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# IMPLICATIONS OF RE-ASSESSED $^{40}Ar/^{39}Ar$ AND K-Ar GEOCHRONOLOGICAL DATA FOR GRENVILLIAN OROGENESIS IN THE EASTERN GRENVILLE PROVINCE

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## ABSTRACT

*Previously published $^{40}Ar/^{39}Ar$ and K–Ar ages from the eastern Grenville Province and its northern hinterland reveal a hitherto mostly unrecognized systematic thermochron pattern, which is now capable of robust interpretation in the context of recent geological mapping and complementary U–Pb geochronological studies.*

*North of the Grenville front, K–Ar data map out a 200-km-wide, north-northwest-trending corridor preserving ages between 1500 and 1000 Ma, interpreted here to be related to Elsonian (1460 to 1230 Ma) anorthositic and related magmatic events. On either side of this corridor, K–Ar ages can be linked to Labradorian (1710 to 1600 Ma) overprinting of older orogenic belts.*

*The Grenville front, as it is currently placed, correlates with a muscovite composite $^{40}Ar/^{39}Ar$ and K–Ar 1000 Ma thermochron. A more significant feature, however, from the perspective of Grenvillian K–Ar thermal history, trends parallel to, but south of the Grenville front, except at its eastern end, where it turns southeast parallel to a recognized terrane boundary. This is a 1000 Ma thermochron, which can be fixed in the same position regardless of whether based on $^{40}Ar/^{39}Ar$ or K–Ar data, plateau or total-gas ages, or hornblende or biotite mineral data; it is here termed the Grenvillian thermal threshold (GTT). South of the GTT, with the exception of a few anomalies, all $^{40}Ar/^{39}Ar$ or K–Ar dates are Grenvillian. North of the GTT, progressively increasing Ar loss is evident as the threshold is approached. A 900 Ma composite biotite–hornblende thermochron can be delineated, parallel to and south of the GTT. The thermochron configuration, especially its easternmost change in orientation, can be explained in terms of Grenvillian thrust-ramp geometry, whereby the southeast-trending thermochrons mark the northeastern lateral-ramp limit of Grenvillian allochthonous terranes that were transported on frontal ramps to the northwest. The thermochron pattern correlates with established structural and geophysical trends, and has a systematic spatial relationship to Grenvillian plutons. The lateral-ramp model has far-reaching implications, especially toward improved understanding of the severity of pre-Grenvillian metamorphism and in interpreting offshore geological extrapolations, of both pre- and post-Grenvillian age.*

## INTRODUCTION

The purpose of this communication is to review published $^{40}Ar/^{39}Ar$ and K–Ar data from the eastern Grenville Province to enhance understanding of Grenvillian orogenesis and late- to post-Grenvillian thermal history. The review is presented within the context of a recently constructed tectonic and geochronological framework for the eastern Grenville Province established through geological mapping, concomitant U–Pb radiometric studies (Gower and Krogh, 2002a, b) and offshore seismic reflection studies (Gower *et al.*, 1997). In the absence of $^{40}Ar/^{39}Ar$ data and only sparse K–Ar data from interior and southern regions, this evaluation is focussed on the northern part of the eastern Grenville Province.

### GEOLOGICAL SETTING

The eastern Grenville Province comprises pre-Labradorian (>1710 Ma, but mostly1800 to 1770 Ma), Labradorian (1710 to 1600 Ma) and Pinwarian (1520 to 1460 Ma) magmatic and metamorphic rocks, onto which Grenvillian (1080 to 985 Ma) orogenesis of variable intensity has been superimposed. The only major post-Grenvillian events were the formation of the Lake Melville rift system and emplacement of the 615-Ma Long Range dykes, both of which are related to the initial stages of Iapetus Ocean formation. The term ‘Grenvillian’ is used here more restrictively in a time sense than in some other parts of the Grenville Province. The geological history of the eastern Grenville Province has been thoroughly reviewed by Gower and Krogh (2002a, b).

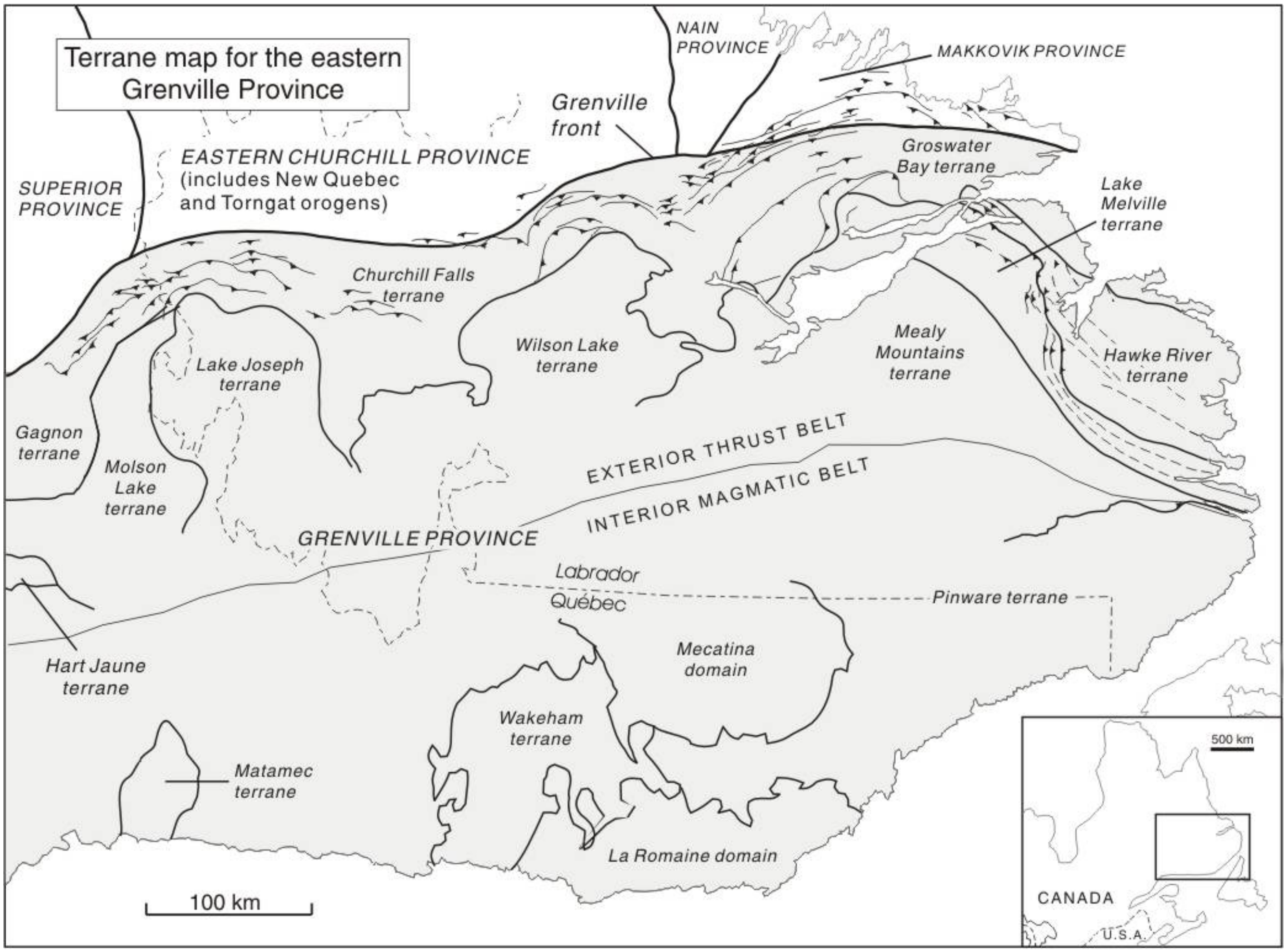


**Figure 1.** *Structural subdivision of the eastern Grenville Province.*

The eastern Grenville Province has also been subdivided into various terranes (Figure 1). These are not regarded as 'suspect' in a tectonic sense. They are distinguished on the basis of contrasting rock types, faulted boundaries, and differing geochronological histories, and have both pre-Grenvillian and Grenvillian tectonic significance (*see* Gower and Krogh, 2002a, b).

## REGIONAL SYNTHESIS OF $^{40}Ar/^{39}Ar$ DATA

The regional synthesis given below utilizes data delivered by Archibald and Farrar (1979), Dallmeyer (1980, 1982a, b, 1987), Dallmeyer and Rivers (1983), Owen *et al*. (1988), van Nostrand (1988), Reynolds (1988), Reynolds *et al.* (1989), Connelly (1991), Wilton (1996) and Culshaw *et al.* (2002). The latter two publications contain age data solely from the Makkovik Province; all of the remainder either report data from the eastern Grenville Province, or the eastern Grenville Province and adjacent areas to the north.

Given differing blocking temperatures, the most sensible approach was deemed to be one that depicted data spatially according to the mineral analyzed. Ages for hornblende, biotite and muscovite (or muscovite-dominated whole-rock analyses) are thus presented in Figures 2, 3 and 4, respectively, although further mention of the Ar muscovite data in the text is delayed until K–Ar muscovite data are addressed.

As a visual aid in discussing the spatial distribution of $^{40}Ar/^{39}Ar$ dates, the data are graphed in Figure 5. The graphs plot age versus distance into the Grenville orogen from an arbitrary starting point and have been constructed by projecting dates normally onto a single line in each of the three areas. As near as is practical, the lines are positioned to be at right angles to the structural grain in each of the three areas. This involves dog-leg changes in trend in western and eastern Labrador. In central Labrador, the data were simply projected onto a north–south line. Particularly in the case of the

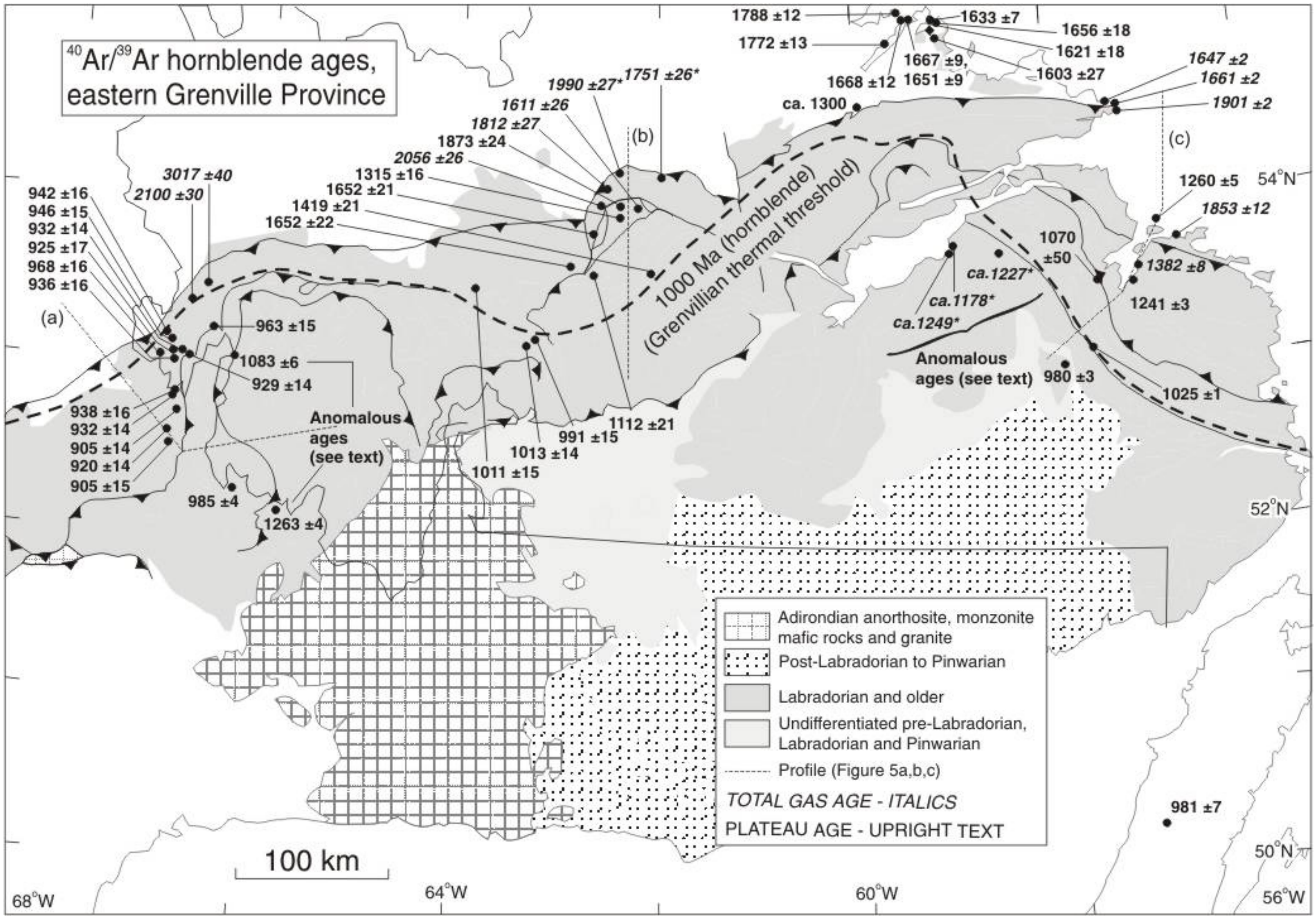


**Figure 2.** *Summary of $^{40}Ar/^{39}Ar$ hornblende data for the eastern Grenville Province and fringe area to the north. Ages with asterisk are averages of duplicates. The 1000 Ma thermochron (Grenvillian thermal threshold) is indicated.*

central Labrador profile, questions can be raised regarding how much the projected position should reflect detailed variations in structural trend between the dated site and the line. In the interests of strict spatial objectivity and being mindful that field interpretations are commonly subject to revision, the most straightforward approach was adopted, namely projection normal to the indicated lines. Whatever method is chosen, the depiction is similar and the derived interpretation little changed.

The key feature that will be emphasized throughout the remainder of this communication is that the $^{40}Ar/^{39}Ar$ hornblende and $^{40}Ar/^{39}Ar$ biotite data both show clearly a 1000 Ma thermochron (a thermochron is defined as an equal-age contour, considered to be temperature dependent; Harper, 1967) dividing an area in the north characterized by pre-Grenvillian dates and an area to the south comprising Grenvillian ages. This boundary, which does not coincide with the Grenville front, is plotted in Figures 2 and 3 ($^{40}Ar/^{39}Ar$ hornblende and biotite data, respectively), and referred to subsequently as the Grenvillian thermal threshold (GTT). This term is defined here as the generalized limit of complete mineral resetting to Grenvillian ages in the K/Ar isotopic system. The line utilizes the flexibility permitted by precision errors rather than rigidly accepting nominal ages (e.g., 1013 ± 14 Ma can be validly be considered <1000 Ma), and disregards some anomalies (the latter are, however, discussed subsequently in context). Observe that GTT threshold is drawn in the same location, regardless of whether it is $^{40}Ar/^{39}Ar$, plateau or total-gas, hornblende or biotite data being considered (or K–Ar analogues, as will be demonstrated later). The number of $^{40}Ar/^{39}Ar$ muscovite ages is insufficient to allow examination in this way; but the data are addressed collectively with K–Ar muscovite results later. Note also that the Grenvillian thermal threshold shows a marked inflection point in eastern Labrador, changing from an east-northeast to southeast direction. This is fundamental in understanding Grenvillian tectonic evolution in the eastern Grenville Province, as addressed in the final discussion.

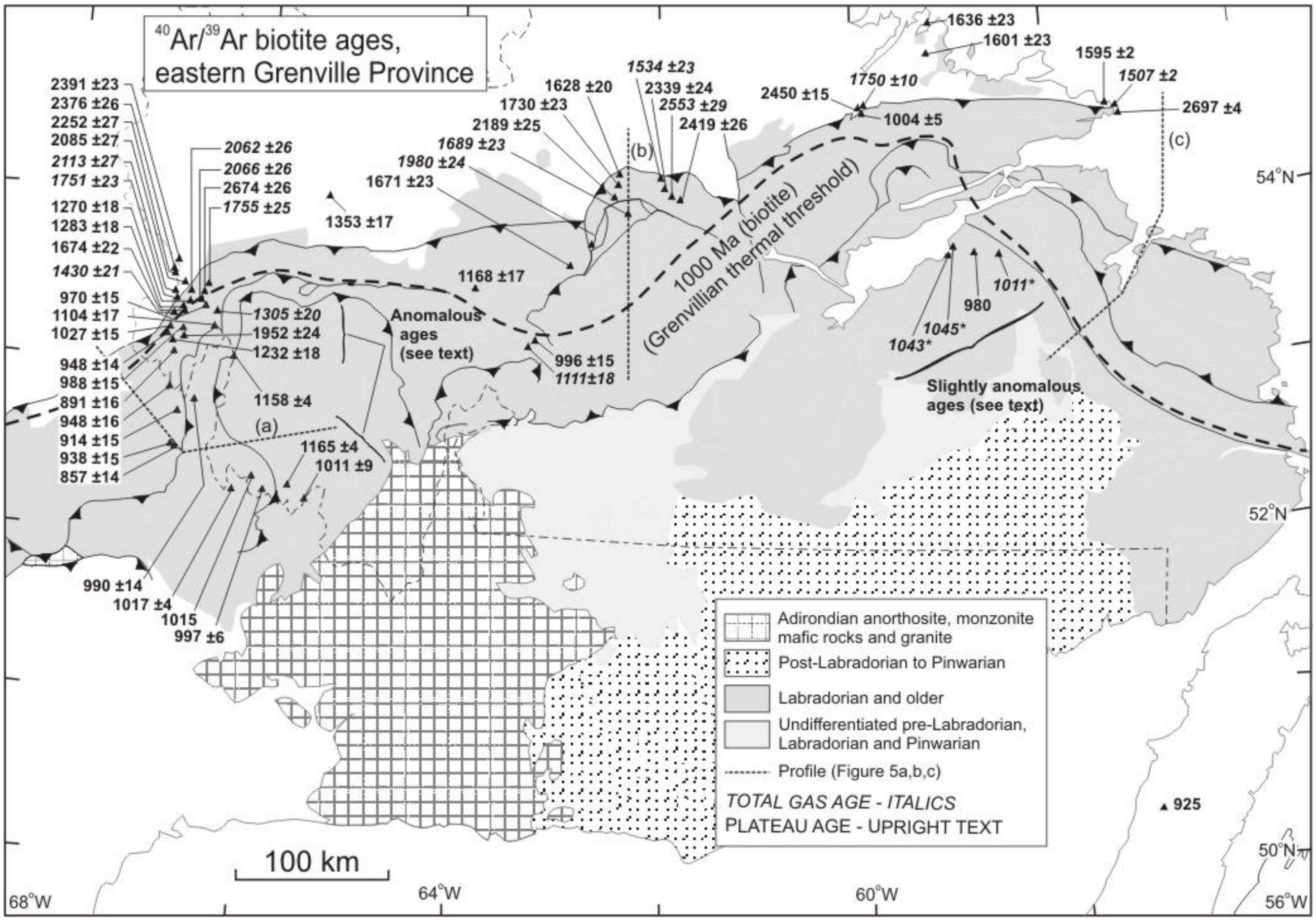


**Figure 3.** *Summary of $^{40}$Ar/$^{39}$Ar biotite data for the eastern Grenville Province and fringe area to the north. Ages with asterisk are averages of duplicates. The 1000 Ma thermochron (Grenvillian thermal threshold) is indicated.*

## NORTH OF THE GRENVILLIAN THERMAL THRESHOLD

North of the Grenvillian thermal threshold, the spatial pattern of dates varies according to location. In western Labrador, the dates show a regular decrease from 2400 Ma to 1000 Ma from northwest to southeast, as has already been observed by Dallmeyer (1982b) and Dallmeyer and Rivers (1983). The pattern is independent of the rock dated, which includes rock types assigned to the Ashuanipi Metamorphic Complex, metasediments of the Knob Lake Group and the Shabogamo gabbro. Dallmeyer and Rivers (1983) attributed pre-Grenvillian ages in many samples to excess Ar, but subsequent mapping (van Gool, 1992), and the patterns discerned as a result of this study, suggest that Ar-gain may have played a much less significant role than Dallmeyer and Rivers (*op. cit.*) supposed. It is argued here that the systematic decrease in ages, as the Grenvillian thermal threshold is approached, can generally be explained better in terms of Ar loss, such that the Ar ages systematically decline to the 'ambient Ar loss' for that portion of the transect, as a result of Grenvillian orogenesis. Note that the Grenvillian thermal threshold in western Labrador, which is the only area where data are sufficient to draw a conclusion, is a regionally narrow band, probably only about 20 km wide.

Anomalous behaviour, from the pattern described above, of two Ar–hornblende ages (3017 ± 40 Ma and 2100 ± 30 Ma) and four spatially related Ar–biotite ages (2674 ± 30 Ma, 2066 ± 26 Ma, 2062 ± 26 Ma and 1755 ± 25 Ma), grouped separately from the remaining Ar–hornblende and biotite ages in Figures 2 and 3, begged close examination of the original data for these samples. One hornblende and three biotite results come from rocks interpreted to belong to Archean tectonic inliers (cf. Rivers and Massey, 1985), the boundaries of which were much expanded by van Gool (1992). The only sample of the group for which Ar-gain possibly needs to be invoked is that yielding a result of 3017 ± 40 Ma (note that the highest-temperature segment of the spectra yielded a date of 2690 ± 41 Ma, which is more in keeping with the probable age of the rock). The four results are encircled in Figure 5a, and annotated as 'Archean tec-

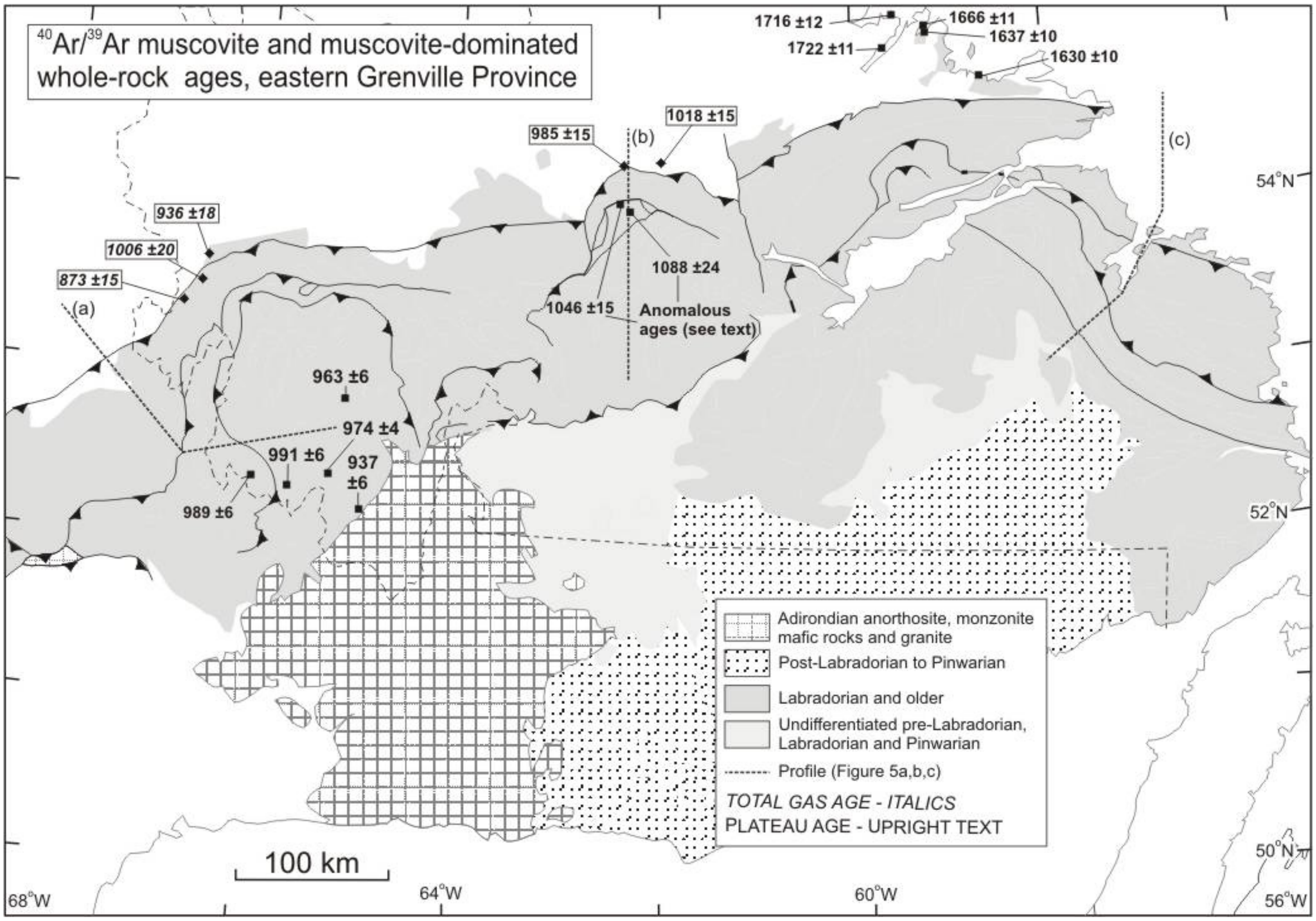


**Figure 4.** *Summary of $^{40}Ar/^{39}Ar$ muscovite and muscovite-dominated whole-rock data for the eastern Grenville Province and fringe area to the north. Whole-rock data in boxes.*

tonic inliers'. The remaining two results of 2100 ± 30 Ma (hornblende) and 1755 Ma (biotite) both come from a single sample ('Shabogamo' gabbro in Figure 5a) that was mapped as Shabogamo gabbro by Rivers and Massey (1985). Unpublished whole-rock geochemical data obtained by Rivers (on file at the Newfoundland and Labrador Department of Mines and Energy) for the same sample demonstrates that this rock is compositionally distinct from the 1450 Ma Shabogamo gabbro (Figure 6). If it belongs to a different (older) unit, then the implied constraint that the date must reflect excess Ar is removed.

In central Labrador, north of the Grenvillian thermal threshold in the Churchill Falls terrane, $^{40}Ar/^{39}Ar$ data have been obtained from four rock types, namely, (i) mildly deformed North Pole Brook granitoid rocks (the local name for this part of the 1654 to 1646 Ma Trans-Labrador batholith), (ii) blastomylonitic granitic gneiss, considered to have been derived from North Pole Brook intrusive suite, (iii) amphibolite in paragneiss, and (iv) amphibolite (Dallmeyer, 1987). No U–Pb data have been obtained on any of these samples. The $^{40}Ar/^{39}Ar$ ages show considerable scatter, which is not explicable as an artifact of an oversimplified plotting procedure in generating Figure 5b. Most of the samples are from the Trans-Labrador batholith, and it is noteworthy that $^{40}Ar/^{39}Ar$ dates obtained are either approximately the same age as the batholith or are older. To explain the pre-Trans-Labrador batholith ages, appeal has been made to excess Ar (Dallmeyer, 1987). Other possibilities, such as the rocks actually being older but erroneously assigned stratigraphically, or the presence of severe contamination by older rocks, are not supported by regionally related U–Pb, Rb–Sr or Nd–Sm data. One pertinent observation is that the three oldest biotite ages (Figure 5b) are from localities closest to the Archean Nain Province. Whether this is geologically significant can only be determined by more detailed sampling. In the Wilson Lake terrane, the data show a systematic decrease in age progressing southward to the Grenvillian thermal threshold, comparable to the pattern recorded in western Labrador. For the southernmost samples in this region, the errors assigned permit them to be on either side of the Grenvillian thermal threshold, and an alternative

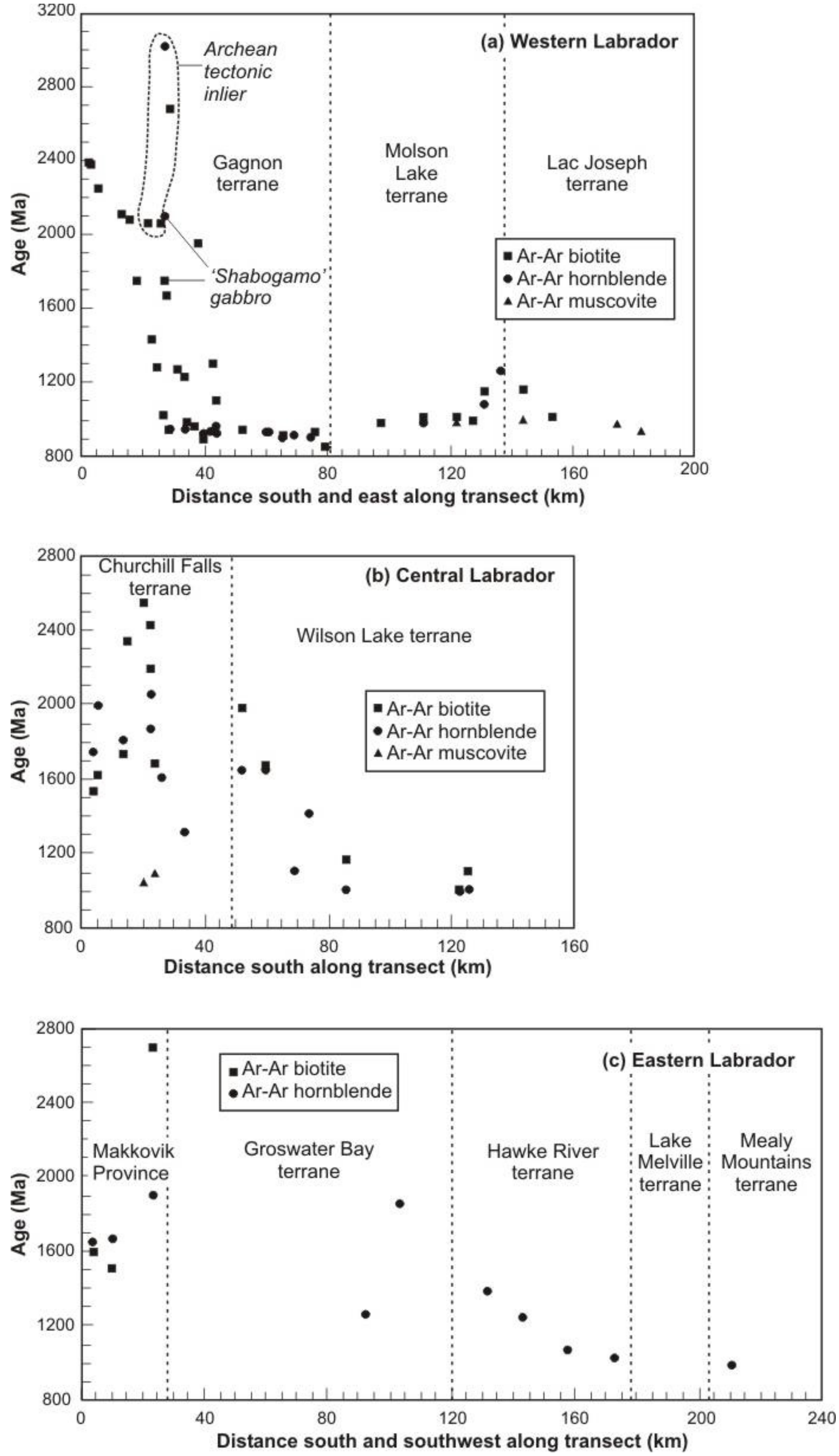


**Figure 5.** *Profiles for $^{40}Ar/^{39}Ar$ ages (plateau and total-gas) projected onto a line constructed normal to structural trend; a) western Labrador, b) central Labrador, c) eastern Labrador. Locations of profiles given in Figures 2, 3 and 4.*

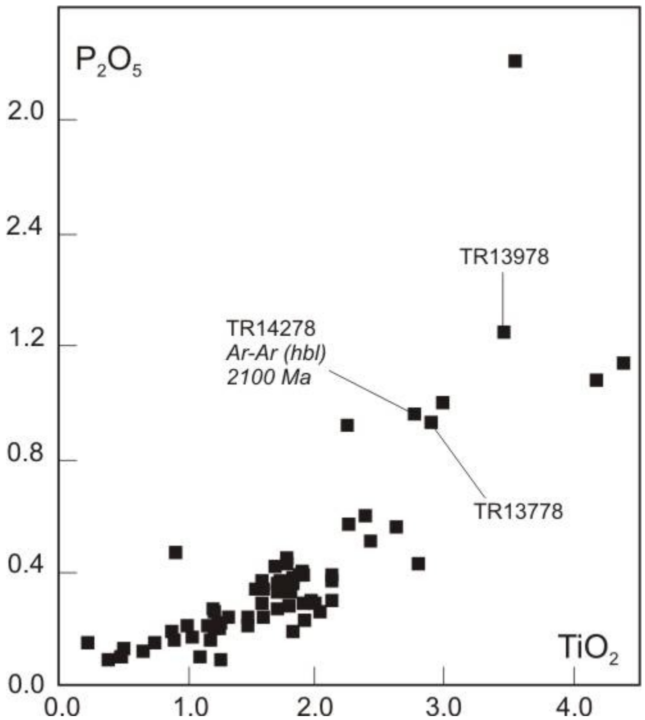


**Figure 6.** *$TiO_2$ versus $P_2O_5$ geochemical variation diagram for rocks mapped as Shabogamo gabbro. The purpose of the diagram is to suggest that sample TR14278 and two other spatially related samples (TR13978 and TR13778) may not belong to this suite (or, indeed, the other high $P_2O_5$ samples, which are from sites farther northeast). If TR14278 is not Shabogamo gabbro, then the implication is removed that the 2100 Ma Ar/Ar total-gas date obtained from this sample must reflect excess argon.*

position for the boundary could be somewhat farther north, where there is a more distinct time break between pre-1350 Ma and post ca.1100 Ma dates. Although departing from the 1000 Ma thermochron concept, such a boundary might better represent a real, and perhaps older Grenvillian thermal threshold in this region. The positioning of the dates (as opposed to their locations) is intended to illustrate this thought.

In eastern Labrador, the Grenvillian thermal threshold excludes the Makkovik Province, Groswater Bay terrane and Hawke River terrane as regions that have experienced a marked Grenvillian metamorphism. Data from the Makkovik Province conclusively demonstrates lack of Grenvillian effects, instead showing Labradorian thermal overprint onto older Paleoproterozoic rocks. In the profile for eastern Labrador (Figure 5c), the only $^{40}Ar/^{39}Ar$ data from the Makkovik Province plotted is that immediately north of Smokey (Owen *et al.*, 1988), but it should be noted that similar Labradorian $^{40}Ar/^{39}Ar$ ages have been reported by Archibald and Farrar (1979), Wilton (1996) and Culshaw *et al.* (2002) from farther west in the Makkovik Province (cf. Figures 2 to 4). The U–Pb ages from north of Smokey are consistent with Ar results from the same area in demonstrating lack of marked Grenvillian overprint. These data include a 1726 ± 34 Ma post-emplacement titanite age from a K-feldspar megacrystic granitoid rock, and a melt pod in the Cutthroat Island mylonite zone (Smokey area) having a post-deformational titanite age of 1662 ± 10 Ma (Krogh, 1994; Krogh *et al.*, 2002).

At the Grenville front, an anomalously old total-gas hornblende age of 1901 ± 2 Ma and a biotite plateau age of 2697 ± 4 Ma, both from the same monzodiorite, are attributed to excess Ar (Owen *et al*., 1988). In the case of the hornblende date, the amount of excess Ar need not be great as the protolith age of the rock at this locality is probably not greatly different. Krogh *et al.* (2002) obtained a zircon age of 1799 +3/-2 Ma from a granodioritic gneiss only four kilometres farther south and which is grouped as part of the same unit (White Bear Island granulite complex), for which Owen *et al.* (1988) had previously interpreted a ca. 2.0 Ga age from Rb–Sr data. Appeal to excess Ar was made to explain results from localities south of the Makkovik Province farther west by Archibald and Farrar (1979), who obtained Ar biotite results of 2450 ± 15 Ma and 1750 ± 10 Ma from a granodiorite, for which a Trans-Labradorian age (1650 Ma) is most probable (Figure 3).

Very sparse $^{40}Ar/^{39}Ar$ data from the Groswater Bay terrane prevent any conclusions on whether or not this region should be classified as north of the Grenvillian thermal threshold based on these results alone. Nevertheless, when K–Ar data from the Groswater Bay terrane and $^{40}Ar/^{39}Ar$ data from the Hawke River terrane are evaluated (topics addressed later), and taken in conjunction with Grenvillian Pb-loss patterns in zircon and titanite (Gower and Krogh, 2002a), a good case can be made that these regions escaped severe Grenvillian metamorphism. The only $^{40}Ar/^{39}Ar$ results from the Groswater Bay terrane are a total-gas age of 1853 ± 12 Ma and a plateau age 1260 ± 5 Ma (van Nostrand, 1988). Both localities have been investigated by other geochronological techniques. The site from which the (very discordant) 1853 ± 12 Ma result was obtained yielded an Rb–Sr whole-rock errorchron of 1610 ± 50 Ma and a Sm–Nd whole-rock age of 1681 ± 186 Ma, so the low-temperature part of the spectra (around 2100 Ma) could well reflect excess argon, whereas the high-temperature part (between 1700 and 1600 Ma) might be the time of pre-Grenvillian (i.e., Labradorian) emplacement or metamorphism. In any case, there is no evidence of resetting to a Grenvillian age. The 1260 Ma result is from an amphibolite dyke having an age between 1658 Ma and 1499 Ma (U–Pb zircon ages of host rock and younger pegmatite at the outcrop). The total-gas age for this sample is 1337 ± 6 Ma (van

Nostrand, 1988). The 1260 Ma date was interpreted by van Nostrand (1988) as due to thermal reheating, but regional U–Pb data do not provide any evidence of such an event (Gower and Krogh, 2002b), so incomplete Ar-loss seems an alternative, equally viable explanation.

Moving farther southwest into the Hawke River terrane, all of the $^{40}Ar/^{39}Ar$ hornblende dates in the Hawke River terrane postdate emplacement ages but predate time of Grenvillian metamorphism. Decreasing ages progressing southwest are evident (Figure 5c), and are attributed here to increasing Ar loss as the Grenvillian thermal threshold is approached. High-grade Grenvillian metamorphism in the Hawke River terrane in districts distal from the Lake Melville terrane is also denied by Labradorian U–Pb titanite ages (cf. Gower and Krogh, 2002a), lending support to the conclusion that the Ar hornblende ages record Ar loss. A previous suggestion (e.g., van Nostrand, 1988; Gower, 1996) that the ca. 1260 to 1240 Ma dates might represent a genuine thermal event in the eastern Grenville Province, approximately correlative with the 1230 to 1180 Ma Elzevirian orogeny of the southwest Grenville Province, requires re-evaluation.

The Lake Melville terrane poses a special case. The Grenvillian thermal threshold could be positioned at the Hawke River–Lake Melville terrane boundary, despite the only two Ar hornblende dates from the Lake Melville terrane (Figure 2) both predating 1000 Ma (even when precision latitude is considered). The U–Pb data clearly show that Grenvillian metamorphism in the Lake Melville terrane occurred earlier than in other regions in the eastern Grenville Province (Gower and Krogh, 2002b). Zircon and monazite data indicate high-grade metamorphism between 1080 and 1040 Ma, and titanite ages demonstrate cooling after 1040 Ma, with which the ca. 1020 Ma Ar–hornblende ages are therefore in complete accord. In short, the Grenvillian thermal threshold can be legitimately placed at the Hawke River–Lake Melville terrane boundary, although the 1000 Ma thermochron is better positioned at the Lake Melville–Mealy Mountains terrane boundary. For quantitative consistency, the latter approach has been adopted in the figures, possibly at the sacrifice of some conceptual consistency.

## SOUTH OF THE GRENVILLIAN THERMAL THRESHOLD

South of the Grenvillian thermal threshold, the patterns are broadly similar across Labrador, i.e., having ages between 1000 and 900 Ma, independent of distance from the Grenville front. However, closer examination of the data reveals pertinent details.

In western Labrador, $^{40}Ar/^{39}Ar$ hornblende ages decrease progressively across the Gagnon terrane from ca. 960 to 905 Ma (Figure 5a), as has been previously noted by Dallmeyer and Rivers (1983). According to Ar blocking-temperature theory, biotite ages should define a line below that for hornblende. This is not the case in western Labrador. Dallmeyer and Rivers (1983) reported that 4 of 5 hornblende–biotite pairs delivered dates from biotite older than those from hornblende, concluding that the biotite ages are unreliable and must be explained by excess Ar. Although not rejecting the excess Ar argument, the consistency evident from the analysis presented here, which indicates that both hornblende and biotite ages show the same pattern (albeit with more 'noise' in the biotite data), suggest that both minerals have similar regional thermochron validity. Moving into the Molson Lake terrane and including data obtained by J. Hanes (reported by Connelly, 1991), the $^{40}Ar/^{39}Ar$ dates jump from 905 to 990 Ma, and show very little variation across the width of the terrane. A similar horizontal pattern is evident in the Lac Joseph terrane, except near its fringe, where pre-Grenvillian dates are represented, including a 1263 ± 4 Ma hornblende plateau age from a partially melted amphibolite-facies Labradorian mafic gneiss. Inasmuch as the same sample yielded a 1281 Ma U–Pb titanite age, the pre-Grenvillian dates in the area cannot be dismissed as spurious, but remain unexplained.

In central Labrador, south of the Grenvillian thermal threshold, $^{40}Ar/^{39}Ar$ data are scarce. Two blastomylonitic granitic gneisses derived from a Labradorian protolith in the southern Churchill Falls terrane, yielded hornblende plateau ages of 1013 ± 13 and 991 ± 15 Ma, and biotite ages from the same samples respectively 1111 ± 18 Ma (total-gas) and 996 ± 15 Ma (plateau). Even accepting shortcomings in the biotite total-gas age and being cognizant of precision errors, it is acknowledged that the Grenvillian thermal threshold could be positioned farther south in this area (in part, anticipating K–Ar data reviewed later).

In eastern Labrador, the 1249 to 1178 Ma hornblende total-gas ages obtained from Mealy dykes by Reynolds (1989) are also anomalously old for samples south of the Grenvillian thermal threshold but these data are consistent with K–Ar dates (*see below*) from the host Labradorian Mealy Mountains intrusive suite that are also are pre-Grenvillian. It has been observed in several publications (originally by Emslie *et al.*, 1984) that the core of the Mealy Mountains intrusive suite lacks evidence of Grenvillian deformation or regional metamorphism. This characteristic is not completely understood, but could be attributed to resistance of anorthosites to strain, which, in turn, would deny fluid ingress and inhibit resetting of Ar ages. Two ages of 980 Ma from the Mealy Mountains terrane (one biotite

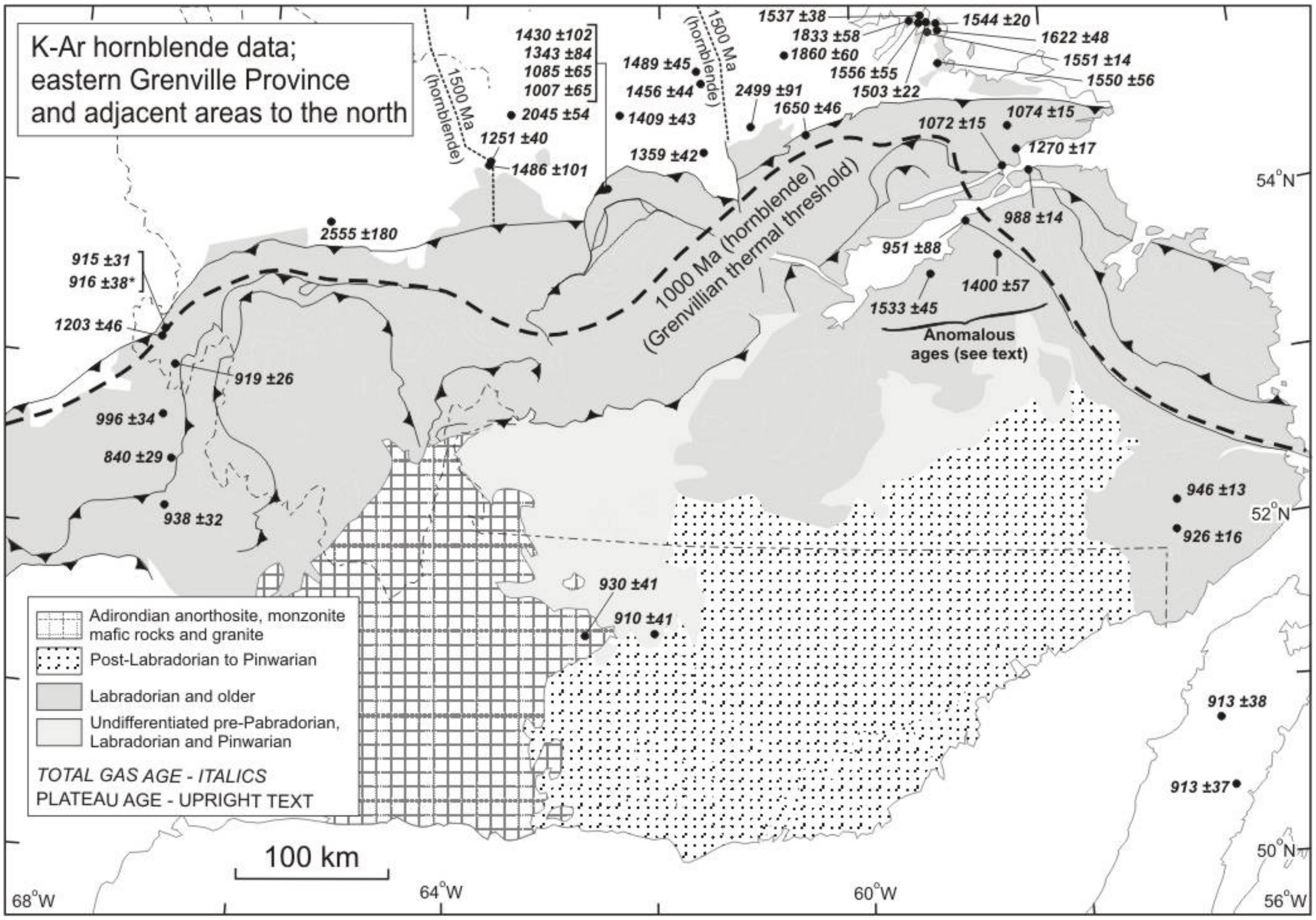


**Figure 7.** *Summary of K–Ar hornblende data for the eastern Grenville Province and adjacent areas to the north.*

within and one hornblende outside the Mealy Mountains intrusive suite) are consistent with K–Ar biotite data (*see below*) and may be a better indication of Grenvillian thermal effects in this part of the Mealy Mountains terrane. They echo a 40-million-year contrast in time of metamorphism between the Mealy Mountains and Lake Melville terranes evident from U–Pb data.

## RE-EVALUATION OF K–Ar GEOCHRONOLOGICAL DATA

Because of new insights arising from a synthesis of available $^{40}Ar/^{39}Ar$ data, it was decided that review of K–Ar data was merited, despite this already having been attempted a few times previously (Harper, 1967; Baer, 1976; Easton, 1986). Following the pattern for $^{40}Ar/^{39}Ar$ data, K–Ar geochronological data for hornblende, biotite and muscovite data are depicted separately on Figures 7, 8 and 9. Two nepheline results and one whole-rock anorthosite date have been excluded from this review, as have whole-rock K–Ar data and one biotite result from mafic intrusions. In particular, the dates from mafic intrusions could reflect emplacement and cooling long after regional metamorphism, hence are not directly pertinent to the topic addressed here. The reader is alerted that several errors have been detected in the original publications, especially with respect to locations; these will be reported elsewhere. Corrections have been made after checking against original records or with their authors, although one interesting problem (an anomalous 1242 Ma date; expanded on below) remains unresolved. The ages have been adjusted, if needed, from those reported in their original publications in accordance with currently accepted decay constants.

### NORTH OF THE GRENVILLIAN THERMAL THRESHOLD

The K–Ar data from north of the Grenville front define a tripartite pattern comprising a central corridor having K–Ar ages between 1500 and 1000 Ma, flanked by sectors to the west and east that each record pre-1500 Ma ages. The central sector is north-northwest trending and about 200 km wide, and is termed here the Elsonian corridor (*see below*).

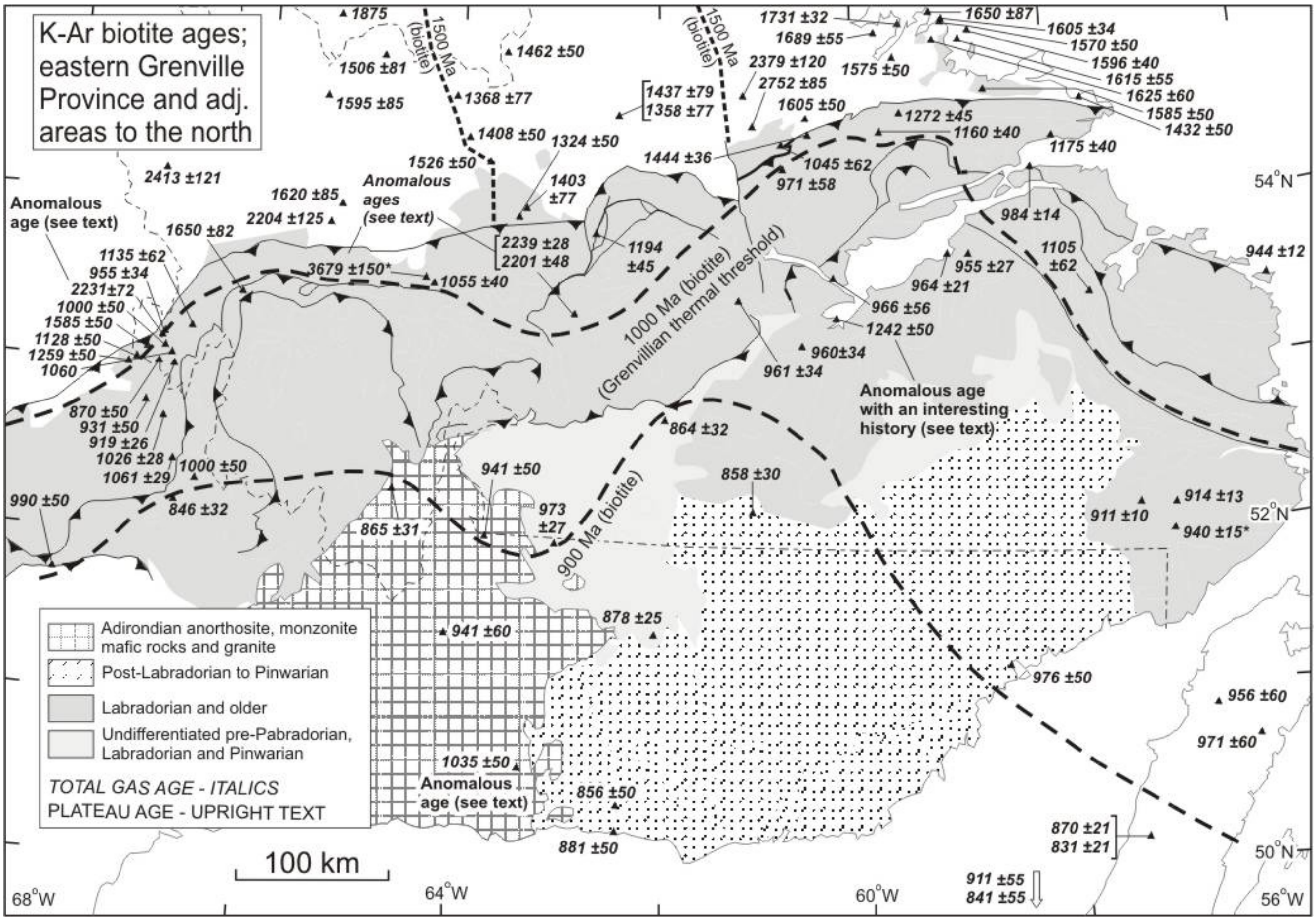


**Figure 8.** *Summary of K–Ar biotite data for the eastern Grenville Province and adjacent areas to the north.*

The sector west of the Elsonian corridor is underlain by the Archean Ashuanipi Metamorphic complex in the west and is succeeded east by Lower Proterozoic supracrustal rocks of the New Quebec orogen (Labrador Trough), then reworked Archean gneissic rocks intruded by Lower Paleozoic granitoid rocks of the Eastern Churchill Province ‘Core Zone’. Apart from the few dates available all being pre-Elsonian, it is difficult to discern any pattern with confidence, although the biotite and muscovite K–Ar dates hint at a 1650 Ma or younger thermal imprint in the southeastern half of the region.

The Elsonian corridor comprises reworked Archean and Lower Proterozoic gneisses and granitoid rocks and is intruded by Elsonian anorthositic suites, hence forming the basis for the name used here. Despite the presence of older rocks, it is Elsonian activity to which all K–Ar dates (with one exception) in the zone can be related, especially to the emplacement of the 1460 Ma Michikamau and 1440 Ma Harp Lake intrusive suites. All the country-rock dates are within the 1460 to 1230 Ma time span for Elsonian magmatism and, if not directly part of the thermal aureole of the Michikamau or Harp Lake intrusions, can be claimed to be linked to elevated thermal conditions in the Elsonian corridor throughout this period. The exception parenthesized above is a 2045 ± 54 Ma hornblende date from an amphibolite within Archean gneiss, which together with a (pre-Elsonian) 1554 +58/-53 Ma U–Pb titanite result from an Archean tonalitic gneiss (Krogh and Heaman, 1988), suggests that the threshold for Elsonian resetting was only barely reached in rocks farthest from Elsonian intrusions.

Extrapolation of the Elsonian corridor southward into the Grenville Province is masked by Grenvillian overprinting. One obvious example is provided by four hornblende ages (Figure 7) between 1430 ± 102 Ma and 1007 ± 65 Ma from the 1337 Ma Red Wine intrusive suite at the northernmost fringe of the Grenville Province (and southernmost Elsonian corridor), which show mixed Elsonian and Grenvillian K–Ar dates. The eastern side of the Elsonian corridor extrapolates structurally into the Grenville Province as the Pocket Knife Lake fault, but no similar structure is evident south of the western boundary of the corridor.

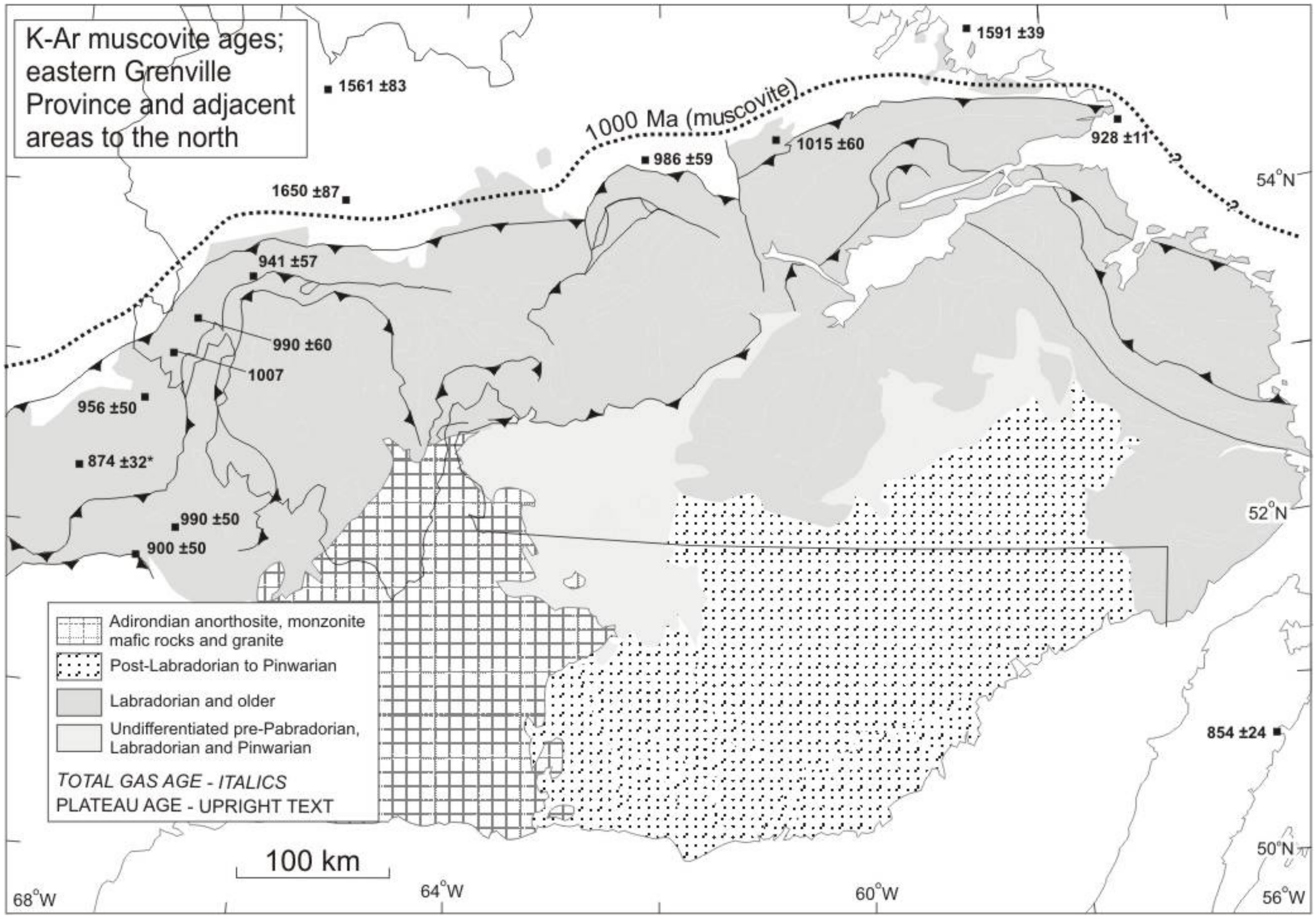


**Figure 9.** *Summary of K–Ar muscovite data for the eastern Grenville Province and adjacent areas to the north.*

The sector east of the Elsonian corridor is underlain by Archean gneissic and supracrustal rocks of the Nain Province in the west, succeeded east by Lower Proterozoic supracrustal and granitoid rocks of the Makkovik Province. In the Makkovik Province, all the K–Ar dates postdate 1700 Ma and can be mostly related to Labradorian metamorphism, or uplift and cooling in its aftermath. Those of the Nain Province either reflect their Archean heritage or Paleoproterozoic orogenic (Makkovikian) overprint. Of particular interest is the southernmost sample in the Nain Province as it denies any post-Archean metamorphism, thus imposing northern limits on Labradorian and Grenvillian metamorphism as well as constraining the eastern boundary of the Elsonian corridor (unless selective appeal is made to excess Ar). A biotite result of 919 ± 26 Ma from this area has been excluded from Figure 8 as it is from a thin mafic intrusion that could belong to a group of east-trending mafic dykes in the Makkovik Province, from which K–Ar whole-rock ages between 1000 and 850 Ma have been obtained.

Between the Grenville front and the Grenvillian thermal threshold, K–Ar dates can be interpreted to reflect incomplete Ar loss related to Grenvillian orogenesis, so comment is restricted to results that are anomalous in this context. The only one from western Labrador is a 2231 ± 72 Ma biotite result from a rock originally collected by Seguin (1973) and noted by him to be a granulitic biotite-hornblende gneiss. The date was reported by Stevens *et al.* (1982), who described the rock as a typical, massive, fresh Shabogamo gabbro, and also delivered a 1203 ± 46 Ma biotite date for the same sample. Given the original description and the fact that the locality is within 2 km of mapped Archean Ashuanipi complex, is it possible that this is not Shabogamo gabbro, and that the rock was, in fact, derived from an Archean protolith?

The most anomalous sample from central Labrador is an averaged biotite result of 3679 ± 150 Ma reported by Leech *et al*. (1963), from a rock believed to be part of the 1650 Ma Trans-Labrador batholith. This is one of the few for which there seems to be no explanation other than extraneous Ar components; even laboratory procedures cannot be doubted as the analysis was duplicated. Farther southeast, in the Wilson Lake terrane, a rock originally described as anorthositic gneiss, but later interpreted to be of metasedimentary origin, gave biotite dates of 2239 ± 28 Ma and 2201 ± 48 Ma (Stevens *et al.*, 1982). In this case, the time of formation of the rocks is not reliably known (currently considered to be Labradorian or older), so the significance of the ca. 2200 Ma results remains equivocal.

From eastern Labrador, the only anomalous date is a 'too young' 944 ± 12 Ma biotite result (Grasty *et al*., 1969). No specific geological explanation is known for the 944 Ma date although several could be invoked (resetting by an adjacent late mafic intrusion, or proximity to a thrust that was reactivated during Grenvillian orogenesis, for example).

**SOUTH OF THE GRENVILLIAN THERMAL THRESHOLD**

The K–Ar ages from south of the Grenvillian thermal threshold have been divided into those having ages between 1000 and 900 Ma and those <900 Ma. Strictly, only K–Ar biotite data are adequate to draw this distinction, but K–Ar hornblende results are consistent with those from biotite. Comment is restricted to three anomalous dates; two hornblende ages of 1533 ± 45 Ma and 1400 ± 57 Ma from the Mealy Mountains intrusive suite, and a 1242 ± 50 Ma biotite date from near Goose Bay. Retention of pre-Grenvillian ages in the Mealy Mountains intrusive suite is in accord with similar behavior shown by the younger Mealy dykes in the same area, as discussed earlier. The 1242 Ma date was reported by Hurley (1958) and, almost certainly, can be attributed to an erroneous location. Although the position indicated on a sketch map accompanying Hurley's report appears to confirm the specified latitude and longitude co-ordinates (53°22'N, 60°12' W), the text of the report states that the sample is from Hopedale (a location 12 km south of which has almost identical co-ordinates of 55°22'N, 60°12'W). As there are no bedrock outcrops within about 14 km of the indicated Lake Melville location (it is in the centre of a large sand plain), it is guessed here that a typographic error exists in the latitude coordinate reported, and that the error was subsequently compounded in the sketch map. The 1242 Ma date in the Lake Melville area is anomalous with respect to five surrounding ca. 960 Ma biotite ages, but can be easily explained in the Hopedale area because a very wide Harp dyke is situated at the revised coordinates (and would have been an obvious target for sampling). A 1242 Ma K–Ar date is entirely consistent as a cooling age from 1273 Ma, which is currently the best estimate for the time of emplacement of the Harp dyke suite. Assiduous attempts to determine the truth of the matter have failed. Unfortunately, it seems that Hurley's analytical records have been discarded, and the whereabouts of field notebooks (assuming they still exist) of Kranck, who collected the sample, are unknown, either to former colleagues or family members.

From the <900 Ma area, there is only one anomalous date; a biotite age of 1035 ± 60 Ma, from a pegmatite intruding gabbroic anorthosite hosting the Lake Tio ilmenite deposit (Leech *et al*., 1963). The gabbroic anorthosite belongs to the Havre St. Pierre body from which U–Pb ages of 1126 and 1079 Ma have been reported. It seems reasonable to suspect that the 1035 biotite date might be related to time of intrusion, especially as the pegmatite is reported to be invaded by ilmenite-hematite veins, which are typically genetically linked to, and form late in the intrusive history of anorthositic suites. Nevertheless, the date is anomalously old compared to other K–Ar biotite data in the region, and some additional explanation is still required, possibly along the same lines as that for anomalously old data from the Mealy Mountains intrusive suite. Note that the 900 Ma boundary can be extrapolated across the Grenvillian Long Range Inlier in Newfoundland.

## $^{40}$Ar/$^{39}$Ar AND K–Ar MUSCOVITE AGES

The $^{40}$Ar/$^{39}$Ar and K–Ar muscovite ages, including whole-rock $^{40}$Ar/$^{39}$Ar dates from rocks dominated by muscovite, are shown in Figures 4 and 9. Data are too sparse to justify interpretation of either alone, but together they are permissive of a 1000 Ma muscovite thermochron essentially coincident with the Grenville front (Figure 9). Thus, although one might be tempted to re-position the Grenville front on the basis of hornblende and biotite ages, muscovite data provide a reason not to tamper (aside from sensible structural arguments). Two additional points require mention. The first is that two $^{40}$Ar/$^{39}$Ar muscovite results, from mylonitic paragneiss, of 1088 ± 24 Ma and 1046 ± 15 Ma (Figure 4) are anomalously old for the location at which they occur, but perhaps reflecting weak Grenvillian metamorphism coeval with 1085-1040 Ma tectonism in the Lake Melville terrane. The 1000 Ma muscovite thermochron could be placed south of these points, yielding greater parallelism with the 1000 Ma biotite-hornblende thermochron. The second point is that the southeast flexure at the eastern end of the muscovite thermochron (Figure 9) is hypothetical, being drawn to be consistent with the Grenvillian thermal threshold determined from $^{40}$Ar/$^{39}$Ar and K–Ar biotite and hornblende data.

## DISCUSSION

It should be clarified that the observations made here are not without some precedent, inasmuch as thermochron maps for the Grenville Province, including the eastern part, have been previously drawn by Harper (1967), Baer (1976) and Easton (1986) (Figure 10). Harper's thermochron map was based on 21 K–Ar biotite ages, Baer's map on 96 mica ages (biotite and muscovite?), and Easton's on about 130 biotite ages from granite and gneiss. The sharp bend to the southeast in the easternmost Grenville Province is evident

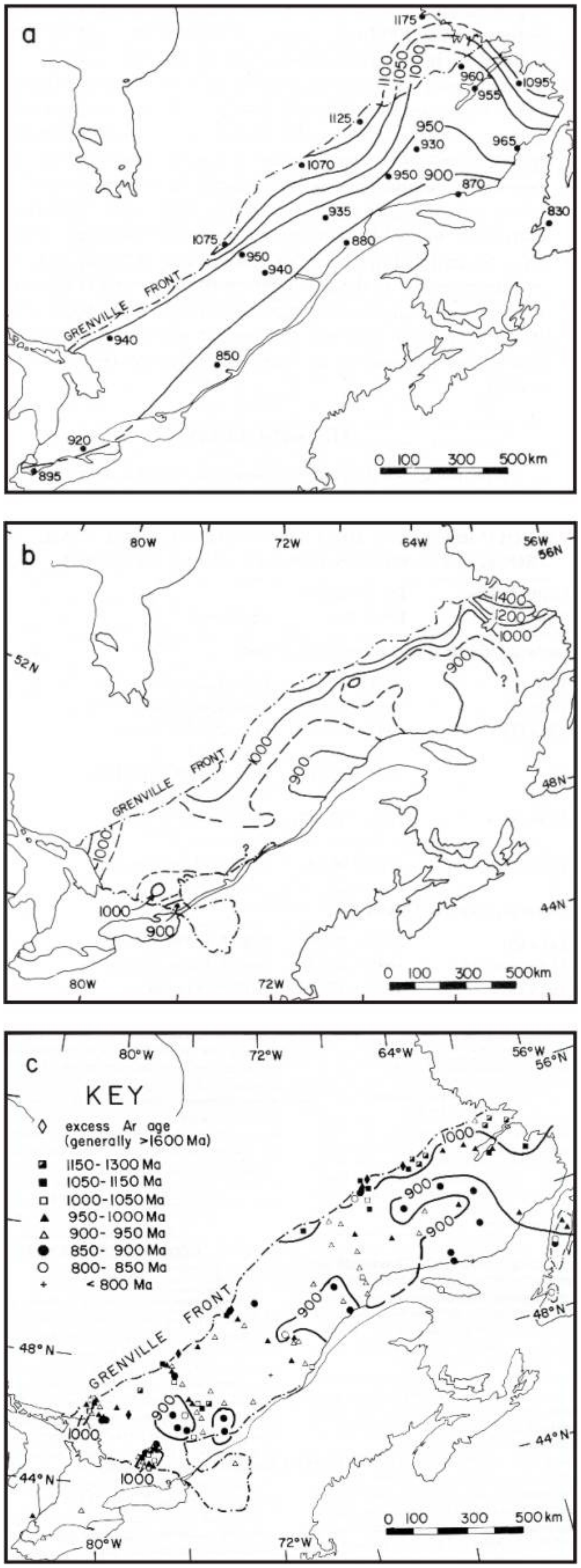


**Figure 10.** *Previous K–Ar thermochron maps for the Grenville Province (reformatted from Easton, 1986). a) After Harper (1967), based on 21 biotite ages from gneisses. b) After Baer (1976), based on 96 mica ages. c) After Easton (1986), based on about 130 biotite ages from gneisses and granite.*

on all three maps (Figure 10), although none of these authors either attempted, or were well positioned, to provide an interpretation. In particular, they lacked the geological mapping, U–Pb geochronological database, and the wealth of $^{40}Ar/^{39}Ar$ ages now available. All three authors limited their syntheses to mica ages, rather than reviewing all the data available, and, furthermore, detailed literature research of individual ages has allowed many inconsistencies to be removed that previously passed undetected. Easton (1986) concluded that “The thermochron approach assumes a uniformity in geologic and tectonic conditions that may not exist. Consequently, the utility of thermochron maps in the Grenville Province is limited.” This was a fair enough comment at the time but this investigation has led to a much more optimistic viewpoint, at least as far as the data apply to the eastern Grenville Province.

## SUMMARY OF OBSERVATIONS

Observations are collected together in Figure 11, and key points are summarized below, in a more-or-less north-to-south context.

i) North of the Grenville front, K–Ar hornblende and biotite data reveal a central north–northwest-trending zone, about 200 km wide, characterized by 1500 to 1000 Ma ages. This is termed here the Elsonian corridor, and is related to the emplacement of 1460 to 1230 Ma Elsonian anorthositic and related rocks.

ii) On the eastern side of the Elsonian corridor, a clear distinction can be drawn between pre- and post-1650 Ma ages along a northeast-trending line coinciding with the northwest margin of the Makkovik Province. This boundary is considered to be the northwest limit of Labradorian overprinting on older Paleoproterozoic rocks.

iii) West of the Elsonian corridor, data are inadequate to draw any firm conclusions, but a similar northeast-trending boundary between pre- and post-1650 Ma ages may exist, which, being the case, could imply dextral displacement along the Elsonian corridor.

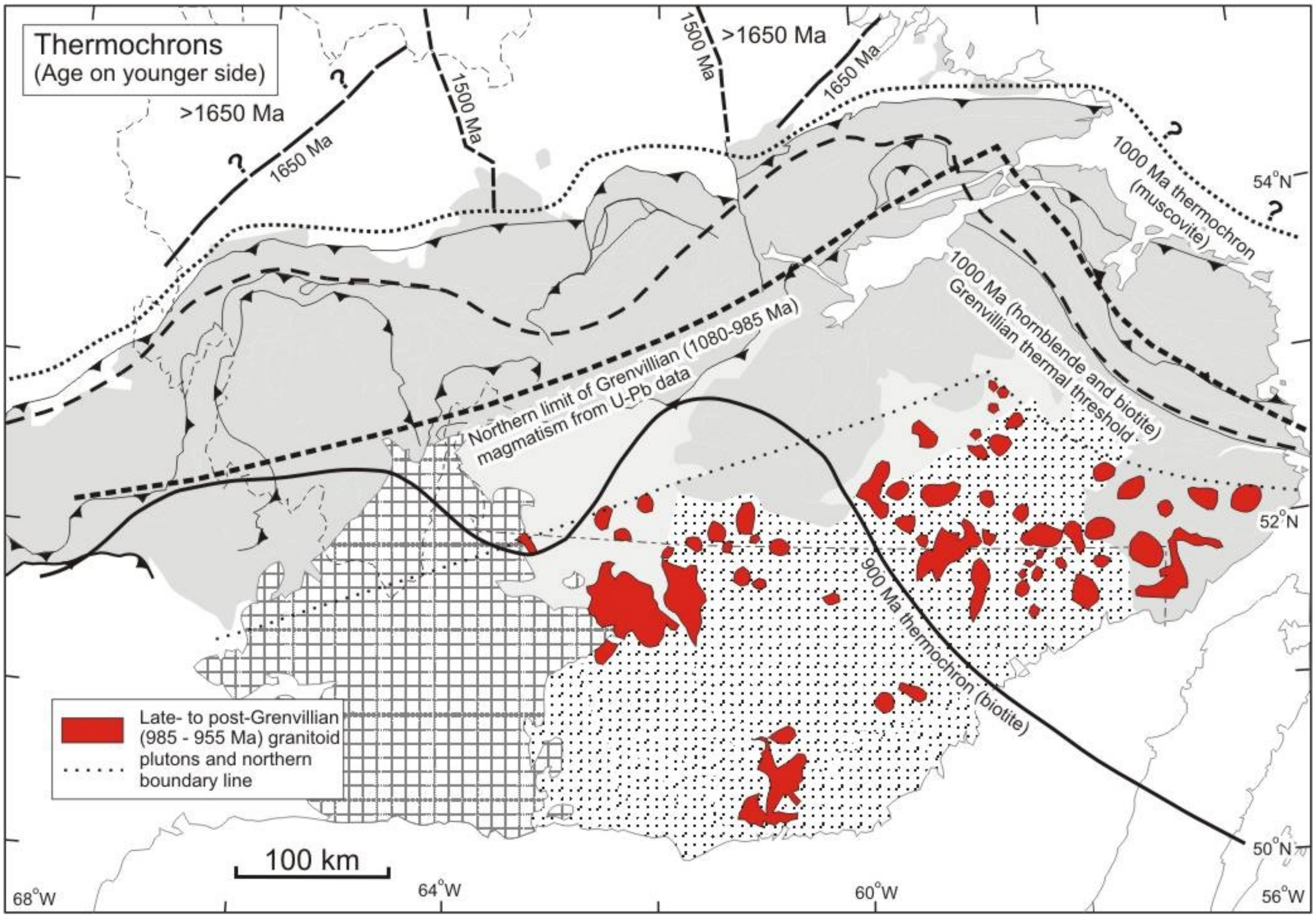


**Figure 11.** *Thermochrons for the eastern Grenville Province, emphasizing the marked inflection from east-northeast to south-east in eastern Labrador. This change in trend shows a correlation with the distribution of both syn-Grenvillian (1080 to 985 Ma) magmatism and late- to post-Grenvillian plutons. It is argued in the text that the partial preservation of pre-Grenvillian $^{40}$Ar/$^{39}$Ar and K–Ar ages in the easternmost area (Groswater Bay and Hawke River terranes) indicates that this region never experienced severe Grenvillian metamorphism.*

(iv) The 1000 Ma muscovite thermochron is essentially in the same position as the Grenville front, and provides a reason for continued acceptance of the northern boundary of the eastern Grenville Province as currently depicted. An offshore bend to the southeast in the position of the thermochron at its eastern end is predicted by consistency between the relative positions of the muscovite and hornblende/biotite 1000 Ma thermochrons onshore.

(v) A single line can be drawn that represents the hornblende and biotite 1000 Ma thermochron, regardless of whether the data are from $^{40}$Ar/$^{39}$Ar or K–Ar, total-gas or plateau determinations. This boundary is termed here the Grenvillian thermal threshold.

vi) North of the Grenvillian thermal threshold, $^{40}$Ar/$^{39}$Ar and K–Ar ages in both hornblende and biotite decrease southward in a systematic way as the threshold is approached. This feature is attributed to Ar loss and very few instances are recognized where there is a need to resort to interpretations involving excess Ar. Appeal to older protolith ages than previously supposed offers a more attractive interpretation than excess Ar in many instances.

vii) Pre-Grenvillian $^{40}$Ar/$^{39}$Ar and K–Ar ages in the Groswater Bay and Hawke River terranes, supported by U–Pb data (e.g., minor Grenvillian Pb-loss in zircon and pre-Grenvillian titanite dates; Gower and Krogh, 2002a,b), demonstrate that this area was only mildly to moderately affected by Grenvillian orogenesis.

viii) The status of the northern Mealy Mountains terrane with respect to the Grenvillian thermal threshold remains equivocal. Grenvillian ages are evident in biotite, but hornblende results suggest only partial resetting (for both $^{40}$Ar/$^{39}$Ar and K–Ar). Hard-to-deform anorthosite in this

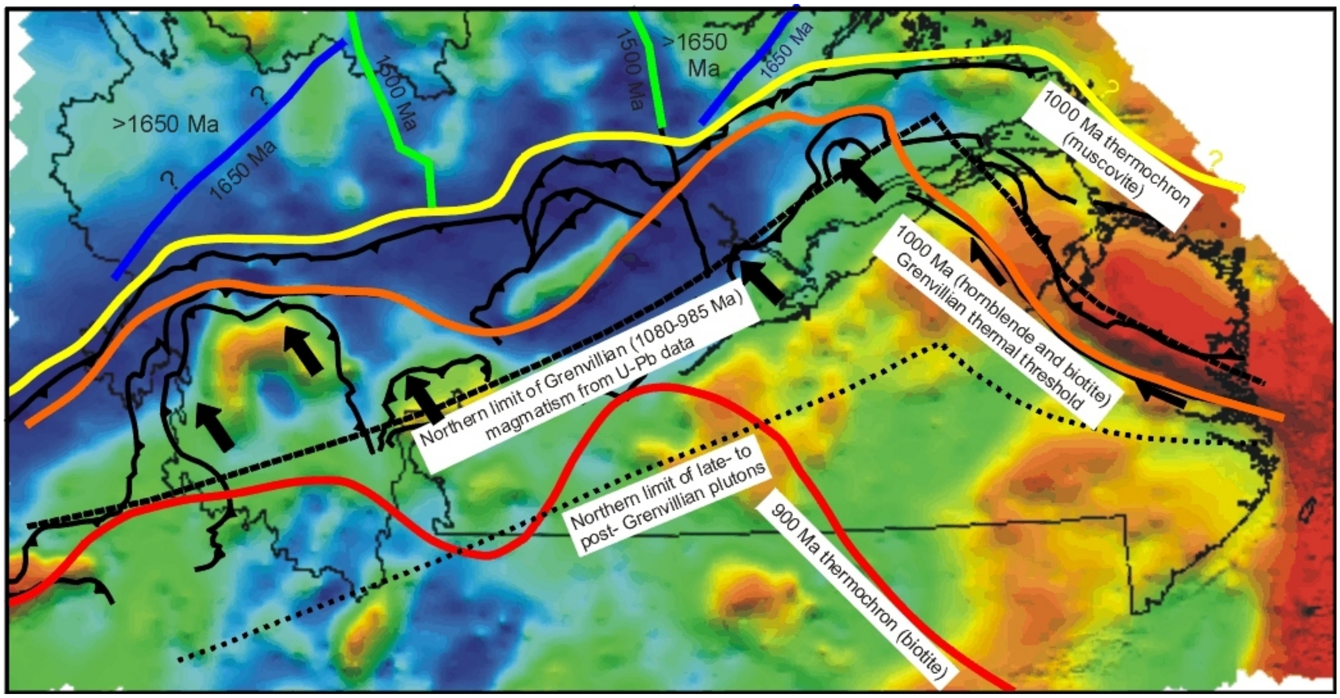


**Figure 12.** *Thermochrons and major structural features superimposed on a gravity anomaly map for the eastern Grenville Province. The main purpose of this figure is to illustrate the relationship between the Grenville front gravity low (in blue) with those areas interpreted as frontal ramps. The dying out of the gravity low in eastern Labrador is explained as due to termination of frontal thrusts along a southeastern-trending lateral ramp. Therefore, the lateral ramp marks the easternmost limit of Grenvillian transported terranes.*

region may have played a role in denying fluid imgress and thereby inhibiting resetting.

ix) A 900 Ma thermochron based on biotite, but with which hornblende data are consistent, can be drawn south of, and parallel to the 1000 Ma thermochron. At its eastern end, the 900 Ma thermochron bends to the southeast, similar to the Grenvillian thermal threshold thermochron. This boundary appears to continue across the Long Range Inlier. If this is the case, then northeast-trending Paleozoic faults interpreted to underlie the Strait of Belle Isle cannot involve huge lateral displacements.

x) The pattern of thermochrons in the eastern Grenville Province is correlated with the distribution of Grenvillian 1080 to 985 Ma magmatism (cf. Gower and Krogh, 2002b) and late- to post-Grenvillian plutons. The interior extent of these plutons is still imperfectly known in eastern Quebec, but the northwestern and northeastern limits are now confidently established and have the same trends as the thermochrons.

## IMPLICATIONS FOR GRENVILLIAN TECTONIC EVOLUTION

Gower *et al.* (1997) offered a model for Grenvillian tectonic configuration whereby the Lake Melville - Mealy Mountains terrane boundary defines the northeastern lateral-ramp limit of Grenvillian allochthonous terranes that were transported on frontal ramps to the northwest. The northeasternmost terranes (Hawke River and Groswater Bay terranes) escaped high-grade Grenvillian metamorphism, in contrast to the Lake Melville terrane, which, defining the lateral ramp margin, was subjected to more intensive Grenvillian effects. The $^{40}Ar/^{39}Ar$ and K–Ar data reviewed here demonstrates convincingly that Grenvillian effects were moderate and sporadic northeast of the Lake Melville terrane, almost to the point of questioning whether the Hawke River and Groswater Bay terranes should be included in the Grenville Province - but see point (iv) above. The lateral ramp hypothesis also explains why the pronounced negative gravity that characterizes the Grenville front in the central and eastern parts of the Grenville coast dies out as the coast is approached (Figure 12). It is simply because crustal thickening that accompanied the northwest-directed frontal ramp thrusting, and to which the negative anomaly is related, did not occur in the east.

Absence of a severe Grenvillian overprint in the Hawke River and Groswater Bay terranes has significant implications regarding their pre-Grenvillian metamorphic history.

Geothermobarometric results from the southern Groswater Bay terrane indicate that high-grade pelitic (kyanite–sillimanite) gneisses achieved pressures of 10 to 12 kb and temperatures of 615 to 850°C (van Nostrand, 1988). Grenvillian metamorphism of this grade would surely have been accompanied by complete resetting of $^{40}Ar/^{39}Ar$ and K–Ar ages. As this is not the case, much of the metamorphism must be pre-Grenvillian. This has far-reaching consequences, not the least of which is that coronitic assemblages in Michael gabbro (and, by implication, Shabogamo gabbro also?) cannot be the product of Grenvillian metamorphism. That the coronitic assemblages might not be Grenvillian (but not denying uplift during Grenvillian orogenesis) was previously argued by Gower and Erdmer (1988). Note that conclusions made here regarding the timing of high-grade metamorphism in the Groswter Bay terrane raise serious difficulties concerning Rivers *et al.*'s (2002) proposed Grenvillian high-pressure belt that they speculatively extrapolate into eastern Labrador from farther west.

The attitude of the lateral ramp remains uncertain. Surface structural data at the Mealy Mountains - Lake Melville terrane boundary suggest the interface to be vertical, whereas that between the Lake Melville and Hawke River terranes implies a steep northeast dip. Seismic reflection data reported by Gower *et al.* (1997) indicates northeast-dipping reflectors at depth. These have been attributed to Labradorian orogenesis, but Grenvillian utilization of pre-existing structures cannot be excluded. Regardless of these details, it seems certain the Lake Melville terrane must include a lateral shear zone of major significance, as previously interpreted by Gower *et al.* (1987; who termed it the Gilbert River shear belt), but rejected by Hanmer and Scott (1990). A key area for further study is the inflection point between the frontal and lateral ramps.

In the southern part of the eastern Grenville Province the most remarkable feature is parallelism between the 1000 Ma biotite thermochron and the northwestern and northeastern flanks of the late- to post-Grenvillian plutons. Note that the existence of these plutons was not suspected when even the most recent previous thermochron map (that of Easton) was published. The northeastern limit of the late plutons is about 50 km from the biotite 1000 Ma thermochron, whereas the northwestern flank is about 150 km distant. This pattern, too, can be explained in terms of frontal and lateral Grenvillian thrust ramps and concomitant crustal thickening. The 900 Ma biotite thermochron transects the region of late- to post-Grenvillian plutons. Evidently, the southwest area cooled later; it is predicted here that even younger post-Grenvillian plutons will be found in eastern Quebec than the 966 to 956 Ma bodies situated closer to the northeast and northwest flanks. It is worth pointing out that the well-exposed north shore of the St. Lawrence estuary provides a superb opportunity to test interpretations offered here in more detail, as they suggest that the shoreline offers a section across the Grenvillian thermal gradient, rather than parallel to it as previously implied by its parallelism with the Grenville front.

The lateral ramp hypothesis also has great significance in relation to the nature of the Precambrian basement that extends for a considerable distance offshore eastern Labrador and northern Newfoundland. If the Grenville front turns southeast as suggested here, it follows that the offshore Grenville Province is drastically reduced in area, with an offsetting increase in the size of the region underlain by Labradorian or Makkovikian crust. According to the model proposed here, efforts to identify an eastward extrapolation of the Grenville front offshore are doomed to failure. It is no wonder that "there is no sign of the whole-crustal south-dipping shear zone reflectivity associated with the Grenville front to the west" (Hall *et al.*, 2002, p. 581). The present-day thinning of the crust across the Grenville front partly attributed to Mesozoic rifting by Hall *et al*. (2002) reflects modification of structures formed long before Grenvillian orogenesis (cf. Krogh *et al*., 2002), albeit somewhat reactivated during Grenvillian tectonism. Hall *et al.* (2002) also questioned the model of Gower *et al.* (1997) that crustal structure in the northeasternmost Grenville Province is largely the product of Labradorian orogenesis; and appealed to post-Labradorian events as having a significant effect on the geology of southern Labrador. While not denying that major post-Labradorian tectonism (Pinwarian and Grenvillian) has certainly played a major role in the Lake Melville and more southerly terranes (and acknowledged by Gower *et al*., 1997), it is difficult to accept that post-Labraadorian tectonism had much impact in either the Hawke River and Groswater Bay terranes, where Pinwarian and Grenvillian effects were moderate at most.

It seems likely that any major Phanerozoic reactivation that might have occurred (of potential relevance to hydrocarbon exploration, for example) would have been along the southeastward extrapolation of the lateral ramp (i.e., Mealy Mountains–Lake Melville terrane boundary), rather than due east of Smokey along the usual seaward extrapolation depicted for the Grenville front.

## CONCLUSIONS

Reassessment of $^{40}Ar/^{39}Ar$ and K–Ar data allows 1000 Ma and 900 Ma thermochrons to be confidently positioned in the eastern Grenville Province. The 1000 Ma thermochron is termed the Grenvillian thermal threshold. Systematically decreasing $^{40}Ar/^{39}Ar$ ages, on approaching the Grenvillian thermal threshold, are attributed to progressively increasing Ar loss. A marked inflection to a southeast trend at their eastern end, departing from a regional northeast trend parallel to the Grenville front farther west, is explained in the context of Grenvillian thrust ramp geometry. According to this model, the southeast trend marks the northeastern lateral-ramp limit of Grenvillian allochthonous terranes that were transported on frontal ramps to the northwest. This geometry mimics well-established structural and geophysical trends and is also reflected in the distribution of Grenvillian plutons. The lateral-ramp model provides better understanding of gravity data, has far-reaching implications regarding better appreciation of the severity of pre-Grenvillian metamorphism, pre-Grenvillian and Grenvillian tectonic processes and is of relevance in interpretation of offshore extrapolations of Precambrian structural provinces.

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## REFERENCES

Archibald, D. and Farrar, E.
1979: $^{40}Ar/^{39}Ar$ mineral ages from the Walker-Benedict granodiorite, Central Mineral Belt, Labrador. Newfoundland and Labrador Department of Mines and Energy, Mineral Development Division, File Lab/454, 13 pages.

Baer, A.J.
1976: The Grenville Province in Helikian times: a possible model of evolution. Royal Society of London Philosophical Transactions, Series A, Volume 280, pages 499-515.

Connelly, J.N.
1991: The thermotectonic history of the Grenville Province of western Labrador. Unpublished Ph. D. thesis, Memorial University of Newfoundland, St. John's, 314 pages.

Culshaw, N. Reynolds, P., Sinclair, G. and Barr, S.
2002: Amphibole and mica $^{40}Ar/^{39}Ar$ ages from the Kaipokok and Aillik domains, Makkovik Province, Labrador: toward characterization of back-arc processes in the Paleoproterozoic. Canadian Journal of Earth Sciences, Volume 39, pages 749-764.

Dallmeyer, R.D.
1980: $^{40}Ar/^{39}Ar$ radiometric dating in western Labrador. Unpublished report to the Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Lab/520, 32 pages.

1982a: $^{40}Ar/^{39}Ar$ incremental-release ages of biotite from a gabbro of the Shabogamo intrusive suite, southwestern Labrador. Canadian Journal of Earth Sciences, Volume 19, pages 1877-1881.

1982b: $^{40}Ar/^{39}Ar$ incremental-release ages of biotite from a progressively remetamorphosed Archean basement terrane in southwestern Labrador. Earth and Planetary Science Letters, Volume 61, pages 85-96.

1987: $^{40}Ar/^{39}Ar$ mineral age record of variably superimposed Proterozoic tectonothermal events in the Grenville Orogen, central Labrador. Canadian Journal of Earth Sciences, Volume 24, pages 314-333.

Dallmeyer, R.D. and Rivers, T.
1983: Recognition of extraneous argon components through incremental-release $^{40}Ar/^{39}Ar$ analysis of biotite and hornblende across the Grenvillian metamorphic gradient in southwestern Labrador. Geochimica et Cosmochimica Acta, Volume 47, pages 413-428.

Easton, R.M.
1986: Geochronology of the Grenville Province. *In* The Grenville Province. *Edited by* J.M. Moore, A. Davidson and A.J. Baer. Geological Association of Canada, Special Paper 31, pages 127-173.

Emslie, R.F., Loveridge, W.D. and Stevens, R.D.
1984: The Mealy dykes, Labrador: petrology, age, and tectonic significance. Canadian Journal of Earth Sciences, Volume 21, pages 437-446.

Gower, C.F.
1996: The evolution of the Grenville Province in eastern Labrador, Canada. *In* Precambrian Crustal Evolution in the North Atlantic Region. *Edited by* T.S. Brewer. Geological Society, Special Publication No. 112, pages 197-218.

Gower, C.F. and Erdmer, P.
1988: Proterozoic metamorphism in the Grenville Province: a study in the Double Mer–Lake Melville area, eastern Labrador. Canadian Journal of Earth Sciences, Volume 25, pages 1895-1905.

Gower, C.F. and Krogh, T.E.,
2002a: A U–Pb geochronological review of the Proterozoic history of the eastern Grenville Province. Canadian Journal of Earth Sciences, Volume 39, pages 795-829.

2002b: A geochronological review of the pre-Labradorian and Labradorian geological history of the eastern Grenville Province. Ministère des Ressources naturelles, Québec. DV2002-03.

Gower, C.F., Hall, J., Kilfoil, G.J., Quinlan, G.M. and Wardle, R.J.
1997: Roots of the Labradorian orogen in the Grenville Province in southeast Labrador : evidence from marine, deep-seismic reflection data. Tectonics, Volume 16, pages 795-809.

Gower, C.F., Neuland, S., Newman, M, and Smyth, J.
1987: Geology of the Port Hope Simpson map region, Grenville Province, eastern Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 87-1, pages 183-199.

Grasty, R.L., Rucklidge, J.C. and Elders, W.A.
1969: New K-Ar age determinations on rocks from the east coast of Labrador. Canadian Journal of Earth Sciences, Volume 6, pages 340-344.

Hall, J., Louden, K.E., Funck, T., Deemer, S.
2002: Geophysical characteristics of the continental crust along the Lithoprobe Eastern Canadian Shield Onshore-Offshore Transect (ECSOOT): a review. Canadian Journal of Earth Sciences, Volume 39, pages 569-587.

Hanmer, S., and Scott, D.J.
1990: Structural observations in the Gilbert River belt, Grenville Province, southeastern Labrador. *In* Current Research, Part C. Geological Survey of Canada, Paper 90-1C, pages 1-11.

Harper, C.T.
1967: On the interpretation of potassium-argon ages from Precambrian shields and Phanerozoic orogens. Earth and Planetary Science Letters, Volume 3, pages 128-132.

Hurley, P.M.
1958: Variation in isotopic abundances of strontium, calcium, and argon and related topics. NYO-3939, Massachusetts Institute of Technology, 6th Annual Report for 1958, pages 129-130.

Krogh, T.E.
1994: Precise U-Pb ages for Grenvillian and pre-Grenvillian thrusting of Proterozoic and Archean metamorphic assemblages in the Grenville Front tectonic zone. Canada. Tectonics, Volume 13, pages 963-982.

Krogh, T.E. and Heaman, L.
1988: Report on 1987-1988 contract geochronology Labrador, Royal Ontario Museum. Unpublished report to Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Lab/765, 102 pages.

Krogh, T.E., Kamo, S., Gower, C.F. and Owen, J.V.
2002: Augmented and reassessed geochronological data from the Labradorian-Grenvillian front in the Smokey archipelago, eastern Labrador. Canadian Journal of Earth Sciences, Volume 39, pages 831-843.

Leech G.B., Lowdon, J.A., Stockwell, C.H. and Wanless, R.K.
1963: Age determinations and geological studies (including Isotopic Ages -Report 4). Geological Survey of Canada, paper 63-17, 140 pages.

Owen, J.V., Dallmeyer, R.D., Gower, C.F. and Rivers, T.
1988: Metamorphic conditions and $^{40}Ar/^{39}Ar$ geochronologic contrasts across the Grenville front zone, coastal Labrador, Canada. Lithos, Volume 21, pages 13-35.

Reynolds, P.H.
1989: $^{40}Ar/^{39}Ar$ dating of the Mealy dykes of Labrador: paleomagnetic implications. Canadian Journal of Earth Sciences, Volume 26, page 1567-1573.

Reynolds, P.H., Zentilli, M., Jamieson, R.A. and Owen, J.A.
1988: Cooling history of the Long Range Inlier, Newfoundland: Argon-Argon and fission-track thermochronometry. *In* Lithoprobe EastTransect Report, pages 37-40.

Rivers, T., Ketchum, J., Indares, A. and Hynes, A.
2002: The High Pressure belt in the Grenville Province: architecture, timing and exhumation. Canadian Journal of Earth Sciences, Volume 39, pages 867-893.

Rivers, T. and Massey, N.
1985: Geology of the Wightman Lake area, Labrador-Quebec. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 85-028.

Seguin, M.K.
1973: Geological evolution of the southern extension of the Labrador Trough. Le Naturaliste Canadien, Volume 100, pages 277-314.

Stevens, R.D., Delabio, R.N. and Lachance, G.R.
1982: Age determinations and geological studies, K-Ar isotopic ages, Report 15. Geological Survey of Canada, Paper 81-2, 56 pages.

van Gool, J.A.M.
1992: The Grenville front foreland fold-and-thrust belt in southwestern Labrador: mid-crustal structural and metamorphic configuration of a Proterozoic orogenic thrust wedge. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 372 pages.

van Nostrand, T.
1988: Geothermometry-geobarometry and $^{40}Ar/^{39}Ar$ incremental release dating in the Sandwich Bay area, Grenville Province, eastern Labrador. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, 203 pages.

Wilton, D.H.C.
1996: Metallogeny of the Central Mineral Belt and adjacent Archean basement, Labrador. Newfoundland Department of Mines and Energy, Mineral Resources Report 8, 178 pages.