^{40}Ar/^{39}Ar and U-Pb mineral ages from the Brookville Gneiss: implications for terrane analysis and evolution of Avalonian "basement" in southern New Brunswick

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New ^{40}Ar/^{39}Ar hornblende and U-Pb zircon data from units previously thought to represent basement to the Avalon composite terrane in southern New Brunswick yield latest Precambrian or early Cambrian metamorphic cooling ages and a late Precambrian protolith age. Hornblendes from the Brookville Gneiss and from an intrusive amphibolite body within the gneiss yield ^{40}Ar/^{39}Ar isotope correlation ages of 542 ± 4 and 538 ± 2 Ma, respectively. These ages are interpreted to date post-amphibolite facies metamorphic cooling. Euhedral zircons from the Point Pleasant orthogneiss, a quartz dioritic gneiss previously interpreted to be the oldest component of the Brookville Gneiss, show slight inheritance and yield ^{207}Pb/^{206}Pb ages ranging from 603 to 631 Ma. The youngest of these is interpreted to be a maximum age for the orthogneiss protolith.

These results, together with other recent U-Pb age data, conflict with previous interpretations of the Brookville Gneiss and the metasedimentary Green Head Group with which it is associated, as a mobilized Proterozoic basement-cover succession upon which an Avalonian ensialic arc developed at c. 600-635 Ma. Instead, the age of the orthogneiss matches that of the arc, and the orthogneiss protolith is likely to have been originally intrusive into the Green Head Group. Although the arc succession is unaffected by high-grade metamorphism, the metamorphic cooling age recorded in the "basement" closely follows evidence of within-arc extension at c. 550 Ma. Hence, the arc/"basement" contrasts in tectonothermal regime could be those of varying structural level within the Avalonian arc rather than requiring the proposed existence of entirely separate terranes.

De nouvelles données ^{40}Ar/^{39}Ar sur hornblendes et U-Pb sur zircons, issues d'unités considérées jadis comme représentant le socle de la Lanière composite d'Avalon au Nouveau-Brunswick méridional, ont livré des âges de refroidissement métamorphique finiprécambriens ou éocambriens ainsi qu'un âge de protolithe tardiprécambrien. Des hornblendes extraites du Gneiss de Brookville ont livré un âge de corrélation isotopique par ^{40}Ar/^{39}Ar de 542 ± 4 Ma; d'autres, provenant d'un bâti amphibolitique intrusif au sein du gneiss, ont livré un âge de 538 ± 2 Ma. On interprète ces âges comme datant le refroidissement métamorphique au-delà du faciès à amphibolites. Des zircons idiomorphes provenant de l'orthogneiss de Point Pleasant, un gneiss quartzodioritique interprété auparavant comme le plus ancient constituant du Gneiss de Brookville, montrent un léger remaniement et livrent des âges ^{207}Pb/^{206}Pb s'étalant de 603 à 631 Ma. On interprète le plus jeune de ces âges comme l'âge maximal du protolithe de l'orthogneiss.

Ces résultats, tout comme d'autres données U-Pb récentes, contredisent les interprétations antérieures considérant le Gneiss de Brookville et le Groupe métasédimentaire de Green Head, auquel il s'associe, comme une succession socle-couverture mobilisée protérozoïque sur laquelle un arc sialique avalonien s'est développé il y a env. 600 à 635 Ma. L'âge de l'orthogneiss correspond plutôt à celui de l'arc et il est probable que le protolithe de l'orthogneiss faisait à l'origine intrusion au sein du Groupe de Green Head. Bien que la succession d'arc n'ait subi aucun métamorphisme de degré élevé, l'âge de refroidissement métamorphique enregistré dans le "socle" concorde étroitement avec la manifestation d'une extension intra-arc vers 550 Ma. Par conséquent, les contrastes de régime tectonothermique arc/"socle" pourraient refléter les variations du niveau structural au sein de l'arc avalonien plutôt que nécessiter l'existence proposée de lanières tout à fait distinctes.

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INTRODUCTION

The Brookville Gneiss and Green Head Group form important and closely associated components of the Avalon composite terrane in southern New Brunswick, Canada, and outcrop in a northeasterly trending belt near the city of Saint John (Fig. 1). Previous studies of the two units, including their field relations (Wardle, 1978; Currie *et al.*, 1981), the paleontology of the Green Head Group (Hofmann 1974), and the geochronology of the Brookville Gneiss (Olszewski and Gaudette, 1982), have been taken to demonstrate their antiquity, and the two units are commonly interpreted to represent a basement-cover succession upon which the late Precambrian (Avalonian) ensialic arc stratigraphy of southern New Brunswick was built (e.g., Currie, 1986, 1988; Nance, 1987).

In an attempt to better define the crystallization age of the Brookville Gneiss and resolve the tectonothermal history of both units, ^{40}Ar/^{39}Ar incremental release hornblende ages have been determined for a Brookville paragneiss and an intrusive amphibolite body within the gneiss, and a U-Pb zircon age has been determined for a Brookville orthogneiss. The results presented here, together with other recent U-Pb age determinations (Bevier *et al.*, 1990), suggest that much younger and more complex geological relations exist between the two units than has previously been assumed.

GEOLOGIC SETTING

The Avalon composite terrane forms a discontinuous tectonostratigraphic zone along the southeastern margin of the northern Appalachian orogen. The terrane is characterized by arc-related volcanic-sedimentary successions and broadly contemporary granitoid bodies of late Precambrian (c. 635-550 Ma) age, and by early Paleozoic shallow-marine overstep sequences containing fossils of the Acado-Baltic faunal province (e.g., O'Brien *et al.*, 1983; Rast and Skehan, 1983; Nance, 1986). However, gneissic complexes that are associated with platformal metasedimentary sequences are preserved locally. These fault-bounded associations are generally thought to predate the late Precambrian successions and have been interpreted as either pre-Avalonian basement (e.g., Currie *et al.*, 1981; Smyth, 1981; Currie, 1983; Donohoe and Wallace, 1985; Barr and Raeside, 1986; Nance, 1987) or, more recently, as components of an entirely separate terrane that was unrelated to Avalon until at least Cambrian and possibly Devonian times (e.g., Barr and Raeside, 1989, 1990; Barr and White, 1989).

In the Avalon composite terrane of southern New Brunswick (Fig. 1), the Brookville Gneiss and adjacent Green Head Group represent such a gneissic complex-platformal metasedimentary rock association. The Brookville Gneiss is predominantly a low-pressure (cordierite ± andalusite) and locally migmatitic quartz-feldspar-biotite ± hornblende paragneiss with minor calc-silicate horizons and cross-cutting orthogneisses of tonalitic to granodioritic composition (Wardle, 1978; Barr and White, 1989). Wardle (1978) distinguished three belts of gneisses in southern New Brunswick which he termed the Brookville, Rockwood Park and Pleasant Point gneisses according to their principal areas of outcrop. However, most subsequent studies have grouped these under the term Brookville Gneiss.

The Green Head Group, in contrast, comprises predominantly low-grade carbonates, quartzites and pelites that only locally reach the amphibolite facies (Wardle, 1978; Nance, 1982). The age of the group is uncertain, although marbles within it locally preserve the stromatolite *Archaeozoon acadiense* which Hofmann (1974) tentatively assigned to the mid-Riphean. The succession has been interpreted to record the evolution of a stable platform (Wardle, 1978) that was presumably floored by still older Precambrian basement. The carbonate olistostromes, slump breccias and turbiditic sandstones and siltstones of the Martinon Formation (Fig. 1) are likely to overlie the Green Head Goup unconformably (e.g., Currie, 1984), and have been interpreted to record the collapse of this Green Head platform (Wardle, 1978; Nance, 1987).

The late Precambrian assemblage in southern New Brunswick is widely attributed to the development of an ensialic volcanic arc and includes small but widespread "compositionally expanded" I-type, calc-alkaline plutons (e.g., Dickson, 1985; Barr and White, 1988) with U-Pb zircon ages in the range 625-600 Ma (Watters, 1987; Bevier and Barr, 1990). These plutons are associated with dacitic to felsic tuffs, andesite-dacite volcaniclastic rocks and volcanogenic sedimentary rocks of the Coldbrook Group. These low-grade volcanic rocks also show geochemical characteristics consistent with their formation in a volcanic arc environment (Barr and White, 1988; Currie, 1988) and some units have yielded U-Pb zircon ages in the range 600-615 Ma (Bevier and Barr, 1990).

The late Precambrian ensialic volcanic arc assemblage was intruded by a younger suite of high-level leucogranites and gabbros that are associated with cogenetic bimodal volcanic rocks and redbeds. This essentially unmetamorphosed "Eocambrian" suite has yielded U-Pb zircon ages of c. 550 Ma (Bevier and Barr, 1990) and has been attributed to the development of an extensional environment within the former volcanic arc (Nance, 1987; Barr and White, 1988; Currie, 1988). The redbeds and volcanic rocks, the mafic lavas of which show continental rift affinity (Greenough *et al.*, 1985), may have formed in small rift and/or pull-apart basins. The suite has also been considered to include the bimodal Kingston dyke complex (e.g., Currie, 1986, 1988; Nance, 1987) immediately northwest of the Kennebecasis fault (Fig. 1). However, U-Pb zircon data from two rhyolite dykes of the Kingston complex indicate an early Silurian emplacement age (Doig *et al.*, 1990).

The "Eocambrian" suite is disconformably overlain by shelf quartzites, sandstones and shales of the Cambro-Ordovician Saint John Group (Tanoli and Pickerill, 1988). These shallow-marine sedimentary rocks contain trilobites of the Acado-Baltic faunal province (Hayes and Howell, 1937) and are considered to represent a platformal overstep sequence to the Precambrian succession in southern New Brunswick.

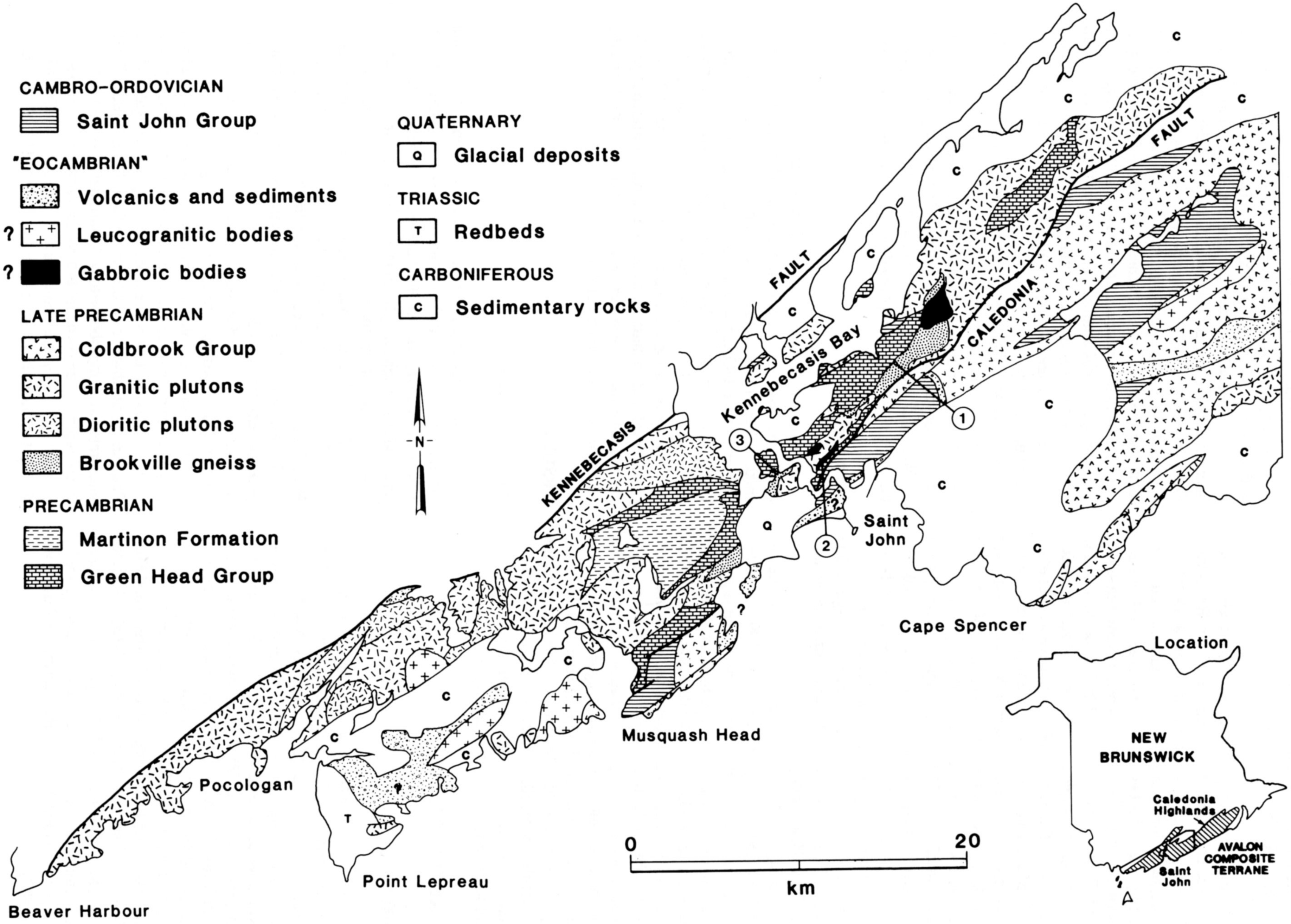

Fig. 1. Late Precambrian - early Palaeozoic geology of the Saint John region of southern New Brunswick (simplified after Currie, 1988, Barr and White, 1989 and Nance *et al.*, 1990). Locations of samples collected for $^{40}Ar/^{39}Ar$ and U-Pb analysis are shown by numbers (1-3).

PREVIOUS GEOCHRONOLOGY OF THE BROOKVILLE GNEISS

Olszewski and Gaudette (1982) reported U-Pb zircon and Rb-Sr whole-rock data from two samples of the Brookville Gneiss. U-Pb analyses of detrital zircon from a sample of Brookville paragneiss failed to plot on a single cord but were interpreted using a curve for two Pb-loss events at c. 780 Ma and 370 Ma. This yielded an upper intercept age of c. 1640 Ma which Olszewski and Gaudette (1982) considered to be that of the source area. In the same sample a single euhedral zircon, which they interpreted to be of metamorphic origin, gave a concordant U-Pb age of 814 Ma. Two U-Pb analyses of zircon from a sample of quartz dioritic gneiss exposed at Pleasant Point (Pleasant Point orthogneiss) yielded upper and lower intercept ages of c. 827 Ma and 333 Ma. Rb-Sr whole-rock data for both samples yielded a combined isochron of 771 ± 55 Ma. Although equivocal, these data were collectively interpreted to indicate that the Brookville Gneiss had experienced a period of high grade (amphibolite facies) metamorphism at c. 800 ± 30 Ma. Hence, Currie *et al.* (1981) and most subsequent workers interpreted this age to date the mobilization of the gneiss and its diapiric emplacement into the overlying Green Head Group.

However, using analytical techniques unavailable to Olszewski and Gaudette (1982), Bevier *et al.* (1990) reported precise U-Pb age data from the Brookville Gneiss that suggest a much younger protolith. Zircons from a tonalitic orthogneiss yielded a protolith age of 605 ± 3 Ma while a titanite age of 564 ± 6 Ma from the same sample was taken to provide a minimum age for its amphibolite facies metamorphism. In addition, single detrital zircons from two samples of Brookville paragneiss provided maximum sedimentary protolith ages of 943 ± 3 and 641 ± 3 Ma. Hence, Bevier *et al.* (1990) concluded that the orthogneiss protolith could not have been much younger than the paragneiss protolith it intruded, and that the Brookville Gneiss is probably younger than the Green Head Group and cannot represent basement to the Avalon composite terrane.

ANALYTICAL TECHNIQUES

^{40}Ar/^{39}Ar analysis

Mineral concentrates were irradiated in either the Ford Reactor at the University of Michigan (sample 1) or the U.S. Geological Survey TRIGA reactor (sample 2). Variations in neutron flux along the length of the irradiation assemblies were monitored with several mineral standards, including MMHb-1 (519.5 Ma; Alexander *et al.*, 1978). The samples were incrementally heated until fused with an RF generator and each heating step was maintained for 30 minutes. Blank-corrected isotopic ratios were corrected for the effects of mass discrimination and interfering isotopes using factors reported by Harrison and Fitzgerald (1986) for the Ford Reactor or Dalrymple *et al.* (1981) for the TRIGA reactor. Apparent ^{40}Ar/^{39}Ar ages were calculated using the decay constants and isotopic abundance ratios listed by Steiger and Jäger (1977) and the methods described in Dallmeyer and Keppie (1987).

Intralaboratory uncertainties are reported and have been calculated by statistical propagation of uncertainties associated with measurement of each isotopic ratio (at two standard deviations of the mean) through the age equation. Interlaboratory uncertainties are approximately 1.25-1.50% of the quoted age. Total-gas ages have been computed for each sample by appropriate weighting of the age and percent ^{39}Ar released within each temperature increment. A "plateau" is here defined if the ages recorded by two or more contiguous gas fractions with generally similar apparent K/Ca ratios, each representing >4% of the total ^{39}Ar evolved and together constituting >50% of the total quantity of ^{39}Ar evolved, are mutually similar to within a ±1% intralaboratory uncertainty.

Regression techniques for correlation of ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar followed the methods of York (1969) and the isotopic correlations have been evaluated using the mean square of the weighted deviation (MSWD). Roddick (1978) suggested that an MSWD >2.5 indicates scatter about a correlation line greater than that which can be explained only by experimental errors.

U-Pb analysis

Zircon was processed by a method similar to that of Krogh (1973), but using a 0.3 mL resin volume and a mixed ^{205}Pb-^{235}U spike. Isotope ratios were measured on a VG-Sector mass spectrometer in the UQAM-McGill laboratory at the University of Quebec. The blank for the entire analytical procedure ranged from 7 to 30 pg Pb. Errors expressed by the dimensions of the error symbols on the concordia diagram are at the 95% confidence level and include measurement error, confidence in the fractionation factors, error in the U-Pb ratio of the spike, and the effect of the common Pb correction.

RESULTS

^{40}Ar/^{39}Ar analysis

Two hornblende concentrates have been analysed by the incremental-release ^{40}Ar/^{39}Ar technique. The first (sample 1; Fig. 1) was prepared from a sample of the Brookville Gneiss collected on the McKay Highway (Route 1), northeast of Saint John, where a broad ductile shear zone containing thin carbonate mylonite bands of dextral shear sense (C.E. White, personal communication, 1990) separates the gneiss from carbonates of the Green Head Group. The sample comprises an amphibolite facies (quartz-plagioclase-biotite-hornblende) paragneiss and contains large poikiloblastic hornblendes, a concentrate of which was separated from material collected at the Highway Department depot, 0.75 km north of the Rothsay Avenue interchange.

The second hornblende concentrate (sample 2; Fig. 1) was prepared from a strongly foliated sample of hornblende-plagioclase amphibolite that borders Brookville paragneiss at the Sears Plaza in the northwestern suburbs of Saint John. Wardle (1978) interpreted this amphibolite to be a marginal phase of the dioritic to gabbroic Indiantown Gabbro which intruded the Brookville Gneiss and developed a contact aureole in the nearby Green Head Group. On the basis of textural criteria, Wardle (1978) concluded that this contact metamorphism predated the earliest tectonothermal event recorded in the Green Head Group, during which the margins of the gabbro were extensively converted to foliated amphibolites. However, the existence of a ductile shear zone between the Brookville Gneiss and the Green Head Group cannot be precluded. Hence, the alternative possibilities that the amphibolite represents a component of the Brookville Gneiss or is part of the Indiantown Gabbro that was pre- or syntectonically intruded into a ductile shear zone separating the gneiss from the Green Head Group, cannot be entirely dismissed. In either case, however, the amphibolite is likely to have experienced the same metamorphic history as the Green Head Group. Where sampled at the northern end of the Sears Plaza below the intersection of Old Adelaide Street and Visart Street, the amphibolite has been intruded by veins of quartz diorite, leucogranite and pegmatite.

Both locations sampled for ^{40}Ar/^{39}Ar analysis are indicated on Figure 1. The analytical data are listed in Table 1 and are portrayed as age spectra in Figures 2 and 3. Apparent K/Ca ratios for the hornblendes are also shown on these figures. The statistics for ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar isotope correlation of the increments identified in Figures 2 and 3 are given in Table 2.

The two hornblende concentrates display internally discordant spectra which define total-gas ages of 548 ± 6.9 Ma (sample 1) and 542.2 ± 2.8 Ma (sample 2). Low-temperature gas fractions display considerable variation in apparent ages. These are matched by fluctuations in apparent K/Ca ratios which suggests experimental evolution of argon from compositionally distinct relatively non-retentive phases. These could be represented by very

Table 1. ^{40}Ar/^{39}Ar analytical data for incremental heating experiments on hornblende concentrates from the Brookville Gneiss, New Brunswick.

Release temp (°C)	(^{40}Ar/^{39}Ar)*	(^{36}Ar/^{39}Ar)*	(^{37}Ar/^{39}Ar)^c	^{39}Ar % of total	%^{40}Ar non-atmos.$^+$	^{36}Ar$_{Ca}$ %	Apparent Age (Ma)**
Sample 1: J - 0.006742							
600	101.97	0.11458	4.687	0.74	67.15	1.17	686.6 ±22.3
650	104.10	0.14193	3.403	1.02	59.95	0.69	634.8 ±19.2
700	83.92	0.05929	2.766	0.78	79.36	1.33	670.1 ±16.3
750	53.23	0.01463	13.949	14.87	94.02	27.27	529.2 ± 6.9
830	54.49	0.00862	13.476	19.71	97.35	44.71	556.2 ± 7.3
890	54.05	0.01017	12.847	10.86	96.38	36.13	547.4 ± 6.1
915	53.77	0.00767	12.755	18.56	97.72	47.59	551.5 ± 4.2
965	53.77	0.01213	12.4731	13.78	95.22	29.32	539.2 ± 5.3
Fusion	54.46	0.01239	12.258	19.67	95.11	28.30	544.5 ± 3.1
Total	55.10	0.01326	12.709	100.00	95.34	35.26	548.3 ± 6.9
Sample 2: J - 0.009245							
650	47.24	0.06414	2.929	1.49	60.36	1.24	422.8 ±10.9
750	28.95	0.01627	4.022	1.44	84.49	6.73	368.6 ±20.4
800	34.57	0.01260	11.140	1.29	91.80	24.04	467.0 ±22.0
825	37.57	0.00759	11.111	2.06	96.39	39.81	524.1 ± 6.4
840	40.20	0.00692	9.723	3.49	96.84	38.20	557.6 ± 5.0
855	40.72	0.00605	9.111	6.22	97.39	40.95	566.2 ± 3.5
870	39.76	0.00506	8.816	10.52	98.01	47.38	557.7 ± 2.3
880	39.00	0.00377	8.581	12.85	98.90	61.93	552.8 ± 1.7
890	38.36	0.00327	8.363	12.52	99.22	69.62	546.4 ± 3.1
900	38.66	0.00367	8.377	9.39	98.92	62.13	548.7 ± 1.8
910	38.51	0.00387	8.308	6.82	98.75	58.36	545.9 ± 3.4
930	38.90	0.00397	8.426	9.22	98.71	57.67	550.6 ± 2.4
960	38.85	0.00379	8.507	5.98	98.86	61.07	550.7 ± 2.1
1000	39.11	0.00372	8.667	10.24	98.95	63.30	554.3 ± 1.8
1050	37.88	0.00741	8.156	4.75	95.93	29.92	524.9 ± 4.6
Fusion	32.29	0.01953	6.045	1.73	83.61	8.42	403.3 ±17.4
Total	38.80	0.00582	8.475	100.00	97.33	53.61	542.2 ± 2.8

*measured.

^{c}corrected for post-irradiation decay of ^{37}Ar (35.1 day 1/2-life).

$^+[^{40}Ar_{tot.} - (^{36}Ar_{atmos.})\,(295.5)]\,/\,^{40}Ar_{tot.}$

**calculated using correction factors of Dalrymple *et al.* (1981); two sigma, intralaboratory errors.

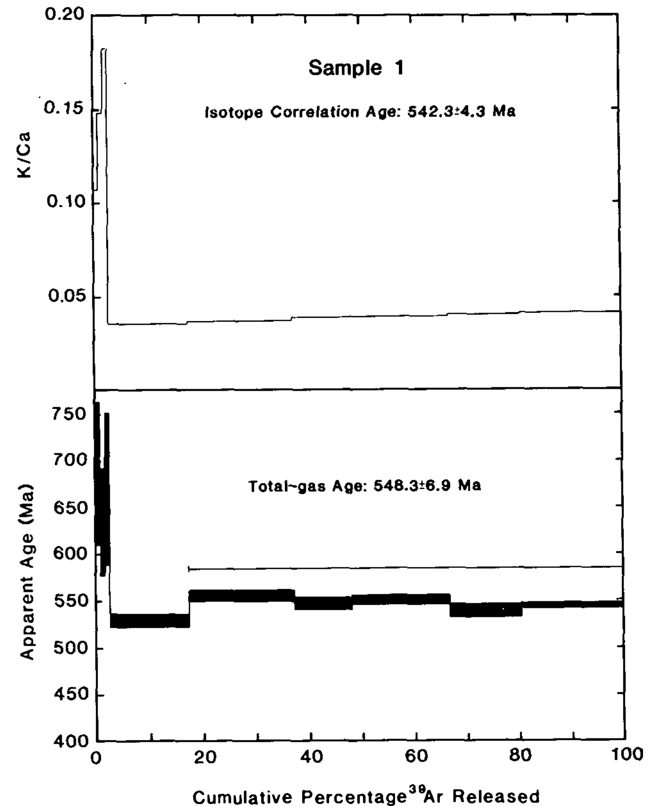

Fig. 2. ^{40}Ar/^{39}Ar age and apparent K/Ca spectra of hornblende concentrates for Brookville paragneiss sampled on Route 1 (McKay Highway), northeast of Saint John (sample 1). Analytical uncertainties (two sigma, intralaboratory) are represented by vertical width of bars. Both total-gas and derived isotope correlation ages are listed on the spectrum. Horizontal line identifies increments included in isotope correlation. See Figure 1 for sample location.

minor, optically undetectable, mineralogic contaminants in the amphibole concentrates and/or petrographically unresolvable exsolution or compositional zonation within constituent hornblende grains. The two high-temperature increments evolved from sample 2 (1050°C and fusion) also display anomalously young apparent ages and fluctuating apparent K/Ca ratios. These likely reflect gas evolved from a relatively refractory contaminate in the concentrate. Most gas fractions liberated from both samples at intermediate and high experimental temperatures show little intrasample variation in apparent K/Ca ratios. This suggests that experimental evolution of gas occurred from compositionally uniform populations of intracrystalline sites. However, in neither sample do these increments rigorously define a plateau.

Analytical data for the 830°C-fusion increments evolved from sample 1 correspond to a well-defined ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar isotope correlation (MSWD = 1.62) with an inverse ordinate intercept of 368.3 ± 12.4. This is not significantly different from the ^{40}Ar/^{36}Ar ratio in the present-day atmosphere and does not suggest any significant intracrystalline contamination with extraneous ("excess") argon components. Using the inverse ordinate intercept (^{40}Ar/^{39}Ar) in the age equation yields an isotope correlation age of 542.3 ± 4.3 Ma.

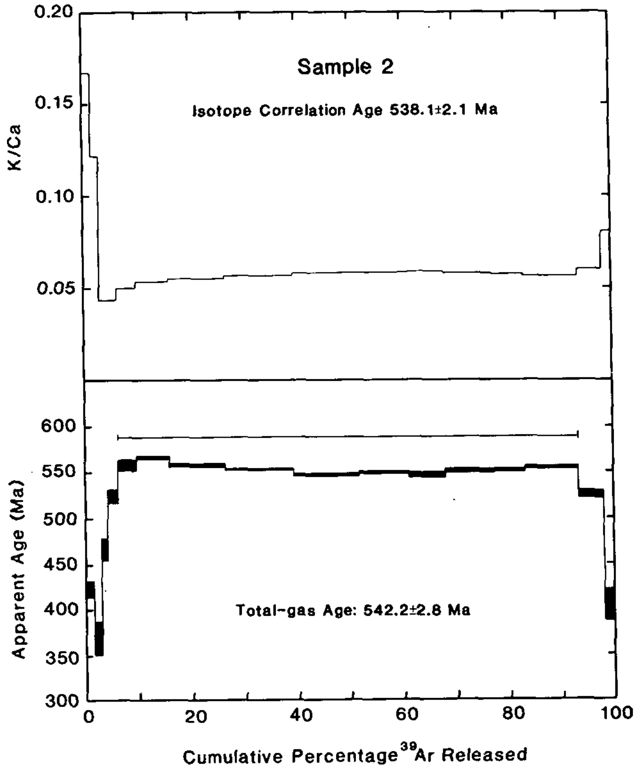

Fig. 3. ^{40}Ar/^{39}Ar age and apparent K/Ca spectra of hornblende concentrates for amphibolite body within the Brookville Gneiss sampled at Sears Plaza, Saint John (sample 2). Analytical uncertainties (two sigma, intralaboratory) are represented by vertical width of bars. Both total-gas and derived isotope correlation ages are listed on the spectrum. Horizontal line identifies increments included in isotope correlation. See Figure 1 for sample location.

The 840-1000°C increments evolved from sample 2 correspond to an isotope correlation (MSWD = 1.21) with an inverse ordinate intercept of 918.8 ± 28.3. This is significantly larger that the ^{40}Ar/^{36}Ar ratio in the present day atmosphere and does suggest intracrystalline contamination with extraneous argon components. The inverse abscissa intercept yields an isotope correlation age of 538.1 ± 2 Ma.

Because calculation of isotope correlation does not require assumption of ^{40}Ar/^{36}Ar ratios, the resultant ages are considered more reliable than those calculated directly with the analytical results. In the present case, the c. 542 and c. 538 Ma ages are considered geologically significant, and are interpreted to date the last cooling through temperatures required for intracrystalline retention of radiogenic argon in the constituent hornblende grains. Harrison (1981) suggested that temperatures of c. 500 ± 25°C are appropriate for argon retention within most hornblende compositions in the range of cooling rates likely to characterize most geologic settings encountered.

U-Pb analysis

U-Pb ages have been obtained for zircons from a single sample of the Brookville Gneiss (sample 3; Fig. 1) collected on Green Head Island, northeast of Saint John. The rock sample is

Table 2. $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlations from incremental heating experiments on hornblende concentrates from the Brookville Gneiss, New Brunswick.

Sample	Isotope Correlation Age (Ma)*	$^{40}Ar/^{36}Ar$ Intercept**	MSWD	Increments Included+	% of Total ^{39}Ar	Calculated $^{40}Ar/^{39}Ar$ Age (Ma)**
1	542.3 ± 4.3	368.3 ± 12.4	1.62	830-fusion	82.59	548.3 ± 5.1
2	538.1 ± 2.1	918.8 ± 28.3	1.21	840-1000	87.24	552.4 ± 1.9

*Calculated using the inverse abscissa intercept ($^{40}Ar/^{39}Ar$ ratio) in the age equation.
**Inverse ordinate intercept.
+°C.

from an outcrop at the junction of Green Head Road and Dominion Park Road which exposes the Pleasant Point orthogneiss. Wardle (1978) considered this orthogneiss to be the oldest of the various rock-types comprising the Brookville Gneiss, and interpreted it to represent a basement diapir injected into cover lithologies of the Green Head Group as a partially crystalline body during the development of the Brookville paragneisses. At this locality, which is presumably close to the location sampled for the same quartz diorite gneiss by Olzsewski and Gaudette (1982), the orthogneiss structurally or magmatically encloses enclaves of diopside-rich skarn (calcite-dolomite-diopside ± grossularite) that could have been derived from the nearby Green Head Group.

The sample contained two populations of zircons; clear, white to pale yellow euhedral crystals with length to width ratios of about 2.5:1, and a number of clear, white acicular crystals. The U-Pb data for both populations are illustrated on a concordia diagram in Figure 4 and compared (inset, Fig. 4) with the more discordant results of Olszewski and Gaudette (1982). Table 3 lists the isotopic data.

The needle-shaped zircon crystals yield a $^{207}Pb/^{206}Pb$ date of 595 Ma that is about 3% discordant. The fractions of the stubby grains are not optically distinguishable, but yield a variety of $^{207}Pb/^{206}Pb$ dates from 603 to 631 Ma (Table 3). There is clearly a small but significant inherited component so that the correct procedure is to interpret the youngest date as the maximum age of crystallization. Because the small needles of zircon could conceivably have lost Pb during metamorphism, a conservative interpretation would be that the igneous protolith of the Point Pleasant orthogneiss sampled is not older than about 603-605 Ma.

DISCUSSION

The c. 540 Ma hornblende ages obtained from the Brookville Gneiss and the intrusive amphibolite body are taken to define a minimum (cooling) age for the amphibolite facies metamorphism of these units and, by inference, a minimum age for the regional metamorphism of the Green Head Group and a maximum age for the retrograde mylonitization of this group along the McKay Highway. On the basis of the U-Pb data, the crystallization age of the Point Pleasant orthogneiss protolith is considered to be no older than c. 605 Ma. These results support the two new U-Pb ages reported from a tonalitic Brookville orthogneiss by Bevier *et al.* (1990), namely a zircon age of 605 ± 3 Ma interpreted to date the protolith, and a titanite age of 564 ± 6 Ma taken to provide a lower limit for the age of its metamorphism. The results require a re-evaluation of the Brookville Gneiss as Avalonian basement and necessitate considerable revision of the tectonothermal history of the region.

Interpretation of the Brookville Gneiss

Although contacts between the Brookville Gneiss and the platformal metasedimentary Green Head Group are commonly mylonitic, the former has become widely assumed to represent the basement to the latter and, by inference, to represent basement to the Avalon composite terrane (e.g., Currie, 1983, 1986, 1988; Nance, 1987). Earlier studies (e.g., Rast *et al.*, 1976) argued that the Brookville paragneisses represented the high-grade metamorphic equivalents of part of the Green Head Group, although Wardle (1978) concluded that mobilized basement, diapirically emplaced into the Green Head Group during the formation of the paragneisses, might be represented by the Pleasant Point orthogneiss which he termed a "swirled" quartz diorite on account of its distinctive metamorphic fabric. On the basis of field relations and available age data, Currie *et al.* (1981) subsequently concluded that all of the Brookville Gneiss represented mobilized basement because it appeared to contain relict mafic dykes not represented in the Green Head Group and had apparently experienced a pre-Avalonian tectonothermal event (Olszewski and Gaudette, 1982).

However, basement-cover relations between any part of the Brookville Gneiss and the Green Head Group are not supported by the U-Pb age data presented here or reported by Bevier *et al.* (1990). Such relations would necessitate deposition of the Green Head Group during the interval 605-565 Ma, in obvious conflict with the tentative mid-Riphean age assigned to the group on the basis of stromatolites (Hofmann, 1974). Although original relations between the two units remain uncertain, the new U-Pb age,

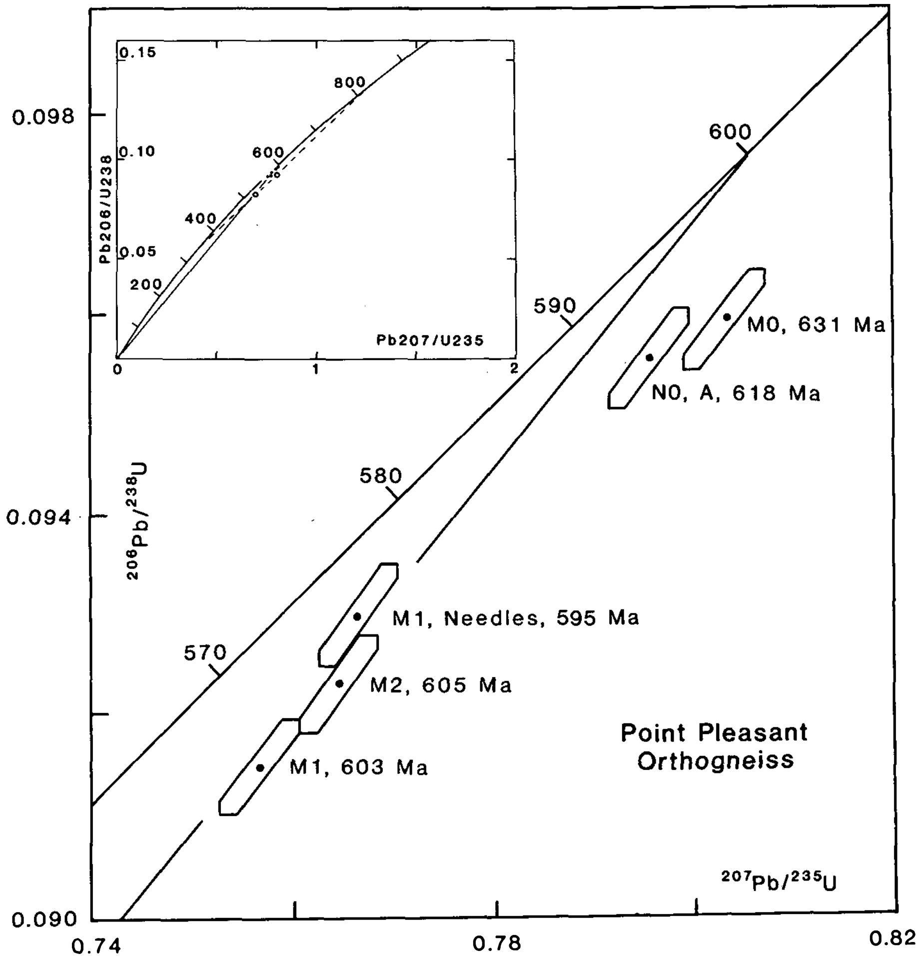

Fig. 4. U-Pb concordia diagram for zircon fractions of the Brookville Gneiss (Pleasant Point orthogneiss) sampled on Green Head Island (sample 3). ^{207}Pb/^{206}Pb dates are shown next to each data point. 600 Ma discordia line shown for reference only. Dimensions of the error symbols are at the 95% confidence level. Insert compares new data (dots) and reference 600 Ma discordia (solid line) with U-Pb results (open circles) and cord (dashed line with intercepts at 827 ± 40 Ma and 333 ± 40 Ma) of Olszewski and Gaudette (1982, fig. 4). See Figure 1 for sample location and Table 1 notes for explanation of other symbols.

Table 3. U-Pb data.

Zircon fraction[a]		Weight (mg)	U (ppm)	Pb$_{rad}$ (ppm)	^{206}Pb[b]/^{204}Pb	^{208}Pb[c]/^{206}Pb	^{206}Pb[c]/^{238}U	^{207}Pb[c]/^{235}U	^{207}Pb[c]/^{206}Pb	^{207}Pb/^{206}Pb age (Ma)
NO, A	50x100	0.022	691	65.5	1 187	0.092	0.09551	0.7954	0.06040	618
MO	75x200	0.033	1013	96.0	1 944	0.088	0.09588	0.8034	0.06077	631
M1	75x175	0.083	918	82.5	2 273	0.083	0.09151	0.7568	0.05998	603
M1	40x250	0.048	889	83.3	3 793	0.113	0.09300	0.7663	0.05976	595
M2	75x200	0.047	876	79.6	1 553	0.084	0.09237	0.7646	0.06003	605

[a] NO/MO are nonmagnetic/magnetic fractions and the numerals 0, 1, etc., are degrees tilt on a Frantz separator. 100x250 are zircon dimensions in microns. A - abraded.

[b] Atomic ratios corrected for fractionation and spike.

[c] Atomic ratios corrected for fractionation, spike, blanks, and common Pb from the model of Stacey and Kramers (1975).

coupled with the presence of calc-silicate and marble enclaves within the Brookville orthogneiss that may be xenoliths of the Green Head Group, is considered to be more compatible with originally intrusive relations.

Tectonothermal implications and terrane analysis

Evidence of a metamorphic event at c. 800 ± 30 Ma proposed by Olszewski and Gaudette (1982) is not substantiated in either the U-Pb age data of this study or that of Bevier *et al.* (1990). Hence, previous models involving high-grade metamorphism and diapiric mobilization of the Brookville Gneiss at c. 800 Ma, based on the earlier age data (e.g., Currie *et al.*, 1981; Currie, 1986, 1988; Nance, 1987), are no longer tenable. However, the record of a low-pressure, amphibolite facies metamorphic event in the Brookville Gneiss with a cooling age of c. 540 Ma contrasts with the tectonothermal record typical of the Avalon composite terrane elsewhere in southern New Brunswick and raises the possibility, first proposed by Keppie (1985), that more than one terrane may be represented in the region.

In the Avalon composite terrane of the Caledonia Highlands, east and northeast of Saint John (Bevier and Barr, 1990), low pressure gneissic-platformal metasedimentary rock assemblages are absent and calc-alkaline granitoid bodies and associated volcanic rocks of the Coldbrook Group with U-Pb zircon ages of 625-600 Ma record no such metamorphism. Instead, they are succeeded by an essentially undeformed "Eocambrian" suite of bimodal volcanic and plutonic rocks with U-Pb zircon ages of c. 550 Ma. Similar relations in Cape Breton Island, Nova Scotia, have been taken to imply the existence of a major terrane boundary between probable correlatives of these contrasting assemblages (Barr and Raeside, 1989). Thus, the low-pressure gneissic complexes and associated platformal metasedimentary rocks of central Cape Breton, and the 565-555 Ma (U-Pb, zircon) calc-alkaline plutons that intruded them (Dunning *et al.*, 1990), have been assigned to the Bras d'Or terrane which Barr and Raeside (1990) interpreted to have been separated from the more typical Avalonian succession of the Mira terrane in southeastern Cape Breton until perhaps the Devonian. On the basis of this, Barr and White (1989) have proposed that, in southern New Brunswick, the Caledonia fault which borders the Caledonian Highlands to the northwest (Fig. 1), coincides with a major terrane boundary separating the gneisses and platformal metasedimentary rocks of the Brookville terrane from the more typically Avalonian successsion of the Caledonia terrane. The age-range of the calc-alkaline plutons that intrude both the Brookville Gneiss and the Green Head Group is uncertain because available Rb-Sr data are unsatisfactory. However, a single U-Pb age of 538 ± 1 Ma has been reported from the Rockwood Park Granodiorite in Saint John (White *et al.*, 1990) and a ^{40}Ar/^{39}Ar hornblende plateau age of 520 ± 3 Ma that is likely to record post-magmatic cooling, has been obtained from the Talbot Road Diorite northeast of Pocologan (Dallmeyer and Nance, 1989). Hence, plutonism within the Brookville terrane of Barr and White (1989) may indeed be younger than that typical of the Avalon composite terrane, thereby strengthening their argument for its correlation with the Bras d'Or terrane of central Cape Breton Island.

However, as a composite terrane (Keppie, 1985), Avalon is a Paleozoic entity defined, not by its late Precambrian history, but by the presence of an early Paleozoic, shallow-marine platformal sequence containing fossils of the Acado-Baltic faunal province. As such, the Avalon composite terrane is considered to represent a tectonic mosaic of several terranes that amalgamated during the late Precambrian and were subsequently accreted as a composite terrane to North America during the early-middle Paleozoic (e.g., Keppie *et al.*, 1990). In this context, the extent to which the Brookville and Caledonia terranes of Barr and White (1989) represent either far-travelled "exotic" terranes or juxtaposed "proximal" terranes (as implied by their correlation with Cape Breton Island), or are simply variations in the tectonic regime within a single terrane, is unclear.

The tectonothermal records of the Brookville and Caledonia terranes contrast in their expression but are similar in their timing. Thus, the protolith age (and compositional variation) of orthogneisses in the Brookville terrane match those of the calc-alkaline activity in the Caledonia terrane, while the metamorphic cooling age in the Brookville terrane closely follows the bimodal "Eocambrian" igneous activity in the Caledonia terrane. Emplacement of the protoliths of the Brookville orthogneisses into the Green Head Group may therefore have coincided with the emplacement of calc-alkaline plutons into the Coldbrook Group at a higher structural level of the same ensialic volcanic arc. The subsequent low-pressure mobilization of the Brookville Gneiss and regional metamorphism of the Green Head Group could then be interpreted to have coincided with extensional activity recorded at higher structural levels in the "Eocambrian" succession. In fact, the well-preserved olivine-pyroxene mineralogy and primary layering in unaltered portions of both the Indiantown Gabbro and the Duck Lake pluton (which intruded the Brookville Gneiss northeast of Saint John) are markedly similar to those of the Mechanic Settlement pluton which forms part of the "Eocambrian" assemblage in the Caledonia Highlands (Barr and White, 1988). Hence, it can be argued that, rather than recording entirely separate evolutions, the apparent contrast in the tectonothermal record across the Caledonia fault merely reflects a history at differing structural levels within a single terrane.

Furthermore, Cambro-Ordovician sedimentary rocks containing Acado-Baltic faunas occur on both sides of the Caledonia fault such that the Brookville and Caledonia terranes can be considered components of the Avalon composite terrane as defined by the overstep sequence. Admittedly, the continuity of the overstep sequence cannot be demonstrated because disconformable relations with the Saint John Group are preserved only in the Caledonia terrane whereas all contacts with the group in the Brookville terrane are faulted. Nevertheless, the distribution of the Saint John Group in the Brookville terrane (Fig. 1) would be difficult to explain entirely through fault movements. Consequently, while the existence of two quite separate terranes in southern New Brunswick remains a possibility, an equally permissible interpretation at our present state of knowledge is that the Brookville terrane is overstepped by the Saint John Group. If so, the Brookville and Caledonia terranes could only be Precambrian entities whose accretion to form part of the Avalon composite terrane occurred prior to the early Cambrian. The present relative positions of the two terranes, which is almost certainly the result of younger fault movements, would then be the product of subsequent dispersal of the Avalon composite terrane rather than the accretion of previously disparate terranes during the Paleozoic.

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