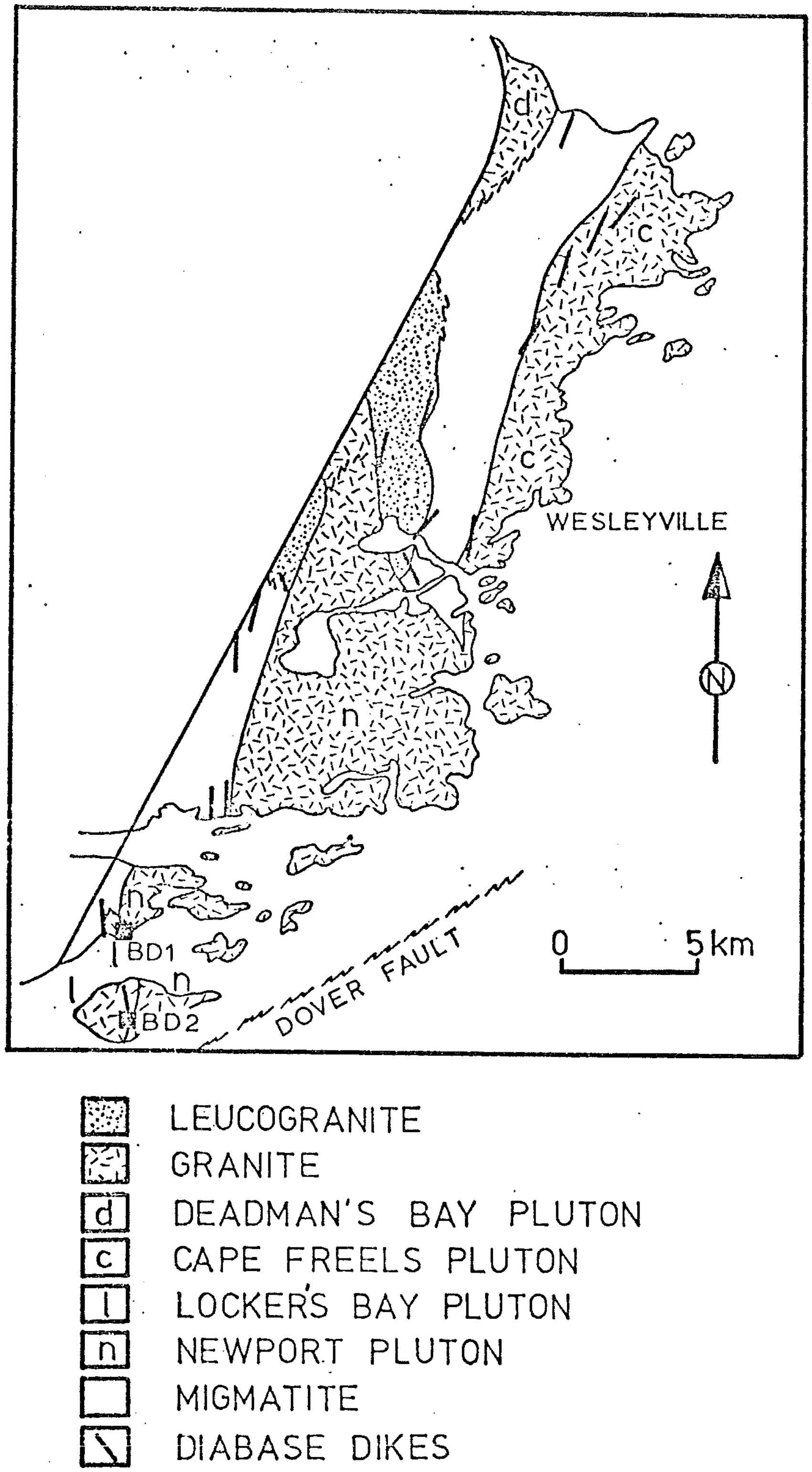


Figure 4

Geologic setting of the Wesleyville Area showing sample locations (after Jayasinghe and Berger, 1976).

metre to ten metres and in some areas the dikes are composite. Joints and foliation structures within the host rocks appear to have been the controlling factor in their emplacement (Jayasinghe and Berger, 1976). Edges of the dikes are chilled against the host rock, whereas the centres contain large plagioclase laths (andesine) along with interstitial augite and opaques. Alteration within the dikes is common. Plagioclases generally alter to sericite and saussurite. Augites have altered to hornblende-actinolite, and biotites are found as secondary products of pyroxene and opaques.

Evidence exists in the Wesleyville area of a complex history of deformation and intrusion. From this field evidence, it is possible to determine the relative age relationships of the intrusive events. The basement gneisses were subjected to at least one episode of migmatization which occurred after two previous deformation events, D1 and D2 (Jayasinghe and Berger, 1976). These migmatites were themselves deformed by a further episode, D3. The migmatites have been cut by a series of sheets and dikes which are also deformed. Inclusions of the gneisses and migmatites are common within the Powder Hill leucogranite. Foliations within the leucogranite indicate that it underwent the D3 event. The pervasive D3 fabric found within the leucogranite is absent from the Cape Freels pluton. This pluton in its northern extremity can clearly be shown to post-date the D3 folding (Jayasinghe and Berger, 1976). The Deadman's Bay pluton is believed to be older than the Cape Freels pluton on the basis of its weak cataclasis and augened megacrysts (Jayasinghe and Berger, 1976). They feel that the subdued cataclasis of the Deadman's Bay pluton indicates that deformation occurred at low temperatures. This fabric results from the D4 and D5 regional cataclasis which is pervasive in the Cape Freels.

The age of the Locker's Bay pluton is unclear as it is not in contact with the other plutons (with the exception of the Newport). Xenoliths of the gneisses and migmatites are found within the granite (Blackwood and Kennedy, 1975). Blackwood (1977) indicates that the pluton shows deformation pre-dating the regional dyke swarm. Blackwood (1977) and Blackwood and Kennedy (1975) conclude that the Locker's Bay pluton is Hadrynian in age. This clearly conflicts with Bell and Blenkinsop's (1977) Rb/Sr age of 300±18 Ma.

The dikes are controlled by the joints and foliation planes of the previous deformations. The dikes themselves are undeformed. The dikes clearly truncate the Locker's Bay, Deadman's Bay, Cape Freels, and Powder Hill plutons. However, they are cut by the Newport granite and inclusions of the dikes are often found within this pluton (Jayasinghe, 1978).

The Newport pluton is unique in that it is generally massive and undeformed except where it is truncated by the Dover Fault (Bell et al., 1979). The pluton is considered 'post-tectonic' with respect to the other plutons in the area.

On the basis of the evidence summarized above, the sequence of intrusion episodes is:

Locker's Bay Pluton (?)

1. Powder Hill Pluton

Locker's Bay Pluton (?)

2. Deadman's Bay Pluton
3. Cape Freels Pluton

Locker's Bay Pluton (?)

4. Diabase Dikes
5. Newport Pluton

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Mount Peyton

Seven samples were prepared and analyzed from the Mount Peyton area. The host rocks consisted of hornblende-diorites containing zoned plagioclase, hornblende, biotite, quartz, and accesory apatites and zircons. One granite sample was also studied. None of the samples were free of alteration. Alteration consisted generally of chloritic alteration of the biotites and actinolitic alteration of the hornblendes. Detailed stepwise outgassing experiments were carried out on all seven samples. See Chapter Three for a complete discussion of sample preparation and laboratory procedures. Age spectrum diagrams and analytical data are presented in Appendices One and Two. Previous results are shown in Table 1 and results obtained from this study are outlined in Table 2.

Samples MPBD (biotite from diorite), MPHD (hornblende from diorite) and MPGD (biotite from granite) were taken from the contact of the two phases. MPBD and MPHD represent the diorite inclusions (see Plate 1). All three samples yield similar discordant age spectra with no discernable plateaus. A striking characteristic of the age spectra obtained for these samples (Appendix 2, Figures 5 to 7) is the anomalous peak at temperatures 900° to 1000°C. These peaks yield ages up to 7% higher than the other temperature

TABLE 2

Radiometric Dates Obtained from this Study on the Mount Peyton Batholith

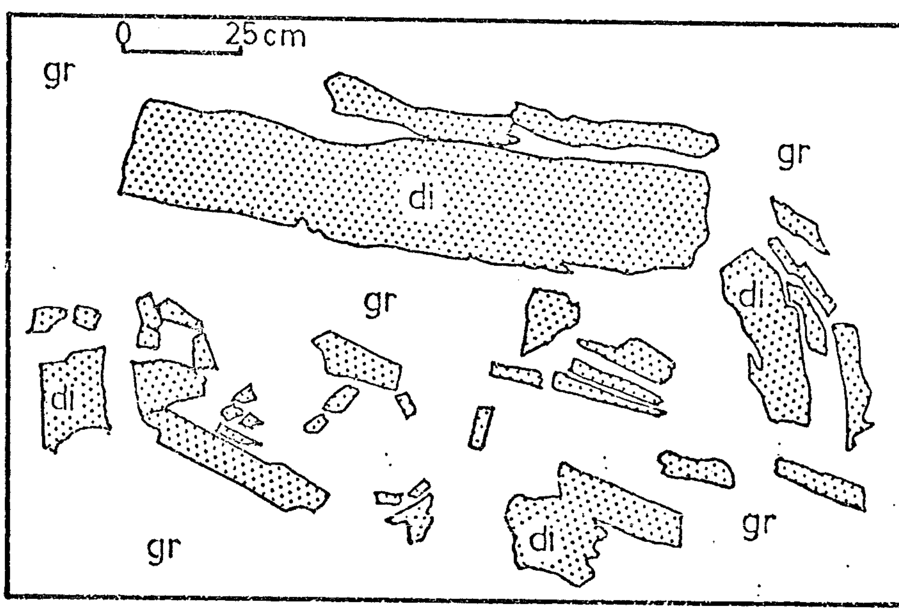
Sample No.	Lithology	Age (Ma)
WB 242 HBL	HBL - Diorite	410.1 ± 7.4
WB 242 BIO	HBL - Diorite	408.8 ± 6.5*
WB 231A HBL	HBL - Diorite	424.5 ± 5.8
WB 231A BIO	HBL - Diorite	421.3 ± 5.6
MPHD	Diorite	400.5 ± 10.6*
MPBD	Diorite	393.5 ± 13.5*
MPBG	Granite	399.5 ± 5.6*

*Total gas ages.

PLATE 1

Contact Between the Early Diorite and the Late Granite Phase of the Mount Peyton Batholith. The Dark Inclusions are Diorite (Photo by P.L. Lapointe).

PLATE 1



fractions. Tetley (1978) found similar spectra for biotites from the Berridale Batholith in Australia and was able to show that lower K and octahedral Al characterized the anomalous samples. He suggested that structural differences account for the discordant spectra.

As discussed in Chapter 2.2, recoil of atoms may cause damage to the crystal lattice which could influence the diffusional behavior of argon within the lattice. This could result in changes in release spectra for micas due to a directional dependence of the recoil range in the mica lattice (Tetley, 1978). Similar release patterns have also been observed from lunar samples (Horn et al., 1975). These were explained by recoil of ^{39}Ar out of K-rich unretentive minerals to K-poor retentive minerals. Tetley did not feel that the latter was a factor in his case, as his samples were free of impurities. However, MPBD, MPHD, and MPBG all contain noticeable impurities, namely chlorite and actinolite. Thus recoil effects may be important. In any case, the presence of chlorite on biotite causes significant changes in the cation and anion proportions within the lattice (Tetley, 1978). This may indicate structural control of the release spectra.

The diorite inclusions and granite late phase yield total gas ages similar to those for the granite determined by K-Ar and Rb-Sr methods (see Table 2), which indicates that the ages of the diorite inclusions have been reset at the time of granite emplacement. Meaningful results therefore are apparently obtained from total gas values despite the anomalous spectra. It should be noted, however, that for MPHD the step 1050-1100°C represents almost forty percent of the gas released. This step has an apparent age of approximately 416 Ma. Clearly, this cannot be considered an age plateau but it may be significant. The relatively low total gas age of 400.5±10.6 Ma may be a function of the initial step.

The remaining four samples, taken from the diorite phase away from the contact, yielded age spectra which are to a variable degree concordant. The spectra are generally characterized by an initial low temperature-low age interval followed by an age plateau at intermediate steps. The high temperature range is characterized by variable ages, but these are concordant with the plateau age (within error limits).

Release spectra for WB 231 hornblende and biotite are found in Appendix 2, Figures 1 and 2. Both yield excellent age plateaus, the values being 424.5±5.8 Ma and 421.3±5.6 Ma respectively. Data for samples WB 242 hornblende and biotite are shown in Appendix 2, Figures 3 and 4. Both spectra exhibit a greater amount of dispersion in apparent age than does WB 231. The biotite sample does not yield a good plateau and a total gas age was computed. The ages 408.8±6.5 Ma (biotite) and 410.1±7.4 Ma (hornblende) are significantly younger than the above values. The higher dispersion in ages and the young overall ages for WB 242 could result from the greater amount of chlorite and actinolite alteration in WB 242 as opposed to WB 231. Similarities between the biotite and hornblende ages and the absence of anomalous age spectra of the sort reported by Berger (1975) and Dallmeyer (1975) would indicate that the rocks have not been affected since cooling below retention temperatures. The older ages, given by the fresher WB 231 diorite would tend to be more significant than the younger ages given by the more heavily altered WB 231 sample. Therefore, the age of the early diorite phase is probably 425 Ma. In light of the behavior of samples MPBD, MPHD, and MPGB, the age of the granite late phase is probably close to the 390 Ma age determined by Bell (1980).

5.2 Wesleyville

Two samples for isotopic analysis were obtained from Lewis Island and two from the mainland to the north in the Wesleyville area. The samples were from granitic-dioritic inclusions within the diabase dikes. It is possible that the inclusions are from the Locker's Bay Pluton. The rocks consist of plagioclase, augite, hornblende, and biotite. Alteration is restricted to sericitization of the plagioclase phenocrysts. The biotites and hornblendes are generally free of alteration. Sample BD2 is actually a composite of four inclusions from within a diabase dike.

Age spectrum diagrams can be found in Appendix 2, Figures 8 to 11. Results are found in Table 3. The age spectra are similar in nature to those of WB 242 and WB 231. All four samples yielded good concordant plateaus with biotites and hornblendes giving similar ages. The older ages for BD1 biotite and hornblende, 387.6±1.4 Ma and 386.4±1.4 Ma respectively, reflect the freshness of the sample and its homogeneity. BD2 was a composite sample from four dikes and this may be expressed in the lower ages. The results indicate that the dikes were emplaced about 390 million years ago.

The age determined for the diabase dikes, 390 Ma, agrees very well with the established field evidence. The isotopic data indicates that the dikes are younger than the Cape Freels pluton and older than the Newport Pluton. An exception to the good correlation between field relations and isotopic ages is provided by the Locker's Bay Pluton. As stated in Section 4.1, Rb-Sr dating and field evidence disagree by some 100 My for the emplacement of this pluton. However, Bell and Blenkinsop's age of 300±18 Ma is difficult to evaluate as the detailed analytical data has not been published. The initial $^{87}Sr/^{86}Sr$ ratio reported by Bell and Blenkinsop is 0.715. This differs from values obtained for other granites in Newfoundland apparently associated with the Acadian Orogeny. The latter values range from 0.704 to 0.709 (Bell and Blenkinsop, 1977). According to these authors, the observed ratio

TABLE 3

Ages of the Plutons and Dikes in the Wesleyville Area

Locality/Sample	Lithology	Method	Age (Ma)	Reference
Cape Freels Pluton	Granite	Rb-Sr	400 ± 5	1
Locker's Bay Pluton	Granite	Rb-Sr	300 ± 18	2
Newport Pluton	Granite	Rb-Sr	332 ± 42	3
Deadman's Bay Pluton	Granite	U/Pb	385 ± 10	4
		U/Pb	404 ± 10	4
		$^{207}Pb/^{206}Pb$	510 ± 10	4
BD1 Biotite	Inclusions	$^{40}Ar/^{39}Ar$	387.6 ± 1.4	5
BD1 Hornblende	Inclusions	$^{40}Ar/^{39}Ar$	386.4 ± 1.4	5
BD2 Biotite	Inclusions	$^{40}Ar/^{39}Ar$	374.4 ± 5.0	5
BD2 Hornblende	Inclusions	$^{40}Ar/^{39}Ar$	374.7 ± 10.4	5

1. Bell et al., 1977
2. Bell and Blenkinsop, 1977
3. Bell et al., 1979
4. Berger and Naylor, 1974
5. This paper

of 0.715 agrees with those of continental-derived granites. However, geochemical data for plutons in the area, including Locker's Bay, indicate no chemical differences between them (Hanmer, personal communication).

Jager, 1979, indicated several factors which may lead to the resetting of Rb-Sr whole rock ages. These include mobile phases and shearing accompanied by recrystallization. Late magmatic fluid migration may also influence the system. It is possible that one or more of these factors may have affected the Locker's Bay pluton.

The observed fact that the deformation within the pluton predates the dike intrusion (Blackwood, 1977) indicates that it must have been emplaced before 390 My. In light of the geologic evidence and the age of the dike emplacement obtained in this thesis, the previous age of 300±18 Ma for the Locker's Bay pluton would appear to be invalid. The Locker's Bay pluton must have been emplaced at least 390 Ma ago, most likely near the time of emplacement of the Cape Freels pluton.

CHAPTER 6

LOCAL PALEOMAGNETIC IMPLICATIONS

6.1 Mount Peyton

From the age studies on the diorite inclusions, it would appear that these rocks have been thermally reset during emplacement of the granite late phase.

Demagnetization curves for a typical sample of the early diorite phase away from the contact are shown in Figure 5. Figure 5b indicates that the stable magnetization carries a blocking temperature of about 500°C. Figure 6 is a similar diagram for the late granite phase. Here, the blocking temperatures are lower, up to about 300°C. Thus, as was discussed earlier, the magnetic blocking temperatures are bracketed by the isotopic blocking temperatures, 180° to 345°C for biotite and 400° to 550°C for hornblende (Dallmeyer, 1978 and Harrison et al., 1979). Therefore, as the biotite and hornblende ages agree very closely, they must constrain the age of magnetization. Thus the magnetization of the early diorite phase was acquired 425 My ago.

Figure 8 shows the locations of the Mount Peyton paleopoles. The pole for the granite and the pole for the diorite inclusions are relatively close together, but both are quite different from the diorite pole. The implication is that the diorite inclusions were magnetized at the time of granitic

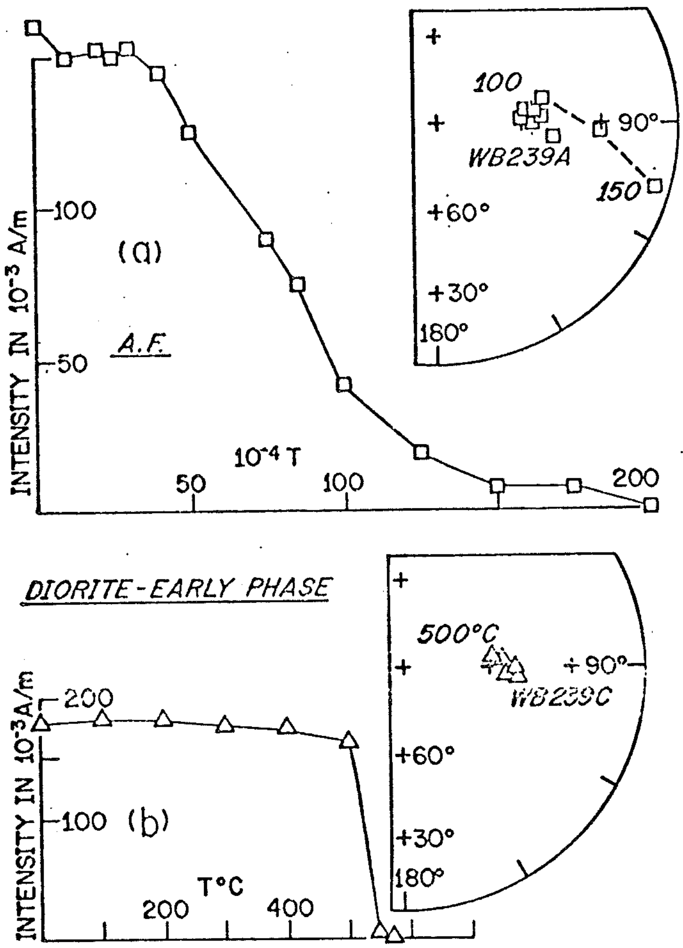


Figure 5

Response of magnetization of two specimens of the diorite early phase (from Lapointe, 1979).

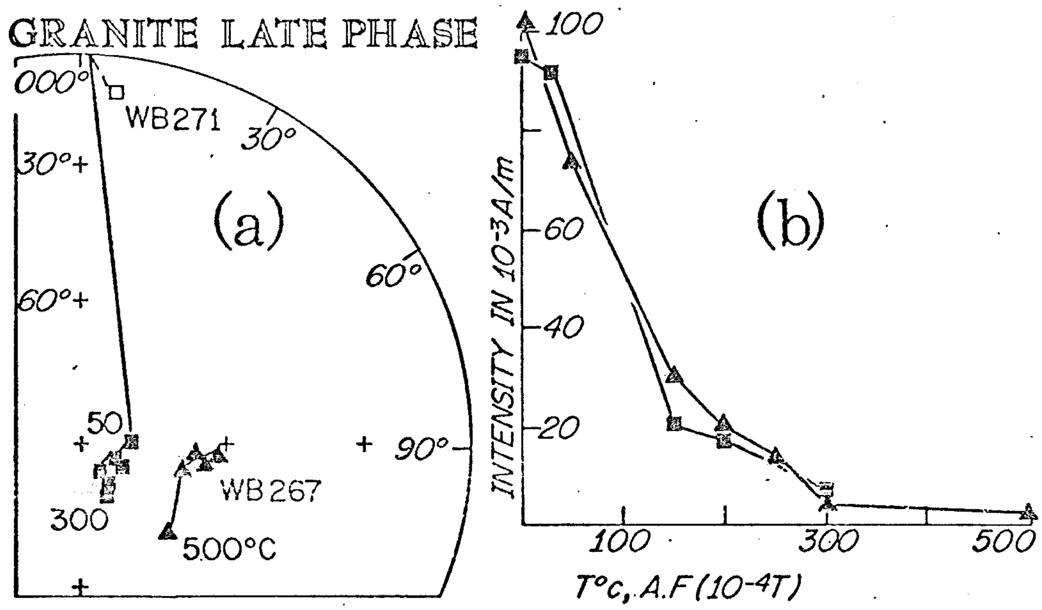


Figure 6

Response of magnetization in samples from the late diorite phase of Mount Peyton (from Lapointe, 1979).

emplacement, 390 My ago.

6.2 Wesleyville

Paleomagnetic data relevant to the present study was made available by G.S. Murthy. As a result, the magnetic blocking temperatures are not known to the writer. If, however, one can assume that they are similar to hornblende and biotite isotopic blocking temperatures (as was shown to be the case in Mount Peyton), then the age of the paleopole is closely constrained by the isotopic data. The agreement in the ages of the biotites and hornblendes must limit acquisition of magnetism to about 390 My ago.

CHAPTER 7

REGIONAL PALEOMAGNETIC STUDIES

7.1 Introduction

Paleomagnetic studies have shown their importance to plate tectonics and geodynamics. They provide an excellent means of determining relative motions between blocks. It was such studies which contributed to the revival of the continental drift theory (Irving, 1979).

Paleomagnetic studies on the Silurian-Devonian rocks of the Northern Appalachians have become increasingly more important to the reconstruction of the paleo-continental margin. These studies have shown that great discrepancies exist between the poles of cratonic ('stable') North America and those of Northern Appalachia (Irving, 1979, and Van Der Voo et al., 1979). Geologic evidence presented by Wilson (1966), Schenk (1971), and others have indicated that eastern New England and the Maritime region were not part of North America during the Early Paleozoic. Kent and Opdyke (1978) were able to make a case for sinistral-lateral movement of Appalachia relative to cratonic North America in the Late Carboniferous.

To date, a comprehensive study on paleomagnetic data related specifically to Northern Appalachia has not been made. This study is an attempt to clarify this situation with respect to the Silurian-Devonian.

An apparent polar wander (APW) path is defined as a time sequence of paleopoles. The paleopoles are calculated on the assumption that the Earth's magnetic field acts as a geocentric axial dipole. This means that APW paths give the movements of continents relative to the rotational pole. Figure 7 shows the APW path for cratonic North America from the Ordovician to the Permian.

Table 4 and Figure 8 present the presently available data for Northern Appalachia. G.S. Murthy has kindly provided his presently unpublished data. Error circles on Figure 8 indicate the 95% confidence level. None of the errors exceed 25°. The time scale used is that determined by Armstrong and McDowall, 1974 (Faure, 1977).

7.2 Discussion

As seen in Figure 8, the paleopoles for Lower-Devonian through Silurian rocks of Northern Appalachia are widely divergent from the APW path of North America. There is also a remarkable divergence between the poles themselves.

It is also apparent from Figure 8 that there are two 'clusters' of paleopoles, one above 10°N and one below. Not only are the clusters spatially different, but their mean age differs as well. The northern-most group is composed mainly of Devonian paleopoles while the southern group contains mostly Silurian poles.

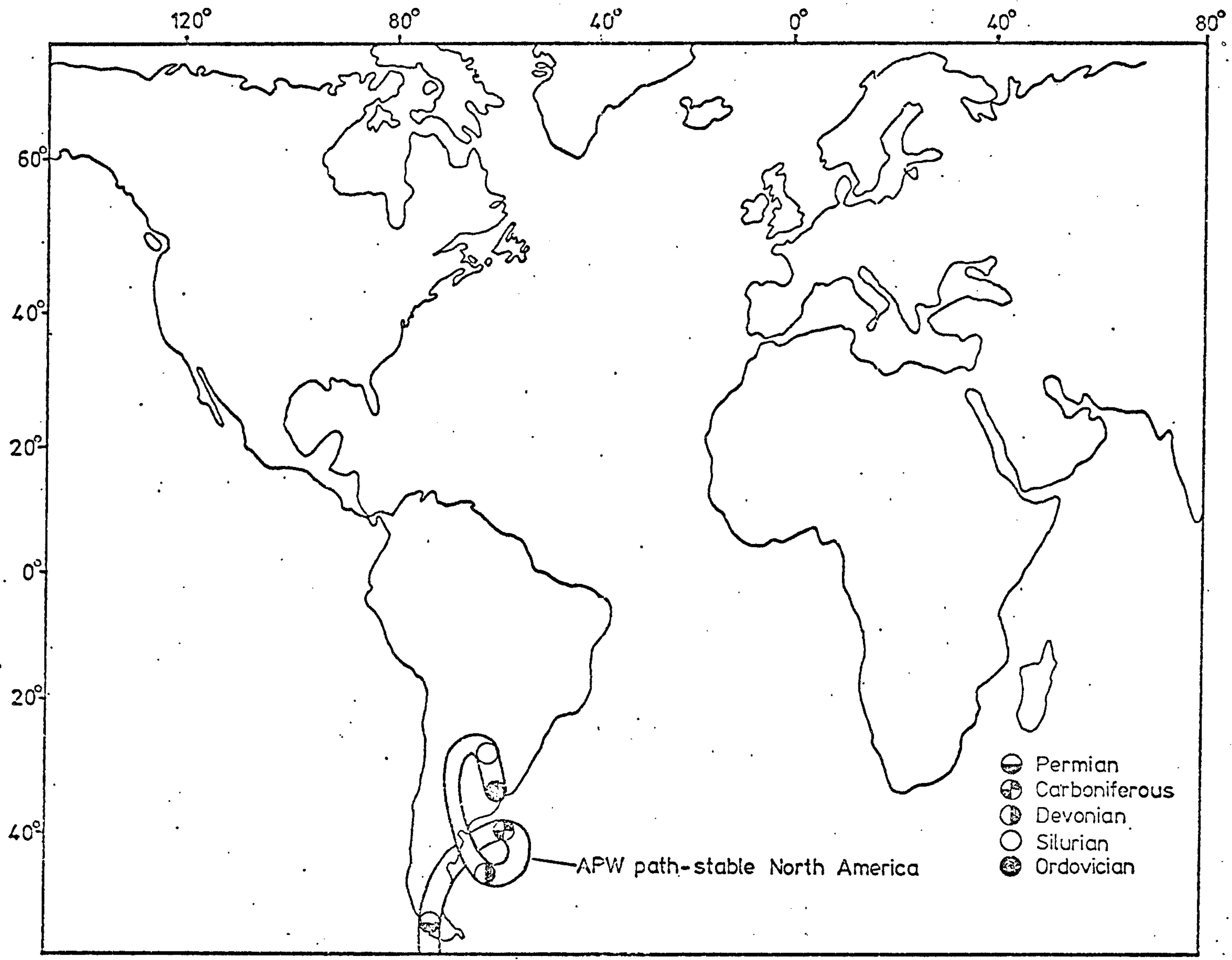


Figure 7

APW path of cratonic North America

TABLE 4

Figure Caption

Lower Carboniferous Poles

HP	Hopewell Gp (N.B.)	Roy and Park (1969)
MG	Maringouin Fm (N.B.)	Roy and Robertson (1968)

Devonian Poles

MP.G	Mount Peyton, granite (Nfld.)	Lapointe (1979)
MP.D1	Mount Peyton, Diorite Inclusions (Nfld.)	Lapointe (1979)
D1, D2	Diabase dikes, Wesleyville area (Nfld.)	Murthy (unpub.)
St.G1, St.G2	St. George Pluton, (N.B.)	Roy et al. (1979)
St.S	St. Stephen Pluton (N.B.)	Roy et al. (1979)
C	Cape Freels granite (Nfld.)	Murthy (unpub.)
M	Middle Brook granite (Nfld.)	Murthy (unpub.)
PIM	Presque Isle (Ma)	Brown (1979)
PF	Perry Fm (N.B.)	Robertson et al. (1968)
MAC	Mafic Complex (Ma)	Schutts et al. (1976)

Silurian Poles

MP.D	Mount Peyton, diorite (Nfld.)	Lapointe (1979)
Bot. Rhy.	Botwood Group, rhyolite (Nfld.)	Lapointe (1979)
Bot. Sst.	Botwood Group, sandstone (Nfld.)	Lapointe (1979)
MF	Mascarene Group (N.B.)	Roy et al. (1979)

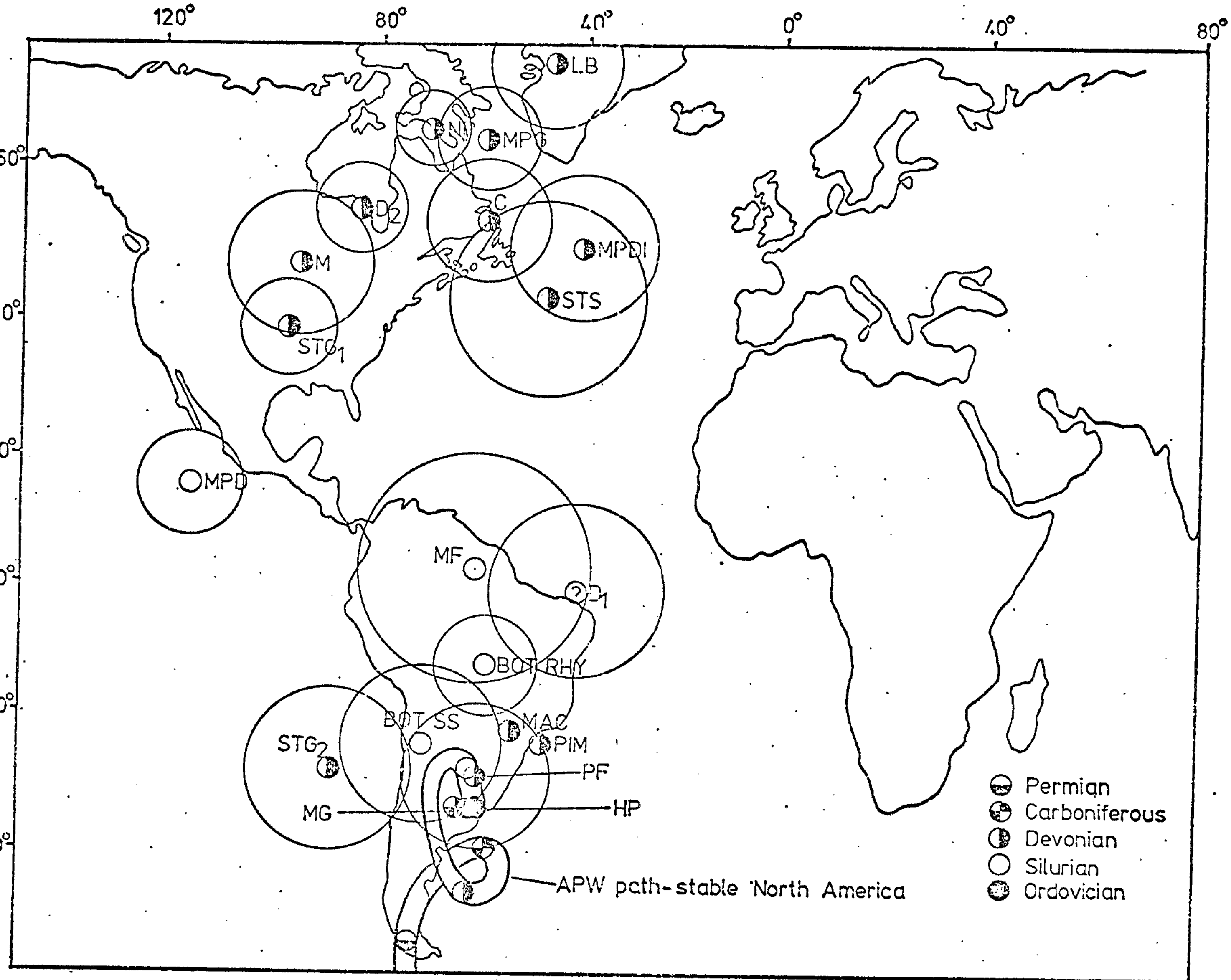


Figure 8

Paleopole locations for the Silurian-Devonian of Northern Appalachia

Scatter between poles within each of the two spatial groups is a striking characteristic. Such scatter can be caused through tectonic tilting or rotation of the measured formations (Symons, 1977). As most of the data presented was obtained from plutons, it is difficult to make accurate tilt corrections (Irving, 1979).

Williams and Anderson (1970) and Williams (1979) indicate that two orogenic events affected the Botwood area during the Paleozoic. The first occurred in the Mid-Ordovician during the Taconic Orogeny. The second, associated with the Devonian Acadian Orogeny (400-380 Ma), is characterized by tight folding, metamorphism, and igneous intrusion. The Mount Peyton batholith yields ages (425 and 390 Ma) which appear to correspond in time to this latter orogeny. Thus it is possible that deformation associated with the orogeny could have affected the Silurian (425 Ma) early diorite pole.

The paleomagnetic data from the Wesleyville area also exhibits scatter. This is so even though the ages of the intrusive bodies are quite similar. The emplacement of these bodies is believed to be associated with the Acadian orogeny.

A possible explanation for the scatter from this area may be related to the direction of the magnetism. Observation of Figure 8 indicates that the magnetization is vertical to near-vertical. The magnetic vector which is used to determine the location of a given paleopole can be resolved into a horizontal and a vertical component. From the horizontal component, one can determine declination. With the dipole model of the Earth's magnetic field, the inclinations of the magnetic flux lines at the poles are vertical. As the magnetic vector approaches the vertical, the horizontal component becomes smaller. As a result, any errors in the vertical component become much greater in horizontal component. Thus, the uncertainty in the declination becomes large. Therefore, it is possible that the scatter observed in poles from the Wesleyville area may be a function of the near-vertical magnetizations observed.

Kent and Opdyke (1978) discussed the possibility that Northern Appalachia was south of its present position relative to North America in Devonian and early Carboniferous times. Indeed, this can be seen in Figure 8 when one fits the Devonian and early Carboniferous paleopoles to the North American APW path. Coherence of the late Carboniferous paleopoles (not shown) indicates that Northern Appalachia was joined to North America by that time (Kent and Opdyke, 1978). The major movement as seen in Figure 8 is one of sinistral strike-slip of some 1500 km. magnitude.

Figure 9 shows the site locations which have yielded

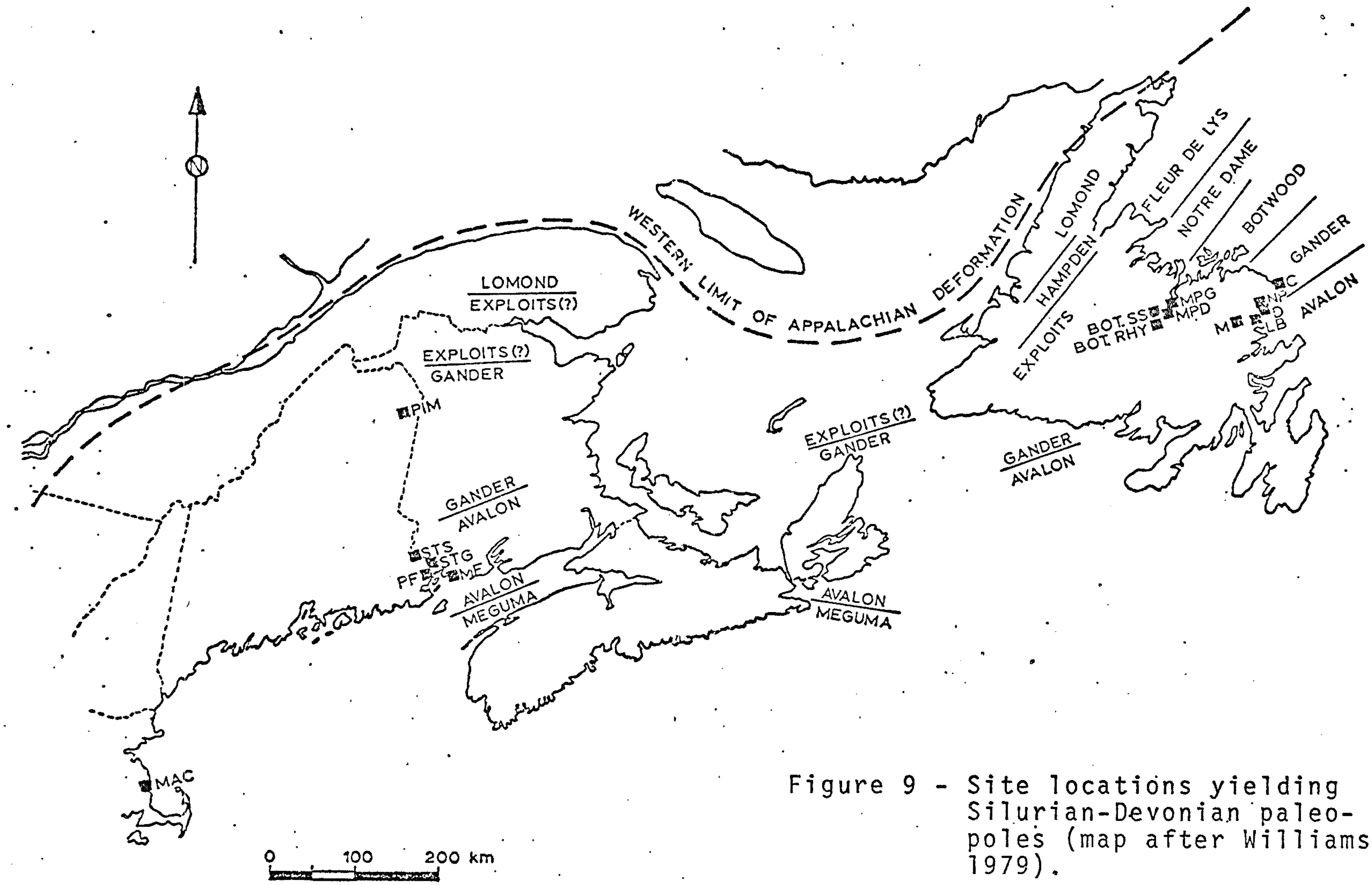


Figure 9 - Site locations yielding Silurian-Devonian paleopoles (map after Williams, 1979).

the Silurian-Devonian paleopoles. Also shown is a simplified version of the tectonic zonation of Northern Appalachia as given by Williams (1974, 1979). One can see that the site locations lie within three of the defined zones: the Gander, Botwood, and Avalon tectonographic zones. Sites from the Gander Zone in Newfoundland in the Devonian all (with the exception of the D1 pole of indeterminate age) plot within the northern pole cluster. Data for Presque Isle, Maine, a similar Silurian-Devonian paleopole, plots within the southern group of poles. Presque Isle is also found within the so-called Gander Zone. The wide variance between the Newfoundland poles and Presque Isle pole may imply that there has been relative movement between the Gander Zones of mainland Appalachia and Newfoundland.

Rocks similar in age to those found in the Newfoundland Gander Zone, but found in the Avalon Zone of New Brunswick and New England, plot in both groups of paleopoles. The St.G1 and St.S poles are problematic. Poles St.G2, PF, and MAC plot close to the Devonian APW path of North America. St.G1 and St.G2 are both from the same formation, yet their directions are significantly different. According to Roy et al. (1979), the St.G1 and St.G2 poles represent two superimposed remnant magnetizations which they were only able to discern after much difficulty. On the basis of their study, they were unable to establish with certainty which was acquired first (although it is implied that the St.G2 pole was acquired first). Rapid field direction changes or hydrothermal alteration may have resulted in the second remnance (Roy et al., 1979). They also pointed out that some of the magnetization of the St.S pole is carried by hematite and as such the remnance should be treated as a thermo-chemical remnance. Due to the uncertainties as to the acquisition of their magnetization poles, St.S and St.G1 can be disregarded in further discussion. Thus, the reliable poles from New Brunswick and New England plot within the southern group. The variance between these poles and the poles from Newfoundland would indicate that the Gander Zone in Newfoundland has moved with respect to the Avalon Zone in mainland Appalachia during the Devonian.

One can also examine data from the Botwood Zone in a similar fashion. The Mount Peyton Diorite paleopole is problematic, as it lies directly between the two groups. As stated previously, this pole may have been affected by tectonism during the Acadian orogeny. The two poles from the Silurian Botwood Formation plot close to the Silurian APW path. Poles from the Devonian intrusions within the Botwood Group plot with the northern cluster of poles. This may indicate that the Botwood Zone was moving relative to cratonic North America during the Silurian, but during the Devonian more rapid movement took place, possibly with the Gander Zone.

The recent paleopole studies would appear to support the idea that the Botwood and Gander Zones in Newfoundland moved during the Devonian relative to the rest of Appalachia. Such movement must have been rapid and occurred over a large distance. If this is the case, then central Appalachia may not have been continuous as Irving (1979) suggests.

Paleomagnetic data from Presque Isle, Maine, presented by Brown (1979) indicates that the Presque Isle paleopole is displaced from the APW path of North America. Its displacement corresponds to a sinistral strike-slip movement, as was proposed by Kent and Opdyke (1978). Brown was able to show that the movement occurred in the Silurian-Devonian, earlier than Kent and Opdyke had suggested. She was also able to place the western limit of the shear zone 150 km. closer to the margin of cratonic North America than previously thought.

Silurian-Devonian paleomagnetic data for the British Caledonides is presented in Table 5 and shown plotted in Figure 10. The data was obtained from Morris (1977); original references are taken from Morris' paper. What is interesting to note is the proximity of the British paleopoles to the Northern Appalachian ones during the Devonian. Morris interpreted the results to indicate that Britain was situated alongside Appalachia during the Devonian. It was during this time that the Atlantic Ocean is believed to have closed (Wilson, 1966). In light of new evidence pre-

TABLE 5

Figure Caption

Devonian Poles

BB	Portishead Beds	Morris et al. (1973)
SW	Dikes and Sills - S.W. England	Creer (1966)
RS	Lower Old Red Sandstone	Chamalaum & Creer (1964)
JE	Upper Old Red Sandstone	Nairn (1960)

Siluro-Devonian Poles

AR	Arrochar Complex	Briden (1970)
CH	Cheviot Lavas	Thorning (1974)
GL	Glencoe Lavas	McMurray (1970)
MV	Midland Valley Lavas	Sallomy and Piper (1937b)
SM	Somerset Lavas	Piper (1975)
LP	Lorne Plateau Lavas	Latham and Briden (1975)
OR	Old Red Sandstone	Chamalaum & Creer (1964)

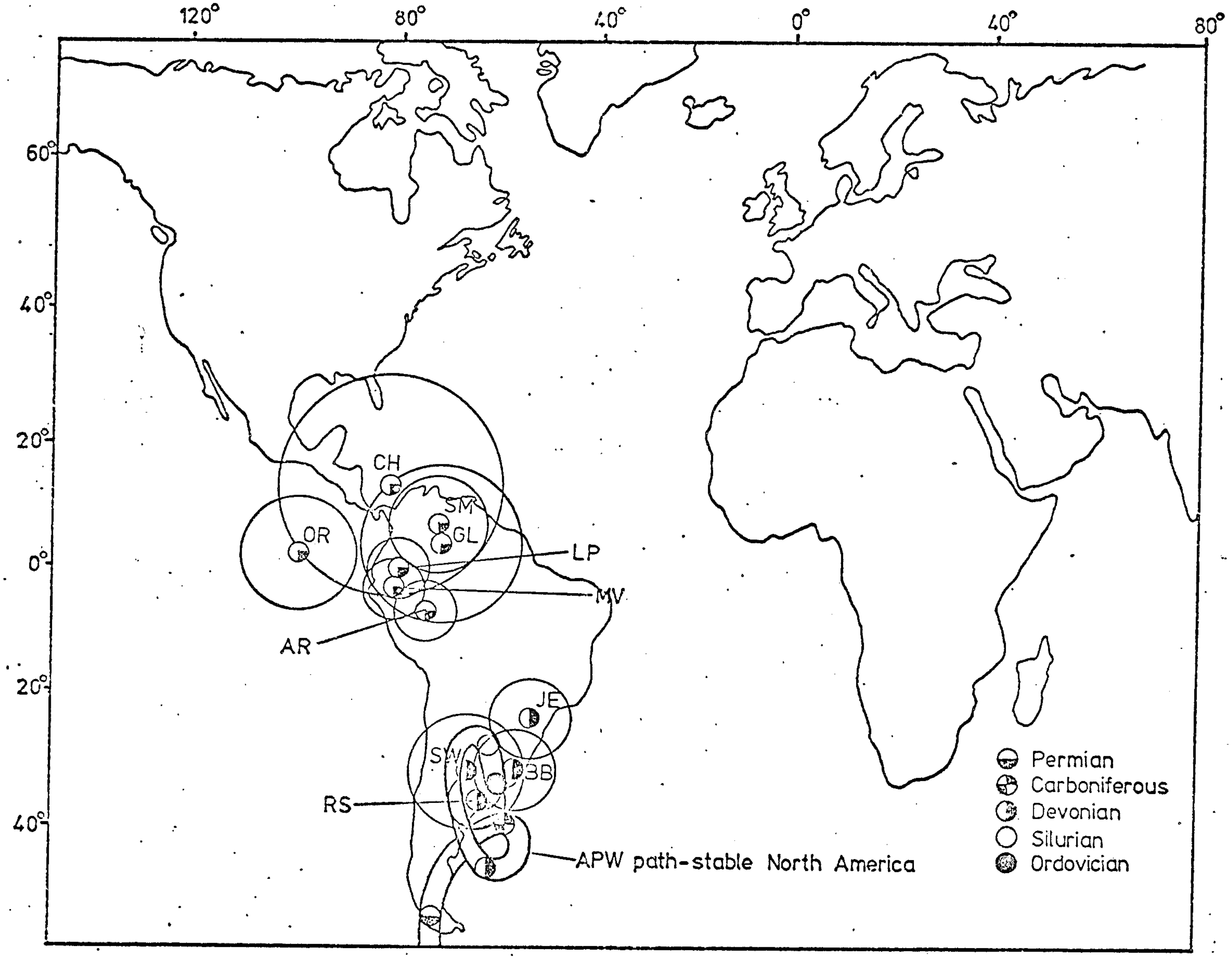


Figure 10

Paleopole locations for the Silurian-Devonian of the British Caledonides.

sented in this paper, Morris does appear to make a valid point. However, the connection must be limited to mainland Appalachia as Newfoundland appears to have acted independently of the rest of Appalachia during the Devonian.

CHAPTER 8

CONCLUSIONS

1. The age of the early diorite phase from Mount Peyton, Newfoundland, has been established at 425 ± 6 Ma based upon the similarities in ages obtained from biotite and hornblende samples. The bracketing of the magnetic blocking temperature by the blocking temperatures for argon (biotite and hornblende) constrains the age of the diorite paleopole to 420 Ma.

2. The disturbance in the argon ages of the diorite inclusions from Mount Peyton, (393.5 Ma to 400.5 Ma) corresponds to the emplacement of the late phase granite. The ages of the inclusions have at least been partially reset by the event. This corresponds to the reported paleomagnetic evidence that the inclusions yield paleopoles similar to the late phase granite.

3. Based on concordant results for biotites and hornblendes, the age of the dikes in Wesleyville has been established at 390 ± 2 Ma. This clarifies the confusion surrounding the age relationships in the area. The Locker's Bay pluton must have been emplaced at least 390 million years ago.

4. The dikes dated in Wesleyville establish the age of the D2 paleopole reported by Murthy at 390 Ma, and hence

the ages of all the Wesleyville group of paleopoles.

5. Paleomagnetic data from Newfoundland and mainland Appalachia indicate that the Botwood and Gander Zones in Newfoundland have moved relative to the rest of Appalachia during the Devonian.

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APPENDIX 1

ANALYTICAL DATA

Sample[1] (J Value[1])	Step (°C)	$^{40}Ar/^{36}Ar$[2]	$^{39}Ar/^{36}Ar$	^{39}Ar (%)	40*/39K	Atmospheric Contamination (%)	Age (my ± 2σ[3])
WB 242 Hbl (.004510)	200-650	345.30	1.34	2.9	37.29	85.58	280 ± 20.4
	650-750	418.17	2.29	6.5	53.65	70.66	390.8 ± 5.0
	750-850	411.66	1.95	7.9	59.43	71.78	428.4 ± 9.4
	850-950	408.15	1.96	7.0	57.36	72.40	414.9 ± 8.8
	950-1000	452.34	2.66	11.9	58.97	65.33	425.3 ± 5.0
	1000-1050	1250.25	16.87	35.6	56.61	23.64	410.1 ± 1.2
	1050-1100	486.03	3.35	23.7	56.89	60.80	411.9 ± 6.2
	1100-1150	325.00	0.54	4.5	55.13	90.92	400.5 ± 20.2
WB 242 Bio (.004510)	200-650	427.90	4.36	2.7	30.37	69.06	231.5 ± 8.2
	650-750	1775.18	26.36	12.9	56.14	16.65	407.1 ± 1.8
	750-800	1668.09	24.21	10.7	56.71	17.71	410.8 ± 3.0
	800-850	807.60	8.94	2.4	57.30	36.59	414.6 ± 6.8
	850-900	988.03	11.98	6.4	57.81	29.91	417.9 ± 7.2
	900-950	932.17	11.06	4.3	57.58	31.70	416.4 ± 14.4
	950-1000	1417.35	19.14	12.4	58.61	20.85	423.0 ± 2.2
	1000-1050	3622.83	58.64	15.4	56.75	8.16	411.0 ± 7.4
	1050-1100	1737.53	25.20	32.7	57.23	17.01	414.2 ± 1.2
WB 231 Hbl (.004489)	200-650	321.55	0.53	0.9	49.16	91.9	359.7 ± 155.2
	650-750	424.04	2.12	3.9	60.66	70.0	434.4 ± 8.0
	750-850	488.77	3.06	6.7	63.21	60.4	450.6 ± 4.0
	850-950	427.52	2.22	7.4	59.55	69.1	427.3 ± 3.4
	950-1000	491.83	3.37	10.3	58.33	60.0	419.5 ± 5.0
	1000-1050	1027.56	12.35	36.5	59.28	28.7	425.6 ± 1.5
	1050-1100	685.39	6.61	15.7	58.98	43.1	423.7 ± 2.0

1. J=Irradiation Parameter 2. Corrected for interferring isotopes 3. Interstep uncertianty (95%)

WB 231 Hbl (Continued)	1100-1150	366.80	1.15	12.5	61.74	80.6	441.2 ± 12.8
	1150-1200	316.03	0.35	5.9	59.38	93.5	426.2 ± 73.4
WB 231 Bio (.004568)	650-750	1150.23	15.27	22.9	55.98	25.69	410.7 ± 1.2
	750-850	1041.81	13.09	15.0	57.02	28.36	417.5 ± 1.4
	850-900	971.04	11.82	17.4	57.78	30.43	422.5 ± 2.8
	900-950	1098.56	13.90	22.2	57.13	26.90	418.3 ± 1.4
	950-1000	956.35	11.59	22.6	57.01	30.90	417.5 ± 1.6
MPHD (.003778)	200-650	323.91	1.31	7.9	21.77	91.23	142.6 ± 47.0
	650-750	578.97	4.28	7.2	66.26	51.04	403.0 ± 6.0
	750-850	630.12	4.84	7.4	69.18	46.90	418.8 ± 6.0
	850-950	803.41	7.12	6.5	71.35	36.78	430.5 ± 10.8
	950-1000	1067.17	10.38	8.7	74.37	27.69	446.7 ± 8.2
	1000-1050	1502.96	17.07	21.6	70.76	19.66	427.3 ± 3.0
	1050-1100	1698.10	20.42	36.3	68.68	17.40	416.1 ± 2.4
	1100-1150	403.01	1.62	4.4	66.45	73.32	404.0 ± 12.0
MPBD (.003600)	200-650	450.35	4.00	7.4	38.72	65.62	235.4 ± 84.0
	650-750	623.31	4.62	18.7	70.93	47.41	410.2 ± 7.6
	750-850	1048.62	10.71	8.3	70.31	28.18	407.2 ± 6.4
	850-900	726.22	5.96	5.6	72.23	40.69	416.9 ± 5.2
	900-950	880.55	7.16	2.5	81.66	33.56	464.9 ± 10.0
	950-1050	1838.56	21.19	28.1	72.82	16.07	419.9 ± 6.4
	1050-1150	1311.14	15.16	29.4	66.98	22.54	389.6 ± 3.2
MPBG (.003785)	200-650	441.49	14.82	9.0	9.85	66.93	66.0 ± 2.4
	650-750	3948.71	57.11	12.1	63.97	7.48	391.1 ± 2.6

MPBG (Continued)	750-850	6447.77	91.88	10.9	66.96	4.58	407.5 ± 2.2
	850-900	3525.43	45.07	12.2	70.67	8.38	427.5 ± 2.0
	900-950	3288.49	38.57	12.7	77.60	8.99	464.5 ± 1.6
	950-1000	7572.03	96.13	21.5	75.70	3.90	454.4 ± 2.2
	1000-1050	9611.16	133.48	10.9	69.79	3.08	422.8 ± 2.4
	1050-1150	4761.08	66.65	10.7	67.00	6.21	407.7 ± 4.6
BD1 Bio (.001839)	200-550			-Lost-			
	550-625	535.28	8.91	3.3	26.92	55.0	84.7 ± 1.6
	625-700	2202.26	15.59	3.4	122.30	17.0	356.5 ± 2.0
	700-775	4345.64	32.12	8.7	126.1	7.0	366.4 ± 1.3
	775-850	2765.52	18.67	8.1	132.3	11.0	382.6 ± 1.5
	850-925	3579.52	24.43	10.6	134.4	8.0	388.1 ± 1.4
	925-1000	10356.50	74.98	39.1	134.2	3.0	387.5 ± 1.2
	1000-1100	5290.65	38.47	25.4	129.9	6.0	376.0 ± 1.1
	1100-1200	498.01	1.58	1.4	128.0	59.0	371.4 ± 10.1
BD1 Hbl (.001787)	200-600			-Lost-			
	600-700	2408.47	16.93	4.0	124.8	12.0	363.0 ± 5.0
	700-800	3101.27	21.66	8.1	129.6	10.0	376.0 + 2.3
	800-875	1557.85	9.50	9.3	132.9	19.0	385.0 ± 2.8
	875-950	1340.39	7.83	12.0	133.4	22.0	386.0 + 3.0
	950-1025			-Lost-			
	1025-1100	1827.25	11.46	32.4	133.7	16.0	387.0 ± 2.5
	1100-1175	713.12	3.26	31.3	128.1	41.0	372.0 ± 5.0
	1175-1250	338.33	0.31	2.9	137.8	87.0	398.0 ± 53.0
BD2 Bio (.003645)	200-650	802.12	12.90	3.0	39.27	36.8	241.3 ± 1.6
	650-750	1838.55	24.93	16.1	61.89	16.1	366.9 ± 1.2

BD2 Bio (Continued)	750-800	2154.75	29.04	11.7	64.02	13.7	378.3 ± 1.0
	800-850	2832.12	39.81	29.2	63.71	10.4	376.7 ± 1.2
	850-900	2333.41	32.44	10.8	62.82	12.7	371.9 ± 1.2
	900-950	1015.93	11.42	12.7	63.08	29.1	373.3 ± 1.0
	950-1000	1108.56	12.96	12.1	62.74	26.6	371.5 ± 1.6
	1000-1050	596.72	4.86	2.0	61.97	49.5	367.3 ± 3.6
	1050-1100	756.90	7.50	1.6	61.49	39.4	364.7 ± 3.4
	1100-1150	365.69	1.13	0.9	62.15	80.8	368.3 ± 9.2
BD2 Hbl (.003758)	200-650	384.71	1.84	2.1	48.55	77.0	302.3 ± 14.8
	650-750	723.12	6.99	2.9	61.18	41.0	373.3 ± 6.4
	750-850	514.16	3.59	4.6	60.90	57.0	371.8 ± 6.4
	850-950	473.98	2.76	6.5	64.78	62.0	393.0 ± 7.6
	950-1000	952.90	10.25	19.6	64.16	31.0	389.7 ± 3.8
	1000-1050	2533.78	36.66	39.3	61.06	12.0	372.7 ± 2.6
	1050-1100	746.58	7.36	18.2	61.28	40.0	373.9 ± 4.6
	1100-1150	382.76	1.43	5.6	60.87	77.0	371.9 ± 17.4
	1150-1200	310.47	0.19	1.2	77.61	95.0	461.7 ± 186.0

APPENDIX 2

AGE SPECTRUM DIAGRAMS

N.B. Half-heights between error bars represent the 2σ (95%) interstep uncertainties

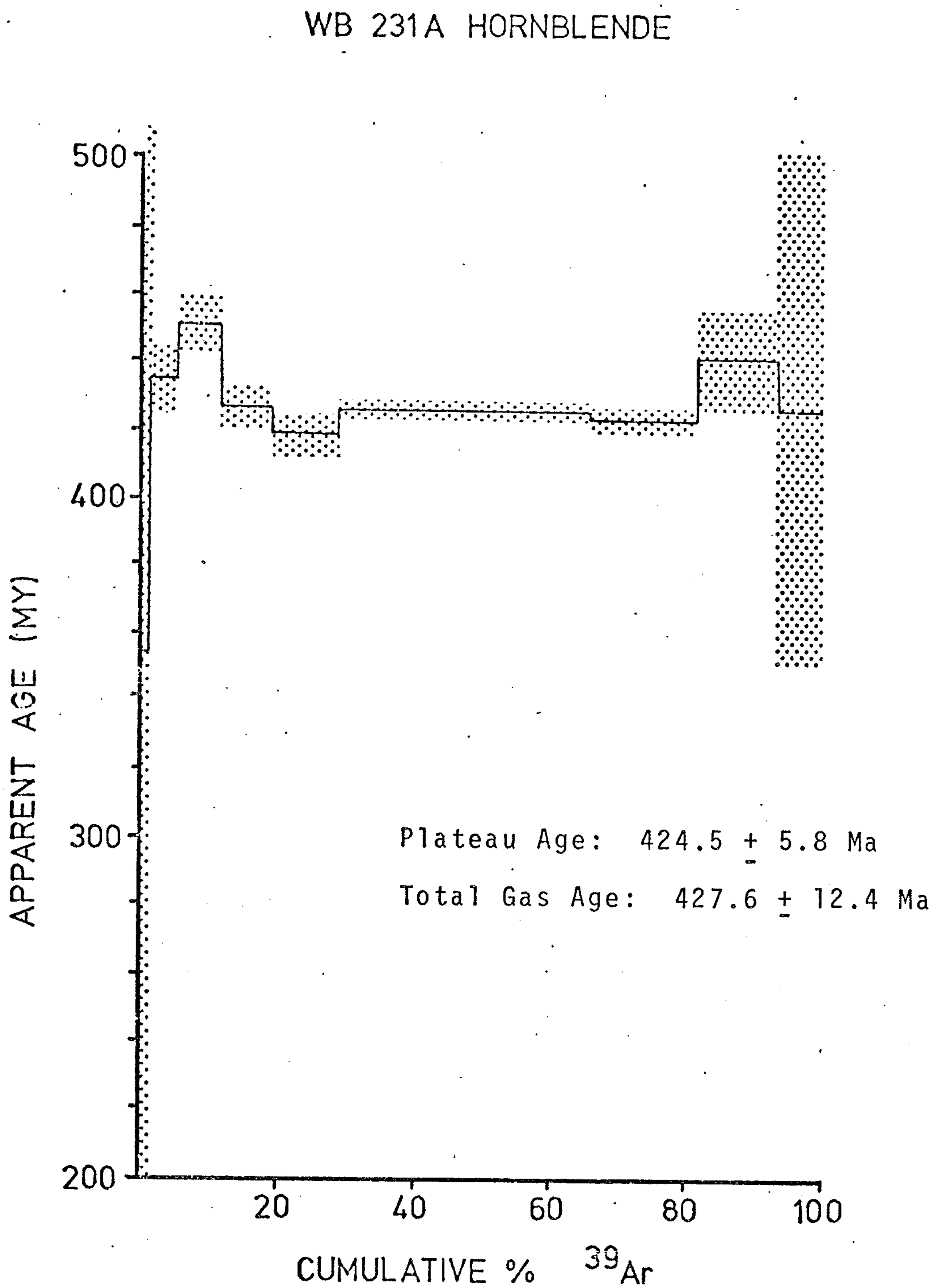

WB 231A HORNBLENDE
500
400
300
200
APPARENT AGE (MY)
20
40
60
80
100
CUMULATIVE % ^{39}Ar
Plateau Age: 424.5 ± 5.8 Ma
Total Gas Age: 427.6 ± 12.4 Ma

FIGURE 1

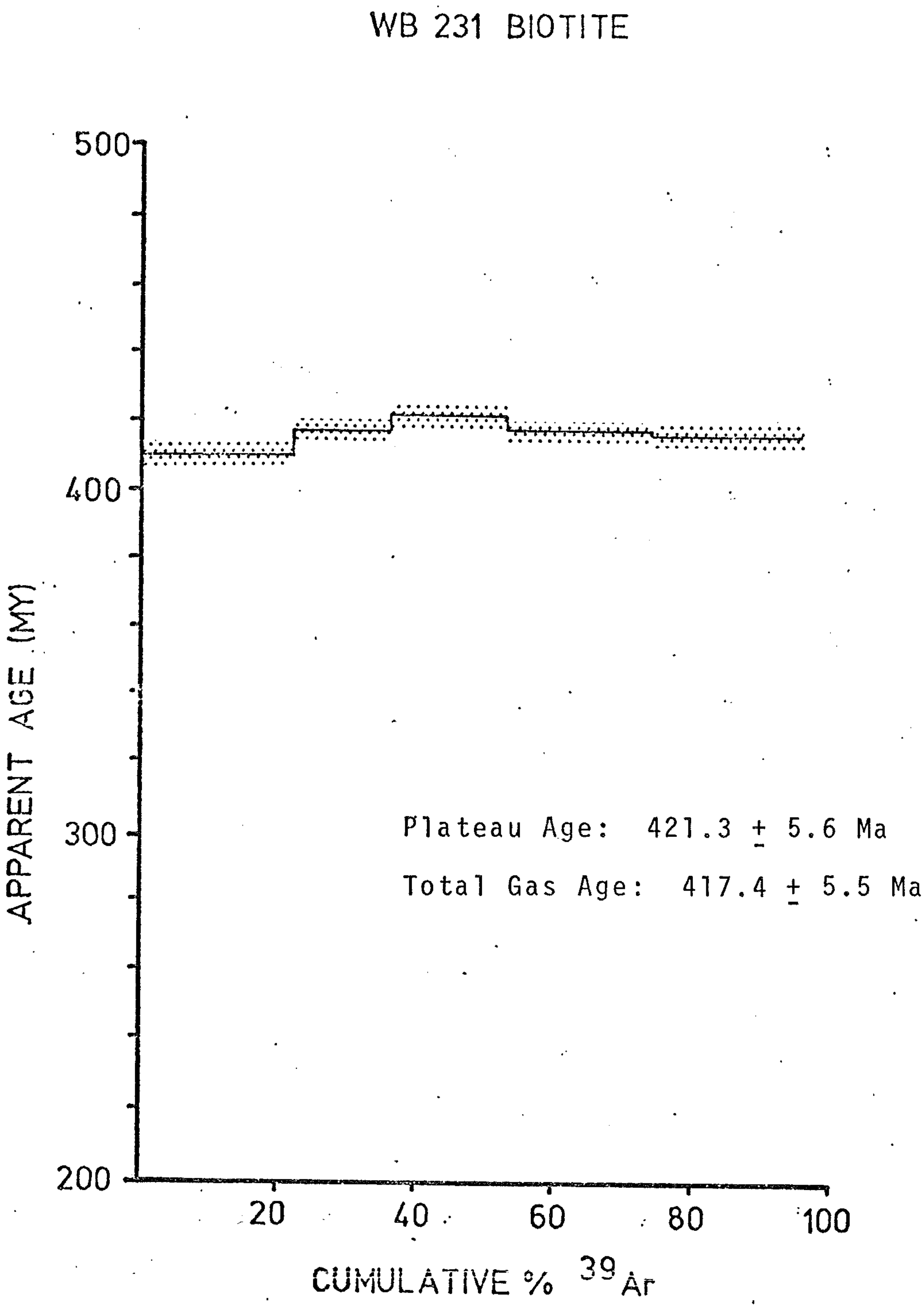

WB 231 BIOTITE
500
400
300
200
APPARENT AGE (MY)
20
40
60
80
100
CUMULATIVE % 39 Ar
Plateau Age: 421.3 ± 5.6 Ma
Total Gas Age: 417.4 ± 5.5 Ma

FIGURE 2

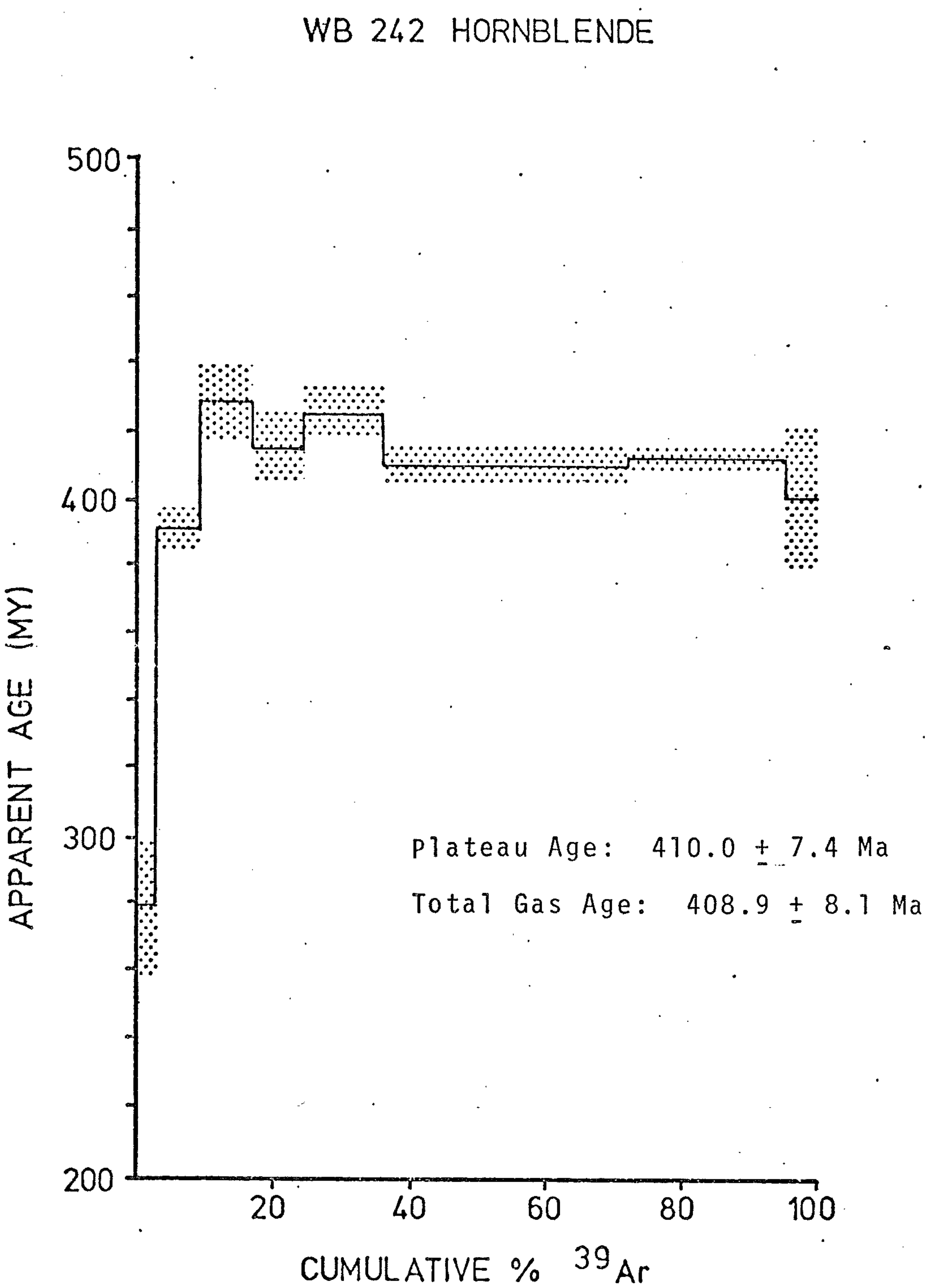

WB 242 HORNBLENDE
500
400
300
200
APPARENT AGE (MY)
20
40
60
80
100
CUMULATIVE % ^{39}Ar
Plateau Age: 410.0 ± 7.4 Ma
Total Gas Age: 408.9 ± 8.1 Ma

FIGURE 3

WB 242 BIOTITE

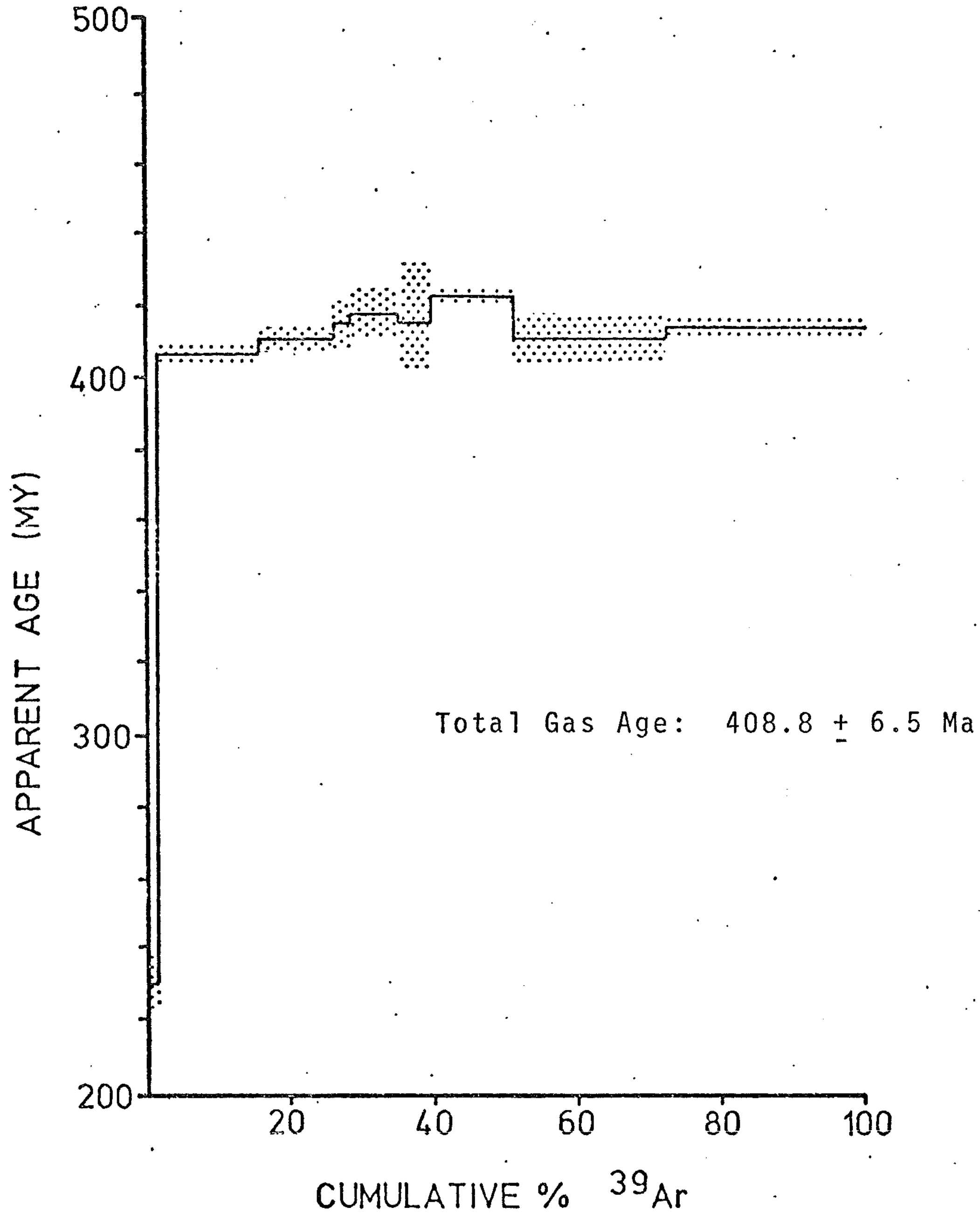


FIGURE 4

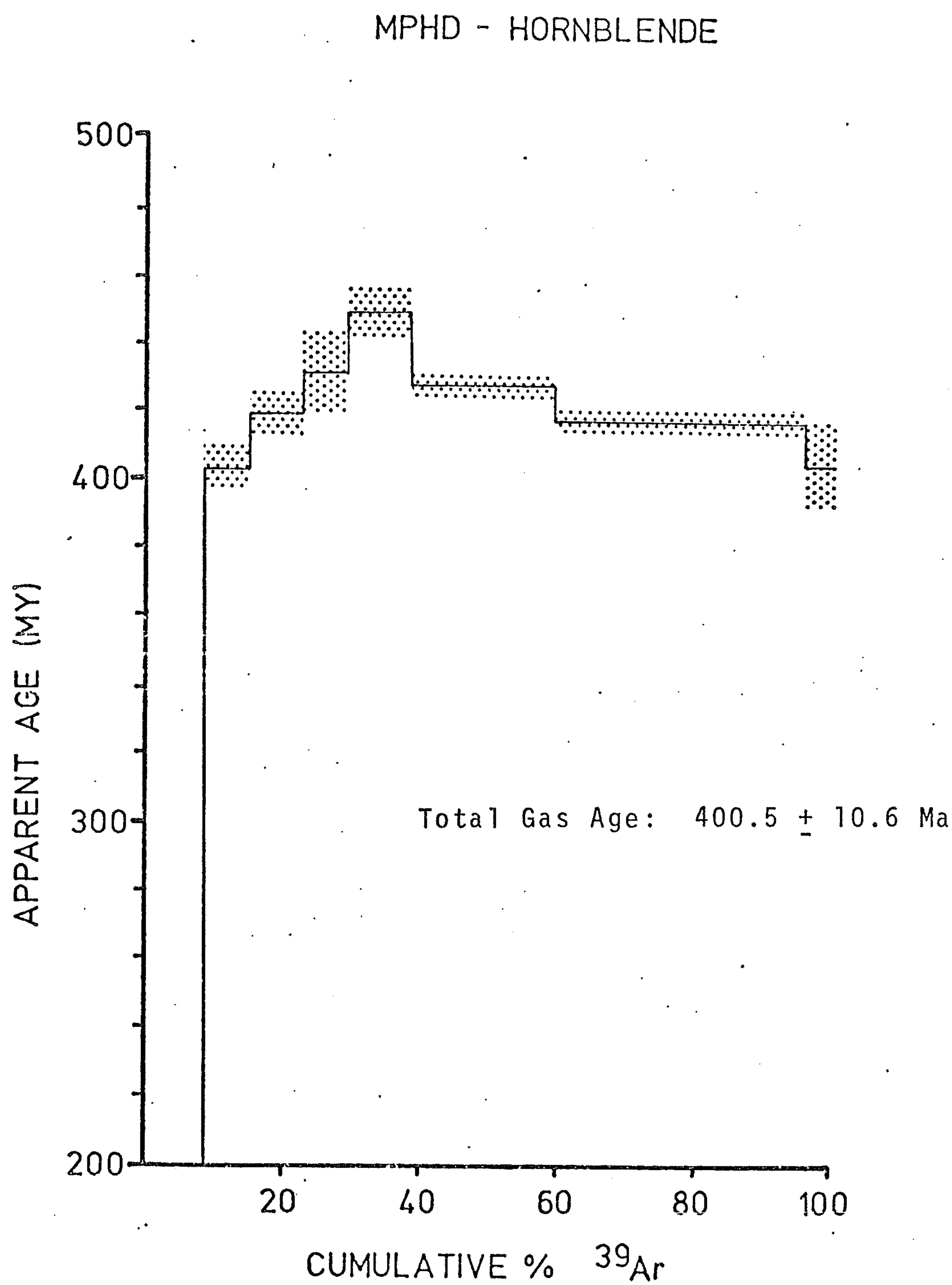

MPHD - HORNBLENDE
500
400
300
200
APPARENT AGE (MY)
20
40
60
80
100
CUMULATIVE % 39Ar
Total Gas Age: 400.5 ± 10.6 Ma

FIGURE 5

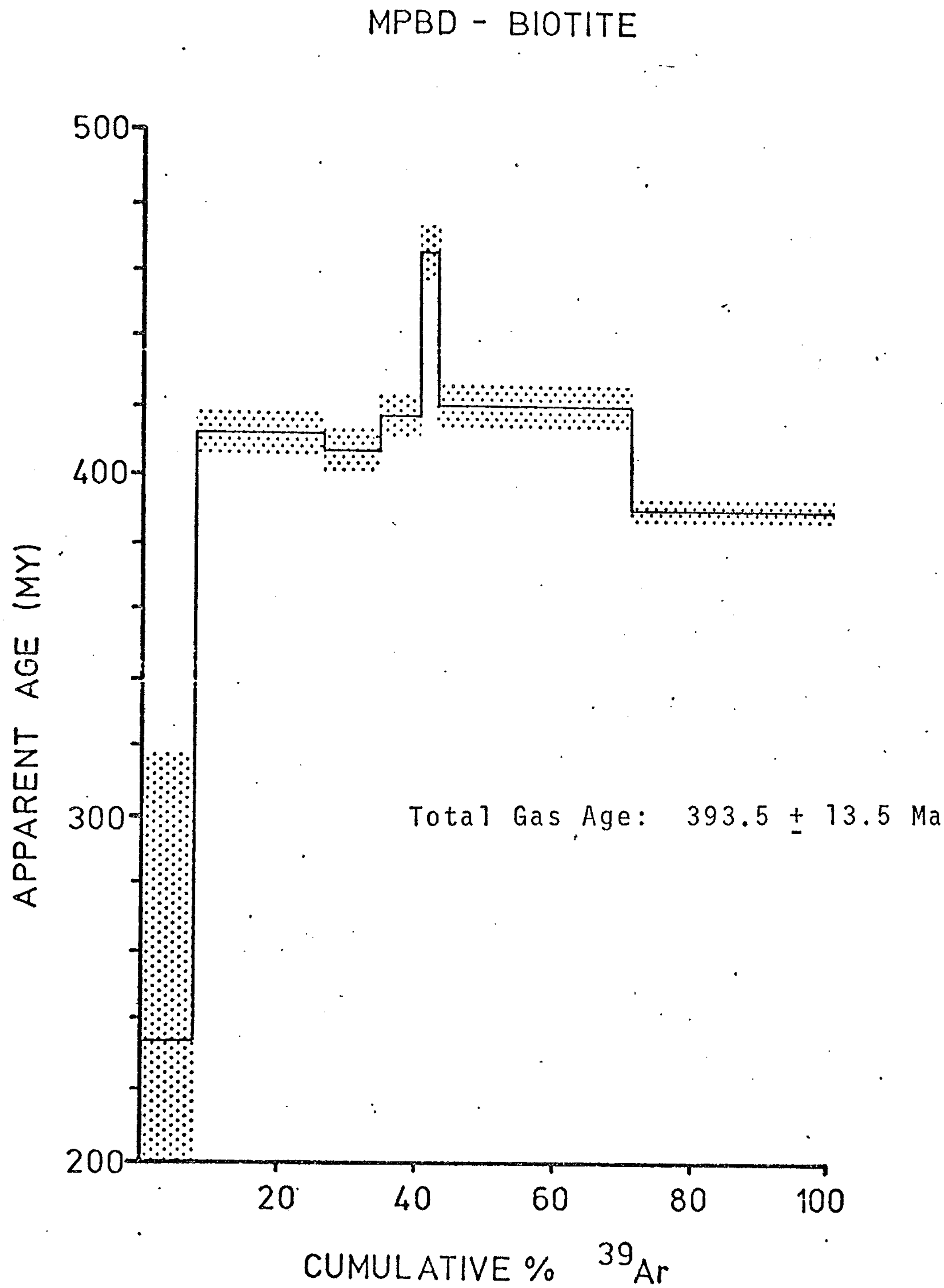
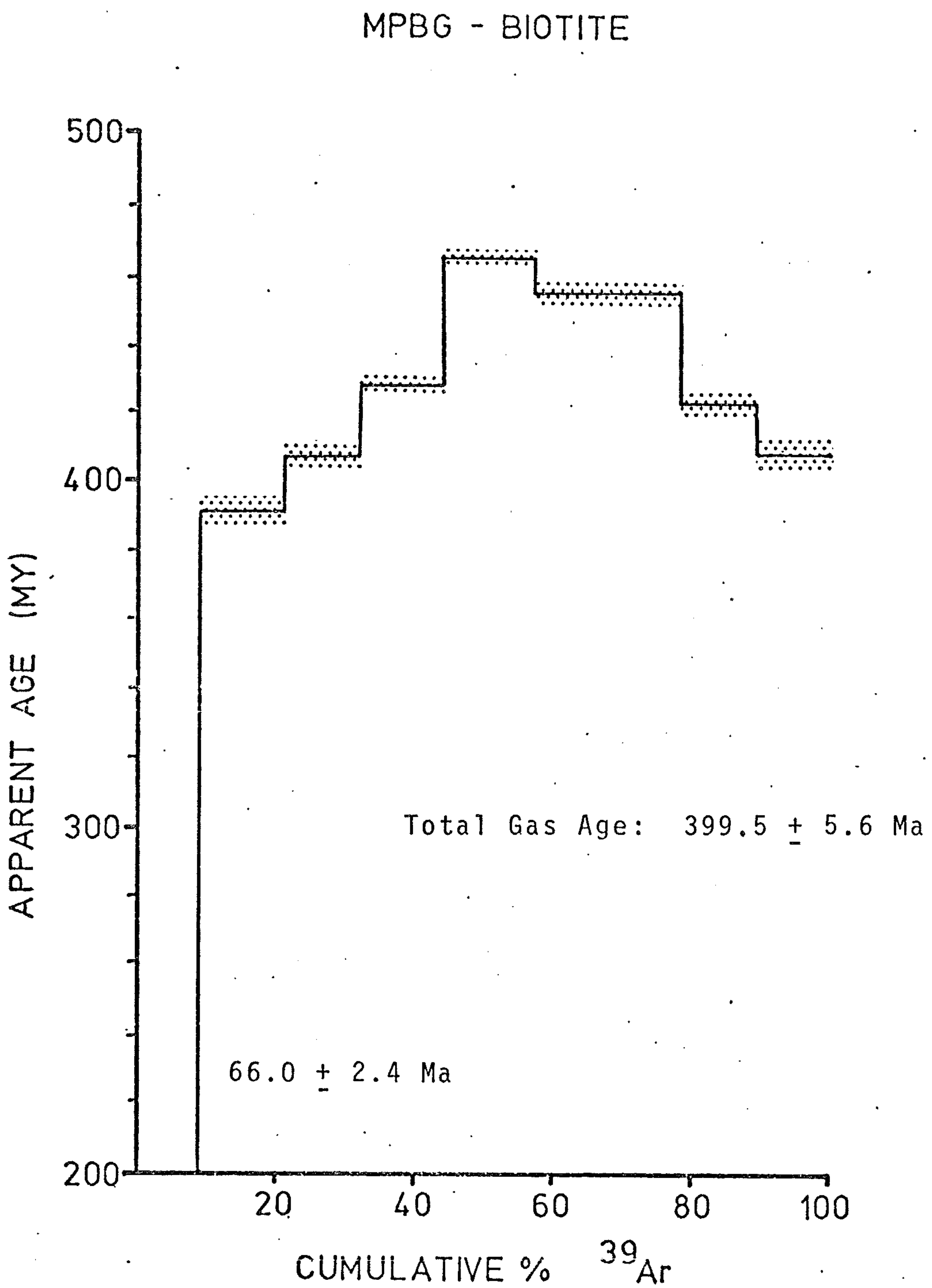

MPBD - BIOTITE
500
400
300
200
APPARENT AGE (MY)
Total Gas Age: 393.5 ± 13.5 Ma
20
40
60
80
100
CUMULATIVE % 39Ar

FIGURE 6



MPBG - BIOTITE
500
400
300
200
APPARENT AGE (MY)
Total Gas Age: 399.5 ± 5.6 Ma
66.0 ± 2.4 Ma
20
40
60
80
100
CUMULATIVE % 39Ar

FIGURE 7

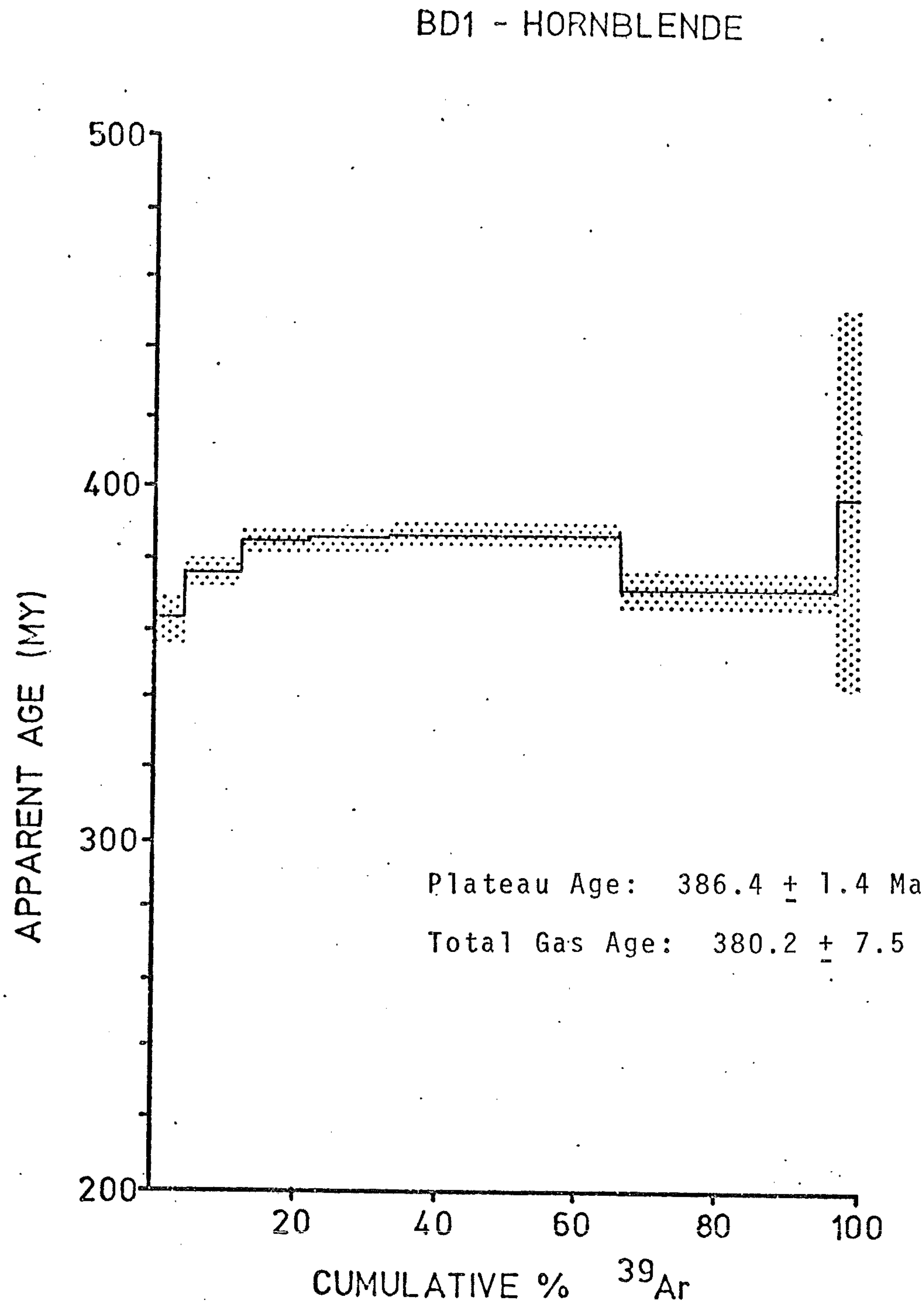
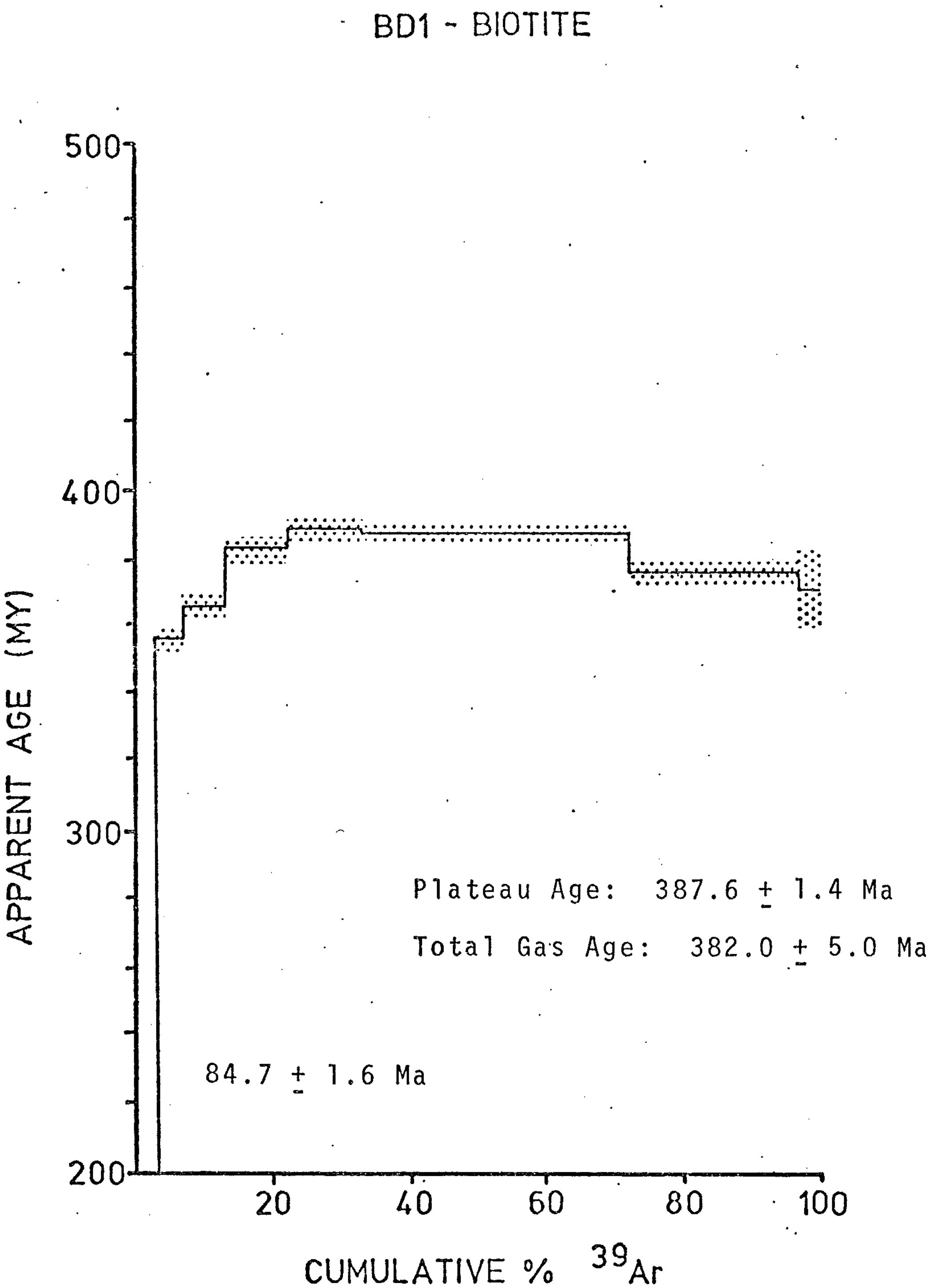

BD1 - HORNBLENDE
500
400
300
200
APPARENT AGE (MY)
20
40
60
80
100
CUMULATIVE % ^{39}Ar
Plateau Age: 386.4 ± 1.4 Ma
Total Gas Age: 380.2 ± 7.5

FIGURE 8



BD1 - BIOTITE
500
400
300
200
APPARENT AGE (MY)
20
40
60
80
100
CUMULATIVE % ^{39}Ar
Plateau Age: 387.6 ± 1.4 Ma
Total Gas Age: 382.0 ± 5.0 Ma
84.7 ± 1.6 Ma

FIGURE 9

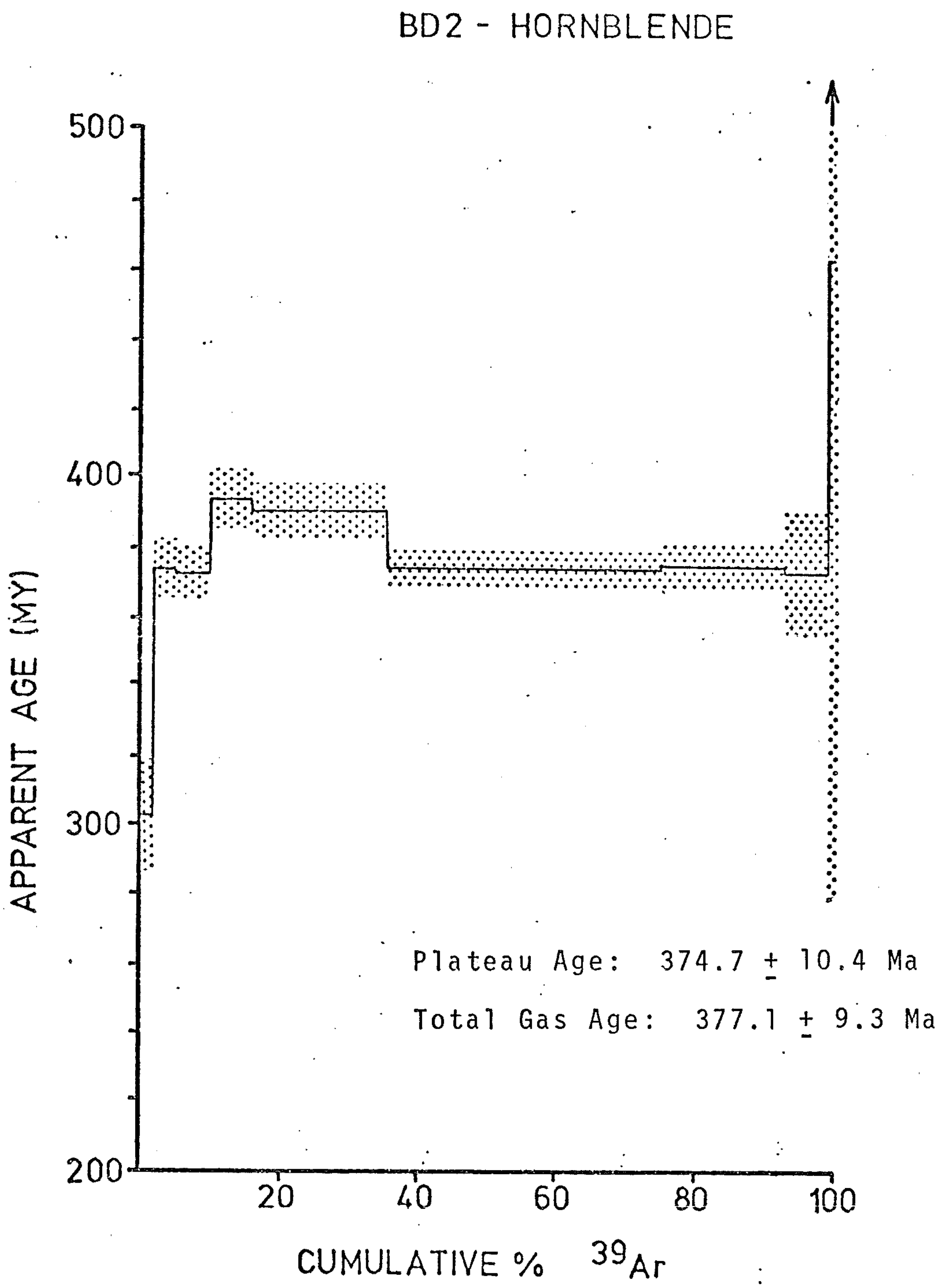

BD2 - HORNBLENDE
500
400
300
200
APPARENT AGE (MY)
20
40
60
80
100
CUMULATIVE % 39Ar
Plateau Age: 374.7 ± 10.4 Ma
Total Gas Age: 377.1 ± 9.3 Ma

FIGURE 10

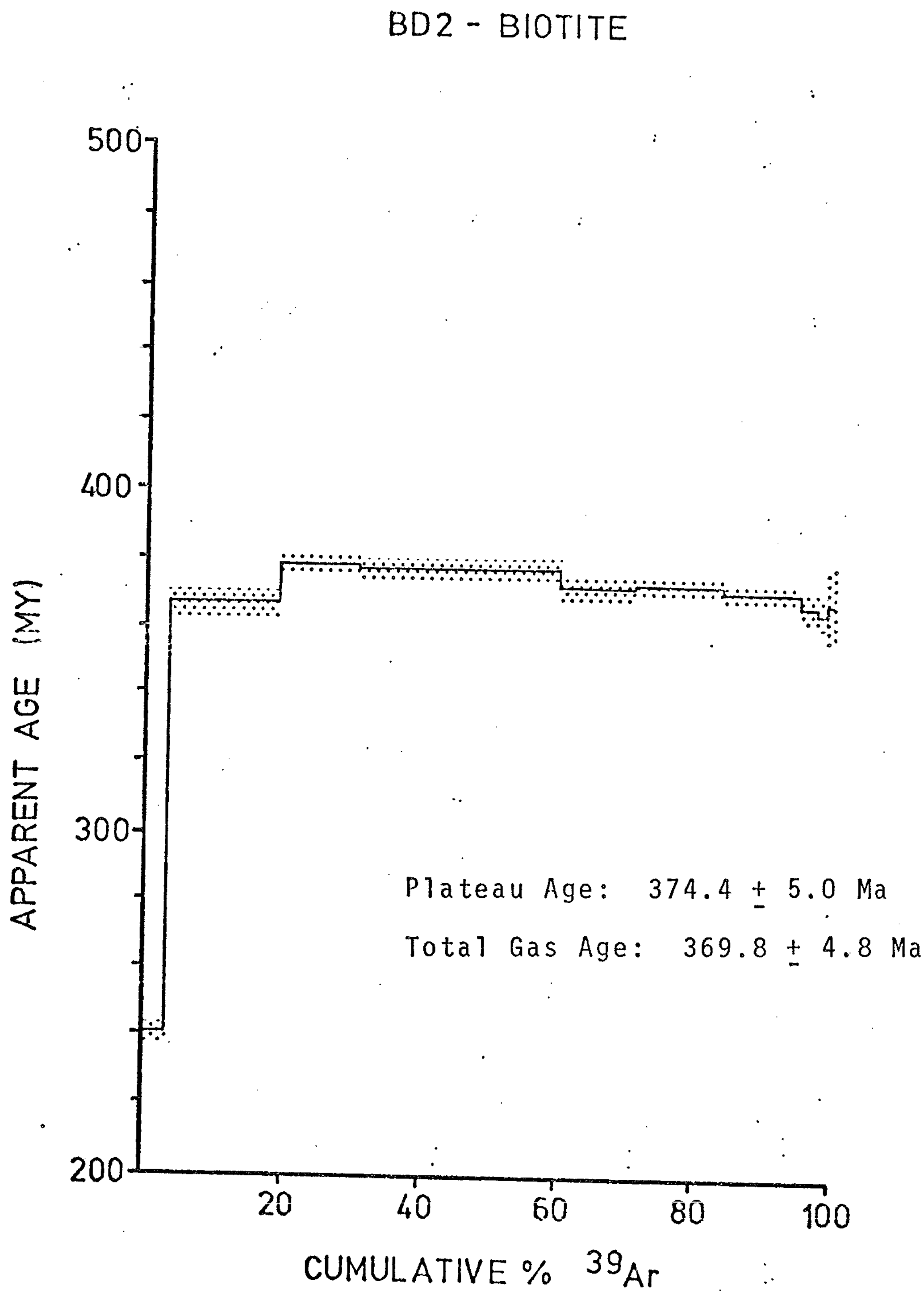

BD2 - BIOTITE
500
400
300
200
APPARENT AGE (MY)
20
40
60
80
100
CUMULATIVE % 39Ar
Plateau Age: 374.4 ± 5.0 Ma
Total Gas Age: 369.8 ± 4.8 Ma

FIGURE 11

APPENDIX 3

GAS RELEASE CURVES

Figure 1

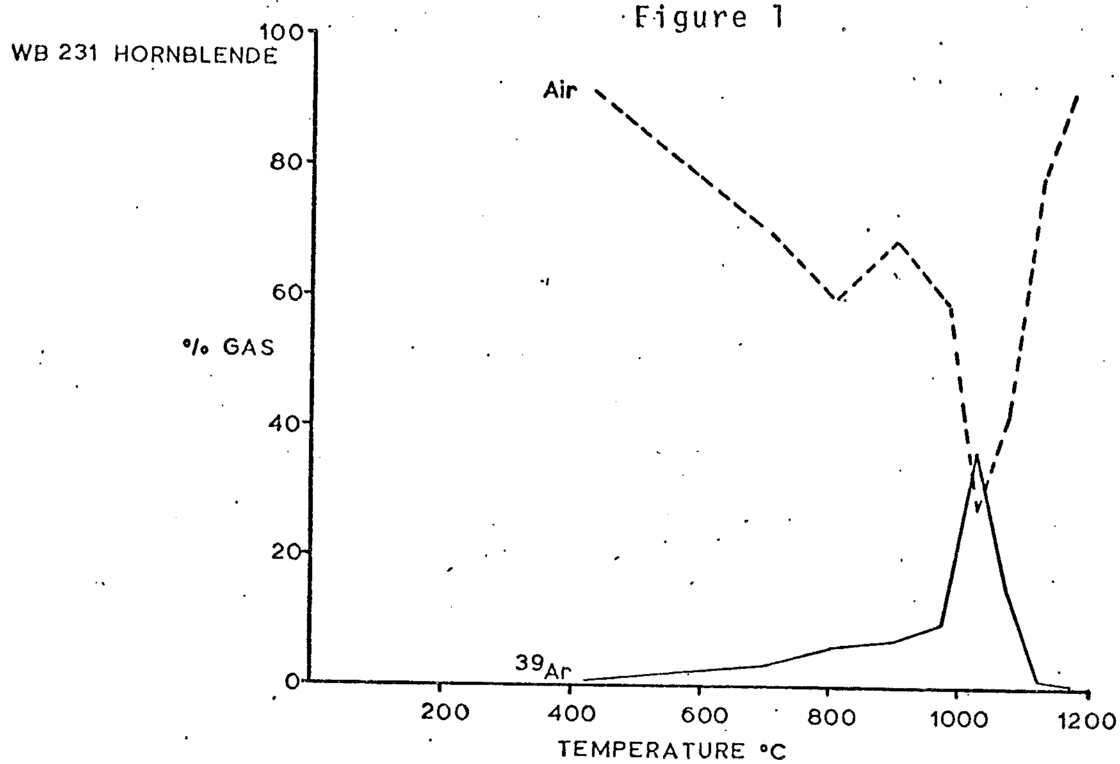


Figure 2

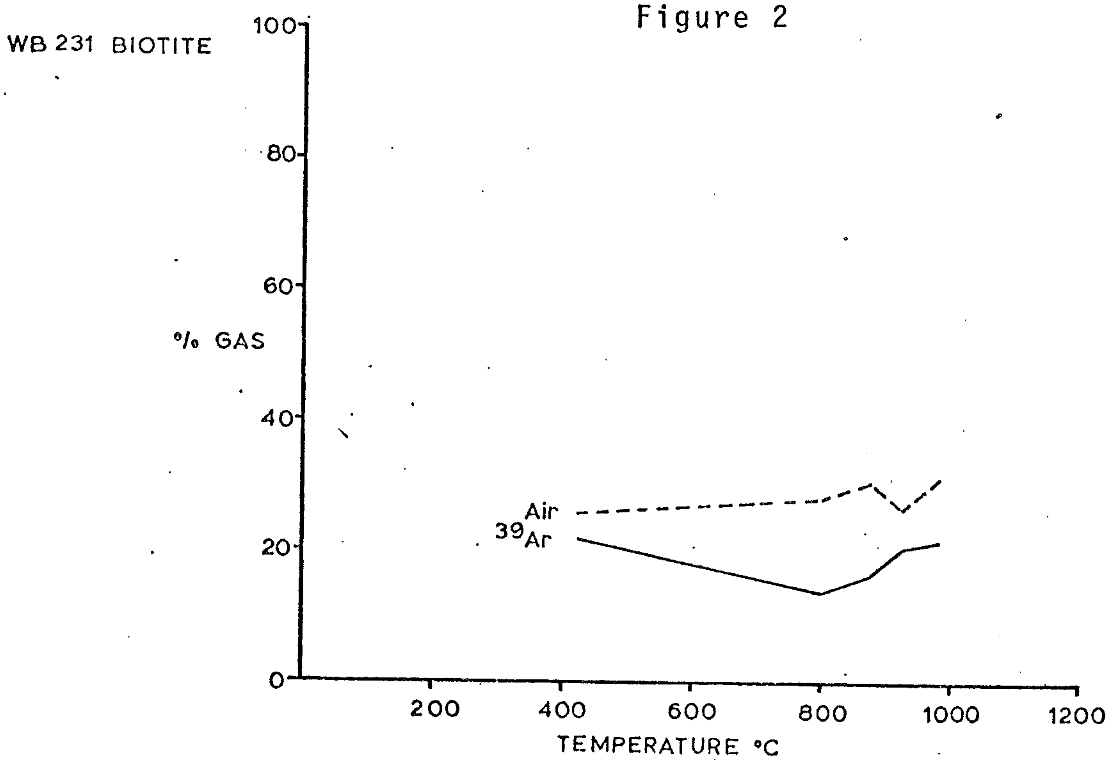


Figure 3

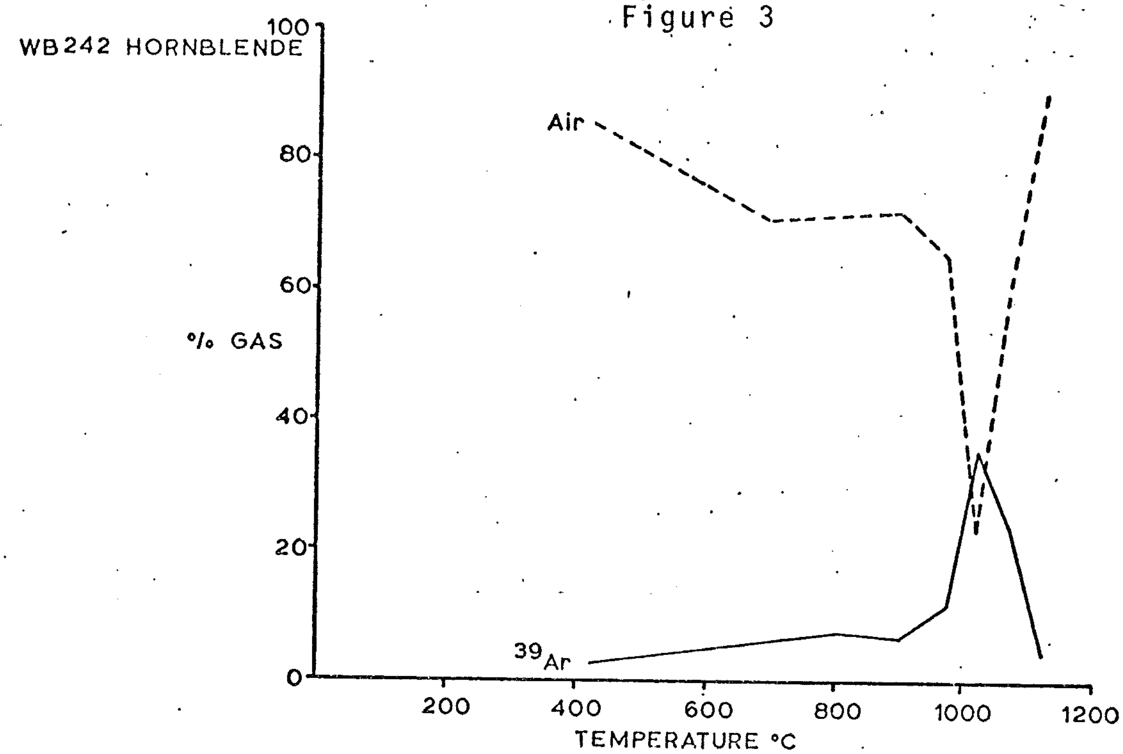


Figure 4

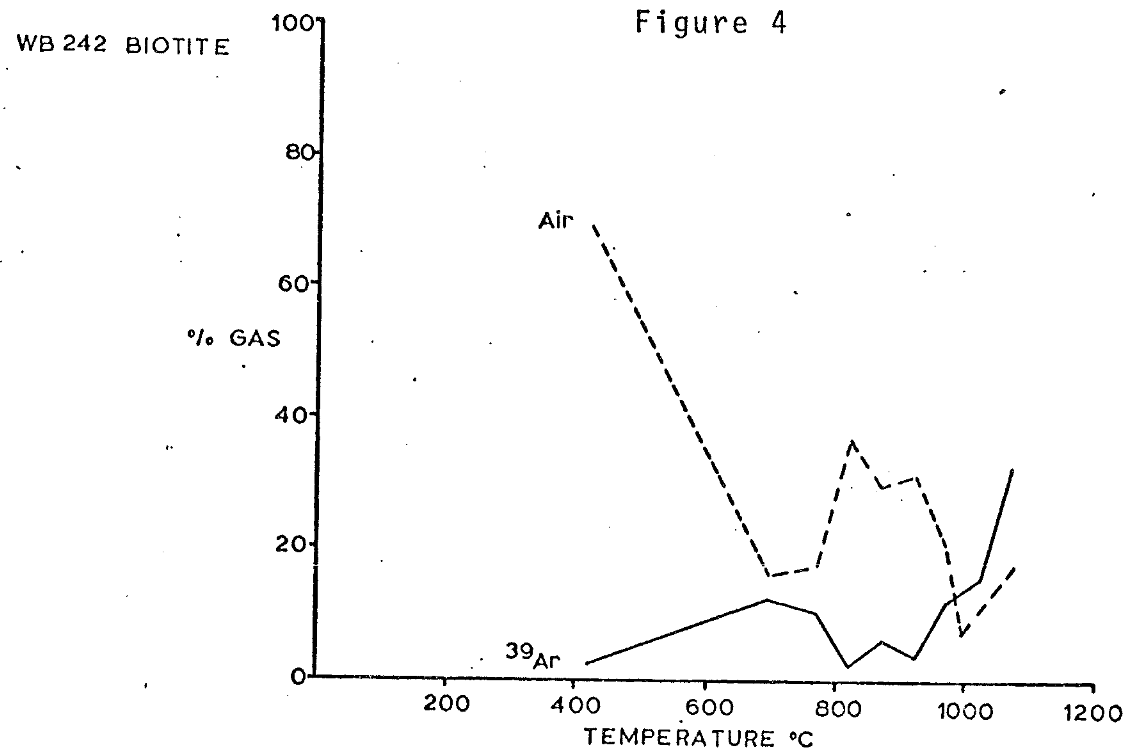


Figure 5

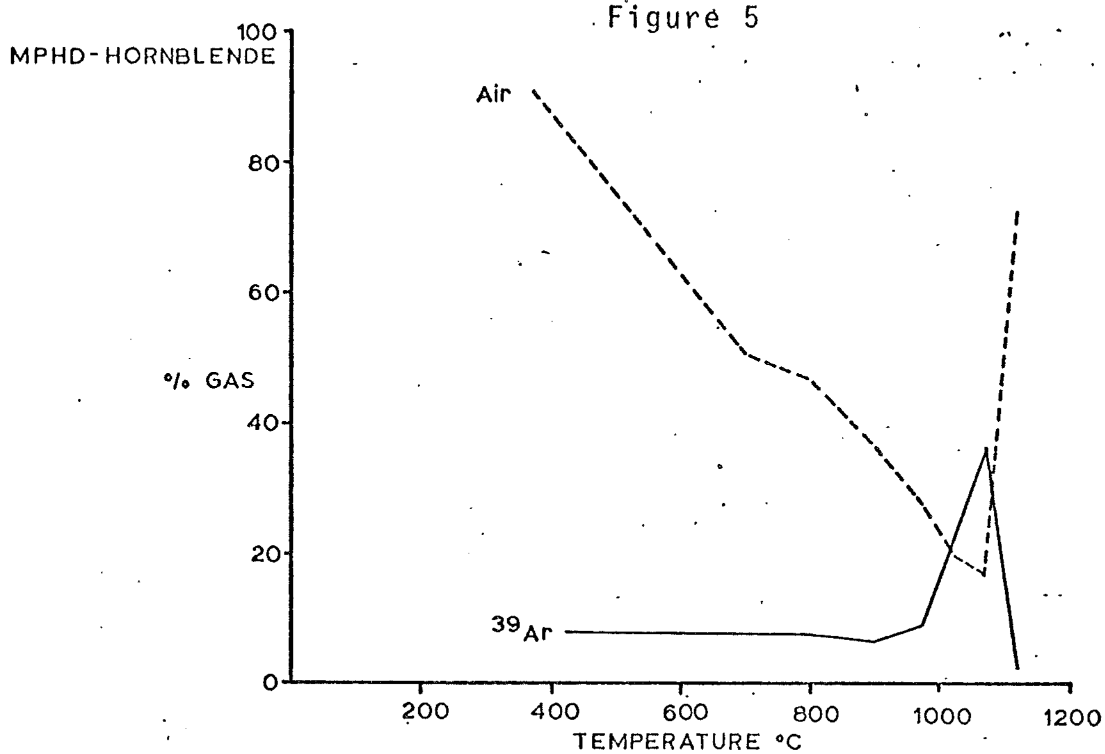


Figure 6

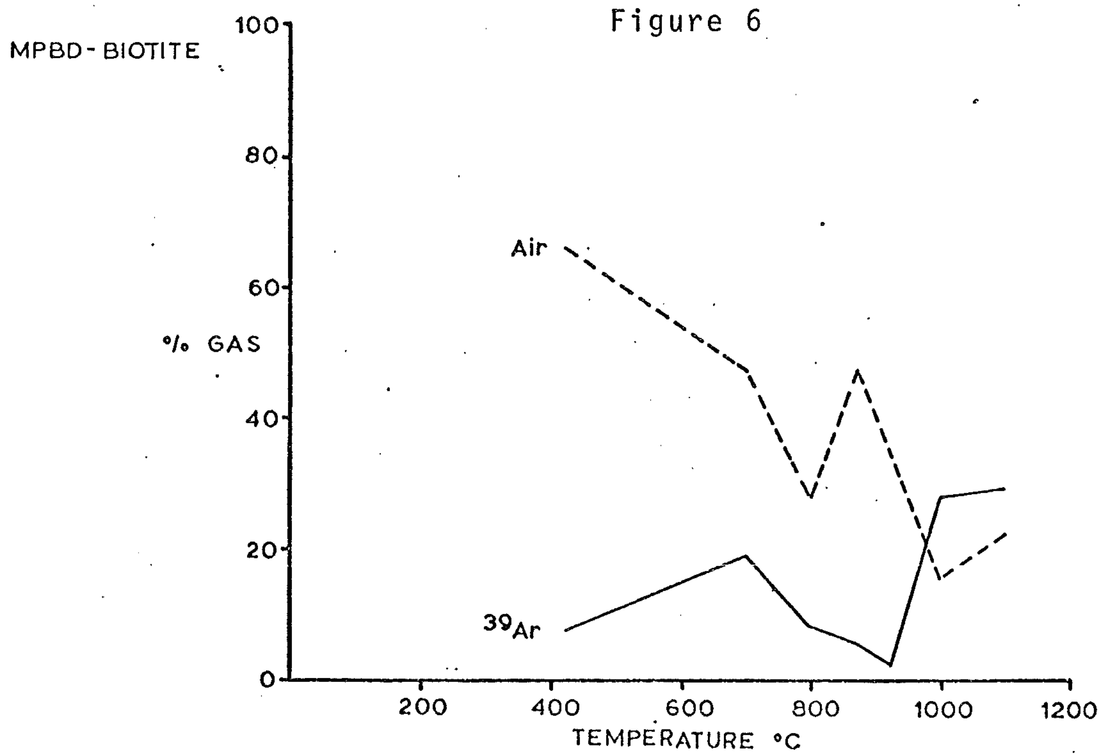


Figure 7

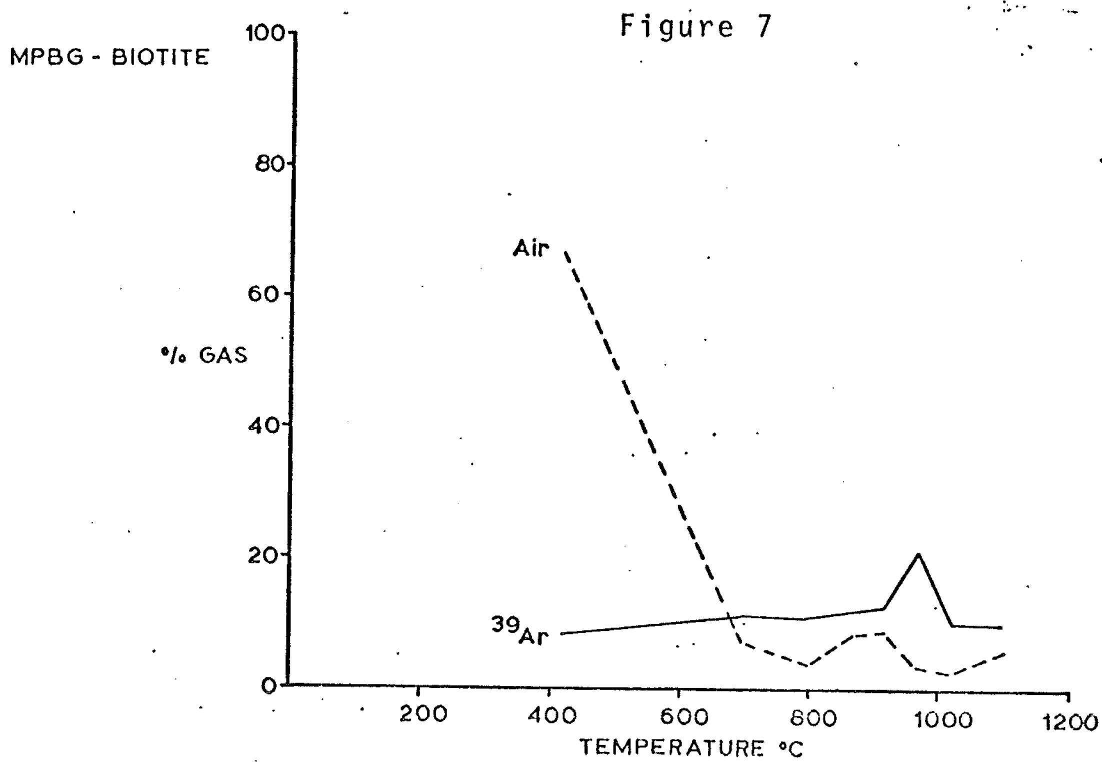


Figure 8

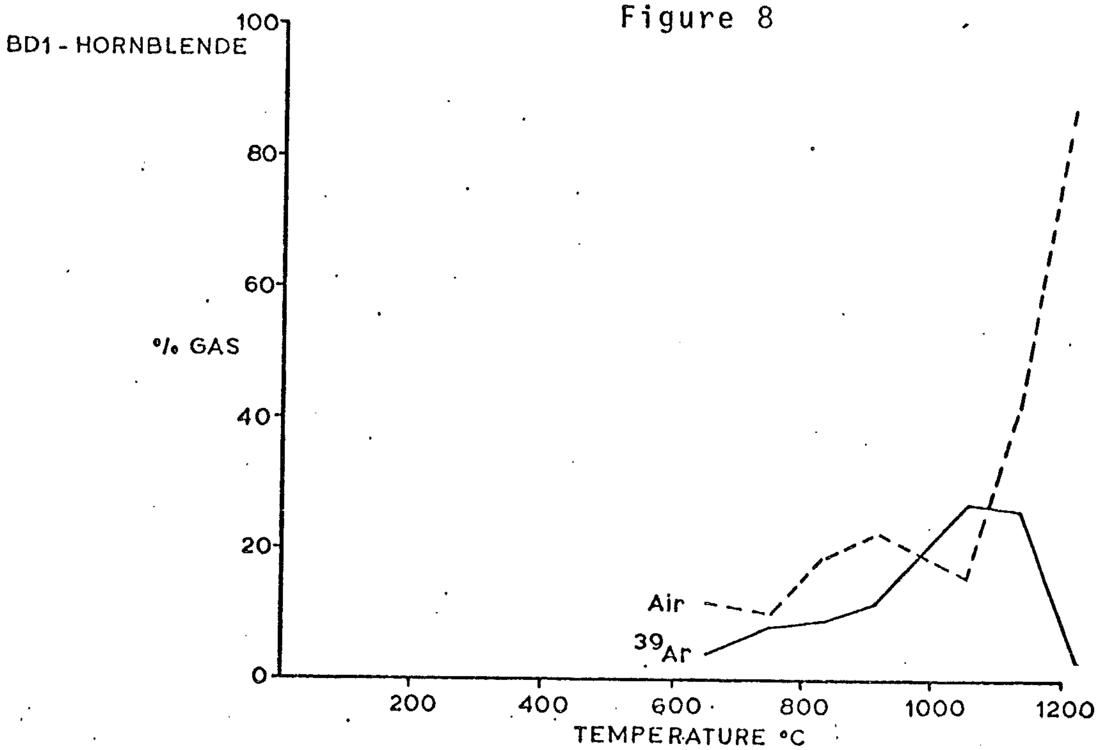


Figure 9

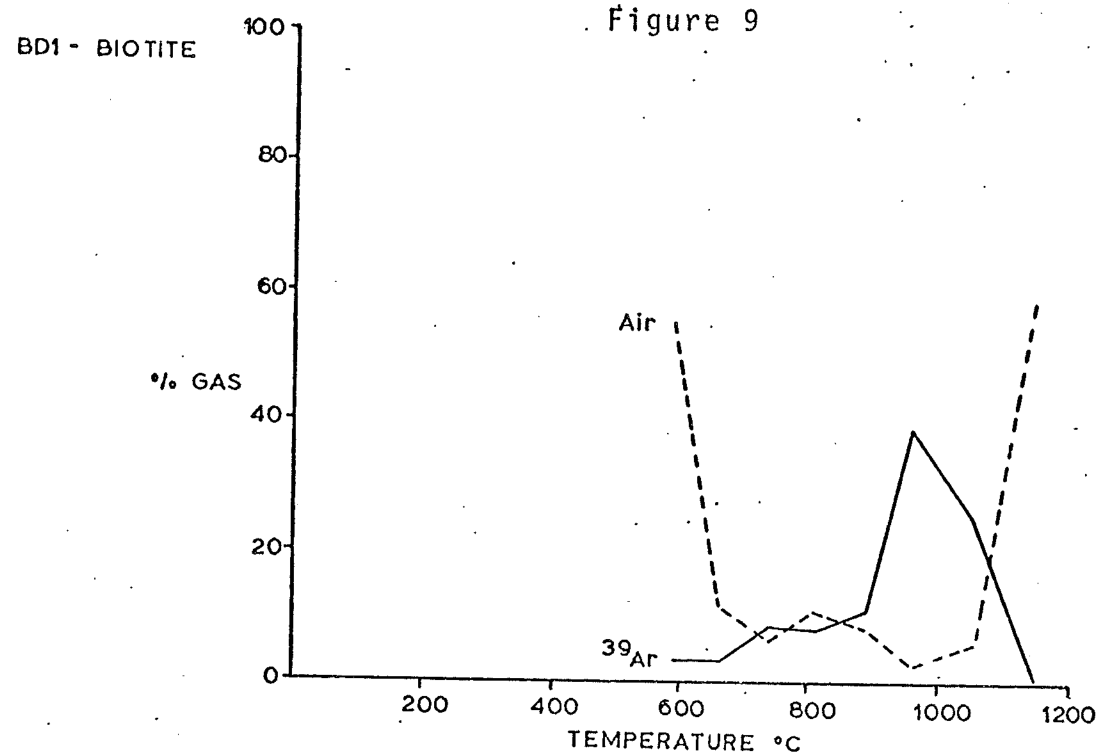


Figure 10

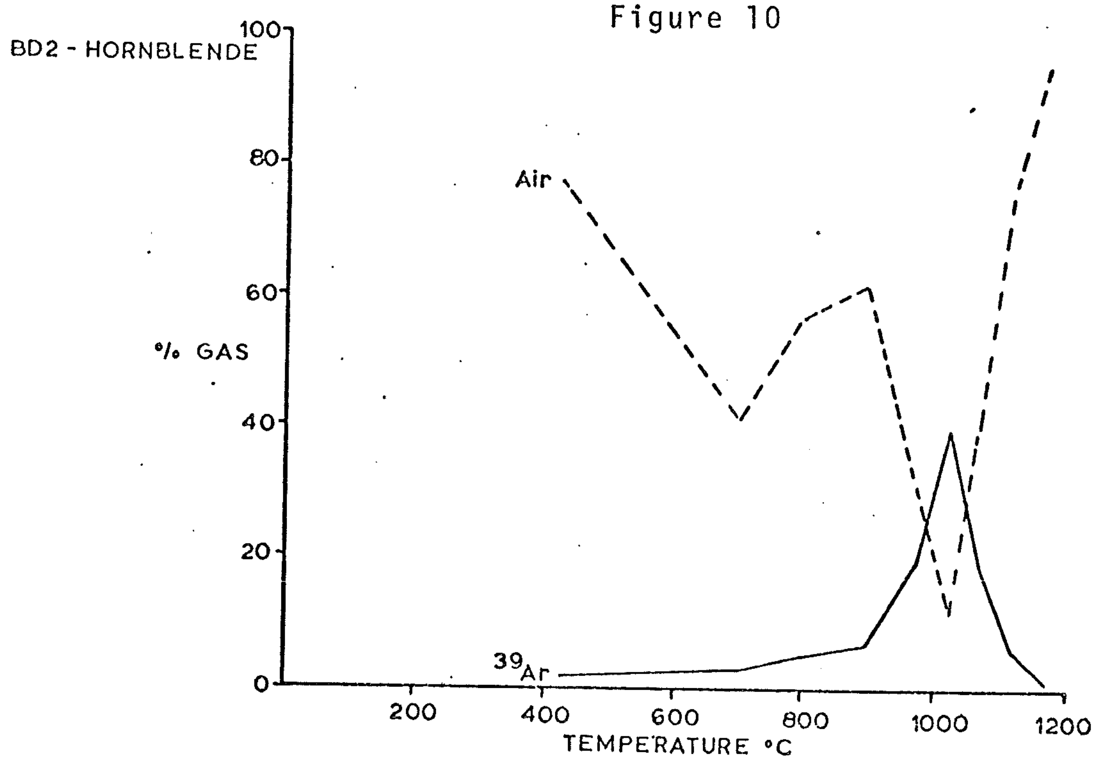
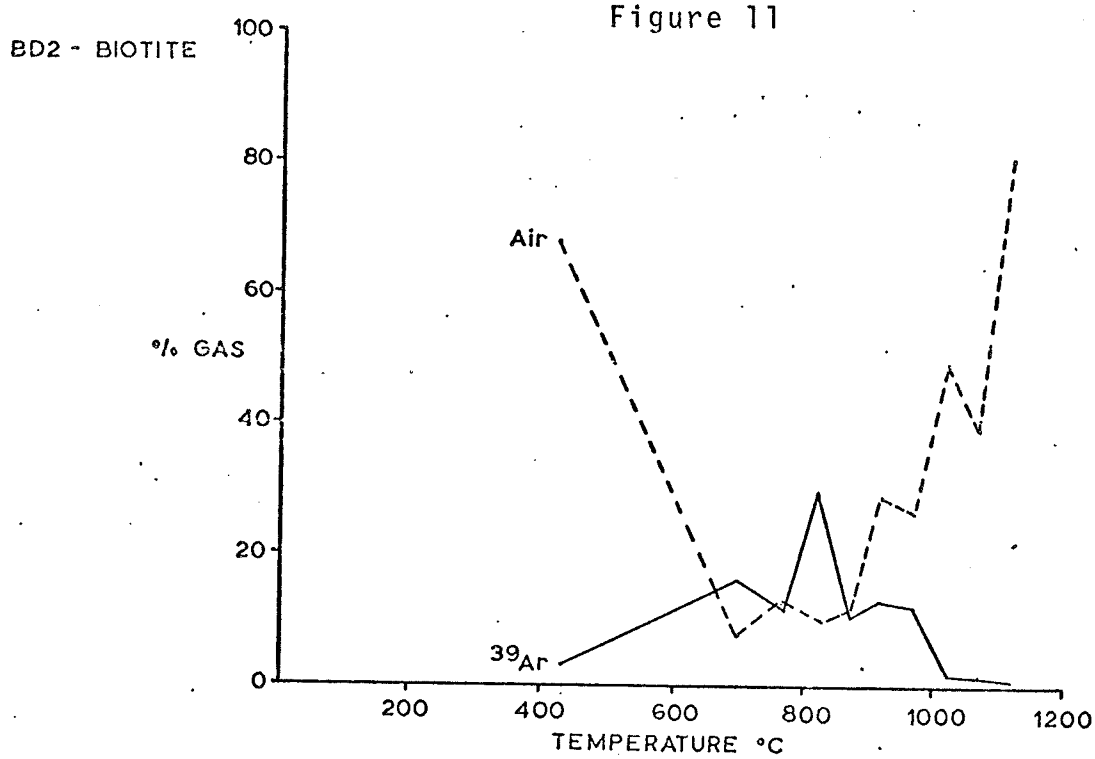


Figure 11


BD2 - BIOTITE
100
80
60
40
20
0
% GAS
Air
^{39}Ar
200
400
600
800
1000
1200
TEMPERATURE °C

APPENDIX 4

SAMPLE DESCRIPTIONS

SAMPLE DESCRIPTIONS

WB 242 Hornblende Diorite

The sample is a medium-grained (crystals up to 2 mm), holocrystalline, hornblende diorite. The sample consists of zoned plagioclase, light green to brown hornblende, moderate amounts of biotite, interstitial quartz, and accessory apatites and zircons. Traces of clinopyroxenes are often seen as cores within the hornblende. The clinopyroxenes typically show anomalous blue extinction colours. Opaques, moderate in number, are generally enclosed by the biotites. These opaques are generally magnetite or ilmenite. The cores of the zoned plagioclases tend to be sericitized and with some minor calcite. Some biotites exhibited minor chloritization and secondary sphene may be visible. The hornblendes are actinolitized in some areas.

Fine-grained ophitic textures are abundant. The fine plagioclase laths average an andesine composition. The rock as a whole shows intergranular textures.

WB 231 Hornblende Diorite

The sample is fine-grained (generally 1 mm or less), holocrystalline hornblende diorite. Intergranular with ophitic textures are common. It is very similar to WB 242. The pyroxenes often show strong exsolution lamellae of opaques. Hornblendes are seen to be replacing clinopyroxenes. Zircons generally are not as abundant as in WB 242. Opaque lamellae and lenses are often associated with the clinopyroxene centres of the hornblendes. Plagioclases are relatively free of sericite and calcite. Hornblendes show some actinolite alteration.

MP1/MP2 (Samples are representative of the Diorite inclusions from the granite late phase)

The samples are fine-grained (less than 1 mm), holocrystalline hornblende diorites. The samples consist of zoned plagioclase, pale green hornblende, and abundant biotite. Hornblendes invariably have a clinopyroxene core. Opaques are rare in both samples and occur as magnetite enclosed by biotite. Accessory apatite and zircon are also present. Plagioclase cores in both samples are more heavily sericitized than in WB 231 or WB 242. Calcite is also apparent within the plagioclases. Biotites are heavily chloritized, often up to 15% of a grain. Hornblendes exhibit abundant actinolitization and chloritization. Secondary sphene is common. The biotites are very dark and strongly pleochroic.

BD1 Granite-Granodiorite

The sample is a holocrystalline, very fine to fine-grained granite-granodiorite. Plagioclase phenocrysts (up to 4.0 mm) dominate the slide. The sample is composed primarily of plagioclase (An_{35}-An_{50}) with abundant interstitial augite. Hornblende and biotite are also present. The slide shows extensive alteration. Nearly all the plagioclase crystals show extensive sericitization or saussuritization. The augites appear altered along margins and contacts to a fibrous bluish-green amphibole, which is most likely tremolite-actinolite. Hornblendes are notably lacking in any major alteration. The biotites appear as small fibers along the interstices of grains.

BD2 Granite-Granodiorite (represents one of the inclusions comprising BD2)

This sample is similar to BD1 although it is much finer-grained, and the plagioclase phenocrysts range up to only 1 mm. The plagioclases range from An_{35} to An_{45} in composition and exhibit strong microclinic textures. The sample is similar to number 1 in composition. The slide has noticeably less alteration, although a few of the plagioclase phenocrysts are very heavily sericitized and show skeletal forms. The fine-grained interstitial plagioclase contains much less sericite. Opaques are very common, showing no crystal faces at all. They are often associated with biotite. The augites show skeletal forms with blebs of plagioclase within the grain. Fibrous actinolite (?) can be seen at the margins. Hornblendes and biotites are relatively clean. The hornblendes often show rounded crystal faces.

TIME ALLOTMENT

1. Laboratory and related work	...200hr
2. Background research and compilation	...150
3. Writing of manuscript	...165
4. Drafting	...30
5. Final proofing,correction, and xeroxing of the typed manuscript	...5
	...550hr

Keith Taylor prepared mineral separates for analysis and provided a great many hours in setting up of the extraction system prior to analysis.