An $^{40}Ar/^{39}Ar$ Study of the Goldenville, Halifax, White Rock, and Torbrook formations of the Digby Area, Southwest Nova Scotia

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ABSTRACT

Cambrian to early-Devonian meta-sedimentary rocks of the Halifax and Goldenville formations of the Meguma Group and the overlying White Rock and Torbrook formations form the part of the Meguma Terrane that underlies southwest Nova Scotia in the Digby area. An $^{40}Ar/^{39}Ar$ study utilizing laserprobe techniques on single muscovite grains and stepwise heating on whole rock samples was used to examine the provenance and metamorphism of the Meguma Group, and the White Rock and Torbrook formations in the Digby area. Single grain muscovite analyses from the Goldenville Formation showed a single population that ranged from 519 to 593 Ma, with an average of 551 ± 6.3 Ma, a range that does not overlap with the whole rock spectrum ages of approximately 250 to 450 Ma. Halifax Formation single grain muscovite analyses gave ages that ranged from 344 to 591 Ma and overlap the range of ages found in the Halifax Formation whole rock spectra. The single grain muscovite analyses from the White Rock Formation encompassed an age range from 448 Ma to 533 Ma. The whole rock spectra for the Meguma Group and White Rock formations generally gave age ranges increasing with $\%^{39}Ar$ released from 250 to 600 Ma, with plateau-like spectra indicating a regional metamorphic overprinting in some samples at approximately 400 Ma. The Torbrook Formation sample gave a whole rock spectrum increasing in a stepwise fashion between 275 Ma and 380 Ma. Microprobe data indicates that all the analyzed single grains are compositionally muscovite. The results from this study indicate a provenance age of approximately 560 to 600 Ma for the Cambrian to Ordovician Halifax and Goldenville formations. Results from the Silurian White Rock Formation are interpreted to indicate a detrital age of ca. 500 Ma with detritus possibly from the Meguma Group or Avalon Terrane. A whole rock analysis from the Lower Devonian Torbrook Formation yielded an age of ca. 370 Ma. The $^{40}Ar/^{39}Ar$ ages from this study showed evidence of resetting due to regional metamorphism and deformation related to the Devonian Acadian Orogeny and the late syntectonic intrusion of the ca. 370 Ma South Mountain Batholith.

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I also want to thank Keith Taylor for helping me prepare my samples and for his hard work in the argon lab analyzing my whole rock and single grain samples. He too was a useful source of knowledge about argon systematics. Also, Dan Kontak deserves thanks for his help in interpreting my argon data and with compiling my microprobe data.

I want to thank my parents for their continuing support and interest, although I think my father is still wondering how one could possibly get an Honours thesis in Earth Sciences for dating Russians!

Finally, I want to thank my classmates in the Honours Class for their humour and support during those long hours in the computer lab.

CHAPTER ONE: INTRODUCTION

1.1 Thesis Statement

The Meguma Terrane of Nova Scotia, the second largest terrane in the Canadian Appalachians, was the last major terrane accreted to eastern North America (Schenk, 1997). It occupies the entire southern mainland of Nova Scotia, and is juxtaposed to the Avalon Terrane. The Meguma Terrane in southwestern Nova Scotia is characterized by a thick sequence of late Cambrian to early-Ordovician turbidites of the Meguma Group (Schenk, 1970, as found in Krough and Keppie, 1989). The Meguma Group is composed of mainly coarse clastic rocks in the Goldenville Formation overlain by the predominantly slaty Halifax Formation (Schenk, 1970).

Disconformably to unconformably overlying the Meguma Group directly in southwestern Nova Scotia are the slates and quartzites of the Silurian White Rock Formation (Smitheringale, 1973; White et al., 1999), which are overlain conformably by the slates, meta-siltstone, and limestone of the Torbrook Formation, characterized by early-Devonian shelly fauna (Bouyx et al., 1997). Both the White Rock and Torbrook formations represent shallow marine and continental meta-sedimentary rocks.

These units were deformed, regionally metamorphosed during the Acadian Orogeny, and intruded by late syntectonic ca.370 Ma granitoid rocks (Williams and Hatcher, 1983). Following uplift, these units were unconformably buried by continental and minor marine Carboniferous rocks that are, in turn, unconformably overlain by Early Mesozoic sedimentary and volcanic rocks along the northwestern margin of the Meguma Terrane.

The Meguma Group was renamed the Meguma Supergroup by Schenk (1997). Along with this change, the Halifax Formation was renamed the Halifax Group and the Goldenville Formation the Goldenville Group. This change is not widely used, however, and thus in this study the older Meguma Group and Halifax Formation and Goldenville Formation names are used.

This thesis examines the provenance of the sediments and general metamorphic history of the formations underlying the southwestern part of the Meguma Terrane, near Digby, Nova Scotia.

1.2 Objectives, Scope and Significance of this Project

Controversy exists over the provenance of the sediments that form the Meguma Group, the White Rock Formation, and the Torbrook Formation in the Meguma Terrane. Previous work has been done on the age and nature of sedimentary sources elsewhere in the Meguma Group. Recent work includes detrital zircon, titanite, muscovite, and other mineral grain studies on rocks from the Meguma Group (Krogh and Keppie, 1990; Hicks, 1999). In the Digby area of the Meguma Terrane, however, there is a lack of consistent information on the provenance of the lithologies and therefore a detailed $^{40}Ar/^{39}Ar$ study was undertaken with the purpose of resolving the ages of the source rocks for the formations in this area. The present work utilizes the $^{40}Ar/^{39}Ar$ single grain laser dating method, a more precise method of obtaining detrital ages, because it has the ability to isolate a detrital signature from the other usually overprinting signatures found in the rocks. This method is used in conjunction with the stepwise heating $^{40}Ar/^{39}Ar$ method on whole rock samples, allowing the two sets of data to be compared and thus achieving a more complete study of the detrital and metamorphic history of the rocks.

The study is restricted to the Meguma Group, the White Rock Formation, and the Torbrook Formation in the map sheet 21A12 in southwestern Nova Scotia (Figure 1.1). This sheet was mapped in the summer of 1998 as part of a five-year bedrock mapping project in southwestern Nova Scotia with the Minerals and Energy Branch of the Nova Scotia Department of Natural Resources. The study consists of the $^{40}Ar/^{39}Ar$ dating of detrital muscovites in a cross-section across the study area and the correlation of the results with previous data, whole rock $^{40}Ar/^{39}Ar$ data, muscovite geochemical data, petrography, and existing theories.

1.3 Organization of thesis

The first section provides an introduction to the thesis, significance of the study, and previous work (Chapter One). The second section gives the regional geology and lithologies of each of the formations being studied (Chapter Two). The next part of the thesis discusses $^{40}Ar/^{39}Ar$ dating in a general sense, and applies it specifically to the thesis in sections dealing with sample selection, preparation and analysis. Results of the $^{40}Ar/^{39}Ar$ work, mineral chemistry and petrography are also given in this section (Chapter Three). Chapter Four provides the discussion and gives the conclusions of the thesis.

1.4 Previous Work

Detrital studies in the Meguma Group using the U-Pb dating method yielded ages of 606 Ma and 552 Ma for titanite and ages of 566 ± 8 Ma for zircon (Krogh and Keppie, 1990). These ages eliminate a northern North American or Baltic Shield provenance, but are unable to distinguish a West African from a Guyana Shield provenance (Krogh and Keppie, 1990).

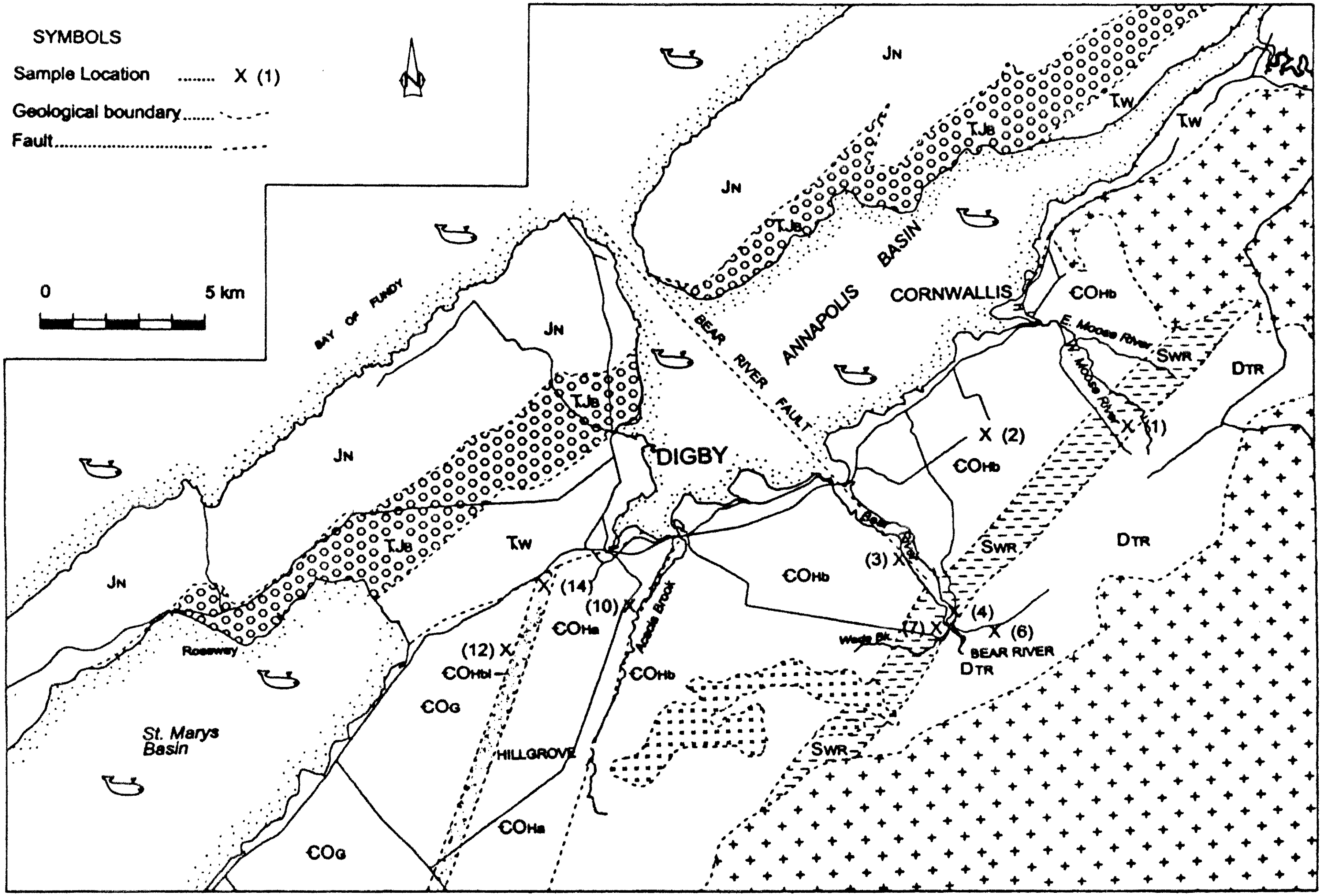

Figure 1.1: Geological map of the Digby area (21A12), showing sample locations (White et al., 1999).

LEGEND

TRIASSIC TO JURASSIC

JN — ***NORTH MOUNTAIN FORMATION***: basalt and rare gabbroic dykes.

TJB — ***BLOMIDON FORMATION***: red to red-brown siltstone, sandstone, shale and minor claystone.

TW — ***WOLFVILLE FORMATION***: red to red-brown sandstone, arkose and minor conglomerate.

LATE DEVONIAN

SOUTH MOUNTAIN BATHOLITH: grey monzogranite to granodiorite.

ELLISON LAKE PLUTON: grey granodiorite.

EARLY DEVONIAN

DTR — ***TORBROOK FORMATION***: dark grey to black shale, siltstone and quartzite; minor limestone and 'iron formation'; locally cleaved; minor mafic sills and dykes.

SILURIAN

SWR — ***WHITE ROCK FORMATION***: grey shale, siltstone and quartzite; minor calcsilicate lenses and rare limestone; locally well cleaved; minor mafic sills and dykes.

CAMBRIAN TO EARLY ORDOVICIAN

MEGUMA GROUP

HALIFAX FORMATION:

ƐOHb — Bear River member: grey silty slate and cleaved metasiltstone with thin quartz arenite laminations; rare metalimestone nodules; abundant mafic sills and dykes.

ƐOHa — Acacia Brook member: grey slate with minor iron-rich laminations and nodules.

ƐOHbl — Bloomfield member: maroon and green, variegated metasiltstone.

ƐOG — ***GOLDENVILLE FORMATION***: light grey metasandstone and minor siltstone and slate

Hicks et. al (1999) used conventional step-heating $^{40}Ar/^{39}Ar$ geochronology to find the ages of detrital muscovite grains in the Meguma Group in southern Nova Scotia. High-temperature ages of 600 Ma and 550 Ma were obtained for Goldenville Formation muscovite grains in that study and were interpreted to be the ages of source rocks for the Meguma Group.

Biostratigraphic work done in the Torbrook and White Rock Formations aids in the understanding of paleogeographical relationships between the Meguma Terrane and major cratons. Two such studies in the 1990s indicate a close paleogeographical relationship between the Meguma Zone and northwestern Europe (Blaise et. al, 1990; Bouyx et. al, 1997).

Schenk's work on sequence stratigraphy supports his contention that the origin of the Meguma Terrane was on the margin of Gondwana. That is, the West African craton was a source for the Meguma Zone's sediments (Schenk, 1997).

CHAPTER 2: REGIONAL GEOLOGY AND LITHOLOGIES

2.1 Regional Geology

Southwestern Nova Scotia is underlain by three different rock assemblages: 1) Cambrian to Early Devonian metamorphosed sedimentary and volcanic rocks, 2) mainly Late Devonian granitoid rocks, and 3) Mesozoic age sedimentary and volcanic rocks.

The Cambrian to Early Devonian sequence, and the Devonian granitoid rocks, are characteristic units of the Meguma Terrane (Williams and Hatcher, 1983). The Acadian Orogeny deformed and metamorphosed these units, resulting in regional NE-trending scale folds with an axial planar cleavage (Keppie, 1993). The granitoid rocks intruded into the Cambrian to Early Devonian sequence and are considered to be late syntectonic. The Mesozoic age rocks lie on the underlying older rocks with an angular unconformity (White et al., 1999).

The Cambrian to Devonian metamorphosed rocks include the Cambrian to Ordovician Meguma Group, which is divided into the Goldenville and the overlying Halifax formations, the Silurian White Rock Formation and the Early Devonian Torbrook Formation. The Halifax Formation has recently been subdivided into three units: the lower Bloomfield, middle Acacia Brook, and upper Bear River members (White et al., 1999). The metamorphosed units are intruded by many suites of mafic sills (Barr et al., 1983; White et al., 1999).

Regional metamorphism was at greenschist facies conditions with chlorite, muscovite, and epidote as common metamorphic minerals. The South Mountain Batholith and the Ellison Lake Pluton constitute the Devonian granitoid rocks and the intrusion of these plutons produced well-developed contact metamorphic aureoles, containing cordierite and andalusite (White et al., 1999). The Wolfville, Blomidon, and North Mountain Formations constitute the Mesozoic age rocks in Southwestern Nova Scotia and were not sampled as part of this study.

2.2 Goldenville Formation

The Goldenville Formation consists of grey, massive to laminated or crosslaminated metasandstone, interbedded with metasiltstone and slate. The metasandstone is generally fine-grained and displays a spaced cleavage. The metasandstone contains carbonate and manganese concretions locally (White et al., 1999). Sedimentary structures typical of the Bouma sequence are common and the formation is interpreted as turbidity flow deposits (Schenk, 1997). The metasiltstone is typically green to locally grey; massive to laminated, and well cleaved. The slate is dark grey and finely laminated (White et al., 1999).

A maximum age of the Goldenville Formation is provided by U/Pb detrital titanite and zircon at 552 ± 5 Ma and 606 Ma, and 566 ± 8 Ma respectively (Krogh and Keppie, 1990).

2.3 Halifax Formation

Based on recent mapping, the Halifax Formation has been divided into three groups in the Digby area. These groups have been given member status (White et al., 1999). This includes the lower Bloomfield Member, middle Acacia Brook Member, and upper Bear River Member.

2.3.1 Bloomfield Member

The Bloomfield Member occurs as a narrow north-northeast trending belt at the contact between the Halifax and Goldenville formations (White et al., 1999). It consists of a distinctively banded maroon and green, thin to medium bedded, locally crossbedded metasiltstone to a finer-grained slate. The exposed width indicates a minimum stratigraphic thickness of 350m (White et al., 1999).

2.3.2 Acacia Brook Member

The Acacia Brook Member overlies the Bloomfield Member. It consists of light to medium grey, mainly planar laminated slate with minor thin laminations and lenses of well-cleaved, light grey metasiltstone with minor crossbedding. The slate contains local small iron nodules and possibly iron-rich laminations parallel to bedding (White et al., 1999). This member is typically well-crenulated.

2.3.3 Bear River Member

The Bear River Member is the uppermost unit of the Halifax Formation in the Digby area. It consists of grey, banded to laminated, cleaved silty slate interlayered with thin metasiltstone and metasandstone. Thick, half-metre size, grey, massive, quartz-rich metasandstone and metasiltstone layers are present. Light grey metalimestone beds, lenses, and nodules are present locally. Minor pyrite and arsenopyrite is common (White et al., 1999).

Two fossil occurrences restrict the age of the Bear River Member. Doyle (1979) reported earliest Ordovician (Tremadoc) acritarch microfossils in this unit. Specimens of the Tremadoc-age graptolite *Rhapdinora flabelliforme* (previously known as *Dictyonema flabelliforme*) were found near the stratigraphic top of this unit by Smitheringale (1973) and White et al. (1999).

2.4 White Rock Formation

In the Digby area, the White Rock Formation consists mainly of dark grey slate and metasiltstone and minor light grey metasandstone. The metasiltstone is laminated to massive, and has weakly to well developed cleavage. The metasandstone is laminated to massive and occurs in beds or discontinuous lenses. There is a thick (approximately 30 m) metasan0dstone layer present, which is typical of the White Rock Formation (Crosby, 1962). At the base of the White Rock Formation in the Digby area there are rare marble beds and calc-silicate lenses are common locally (White et al., 1999). The upper part of the White Rock Formation has been dated using biostratigraphy. Invertebrate and crinoid fossils and various microfossils have been found that indicate an Upper Silurian age (Bouyx et al., 1997).

The stratigraphic thickness of the White Rock Formation in this area is approximately 1200m (White et al., 1999).

2.5 Torbrook Formation

The Torbrook Formation conformably overlies the White Rock Formation, and consists mainly of metasiltstone with minor slate, metasandstone, marble and rare ironstone (White et al., 1999). The metasiltstone is dark grey, massive to laminated, and interbedded with metasandstone or slate. Marble or calcsilicate beds or nodules are also interbedded with the metasiltstone. Cleavage is not well developed in this formation.

The fossil assemblage indicates an Early Devonian age, and contains brachiopods, corals, crinoids and pelycypods (Smitheringale, 1973; Jenson, 1975a,b; Blaise et al., 1991, Bouyx et al., 1997).

CHAPTER THREE: $^{40}Ar/^{39}Ar$ GEOCHRONOLOGY, MINERAL CHEMISTRY AND PETROGRAPHY

3.1 Introduction

Until recently, most of the argon research in the Meguma Terrane has been done using whole rock or large aliquots of mineral separates.

This study reports the first single-grain $^{40}Ar/^{39}Ar$ study combined with whole rock analysis of Meguma Terrane units exposed in the Digby area. Electron microprobe and petrographic analyses were also completed on three of the samples.

3.2 $^{40}Ar/^{39}Ar$ Systematics

The $^{40}Ar/^{39}Ar$ dating method, like the K-Ar method that it has its foundations in, is based upon the naturally-occurring radioactive isotope of potassium, ^{40}K, and the decay of this parent isotope to a stable daughter isotope, ^{40}Ar (McDougall and Harrison, 1988). The ^{40}Ar present in the mineral being examined is generally almost solely radiogenic argon, argon occurring from the in-situ decay of ^{40}K only, since this argon gets trapped within crystal structures due to its large size, and because argon from other sources is not likely to be entrapped in minerals during their growth.

The samples are irradiated with fast neutrons in a nuclear reactor, where a proportion of the ^{39}K atoms is transformed to ^{39}Ar atoms (McDougall and Harrison, 1988). The sample is then placed in an ultrahigh vacuum system, where it is heated. The evolved argon gas is then analyzed in a mass spectrometer and the $^{40}Ar/^{39}Ar$ ratio is determined. In this ratio, ^{40}Ar is the radiogenic argon, and ^{39}Ar is the argon that is produced from ^{39}K through the process of irradiation. This ratio is proportional to the

$^{40}Ar/^{40}K$ ratio in the sample, and thus is proportional also to the age of the sample. This is because the amount of ^{39}Ar depends upon the amount of ^{39}K that is in the sample, and the $^{39}K/^{40}K$ ratio is a constant in nature (McDougall and Harrison, 1988).

The $^{40}Ar/^{39}Ar$ age, t, of a sample is found with the equation

$$t = 1/\lambda \ln [1 + (J)(^{40}Ar/^{39}Ar)],$$

where λ is the decay constant, and J is a dimensionless irradiation parameter, which is related to the production of ^{39}Ar from ^{39}K during irradiation. J is calculated by irradiating a mineral of known K-Ar age, analyzing the gas for its $^{40}Ar/^{39}Ar$ ratio, and using the equation:

$$J = [(\exp \lambda t) - 1]/(^{40}Ar/^{39}Ar),$$

where t is the age of the standard sample and the $^{40}Ar/^{39}Ar$ is the ratio measured from this standard. In this laboratory, the standard (or flux monitor) is the hornblende MMHb-1.

3.3 Sample Selection

The initial purpose of the study was to obtain samples across a cross-section of the Goldenville, Halifax, White Rock and Torbrook formations. Fourteen sites were selected and sampled representing the complete stratigraphy exposed in the Digby area (Figure 1.1).

Two samples were taken in the Goldenville Formation, eight in the Halifax Formation, three in the White Rock Formation, and one in the Torbrook Formation. Of the samples taken in the Halifax Formation, one was in the Bloomfield Member, two were in the Acacia Brook Member, and five were in the Bear River Member.

Samples were taken from outcrops in locations where the rocks were coarser-grained and relatively uncleaved thus detrital muscovite grains were more likely to be found.

3.4 Description of Extraction and Preparation Processes

Of the fourteen samples collected, muscovites were extracted from ten for single grain analyses; however, due to the small grain size only five were ultimately selected. The same five samples used for the single grain analyses were used in the whole rock analysis. The Torbrook Formation sample was analyzed as a whole rock, due to the small grain size of the muscovite. Thus, six whole rock samples and five single grain samples were analyzed (Table 3.1).

For the single grain analyses, each rock sample was crushed into smaller, 5-10 cm size rock pieces with a hammer. These pieces were examined under a binocular microscope at low power, and muscovites were picked out using a fine-pointed metal pick, tweezers, and a small brush. Approximately 20 to 40 single muscovite grains were picked out of each sample. An attempt was made to pick the largest muscovite grains from the bedding plane of each sample.

For the whole rock analysis, the rocks were broken into small pieces, of which approximately five mg were used for the argon analyses.

All samples were packaged with standards for irradiation in the McMaster University reactor in Hamilton, Ontario.

Table 3.1: Samples dated in this study.

FORMATION	SAMPLE #	WHOLE ROCK ANALYSIS	SINGLE GRAIN ANALYSIS
GOLDENVILLE	12	⊗	⊗
HALIFAX			
Bloomfield Member	14		
Acacia Brook Member	10	⊗	⊗
Bear River Member	2	⊗	⊗
Bear River Member	3		
WHITE ROCK	1	⊗	⊗
WHITE ROCK	4	⊗	⊗
WHITE ROCK	7		
TORBROOK	6	⊗	

3.5 Sample Analysis

3.5.1 Whole Rock Analysis

Upon their return from irradiation, whole rock samples were placed individually into a tantalum furnace and heated in a stepwise fashion. The argon gas was extracted at each step and the isotope ratios measured. An age spectrum was produced by plotting the apparent age at each step against the percentage of total ^{39}Ar that is released at each step.

3.5.2 Laserprobe $^{40}Ar/^{39}Ar$ analysis

For laserprobe dating, the $^{40}Ar/^{39}Ar$ geochronology lab at Dalhousie University uses a Quantronix 117 Nd-YAG laser to extract argon from samples. The grains to be analyzed are placed in shallow, machined holes drilled in a circular aluminum holder $\approx$ 2 cm in diameter. After irradiation, the holders are placed inside the vacuum system, each holder containing the grains for only one sample. In this study, eight to ten holes in a given holder were used, with each hole containing usually one single grain but two to five grains were used if the grains were very small.

The intensity of the laser beam is regulated using a calcite attenuator in the beam delivery system. A motorized stage moves a target hole to a designated location under the laser beam that has been defocused from a diameter of approximately 75 microns to 1-2 mm. The strength of the beam is slowly increased by adjusting the attenuator (Figure 3.1), increasing the temperature of the grain or grains until melting occurs. During this process, the grain(s) undergo a series of structural changes before fusing, and after fusion, there remains only a small glass bead. For each sample, the gas evolved from this fusion is extracted and analyzed in the mass spectrometer.

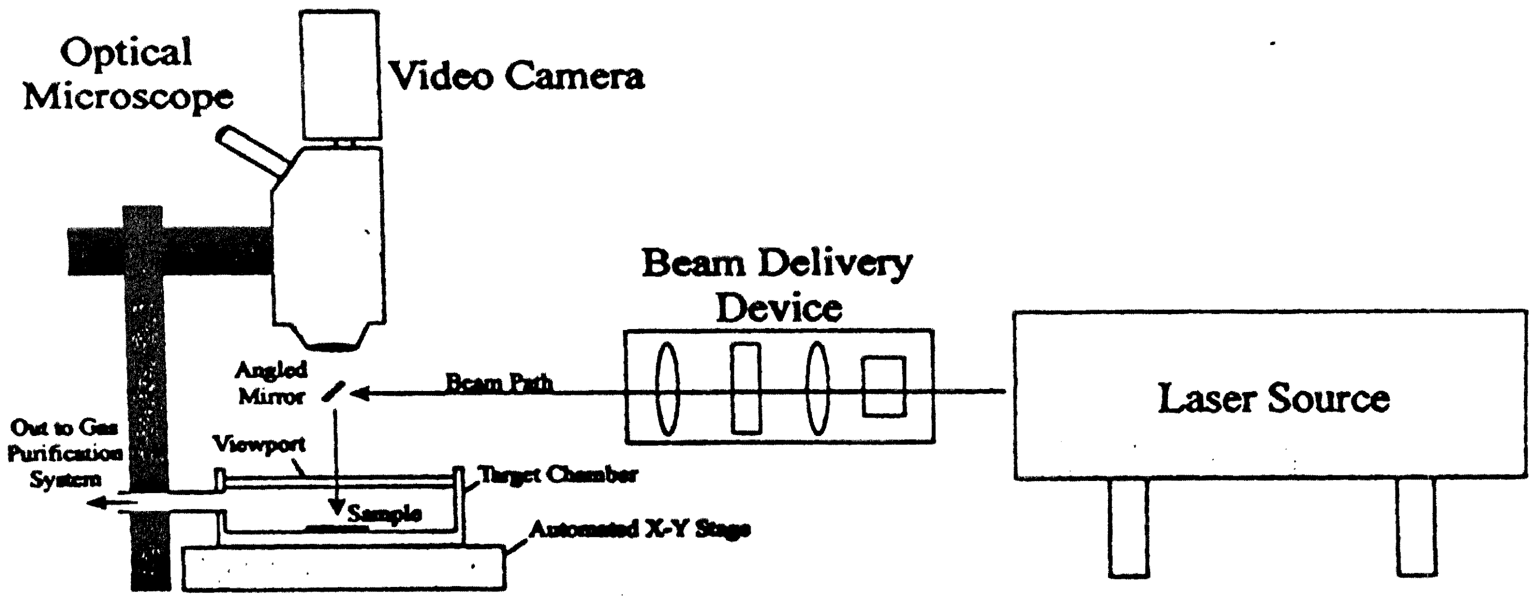

Figure 3.1: Schematic side view of a simple laser system, like the one used in this study (taken from Fallon, 1998).

3.6 $^{40}Ar/^{39}Ar$ Results

3.6.1 Whole Rock Results

Six samples, two from the White Rock Formation, two from the Halifax Formation, and one each from the Torbrook and the Goldenville Formations provided whole rock data, as is described in Section 3.3.

A whole rock spectrum reflects the presence of all the K-bearing minerals in a given rock (see section 3.7), and thus is difficult to interpret. Generally, the whole rock spectra give age ranges increasing with $\%^{39}Ar$ released from 250 Ma to 600 Ma, with segments of approximately uniform age generally at about 400-450 Ma.

The whole rock spectrum for Goldenville Formation Sample 12 shows a range of ages increasing in a stepwise fashion from 250 Ma to approximately 480 Ma. The great majority of the ages, from about 20% to 80% ^{39}Ar released, lie between 380 Ma and 480 Ma. Some plateau-like segments in this range show an age of approximately 400 Ma (Figure 3.2).

Sample 2 from the Bear River Member of the Halifax Formation gave whole rock ages ranging from 350 Ma to ca. 540 Ma, with plateau-like segments between 20% and 70% ^{39}Ar released displaying an age of ≈ 440 Ma (Figure 3.3). The spectrum for Sample 10 from the Acacia Brook Member of the Halifax Formation also shows a wide range of ages from 300 Ma to 530 Ma (Figure 3.4).

The White Rock Formation Sample 4 shows a whole rock spectrum with ages increasing in a stepwise fashion from 260 Ma to ca. 550 Ma (Figure 3.5). The whole rock

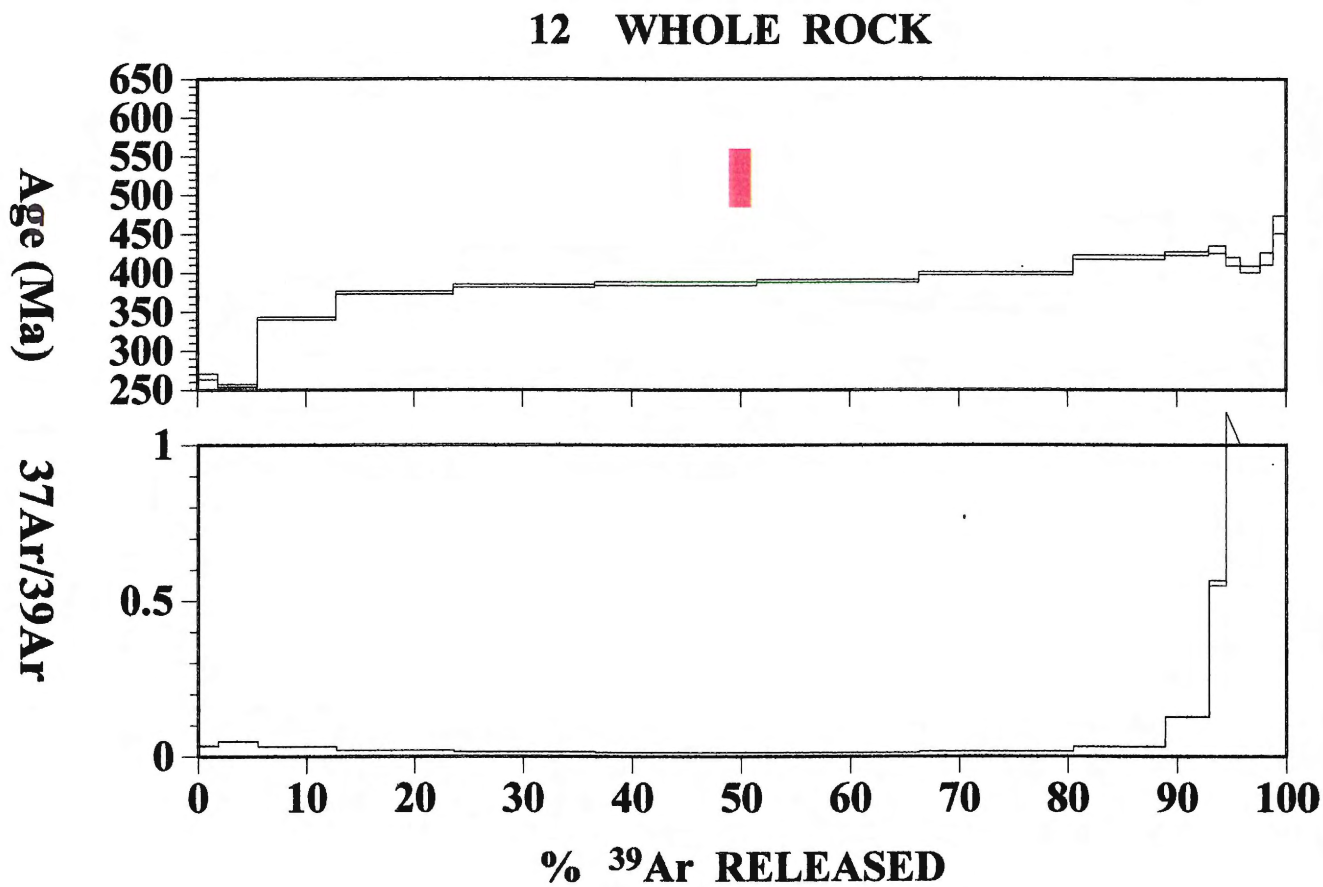

Figure 3.2: Whole rock spectrum from sample 12 of the Goldenville Formation. Also shown in red is the range of ages from the single grain muscovite analyses of sample 12.

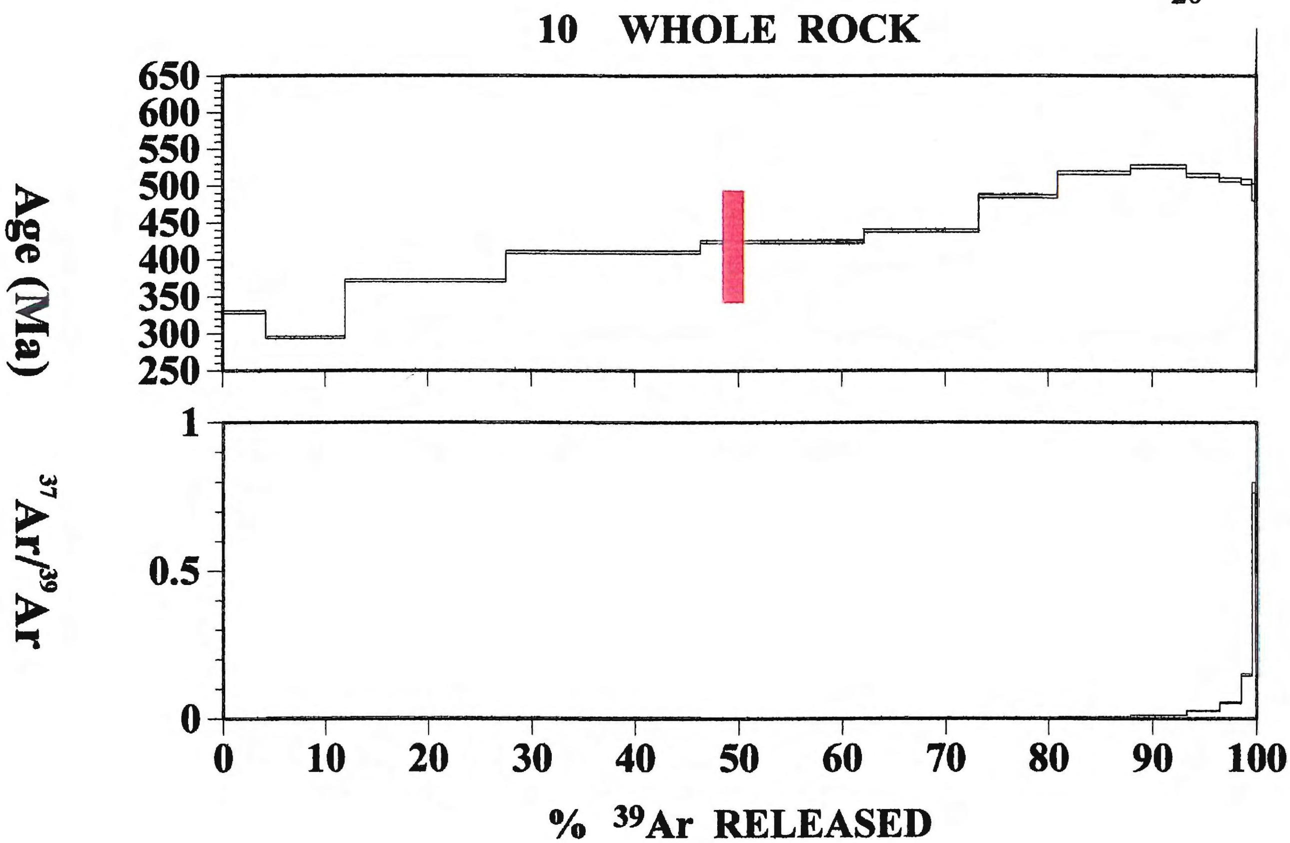

Figure 3.3: Whole rock spectrum from sample 10 of the Acacia Brook Member of the Halifax Formation. Also shown in red is the range of ages from the single grain muscovite analyses of sample 10.

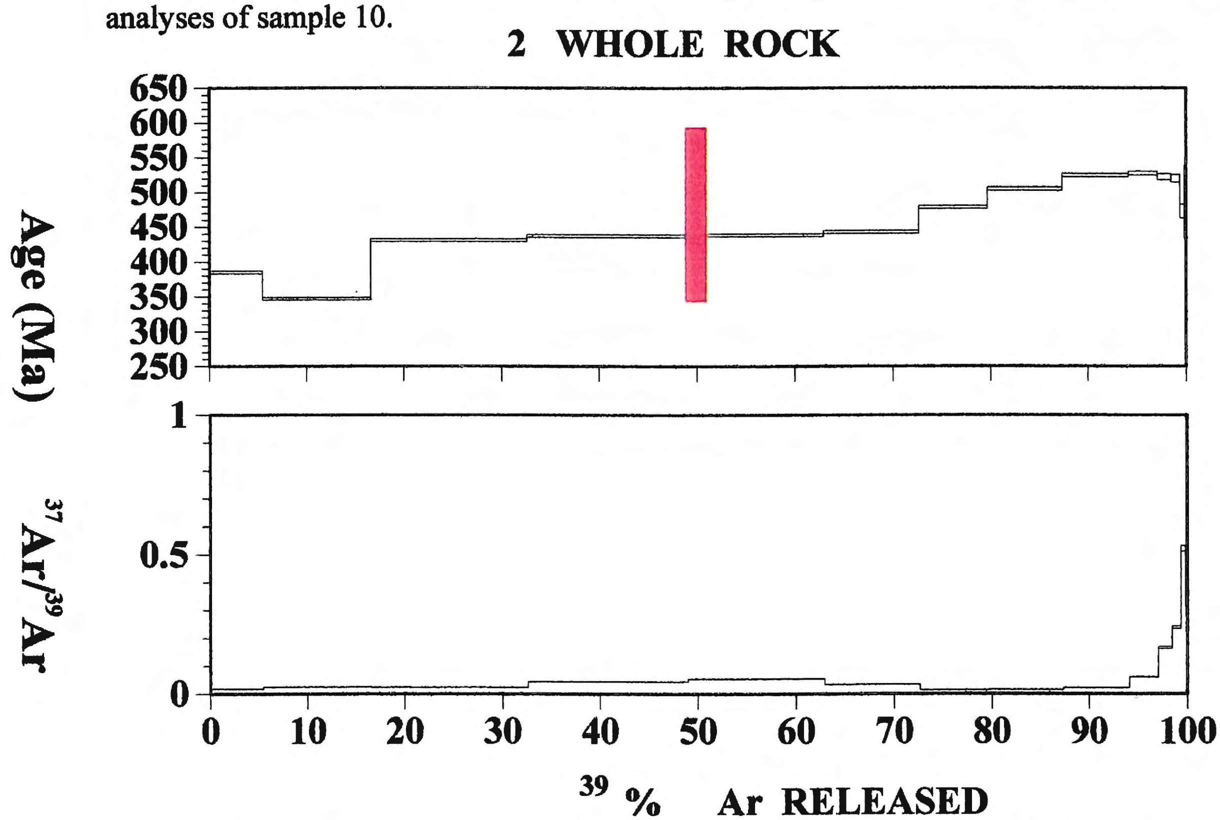

Figure 3.4: Whole rock spectrum from sample 2 of the Bear River Member of the Halifax Formation. Also shown in red is the range of ages from the single grain muscovite analyses of sample 2.

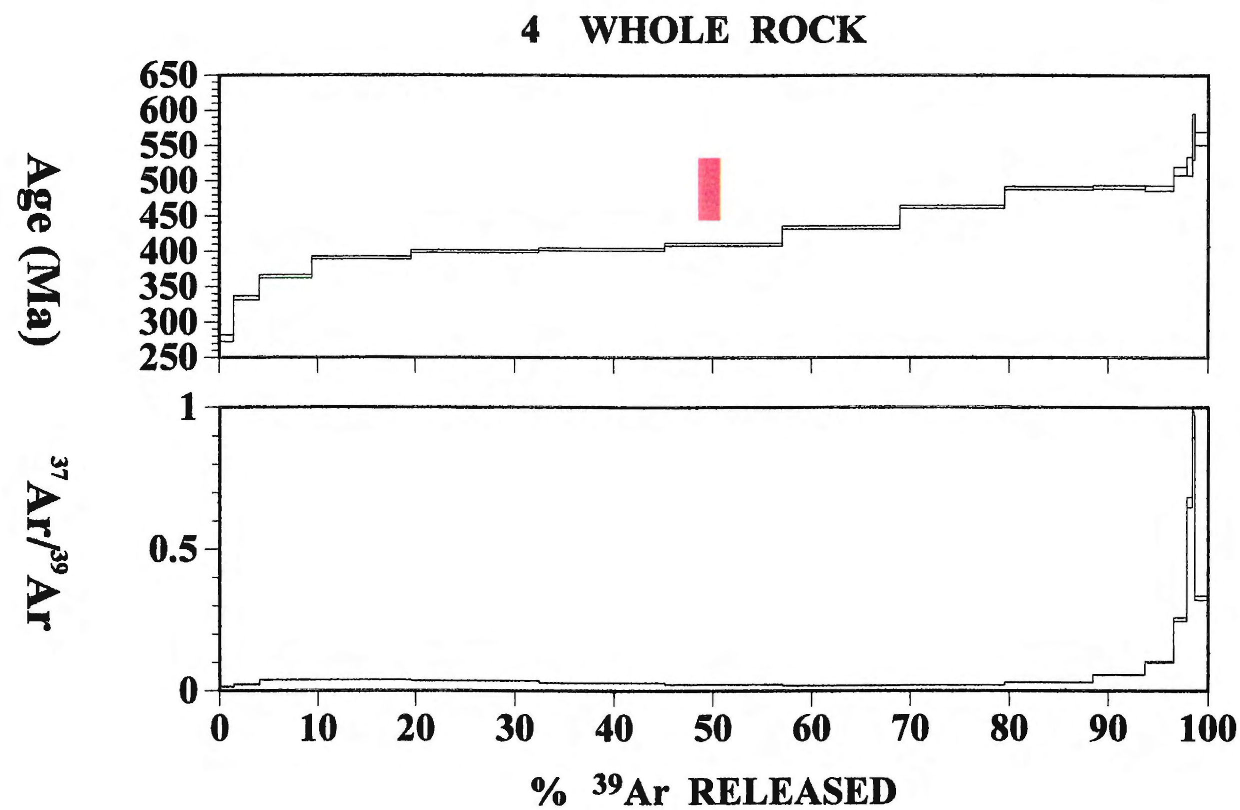

Figure 3.5: Whole rock spectrum from sample 4 of the White Rock Formation. Also shown in red is the range of ages from the single grain muscovite analyses of sample 4.

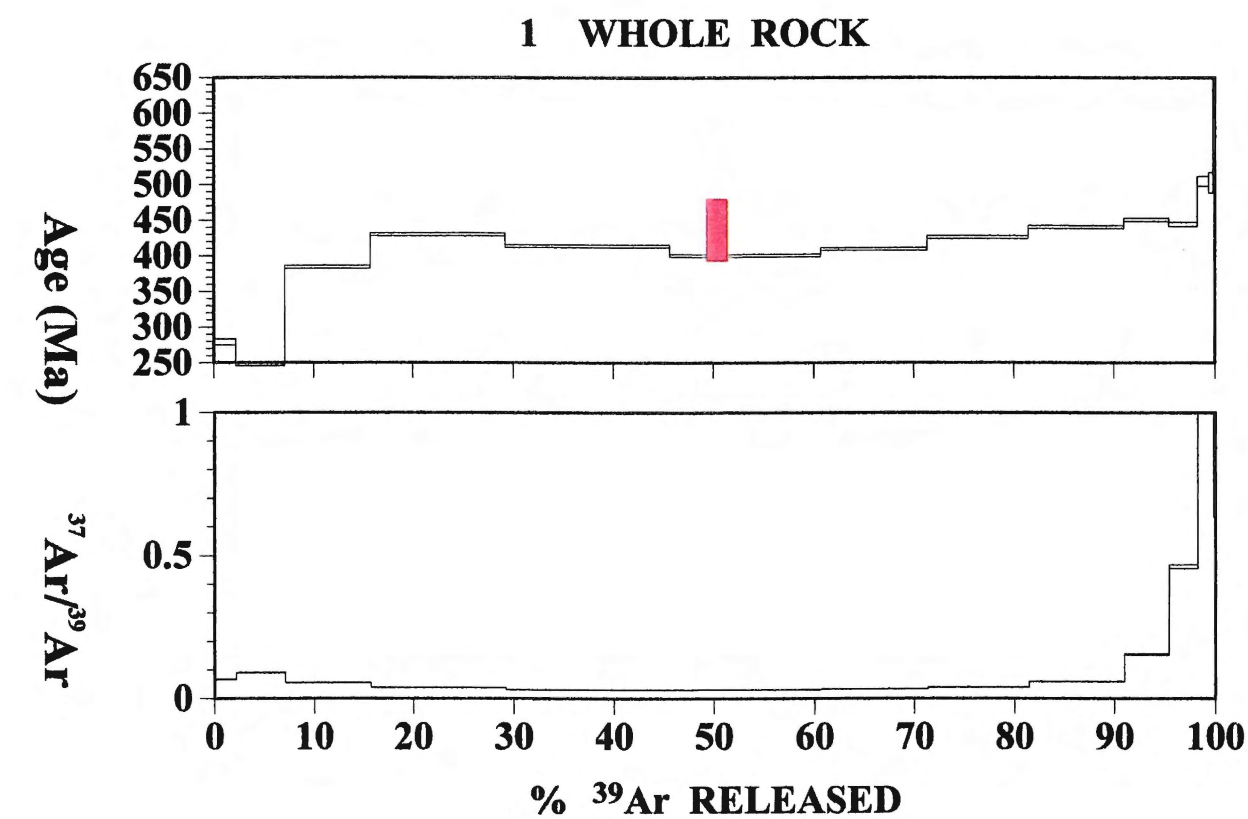

Figure 3.6: Whole rock spectrum from sample 1 of the White Rock Formation. Also shown in red is the range of ages from the single grain muscovite analyses of sample 4.

spectrum for the White Rock Formation Sample 1 shows a range of ages, generally increasing with %^{39}Ar released, from < 250 Ma to ca. 520 Ma, with the majority of the ages, between 20% and 80% ^{39}Ar released, from 410 Ma to 430 Ma (Figure 3.6).

Sample 6, from the Torbrook Formation, gave a whole rock spectrum increasing in a stepwise fashion between 275 Ma and 380 Ma (Figure 3.7). This is the smallest age range and lowest ages of all the whole rock spectra.

3.6.2 Laserprobe Results

One sample from the Goldenville Formation, one from the White Rock Formation and two from the Halifax Formation provide data on muscovites. The fifth sample, from the White Rock Formation, yielded very low amounts of argon, and hence very high margins of error and therefore the data for that analysis are not reported. Several total fusion ages were obtained for these single grains. Data are shown in plots of apparent age versus abundance of ^{39}Ar (in arbitrary units) in Figures 3.8 to 3.11.

Muscovites from the Goldenville Formation (sample 12), show single grain ages that range from 519 Ma to 593 Ma, with an average of 551 ± 6.3 Ma (Figure 3.8). They appear to represent a single population, as evidenced by the general overlapping of errors associated with the ages.

The muscovite grains from sample 2, from the Bear River Member of the Halifax Formation, range in age from 344 ma to 591 Ma, spanning approximately 250 Ma (Figure 3.9). Unlike sample 12, however, these grains do not appear to be from one population but from possibly two distinct populations.

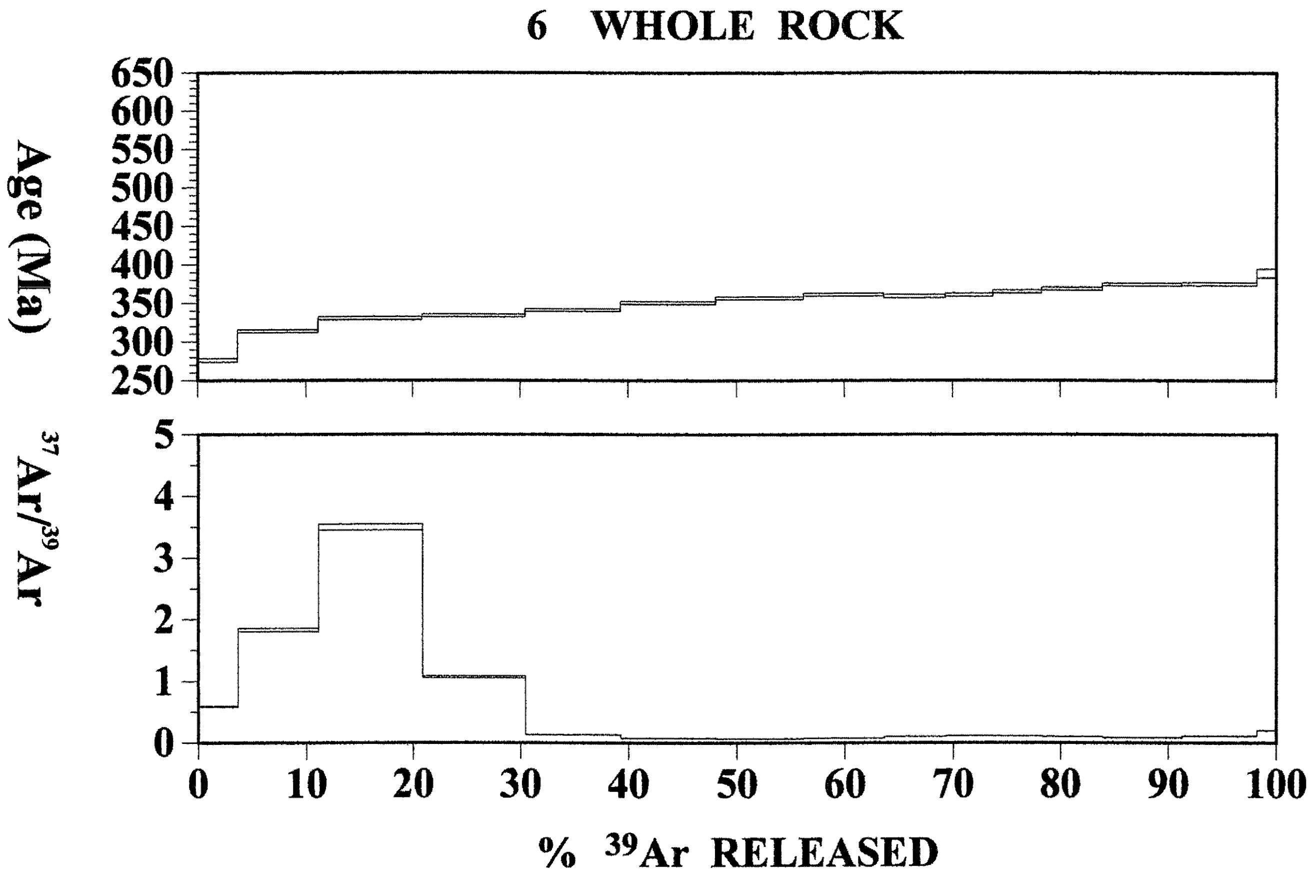

Figure 3.7: Whole rock spectrum from sample 6 of the Torbrook Formation.

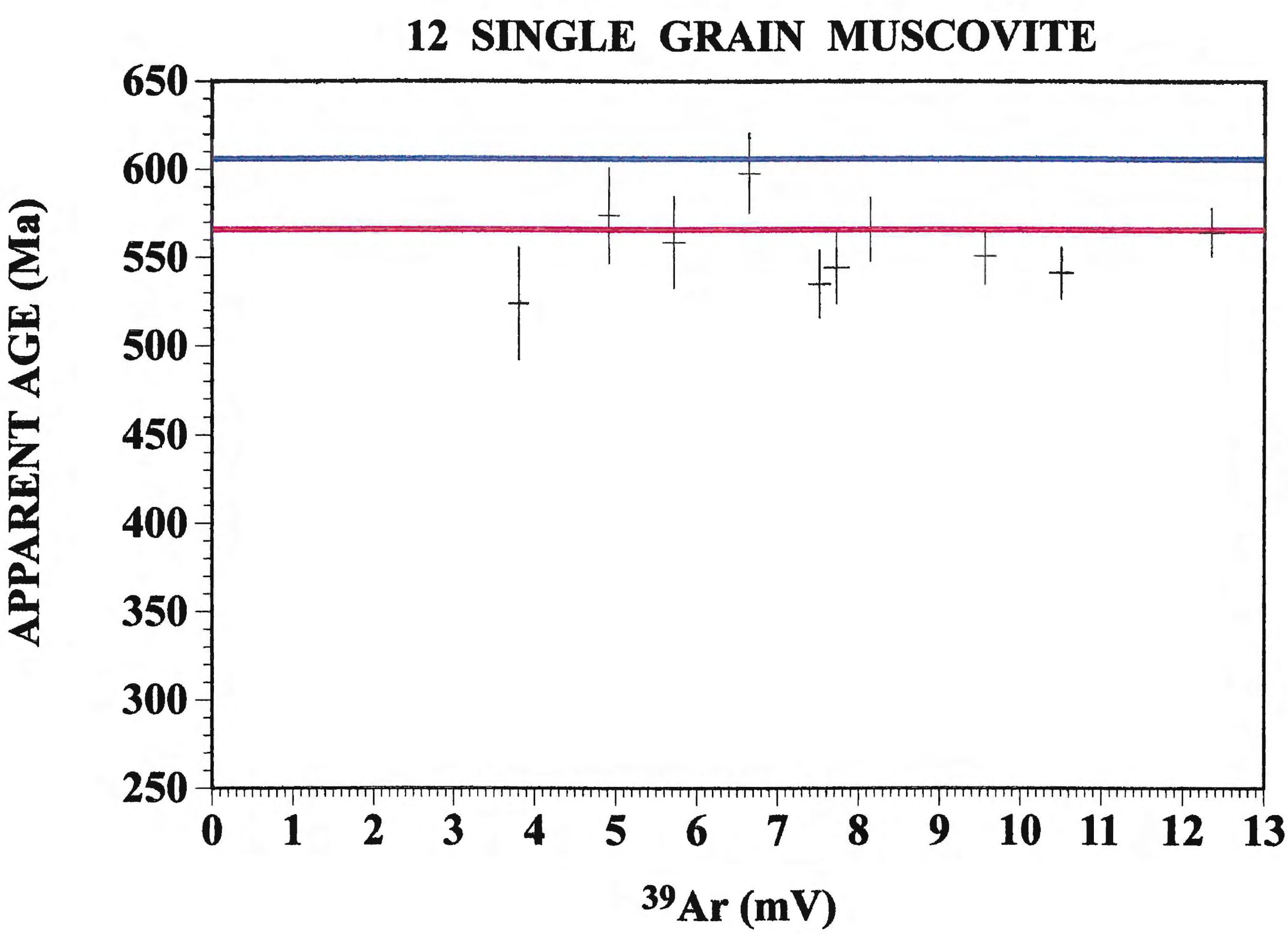

Figure 3.8: Single grain muscovite analyses of sample 12 of the Goldenville Formation. Also shown are two reference ages; the detrital titanite age of 606 Ma (blue line) and the detrital zircon age of 566 Ma (red line) for the Goldenville Formation (from Krogh and Keppie, 1990).

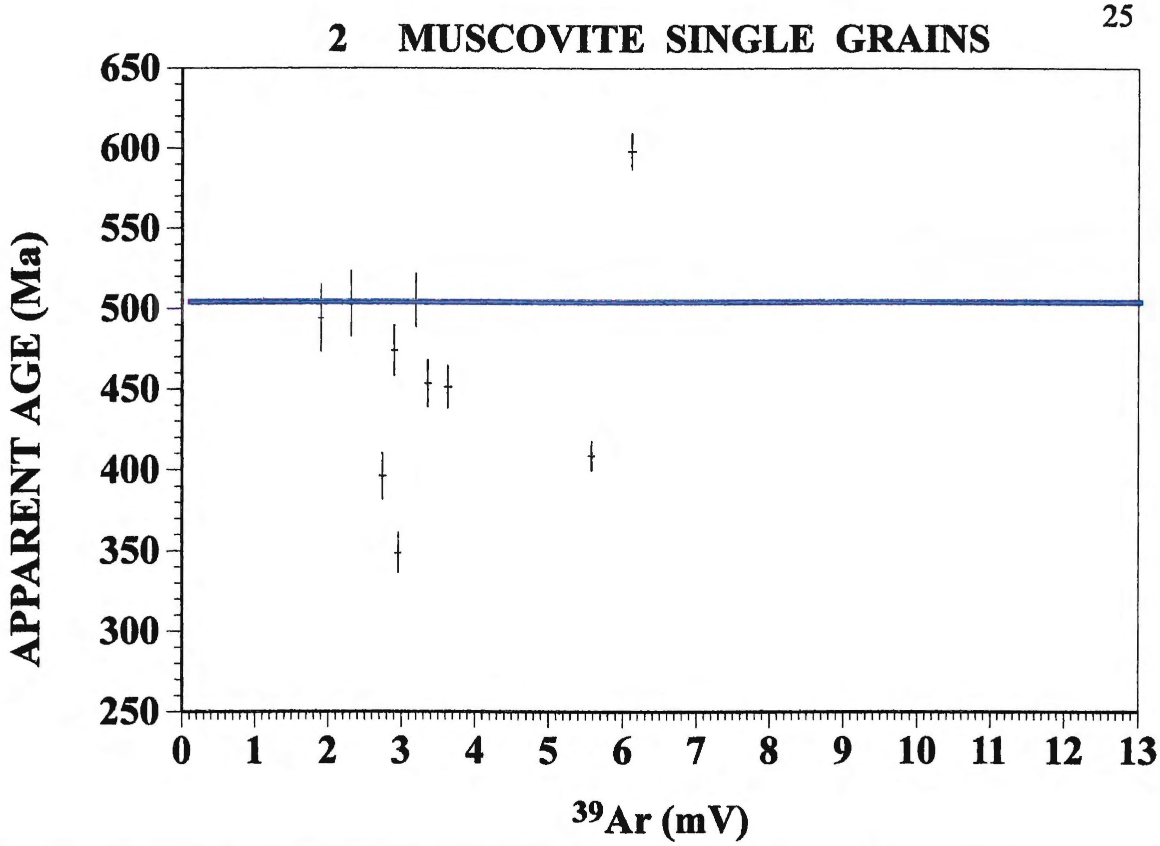

Figure 3.9: Single grain muscovite analyses of sample 2 of the Bear River Member of the Halifax Formation. Also shown is the age of deposition of this member (blue line) as indicated by graptolite fossils (Smitheringale, 1973, and White, 1999).

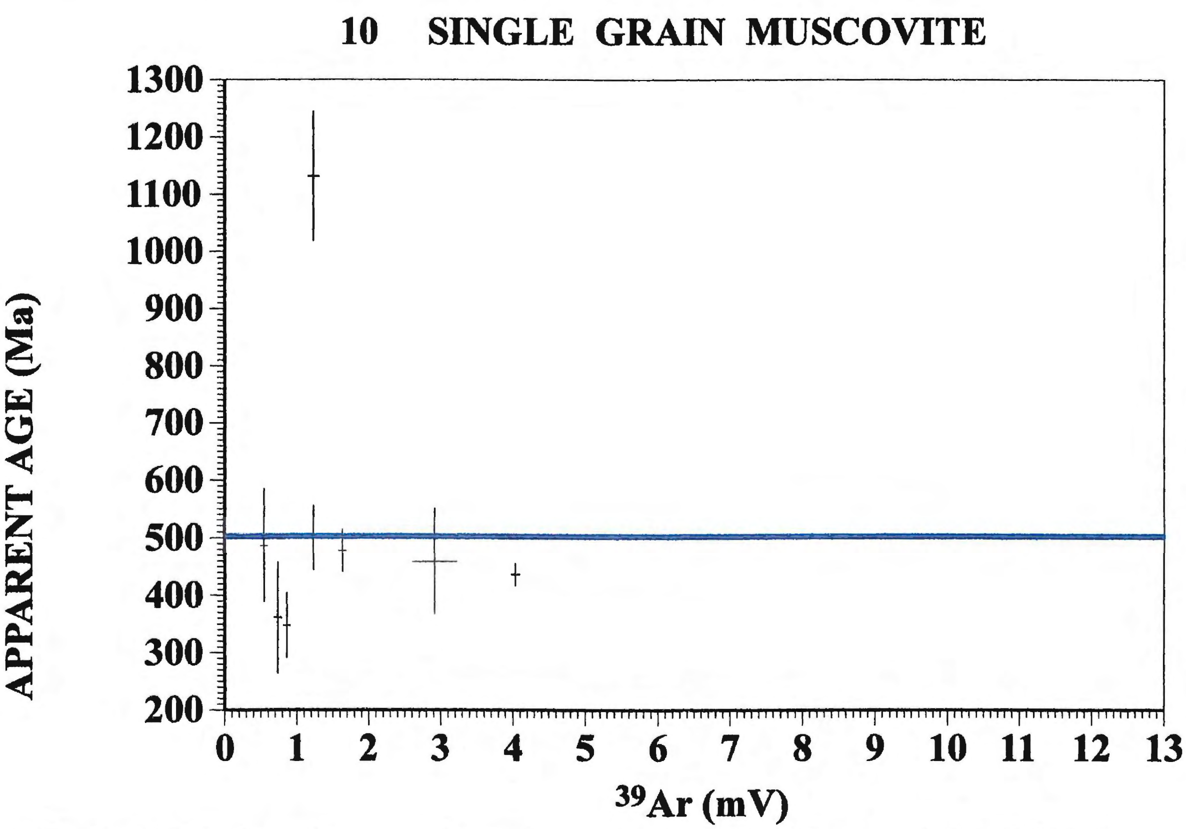

Figure 3.10: Single grain muscovite analyses of sample 10 of the Acacia Brook Member of the Halifax Formation. Also shown is a reference age, the depositional age of the Bear River Member (blue line) of the Halifax Formation (Smitheringale, 1973, and White, 1999).

Seven of the eight single grains analyzed from sample 10 of the Acacia Brook Member of the Halifax Formation show ages similar to those from the other samples, with a range between 344 and 495 Ma (Figure 3.10). One grain has an apparent age of 1123 ± 113 Ma, well outside of the above range, and therefore is not included in the interpretations of the data.

The 11 muscovite grains from sample 4, from the White Rock Formation, vary in age from 448 Ma to 533 Ma, spanning 85 Ma (Figure 3.11). These grains appear to be from possibly a single population.

Figure 3.12 shows a composite image of all the single grain muscovite ages obtained in this study.

3.7 Petrography

The Goldenville Formation samples are dominated by quartz and plagioclase feldspar grains surrounded by a matrix of very fine-grained muscovite and sericite. Large detrital grains of muscovite are found parallel to bedding planes, but muscovite also exists as metamorphic grains that are oriented parallel or sub-parallel to a weak cleavage observed in the matrix.

Samples from the Halifax and White Rock formations are generally much finer-grained than the samples from the Goldenville Formation, although the basic mineral constituents are the same. A few larger grains of muscovite are seen lying parallel to the coarser quartz-rich layers, and are considered to be detrital; hoevever, small grains of muscovite exist almost solely in the matrix as metamorphic grains that are oriented parallel and sub-parallel to the cleavage.

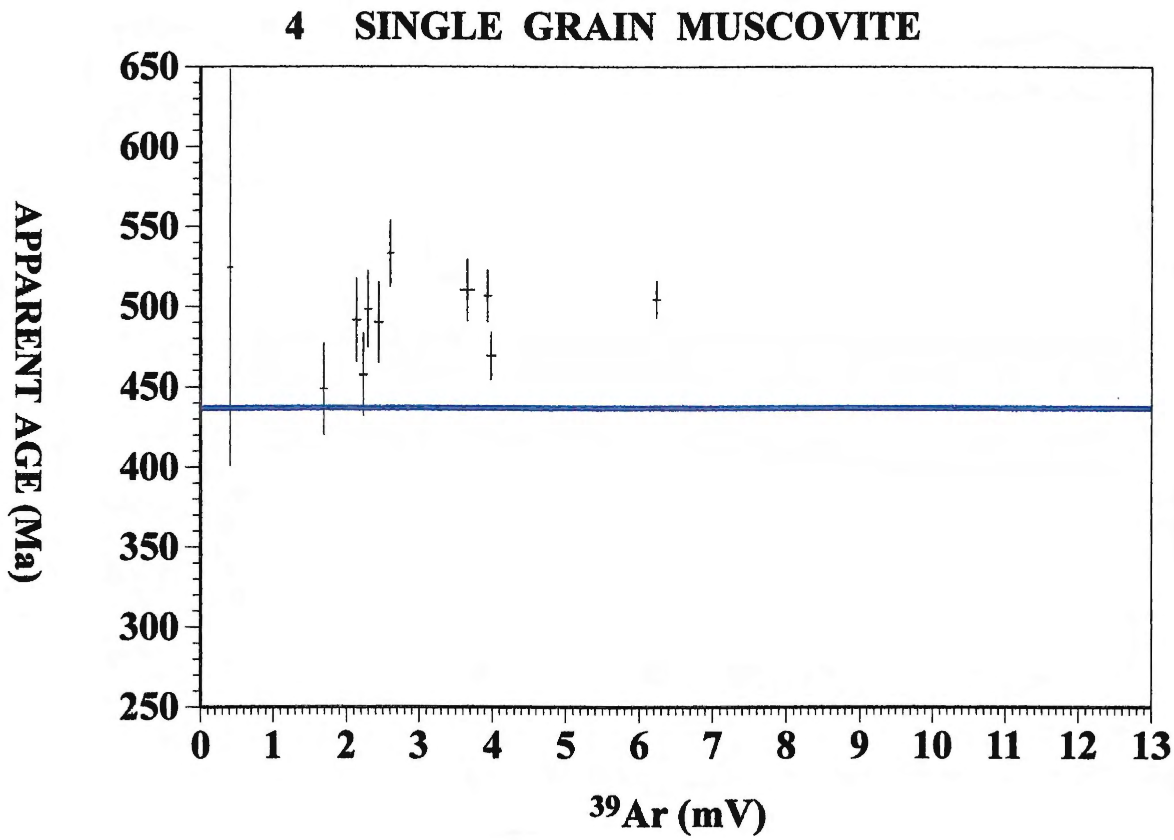

Figure 3.11: Single grain muscovite analyses of sample 4 of the White Rock Formation. Also shown is a reference age, the depositional age for the base of the White Rock Formation (blue line) (Lisa MacDonald, personal communication, 2000).

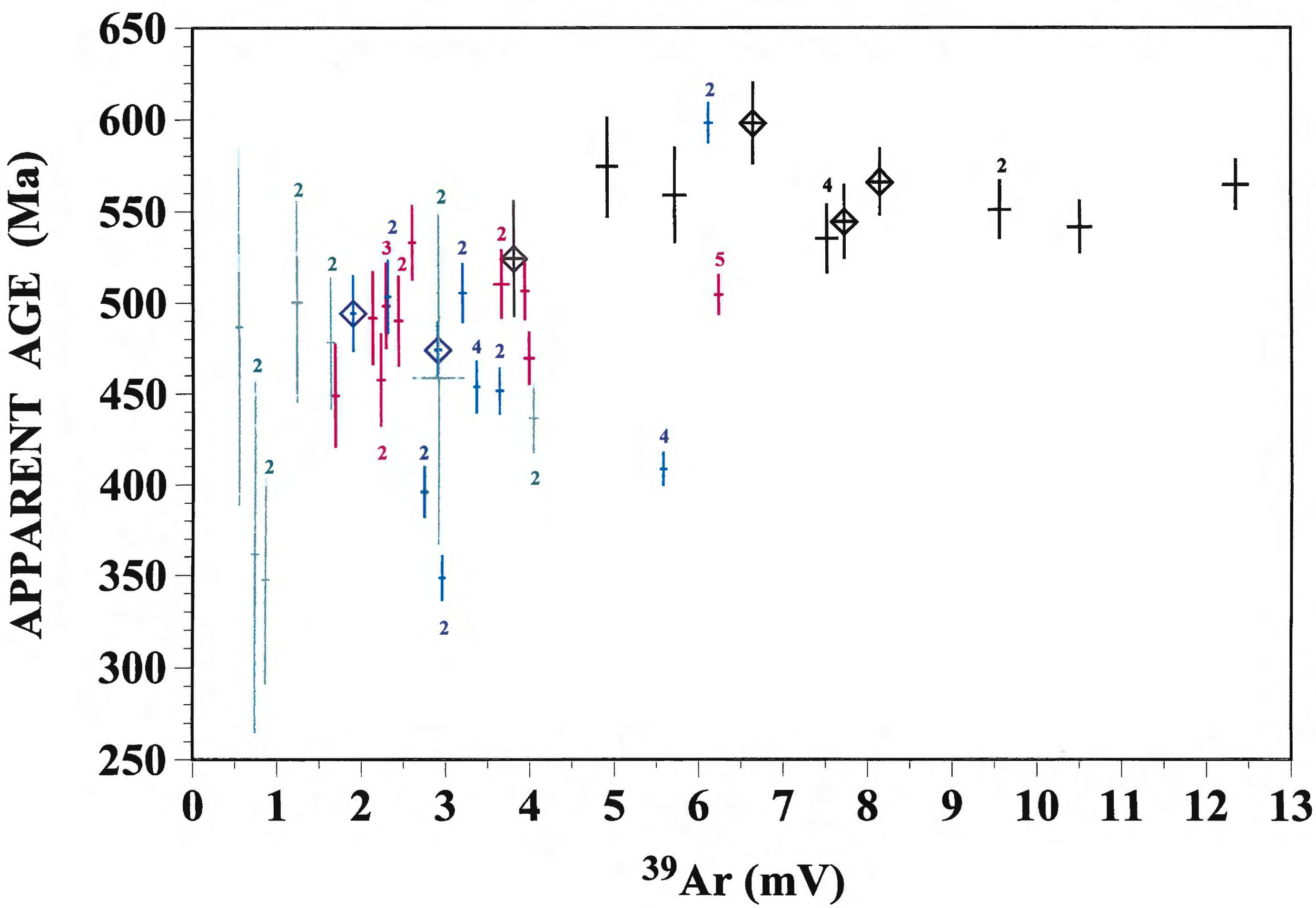

Figure 3.12: Composite image of all of the single grain muscovite analyses, showing numbers of grains laserprobed for each analysis. Black represents sample 12 from the Goldenville Formation, blue represents sample 2 of the Bear River Member of the Halifax Formation, red represents sample 4 of the White Rock Formation, and green represents sample 10 of the Acacia Brook Member of the Halifax Formation. Euhedral grains are shown by a diamond shape.

Typically, the muscovite grains are less parallel to bedding and more parallel to cleavage in the Halifax and White Rock Formations than in the Goldenville Formation. Another general trend is that the Goldenville Formation contains more detrital muscovite than the Halifax and White Rock Formations.

The Torbrook Formation sample is similar mineralogically to the other samples in this study that are described above; it consists of quartz and feldspar grains in a fine-grained muscovite and sericite matrix. This sample does not display cleavage as prominently as the more slaty Halifax and White Rock Formations.

3.8 Mineral Chemistry

Muscovite grains were separated from samples 12, 2 and 4 and placed on double-sided, carbon-coated tape that was mounted on a glass slide. The mineral chemistry on these grain mounts was investigated using the JEOL 733 Superprobe at the Dalhousie University Electron Microprobe Laboratory.

Microprobe analyses for muscovite compositions are summarized in the Appendices. Appendix B gives the weight percent oxide analyses and Appendix C gives the formulas.

Muscovite compositions from microprobe analyses on sample 12, sample 2, and sample 4 are shown in Figures 3.13 and 3.14. Figure 3.13, a muscovite classification scheme after Guidotti (1984) plots Fe^T + Mg versus Al(iv) versus Al(vi). All grains plot within a small field, near the muscovite end member. The Goldenville Formation samples plot slightly higher towards phengite compositions than the Halifax Formation and White Rock samples.

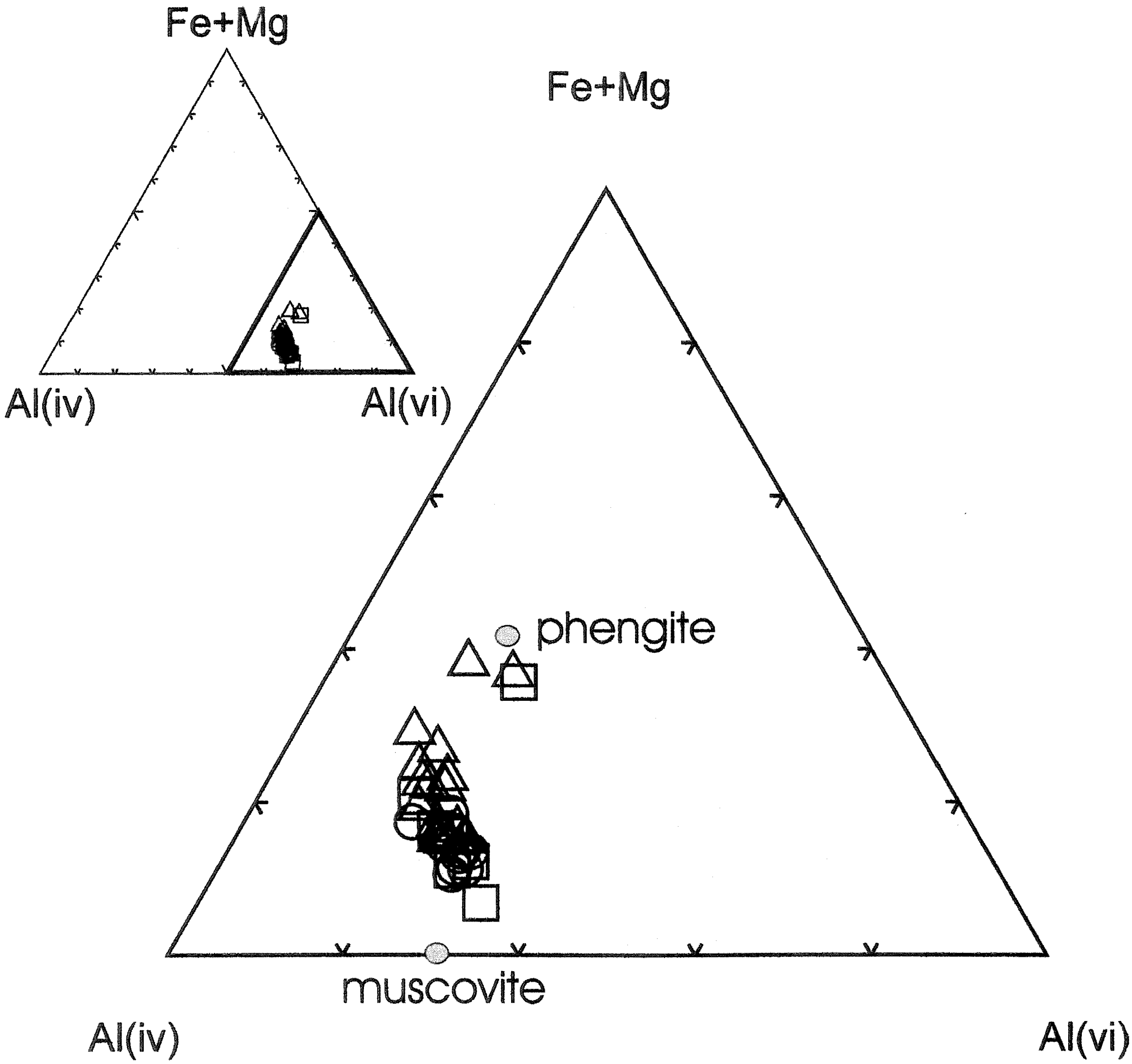

Figure 3.13: Muscovite classification of all muscovite microprobe analyses. Bottom diagram is enlargement of outlined triangle at bottom right corner of top diagram.
Symbols: Triangle represents Goldenville Formation samples
Square represents White Rock formation samples
Circle represents Bear River Member, Halifax Formation samples
(classification after Guidotti, 1984).

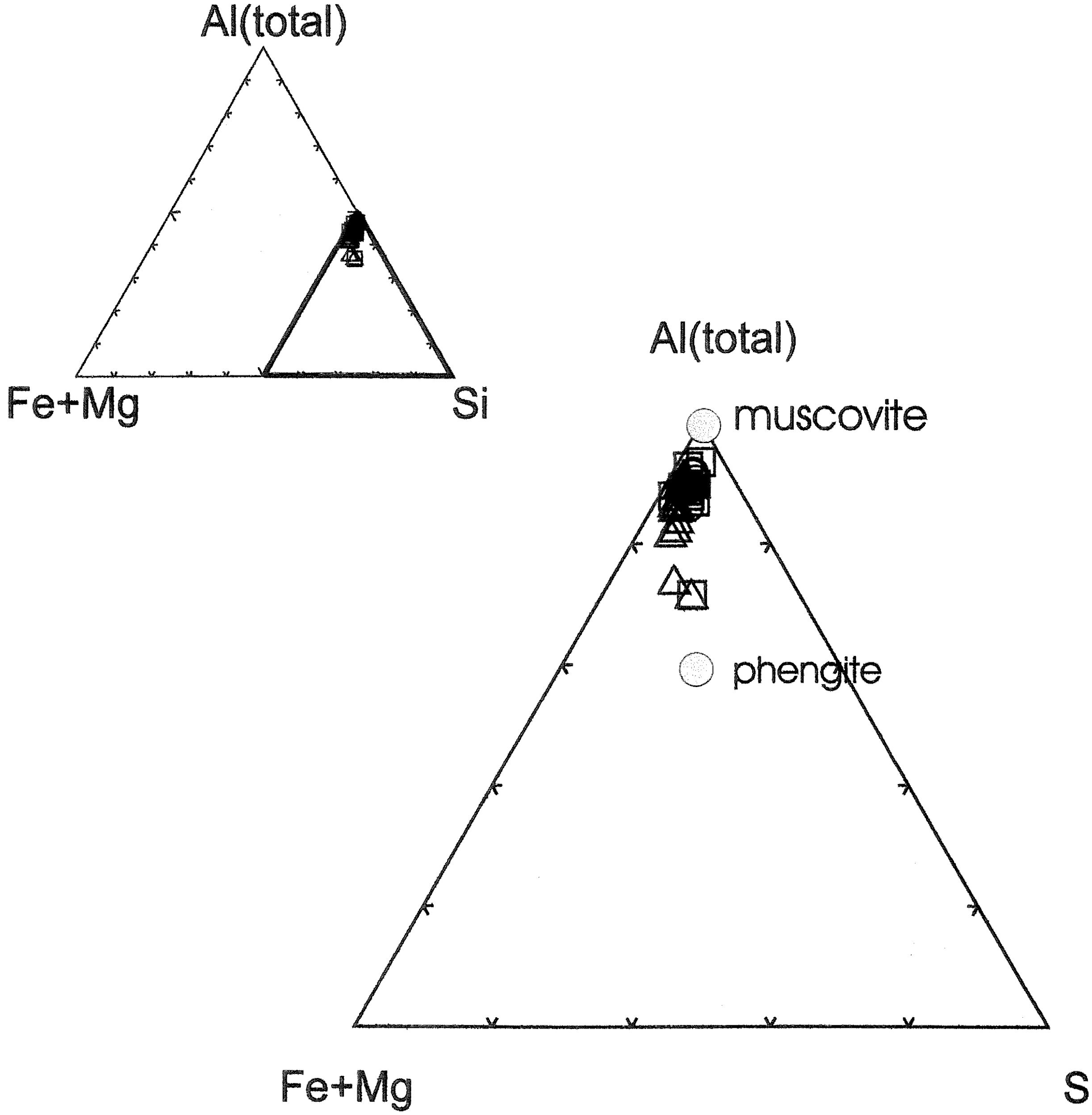

Figure 3.14: Muscovite classification of all muscovite microprobe analyses, showing Si, total Al, and Fe + Mg content. Phengite and muscovite compositions are shown for reference. Bottom diagram is enlargment of outlined triangle at bottom right corner of top diagram.
Symbols: Triangle represents Goldenville Formation samples
Square represents White Rock formation samples
Circle represents Bear River Member, Halifax Formation samples.

Figure 3.14, a general muscovite classification scheme that plots total Al (total) versus Fe^2 + Mg versus Si, displays a tight field near the muscovite end member. But some of the Goldenville samples are slightly more phengitic in composition.

CHAPTER FOUR: DISCUSSION AND SUMMARY

4.1 Interpretation of $^{40}Ar/^{39}Ar$ Results

Table 4.1 summarizes ages obtained from laserprobe $^{40}Ar/^{39}Ar$ dating in this thesis.

4.1.1 Goldenville Formation - Sample 12

Sample 12 gave an average of 551 ± 6 Ma, with a maximum of ca. 600 Ma, which is in good agreement with $^{40}Ar/^{39}Ar$ ages found by Hicks (1999) and U/Pb zircon and titanite dates obtained by Krogh and Keppie (1990). These dates of ca. 550 to 600 Ma are interpreted to be ages of the source rocks of the sediments that make up the Goldenville Formation of the Meguma Group. The lower-end ages of 519 to 545 Ma, however, are probably partially reset detrital grains, which lower the average of the population. Without these lower-end grains, the average is ca. 565 Ma, a better estimate of the age of source rocks for the Goldenville sediments, based on comparison with the Hicks (1999) and Krogh and Keppie (1990) data. The range of ages found in this study supports the contention made by Krogh and Keppie (1990) that the Goldenville Formation sediments are probably of a West African or Guyana Shield provenance, but not a northern North American or Baltic Shield provenance (Krogh and Keppie, 1990). Since the U-Pb ages and $^{40}Ar/^{39}Ar$ ages agree, an unusual but not abnormal phenomenon, a possible interpretation is that the source of the sediments, the original terrain of provenance, had a relatively quick cooling history or uneventful metamorphic history.

Table 4.1: Laserprobe 40Ar/39Ar Ages from Thesis Samples of Muscovite

Age (Ma)	Significance (Interpretation)	Sample	Number of Grains
344.2 ± 12.3	Metamorphic age	2	2
347.5 ± 56.6	Metamorphic age	10	2
361.5 ± 96.9	Metamorphic age	10	2
391 ± 14	Metamorphic age	2	2
403.5 ± 9.2	Metamorphic age	2	4
436.5 ± 19.3	Partial metamorphic resetting	10	2
445.8 ± 12.9	Partial metamorphic resetting	2	2
448 ± 14.5	Partial metamorphic resetting	2	4
448.7 ± 28.5	Partial metamorphic resetting	4	1
457.4 ± 25.7	Partial metamorphic resetting	4	2
458.6 ± 92	Partial metamorphic resetting	10	2
468.2 ± 15.4	Partially reset detrital age	2	1
469.3 ± 14.5	Partially reset detrital age	4	1
477.9 ± 36.6	Partially reset detrital age	10	2
486.6 ± 98.2	Partially reset detrital age	10	1
488.1 ± 20.9	Partially reset detrital age	2	1
490 ± 25.1	Partially reset detrital age	4	2
491.4 ± 25.9	Partially reset detrital age	4	1
497.1 ± 20.2	Partially reset detrital age	2	2
498.2 ± 23.9	Partially reset detrital age	4	3
499.2 ± 16.3	Partially reset detrital age	2	2
500.3 ± 55.5	Partially reset detrital age	10	2
504.4 ± 11.3	Partially reset detrital age	4	5
506.4 ± 16.1	Partially reset detrital age	4	1
510.2 ± 19.1	Partially reset detrital age	4	2
519.2 ± 31.8	Partially reset detrital age	12	1
530.2 ± 18.9	Partially reset detrital age	12	1
533 ± 20.6	Partially reset detrital age	4	1
536.5 ± 14.5	Partially reset detrital age	12	1
539.3 ± 20.3	Partially reset detrital age	12	1
545.8 ± 16	Partially reset detrital age	12	1
553.6 ± 25.8	Partially reset detrital age	12	2
559.3 ± 13.6	Detrital age	12	1
560.7 ± 18.1	Detrital age	12	1
568.8 ± 27.2	Detrital age	12	4
591.1 ± 11.2	Detrital age	2	2
592.5 ± 22.6	Detrital age	12	1

Sample 12 has a whole rock spectrum dominated by a plateau-like region at ca. 400 Ma. This can be interpreted as a reflection of a regional metamorphic event, probably the Acadian Orogeny, on Goldenville sediments. The single grain ages are completely distinct from the range of ages displayed in the whole rock spectrum (Figure 3.2). The metamorphic influence that is seen to dominate the whole rock spectrum does not appear to have had much influence on the single muscovite grains that were analyzed. The petrography of Sample 12 offers an explanation. The micaceous material in the sample is dominated by metamorphic secondary grains that help to define cleavage, while a few large detrital grains are found in the matrix as well. The whole rock spectrum is dominated by reset phyllosilicates and feldspars, and new mica growth, while the single grains analyzed were detrital grains.

Both muscovite classification diagrams based on microprobe data show that the only real difference in composition between the muscovite grains from the Goldenville, Halifax, and White Rock formations is that the Goldenville Formation samples are slightly more phengitic in composition than the Halifax and White Rock Formation samples. A possible interpretation for this, which supports petrographic and argon findings, relies on the fact that the grains that trend towards being phengitic in composition are detrital grains (see above). The higher phengite content, then, is a compositional difference due to the fact that the grains have retained their detrital signature in argon-retention, size, and, most important here, composition.

4.1.2 Halifax Formation - Samples 2 and 10

Sample 2 from the Bear River Member of the Halifax Formation gave a wide range of apparent ages, which can be interpreted to represent two distinct populations: a detrital one, and one that has been totally and partially reset by contact or regional metamorphic events. The detrital population is represented by a single fused grain giving an age of 591 Ma. The group of grains that gave ages ranging from 344 to 499 Ma is interpreted to have been partially reset by metamorphism. Specimens of Tremadoc graptolites were found in the unit now known as the Bear River Member of the Halifax Formation by Smitheringale (1973) and White et al. (1999), and thus another possible though less favoured interpretation is that the ages ranging from ca. 450 to 500 Ma record the timing of deposition or diagenesis of Halifax Formation sediments, as was suggested for 460-480 Ma ages found in some of the muscovite age spectra as reported by Hicks (1999).

Sample 10 for the Acacia Brook Member of the Halifax Formation gave ages in support of the theories given above for the other unit of the Halifax Formation being studied, the Bear River Member, however, its weight must be given less emphasis relative to the other analyses, due to the large error associated with it. Ages are similar to the ones above ranging between ca. 340 Ma to ca. 500 Ma and are similarly interpreted to be evidence of partial resetting of the mica grains due to a metamorphic event. Again, an alternate interpretation is that these ages represent the diagenetic or depositional age of Halifax Formation sediments discussed above.

The whole rock spectra for these two samples, 2 and 10, are very similar, and can be interpreted together. Both show a wide range of ages, with small plateau-like segments occurring from ca. 300 to 525 Ma showing a wide range of possible diagenetic, depositional, and/or metamorphic events. The age ranges in the whole rock spectra for the two samples are similar to the ranges in the single grain fusion ages. That is, the selected single grains are representative of all the muscovite populations in the rock for the Halifax Formation samples. The reason for this is hypothesized to be the rock type of this formation; characterized by slaty cleavage, and less sandy, detrital grains are less able to survive diagenetic and/or metamorphic events.

4.1.3 White Rock Formation - Samples 4 and 1

In Sample 4, the single grain muscovite ages spanning approximately 85 Ma from 448 to 533 Ma can be interpreted as representing a single population of grains. The interpretation that diagenesis was of some influence on the single grain samples does not apply to the White Rock Formation because the age of this formation is known, and all single grain ages are greater than this formation age of 438 +3/-2 Ma (Lisa MacDonald, personal communication, 2000). Also, there is no regional or contact metamorphic overprinting, since none of the ages falls earlier than 449 Ma, ≈ 50 Ma before regional metamorphism and ≈ 80 Ma before the intrusion of the South Mountain Batholith. The interpretation of the single grain ages, therefore, is that they are detrital grains originating from the Meguma Group sediments, or from the Avalon Terrane, that may possibly have been altered diagenetically during deposition of the Halifax Formation before being shed as detritus and forming part of the White Rock Formation.

The whole rock spectra obtained for the White Rock Formation samples 1 and 4 are characterized mainly by signatures representing resetting by a regional metamorphic event around 400 Ma, probably the Acadian Orogeny.

The age range of the sample 4 single grain data is contained within the range of ages obtained in the whole rock spectra for this White Rock sample, showing that the single grain data is to some extent representative of the whole rock data. The range of single grain ages, however, is at the higher end of the whole rock age spectrum, and thus the single grain age range can also be said to be somewhat distinct from the whole rock spectrum age range. The interpretation for this is similar to the explanation given for similar age range overlapping in sample 12 of the Goldenville Formation; the single grain ages represent a detrital population of muscovites that is not the major muscovite or mica population in the rock.

4.1.4 Torbrook Formation - Sample 6

Sample 6 represents the Torbrook Formation. Because it was difficult to extract single muscovite grains from the Torbrook samples, the whole rock analysis provides the only available information on this formation that this study provides. The whole rock spectrum displays a staircase pattern, one typical of resetting, with a relatively large amount of Ca released at the lower end of $\%^{39}$Ar released. This is different from all of the whole rock spectra discussed up to this point, which have two events in common, displayed in all spectra from the Meguma Group and the White Rock Formation samples: a resetting event at 270 Ma or less, shown at the lowest percentage of $\%^{39}$Ar released, and a probable detrital influence of a Ca-bearing mineral, possibly plagioclase, shown at the highest percentage of $\%^{39}$Ar released.

In the spectra from sample 6, the age range is 276 Ma to 389 Ma with most of the apparent ages lying between 350 and 370 Ma. These data along with the proximity of the Torbrook Formation in the Digby area to the ca. 370 Ma granitic South Mountain

Batholith (Figure1.1) indicate that most of the micaceous minerals in this rock were reset by the intrusion of this batholith and possibly by later events.

4.2 Factors Affecting $^{40}Ar/^{39}Ar$ Ages

The laserprobe $^{40}Ar/^{39}Ar$ ages obtained in this study have been influenced by a number of different factors, both human and nature induced. The largest factor, which has ended up changing the scope of the study's original purpose, is the characteristics of the muscovite grains that were originally hand picked from the rock. Whereas detrital grains were the principal targets in this study, in theory recognizable because of their size (ie. large in comparison to the other muscovite grains), and their orientation (ie. parallel to the bedding plane), such distinctions were not readily apparent except in the case of the Goldenville Formation sample, hence most of the selected grains evidently were ones which had been partially or totally reset by metamorphic or later events or grew as new muscovites during these events.

Another factor affecting the age data obtained is the size of the grains that were used for dating. The size of the grains was relatively small with respect to both the diameter and the thickness of the grains in comparison to grains previously used with the $^{40}Ar/^{39}Ar$ laserprobe technique, and thus smaller amounts of argon gas released and hence larger margins of error resulted. Also, due to the size of the grains and the methods used for their removal from the rocks, inevitably, some of the ones selected were broken pieces of larger grains.

Lastly, the nature of the sediments involved in the study influenced the results. As in Hicks (1997), it was found that cleavage is much less prominent in the generally sandy Goldenville Formation and thus detrital grains from the Goldenville are more likely to show their pre-metamorphic age than formations that are characterized by slaty cleavage, namely the Halifax Formation.

4.3 Summary

The results from this study for the Goldenville Formation indicate a provenance age of approximately 560 Ma to 600 Ma for source rock sediments. A detrital signature of similar type, an age of approximately 590 Ma, was also detected in the Bear River Member of the Halifax Formation.

The whole rock samples and the single grain analyses for the Halifax Formation all gave evidence of resetting due to metamorphism; both the influences of the regional metamorphic Acadian Orogeny event and the South Mountain Batholith contact metamorphic event are seen in the spectra.

The information on the White Rock Formation obtained in this study indicates the existence of a ca. 500 Ma detrital muscovite population retained within the rocks, probably from detritus from the Meguma Group or Avalon Terrane sediments. Evidence for the occurrence of metamorphic resetting events is also found in the White Rock Formation data in this study.

The results from this study for the Torbrook Formation indicate a complete resetting of the K-bearing phases within the rock by the intrusion of the South Mountain Batholith.

A general trend noted in this study is that in formations that are composed mainly of sandstone, such as the Goldenville Formation, metamorphic influences dominate the whole rock spectra, while this influence is not seen at all in the single grain muscovite data. In formations that are mainly silty and slaty in composition, however, resetting metamorphic events have either affected both the single muscovite grains and the whole rock analyses to about the same degree, as in the Halifax Formation, or have affected the whole rock analyses more than the single grain analyses, as in the White Rock Formation. This is due to the petrography and grain size of the rocks. The Goldenville Formation samples managed to retain a detrital signature in the single grain muscovites but not in the generally fine-grained mica and feldspar-rich matrix material of the rock, which dominated the whole rock spectrum. The Halifax Formation did not retain much of a detrital signature in either the single grain or whole rock analyses, due to the finer-grain size of these rocks and thus more susceptibility to metamorphism. The White Rock Formation did retain a detrital signature in its single grain analyses, but this is more of a reflection of the success in removal of the detrital grains than of the slaty nature of the rock.

4.4 Recommendations for Future Work

Five main recommendations can be made for projects that would further knowledge about ages of source rocks for the sedimentary rock formations of the Digby area and the metamorphic and other resetting events that make up the thermal history of the rocks, both in the Digby area and other areas where these formations outcrop. First, more studies using single muscovite grains need to be done using the argon laserprobe method, especially in other areas of the Goldenville Formation, where the detrital muscovite is easier to pick out and retains its detrital signature better than the rocks with a more slaty cleavage. Also, In this study, it was apparent that the grains that gave good single grain muscovite results using the $^{40}Ar/^{39}Ar$ laserprobe method were those with phengitic compositions. Thus, before picking the grains to use for future studies, it might be useful to do a detailed mineral chemistry study to determine the samples with phengite composition and use these for $^{40}Ar/^{39}Ar$ dating. Second, more U-Pb studies need to be carried out on other detrital minerals, such as titanite and zircon. Third, this study was instrumental in seeking the limits of the laserprobe argon technique with respect to single grain size and amount of Ar released per grain to give an apparent age without excessive error. More studies testing the limits of this technique are needed since this is a relatively new age-dating method. Fourth, more $^{40}Ar/^{39}Ar$ studies are needed in the Digby area and other areas of the White Rock Formation, to better constrain the source and age of detrital material in this formation.

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APPENDIX A: ANALYTICAL DATA FOR $^{40}Ar/^{39}Ar$ GEOCHRONOLOGY

Whole Rock Data

Sample 12	Goldenville Formation
Sample 2	Halifax Formation – Bear River Member
Sample 10	Halifax Formation – Acacia Brook Member
Sample 4	White Rock Formation
Sample 1	White Rock Formation
Sample 6	Torbrook Formation

Single Grain Muscovite Data

Sample 12	Goldenville Formation
Sample 2	Halifax Formation – Bear River Member
Sample 10	Halifax Formation – Acacia Brook Member
Sample 4	White Rock Formation

12 WHOLE ROCK ARGON SUMMARY

T°C	mV 39	% 39	AGE (Ma)±1σ	% ATM	37/39	36/40	39/40	% IIC
500	30.2	1.8	267 ± 3.6	5.5	.03	.000188	.013237	0
550	59.9	3.6	255.6 ± 1.8	1.4	.04	.000049	.01447	0
600	119.1	7.2	341.6 ± 1.7	.8	.03	.000029	.010624	0
650	178.3	10.8	374.5 ± 1.7	.4	.02	.000014	.009644	0
700	213	12.9	383.5 ± 1.7	.3	.01	.000012	.009398	0
750	243.9	14.8	386 ± 2.2	0	.01	.000001	.00936	0
800	243	14.8	389.7 ± 1.8	0	.01	.000001	.009264	0
850	233.2	14.2	399.2 ± 1.8	.1	.01	.000006	.009004	0
900	137.2	8.3	420.1 ± 2.7	.2	.03	.000007	.008502	0
950	66.4	4	425 ± 2.4	.8	.12	.000027	.008343	.01
1000	25.4	1.5	430.1 ± 4.8	1.2	.55	.000044	.008192	.07
1050	21.1	1.2	414.7 ± 5.4	2.4	1.08	.000085	.008431	.14
1150	29.6	1.8	404.8 ± 4.1	10	2.17	.000341	.007988	.28
1250	19.2	1.1	418.3 ± 7.8	21	1.76	.000711	.006765	.22
1450	19.9	1.2	462.2 ± 11.4	50.1	2.27	.001696	.003816	.27

TOTAL GAS AGE = 384.2 ± 2.2 Ma

J = .002235 ± 1.1175E-05 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

2 WHOLE ROCK ARGON SUMMARY

T°C	mV 39	% 39	AGE (Ma)±1σ	% ATM	37/39	36/40	39/40	% IIC
500	164.2	5.4	385.1 ± 2	2.5	.01	.000084	.009106	0
550	337.3	11.1	347 ± 1.6	1.8	.02	.000063	.010282	0
600	482.7	15.9	431.2 ± 1.9	.8	.02	.00003	.008158	0
650	496	16.4	437.2 ± 1.9	.6	.04	.00002	.008053	0
700	420	13.9	438.5 ± 1.9	.6	.05	.000022	.008023	0
750	293.9	9.7	443 ± 2	.4	.03	.000014	.007952	0
800	212.8	7	478.8 ± 2.2	.3	.01	.000011	.007286	0
850	231.7	7.6	505.1 ± 2.2	.3	.01	.000013	.006851	0
900	205.5	6.8	524.6 ± 2.3	.3	.02	.000012	.006561	0
950	87.3	2.8	527.7 ± 2.7	.4	.06	.000015	.006511	0
1000	42.6	1.4	522.3 ± 4.3	.9	.16	.000031	.00656	.01
1050	27.2	.9	520.3 ± 5.4	1.2	.23	.000043	.006566	.02
1150	14.3	.4	473.1 ± 9.9	8.4	.52	.000286	.006793	.06
1250	3.2	.1	486.6 ± 52.8	46.6	.33	.001582	.003839	.03
1450	1.7	0	899.4 ± 267	82.2	.17	.002784	.000611	.01

TOTAL GAS AGE = 443.9 ± 2.4 Ma

J = .002223 ± 1.1115E-05 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

10 WHOLE ROCK ARGON SUMMARY

T°C	mV 39	% 39	AGE (Ma)±1σ	% ATM	37/39	36/40	39/40	% IIC
500	115.4	4.1	329 ± 1.8	7.7	0	.000263	.010288	0
550	216.2	7.8	294.6 ± 1.4	1.8	0	.000062	.012345	0
600	432.1	15.5	371.5 ± 1.7	.5	0	.000019	.009701	0
650	520.1	18.7	410.1 ± 1.8	.4	0	.000015	.008701	0
700	438.1	15.8	424.3 ± 1.9	.7	0	.000024	.008354	0
750	306.8	11	439.1 ± 1.9	.5	0	.000018	.008051	0
800	212.8	7.6	486.2 ± 2.1	.3	0	.000012	.007186	0
850	194.6	7	518.2 ± 2.3	.3	0	.00001	.006686	0
900	148.5	5.3	526.6 ± 2.3	.4	.01	.000014	.006554	0
950	87.2	3.1	514.7 ± 2.5	.5	.02	.000019	.006719	0
1000	57.8	2	508.7 ± 2.6	.9	.05	.000031	.006788	0
1050	28.7	1	505.9 ± 3.5	1.7	.14	.00006	.006772	.01
1150	8.6	.3	491.7 ± 11.5	13.5	.78	.00046	.006159	.09
1250	1.5	0	518.1 ± 63.6	48.6	.22	.001649	.003455	.02
1450	2	0	636 ± 79.4	61.6	.17	.002087	.002028	.01

TOTAL GAS AGE = 424.8 ± 2.3 Ma

J = .002232 ± 1.116E-05 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

4 SINGLE GRAIN MUSCOVITE ARGON SUMMARY

SPOT NO.	CODE NO.	mV 39	AGE (Ma)±2σ	% ATM	37/39	36/40	39/40	% IIC
1	A46-11	.4	524.5 ± 124	17.8	.19	.000605	.005508	.02
2	A46-1	1.6	448.7 ± 28.5	1.2	0	.00004	.007909	0
3	A46-2	2.4	490 ± 25.1	4.8	0	.000163	.006893	0
4	A46-3	3.9	469.3 ± 14.5	.7	0	.000025	.007549	0
5	A46-5	3.9	506.4 ± 16.1	1.9	0	.000066	.006836	0
6	A46-6	2.1	491.4 ± 25.9	1.3	0	.000044	.007122	0
7	A46-8	2.6	533 ± 20.6	.3	0	.00001	.006554	0
8	A46-9	2.2	498.2 ± 23.9	2.9	0	.000099	.006897	0
9	A46-12	3.6	510.2 ± 19.1	.7	0	.000024	.006863	0
10	A46-15	2.2	457.4 ± 25.7	6.9	0	.000235	.007287	0
11	A46-17	6.2	504.4 ± 11.3	.4	0	.000013	.006976	0

AGE UNCERTAINTIES AT 2σ LEVEL,INCLUDING ERROR IN J

MEAN AGE (SPOTS 1 - 11)= 494.9 ± 6.4 MA (2σ UNCERTAINTY,INCLUDING ERROR IN J)

J = .00226 ± .0000115 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

1 WHOLE ROCK ARGON SUMMARY

T°C	mV 39	% 39	AGE (Ma)±1σ	% ATM	37/39	36/40	39/40	% IIC
500	33.7	2.1	278.8 ± 4.2	30	.06	.001016	.009285	.01
550	77	4.9	247.7 ± 1.9	11.2	.09	.000379	.013379	.01
600	134.6	8.6	384.2 ± 2	7.8	.05	.000265	.00861	0
650	210.4	13.4	429.9 ± 2	4.4	.03	.000151	.007871	0
700	256.2	16.4	413.6 ± 1.9	3.2	.03	.000108	.008328	0
750	235.4	15	400.3 ± 1.8	.5	.03	.000018	.008876	0
800	166.3	10.6	409.4 ± 1.9	.3	.03	.000011	.008675	0
850	158.5	10.1	426 ± 2	.3	.03	.000011	.008295	0
900	148.6	9.5	440.3 ± 2.1	.5	.05	.000019	.007976	0
950	69.3	4.4	450.5 ± 2.3	.9	.15	.000031	.007744	.01
1000	43.9	2.8	444.1 ± 2.9	1.8	.46	.000062	.0078	.05
1050	17.4	1.1	504.9 ± 6.8	7.4	2.48	.000253	.006355	.29
1150	6.8	.4	502.9 ± 14.5	23.3	2.97	.000793	.005287	.34
1250	1.4	0	617.2 ± 105	50.9	.68	.001728	.002672	.07
1450	1.1	0	1487.7 ± 224	64.3	.46	.002178	.000617	.03

TOTAL GAS AGE = 409.3 ± 2.3 Ma

J = .002218 ± 1.109E-05 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

6 WHOLE ROCK ARGON SUMMARY

T°C	mV 39	% 39	AGE (Ma)±1σ	% ATM	37/39	36/40	39/40	% IIC
550	81.8	3.6	276.1 ± 2.3	11.3	.58	.000383	.01202	.09
600	166.8	7.4	313.8 ± 1.8	8.9	1.83	.000301	.010747	.28
650	217.1	9.7	330.5 ± 1.9	12.7	3.5	.00043	.009729	.52
700	213.2	9.5	334 ± 1.7	6	1.06	.000205	.010352	.15
750	197.5	8.8	341.2 ± 1.6	.6	.13	.00002	.010702	.01
800	195.6	8.7	350.6 ± 1.7	.4	.07	.000015	.010402	.01
850	181.3	8.1	356.6 ± 1.7	.4	.06	.000016	.010204	0
900	166.6	7.4	361.2 ± 1.8	.9	.07	.000033	.010012	.01
950	126.3	5.6	359.2 ± 2	1.2	.1	.000041	.010049	.01
1000	98.7	4.4	360.9 ± 2	1.5	.11	.000052	.009965	.01
1050	101.1	4.5	365.2 ± 2.1	1.4	.11	.00005	.00984	.01
1100	126.2	5.6	368.9 ± 1.9	.8	.1	.00003	.00979	.01
1150	163.6	7.3	374.5 ± 1.8	.9	.08	.000031	.009623	.01
1250	154.7	6.9	375 ± 1.9	3.7	.11	.000125	.009341	.01
1450	40.2	1.8	389 ± 5.5	30.7	.19	.001039	.006454	.02

TOTAL GAS AGE = 348.9 ± 1.8 Ma

J = .002242 ± 1.121E-05 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

12 SINGLE GRAIN MUSCOVITE ARGON SUMMARY

SPOT NO.	CODE NO.	mV 39	AGE (Ma)±2σ	% ATM	37/39	36/40	39/40	% IIC
1	A47-1	4.9	574 ± 27.4	.6	.07	.000022	.006024	0
2	A47-2	6.6	597.8 ± 22.8	.3	.05	.000013	.005758	0
3	A47-3	5.7	558.7 ± 26	.5	.14	.000018	.006223	.01
4	A47-12	7.7	544.3 ± 20.4	.7	.04	.000026	.0064	0
5	A47-8	3.8	524 ± 32.1	2.3	.14	.00008	.006579	.01
6	A47-4	8.1	565.8 ± 18.3	.1	0	.000006	.006153	0
7	A47-7	12.3	564.4 ± 13.7	.1	0	.000006	.006171	0
8	A47-6	10.5	541.4 ± 14.6	0	0	.000001	.006487	0
9	A47-10	7.5	535.1 ± 19	.6	.05	.000021	.006538	0
10	A47-14	9.5	550.8 ± 16.2	.5	.01	.000017	.006329	0

AGE UNCERTAINTIES AT 2σ LEVEL,INCLUDING ERROR IN J

MEAN AGE (SPOTS 1 - 10)= 556 ± 6.4 MA (2σ UNCERTAINTY,INCLUDING ERROR IN J)

J = .002272 ± .0000115 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

2 MUSCOVITE SINGLE GRAINS ARGON SUMMARY

SPOT NO.	CODE NO.	mV 39	AGE (Ma)±2σ	% ATM	37/39	36/40	39/40	% IIC
1	A45-1	1.9	494.1 ± 21.2	4.7	0	.000161	.006801	0
2	A45-2	2.9	473.9 ± 15.6	1	0	.000033	.007412	0
3	A45-3	6.1	598.1 ± 11.3	.3	0	.00001	.005704	0
4	A45-4	2.3	503.2 ± 20.4	5.8	.01	.000198	.006581	0
5	A45-6	5.5	408.5 ± 9.3	4.3	.32	.000148	.008462	.04
6	A45-7	2.9	348.5 ± 12.5	5.2	.37	.000179	.009996	.05
7	A45-9	2.7	395.9 ± 14.1	2.3	.27	.000081	.008946	.03
8	A45-10	3.3	453.6 ± 14.6	7	.14	.000239	.007314	.01
9	A45-12	3.6	451.4 ± 13.1	1.5	.03	.000053	.007788	0
10	A45-14	3.1	505.3 ± 16.5	4.4	0	.000149	.006652	0

AGE UNCERTAINTIES AT 2σ LEVEL,INCLUDING ERROR IN J

MEAN AGE (SPOTS 1 - 10)= 471.6 ± 4.7 MA (2σ UNCERTAINTY,INCLUDING ERROR IN J)

J = .00225 ± .0000115 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

10 SINGLE GRAIN MUSCOVITES ARGON SUMMARY

SPOT NO.	CODE NO.	mV 39	AGE (Ma)±2σ	% ATM	37/39	36/40	39/40	% IIC
1	A48-1	.7	361.5 ± 96.9	36.2	.42	.001228	.006559	.06
2	A48-7	1.6	477.9 ± 36.6	2.5	.1	.000085	.007325	.01
3	A48-4	.5	486.6 ± 98.2	2.2	.15	.000076	.007198	.01
4	A48-5	.8	347.5 ± 56.6	7.6	.59	.000259	.009912	.08
5	A48-6	4	436.5 ± 19.3	7.7	.1	.000261	.007679	.01
6	A48-11	2.9	458.6 ± 92	.6	1.53	.000025	.007823	.19
7	A48-12	1.2	1131.5 ± 113	1	.08	.000034	.002584	0
8	A48-13	1.2	500.3 ± 55.5	2.2	.27	.000075	.006973	.03

AGE UNCERTAINTIES AT 2σ LEVEL, INCLUDING ERROR IN J

MEAN AGE (SPOTS 1 - 8)= 522.1 ± 27.1 MA (2σ UNCERTAINTY, INCLUDING ERROR IN J)

J = .002278 ± .0000115 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION, INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

4 WHOLE ROCK ARGON SUMMARY

T°C	mV 39	% 39	AGE (Ma)±1σ	% ATM	37/39	36/40	39/40	% IIC
450	19.4	1.4	277.1 ± 4.7	18.8	.01	.000637	.010876	0
500	34.9	2.5	334.2 ± 2.9	5.8	.02	.000196	.010291	0
550	72	5.3	364.2 ± 2.1	2.9	.03	.0001	.009645	0
600	136.4	10.1	390.9 ± 1.9	2.2	.03	.000074	.008986	0
650	172.8	12.8	399.8 ± 1.8	1	.03	.000035	.008866	0
700	170.9	12.7	402.8 ± 1.8	.8	.02	.000029	.00881	0
750	160.2	11.9	409.9 ± 1.9	.5	.02	.000019	.008665	0
800	160.2	11.9	434 ± 2.2	.4	.01	.000013	.008141	0
850	142.6	10.6	463.1 ± 2.1	.4	.01	.000016	.007559	0
900	119.9	8.9	489.8 ± 2.2	.7	.02	.000025	.007074	0
950	70.5	5.2	491.2 ± 2.5	1.3	.05	.000046	.007007	0
1000	38.6	2.8	489.6 ± 3.6	2.4	.1	.000082	.006958	.01
1050	17.5	1.3	514 ± 5.8	4.7	.25	.000161	.006424	.02
1100	6.9	.5	521.1 ± 13.1	11.6	.66	.000396	.005868	.07
1150	3.3	.2	563.2 ± 32.6	24.3	.93	.000825	.004596	.1
1250	17.8	1.3	560.3 ± 9.2	34.5	.32	.001168	.003998	.03

TOTAL GAS AGE = 426.6 ± 2.3 Ma

J = .002224 ± 1.112E-05 (.5 %)

37/39,36/40 AND 39/40 Ar RATIOS ARE CORRECTED FOR MASS SPECTROMETER DISCRIMINATION,INTERFERING ISOTOPES AND SYSTEM BLANKS

% IIC - INTERFERING ISOTOPES CORRECTION

APPENDIX B: MICROPROBE DATA: WEIGHT PERCENT OXIDES

Appendix B Microprobe Analyses, Weight % Oxide - Muscovite

Goldenville Formation

Sample	Analysis	SiO2	TiO2	Al2O3	FeO	MgO	Na2O	K20	Total
12	1a	48.08	0.45	33.62	4.11	1.07	0.36	8.72	96.40
12	1b	46.41	0.55	32.70	3.93	0.95	0.34	8.59	93.46
12	3b	53.68	ND	28.52	5.39	2.05	0.29	9.51	99.44
12	3c	50.39	ND	28.65	5.52	2.17	ND	8.75	95.47
12	3d	47.84	0.95	34.99	2.93	0.74	0.50	7.73	95.67
12	3e	47.26	1.09	34.88	2.89	0.70	0.51	9.07	96.39
12	4a	45.79	0.91	29.95	4.73	1.38	0.29	9.93	92.97
12	4b	48.86	1.01	32.26	4.58	1.34	ND	9.47	97.52
12	5a	48.77	ND	35.66	2.32	1.00	0.61	9.33	97.69
12	5b	46.56	ND	34.42	1.92	1.06	0.55	8.90	93.41
12	6a	45.62	0.75	30.75	4.14	1.07	0.32	10.34	92.99
12	6b	46.20	0.76	32.14	3.91	0.97	0.32	9.74	94.04
12	7a	47.78	ND	35.65	2.73	0.80	1.62	9.21	97.78
12	7b	45.31	0.34	34.10	2.59	0.78	1.05	7.96	92.12
12	8a	44.34	0.28	32.89	3.83	0.68	1.10	8.59	91.70
12	8b	45.80	0.36	33.96	2.90	0.76	0.89	8.92	93.59
12	10a	45.31	0.42	32.18	3.98	0.93	0.38	10.33	93.53
12	12a	45.34	0.56	33.59	3.05	0.74	0.47	9.19	92.94

Appendix B Microprobe Analyses, Weight % Oxide - Muscovite

Sample	Analysis	SiO2	TiO2	Al2O3	FeO	MgO	Na2O	K20	Total
White Rock Formation									
4	1a	48.20	0.58	35.75	1.28	1.06	0.50	10.83	98.20
4	3a	45.79	0.46	31.75	1.67	1.56	1.06	9.49	91.78
4	4a	45.83	0.58	33.22	1.44	1.07	0.28	9.98	92.39
4	4b	47.31	0.46	34.66	1.54	1.12	0.28	9.23	94.58
4	5a	46.89	0.31	35.44	1.61	0.67	0.75	10.41	96.08
4	6a	46.11	0.35	33.66	1.72	1.10	0.33	11.06	94.33
4	7a	47.39	0.35	34.52	1.61	1.07	0.32	10.19	95.46
4	7b	48.38	0.28	35.40	1.61	1.16	0.31	10.17	97.31
4	8a	43.87	0.83	31.95	2.76	0.86	0.35	11.11	91.71
4	10a	45.45	0.40	34.35	1.74	0.67	0.32	9.23	92.15
Halifax Formation - Bear River Member									
2	1a	46.15	0.69	35.72	1.56	0.72	0.57	8.68	94.08
2	1b	48.58	0.41	37.38	0.85	0.63	1.02	8.32	97.20
2	3a	53.97	ND	28.96	2.99	3.36	0.35	8.89	98.50
2	5a	46.40	0.91	34.19	3.04	0.74	0.32	9.36	94.95
2	5b	45.36	0.77	33.14	3.84	0.83	0.49	9.76	94.18
2	6a	46.53	0.67	33.69	2.39	0.94	0.34	9.96	94.52
2	7a	47.34	0.72	33.10	2.65	0.76	0.91	10.17	95.65
2	8b	46.47	0.83	33.20	2.65	0.73	0.91	9.76	94.55
2	10a	46.72	0.86	34.11	1.74	0.77	0.27	8.23	92.70

APPENDIX C: MICROPROBE DATA: FORMULAS

Appendix C Microprobe Analyses, Formulas - Muscovite

Goldenville Formation

Sample	Analysis	Si	Ti	Al	Fe	Mg	Na	K
12	1a	0.288	0.002	0.237	0.021	0.01	0.004	0.067
12	1b	0.287	0.003	0.238	0.020	0.009	0.004	0.068
12	3b	0.313	ND	0.196	0.026	0.018	0.003	0.071
12	3c	0.305	ND	0.204	0.028	0.02	ND	0.068
12	3d	0.285	0.004	0.246	0.015	0.007	0.006	0.059
12	3e	0.282	0.005	0.245	0.014	0.006	0.006	0.069
12	4a	0.289	0.004	0.223	0.025	0.013	0.004	0.08
12	4b	0.291	0.005	0.226	0.023	0.012	ND	0.072
12	5a	0.286	ND	0.246	0.011	0.009	0.007	0.07
12	5b	0.285	ND	0.248	0.010	0.01	0.006	0.069
12	6a	0.287	0.004	0.228	0.022	0.01	0.004	0.083
12	6b	0.286	0.004	0.234	0.020	0.009	0.004	0.077
12	7a	0.282	ND	0.248	0.013	0.007	0.019	0.069
12	7b	0.282	0.002	0.250	0.013	0.007	0.013	0.063
12	8a	0.280	0.001	0.245	0.020	0.006	0.013	0.069
12	8b	0.282	0.002	0.247	0.015	0.007	0.011	0.07
12	10a	0.284	0.002	0.237	0.021	0.009	0.005	0.082
12	12a	0.282	0.003	0.246	0.016	0.007	0.006	0.073

Appendix C Microprobe Analyses, Formulas - Muscovite								
Sample	Analysis	Si	Ti	Al	Fe	Mg	Na	K
White Rock Formation								
4	1a	0.283	0.003	0.247	0.006	0.009	0.006	0.081
4	3a	0.288	0.002	0.235	0.009	0.015	0.013	0.076
4	4a	0.285	0.003	0.244	0.007	0.01	0.003	0.079
4	4b	0.286	0.002	0.247	0.008	0.01	0.003	0.071
4	5a	0.281	0.001	0.251	0.008	0.006	0.009	0.08
4	6a	0.283	0.002	0.244	0.009	0.01	0.004	0.087
4	7a	0.285	0.002	0.245	0.008	0.01	0.004	0.078
4	7b	0.285	0.001	0.246	0.008	0.01	0.004	0.076
4	8a	0.280	0.004	0.241	0.015	0.008	0.004	0.091
4	10a	0.283	0.002	0.252	0.009	0.006	0.004	0.073
Halifax Formation - Bear River Member								
2	1a	0.280	0.003	0.255	0.008	0.007	0.007	0.067
2	1b	0.283	0.002	0.256	0.004	0.005	0.012	0.062
2	3a	0.313		0.198	0.014	0.029	0.004	0.066
2	5a	0.282	0.004	0.245	0.015	0.007	0.004	0.073
2	5b	0.281	0.004	0.242	0.020	0.008	0.006	0.077
2	6a	0.284	0.003	0.243	0.012	0.009	0.004	0.078
2	7a	0.287	0.003	0.236	0.013	0.007	0.011	0.079
2	8b	0.285	0.004	0.240	0.014	0.007	0.011	0.076
2	10a	0.286	0.004	0.246	0.009	0.007	0.003	0.064