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INTERPRETATION OF K-AR MINERAL DATES FROM THE GRENVILLE OROGENIC BELT

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ABSTRACT. Two previous studies using K-Ar dates suggested that regional cooling after the Grenville Orogeny followed a systematic pattern, starting along the Grenville Front 1100 to 1200 Ma ago and progressing southeastward (Harper, 1967; Baer, 1976). Many additional K-Ar and ^{40}Ar-^{39}Ar dates have been published since 1976, and reliable cooling ages now available from hornblende, muscovite, and biotite indicate that the main phase of post-peak cooling recorded in mainland Canada possibly began as late as 1050 Ma ago, but more likely around 1100 Ma; this age approximates the time of the final thermal peak of the Grenville Orogeny. Most of the K-Ar dates older than this, especially near the Grenville Front, appear to be either partially reset from pre-Grenville dates or affected by excess argon, apparently a particular problem for biotite dates in this region. There may also be some preservation of hornblende and muscovite cooling ages from earlier phases of the Grenville Orogeny. The post-peak Grenville cooling ages no longer appear to have a regional-scale systematic geographic pattern. Mixing of cooling ages from 800 to 1100 Ma on a small scale throughout the Orogen suggests variations on a scale of tens of kilometers in some combination of peak age, peak metamorphic grade, and cooling and uplift rate.

INTRODUCTION

Over the last 30 yrs several hundred isotopic dates have been published from the late Proterozoic Grenville Orogen in eastern North America. More than half of these are K-Ar and ^{40}Ar-^{39}Ar dates from mineral separates, primarily hornblende, muscovite, and biotite. These dates, like all isotopic dates, are controlled by thermal diffusion, so they can only be used to study limited aspects of an orogeny and appear to be mainly appropriate for studying post-orogenic cooling, although they can also be used to set an age limit on the last thermal peak of regional metamorphism. This paper examines these dates for what they may reveal about areal variations in post-peak cooling and uplift rates and about the age of the last thermal peak of regional metamorphism during the Grenville Orogeny. As suggested by Dewey and Burke (1973), the dominant regional metamorphic event in the Grenville Orogen is attributed to a terminal continent-continent collision, variably overprinting the effects of earlier tectonic events, including some that may have occurred only slightly earlier (see Anderson and Burke, 1983, for discussion). This study attempts to make the best use of existing K-Ar and ^{40}Ar-^{39}Ar dates from hornblende, muscovite, and biotite to understand the post-peak phase of the Grenville Orogeny. This effort primarily involves distinguishing genuine cooling ages from those affected by excess argon or by partial resetting of cooling ages from earlier thermal events.

The dates used were published from 1960, the year of the first annual report of K-Ar dates by the Geological Survey of Canada (Lowdon, 1960), through July 1987. Dates were generally not used if they were published in abstracts or replies to published papers or were cited as "personal communication" in a secondary source. Dates from whole-rock samples were excluded because they are difficult to interpret in regionally metamorphosed rocks (Armstrong, 1966). Few dates from minerals other than hornblende, muscovite, and biotite have been published from this region. A list of dates from the Grenville Orogen using broader criteria was published recently by Easton (1986). Note that the words "date" and "age" are used here as recommended by Armstrong (1966): "date" for a result from the laboratory and "age" for a number with geological significance.

All the dates used conform with current IUGS standard decay constants (Steiger and Jäger, 1977). Dates originally calculated using obsolete constants have been converted using a table by Dalrymple (1979); for dates from 750 to 1250 Ma this adjustment is an increase of about 10 Ma, which is less than the analytical uncertainty for most of the dates.

"Typical Grenville" Dates

One motivation for this study is the lack of agreement in the literature regarding the ages of important events affecting the Grenville Orogen. Dates apparently considered "typical" of the Orogen range from 750 to 1250 Ma, although Stockwell (1976) suggested limiting the span to 800 to 1100 Ma, which is still approximately as long as the Paleozoic Era. This entire age range has been associated with a single episode of major regional metamorphism and widespread deformation, accompanied by the intrusion of various igneous rocks. K-Ar dates historically were critical to recognition of the areal extent of the metamorphic and structural effects of this event. Several dates outside the 750 to 1250 Ma range have been reported from the Orogen but are generally attributed to events before or after the Grenville Orogeny, particularly if the samples came from near the Grenville Front, or the Paleozoic orogenic belts of the Appalachians, or features such as the Ottawa-Bonnechere Rift.

One age, or age range, of great interest has been that of the "peak of the Grenville Orogeny," loosely interpreted to include the time of the highest metamorphic temperatures and pressures, the most intense deformation, and the most abundant syn-orogenic igneous activity. However, the search for a single peak age, applying uniformly to the whole region, may be unrealistic. The events associated with the "peak" may not have been strictly contemporaneous (see Armstrong, 1966, for example) or may show a systematic, progressive variation along the length of the orogenic belt (Dewey, 1980). Orogenic activity may also continue for a substantial time. For example, the terminal collision of India with Asia began about 40 Ma ago (Molnar and Tapponier, 1975), but the Himalayan Orogeny may be far from over. Recent work in the Tibetan Plateau (Chang and others, 1986) has shown that this terminal continent-continent collision was preceded by 150 Ma of subduction-related tectonic activity, involving the successive accretion to Asia of at least three microcontinents. Dewey and Burke (1973) suggested that the Grenville Orogen was formed by the same process as the Himalayas and the Tibetan Plateau: the large areas of upper amphibolite to granulite facies were developed when continental crust in the region was twice normal thickness and were exposed as erosion reduced the height of the plateau. (The Grenville Front is considered to be analogous with the northern edge of the Tibetan Plateau, not with the Indus Suture.) In terms of this Tibet analogy, K-Ar mineral dates should record cooling from the thermal peak of the terminal continent-continent collision. It may, however, be difficult to distinguish K-Ar cooling ages preserved from slightly earlier microcontinent or island-arc collisions.

Moore and Thompson (1980) suggested that there may have been two separate orogenies within the "typical Grenville" range: the Elzevirian Orogeny at 1225 Ma and the Ottawan Orogeny at 1125 Ma, separated by a short period of rifting and the deposition of the Flinton Group in eastern Ontario. Douglas (1980) and Stockwell (1982) referred to the second event as the Grenvillian Orogeny, in a more restricted sense than most previous usage.

Argon Diffusion Closure Temperature

A K-Ar or ^{40}Ar-^{39}Ar mineral date records the time since this mineral last cooled below its argon diffusion closure temperature. A number of factors can affect this temperature, including the regional cooling rate, the "mean effective diffusion radius" (Dodson, 1973, pointed out that this will be smaller than the grain size measured by seiving), and the mineral composition (for examples, see O'Nions and others, 1969, for hornblende; Harrison, Duncan, and McDougall, 1985, for biotite). In regional analyses it is assumed that factors like these have less effect than those determined by basic differences between the mineral species used.

The following argon diffusion closure temperatures are used for all the K-Ar and ^{40}Ar-^{39}Ar dates examined here, because they appear to be geologically reasonable for samples affected by regional metamorphism: hornblende—535°C (Harrison and McDougall, 1980); muscovite—350°C (Jäger, 1979); biotite—310°C (Harrison, Duncan, and McDougall, 1985).

The argon diffusion closure temperature for a particular sample can be calculated from the same stepwise argon extraction procedure used to obtain a ^{40}Ar-^{39}Ar plateau age (using a formula from Dodson, 1973) but not if the standard *in vacuo* extraction procedure is used on hydrous minerals (Harrison, 1981). Therefore, the very high hornblende closure temperatures (up to 747°C) calculated by Berger and York (1981b) for gabbroic samples from the Grenville Orogen in Ontario are unreliable. In any case, such high closure temperatures imply that pre-Grenville hornblende dates could only be reset by Grenville metamorphism in the highest-grade granulite facies portions of the Orogen, whereas they are known to have been reset in amphibolite facies areas as well (see, for example, Dallmeyer and Rivers, 1983).

PREVIOUS REGIONAL ANALYSES

A map of K-Ar dates for a given mineral shows when each sample in the area last passed through the argon diffusion closure temperature for that mineral. If it is assumed that one heating event was responsible for all the dates shown and expelled all radiogenic argon that had accumulated following any earlier heating events, then systematic variations in the dates can be attributed primarily to variations in the age of the heating event or in the cooling and uplift rates. Dates from minerals with high closure temperatures, such as hornblende, may approximate the age of the thermal peak, or at least set a reasonable limit on how late it could have been. Dates from minerals with lower closure temperatures, such as biotite, are more likely to reflect variations in uplift rates or cooling processes.

Harper (1967) constructed the first such map for the Grenville Orogen in Canada, using twenty-one biotite K-Ar dates (fig. 1A), contoured with what he called "thermochron lines," to emphasize the joint influence of temperature and time. He suggested that older dates are found near the Grenville Front because that zone cooled first, and then cooling and uplift gradually advanced southeastward into the interior of the Orogen. Cooling to the argon diffusion closure temperature for biotite, for samples now exposed at the surface, apparently took 300 Ma or more to advance from the Grenville Front 400 km to the St. Lawrence River.

Baer (1976) updated Harper's thermochron map, using ninety-six K-Ar dates (fig. 1B). (He stated only that the dates were from "micas," so they may have come from both biotite and muscovite.) Through most of Labrador and Quebec the thermochron lines are parallel with the Grenville Front, but this simple pattern does not extend into Ontario; Baer maintained that this change occurred along the Chibougamau-Gatineau Lineament, which he described as a major pre-Grenville structure; however, he linked the thermochron pattern in general with the last thermal peak of regional metamorphism during the Grenville Orogeny. Baer suggested that rocks now exposed near the Grenville Front were metamorphosed at relatively shallow depths, while rocks exposed toward the southeast had to come up from progressively greater depths. That is, the Grenville Front acted as a long hinge during post-orogenic uplift and cooling.

Easton (1986) compiled lists of isotopic dates of all kinds from the Grenville Province and produced a thermochron map using biotite K-Ar

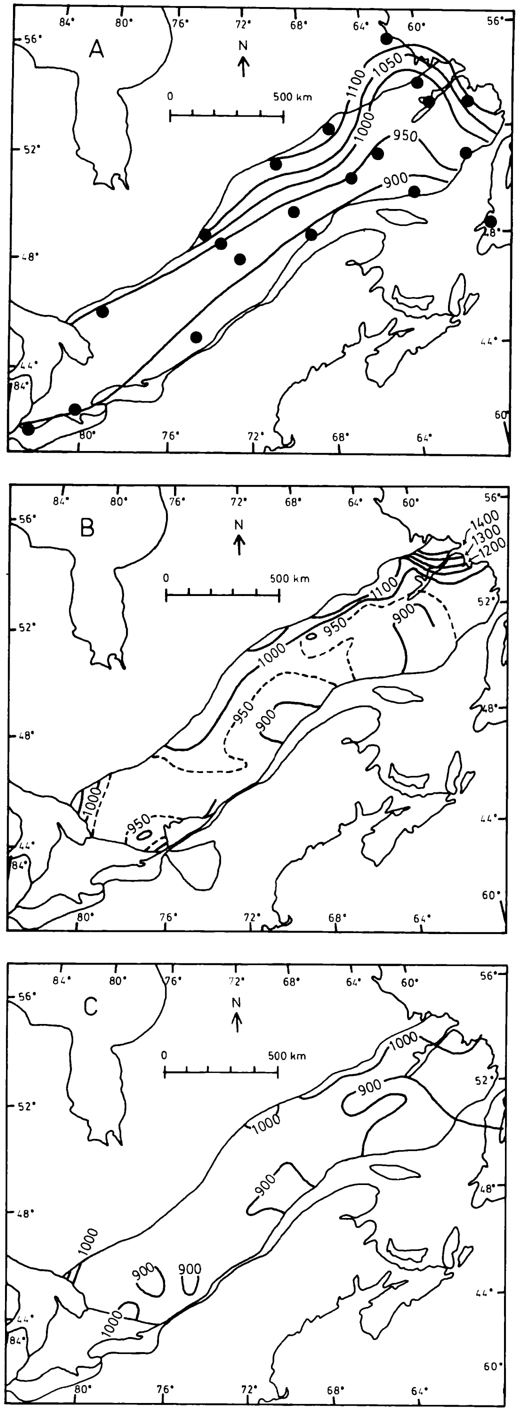

Fig. 1. Thermochron maps for the Grenville Orogen in Canada: (A) by Harper (1967) using twenty-one biotite K-Ar dates; (B) by Baer (1976) using ninety-six mica K-Ar dates; (C) by Easton (1986) using biotite K-Ar dates from gneiss and granite.

dates only from gneisses and granites (fig. 1C) which strongly resembles that of Baer (1976), but the common occurrence of individual dates that do not conform with the contours as drawn suggests more complexity.

DATES NOW AVAILABLE

The analyses that follow consider K-Ar and ^{40}Ar-^{39}Ar mineral dates together and focus on the main area of autochthonous Grenville rock exposures: the Grenville Province in mainland Canada, the Adirondacks, and western Newfoundland. Some dates from adjacent areas are included for comparison. Complete lists of the dates used, including locations and sample descriptions, are given in appendices available from the author:[1]

Hornblende: one hundred and eleven dates from 842 to 3017 Ma (fig. 2; app. 1); Muscovite: forty-three dates from 854 to 2331 Ma (fig. 3; app. 2); Biotite: two hundred and twenty-nine dates from 775 to 3771 Ma (fig. 4; apps. 3 and 4).

Most of the dates from hornblende and muscovite are from the southwestern half of the Grenville Orogen in Canada, and there are large parts of the region without any of these dates, so biotite remains the only mineral for which a map comparable to Harper's (1967) can be constructed, even though several times as many dates are now available. However, other analytical approaches can be applied to dates from all three minerals, most of which are assumed to be reliable Grenville cooling ages marking three successive temperatures achieved during post-peak uplift.

Hornblende Dates

If a typical closure temperature (535°C) is used, then hornblende K-Ar dates from metamorphic rocks in the amphibolite and granulite facies should have been set relatively soon after the thermal peak of the last regional metamorphism. In greenschist facies rocks hornblende would be a relict phase and might either preserve the age of some earlier heating event or be partially to completely reset. In the Grenville Orogen in mainland Canada amphibolite and granulite facies rocks cover much of the area, so most of the hornblende K-Ar dates ought to be somewhat younger than the age of the thermal peak of the last Grenville episode of regional metamorphism, unless the high-grade imprint is pre-Grenville as may be the case in part of Labrador (Thomas, Nunn, and Krogh, 1986).

Hornblende K-Ar dates from the Grenville Orogen in Canada show no gaps greater than 50 Ma between 842 and 1230 Ma, but most of the dates are in fact between 900 and 1020 Ma (fig. 5). There are few between 1230 and 1900 Ma, and only one date older than 1200 Ma is from a sample more than 50 km southeast of the Grenville Front.

[1] The appendices are available directly from the author as paper copies or Microsoft WORD document files (please send a blank, 5¼", DS-DD, floppy diskette formatted for MS-DOS.)

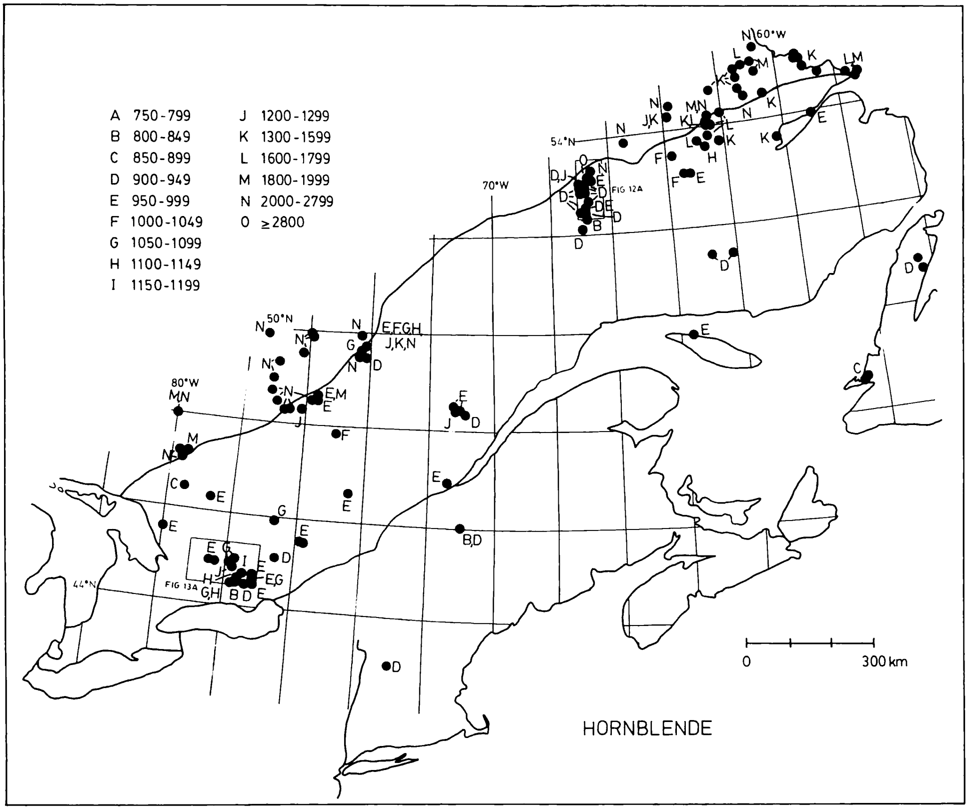

Fig. 2. Map of hornblende K-Ar and ^{40}Ar-^{39}Ar dates from the Grenville Orogen and adjacent areas. The position of the Grenville Front is from Fraser, Heywood, and Mazurski (1978), except for adjustment at the northeast end from Gower and others (1980) and at the southwest end by Davidson (1986a).

A graph of hornblende dates versus distance from the Grenville Front (fig. 6A) shows a conspicuous gap from 150 to 220 km, because so many of the samples were either from close to the Grenville Front or from southeastern Ontario. Except for this gap, a mixture of dates from 840 to 1000 Ma extends in a horizontal band across the full width of the exposed autochthonous Grenville Orogen, although there may be a decline beyond the St. Lawrence River. Sparse dates up to 1202 Ma also extend nearly across the mainland Canadian portion, with no obvious gap between 1000 and 1200 Ma.

Muscovite Dates

The argon diffusion closure temperature for muscovite is substantially lower than that for hornblende but probably slightly higher than that for biotite. Therefore, muscovite K-Ar dates should represent a

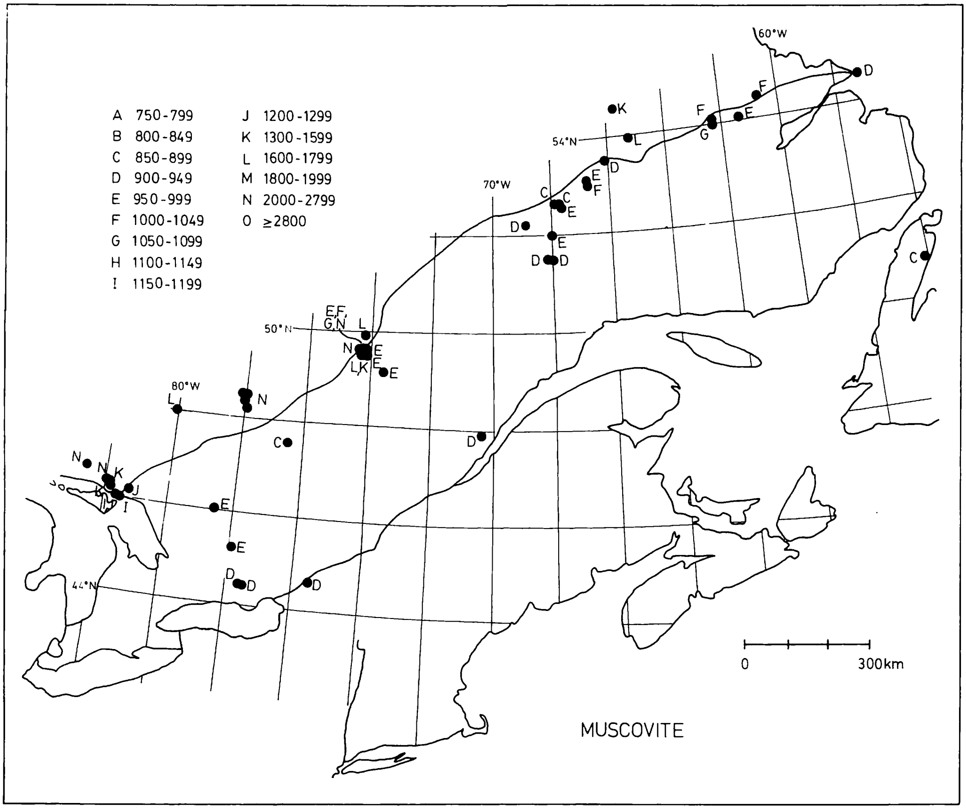

Fig. 3. Map of muscovite K-Ar dates from the Grenville Orogen and adjacent areas.

significantly later stage in post-peak cooling than do the hornblende dates. The typical closure temperature used here (350°C) suggests that, except in lowest greenschist facies rocks, muscovite dates are unlikely to preserve the age of some pre-Grenville thermal event.

Most of the muscovite K-Ar dates are between 850 and 1000 Ma (fig. 5), a range quite similar to that for the bulk of the hornblende dates. A few muscovite dates continue up to 1070 Ma, and there is a small cluster around 1200 Ma, but dates older than 1000 Ma only occur less than 50 km from the Grenville Front. As is the case for hornblende, the location of muscovite dates between 850 and 1000 Ma shows no strong correlation with distance from the Grenville Front (fig. 6B). Although rather sparse, the dates on this diagram also suggest a broad horizontal band between 850 and 1000 Ma across the full 400 km width of the Grenville Orogen in mainland Canada.

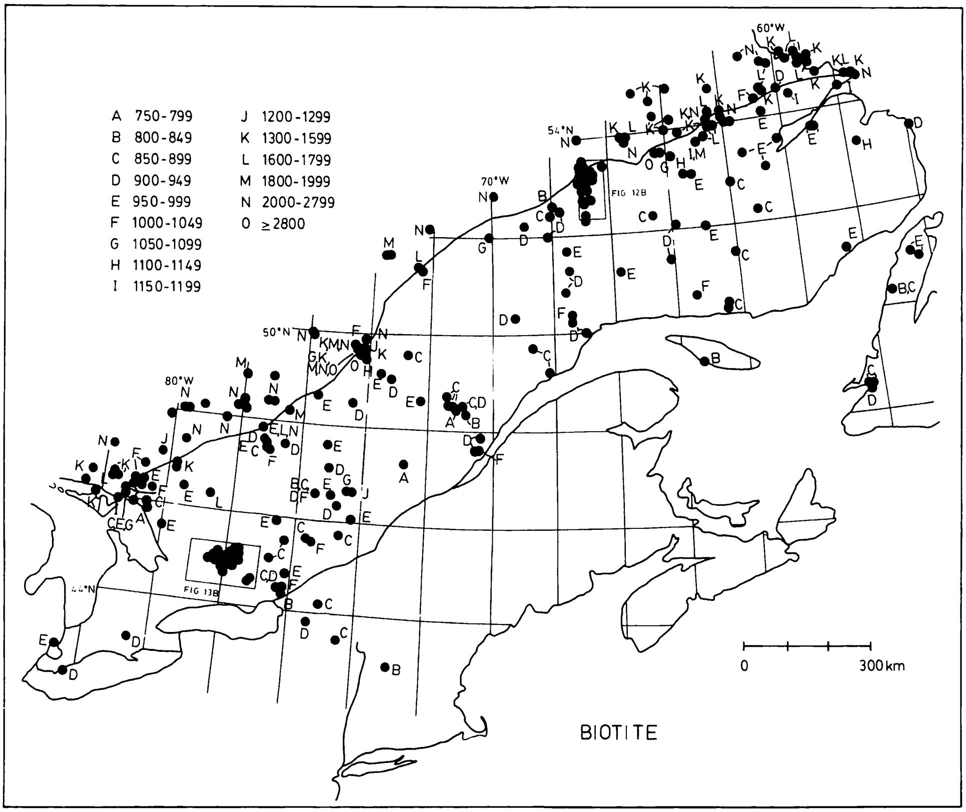

Fig. 4. Map of biotite K-Ar and ^{40}Ar-^{39}Ar dates from the Grenville Orogen and adjacent areas.

Biotite Dates

Biotite typically has the lowest argon diffusion closure temperature of the three minerals considered here, so biotite K-Ar dates should record a slightly later stage in cooling than muscovite dates in nearly all the rocks affected by Grenville regional metamorphism. Given the closure temperature used here (310°C), these dates are unlikely to preserve evidence of earlier thermal events, even in greenschist facies areas.

Figure 5 shows that most of the biotite K-Ar dates are between 800 and 1000 Ma, similar to the main ranges for hornblende and muscovite, but continuing up to a small cluster around 1060 Ma. Dates between 1060 and 1200 Ma are less common, although they too are found across nearly the full width of the Canadian Grenville Orogen. There are several biotite dates between 1250 and 2500 Ma, but only one in this

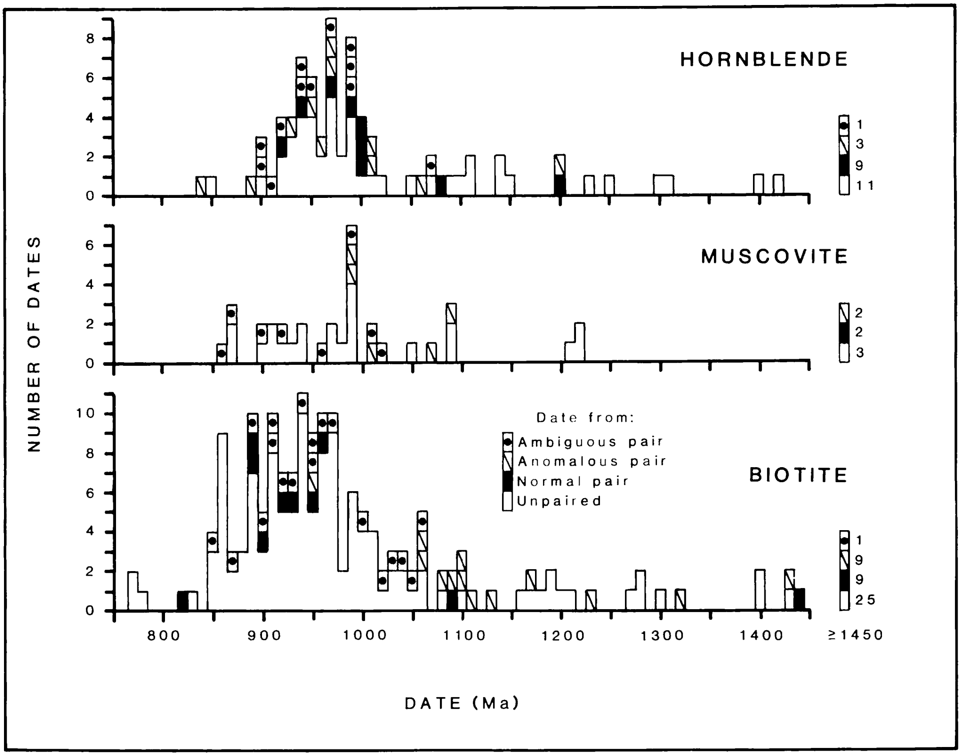

Fig. 5. Graphs of frequencies of hornblende, muscovite, and biotite dates, from the Grenville Orogen in mainland Canada, 400 km or less from the Grenville Front.

range is from more than 50 km southeast of the Grenville Front (fig. 4).

Figure 6C shows that across the Grenville Orogen in mainland Canada most of the biotite dates fall into a broad horizontal band between 800 and 1000 Ma. As for hornblende and muscovite, young to old dates in this range are mixed throughout the area.

Figure 6C in effect projects the biotite dates to a single profile across the Orogen. Excluding Labrador, an equivalent profile from Harper's or Baer's thermochron maps would consist of a relatively narrow linear trend with a negative slope, from more than 1100 Ma at the Grenville Front down to less than 900 Ma at the St. Lawrence River. A profile of this type is also implied by both Harper's and Baer's explanations of the nature of post-Grenville regional cooling.

Possible Preservation of Older Dates

For all three minerals considered here, most of the K-Ar mineral dates older than 1100 Ma are from a 50-km wide zone roughly coinciding with Wynne Edwards' (1972) Grenville Front Tectonic Zone (GFTZ), which is characterized by northeast-trending Grenville-age mylonite zones and metamorphic isograds superimposed on recognizably older rocks. Many of these older dates could simply be cooling ages preserved from pre-Grenville heating events recognized northwest of the Grenville Front. Dates from U-Pb zircon concordia and Rb-Sr whole-rock isochrons indicate that Archean rocks in Quebec extend at least 200 km inside the Grenville Orogen (as pointed out by Doig, 1977, for a traverse southeast from Val d'Or; Anderson and Burke, 1983, evaluated evidence for the broader region). Recent work in Labrador shows evidence of a 1600 to 1650 Ma high-grade metamorphic event that extends into the Orogen a similar distance. However, few K-Ar mineral dates near the Front are identical with K-Ar dates nearby on the northwest side of the Front, where cooling ages from pre-Grenville thermal events should be better preserved. Most of the dates older than 1100 Ma from within the Grenville Orogen appear to be younger than nearby dates across the Front, but a few are considerably older. The GFTZ also contains many K-Ar dates from the "typical Grenville" range and is the site of most of the length of the 1000 Ma and older contour lines in both Harper's (1967) and Baer's (1976) thermochron maps. There are also several dates younger than 900 Ma in the zone. While many of the dates younger than 1100 Ma are probably reliable Grenville cooling ages, some could have resulted from igneous intrusion events not directly related to the Grenville Orogeny. For example, in the Nain Province on the Labrador Coast, intrusion ages of anorthositic and alkalic bodies are as young as 1150 Ma (see Taylor, 1979, for summary). If any of the anorthosite bodies within the Grenville Orogen were intruded this late (as suggested by Emslie, 1978), then their igneous cooling ages could overlap the older end of the range of Grenville metamorphic cooling ages.

Partial Resetting

Several of the K-Ar dates near the Front, from all three minerals, appear to be too young to be cooling ages from heating events recognized in the adjacent age provinces but too old to be Grenville cooling ages. For example, dates between 2200 and 1250 Ma next to the Superior Province may have been partially reset by Grenville heating: radiogenic argon that accumulated following the Archean heating event was not all expelled during Grenville metamorphism. Partial resetting can be seen clearly in some ^{40}Ar-^{39}Ar release spectra from Dallmeyer and Rivers (1983), in which the initial release steps show argon loss; the higher temperature steps may preserve a plateau age for normal cooling from the earlier event. However, recognizing partial resetting from a single K-Ar date requires independent knowledge of the ages of both heating events; it is easier if one has a pair of K-Ar mineral dates from one sample, as their dates will be in the normal order expected from their argon diffusion closure temperatures but farther apart than

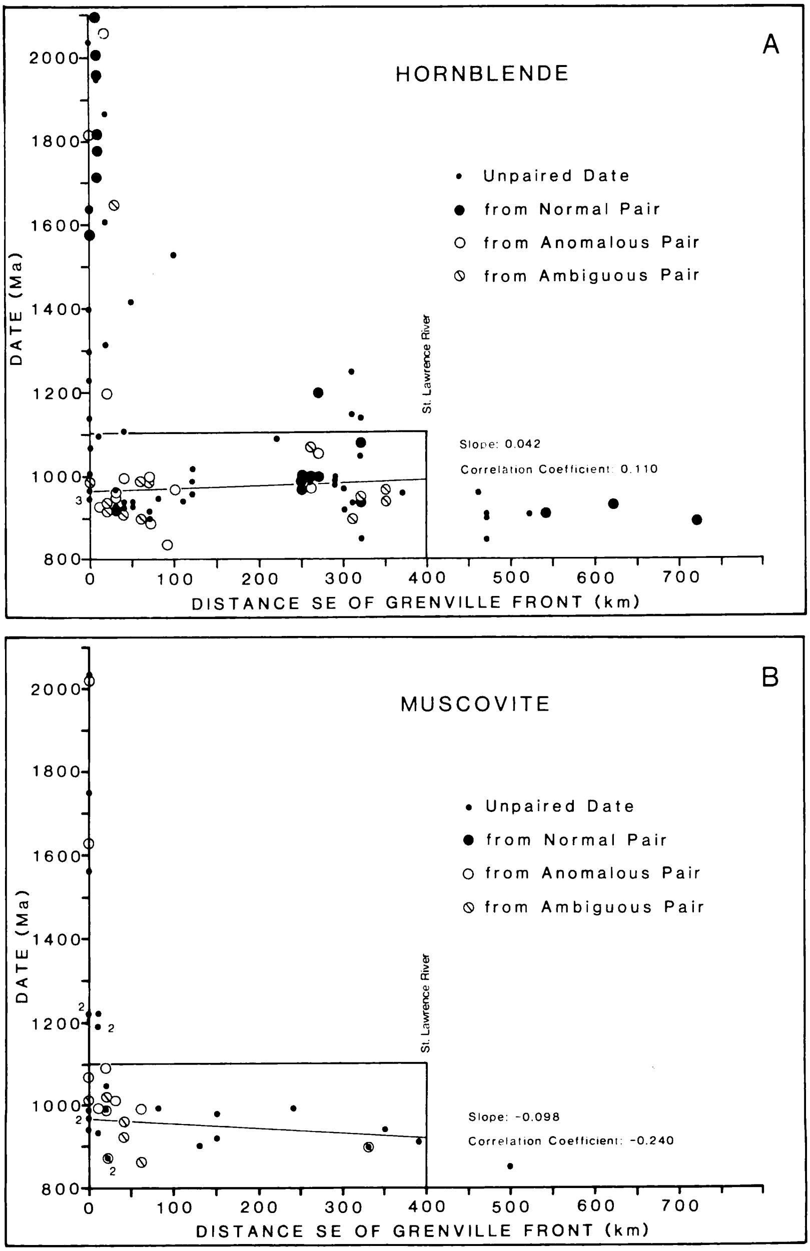

Fig. 6. Dates versus distance southeast of the Grenville Front: (A) hornblende—with simple regression line for cooling ages inside small box; (B) muscovite—with simple regression line for cooling ages inside small box.

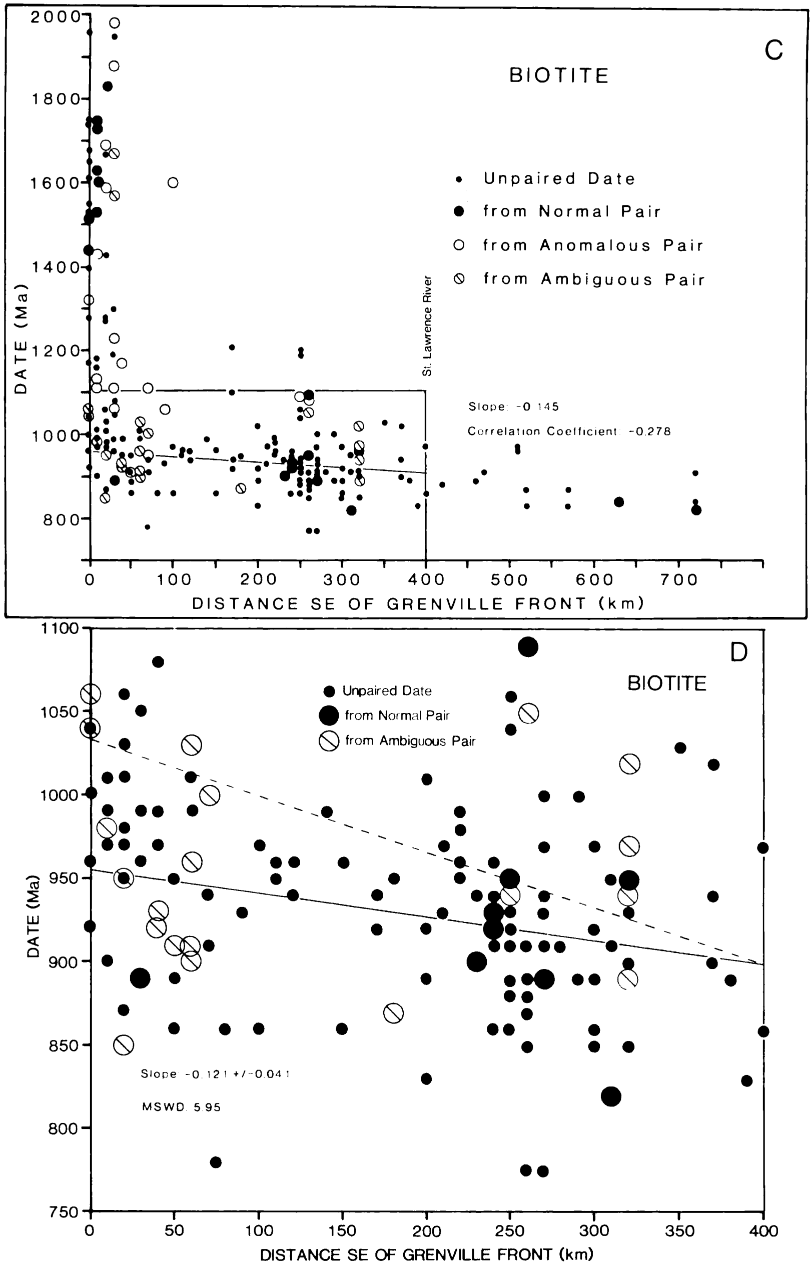

Fig. 6. (continued)
(C) Biotite—with simple regression line for cooling ages inside small box; (D) biotite—using cooling ages from figure 9, less than 400 km from the Front—with regression line that takes errors into consideration (If no error was published with a date then ±25 Ma was used in the regression; all distances were assigned errors of ±10 km.) The dashed sloping line is a simple regression line for twenty of the biotite K-Ar dates used by Harper (1967).

expected from normal cooling rates (Armstrong, 1966). Table 1 contains five conspicuous pairs of this type: three hornblende-biotite and two muscovite-biotite, all from near the Grenville Front adjacent to the Archean Superior Province. The hornblende and muscovite dates look like normal Superior Province cooling ages, while the biotite dates are substantially younger, although not young enough to be considered normal Grenville cooling ages. The peak metamorphic temperature may have been just high enough to allow escape of some of the old radiogenic argon from biotite but not high enough to affect muscovite or hornblende. In two other muscovite-biotite pairs the muscovite dates appear to have been partially reset from Superior Province cooling ages, whereas the biotite dates are much too old. These suggest a slightly higher temperature, affecting muscovite and biotite in distinctly different ways by allowing release of argon from muscovite but addition to biotite.

Excess Argon

It is well known that argon can be added during heating to many minerals (Armstrong, 1966), as shown by:

1. dates that are far too old to be reasonable cooling ages for any known heating event in the vicinity;

2. dates that are in "anomalous pairs" (Wanless, Stevens, and Loveridge, 1970) from a single sample, in which the mineral that usually has the lower argon diffusion closure temperature gives the older date (in contrast with "normal pairs");

3. abnormal ^{40}Ar-^{39}Ar release spectra, most obviously ones with high radiogenic argon in the first release steps, leveling down to a plateau in the higher-temperature steps. The plateau may give a cooling age for the earlier heating event, but Seidemann (1976) described three other common excess-argon spectra that do not give even this much information. For example, Dallmeyer (1987) showed a normal-looking biotite plateau which gave a date of 1168 Ma, but it is from an anomalous pair, since the hornblende plateau from the same sample gave a date of only 1011 Ma. An isochron diagram of $^{39}Ar/^{40}Ar$ versus $^{36}Ar/^{40}Ar$ from stepwise extraction may help in distinguishing the excess argon component and in compensating for it in calculation of a reliable cooling age; it may even be possible to distinguish multiple excess components that are thermally distinct (M. Heizler and T. M. Harrison, personal commun., 1987).

As shown in figures 4 and 6C, excessively old biotite dates and anomalous pairs are most abundant near the Front and suggest that biotite is more vulnerable to excess-argon problems than either hornblende or muscovite. Wanless, Stevens, and Loveridge (1970) found that biotite K-Ar dates near Chibougamau, Quebec, showed clear evidence of excess Ar (the most extreme example being the date of 3771 Ma) and reached a maximum 2 to 3 km northwest of the Grenville Front, where hornblende and muscovite K-Ar dates showed partial to complete resetting. At the Front (structurally defined), biotite dates were apparently completely reset by Grenville reheating, but 2 to 3 km southeast of the Front acquired minor excess argon again. A few kilometers northeast, Baker (ms., 1980) found signs of minor excess argon in hornblende ^{40}Ar-^{39}Ar spectra just northwest of the Front. Less dramatic problems with excess argon can be seen in biotite ^{40}Ar-^{39}Ar spectra along the Front at the intersection with the Labrador Fold Belt (Dallmeyer and Rivers, 1983), in the Trans Labrador Batholith (Dallmeyer, 1987), and can also be inferred from the abundance of anomalous pairs in both areas.

Reliable Biotite Cooling Ages

In spite of its obvious vulnerability to excess argon, biotite is still the only mineral for which sufficient dates exist to draw a K-Ar thermochron map like Harper's (1967) for the whole Grenville Orogen. However, K-Ar dates from the other two minerals can aid in deciding which of the two hundred and twenty-nine biotite dates are reliable Grenville cooling ages. Five biotite dates older than 2800 Ma can be excluded immediately, because they are older than any K-Ar mineral dates in the adjacent Archean areas. Away from the Grenville Front, the absence of hornblende and muscovite K-Ar dates older than 1250 Ma suggests there are unlikely to be any Grenville biotite cooling ages older than 1250 Ma, since biotite has a lower argon diffusion closure temperature; this criterion eliminates another fifty biotite dates. The fact that most of the dates from all three minerals are between 800 and 1000 Ma, or at most 1100 Ma, suggests that most of the region was last affected by a major heating event not much earlier. For the 1000 to 1250 Ma interval, normal and anomalous pairs of dates provide additional clues.

Table 1 lists sixty-six pairs of dates, each from one sample. Forty-eight pairs are from hornblende-biotite, and seventeen from muscovite-biotite. Twenty-two of these pairs are anomalous, and twenty-three are normal. Unfortunately, the remaining twenty-one pairs might best be described as "ambiguous": when analytical uncertainties are considered, these pairs could be either normal or anomalous. Hornblende-biotite pairs giving identical cooling ages might be expected in quickly-cooled volcanic rocks but seem unlikely in a high-grade regional metamorphic terrane. In addition, the Geological Survey of Canada did not state errors for individual dates they published before 1965, including most of the muscovite dates in table 1. For hornblende and biotite dates less than 1100 Ma (in table 1), the mean two-sigma error is approx 25 Ma. Therefore, a crude estimate of the error in the date difference for most of the muscovite-biotite pairs is 50 Ma, which is greater than the difference itself for nearly all of them, rendering them "ambiguous."

Thirty-two of the hornblende-biotite pairs have one or both dates within the "typical Grenville" range, 750 to 1250 Ma, so that at least one of the dates in each pair is potentially a reliable Grenville cooling age.

TABLE 1

Pairs of biotite-muscovite and biotite-hornblende dates from the same sample, for samples from the Grenville orogen in Canada

Biotite		Muscovite		Hornblende		Pair Difference		Pair Type	Lat (°N)	Long (°W)
Date	Error	Date	Error	Date	Error		Error			
521	20			914	38	+393	58	N	50.5	56.3
818	30			944	37	+126	67	N	48.3	70.9
823	15			890	15	+67	30	N	48.5	58.4
846	32	873	32			+27	64	B	52.5	67.9
868	25			900	41	+32	66	B	51.4	62.0
888	24			996	30	+108	54	N	48.5	71.3
889	—	904	—			+15	—	B	44.5	77.4
891	16			925	17	+34	33	N	52.9	66.9
898	7?			966	8?	+68	15	N	44.9	78.5
905	—	859	—			−46	—	B	47.5	76.5
911	—	921	—			+10	—	B	52.2	68.9
914	15			905	14	−9	29	B	52.6	66.8
916	7?			988	9?	+72	16	N	44.9	78.5
919	26			914	31	−5	57	B	52.9	66.8
930	3?			999	5?	+69	8	N	44.9	78.5
930	—	956	—			+26	—	B	52.5	67.7
944	—			943	—	−1	—	B	44.5	77.4
948	14			942	16	−6	30	B	53.0	67.0
951	—			895	31	−56	—	A	46.4	79.5
955	7?			998	7?	+43	14	N	44.9	78.3
955	34			916	38	−39	72	B	53.0	67.0
956	—			1080	—	+124	—	N	44.6	77.2
960	—	990	—			+30	—	B	49.1	73.6
969	—			951	—	−18	—	B	44.7	77.2
984	36			988	40	+4	76	B	48.6	75.5
996	15			991	15	−5	30	B	53.1	63.2
1016	—			974	—	−42	—	B	44.5	77.2
1026	28			995	34	−31	62	B	52.6	66.8
1045	—	1015	—			−30	—	B	54.4	60.7
1055	—			1075	—	+20	—	B	44.8	77.9
1060	—	1020	—			−40	—	B	49.6	74.3

Figure 7A shows that for any hornblende date from these pairs the difference between it and the biotite date from the same sample is equally likely to be either positive or negative and, if negative, either large or small. Figure 7B shows that biotite dates from 818 to 1000 Ma are associated with either small positive differences or small negative differences (normal and ambiguous pairs), but for biotite dates older than 1000 Ma the differences are nearly all negative (anomalous pairs) and become progressively larger for older biotite dates. A least-squares-fit line through the anomalous pairs has a slope of about −1, suggesting that the anomaly, attributed to excess argon, is entirely in the biotite dates.

Thirteen of the muscovite-biotite pairs also have one or both dates in the "typical Grenville" range. Figure 8A shows that for muscovite dates younger than 990 Ma the pair differences are all small; above 990 Ma the differences are mostly negative, but the amount of the difference does not show much correlation with the muscovite date itself. Figure 8B strongly resembles figure 7B: biotite dates younger than 1000 Ma are

TABLE 1
(Continued)

Biotite		Muscovite		Hornblende		Pair Difference		Pair Type	Lat (°N)	Long (°W)
Date	Error	Date	Error	Date	Error		Error			
1060	—	1007	—			−53	—	A	52.9	66.8
1061	29			842	29	−219	58	A	52.3	66.8
1083	8 ?			1056	8 ?	−27	16	A	45.0	77.7
1090	8 ?			1202	10 ?	+112	18	N	45.0	77.7
1090	40			966	82	−124	122	A	46.6	74.5
1104	17			963	15	−141	32	A	53.1	66.5
1111	18			1013	14	−98	32	A	53.1	63.4
1115	—			931	32	−184	—	A	49.4	74.1
1135	—	990	—			−145	—	A	53.1	66.7
1168	17			1011	15	−157	32	A	53.5	63.8
1232	18			946	15	−286	33	A	53.0	66.9
1323	—	1070	—			−253	—	A	49.6	74.3
1432	50	995	30			−437	80	A	49.5	74.2
1444	36			1579	46	+135	82	N	54.5	60.5
1506	17			1645	13	+139	30	N	54.6	57.3
1534	23			1713	27	+179	50	N	54.2	62.0
1534	23			1788	25	+254	48	N	54.2	62.0
1602	11			1639	15	+37	26	N	54.6	57.6
1603	40			975	33	−628	73	A	46.3	78.7
1626	20			1965	27	+339	47	N	54.2	62.4
1626	20			2014	25	+388	45	N	54.2	62.4
1671	23			1652	22	−19	45	B	53.7	62.9
1689	23	1088	15			−601	38	A	54.0	62.3
1730	23			1812	27	+82	50	N	54.1	62.5
1755	25			2100	30	+345	55	N	53.3	66.6
1816	—	2331	—			+515	—	N	49.6	74.4
1826	60			2453	75	+627	135	N	48.3	76.5
1980	24			1652	21	−328	45	A	53.8	62.6
2081	70	2287	80			+206	150	N	49.6	74.4
2169	26			2056	26	−113	52	A	54.1	62.5
2189	25			2056	26	−133	52	A	54.1	62.5
2231	72			1203	46	−1028	118	A	53.0	67.0
2472	70	2023	60			−449	130	A	49.6	74.3
2751	17			1822	13	−929	30	A	54.5	57.2
3264	90	1635	50			−1629	140	A	49.5	74.3

Date differences are positive for normal pairs and negative for anomalous pairs.
Pair types are N = normal, B = ambiguous, and A = Anomalous.
Standard deviations for errors are 2-sigma, except for dates indicated by "?", for which they are probably 1-sigma.

mainly from ambiguous pairs, whereas those older than 1000 Ma are mainly from anomalous pairs, and the older the biotite date the larger the difference. Again, a least-squares-fit line through the anomalous pairs has a slope of about −1, suggesting that excess argon mainly affected biotite.

The twenty-two biotite dates from anomalous pairs are unlikely to be reliable cooling ages, even the eleven within the "typical Grenville" range. In addition, biotite dates between 1100 and 1250 Ma are seen only in 6 anomalous pairs and no normal or ambiguous pairs, so these dates are also excluded along with nine unpaired biotite dates from this range. This leaves one hundred and fifty-six biotite dates considered most likely to be reliable Grenville cooling ages, including eleven from

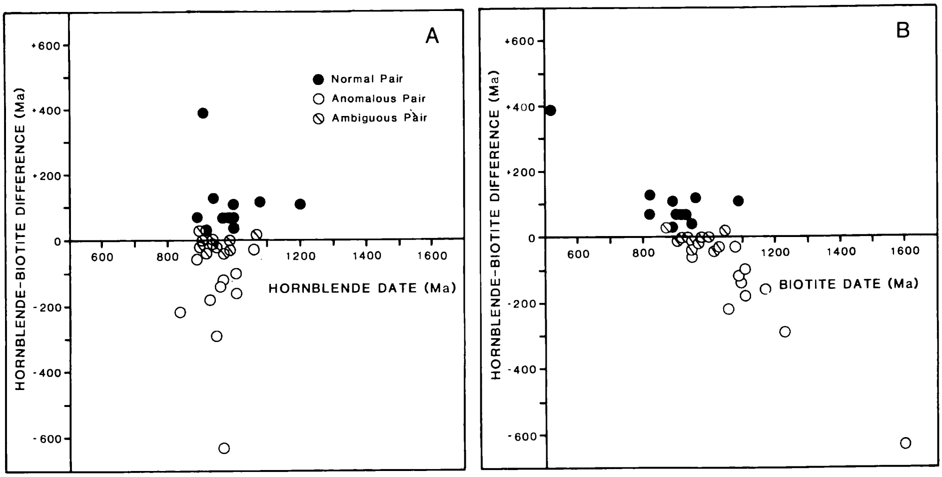

Fig. 7(A) Hornblende dates versus the differences between hornblende and biotite dates for pairs from the same sample, with at least one date in each pair between 750 and 1250 Ma; (B) biotite dates versus the differences between hornblende and biotite dates.

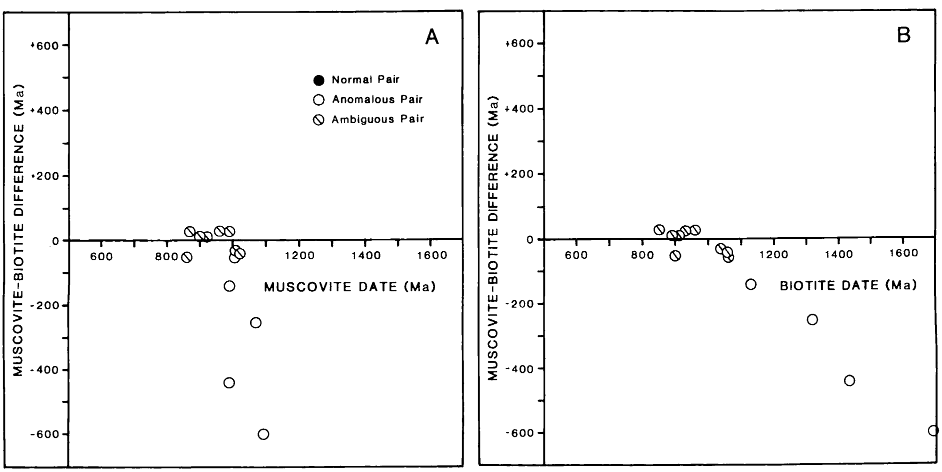

Fig. 8(A) Muscovite dates versus the differences between muscovite and biotite dates; (B) biotite dates versus the differences between muscovite and biotite dates.

normal pairs and twenty from ambiguous pairs. Twenty-three of the total, those between 1000 and 1100 Ma, should also probably be viewed with some caution, as only one of them is from a normal pair, while five are from ambiguous pairs.

New Thermochron Map

Figure 9 is a thermochron map using these one hundred and fifty-six selected biotite K-Ar and ^{40}Ar-^{39}Ar dates between 775 and 1100 Ma, from all rock types and metamorphic grades. The pattern on this thermochron map is more complex than that shown on the maps by Harper (1967), Baer (1976), or Easton (1986). If the twenty dates from ambiguous pairs were excluded, there would be only minor changes in the positions of the contour lines, primarily in the two subareas with particularly abundant paired dates, shown in detail in figures 12 and 13.

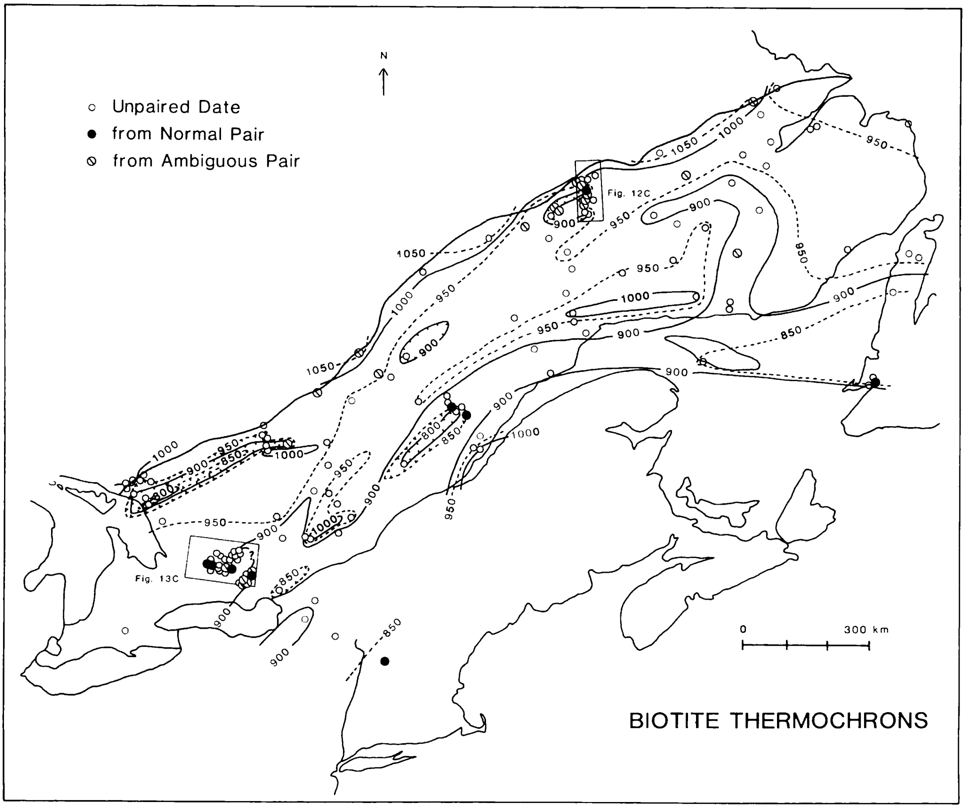

Fig. 9. Thermochron map of the Grenville Orogen, using one hundred and fifty-six biotite dates from mainland Canada, Newfoundland, and the Adirondacks. Solid lines are contours for 800, 900, and 1000 Ma; dashed lines are contours for 850, 950, and 1050 Ma.

Because the average analytical uncertainty on any of these dates is 25 Ma, use of a 50 Ma contour interval may be questionable, but even if the dashed contours (850, 950, and 1050 Ma) are ignored, many aspects of the pattern do not change, and it certainly does not revert to the monotonic southeastward decrease shown in earlier maps. In Labrador, the similarity between this map and Baer's is the result of using the same sparse dates. Differences are more conspicuous in the areas where dates are more closely spaced and where additional dates have been obtained in the last 10 yrs. As shown here, and on the graph of these selected biotite dates versus distance from the Front (fig. 6D), dates from 800 to 1000 Ma occur at all distances from the Front, and dates from the extremes of this range are sometimes quite close together. For a majority of the dates 1000 Ma and older, a date younger than 900 Ma can be found less than 50 km away. Thermochron lines are most closely spaced in areas containing the highest density of dates.

The closure temperature for strontium diffusion in biotite appears to be similar to that for argon (Jäger, 1979), so Rb-Sr biotite dates could be a useful supplement in areas where excess argon in biotite is known to be a problem. Easton's (1986) compilation contains a dozen Rb-Sr biotite dates between 850 and 1100 Ma within the Grenville Orogen, but nearly all are from two small areas near the Grenville Front, one near Lake Huron, and the other near Chibougamau. In each area, the dates cover a range from 880 to 1030 Ma across less than 50 km. That is, the Rb-Sr biotite cooling ages also show nearly the full range seen in the biotite K-Ar cooling ages within small areas, and rather young Rb-Sr cooling ages are also found close to the Grenville Front.

Comparing the thermochron map with the metamorphic facies map by Fraser, Heywood, and Mazurski (1978) does not show the correlation between dates and metamorphic grade predicted by Baer's (1976) model of post-peak uplift. Grade has also been crudely estimated from the sample descriptions for approximately one hundred fifty of the biotite cooling ages, and these also show no clear correlation between dates and grade. However, the low-grade samples do have more than the average proportions of both anomalous pairs and dates over 1250 Ma (fig. 10), whereas the high-grade rocks have more than a proportional share of normal pairs and only one date over 1050 Ma.

Nearly all the dates used in the biotite thermochron map were also assigned to classes by rock type, and there is no clear relationship between dates and lithologies (fig. 11). In particular, rock types likely to be pre-Grenville, such as alkalic and anorthositic rocks, do not give markedly older dates. However, mafic rocks show a slightly higher proportion of anomalous and ambiguous pairs, suggesting particular problems with excess argon in biotite in this rock type, even well within the Grenville Province.

Two areas outlined by rectangles in figure 9 contain too many biotite dates to show full detail in the contour lines on that scale. Detailed Grenville metamorphic isograds have previously been mapped

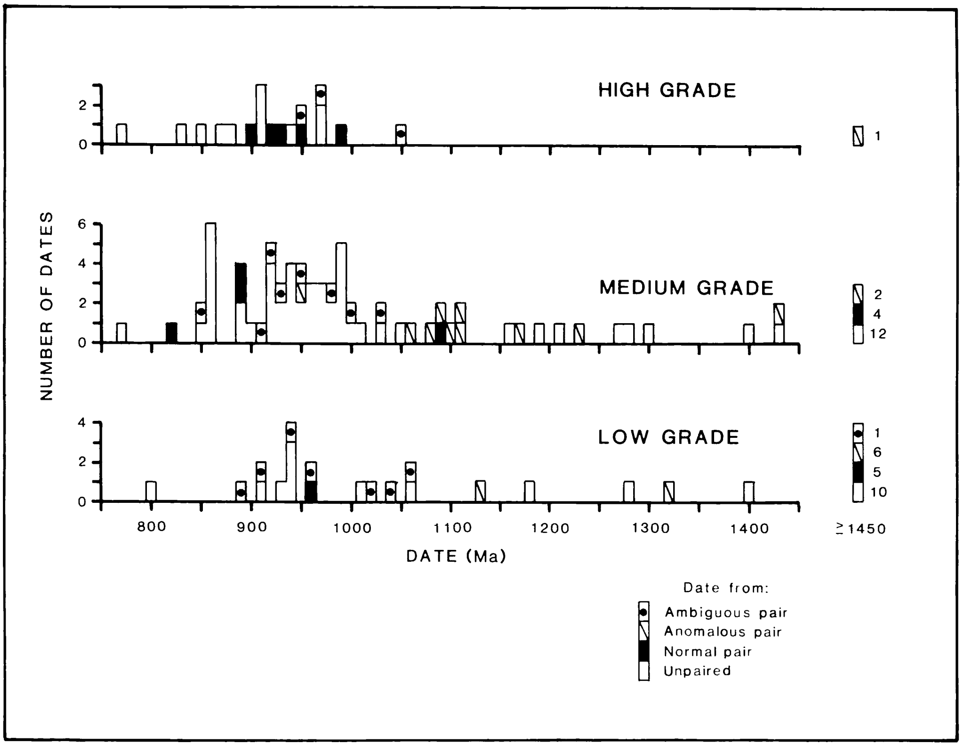

Fig. 10. Biotite dates divided by metamorphic grade, for dates from the Grenville Orogen in Canada 400 km or less from the Grenville Front.

in both areas, and they each also contain several hornblende dates. These areas are shown in more detail in figures 12 and 13.

Figure 12 shows an area near the intersection of the Grenville Front with the west side of the Labrador Fold Belt, much of it within the GFTZ. In the lowest-grade rocks, close to the Front, preserved and partially reset pre-Grenville hornblende dates are dominant (fig. 12A). In the middle and upper amphibolite facies most of the hornblende dates are between 900 and 950 Ma and are likely to be reliable Grenville cooling ages. They show only a weak correlation with distance from the Front, with slightly older hornblende dates toward the northwest. The only biotite date from a normal pair, 891 Ma, is close to Front, and the biotite date shown farthest from the Front is 857 Ma (fig. 12B); these are considered reliable Grenville cooling ages by Dallmeyer and Rivers (1983). Other than these two, most of the biotite dates in the area are between 900 and 1100 Ma and might be interpreted as reliable cooling ages except that many of them come from anomalous or ambiguous pairs. Figure 12C shows thermochron lines for unpaired dates and those

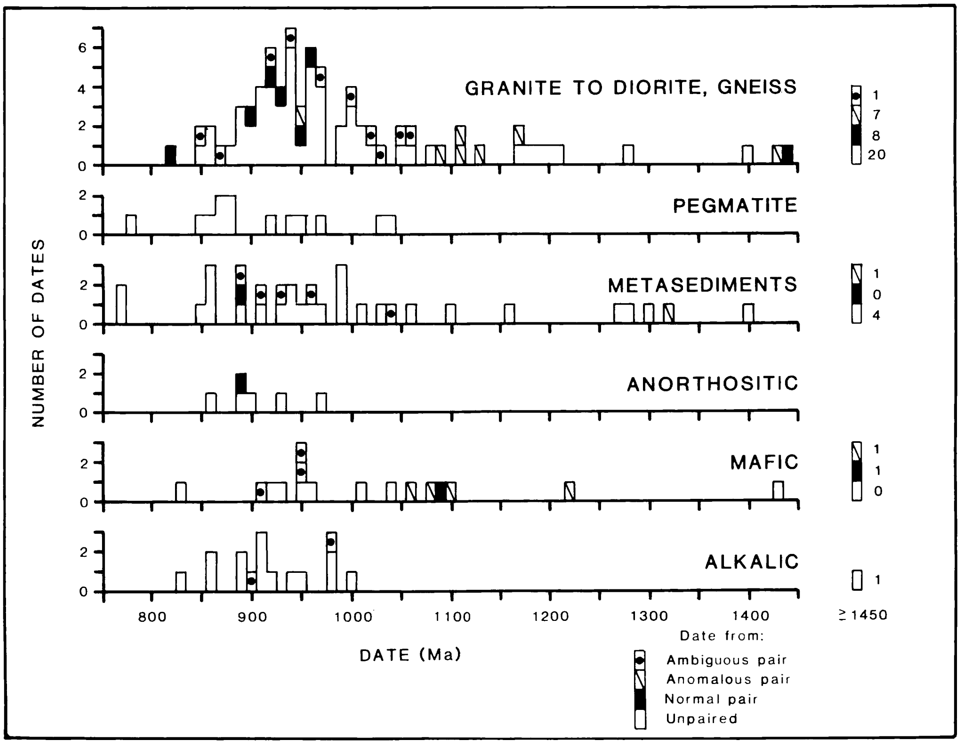

Fig. 11. Biotite dates divided by rock type, for dates from the Grenville Orogen in Canada 400 km or less from the Grenville Front.

from normal and ambiguous pairs. Near the Front is a steep gradient, from over 1000 Ma to less than 900 Ma in less than 20 km. If the dates from ambiguous pairs were not used, the thermochron lines might be smoother, but this feature would remain.

Figure 13 shows a part of the Central Metasedimentary Belt in Ontario, including an area of low metamorphic grade far from the Grenville Front. Some of the older hornblende dates here (fig. 13A) have been attributed to pre-Grenville gabbro intrusion, seeing "through the veil" of Grenville metamorphism (Berger and York, 1981a). Preservation of cooling ages from this intrusion event at 1250 Ma (Silver and Lumbers, 1966; Bell and Blenkinsop, 1980) would be most likely in the lowest-grade zones, and this appears to be the case for the 1202 Ma hornblende date from the Thanet Gabbro. However, two other conspicuously old hornblende dates (1080 and 1075 Ma) (Mcintyre, York, and Moorhouse, 1967) are from upper to middle amphibolite facies areas, where pre-Grenville hornblende dates ought to have been reset.

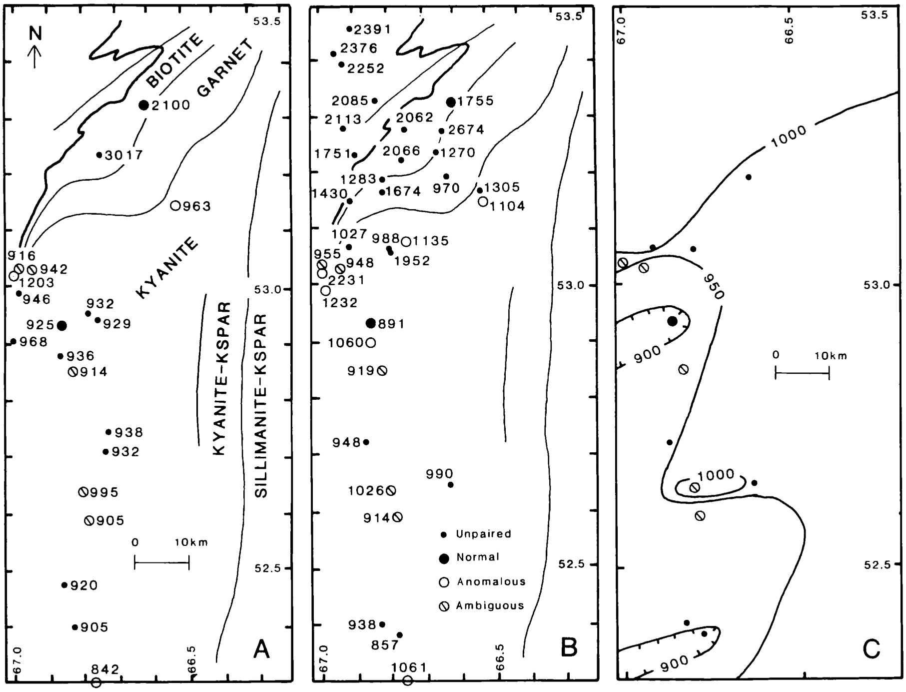

Fig. 12. Detail maps of the intersection of the Grenville Front and the Labrador Fold Belt: (A) hornblende dates and metamorphic zones (from Dallmeyer and Rivers, 1983); (B) all biotite dates; (C) reliable biotite cooling ages, with thermochron lines.

Younger hornblende dates are mainly from higher grade rocks, including both gabbro and granite, but also extend into low-amphibolite facies (fig. 13B).

This small area contains the full range of biotite dates seen in the Orogen as a whole, and the thermochron lines (fig. 13C) are not parallel with the metamorphic isograds, in contrast with the relationship seen by Dewey and Pankhurst (1969) for biotite and muscovite dates in a somewhat larger area in the Scottish Caledonides. Cosca, Essene, and Sutter (1988) have reported preliminary ^{40}Ar-^{39}Ar mineral dates from this area and higher grade areas to the east and west. They suggest that cooling to argon diffusion closure in hornblende occurred much later in the low grade area. From west to east, they obtained hornblende dates from 970 to 1000 Ma in the Central Gneiss Belt, 920 to 950 Ma in the Hastings Low, and 1070 to 1110 Ma in the Frontenac Axis. The 1000 and 1050 Ma thermochron lines in figure 13C may be biased by excess argon, suggested by the presence of anomalous pairs, or perhaps even partial resetting from pre-Grenville ages, since many of the samples were from gabbroic plutons.

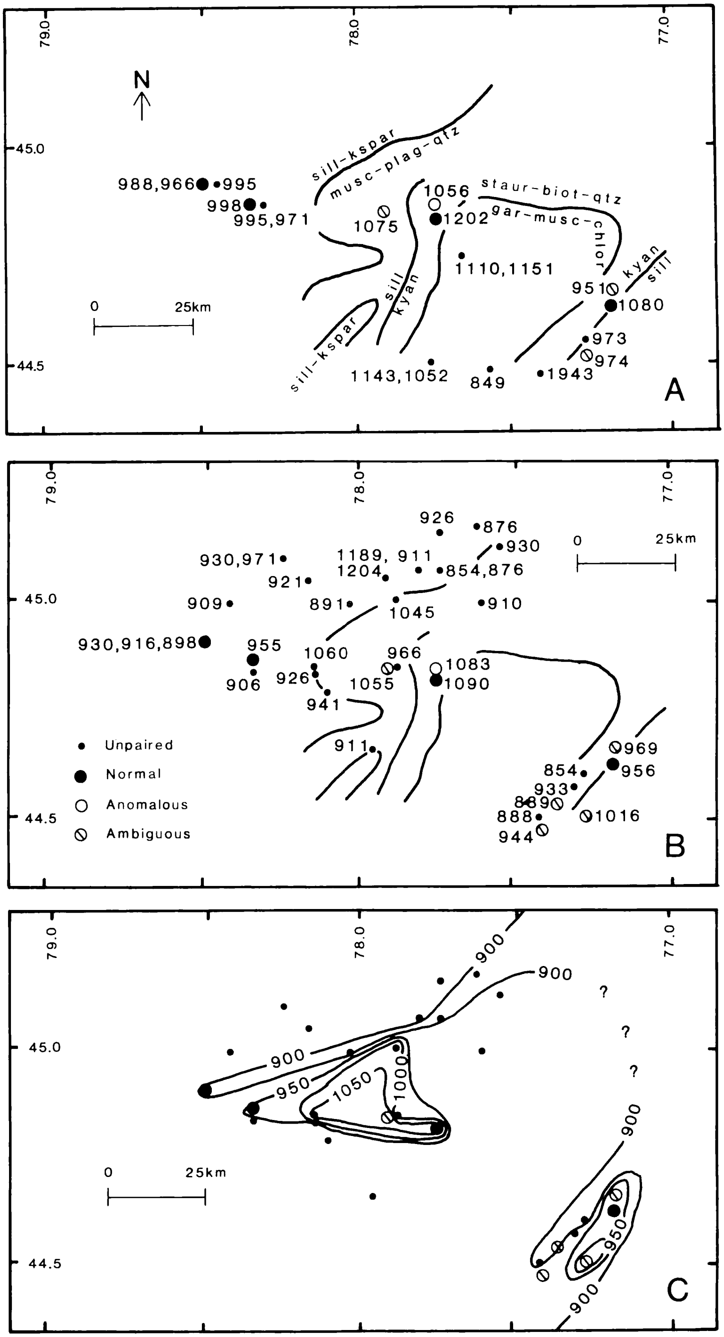

Fig. 13. Detail maps of part of the Central Metasedimentary Belt in Ontario: (A) hornblende dates and metamorphic isograds (from Carmichael, Moore, and Skippen, 1978); (B) all biotite dates; (C) reliable biotite cooling ages, with thermochron lines.

COOLING AND UPLIFT RATES

Previous Estimates

Berger and York (1981a) determined ^{40}Ar-^{39}Ar dates from hornblende, biotite, potassium feldspar, and plagioclase, from the Thanet Gabbro in the Central Metasedimentary Belt (within fig. 13) and calculated closure temperatures from the *in vacuo* argon extraction data. The dates cover a broad range, with the oldest (1202 Ma from hornblende) inferred to be a cooling age from original intrusion at 1250 Ma. The cooling rate to argon diffusion closure in hornblende would be rapid following intrusion into cold host rock, so the authors proposed that lower-amphibolite grade Grenville metamorphism, with a peak at about 1125 Ma, did not reset the hornblende date but set the biotite date for the same sample at 1090 Ma. Their figure 5 shows nearly instantaneous cooling following gabbro intrusion, followed by a peak-to-biotite cooling rate of approx 4°C/Ma and a biotite-to-plagioclase rate of approx 0.6°C/Ma. The closure temperatures for hornblende and biotite used by Berger and York (1981a) are higher than those preferred in the present work; if the values preferred here are substituted (535°C for hornblende, 310°C for biotite), the peak-to-biotite cooling rate would be 6.8°C/Ma, the average hornblende-to-biotite rate 2.0°C/Ma (ignoring the metamorphic peak between), and the biotite to plagioclase rate 0.6°C/Ma.

Berger and York (1981b) examined several diorite bodies in an upper amphibolite facies area on the western margin of the Central Metasedimentary Belt (within fig. 13). The hornblende dates are all between 966 and 998 Ma, and the biotite dates are all between 898 and 955 Ma (the plagioclase dates cover a broader range: 540 to 859 Ma). The closure temperatures preferred in the present study lead to an average hornblende-to-biotite cooling rate of 3.3°C/Ma (compared with 6.2°C/Ma using the authors' closure temperatures), and a biotite-to-potassium feldspar cooling rate of 0.7°C/Ma (using 310°C as the closure temperature for biotite and 230°C for the feldspar, the latter from Berger and York, 1981b).

Dallmeyer and Rivers (1983) estimated cooling rates from selected dates at the intersection of the Grenville Front and the Labrador Fold Belt (in the area shown in fig. 12). They recognized the abundance of anomalous and ambiguous pairs and signs of excess argon in nearly all the biotite release spectra, which limited their choice of samples. In lower amphibolite facies rocks near the Front and in higher grade rocks farther to the southeast, they obtained the same cooling rate: 3.6°C/Ma for the hornblende-to-biotite interval. The authors assumed that the peak of Grenville metamorphism occurred 1000 Ma ago throughout the area, leading to a peak-to-hornblende cooling rate of 1.4°C/Ma near the Front and 1.8°C/Ma in the higher grade portion of the area, to the southeast.

Cosca, Essene, and Sutter (1987) reported preliminary ^{40}Ar-^{39}Ar plateau ages in the Parry Sound region in southwestern Ontario, from

970 to 1000 Ma for hornblende, from 920 to 860 Ma for biotite, and from 854 to 875 Ma for plagioclase, leading to cooling rates, for unspecified intervals, from 2 to 4°C/Ma. Averages of these dates and the reported closure temperatures from Cosca, Essene, and Sutter (1987) (which are similar to those used in this study), produce cooling rates of 2.3°C/Ma for the hornblende-to-biotite cooling interval and 3.3°C/Ma for the biotite-to-microcline interval.

Cosca, Essene, and Sutter (1987) also calculated uplift rates for the Parry Sound area. They independently determined a geothermal gradient of 28°C/km from zoned garnets and calculated average uplift rates of 0.07 to 0.14 km/Ma for the hornblende-to-microcline interval. Cosca, Essene, and Sutter (1988) have recently reported the same range of uplift rates for both high and low grade areas in southeastern Ontario.

Cooling Rates from Normal and Ambiguous Pairs

Hornblende-biotite and muscovite-biotite.—Cooling rates in table 2 were calculated from ten normal and twelve ambiguous hornblende-biotite pairs and from eight ambiguous muscovite-biotite pairs. These also appear in table 1 and are widely dispersed across the Grenville Orogen in mainland Canada. The distinction between a normal and an ambiguous pair depends on both the difference between the dates and the analytical uncertainties for each date, and a small nominal difference may be due either to genuinely rapid cooling or a small proportion of excess argon in the mineral having the lower argon diffusion closure temperature. Precise dates (and ^{40}Ar-^{39}Ar spectra) are needed to distinguish between these two cases. In table 1, the average analytical uncertainty for hornblende and biotite dates younger than 1100 Ma is ±25 Ma, for an average uncertainty of ±50 Ma for a pair difference. Therefore, an "average" pair would be considered normal only if the pair difference exceeded 50 Ma, and the most rapid cooling rate possible would be 4.5°C/Ma, if the errors were not considered. Actually, some of the more recently published hornblende-biotite pairs have pair difference errors as small as ±8 Ma (although the standard deviations for these dates may be only one-sigma).

The ten normal hornblende-biotite pairs give nominal cooling rates of 1.8 to 6.6°C/Ma, with a mean of 3.2°C/Ma. If the errors for these pairs are considered, then the range of possible cooling rates is much broader: 1.2 to 225.0°C/Ma, and if the ambiguous pairs are also considered then the maximum cooling rate is infinitely rapid. (It is not reasonable to calculate an average cooling rate for the ambiguous pairs using the nominal pair differences, since some are negative). If the errors are added to all the pair differences (to produce the maximum positive difference between the two dates) then the average cooling rate from the normal pairs is 2.4°C/Ma, while that from the normal and ambiguous pairs combined is 5.4°C/Ma, or a little more than twice as fast. These cooling rates are the slowest possible from these pairs but provide some sense of comparison.

TABLE 2

Cooling and uplift rates from normal and ambiguous pairs of dates

Dates (Ma)				Differences (Ma)		Pair Types	Cooling rates (°C/Ma)			Uplife rates (km/Ma) for gradients of 30			40 (°C/km)		
Hornblende		Biotite													
Date	Err	Date	Err	Diff	Err		−Err		+Err	−Err		+Err	−Err		+Err
890	15	823	15	+67	30	N	6.1	3.4	2.3	0.20	0.11	0.08	0.15	0.09	0.06
900	41	868	25	+32	66	B	+I	7.0	2.3	+I	0.23	0.08	+I	0.18	0.06
905	14	914	15	−9	29	B		+I	11.2		+I	0.38		+I	0.28
914	31	919	26	−5	57	B		+I	4.3		+I	0.14		+I	0.11
916	38	955	34	−39	72	B		+I	6.8		+I	0.23		+I	0.17
925	17	891	16	+34	33	N	225.0	6.6	3.4	7.50	0.22	0.11	5.63	0.17	0.09
942	16	948	14	−6	30	B		+I	9.4		+I	0.31		+I	0.24
943	—	944	—	−1	—	B		+I	4.6		+I	0.15		+I	0.12
944	37	818	30	+126	67	N	3.8	1.8	1.2	0.13	0.06	0.04	0.10	0.05	0.03
951	—	969	—	−18	—	B		+I	7.0		+I	0.23		+I	0.18
966	7	898	7	+68	14	N	4.2	3.3	2.7	0.14	0.11	0.09	0.11	0.08	0.07
974	—	1016	—	−42	—	B		+I	28.1		+I	0.94		+I	0.70
988	40	984	36	+4	76	B	+I	56.3	2.8	+I	1.88	0.09	+I	1.41	0.07
988	9	916	7	+72	16	N	4.0	3.1	2.6	0.13	0.10	0.09	0.10	0.08	0.07
991	15	996	15	−5	30	B		+I	9.0		+I	0.30		+I	0.23
995	34	1026	28	−31	62	B		+I	7.3		+I	0.24		+I	0.18
996	30	888	24	+108	54	N	4.2	2.1	1.4	0.14	0.07	0.05	0.11	0.05	0.04
998	7	955	7	+43	14	N	7.8	5.2	4.0	0.26	0.17	0.13	0.20	0.13	0.10
999	5	930	3	+69	8	N	3.7	3.3	2.9	0.12	0.11	0.10	0.09	0.08	0.07
1075	—	1055	—	+20		B	+I	11.2	3.2	+I	0.37	0.11	+I	0.28	0.08
1080	—	956	—	+124	—	N	3.0	1.8	1.3	0.10	0.06	0.04	0.08	0.05	0.03
1202	10	1090	8	+112	18	N	2.4	2.0	1.7	0.08	0.07	0.06	0.06	0.05	0.04
Muscovite		Biotite													
859	—	905	—	−46	—	B		+I	10.0		+I	0.33		+I	0.25
873	32	846	32	+27	64	B	+I	1.5	0.4	+I	0.05	0.13	+I	0.04	0.01
904	—	889	—	+15	—	B	+I	2.7	0.6	+I	0.09	0.02	+I	0.07	0.02
921	—	911	—	+10	—	B	+I	4.0	0.7	+I	0.13	0.02	+I	0.10	0.02
956	—	930	—	+26	—	B	+I	1.5	0.5	+I	0.05	0.17	+I	0.04	0.01
990	—	960	—	+30	—	B	+I	1.3	0.5	+I	0.04	0.17	+I	0.03	0.01
1015	—	1045	—	−30	—	B		+I	2.0		+I	0.07		+I	0.05
1020	—	1060	—	−40	—	B		+I	4.0		+I	0.13		+I	0.10

Pair types are A = anomalous, B = ambiguous, and N = normal. "+I" indicates an infinitely rapid cooling or uplift rate.

If the errors for the eight ambiguous muscovite-biotite pairs are considered, they give cooling rates from 0.4°C/Ma up to instantaneous cooling. If the errors are added to all the pair differences, then the mean of these "minimum cooling rates" is 2.3°C/Ma, less than half as fast as the comparable result from the combined normal and ambiguous hornblende-biotite pairs.

There is no obvious regional-scale pattern to the cooling rates, such as faster cooling for samples near the Grenville Front. Also, there is no obvious difference between the cooling rates for older versus younger dates. For example, if the pairs involving the three oldest hornblende dates are ignored, the range of cooling rates is no different, so the hornblende-to-biotite cooling rate from the Thanet gabbro, which Berger and York (1981a) considered slow enough to conceal post-intrusion cooling followed by Grenville reheating, is not unique.

Peak-to-hornblende.—The dates here considered to be reliable cooling ages, from all three minerals, suggest that the age of the peak of metamorphism for most of the area cannot be younger than 1000 Ma and is probably not much older than 1100 Ma. Three recent estimates of Grenville peak ages use U-Pb concordia dates, and they show a range of 130 Ma: metamorphic zircons in granulite facies gneisses indicate a peak age of 1030 Ma in the Parry Sound Domain and 1160 in the Algonquin Domain, about 75 km east (van Breemen and others, 1986); while sphene in middle to upper amphibolite facies quartz monzonite in the Central Metasedimentary Belt suggests a peak age there of 1085 Ma (Heaman, McNutt, and Krogh, 1986). Cosca, Essene, and Sutter (1987) reported a narrow range of hornblende dates, 970 to 1000 Ma, from the vicinity of Parry Sound but did not specify from which of the domains defined by Davidson (1986b) the samples were obtained (these dates are not included in any of the figures or appendices), although they did state that they had found evidence for "some differential cooling between structural domains." If their hornblende dates are used for the Parry Sound Domain, then average peak-to-hornblende closure cooling rates are 3.6 to 7.2°C/Ma, but if the same hornblende dates are used for the Algonquin Domain, then cooling rates for the same interval are only 1.1 to 1.3°C/Ma (assuming a peak temperature of 750°C). For the middle to upper amphibolite rocks of the Central Metasedimentary Belt, a peak age of 1085 Ma combined with hornblende dates of 966 to 998 Ma from approximately this area, from Berger and York (1981b, also shown in fig. 13A), give cooling rates of 0.6 to 0.8°C/Ma (assuming a peak temperature of 600°C). These crude estimates of peak-to-hornblende cooling rates, for different parts of the Grenville Orogen, range from 0.6 to 7.2°C/Ma or more than an order of magnitude.

Uplift Rates

Uplift rates can be calculated from cooling rates if an assumption is made about the geothermal gradient at the time the cooling ages were set. In normal-thickness continental crust this gradient is approx 30°C/

km; in active orogenic belts the same gradient has often been applied, except where the cooling rates appear to be faster than average, in which case 35° to 40°C/km may be more appropriate (Zeitler, 1985).

Nominal cooling rates calculated above from the ten normal hornblende-biotite date pairs lead to uplift rates of 0.06 to 0.22 km/Ma for a gradient of 30°C/km (mean: 0.11 km/Ma), or 0.05 to 0.17 km/Ma for a gradient of 40°C/km (mean: 0.08 km/Ma) (table 2). If the errors are added to the pair differences and both normal and ambiguous pairs are considered, the range is 0.04 to 0.94 km/Ma for 30°C/km (mean: 0.18 km/Ma), or 0.03 to 0.70 km/Ma for 40°C/km (mean: 0.14 km/Ma). These are the slowest uplift rates obtainable from the pairs and are provided only because a representative rate cannot be obtained from the ambiguous pairs otherwise. If the errors are subtracted from all the date differences (to obtain the maximum uplift rates) then the rates are 0.08 km/Ma to infinitely rapid for 30°C/km, or 0.06 km/Ma to infinitely rapid for 40°C/km.

For the peak-to-hornblende interval, the cooling rates estimated in the previous section from published peak ages and hornblende cooling ages lead to uplift rates of 0.02 to 0.24 km/Ma for a gradient of 30°C/km, or 0.02 to 0.18 km/Ma for a gradient of 40°C/km. With either geothermal gradient the range of uplift rates covers an order of magnitude.

DISCUSSION

In the Grenville Orogen K-Ar and ^{40}Ar-^{39}Ar dates from hornblende, muscovite, and biotite are primarily between 800 and 1000 Ma. Reliable post-Grenville cooling ages from hornblende and muscovite probably also include several dates up to 1100 Ma found across the Orogen, suggesting that the peak affecting most of the region occurred not much earlier than 1100 Ma ago. This is reasonably consistent with more direct estimates of peak age, recently published, which use concordia dates from metamorphic zircons and sphene (van Breemen and others, 1986; Heaman, McNutt, and Krogh, 1986). Sparse additional dates between 1100 and 1200 Ma from hornblende and muscovite may be partially reset from much older dates, but some, especially those well within the Orogen, could mark local preservation of reliable cooling ages from an earlier phase in overall Grenville convergence, such as the Elzevirian Orogeny of Moore and Thompson (1980) at 1225 Ma, or from an entirely separate tectonic event, such as anorthosite intrusion, which has been suggested by Taylor (1979) to have continued as late as 1150 Ma in the Nain Province.

Biotite in the Grenville Orogen appears to have been much more susceptible to excess argon than the other two minerals considered here. Anomalous and ambiguous pairs of hornblende-biotite and muscovite-biotite dates suggest that biotite dates older than 1100 Ma, and possibly as young as 1000 Ma, may not be reliable post-peak cooling ages because of excess argon introduced during Grenville metamorphism. This problem appears to be especially common near the Grenville Front, but the anomalous pairs scattered across the whole Orogen suggest that excess argon in biotite is a hazard that can occur anywhere.

The monotonic southeastward decrease in biotite cooling ages in Harper's biotite thermochron map (1967), required for his model of post-Grenville cooling, has been virtually lost (fig. 9). The new biotite thermochron map and the graphs of dates versus distance from the Front for all three minerals show that reliable cooling ages from 800 to 1100 Ma are mixed throughout the region, down to a small scale. For example, the two small subareas shown in figures 12 and 13, each only tens of kilometers across, contain nearly the full range of dates seen in the Orogen as a whole. It appears that any date between 750 and 1100 Ma, from any of the three minerals, can be found at any distance from the Front, at least in the mainland Canada portion of the Orogen. Another important difference between figure 9 and the earlier thermochron maps is the elimination of all biotite dates older than 1100 Ma and several between 1000 and 1050 Ma (from anomalous pairs), so that there can be no thermochron lines older than 1050 Ma. Figure 9 and Easton's thermochron map (1986) are based on somewhat different data sets, but the most conspicuous difference is the apparent "smoothing" of contour lines in Easton's map, by which he ignores cooling ages that are exceptionally older or younger than their near neighbors, a procedure that is not justified when the presence or absence of a regional-scale cooling-age pattern is the hypothesis being tested.

In order to determine whether a subtle regional-scale pattern is present, reliable cooling ages (within the rectangular boxes in fig. 6A, B, and C) were subjected to simple linear regressions. The line in figure 6D was determined using a program modified from York (1969), which takes analytical uncertainties into account; on the scale of these illustrations the regression lines in figure 6C and D are nearly identical, so it appears that the analytical uncertainties in the cooling ages have little influence on the position or slope of the regression line. The regression line for hornblende (fig. 6A) has a slight positive slope, suggesting that the average hornblende cooling ages actually increase with distance from the Front, but the correlation coefficient is very low. The regression line for muscovite (fig. 6B) is nearly indistinguishable from the regression lines for biotite, with a small negative slope and a low correlation coefficient. The simple regression line for biotite (fig. 6C) also has a low correlation coefficient. The line in figure 6D has a y-intercept at the Grenville Front of 959 ± 8 Ma and 911 ± 8 Ma at 400 km from the Front (the approximate position of the St. Lawrence River). That is, the average biotite cooling age decreases 46 ± 16 Ma across the mainland Canada portion of the Grenville Orogen, the equivalent of one contour interval on figure 9, compared with a decrease of 130 Ma from a regression line for twenty of the biotite dates used by Harper (1967), also shown on figure 9. Since the average analytical uncertainty on a single biotite cooling age is typically ±25 Ma, this 50 Ma change across the entire mainland Canada portion of the Grenville Orogen may have little significance for the regional cooling history. The low correlation coefficients for all three regression lines (fig. 6A, B, and C) also indicate that little confidence should be placed in any implied regional-scale pattern.

The common close juxtaposition of reliable cooling ages from the whole 750 to 1100 Ma range gives the region a peculiar uniformity, quite unlike the smooth regional-scale variation seen in Harper's thermochron map, and suggests variation, on a scale considerably smaller than the width of the Orogen in mainland Canada, in some combination of peak age, peak grade, and cooling and uplift rate. The abrupt variations seen in hornblende and biotite dates in several portions of the Grenville Orogen suggest that it is misleading to speak of an "average" hornblende or biotite cooling age applicable to the whole Orogen or any large part of it. The abrupt difference of 130 Ma in peak ages between the Parry Sound and Algonquin Domains, both in granulite facies (van Breemen and others, 1986), suggests there may also be no "average" peak age. Davidson's (1986b) studies in southwestern Ontario have shown that other domains nearby had distinctly different metamorphic histories, with different peak grades. Such discontinuities may explain why there is no clear correlation between cooling ages and metamorphic grade (unlike the relationship seen by Dewey and Pankhurst, 1970, in Scotland). These domains, separated by narrow mylonite zones, are on the order of 10 to 100 km across, smaller than the distance between adjacent K-Ar dates in much of the Grenville Orogen but similar in scale to the areas shown in figures 12 and 13. In southeastern Ontario, it is interesting to note that the maximum contrast in hornblende dates in the study by Cosca, Essene, and Sutter (1988) is nearly equal to the full range of hornblende cooling ages for the Orogen and appears to occur near one of the better candidates for a Grenville suture (Moore and Thompson, 1980; see Anderson and Burke, 1983; and Windley, 1986, for discussions). Abrupt variations in cooling ages from a single mineral and truncations of closely-spaced thermochron lines across well-defined tectonic boundaries have been reported by Zeitler (1985) in the western Himalayas and are also suggested near Lhasa by Copeland and others (1987). Similar truncations could explain the lack of a regional-scale pattern for cooling ages in the Grenville Orogen, as well as the complex pattern seen in figure 9.

Grenville uplift rates estimated for the peak-to-hornblende closure interval (0.2–0.24 km/Ma) and from ten normal hornblende-biotite cooling-age pairs (0.05–0.22 km/Ma) cover an order of magnitude but are generally slower than those calculated in more sophisticated ways in the Alps (0.4–0.8 km/Ma—Clark, 1979; 0.45–2.2 km/Ma—Hurford, 1986) and similar to the slowest rates reported from the western Himalayas (0.07–4.5 km/Ma—Zeitler, 1985) and the southern Tibetan Plateau (0.07–3.7 km/Ma—Copeland and others, 1987). If the analytical uncertainties for the Grenville hornblende-biotite pairs are considered, the minimum possible difference produces the fastest possible uplift rate, which is 225 km/Ma for the normal pairs and infinitely rapid for the ambiguous pairs. The few cooling-age pairs currently available, and the poor precision for many of them, do not allow a fair evaluation of the possible role of variations in uplift rates on the distribution of cooling ages. Further studies of uplift rates and the other factors that have influenced Grenville cooling ages require closely-spaced samples and more precise dating methods than were used to generate most of the dates currently available.

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