$^{40}Ar/^{39}Ar$ age of the Jurassic North Mountain Basalt, southwestern Nova Scotia

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ABSTRACT

Two whole-rock samples of the Jurassic North Mountain Basalt have been dated using the $^{40}Ar/^{39}Ar$ method. A single sample of fresh, medium-grained, holocrystalline basalt from the lower flow unit of this thick (i.e., 400 m) sequence gave coincident plateau and isochron correlation ages of 201 ± 2.5 Ma, in agreement with a zircon U-Pb age of 202 ± 1 Ma for this same flow unit. This $^{40}Ar/^{39}Ar$ age contrasts with earlier conventional K-Ar whole-rock ages of ca. 192 Ma for the North Mountain Basalt, which are similar to other K-Ar and Ar/Ar ages for correlative basalts of eastern North America. The second dated sample is a zeolite-bearing basalt from the middle flow unit of the North Mountain Basalt. This sample gave a discordant age spectrum with excess argon, but the isochron correlation age of 206 Ma, albeit with a large error (i.e., 56 Ma), is similar to that for the fresh sample. The data indicate that reliable whole-rock $^{40}Ar/^{39}Ar$ ages for the basalts are attainable, but that fresh samples must be used. In light of this, it is suggested that the younger 192 Ma ages may reflect a widespread thermal event related to zeolite formation.

RÉSUMÉ

Deux échantillons de roche totale de basalte jurassique du mont North ont été datés au moyen de la méthode $^{40}Ar/^{39}Ar$. Un échantillon unitaire de basalte holocristallin à grain moyen frais de l'unité d'écoulement inférieure de cette séquence épaisse (c.-à-d. 400 m) a fourni des âges concordants par corrélation tabulaire et isochrone de 201 ± 2,5 Ma, ce qui correspond à la datation au U-Pb à partir de zircon situant la même unité d'écoulement à 202 ± 1 Ma. Cette datation $^{40}Ar/^{39}Ar$ fait contraste avec les datations de la roche totale conventionnelles antérieures au K-Ar situant à environ 192 Ma le basalte du mont North, soit des âges semblables à d'autres datations au K-Ar et Ar/Ar de basaltes corrélatifs de l'Est de l'Amérique du Nord. Le deuxième échantillon daté est un basalte renfermant de la zéolite et provenant du milieu de l'unité d'écoulement du basalte du mont North. Cet échantillon a fourni un spectre d'âges discordant présentant un excès d'argon, mais la datation par corrélation isochrone le situant à 206 Ma, en dépit d'une erreur importante (c.-à-d. 56 Ma), fournit un âge semblable à celui de l'échantillon frais. Les données révèlent qu'il est possible d'obtenir des dates de roche totale fiables au moyen de la méthode $^{40}Ar/^{39}Ar$, mais qu'il faut utiliser des échantillons frais. Compte tenu de ce fait, on suppose que les âges plus récents de 192 Ma pourraient correspondre à un phénomène thermique répandu apparenté à la formation de zéolite.

INTRODUCTION

The Jurassic North Mountain Basalt (NMB) outcrops along the southern and northern shores of the Bay of Fundy, in part also the Minas Basin, of southern Nova Scotia (Fig. 1). The NMB sequence forms part of the Late Jurassic-Early Triassic infill of the Fundy Rift, one of several exposed remnants of syn-rift basins that extend for over 2000 km along eastern North America and is part of the Newark Supergroup (Olsen *et al.* 1982; Froelich and Olsen 1985; Mansperzer and Cousminer 1988). Basins of equivalent age and similar geological setting are found along the margins of the Central Atlantic in north-west Africa and western Europe and represent correlatives (Olsen 1997; Marzoli *et al.* 2003; Rapaille *et al.* 2003). Within the Newark Supergroup, the basalt flows in the various sub-basins have been paleontologically assigned to the earliest Jurassic (Hettangian) and fall just above the Triassic-Jurassic boundary (Olsen *et al.* 1982). Within the Fundy Basin, this assignment is consistent with a U-Pb zircon age of 202 ± 1 Ma for a flow from the lower part of the basalt sequence (Hodych and Dunning 1992). However, the U-Pb age contrasts with previous K-Ar whole-rock dating of the NMB that indicated ages of ca. 180 to 200 Ma (Carmichael and Palmer 1968; ages recalculated by Hayatsu 1979), with a single anomalously old age of 333 Ma for one sample. Subsequently, Hayatsu (1979), using the K-Ar isochron method, obtained an age of 191 ± 2 Ma using the same sample set as Carmichael and Palmer (1968). Most recently, Cox *et al.* (2001) obtained an apatite fission track age of 190 ± 2 Ma for basalt from the lower part of the basalt sequence and from the same area as the sample for

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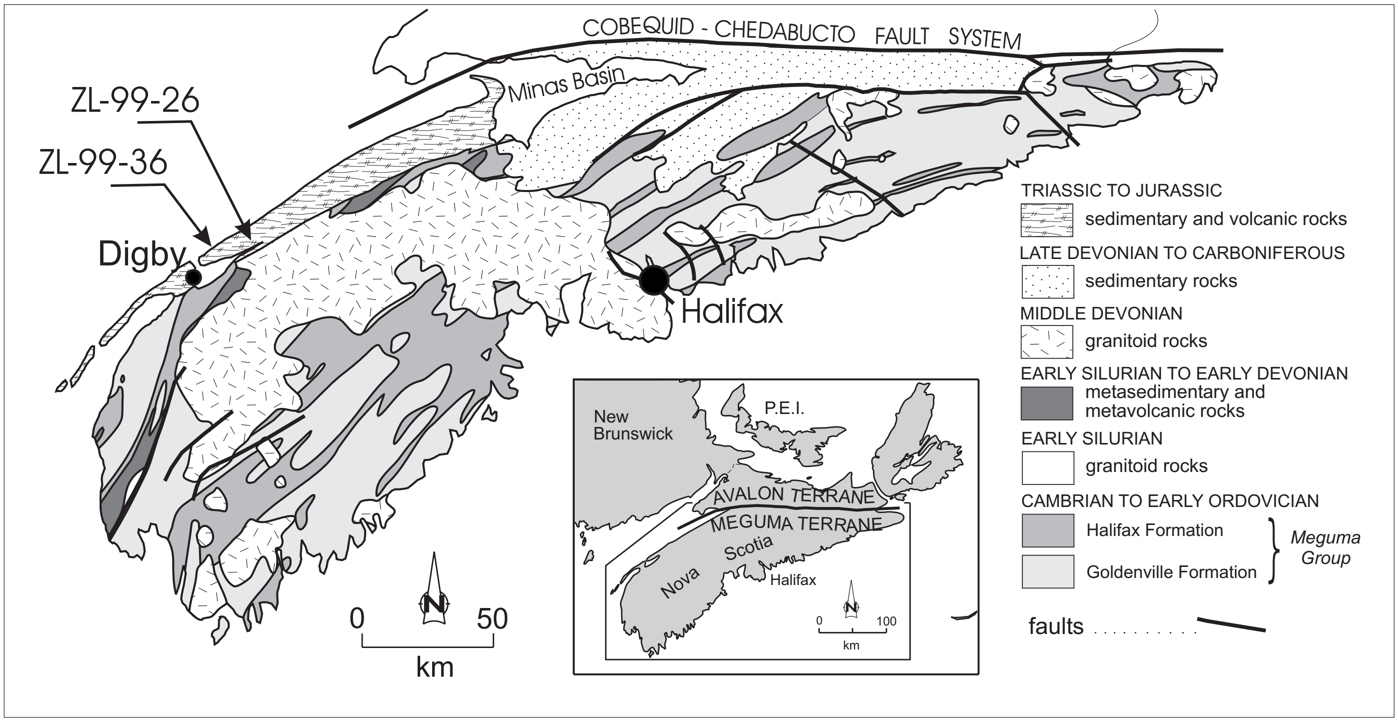

Fig. 1 Geological setting of the North Mountain Basalt in southwestern Nova Scotia with locations of the samples used in this study. Note that the sample dated by Hodych and Dunning (1992) is located west of Digby.

the U-Pb zircon age determination. Interestingly, the apatite fission track age is similar to the K-Ar age of Hayatsu (1979). These apparently young K-Ar ages contrast with $^{40}Ar/^{39}Ar$ ages of ca. 200 Ma for dyke rocks and basalt flows within parts of the Newark Supergroup of eastern North America (summary in McHone 2003) and similar ages for basalts and dyke rocks of the Central Atlantic Magmatic Province (CAMP; summaries in Sebai *et al.* 1991 and Marzoli *et al.* 1999).

In order to address this apparent discrepancy in ages for the NMB, samples of fresh and zeolite-bearing basalt were selected for whole-rock $^{40}Ar/^{39}Ar$ dating. Sample selection was focussed on firstly addressing whether reliable extrusion ages could be obtained on the NMB and, therefore, correlative units in the Newark Supergroup using the $^{40}Ar/^{39}Ar$ method, and secondly on the possible relationship between the younger apparent ages and timing of zeolite formation.

GEOLOGY OF THE NORTH MOUNTAIN BASALT

The North Mountain Basalt (NMB) occurs as a series of three flow units of ca. 400 m aggregate thickness that outcrop along the shores of the Bay of Fundy and some offshore islands (i.e., Isle Haute, Grand Manan Island). Along the southern shore of the Bay of Fundy, the NMB overlies red siltstone and shale of the Late Triassic Blomidon Formation and is subsequently overlain by terrestrial red siltstone, shale, and minor carbonate rocks of the Scots Bay Formation (De Wet and Hubert 1989). Somewhat similar geological relationships are observed on the north side of the Bay of Fundy, but in places the NMB rests on basement rocks of Carboniferous age and is overlain by sandstone and siltstone of the Jurassic McCoy Brook Formation (Greenough *et al.* 1989; Olsen *et al.* 1987). The stratigraphy of the NMB has recently been reviewed by Kontak (2002) based on recent field studies which follow on the earlier work of Lollis (1959), Papezik *et al.* (1988), and Greenough *et al.* (1989), and a summary of this stratigraphy follows.

The NMB is subdivided into three distinct flow units, referred to as lower, middle, and upper (LFU, MFU, and UFU, respectively). The LFU, ≤180 m thick, is dominated by massive, mostly holocrystalline, medium-grained basalt with well-developed columnar jointing. The upper 1–2 m is vesiculated and generally has zeolite minerals filling the vugs. The MFU, ≤150 m thick, consists of numerous thin flows (≤10–15) of fine-grained basalt with abundant amygdules arranged in a consistent zonal pattern (Aubele *et al.* 1988; Kontak 2000). Rare interflow sediments and sedimentary dykes of aeolian nature occur between and within these flows. The UFU, of minimum 100 m thickness, is again dominated by massive, columnar-jointed, medium-grained basalt containing <20–30 % mesostasis, and with minor amygdaloidal zones containing zeolite minerals. Detailed work in parts of the Newark Supergroup indicates eruption of the full sequence in less than 580 ka based on detailed paleontological, paleomagnetic, and K-Ar dating (Olsen and Fedosh 1988; Olsen 1997).

SAMPLING AND ANALYTICAL PROCEDURES

Two samples of the NMB were selected for argon dating with selection specifically aimed at obtaining ages of eruption and, possibly, the thermal event related to zeolite formation. The

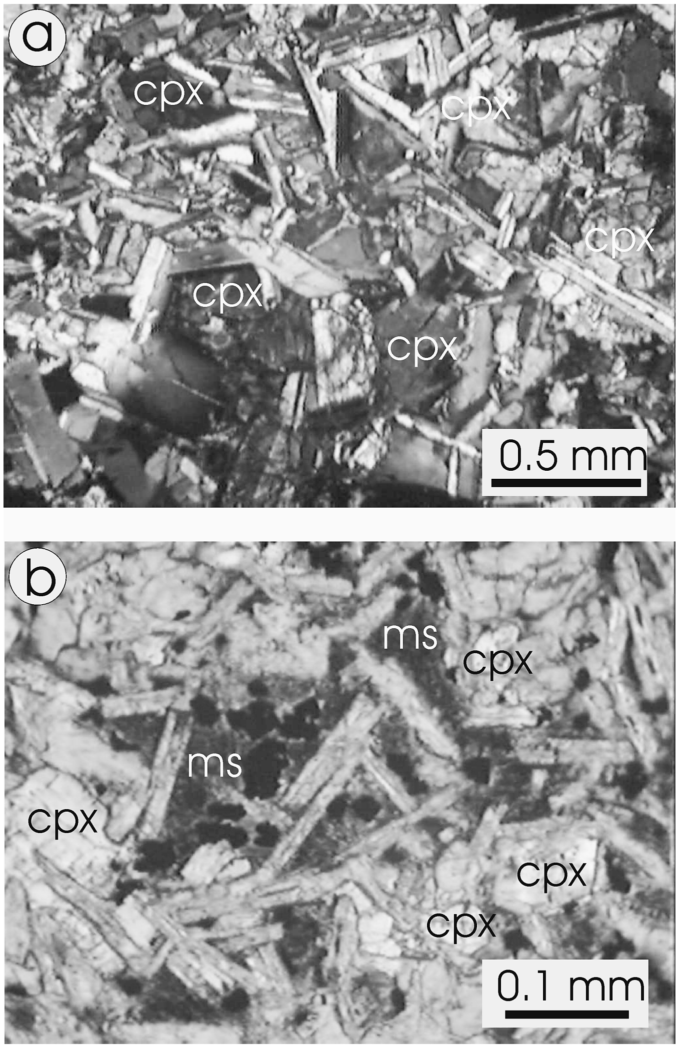

Fig. 2 Photomicrographs of the samples used in this study. (a) Lower flow unit basalt (ZL-99-26) from Parker Cove quarry in crossed nicols. This fresh, holocrystalline basalt has with ophitic-type texture. Subehdral clinopyroxene grains (calcic augite) are indicated by cpx, whereas calcic (i.e., An_{70-50}) plagioclase is noted by polysynthetic twinning. (b) Middle flow unit basalt with zeolite mineralization (ZL-99-36) from near Green Point in plane-polarized light. Photomicrograph shows the fine-grained nature of the rock compared to sample ZL-99-26 and the occurrence of the mesostasis (ms) with skeletal Fe-Ti oxide phases (i.e., opaques). Clinopyroxene (cpx) is unaltered, but plagioclase laths are replaced by a mixture of albite and stilbite.

first sample, ZL-99-26, is from the LFU at Parker Cove quarry near Annapolis Royal (Fig. 1). This sample is medium grained, holocrystalline, very fresh (i.e., complete absence of any deuteric alteration such as chlorite, white mica, carbonate, etc.), and most importantly is barren of megacrysts and xenoliths (Fig. 2a). The fact that this sample is both holocrystalline and free of megacrysts is highlighted, as McDougall and Harrison (1988) emphasized these features for selecting samples of volcanic rocks for whole-rock $^{40}Ar/^{39}Ar$ dating; failure to follow

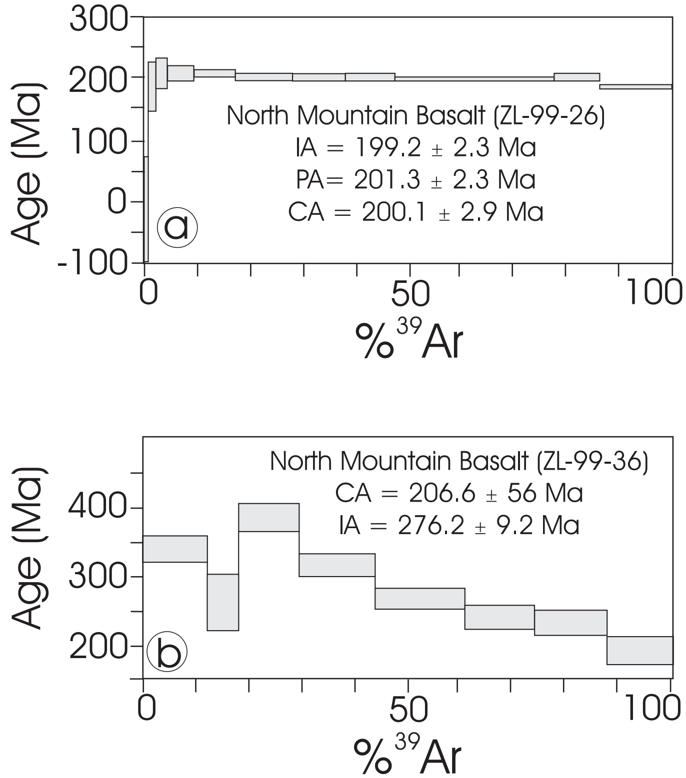

Fig. 3 $^{40}Ar/^{39}Ar$ age spectrum plots for the two samples dated in this study. (a) Fresh basalt ZL-99-26 from Parker Cove quarry, and (b) zeolite-bearing basalt ZL-99-36 from near Green Point. The abbreviations are as follows: IA = integrated age, PA = plateau age, CA = correlation age.

these suggestions may result in excess argon being detected in the analysis. The second sample, ZL-99-36, is from the upper, zeolite-rich part of a flow in the MFU near Green Point just east of Digby Gut. This sample is amygdaloidal and fine grained, with about 10–15% mesostasis that is intergranular to matrix plagioclase and clinopyroxene (Fig. 2b). We note that whereas the clinopyroxene is fresh, the plagioclase is variably altered to albite and stilbite. The mesostasis contains altered glass (i.e., hydrous Fe-Mg clays and micas), quenched Fe-Ti oxides, and Fe-rich pyroxenes and is similar petrographically to mesostasis textures described by Kontak *et al.* (2002). This sample was crushed and amygdale-free matrix material hand picked under a binocular microscope. A feature common to many samples of the MFU and less common in the LFU and UFU is the presence of a fine-grained chloritic phase lining vesicles. This feature is noted given that samples with such material may be susceptible to argon recoil during irradiation (e.g., Lo and Onstott 1989).

The two samples selected for dating were crushed to <2–3 mm grain size, washed in de-ionized water and dried. Analysis of the two samples was done at the Geochronology Laboratory, Queen's University, Kingston, Ontario, following the procedures outlined in Kontak *et al.* (1999). Dates and errors are calculated using formulae of Dalrymple *et al.* (1981), and the constants recommended by Steiger and Jager (1977). Errors shown in Table 1 and on the age spectra (Fig. 3) represent

Table 1. Ar-Ar data for North Mountain Basalt, southwestern Nova Scotia.

Step	$^{36}Ar/^{40}Ar$ (± 2σ)	$^{39}Ar/^{40}Ar$ (± 2σ)	Ca/K	$\%^{40}Ar$ Atm.	$\%^{39}Ar$ of total	$^{40}Ar/^{39}Ar$ (± 2σ)	Age (± 2σ)
Sample ZL-99-26, J value = 0.007653 ± 0.000064, Integrated age = 199.2 ± 2.3, Correlation age = 200.0 ± 2.9 Ma (84.9% of ^{39}Ar), Plateau age = 201.3 ± 2.3 Ma (84.9% of ^{39}Ar)							
1	0.003094 ± 0.000067	0.005967 ± 0.000108	8.19	91.41	1.40	14.37 ± 3.27	188.2 ± 40.6
2	0.002649 ± 0.000086	0.013718 ± 0.000165	8.78	78.26	1.98	15.83 ± 1.86	206.2 ± 22.9
3	0.002400 ± 0.000053	0.018316 ± 0.000121	9.24	70.89	5.29	15.87 ± 0.85	206.8 ± 10.5
4	0.001206 ± 0.000067	0.040956 ± 0.000222	6.62	35.59	8.00	15.72 ± 0.49	204.9 ± 6.1
5	0.000465 ± 0.000062	0.056080 ± 0.000309	5.02	13.73	10.81	15.38 ± 0.34	200.7 ± 4.2
6	0.000252 ± 0.000063	0.059933 ± 0.000291	4.02	7.42	10.48	15.44 ± 0.32	201.6 ± 4.0
7	0.000329 ± 0.000067	0.058619 ± 0.000290	3.98	9.69	9.32	15.40 ± 0.35	201.0 ± 4.3
8	0.000210 ± 0.000070	0.061232 ± 0.000329	3.44	6.20	9.16	15.32 ± 0.35	200.0 ± 4.3
9	0.000136 ± 0.000065	0.062835 ± 0.000371	3.402	4.02	9.96	15.27 ± 0.32	199.4 ± 4.0
10	0.000140 ± 0.000059	0.062715 ± 0.000326	4.01	4.11	11.07	15.29 ± 0.29	199.6 ± 3.6
11	0.000077 ± 0.000072	0.063606 ± 0.000375	6.43	2.26	8.86	15.37 ± 0.35	200.6 ± 4.3
12	0.000243 ± 0.000058	0.065076 ± 0.001641	29.17	7.16	13.68	14.26 ± 0.43	186.9 ± 5.4
Sample ZL-99-36, J value = 0.007840 ± 0.000194, Integrated age = 276.2 ± 9.2, Correlation age = 206.5 ± 55.9 Ma (69.1% of ^{39}Ar)							
1	0.001154 ± 0.000136	0.025224 ± 0.000233	4.29	34.05	12.17	26.13 ± 1.62	336.3 ± 19.0
2	0.001505 ± 0.000315	0.028235 ± 0.000356	14.92	44.42	5.89	19.67 ± 3.31	258.7 ± 40.5
3	0.000873 ± 0.000144	0.024733 ± 0.000239	3.85	25.77	11.27	30.00 ± 1.74	381.1 ± 20.0
4	0.000606 ± 0.000158	0.034077 ± 0.000236	4.86	17.89	14.26	24.09 ± 1.38	312.1 ± 16.4
5	0.000388 ± 0.000182	0.044049 ± 0.000267	7.65	11.46	16.89	20.10 ± 1.23	264.0 ± 15.0
6	0.000382 ± 0.000382	0.049400 ± 0.000370	10.75	11.28	13.02	17.96 ± 1.38	237.6 ± 17.1
7	0.000295 ± 0.000262	0.052740 ± 0.000371	13.2	8.7	13.68	17.31 ± 1.47	229.6 ± 18.3
8	0.000758 ± 0.000300	0.054881 ± 0.000539	102	22.35	12.82	14.14 ± 1.56	189.7 ± 19.8

analytical precision at 2σ, assuming that the errors in the ages of the flux monitors are zero. This technique is suitable for comparing within-spectrum variation and determining which steps form a plateau (McDougall and Harrison 1988, p. 89). A conservative estimate of this error in the J-value is 0.5 % and can be added for inter-sample comparison.

We note that several samples of zeolite material were prepared and analyzed, but the results were not successful and therefore are not reported here. This unsuccessful attempt is in keeping with the conclusions of others (Dalrymple and Lanphere 1969).

ANALYTICAL RESULTS

The analytical results are given in Table 1 and shown graphically in Figure 3. For each sample the plateau age (PA), where appropriate, integrated age (IA), and correlation age (CA; isochron method) are given, following the normal procedures in $^{40}Ar/^{39}Ar$ dating (McDougall and Harrison 1988).

The results of analysis of sample ZL-99-26 from Parker Cove quarry yield a flat age spectrum with 85% of the gas released defining a plateau of 201.3 ± 2.3 Ma (MSWD = 0.5). In addition, the uniform Ca/K ratios for the release spectrum of the plateau indicate gas was liberated from a chemically uniform reservoir. As expected, the correlation age of 200 ± 2.9 Ma (MSWD = 0.3; Table 1, Fig. 3a) is essentially identical to the plateau age. The slightly younger integrated age of 199.2 ± 2.3 Ma reflects an anomalously low age for the lowest temperature fraction (Table 1), but interestingly, is significantly older than the equivalent whole-rock K-Ar ages for the NMB noted earlier. We adopt an age of 201 ± 2.5 Ma for this sample. Results for this sample indicate a simple thermal history with no overprinting thermal event, consistent with the very fresh nature of the sample.

The results for sample ZL-99-36, from a zeolite-bearing MFU horizon, yielded a very disturbed age spectrum (Table 1, Fig. 3b). Seven of the eight steps, comprising 87% of the release spectrum, record ages in excess of the known extrusion age of ca. 200 Ma. The hump-type pattern, with a maximum age of 380 Ma for the low temperature steps, is a classic example of combined excess argon and recoil effects (McDougall and Harrison 1988; Lo and Onstott 1989). The remaining steps gave progressively lower ages, but only the final step, the last 13% of the gas release, has an age (i.e., 190 Ma) that is similar to that for the fresh sample. Although the integrated age of 276.2

± 9.2 Ma is clearly too old, the correlation age of 206.5 ± 55.9 Ma (MSWD = 0.36), albeit with a large error, approximates the age of NMB extrusion. As expected, the initial $^{40}Ar/^{36}Ar$ ratio of 730 is well in excess of that for atmospheric argon (i.e, 295.5; Dalyrmple and Lanphere 1969) and contrasts markedly with the near-atmospheric $^{40}Ar/^{36}Ar$ ratio of 302 ± 14 for sample ZL-99-26.

DISCUSSION AND CONCLUSIONS

Age of basalt extrusion

The results of $^{40}Ar/^{39}Ar$ analysis for LFU sample ZL-99-26 indicate an age of 201 ± 2.5 Ma, which is identical to the U-Pb zircon age of 202 ± 1 Ma obtained by Hodych and Dunning (1992) for a LFU sample, and both are coincident within error of the Triassic-Jurassic boundary (200 ± 1 Ma, Okulitch 2002). Clearly these results indicate that the $^{40}Ar/^{39}Ar$ age is credible and that argon has not been mobile within this sample since rock formation. The very fresh nature of the dated sample, with no evidence of low-temperature alteration phases, is consistent with the lack of any disturbance suggested from the flat age spectrum. Thus, this result reinforces the importance of using the freshest possible samples for whole rock $^{40}Ar/^{39}Ar$ analysis and also indicates that very reliable ages are obtainable for basalt and dyke samples throughout the Newark Supergroup and CAMP.

Both the sample from this study and that used for U-Pb study by Hodych and Dunning (1992) come from the LFU and the concordant ages for chronometers with drastically different closure temperatures indicate rapid post-crystallization cooling of the basalt. The coincidence of these chronometers and implication of rapid post-eruption cooling of the basalt sequence based on estimated cooling times (Papezik *et al.* 1988) are consistent with the inferred duration of 580 ka for the Mesozoic basaltic magmatism in the Newark Supergroup (Olsen and Fedosh 1988; Olsen 1997). We have no reason to doubt the younger ages reported earlier for the NMB (Carmichael and Palmer 1968; Hayatsu 1979); however, given the presence of alteration within these rocks it may be that this phenomenon is more significant than realized. Similar discrepancies are noted elsewhere in the Newark Supergroup of Atlantic Canada and New England. For example, the U-Pb zircon and baddeleyite ages of 201 Ma for the Palisades and Gettysburg sills obtained by Dunning and Hodych (1990) contrast with variably younger ages obtained using the K-Ar and $^{40}Ar/^{39}Ar$ methods (Erickson and Kulp 1961; Dallmeyer 1975), whereas K-Ar ages of 191 Ma and 201 Ma reported for the Avalon dyke in Newfoundland depend on sample location (Hodych and Hayatsu 1980, 1988) and the recent $^{40}Ar/^{39}Ar$ age of 202 ± 4 Ma (Dunn *et al.* 1998) for the Shelburne dyke, Nova Scotia, exceeds an earlier 193 ± 4 Ma K-Ar age (Hodych and Hayatsu 1988).

Although there are clearly age discrepancies among the data for the basaltic magmatism of the Newark Supergroup, the $^{40}Ar/^{39}Ar$ age of 201 Ma for the NMB is similar to other radiometric ($^{40}Ar/^{39}Ar$, U-Pb) ages for basalts and dyke rocks from the Central Atlantic Magmatic Province (CAMP; Marzoli *et al.* 1999, 2003; Rapaille *et al.* 2003) and Jurassic basalts and dyke rocks from eastern North America (e.g., Dunning and Hodych 1990; Hodych and Dunning 1992; Sebai *et al.* 1991; West and McHone 1997; Dunn *et al.* 1998; Marzoli *et al.* 1999; McHone 2003). We also note that the age for the NMB is within error of $^{40}Ar/^{39}Ar$ ages of 209 ± 6 and 203 ± 15 Ma obtained on alkaline mafic dykes from the Plymouth area of southwestern Nova Scotia (Pe-Piper and Reynolds 2000).

Origin of the younger ages of ca. 190 Ma and possible relationship to zeolite formation

Although it is not the intent of this paper to provide an absolute age for zeolite mineralization, we offer an interpretation of the younger K-Ar ages in the context of zeolite formation. Firstly, it is important to note that zeolites are found not only within the thin flows of the MFU, but also lining fractures and infilling veins within the overlying UFU and sedimentary rocks of the McCoy Brook Formation, and as veins cross-cutting sedimentary dykes within flows of the MFU (Kontak 2000; Kontak and Kyser 2003). Thus, zeolite formation post-dated eruption of the NMB sequence and deposition of the overlying Jurassic sediments.

Analysis of both the whole-rock samples and zeolite minerals (data not reported here) by the $^{40}Ar/^{39}Ar$ method proved to be unsuccessful in terms of obtaining meaningful absolute ages. In the case of the zeolites, our results are consistent with those of previous workers who have also noted considerable post-crystallization mobility of argon from zeolite minerals, which relates to the sieve-like nature of these minerals (Dalrymple and Lanphere 1969). The presence of excess argon in sample ZL-99-36 (Fig. 3b), resulting in an age in excess of NMB eruption, was also noted in some analyzed Jurassic flows of the Newark Supergroup (Seidemann *et al.* 1984; Seidemann 1988). These anomalously older ages maybe related to one or both of: (1) recoil effects due to the presence of K-free chloritic phases in the altered samples that are synchronous with zeolite formation (Kontak 2000), or (2) incorporation of excess argon during post-eruptive alteration attending zeolite formation. The low potassium contents of the NMB flows (i.e., 0.5 wt. % K_2O) make these rocks susceptible to excess argon in the form of fluid inclusions formed during hydrothermal alteration (Kelley 2002). However, given that ages exceeding basalt eruption are not commonly reported for the Newark Supergroup (e.g., in McHone 2003), the processes leading to excess argon were evidently not common. Instead, it is the younger ages, notably around ca. 190 Ma, that are common, as alluded to previously, which is coincident with the 192 Ma apatite fission track ages reported by Cox *et al.* (2001) for samples from the NMB and also the Newark Supergroup. The question we pose here is whether this similarly is fortuitous or meaningful?

Although speculative, we note the coincidence of the ca.190 Ma age obtained by numerous workers, including both K-Ar and $^{40}Ar/^{39}Ar$ methods, which argues in favour of a widespread thermal event. Given that development of zeolites in the NMB is widespread and that the mineral assemblage records elevated temperatures (Kontak 2000; Pe-Piper 2000), the ages may in fact record the infiltration of the fluid related to this event. Clearly a more precise age of zeolite formation is required; nevertheless, the ca. 190 Ma age recorded by several independent studies must reflect a thermal event and timing of this event would be consistent with zeolite formation constrained from field relationships. That similar younger ages are extensively reported for basalt of the Newark Supergroup throughout eastern North America may indicate that this 190 Ma age records a widespread reheating event. Based on the ca. 192 Ma plateau ages for the Palisades Sill, Dallmeyer (1975) interpreted the data to indicate either the time of crystallization or resetting by a thermal event; clearly the latter would be a more consistent interpretation based on the 201 Ma age for this sill based on U-Pb dating (Dunning and Hodych 1990).

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