Age and geochemistry of Late Neoproterozoic and Early Cambrian igneous rocks in southern New Brunswick: similarities and contrasts

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ABSTRACT

Late Proterozoic to Early Cambrian igneous rocks are major components of the fault-bounded Caledonia, Brookville, and New River terranes of southern New Brunswick. As previously demonstrated, ca. 620 Ma and ca. 560–550 Ma volcanic and plutonic rocks of the Caledonia terrane are petrologically similar to coeval units elsewhere in the Avalon terrane *sensu stricto* of the northern Appalachian orogen. In contrast, the Golden Grove Plutonic Suite and volcanic rocks of the Dipper Harbour Formation in the Brookville terrane are mainly younger, ranging in age from ca. 555 Ma to 525 Ma. A new U-Pb (zircon) age reported here confirms that rhyolite in the Dipper Harbour Formation crystallized at 553 ± 3 Ma, like the older units of the Golden Grove Plutonic Suite to which they are chemically similar. However, they differ chemically from felsic units of similar age in the Caledonia terrane, with higher K_2O and Rb, lower Na_2O, and negative epsilon Nd values, although they also appear to have formed in an extensional setting. The Early Cambrian history of the two terranes is also very different, with clastic sediment deposition dominating in the Caledonia terrane while an active continental margin subduction zone developed on the Brookville terrane.

A U-Pb (zircon) age of 539 ± 4 Ma shows that volcanic rocks in the Simpsons Island Formation in the New River terrane are early Cambrian, similar to the ages of some plutons of the Golden Grove Plutonic Suite. More petrological studies of the Simpsons Island Formation are needed to assess it tectonic setting and relationship to the older (ca. 555 Ma) Leavitts Head Formation and Ragged Falls Plutonic Suite. These units are chemically similar to one another, consistent with their inferred comagmatic relationship, and are interpreted to have formed in an extensional setting. They are more similar to ca. 555–545 Ma volcanic and plutonic rocks of the Brookville terrane than to 560–550 Ma volcanic and plutonic rocks of the Caledonia terrane, although all of these units apparently formed in extensional settings. Too few data are available from volcanic units in the northeastern part of the New River terrane (Lobster Brook Formation) to compare them to the Leavitts Head Formation or to assess their tectonic setting.

A U-Pb age of 622 ± 2 Ma from the Blacks Harbour Granite in the southern part of the New River terrane is similar to previously reported ages from the Lingley Suite in the northeastern part of the terrane. More mapping and sampling are needed to define the extent of these ca. 625 Ma units in the New River terrane and assess their tectonic setting, although a subduction environment is suggested by the available data.

RÉSUMÉ

Les roches ignées du Protérozoïque tardif au Cambrien précoce constituent des éléments importants des terranes limités par des failles de Caledonia, de Brookville et de New River dans le Sud du Nouveau-Brunswick. Il a déjà été démontré que les roches volcaniques et plutoniques d'environ 620 Ma et de 560 à 550 Ma du terrane de Caledonia sont pétrologiquement semblables aux unités contemporaines ailleurs à l'intérieur du terrane d'Avalon, faisant partie, au sens strict, du nord de l'orogène des Appalaches. Par contraste, le cortège plutonique de Golden Grove et les roches volcaniques de la Formation de Dipper Harbour dans le terrane de Brookville sont essentiellement plus récentes; leurs âges varient entre 755 Ma et 525 Ma. Une nouvelle datation au U-Pb (à partir de zircon) signalée aux présentes confirme que la rhyolite de la Formation de Dipper Harbour s'est cristallisée vers 553±3 Ma, tout comme les unités plus anciennes du cortège plutonique de Golden Grove auxquelles ces roches ressemblent sur le plan chimique. Elles diffèrent toutefois du point de vue chimique des unités felsiques d'âge analogue du terrane de Caledonia, en présentant des concentrations plus élevées de K_2O et de Rb, des concentrations inférieures de Na_2O, et des valeurs Nd epsilon négatives, même si elles semblent s'être formées dans un cadre d'extension. Le passé des deux terranes au cours du Cambrien précoce est également très différent : un dépôt de sédiments clastiques prédomine dans le terrane de Caledonia, tandis qu'une zone active de subduction de la marge continentale s'est développée dans le terrane de Brookville.

Une datation au U-Pb (à partir de zircon) situant les roches volcaniques de la Formation de Simpsons Island dans le terrane de New River à 539 ±4 Ma, révèle qu'elles remontent au Cambrien, ce qui leur confère des âges semblables à certains plutons du cortège plutonique de Golden Grove. Il faudrait réaliser d'autres études pétrologiques de la Formation de Simpsons Island pour évaluer son cadre tectonique et ses rapports avec la Formation plus ancienne (environ 555 Ma) de Leavitts Head et le cortège plutonique de Ragged Falls. Ces unités sont chimiquement semblables les unes aux autres, ce qui correspond à leur présumée relation comagmatique. Elles sont interprétées comme des unités s'étant formées dans un cadre d'extension. Elles ressemblent plus aux roches plutoniques et volcaniques d'environ 555 à 545 Ma du terrane de Brookville qu'aux roches plutoniques et volcaniques de 560 à 550 Ma du terrane de Caledonia, même si ces unités se sont apparemment constituées dans des cadres d'extension. On dispose de trop peu de données des unités volcaniques du nord-est du terrane de New River (Formation de Lobster Brook) pour les comparer à la Formation de Leavitts Head ou pour évaluer leur cadre tectonique.

L'âge au U-Pb de 622 ±2 Ma du granite de Blacks Harbour dans le sud du terrane de New River est semblable aux âges précédemment signalés dans le cas du cortège de Lingley dans le nord-est du terrane. D'autres travaux de cartographie et d'échantillonnage s'avèrent nécessaires pour définir l'étendue de ces unités d'environ 625 Ma dans le terrane de New River ainsi que pour évaluer leur cadre tectonique, même si les données dont on dispose laissent supposer un environnement de subduction.

INTRODUCTION

Late Neoproterozoic igneous rocks are abundant in the Caledonia, Brookville, and New River terranes of southern New Brunswick (Figs. 1, 2). Some workers (e.g., Barr and White 1996; Samson *et al.* 2000) have proposed that differences in age and composition of these igneous rocks among the terranes are indicative of unrelated origins, and hence that each terrane had a separate history into the Paleozoic. Other workers (e.g., Eby and Currie 1996; Currie and McNicoll 1999; Whalen *et al.* 1996; Johnson 2001) emphasized linkages in age and composition among the plutonic and volcanic rocks, and suggested that these similarities indicate that at least parts of these terranes were together in the late Neoproterozoic.

This difference in interpretation has implications for the number of crustal blocks or terranes involved in building the Appalachian orogen, and hence for interpretations of Silurian and Devonian orogenic events. Some tectonic models have suggested that the Late Neoproterozoic rocks in outboard parts of the northern Appalachian orogen were all part of a single block (inset, Fig. 1), variously termed Avalon zone (Williams 1979), Avalon microcontinent (e.g., Landing 1996), West Avalonia (e.g., Murphy *et al.* 1999; Nance *et al.* 2002) or Avalon composite terrane (e.g., Dorais *et al.* 2001; Robinson *et al.* 1998). According to these authors, "Avalonia" interacted with the Laurentian margin as a single continental entity in the mid-Paleozoic. In contrast, other models have postulated that at least two separate blocks amalgamated independently and sequentially with the Laurentian margin in the Paleozoic (e.g., van Staal *et al.* 1998; Barr *et al.* 1998, 2002). These authors suggested that the New River and possibly Brookville terranes are related to a separate crustal block (Ganderia or Bras d'Oria), and that only the Caledonia terrane is part of Avalon terrane *sensu stricto*, as exemplified by the part of Newfoundland east of the Dover-Hermitage Bay Fault (Williams 1978).

The purpose of this paper is to further investigate relationships among the Caledonia, Brookville, and New River terranes of southern New Brunswick in the Late Neoproterozoic and Early Cambrian by comparing the igneous units formed in those areas during that time. To better constrain unit ages, three new U-Pb (zircon) ages are presented for igneous rocks in the Brookville and New River terranes, and a compilation of the new and previous U-Pb ages is used to compare ages of igneous units in the three terranes. In addition, new chemical data are presented for igneous units in the New River terrane, and combined with earlier data to make a chemical comparison among the three terranes. Although such comparisons were made previously between the Brookville and Caledonia terranes (Barr and White 1996; White and Barr 1996), new work in the New River terrane (Johnson and McLeod 1996; Johnson 2001, 2003; Currie and McNicoll 1999) now enables a preliminary comparison among all three terranes. Also, since the earlier comparisons, additional mapping, geochemistry, and U-Pb dating have resulted in a better understanding of the Brookville terrane (White *et al.* 2002). Based on these comparisons, we suggest that igneous activity in the three terranes was not directly related, in support of other geological evidence that the three terranes were separate in the Late Neoproterozoic and Early Paleozoic.

GEOLOGICAL OVERVIEW

Caledonia terrane

The Caledonia terrane (Fig. 2a) includes mainly Neoproterozoic and Cambrian rocks located south of the Caledonia-Clover Hill fault, which has been interpreted to mark a cryptic suture between the Caledonia and Brookville terranes (White *et al.* 2001). Based on differences in lithology and age, Neoproterozoic volcanic and sedimentary rocks of the Caledonia terrane have been divided into the ca. 620 Ma Broad River Group, exposed mainly in the northeastern and southern parts of the terrane, and the ca. 560–550 Ma Coldbrook Group which forms most of the western and northern parts (Bevier and Barr 1990; Barr *et al.* 1994; Barr and White 1999). Ca. 620 Ma compositionally expanded gabbroic to granitic plutons and ca. 560–550 Ma bimodal gabbroic and granitic plutons
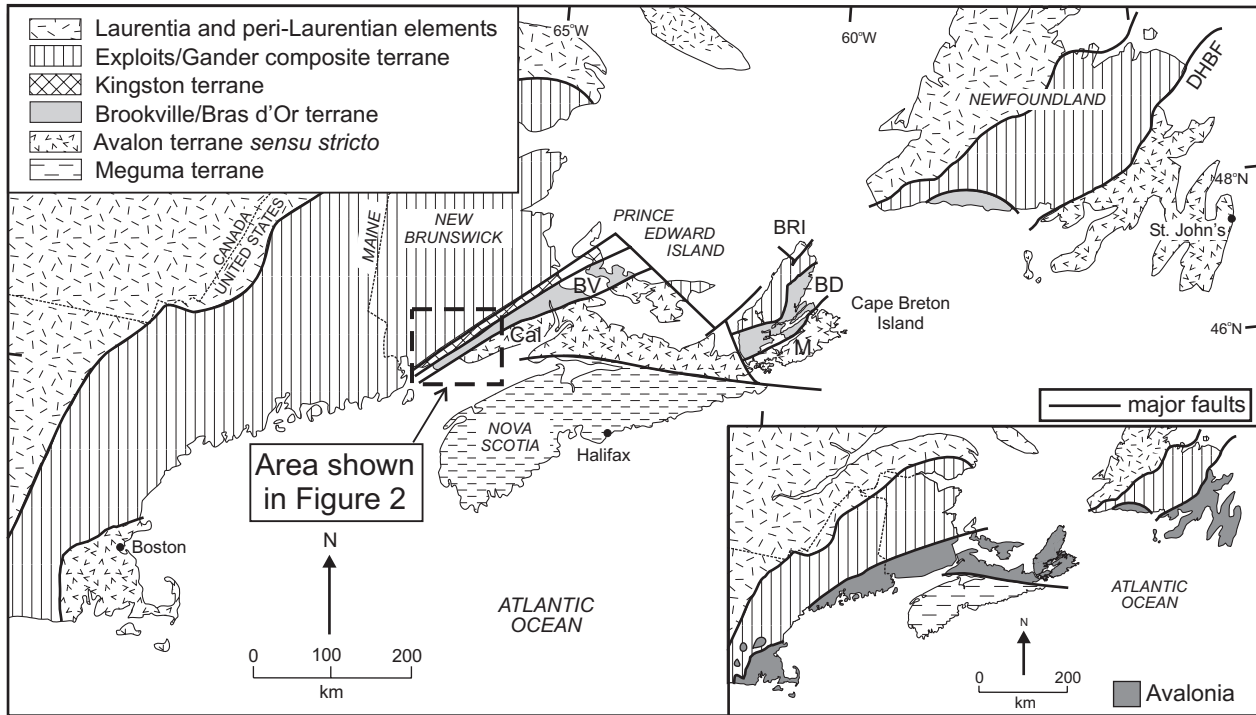
Fig. 1 Simplified map showing terranes of the northern Appalachian orogen modified from Barr *et al*. (2002). Heavy solid lines are inferred terrane boundaries. New River terrane of southern New Brunswick is included in the Exploits/Gander composite terrane on this figure. Abbreviations: BV, Brookville terrane; BD, Bras d'Or terrane ; BRI, Blair River inlier; Cal, Caledonia terrane; DHBF, Dover-Hermitage Bay Fault; M, Mira terrane. Inset map shows parts of the orogen typically included in broader definitions of West Avalonia, Avalon Zone, or Avalon composite terrane, as described in the text.
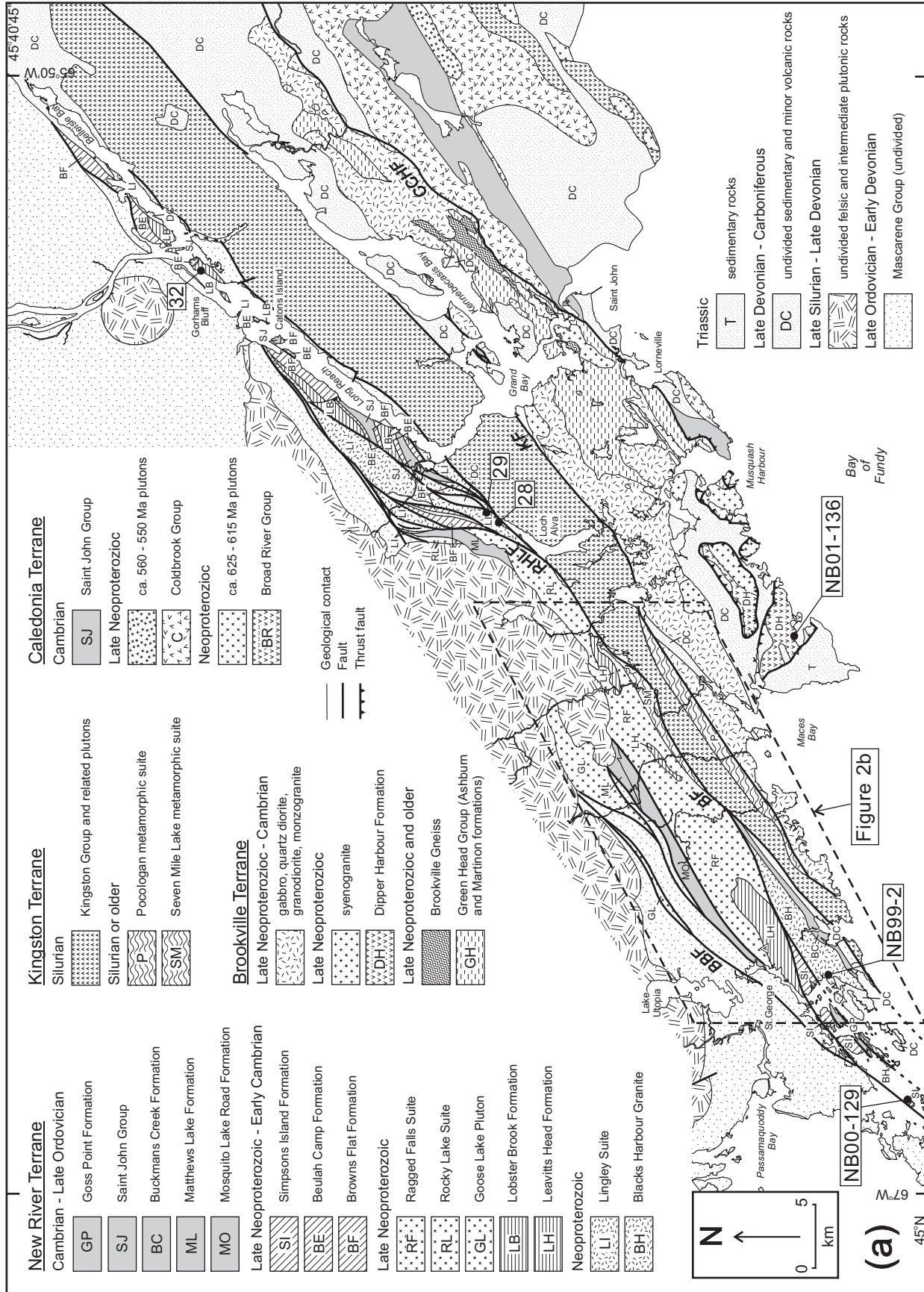
are interpreted to be cogenetic with the Broad River Group and basalt and rhyolite of the upper part of the Coldbrook Group, respectively (Barr and White 1999). On the basis of petrological characteristics, the ca. 620 Ma rocks are interpreted to have formed in a continental margin magmatic arc, whereas the ca. 560–550 Ma rocks formed during subsequent extension (Barr and White 1999). The Coldbrook Group is overlain by a Lower Paleozoic platformal sedimentary sequence containing an "Avalonian" fauna (e.g., Tanoli and Pickerill 1988; Landing 1996; Landing and Westrop 1998).

A fault-bounded area of high-pressure and low-temperature metamorphic rocks located near the northwestern margin of the Caledonia terrane has been interpreted to represent an accretionary complex formed at ca. 620 Ma in association with a southeast-dipping subduction zone that generated the Broad River Group and related plutons (White *et al.* 2001). This unit is evidence for a terrane boundary between the Caledonia and now-adjacent Brookville terrane.

Brookville terrane

In contrast to the Caledonia terrane, the Brookville terrane is characterized by mainly metasedimentary rocks (Green Head Group) and abundant plutons (White and Barr 1996; White *et al.* 2002). The terrane-bounding brittle faults, Caledonia - Clover Hill on the southeast and Kennebecasis on

the northwest (Fig. 1), are Carboniferous or younger faults interpreted to mark the approximate locations of older cryptic sutures. The Green Head Group consists of the Ashburn (dominantly marble with minor metaclastic rocks) and Martinon (dominantly metasiltstone with minor calc-silicate rocks, quartzite, conglomerate, and marble) formations, interpreted to be lateral facies equivalents. The early Neoproterozoic or late Mesoproterozoic age proposed for the Green Head Group based on locally preserved stromatolite occurrences (Hofmann 1974) is supported by a minimum U-Pb age of 1230 Ma for detrital zircon grains in a quartzite sample (Barr *et al.* 2003). The Green Head Group is in tectonic contact along the MacKay Highway shear zone (Nance and Dallmeyer 1994; White 1996) with the Brookville Gneiss, a locally migmatitic paragneiss with sheets of granodioritic to tonalitic orthogneiss, minor calc-silicate and marble layers, and rare quartzite and amphibolite. The paragneiss comprises about 75% of the Brookville Gneiss, and contains detrital zircon indicating a maximum depositional age of ca. 640 Ma (Bevier *et al.* 1990). The orthogneiss has an igneous crystallization age of 605 ± 3 Ma, and was metamorphosed to amphibolite facies at 564 ± 6 Ma (Bevier *et al.* 1990; Dallmeyer *et al.* 1990). These ages indicate that the Brookville Gneiss is younger than the Green Head Group and, hence, does not represent its basement, although the original relationship between the two units remains problematic (White and Barr 1996).
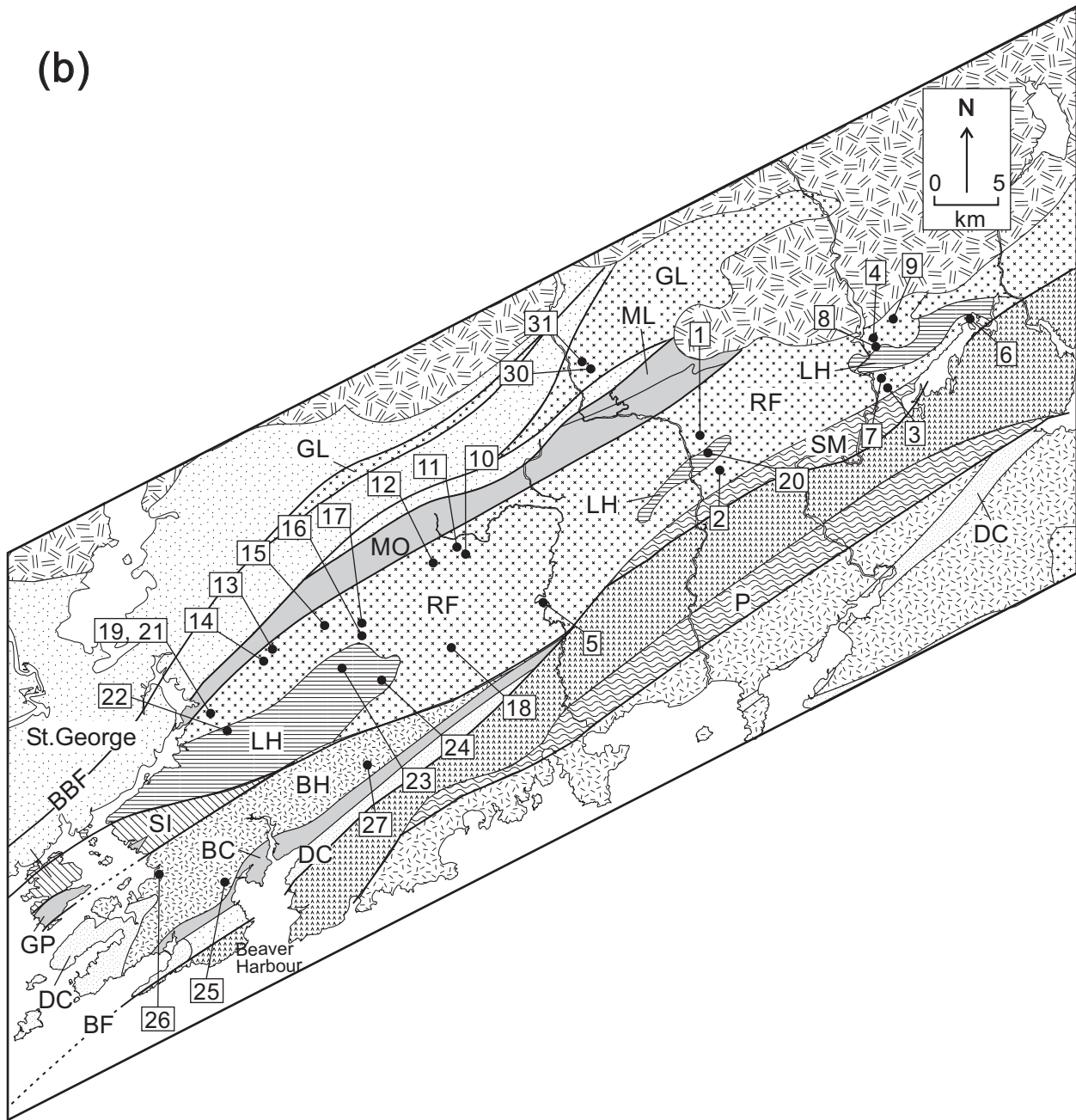
New River Terrane

Cambrian - Late Ordovician

- GP   Goss Point Formation
- SJ   Saint John Group
- BC   Buckmans Creek Formation
- ML   Matthews Lake Formation
- MO   Mosquito Lake Road Formation

Late Neoproterozoic - Early Cambrian

- SI   Simpsons Island Formation
- BE   Beulah Camp Formation
- BF   Browns Flat Formation

Late Neoproterozoic

- RF   Ragged Falls Suite
- RL   Rocky Lake Suite
- GL   Goose Lake Pluton
- LB   Lobster Brook Formation
- LH   Leavitts Head Formation

Neoproterozoic

- LI   Lingley Suite
- BH   Blacks Harbour Granite

Kingston Terrane

Silurian

- Kingston Group and related plutons

Silurian or older

- P   Pocologan metamorphic suite
- SM   Seven Mile Lake metamorphic suite

Brookville Terrane

Late Neoproterozoic - Cambrian

- gabbro, quartz diorite, granodiorite, monzogranite

Late Neoproterozoic

- syenogranite
- DH   Dipper Harbour Formation

Late Neoproterozoic and older

- Brookville Gneiss
- GH   Green Head Group (Ashburn and Martinon formations)

Caledonia Terrane

Cambrian

- SJ   Saint John Group

Late Neoproterozoic

- ca. 560 - 550 Ma plutons
- C   Coldbrook Group

Neoproterozoic

- ca. 625 - 615 Ma plutons
- BR   Broad River Group

— Geological contact

Fault

Thrust fault

Triassic

- T   sedimentary rocks

Late Devonian - Carboniferous

- undivided sedimentary and minor volcanic rocks

Late Devonian

- DC   undivided felsic and intermediate plutonic rocks

Late Silurian - Late Devonian

- undivided sedimentary rocks

Late Ordovician - Early Devonian

- Mascarene Group (undivided)

(a)

N

0   5 km

45°N

67°W

45°40'45"

65°50'W

Passamaquoddy Bay

St George

Lake Utopia

BBF

BF

RHLF

KF

CCHF

Belleisle Bay

Long Reach

Gorhams Bluff

Catons Island

Grand Bay

Kennebecasis Bay

Saint John

Lorneville

Loch Alva

Musquash Harbour

Maces Bay

Bay of Fundy

NB00-129

NB99-2

NB01-136

Figure 2b

32

28

29

DC

(b)

Fig. 2 (a) Simplified geological map of part of southern New Brunswick, showing the distribution of major units in the southwestern parts of the New River, Brookville, and Caledonia terranes. Geology for the New River terrane is after Johnson (2001), for the Brookville terrane after White *et al.* (2002), and for the Caledonia terrane after Barr and White (1999). Locations are indicated for the three dated samples NB00-129, NB99-2, and NB01-136 and geochemistry samples 28, 29, and 32. Abbreviations: BBF, Back Bay Fault; BF, Bellisle Fault; CCHF, Caledonia - Clover Hill Fault; KF, Kennebecasis Fault; RHLF, Robin Hood Lake Fault. (b) Enlarged view of the dashed area on Fig. 2a, showing locations of geochemistry samples other than 28, 29, and 32. Unit designations, patterns, and abbreviations are the same as on Fig. 2a.

The Green Head Group and Brookville Gneiss have been intruded by plutons of the redefined Golden Grove Plutonic Suite (White *et al.* 2002). The plutons range in composition from gabbroic to granitic, and have yielded U-Pb and $^{40}Ar/^{39}Ar$ dates of ca. 550 Ma to 527 Ma (Dallmeyer and Nance 1992; White 1996; Currie and Hunt 1991; Currie and McNicoll 1999; White *et al.* 2002). Petrological characteristics suggest that they constitute a calc-alkalic I-type granitoid suite, probably emplaced in a continental margin subduction zone (White 1996; Eby and Currie 1996), although the older components of the suite (ca. 550 Ma) have characteristics indicative of an early extensional environment that evolved to subduction (White *et al.* 2002). Eby and Currie (1996) and Currie and McNicoll (1999) suggested that the plutons of the Brookville terrane are related to those in the Caledonia and New River terranes, but Barr and White (1996) argued that they are mainly younger and part of a separate and unrelated tectonic regime. Volcanic rocks of the Dipper Harbour Formation, locally preserved in faulted blocks in the southwestern part of the Brookville terrane (Fig. 2), are chemically similar to the early felsic granitoid components of the terrane (White *et al.* 2002). However, other workers have suggested that the Dipper Harbour Formation is related to volcanic rocks of broadly similar age in the Coldbrook Group of the Caledonia terrane, although the ages reported for samples from the Dipper Harbour Formation and associated plutons had large errors associated with them (Zain Eldeen 1991; Currie and Hunt 1991).

New River terrane

The most northwesterly exposures of Precambrian rocks known in southern New Brunswick occur in the New River terrane. Rock units in the New River terrane have been described by Johnson and McLeod (1996) and Johnson (2001; 2003), and the interpretations of these authors are generally followed here (Fig. 2).

The New River terrane is cut by numerous faults, and hence relationships among units are uncertain in many cases. The southern part of the belt is dominated by the Blacks Harbour Granite and Ragged Falls suite (Fig. 2). The Blacks Harbour Granite occurs with minor felsic volcanic rocks in a fault-bounded strip on the southern margin of the terrane. Prior to the new age reported here, it was undated. The Ragged Falls suite, as defined by Johnson (2001, 2003), includes syenogranite, monzogranite, tonalite, and gabbro. Ages of 555 ± 2 Ma and 555 ± 10 Ma have been reported for granodiorite and granite, respectively, from the suite (Johnson and McLeod 1996; Currie and Hunt 1991). The Ragged Falls Suite is closely associated with volcanic rocks (Leavitts Head Formation of Johnson 2001, 2003), a felsic component of which has yielded a U-Pb age of ca. 550 Ma (Johnson and McLeod 1996). Also in the area are numerous faulted blocks of volcanic and sedimentary rocks that were assigned to the Ordovician Simpsons Island volcanics and Goss Point Formation by Johnson and McLeod (1996). Based on the U-Pb (zircon) age reported here, Johnson (2003) separated the Simpsons Island volcanics (Simpsons Island

Formation) from the fossiliferous Late Ordovician rocks of the Goss Point Formation (Nowlan *et al.* 1997).

A fault-bounded belt of Early Cambrian and Silurian volcanic and sedimentary rocks separates the Ragged Falls suite and Leavitts Head Formation from the Goose Lake Pluton (undated granodiorite and granite) to the north (Fig. 2a). To the northeast, Johnson (2001, 2003) interpreted the Ragged Falls suite to pass gradationally into similar granitoid rocks of the undated Rocky Lakes Suite, which she described as granite, granodiorite , tonalite, and quartz diorite, cut by numerous mafic dykes. Farther to the northeast, Johnson (2001, 2003) terminated the Rocky Lakes suite at the major northeast-trending Robin Hood Lake Fault (Fig. 2a). Northeast of this fault, ca. 625 Ma granitoid rocks are in complexly faulted relationships with ca. 555 Ma felsic tuff and porphyry, Neoproterozoic to Cambrian mafic and felsic volcanic and sedimentary rocks, and Cambrian rocks assigned to the Saint John Group (Tanoli and Pickerill 1988; Johnson and McLeod 1996; Johnson 2001, 2003). The ca. 625 Ma granitoid rocks were termed the Lingley and Brittain Creek plutons by Currie and McNicoll (1999). However, chemical data from granitic samples reported by Eby and Currie (1996) to be from the Lingley Pluton are at least in part from younger quartz-eye granitic porphyry that Johnson (2001) included with the Lobster Brook Formation. A sample from the Lobster Brook Formation which yielded a U-Pb age of ca. 550 Ma (McLeod *et al.* in press).

As a result of her work, Johnson (2001, 2003) suggested that the New River terrane is composite. She proposed that units northeast of the Robin Hood Lake Fault, as well as the Blacks Harbour Granite and spatially associated units in the Beaver Harbour area (Fig. 2b), are part of the Avalon zone, and hence comparable to rocks in the Caledonia terrane. In contrast, units southwest of the fault and north of the Blacks Harbour Granite may be related to the Brookville terrane and/or the St. Croix terrane and related units in Maine, which have been linked to the Gander terrane (van Staal *et al.* 1998; Fyffe *et al.* 1999).

U-PB GEOCHRONOLOGY

Introduction

Samples from the Simpsons Island Formation and Blacks Harbour Granite in the New River terrane and the Dipper Harbour Formation in the Brookville terrane (Fig. 2) were dated by the U-Pb (zircon) method as part of the present study. The analyses were done at the University of North Carolina (Chapel Hill) Isotope Geochemistry Laboratory. Zircon grains were separated from samples weighing ca. 25 kg using standard techniques, and hand picked under a binocular microscope in order to select groups of grains that were similar in morphology and as clear, crack-free, and inclusion-free as possible. All zircon fractions were highly abraded to remove the outermost portions of grains that are most likely to have been affected by Pb-loss. Detailed analytical procedures were similar to those described by Miller *et al.* (2001).

Table 1. U-Pb isotopic data for dated samples.

Analysis#, Fraction (number of grains)	weight (mg)[1]	Total[1] U (ng)	Total[2] Pb (pg)	Total[2] Com.Pb (pg)	U (ppm)	Pb (ppm)	$\frac{206Pb}{204Pb}$[2]	$\frac{206Pb}{208Pb}$	$\frac{206Pb}{238U}$[3]	% Error[4]	$\frac{207Pb}{235U}$[3]	% Error[4]	$\frac{207Pb}{206Pb}$[3]	% Error[4]	$\frac{206Pb}{238U}$	$\frac{207Pb}{235U}$	$\frac{207Pb}{206Pb}$	r[5]
NB00-129 (Simpsons Island Formation) (NTS 21G/2, UTM coordinates: ca. 665500E, 4986475N)																		
1) medium prism #2 (1)	0.002	0.45	40.7	1.40	227	20	1710	0.211	0.08209	1.330	0.65743	1.383	0.05809	0.372	508.6	513.0	533.0	0.96
2) equant (5)	0.004	0.66	61.3	1.73	166	15	2061	0.226	0.08359	0.505	0.67046	0.518	0.05818	0.114	517.5	521.0	536.4	0.98
3) short prisms (5)	0.010	0.57	53.2	5.23	57	5	612	0.213	0.08549	0.704	0.68476	0.730	0.05809	0.186	528.8	529.6	533.2	0.97
4) medium grain tips (4)	0.009	0.39	37.1	1.62	43	4	1323	0.236	0.08583	0.925	0.68937	0.935	0.05825	0.131	530.8	532.4	539.3	0.99
5) large prism #1 (1)	0.002	0.32	29.0	9.54	159	14	193	0.236	0.08189	3.400	0.65568	3.943	0.05807	1.942	507.4	512.0	532.6	0.87
6) medium prism #3 (1)	0.002	0.21	18.8	2.63	105	9	437	0.209	0.08185	2.358	0.65700	2.533	0.05822	0.875	507.2	512.8	537.9	0.94
7) medium prism #4 (1)	0.002	0.06	6.3	1.44	32	3	263	0.257	0.08619	3.512	0.69518	4.065	0.05850	1.929	532.9	535.9	548.6	0.88
8) small equant (5)	0.011	0.23	24.1	1.35	21	2	998	0.285	0.08946	2.254	0.73561	2.278	0.05964	0.312	552.4	559.8	590.4	0.99
9) medium prism #5 (1)	0.002	0.08	7.4	1.18	39	4	388	0.188	0.08771	1.343	0.74232	1.523	0.06138	0.679	542.0	563.8	652.6	0.90
10) medium prism #6 (1)	0.002	0.06	6.4	1.64	30	3	229	0.303	0.08870	1.419	0.77269	1.690	0.06318	0.865	547.9	581.3	714.3	0.86
11) small short prisms (2)	0.003	1.73	338.8	2.61	577	113	7355	0.208	0.17359	0.270	2.42345	0.281	0.10125	0.077	1031.9	1249.6	1647.2	0.96
NB99-2 (Blacks Harbour Granite) (NTS 21G/2, UTM coordinates: 672550E, 4993025N)																		
27) medium prisms (7)	0.018	5.23	645.5	1.72	291	36	21143	0.248	0.10911	0.249	0.97863	0.255	0.06505	0.056	667.6	692.9	775.9	0.98
28) prism tips (8)	0.015	7.92	904.2	2.68	528	60	19404	0.224	0.10312	0.100	0.89310	0.118	0.06281	0.063	632.7	648.0	701.9	0.85
29) large football (1)	0.003	6.79	722.2	5.23	2263	241	8402	0.156	0.10147	0.096	0.87211	0.161	0.06233	0.123	623.0	636.7	685.6	0.65
30) large soccer ball (1)	0.002	3.58	378.1	7.72	1792	189	3015	0.150	0.10129	0.110	0.84473	0.143	0.06048	0.090	622.0	621.8	621.0	0.78
31) partly metamict prisms (2)	0.009	18.91	1778.7	14.93	2101	198	7730	0.071	0.09644	0.126	0.80079	0.141	0.06022	0.061	593.5	597.3	611.5	0.90
32) acicular prisms (7)	0.011	3.96	482.2	1.64	360	44	15480	0.346	0.10057	0.101	0.83877	0.124	0.06049	0.071	617.8	618.5	621.0	0.82
33) small stubby prisms (12)	0.024	4.44	513.9	2.62	185	21	10740	0.292	0.09928	0.147	0.82749	0.160	0.06045	0.062	610.2	612.2	619.9	0.92
34) large stubby prisms (6)	0.013	6.42	704.7	2.86	494	54	14400	0.208	0.10047	0.191	0.83830	0.207	0.06052	0.077	617.1	618.2	622.1	0.93
NB01-136 (Dipper Harbour Formation) (NTS 21G/1, UTM coordinates: 704000E, 4997100N)																		
19) medium prism tip (1)	0.002	0.25	24.5	0.83	166	16	1739	0.205	0.09048	0.516	0.73792	0.639	0.05915	0.360	558.4	561.2	572.7	0.83
20) large prism center fragment #1 (1)	0.001	0.30	29.8	0.94	253	25	1885	0.198	0.09084	0.282	0.73747	0.315	0.05888	0.136	560.5	560.9	562.7	0.90
21) medium equant (5)	0.011	0.57	55.4	1.77	52	5	1875	0.189	0.08976	0.392	0.72537	0.410	0.05861	0.116	554.1	553.8	552.7	0.96
22) large prism center fragment #2 (1)	0.002	0.76	72.8	1.21	378	36	3586	0.194	0.08949	0.106	0.72336	0.266	0.05862	0.236	552.5	552.7	553.2	0.47
23) medium prism (1)	0.002	0.50	48.0	0.92	335	32	3130	0.185	0.08942	0.180	0.72261	0.227	0.05861	0.138	552.1	552.2	552.7	0.80
24) large prism (1)	0.003	0.55	55.7	1.01	182	19	3070	0.272	0.08899	0.201	0.72063	0.227	0.05873	0.102	549.6	551.0	557.2	0.89
25) small equant (8)	0.011	0.65	62.5	1.11	59	6	3319	0.202	0.08851	0.247	0.71553	0.267	0.05863	0.098	546.7	548.0	553.4	0.93
26) medium prisms (5)	0.015	1.12	108.9	0.85	75	7	7498	0.207	0.08923	0.111	0.72078	0.134	0.05859	0.076	551.0	551.1	551.8	0.83

[1] Weight estimated from measured grain dimensions and assuming density = 4.67g/cm³, ~20% uncertainty affects only U and Pb concentrations

[2] Corrected for fractionation (0.12± 0.08%/amu - Faraday-Daly; 0.20± 0.1%/amu - Daly) and spike

[3] Corrected for fractionation, blank, and initial common Pb

[4] Errors quoted at 2σ

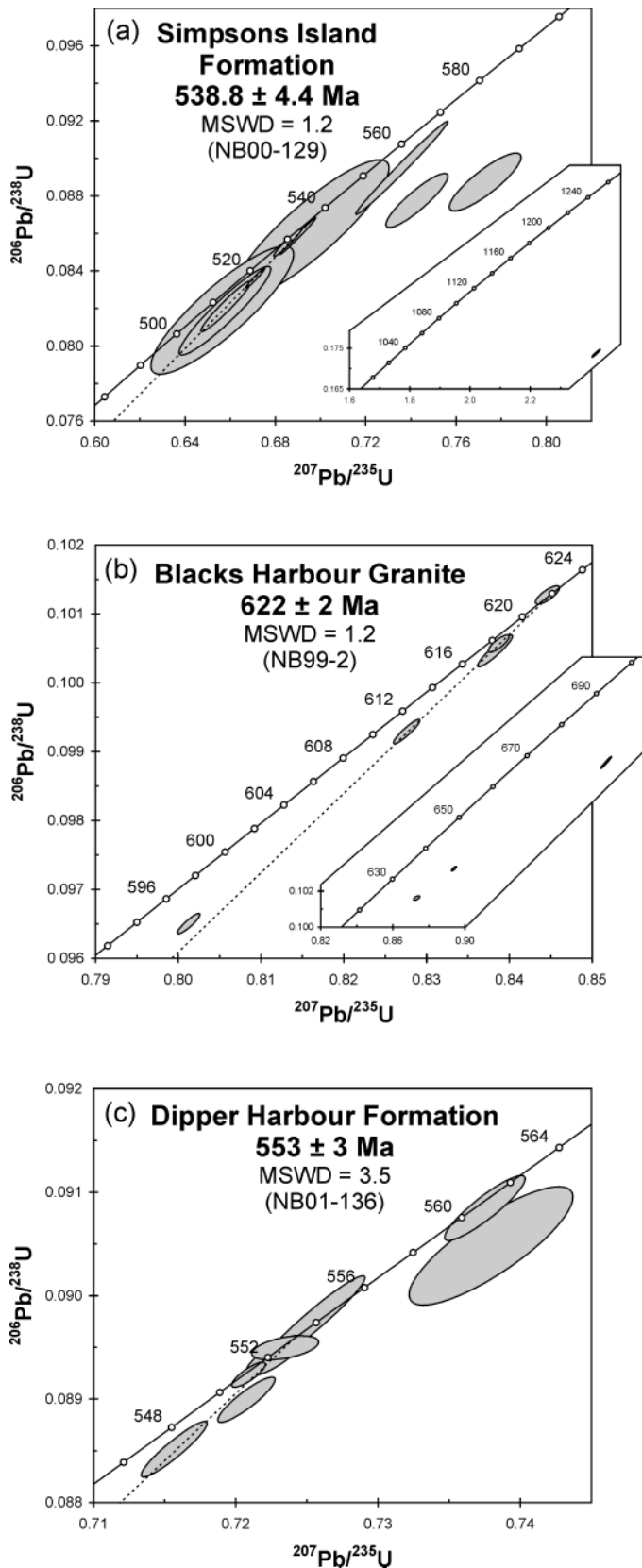[5] ^{207}Pb/^{235}U - ^{206}Pb/^{238}U correlation coefficient of Ludwig (1989)

Fig. 3 Concordia diagrams for (a) NB00-129, (b) NB99-2, and (c) NB01-136, based on data presented in Table 1.

Simpsons Island Formation (Sample NB00-129)

Rhyolite sample NB00-129 was collected from the Simpsons Island Formation on Adam Island in the southwestern part of the New River terrane (Fig. 2). Johnson and McLeod (1996) interpreted this unit to be Ordovician, because of close spatial association with faulted slivers of sedimentary rocks that contain Late Ordovician fossils. The dated sample is a fine-grained flow-banded rhyolitic flow with well-developed eutaxitic and locally spherulitic texture.

Zircon grains separated from sample NB00-129 were mostly prismatic, and large enough (~150–200 μm x 30–40 μm) for analysis of single grains and fractions of a small number of grains (Table 1). Eleven fractions were analyzed and four appear to contain an inherited component (Fig. 3a). Three fractions have relatively large errors due to low radiogenic to common Pb ratios (Table 1). Two of the highest-precision analyses are nearly concordant and one relatively lower precision analysis is concordant within error. The seven analyses define a concordant-to-discordant trend with an upper intercept of 538.8 ± 4.4 Ma and a lower intercept suggestive of recent Pb-loss. We consider the upper-intercept age as the time of zircon crystallization in the magma, and within error of the time of rhyolite extrusion.

This age indicates that the Simpsons Island Formation is earliest Cambrian in age (time scale of Okulitch 2002), consistent with the earlier interpretation of Currie (1997). The new age suggests that volcanic rocks in the area, assigned previously to the Simpsons Island and Goss Point formations, are of early Cambrian age (S. Johnson, personal communication 2003).

Blacks Harbour Granite (Sample NB99-2)

The Blacks Harbour Granite is located in a complexly faulted area, associated with unnamed and undated volcanic and sedimentary rocks, in faulted contact with Middle Cambrian mafic volcanic and sedimentary rocks. The volcanic and sedimentary unit, termed the Buckmans Creek beds (Currie 1988; Johnson 2001), has been interpreted to unconformably overlie the Blacks Harbour Granite (Greenough *et al.* 1985; Currie 1988; Johnson 2001). Helmstaedt (1968) described the granite as mainly alaskite, described intrusive contacts with adjacent units, and considered the pluton to be Devonian. The dated sample NB99-2 is coarse-grained granodiorite collected in the village of Blacks Harbour. It consists of plagioclase, quartz, and less abundant orthoclase in allotriomorphic granular texture with less than 5% chlorite (after biotite).

Zircon grains separated from sample NB99-2 were of a wide variety of morphologies and sizes (Table 1). Eight zircon fractions ranging from a large single grain to 12 small prismatic grains were analyzed (Fig. 3b). Three fractions have $^{207}Pb/^{206}Pb$ ages of >685 Ma, which we interpret to contain an inherited component. One fraction is concordant at ~622 Ma and three others form a discordant line from that age. The four analyses yield an upper intercept age of 622 ± 2 Ma and a lower intercept suggesting recent Pb loss. One highly discor-

dant fraction of partly metamict zircon grains plots to the left of this discordant trend, likely due to ancient Pb-loss, the age of which cannot be estimated reasonably from the data at hand. We interpret the upper intercept age of 622 ± 2 Ma to be the time of crystallization of the Blacks Harbour Granite.

Dipper Harbour Formation (Sample NB01-136)

A previous U-Pb (zircon) age for the Dipper Harbour Formation had a large error (Zain Eldeen 1991). Leucogranite of the Musquash Harbour Pluton, which appears to have a gradational relationship with the volcanic rocks (Currie and Hunt 1991), also yielded an age with a very wide error (555 ± 15 Ma). In order to better constrain the ages of both of these important units, felsic tuff sample NB01-136 was collected for dating. The sample consists of scattered embayed quartz and less abundant feldspar clasts in a fine-grained groundmass of quartz and feldspar. Zircon grains separated from sample NB01-136 were mainly prisms of sufficient size (70–150 µm x 20–40 µm) to do single-grain analyses or analyses of a small number of grains (Table 1). One analysis was a single pyramidal grain tip broken from a prismatic grain during sample processing. Of the eight analyzed zircon fractions, two appear to contain an inherited component (Fig. 3c). The remaining six form a discordant trend with an upper intercept age of 553 ± 3 Ma. One fraction in this discordant trend lies slightly to the right of the others and may contain a small inherited component. It was, nevertheless, included in the regression, which causes a high mean square of weighted deviates (MSWD). By excluding this fraction, the upper intercept age remains essentially the same, but the MSWD is reduced to <1. We consider the upper-intercept age of 553 ± 3 Ma as the time of zircon crystallization in the magma, and within error of the age of the volcanic rock.

Age compilation

Previous U-Pb crystallization ages for igneous units in the Caledonia, Brookville, and New River terranes are compiled on Fig. 4, together with the three new ages reported here. Ages in the Caledonia terrane fall into two main groups - older ages in the range 625–615 Ma representing the Broad River Group and co-genetic plutons, and younger ages in the range 560–550 Ma representing the Coldbrook Group and co-genetic plutons. A crystallization age of ca. 600 Ma reported for a tuffaceous sample previously assigned to the Broad River Group (Bevier and Barr 1990) may represent inherited zircon in a ca. 560–550 Ma unit of the Coldbrook Group. Ash beds in the overlying Cambrian Saint John Group yielded zircon ages of 533 ± 2 Ma (Samson 1995); 531 ± 1 Ma (Isachsen et al. 1994), and ca. 511 Ma (Landing et al. 1998), as well as a detrital zircon population at ca. 523 Ma (Landing et al. 1998).

In the Brookville terrane, orthogneiss in the Brookville Gneiss yielded an age of ca. 605 Ma, interpreted to represent its igneous crystallization age (Bevier et al. 1990). However, plutons in the terrane yielded ages between ca. 553 Ma and 527 Ma, reflecting a long-lived magmatic event. The new age

presented here for the Dipper Harbour Formation also constrains the age of the Musquash Harbour and similar plutons in the area because of the gradational relationship between the volcanic and plutonic units in the Dipper Harbour area.

In the New River terrane, ca. 625 Ma ages were reported for the Lingley and Brittain Creek plutons by Currie and McNicoll (1999); both plutons were included in the Lingley Suite by Johnson (2001, 2003). A similar age (622 Ma) was obtained in the present study for the Blacks Harbour Granite in the southwestern part of the New River terrane. In contrast, ca. 555 Ma ages have been obtained throughout the terrane, from the Lobster Brook Formation in the northeast and both the Ragged Falls suite and Leavitts Head Formation in the southwest. The new age reported here for the Simpsons Island Formation is significantly younger at ca. 539 Ma. The youngest dated volcanic unit in the terrane is the ca. 515 Ma Mosquito Lake Road Formation.

Close spatial relationships and chemical similarities support a co-magmatic relationship between volcanic and plutonic units of similar age in each of the Caledonia and Brookville terranes, with a range in U-Pb ages from each suite that likely reflects protracted magmatic activity (Barr and White 1999; White et al. 2002). However this relationship has yet to be tested in the New River terrane. Furthermore, the relationship between igneous units of similar age in different terranes is problematic. Currie and McNicoll (1999) and Johnson (2001) emphasized that the presence of ca. 625 Ma and 550 Ma igneous rocks, combined with the presence of the Cambrian Saint John Group or equivalent units containing Avalonian fauna, in both terranes strongly suggests that at least parts of the New River terrane have close links with the Caledonia terrane. Ca. 550 Ma igneous rocks also occur in the Brookville terrane, and ca. 531 Ma zircon grains in ash layers in the Saint John Group of the Caledonia terrane have similarities to the ages of some plutonic units in the Brookville terrane.

One way to assess whether or not units of similar age are likely to be related to one another is to compare their chemical characteristics, as done in the subsequent section for igneous units in the Caledonia, Brookville, and New River terranes.

GEOCHEMISTRY

Major and trace elements

A large database of whole-rock chemical analyses is available for the Caledonia (Barr and White 1999) and Brookville (White 1996; White et al. 2002) terranes, but relatively few analyses have been published previously for volcanic and plutonic units in the New River terrane (Johnson and McLeod 1996; Eby and Currie 1996). To enable a preliminary comparison with units of similar ages in adjacent terranes, additional analyses were obtained for 32 granitoid and volcanic samples from units in the New River terrane (Table 2). However, the data are mainly from the southwestern part of the terrane, and units northeast of the Robin Hood Lake Fault are poorly represented. Most
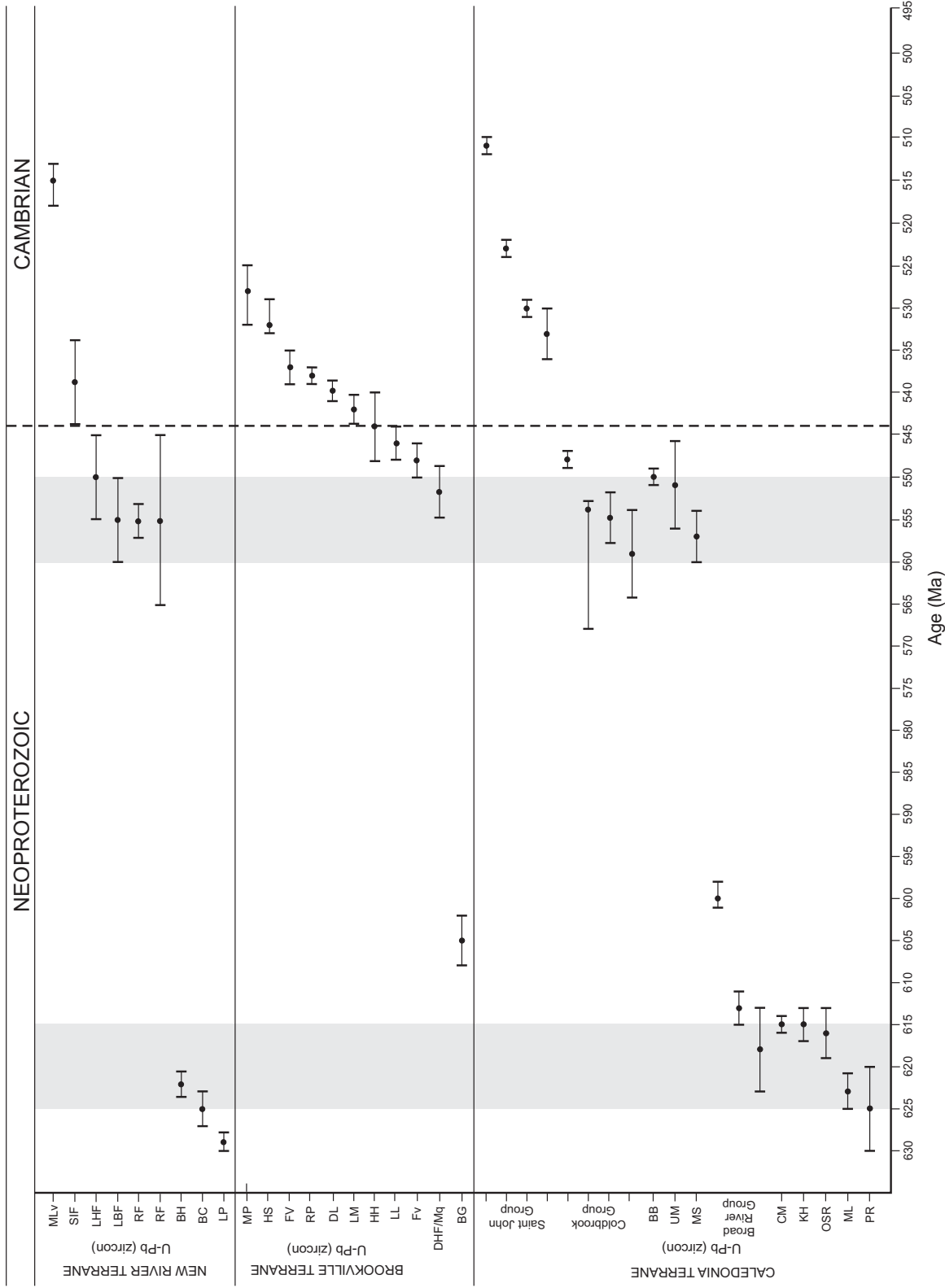
Fig. 4 Compilation of previous and new U-Pb (zircon) ages from the Caledonia, Brookville, and New River terranes. Data are compiled from this study and Currie and Hunt (1991), Bevier and Barr (1990), Bevier *et al.* (1990), Barr *et al.* (1994), White *et al.* (2002), Barr *et al.* (2000), Currie and McNicoll (1999), and McLeod *et al.* (in press). Unit abbreviations (alphabetical): BB, Bonnell Brook Granite; BC, Brittain Creek Pluton; BG, Brookville Orthogneiss; BH, Blacks Harbour Granite; CM, Caledonia Mountain Gabbro; DHF, Dipper Harbour Formation; DL, Duck Lake Gabbro; FV, French Village Quartz Diorite; Fv, Fairville Granite; HH, Harvey Hill Granite; HS, Hanson Stream Granite; KH, Kent Hills Granodiorite; LBF, Lobster Brook Formation; LHF, Leavitts Head Formation; LL, Ludgate Lake Granodiorite; LM, Lutes Mountain Quartz Diorite; LP, Lingley Pluton; ML, Millican Lakes Granodiorite; MLv, Mosquito Lake volcanics; MP, McCarthy Point Granodiorite; Mq, Musquash Harbour Pluton; MS, Mechanic Settlement Pluton; OSR, Old Shepody Road Granite; PR, Pollett River Granodiorite; RF, Ragged Falls Pluton; RP, Renforth Pluton; SIF, Simpsons Island Formation; UM, Upham Mountain Granite.

Table 2. New chemical data from units in the New River terrane.

Map #	Sample #	SiO₂	TiO₂	Al₂O₃	Fe₂O₃ᵗ	MnO	MgO	CaO	Na₂O	K₂O	P₂O₅	LOI	Total	U	Th	Zr	Nb	Rb	Ba	Sr	Ni	Cr	Co	Sc	V	Y	Cu	Zn	Ga	Pb	La	Ce	Nd
	Ragged Falls Suite																																
1	NRR2	65.79	0.47	14.22	4.62	0.08	2.41	2.52	3.30	3.34	0.09	3.00	99.84	-	10	137	11	92	404	146	15	55	-	-	121	27	39	38	11	12	-	-	-
2	MBR2	78.32	0.13	11.37	0.48	0.01	0.11	0.01	2.38	5.74	0.02	0.40	98.97	-	21	113	16	173	186	29	5	12	-	-	6	42	5	8	11	16	-	-	-
3	K98-325	69.94	0.57	13.78	3.02	0.04	0.97	2.19	4.17	2.39	0.12	1.46	98.65	5	10	218	11	68	683	150	14	<4	49	-	71	50	48	18	13	11	28	-	26
4	K98-326	75.76	0.21	12.11	1.11	0.02	0.24	0.40	3.21	5.14	0.03	0.62	98.85	6	15	143	15	215	851	48	6	<4	53	-	29	62	<4	21	12	26	38	-	32
5	K98-356	61.38	0.96	15.28	6.97	0.12	2.49	3.94	2.96	2.32	0.24	2.34	99.00	2	3	260	14	76	656	218	22	11	37	-	134	37	80	79	14	12	30	-	12
6	K98-380	74.23	0.25	12.96	1.42	0.02	0.47	0.10	3.93	4.32	0.04	0.78	98.51	6	18	167	15	135	788	62	7	<4	54	-	34	55	5	25	11	12	51	-	45
7	NB91-8577	75.15	0.20	11.74	0.98	0.05	0.17	0.99	3.34	4.90	0.03	1.02	98.57	6	18	148	15	192	826	51	11	<4	82	-	28	69	5	20	11	20	42	-	34
8	NB91-8578	77.33	0.18	11.64	0.95	0.01	0.21	0.12	2.99	5.31	0.02	0.64	99.40	7	27	143	17	233	520	24	7	<4	79	-	25	80	<4	24	9	19	52	-	46
9	NB91-8582	75.94	0.20	13.30	1.30	0.07	0.18	0.26	4.24	3.57	0.03	0.71	99.80	6	22	107	12	128	648	82	8	<4	76	-	31	25	8	53	10	37	34	-	23
10	NR98-01	74.03	0.22	13.70	1.93	0.04	0.43	0.87	4.04	4.14	0.05	0.68	100.12	5	19	207	13	176	480	53	0	1	29	22	12	24	0	36	20	23	28	10	22
11	NR98-02	76.41	0.18	13.33	1.62	0.03	0.16	0.69	4.25	4.55	0.04	0.35	101.61	4	21	179	19	237	210	37	0	2	12	32	8	31	0	20	16	21	30	121	34
12	NR98-04A	73.81	0.23	13.65	1.95	0.03	0.41	0.93	6.17	0.77	0.06	0.59	98.60	2	12	241	12	91	97	121	0	0	25	24	8	7	0	12	17	12	42	34	36
13	NR98-05	76.06	0.19	12.19	0.92	0.01	0.21	0.09	2.89	5.19	0.02	0.70	98.47	6	23	153	17	204	444	26	30	6	22	49	0	33	0	4	14	18	45	106	38
14	NR98-06	79.04	0.20	12.12	0.87	0.02	0.05	0.14	3.96	4.07	0.02	0.59	101.08	4	20	169	18	163	364	32	3	3	26	38	0	34	0	0	12	18	43	105	33
15	NR98-07	77.34	0.15	12.58	1.27	0.02	0.10	0.42	3.85	4.72	0.02	0.38	100.86	7	20	152	15	207	132	21	3	0	40	48	1	21	0	8	17	33	17	115	10
16	NR98-09	77.70	0.09	11.40	1.58	0.01	0.04	0.03	3.62	4.54	0.01	0.37	99.39	6	21	340	22	174	391	9	0	0	32	44	0	42	0	14	20	20	14	37	15
17	NR98-10	73.63	0.19	12.96	1.94	0.03	0.16	0.46	4.20	4.61	0.04	0.10	98.32	7	20	368	22	163	197	25	29	5	28	38	5	56	0	36	24	29	69	99	60
18	NR98-12	72.36	0.51	12.89	2.87	0.02	0.79	0.20	3.71	3.97	0.08	1.01	98.41	3	14	215	14	149	690	77	0	6	25	40	38	23	0	37	17	15	40	177	26
19	G214-90-1A	79.60	0.20	11.30	0.97	0.02	-	0.09	4.23	3.30	0.02	0.60	-	-	22	147	17	106	178	20	5	20	-	-	7	50	7	13	10	17	-	-	-
	Leavits Head Formation																																
20	ENR14	76.87	0.08	12.21	0.65	0.03	0.25	0.70	3.22	3.90	0.02	0.70	98.63	-	17	307	16	88	220	33	5	15	-	-	5	66	15	44	12	126	-	-	-
21	G214-90-1B	74.06	0.13	13.29	1.04	0.03	0.11	1.40	3.29	3.42	0.02	2.20	98.99	-	17	151	9	173	326	54	5	9	-	-	5	28	5	30	12	29	-	-	-
22	G214-90-2	78.01	0.27	11.08	2.60	0.02	0.13	0.41	3.07	4.03	0.02	0.90	100.54	-	15	345	22	120	509	43	5	10	-	-	5	69	20	48	12	20	-	-	-
23	NR98-08A	74.78	0.34	12.32	2.29	0.04	0.26	0.78	3.51	4.29	0.05	0.56	99.22	1	14	298	18	170	1061	53	0	2	16	39	20	40	0	23	13	22	57	69	42
24	NR98-11	77.13	0.12	12.04	1.07	0.01	0.06	0.20	3.93	4.27	0.02	0.30	99.15	4	16	250	18	174	405	18	0	0	14	19	0	40	0	0	15	10	44	129	39
	Blacks Harbour Granite																																
25	G290-94-1	73.33	0.22	11.96	2.06	0.08	0.35	3.21	3.25	2.06	0.05	3.80	100.37	-	10	167	14	72	279	160	5	26	-	-	9	40	5	28	13	13	-	-	-
26	NB99-2	67.76	0.40	16.72	2.37	0.03	1.05	2.25	4.91	1.95	0.13	2.35	99.92	2	11	191	10	83	932	704	0	0	21	-	40	0	0	45	23	14	18	65	20
27	K98-391	65.66	0.47	15.39	3.03	0.05	1.49	2.47	4.43	2.37	0.16	3.42	98.94	4	8	152	7	102	776	250	17	<4	32	-	67	11	6	68	20	11	32	-	25
	Lingley Suite																																
28	K98-399	77.28	0.23	11.08	1.77	0.01	0.11	0.13	3.52	4.15	0.04	0.46	98.79	6	13	229	13	122	932	42	7	<4	78	-	31	63	-	15	6	13	57	69	45
29	K99-527	59.03	1.18	16.09	8.33	0.16	2.56	2.63	3.11	2.71	0.33	2.58	98.71	2	<2	311	15	90	620	240	17	13	37	-	151	42	55	112	20	11	28	129	27
	Goose Lake Pluton																																
30	FL12	78.00	0.15	11.81	0.94	0.02	0.16	0.62	3.39	4.51	0.02	0.50	100.12	-	21	89	20	137	177	47	5	9	-	-	26	33	21	5	10	10	-	-	-
31	FL60	75.59	0.21	12.55	2.22	0.04	0.11	1.36	3.52	3.30	0.02	0.50	99.42	-	11	325	14	94	280	21	5	5	-	-	5	92	5	33	16	10	-	-	-
	Lobster Brook Formation																																
32	G9-21-91	74.99	0.41	12.14	2.14	0.02	0.12	0.17	2.37	5.09	0.08	0.80	98.33	-	15	224	13	143	1042	90	5	7	-	-	20	34	5	20	9	16	-	-	-

Note: Analyses by X-ray Fluorescence at the Regional Geochemical Centre, Saint Mary's University, Halifax, Nova Scotia. Major elements and some trace elements were determined on fused glass disks and other trace elements were measured in pressed powder pellets (methodology as described by Slauenwhite 1999). Analytical error is generally less than 5% for major elements and 2-10% for trace elements. Fe₂O₃ᵗ is total Fe as Fe₂O₃. LOI is loss on ignition at 1000°C. Dash means not determined and 0 indicates below detection limit of 1 or 2 ppm.
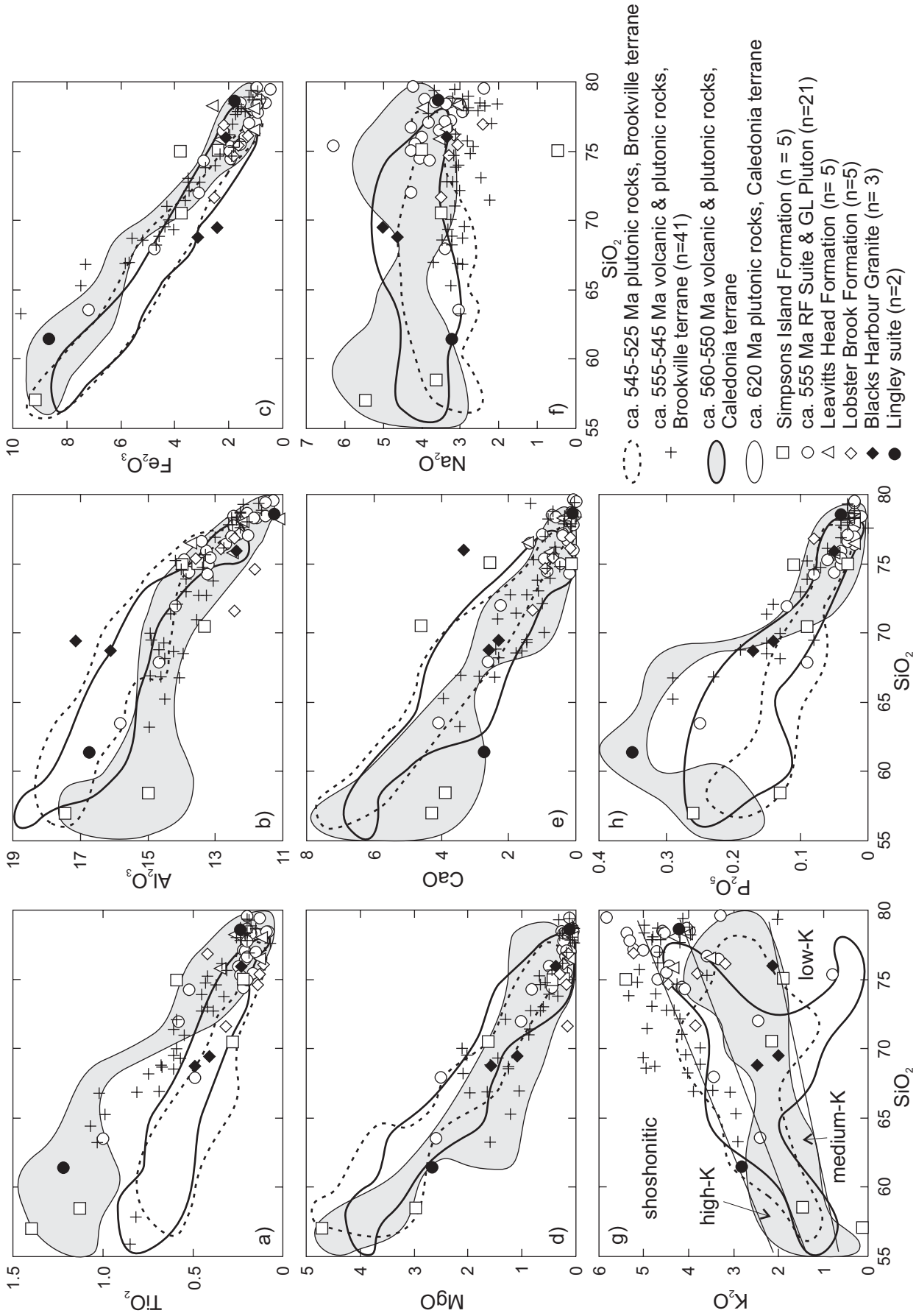
FIG. 5 Plots of major element oxides against SiO_2. Chemical data are from Table 2 and Barr and White (1999), White *et al.* (2002), Eby and Currie (1996), and Johnson and McLeod (1996). Fields in (g) are from Middlemost (1975). Abbreviations in legend: RF, Ragged Falls; GL, Goose Lake.
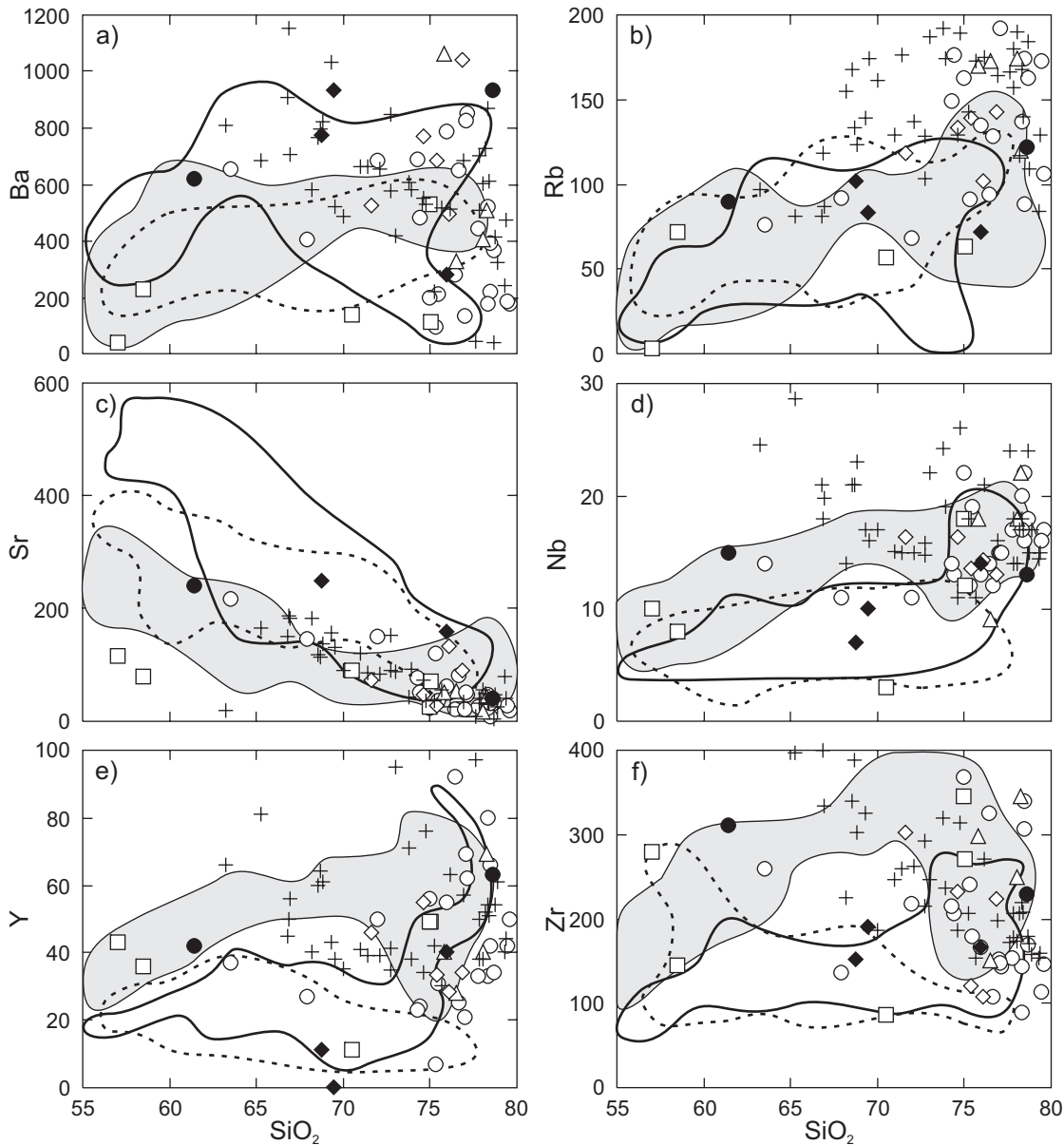
Fig. 6 Plots of Ba, Rb, Sr, Nb, Y, and Zr against SiO$_2$. Symbols and sources of chemical data are as in Fig. 5.

of the analysed samples have high SiO$_2$ content, over 74%, reflecting the highly felsic compositions of the sampled units. Because the ages of mafic units are not well constrained, mafic samples were not included in the present study.

To illustrate compositional similarities and differences among the sample suites, major element oxides and selected trace elements are plotted against SiO$_2$ (Figs. 5, 6). For visual clarity, suites with large numbers of analyses are represented by fields on the diagrams. Individual data points are shown for samples from the New River terrane and the Dipper Harbour Formation and related plutons of the Brookville terrane, as the smaller number of samples makes drawing fields less appropriate.

The ca. 620 Ma granitoid suite from the Caledonia terrane and the ca. 545–525 Ma granitoid suite of the Brookville

terrane show similar compositional trends in major element oxides, with overlapping fields for TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3^t$, MgO, CaO, Na$_2$O, K$_2$O, and P$_2$O$_5$ on plots against SiO$_2$ (Fig. 5). This similarity is consistent with the interpretations of Barr and White (1999) and White *et al.* (2002) that both suites formed in continental margin subduction zones. In contrast, the ca. 560–550 Ma volcanic and granitoid rocks of the Caledonia terrane show similar fields for MgO, CaO, Na$_2$O, and K$_2$O but have higher TiO$_2$ and Fe$_2$O$_3^t$, and lower Al$_2$O$_3$ (Fig. 5), interpreted to be indicative of their origin in an extensional setting. The ca. 555–545 Ma volcanic and granitoid rocks of the Brookville terrane (Dipper Harbour Formation and related plutons) also likely formed in an extensional setting, but differ from the Caledonia terrane units of similar age in that they show limited range in SiO$_2$, lower Na$_2$O, and higher K$_2$O (Fig.
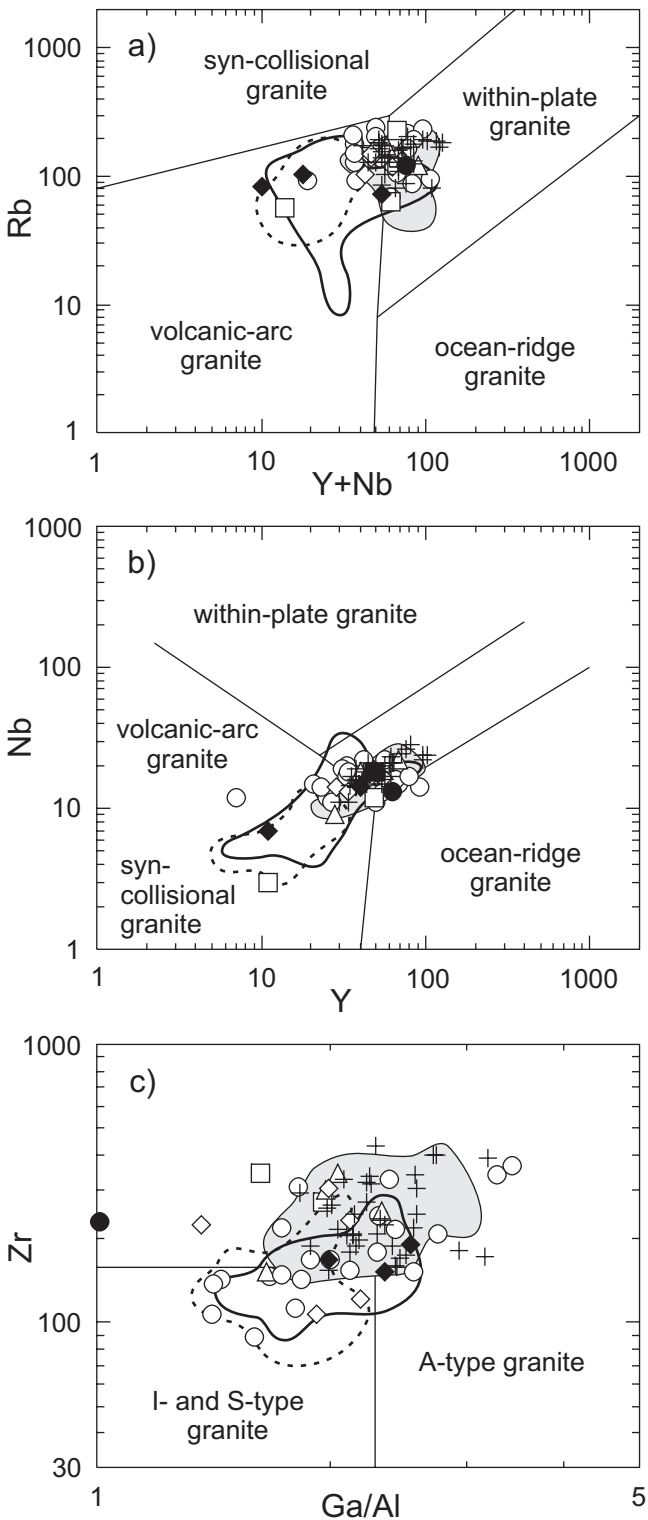
Fig. 7 Plots of (a) Rb - Y+Nb, (b) Nb -Y, and (c) Zr - Ga/Al for samples with more than 65% SiO$_2$ (intermediate to felsic). Field in (a) and (b) are from Pearce *et al.* (1984), and in (c) from Whalen *et al.* (1987). Symbols and sources of chemical data are as in Fig. 5.

5). Although Na$_2$O and K$_2$O can be mobile during alteration and weathering, petrographic observations showed no significant differences in these rocks that might be expected to result in the systematic differences in the oxide abundances, so the observed differences are considered to be significant. The ca. 555 Ma volcanic and plutonic units of the New River terrane also show most similarity in major element compositions to the ca. 560–550 Ma Caledonia terrane units, but have higher K$_2$O contents in the most felsic samples (Fig. 5g). The number of samples (5) from ca. 625 Ma plutonic units in the New River terrane is too small to make any generalizations or comparisons with plutonic units of similar age in the Caledonia terrane, although the overall compositional variations are similar to those in the ca. 620 Ma Caledonia terrane suite.

In terms of trace elements, the ca. 620 Ma Caledonia terrane and ca. 545–525 Ma Brookville terrane suites have similarities in Rb, Zr, Nb, and Y (Fig. 6), and hence plot in similar positions of chemical affinity and tectonic setting discrimination diagrams, consistent with their similar tectonic settings. However, the Brookville suite throughout the full range of SiO$_2$ contents has lower Ba and Sr than the Caledonia suite. Samples from ca. 625 Ma plutonic units in the New River terrane have trace element signatures similar to those in the ca. 620 Ma Caledonia suite, especially the low Y and Zr values in intermediate samples (Fig. 6e, f), and a continental margin subduction zone setting is suggested (Fig. 7).

The ca. 560–550 Ma Caledonia volcanic and plutonic units have lower Ba (similar to the Brookville plutons in this case) and Sr, but higher Zr, Nb, and Y than the ca. 620 Ma suite from the same terrane. The difference is consistent with the inferred within-plate setting and enhanced "A-type" character of the ca. 560–550 Ma suite compared to the volcanic-arc signature and more I-type features of ca. 620 Ma Caledonia terrane plutons. Barr and White (1996, 1999) interpreted the change to be related to later extension within a former subduction environment. The opposite pattern is true for the Brookville terrane, in which the younger ca. 545–525 Ma plutons have a clear subduction-related signature, whereas the older ca. 555–545 Ma Dipper Harbour Formation and related plutons have more extensional characteristics. The change was recognized by White *et al.* (2002), who suggested that magmatism in the Brookville terrane began with A-type magmatism, presumably related to crustal extension, but quickly evolved into a regime of continental margin-type subduction. Subduction continued to about 525 Ma and generated the voluminous gabbroic to monzogranitic (but dominantly tonalitic and granodioritic) plutons that comprise most of the Golden Grove Plutonic Suite.

Trace elements show some differences between the ca. 560–550 Ma units of the Caledonia terrane and the ca. 555–545 Ma units of the Brookville terrane, in spite of their similar ages and inferred tectonic settings, in that the Brookville terrane units tend to have higher Ba, Rb, and Nb (Fig. 6b, d, e). Comparing both of these units to the ca. 555 Ma volcanic and plutonic rocks of the New River terrane, some differences are also apparent, such as higher Rb in New River terrane units (Fig. 6b),

although again the inferred tectonic setting is similar. It is interesting that the ca. 555–545 Ma felsic units of the Brookville terrane and the ca. 555 Ma units of the New River terrane show more similarity to one another than to units of similar age in the Caledonia terrane. However, some subtle differences are apparent between the New River and Brookville terrane units, such as a tendency for lower Y and Zr in the New River terrane samples (Fig. 6e, f), and lower Ga/Al ratios (Fig. 7c).

Too few data are available from the ca. 555 Ma Lobster Brook and ca. 540 Ma Simpsons Island formations of the New River terrane to make any generalizations, except that they are broadly comparable to the other units and probably also formed in extensional tectonic settings. It appears that wherever these units were located relative to one another in the Late Neoproterozoic, all were forming in an extensional regime. However, it should be noted that Johnson and McLeod (1996) considered that the Simpsons Island Formation formed in a subduction environment, based on analyses from mafic samples in the unit. It is apparent that more detailed studies of these units are needed in order to make more meaningful interpretations.

It is important to emphasize that the lithological components of the Coldbrook Group and associated plutons also serve to distinguish them from units of overlapping age in the Brookville and New River terranes. The Coldbrook Group and associated plutons range in composition from basalt/gabbro to rhyolite/granite, with abundant dacitic volcanic units. None of these rocks match the almost entirely rhyolitic/granitic Dipper Harbour Formation and related ca. 555–545 Ma plutons. Although not yet described in detail, it appears that lithological similarities are more apparent between the Dipper Harbour Formation and related plutons and the ca. 555 Ma plutonic and volcanic rocks of the Leavitts Head Formation and Ragged Falls suite in the New River terrane, which are also mainly rhyolitic and granitic.

Isotopic data

Previous studies (e.g., Whalen *et al.* 1994, 1996; Samson *et al.* 2000) suggested that Sm-Nd isotopic data indicate differences among terranes in southern New Brunswick. As part of the present study, two additional samples from the Brookville terrane and one from the New River terrane were analysed for Sm and Nd isotopes (Table 3). Samples from the Lutes Mountain and McCarthy Point plutons (Brookville terrane) have small positive epsilon Nd values of 0.87 and 0.89, whereas the Blacks Harbour granite sample (New River terrane) has a lower epsilon Nd of –3.13. These new data have been plotted together with pre-existing data against age on Fig. 8, and fit in with the trend for samples from the Brookville and New River
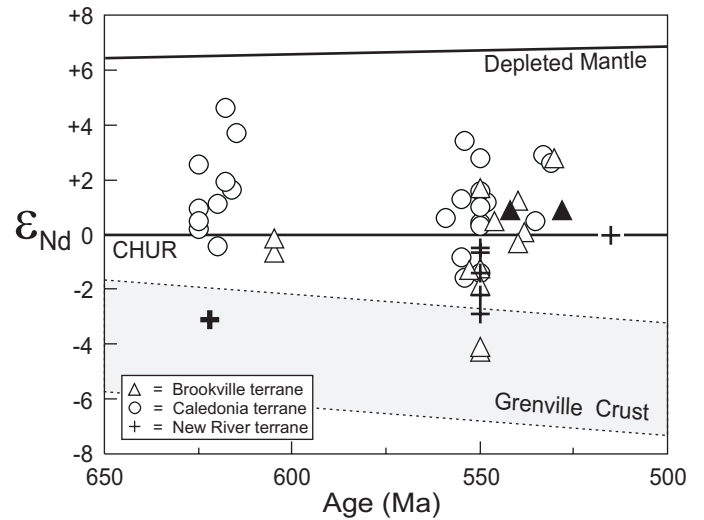
Fig. 8 Plot of epsilon Nd against age for samples from the New River, Brookville, and Caledonia terranes. Heavy black cross and filled triangles are data from Table 3 (this study). Other data are from the compilation of Samson *et al.* (2000) and Barr *et al.* (2000).

Table 3. New Sm-Nd data for samples from the Brookville and New River terranes.

Unit	Sample #	Age(t) Ma	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	Epsilon (t)	T_{DM}
Lutes Mtn Diorite	NB00-11	542	15.79	3.714	0.1422	0.512489	4	0.87	1179 Ma
McCarthy Pt Granodiorite	NB99-5	528	16.39	3.510	0.1295	0.512451	5	0.89	1073 Ma
Blacks Harbour Granite	NB99-2	622	21.73	3.782	0.1052	0.512105	3	-3.13	1316 Ma

Notes: Analyses by Alain Potrel, Memorial University of Newfoundland. Concentration data are standard ICP-MS analyses and are precise to ±5%(2 σ) (Longerich et al. 1990). Ratios of $^{147}Sm/^{144}Nd$ were measured directly by high-precision ICP-MS with estimated precision of ±0.5% (2σ). 2σ error in last two figures in brackets. Ratios of $^{143}Nd/^{144}Nd$ were measured by thermal ionization mass spectrometry with errors of ±0.000020 (2σ) or better. 2σ error in last two figures in brackets. Isotopic data were corrected to the LaJolla value of 0.511850. T_{DM} model age was calculated according to the model of DePaolo (1988). Epsilon Nd values were calculated with respect to CHUR using a present-day $^{143}Nd/^{144}Nd$ ratio of 0.512638 and $^{147}Sm/^{144}Nd$ ratio of 0.196593. Sample locations and geochemistry for the first two samples are presented in White et al. (2002), and for NB99-2 in Table 2, this paper.
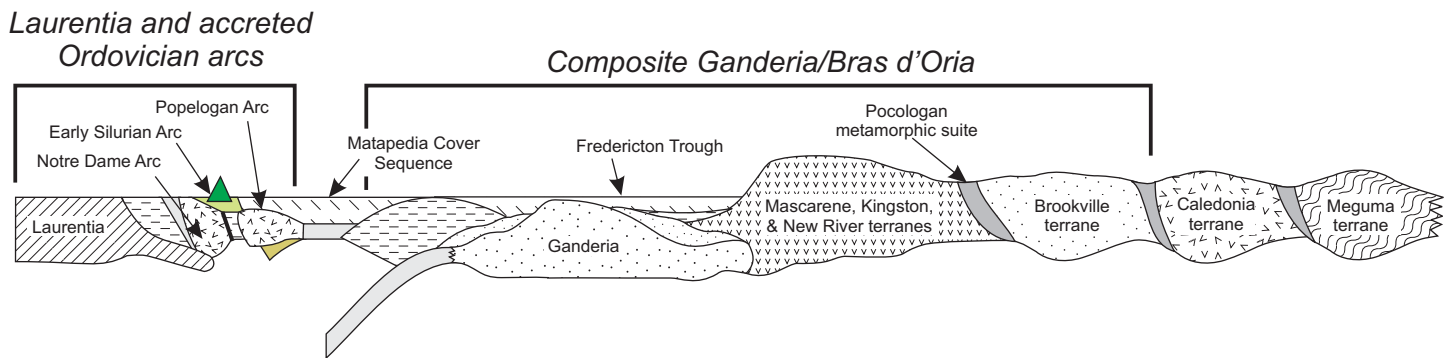
Fig. 9 A schematic diagram showing tectonic elements in New Brunswick. The Brookville, Caledonia (Avalon terrane *sensu stricto*), and Meguma terranes are inferred to have docked sequentially and independently against the New River-Mascarene-Kingston terranes, representing the margin of Ganderia. Together, Ganderia, Mascarene, New River, Kingston, and Brookville terranes have been termed Composite Ganderia or Bras d'Oria. The area from the Fredericton Trough to Laurentia is taken from van Staal *et al.* (1996, 1998).

terranes which have generally lower epsilon Nd, and more samples with negative values, than the Caledonia terrane (Fig. 8).

The data generally support the suggestion that magma generation was different in the different terranes, although the ranges show some overlap. Too few chemical data are available to provide a characterization of the ca. 620 Ma plutons in the New River terrane relative to ca. 625–615 Ma plutons in the Caledonia terrane, but the negative signature (epsilon Nd –3.13) of the Blacks Harbour granite is a major contrast compared to the signatures of ca. 625–615 Ma units in Caledonia terranes which average 1.67. Similarly, the younger suite also differ on average, with ca. 560–550 Ma plutons in the Caledonia terrane having average epsilon Nd of 1.0, units of ca. 555 to 525 Ma age in the Brookville terrane an average value of –0.57, and in the New River terrane of –1.28.

Kerr *et al.* (1995) showed that mainly positive epsilon Nd signatures characterize the Avalon terrane *sensu stricto* in its type area in Newfoundland, whereas negative values are typical of the adjacent Gander zone. Whalen *et al.* (1996) showed that in southern New Brunswick, Silurian and Devonian plutons have more transitional values in the vicinity of the boundary between the Mascarene and St. Croix terranes, which they considered to be the Avalon - Gander boundary, and that Silurian and Devonian rocks of the Saint George Batholith and the Kingston terranes have high values typical of "Avalon". However, these values are too high to have been derived from the crust of Avalon terrane *sensu stricto,* which would have had mainly negative values in the Silurian-Devonian. It is likely that the juvenile signatures of those rocks are related to the mainly mantle source, with little crustal contamination, and the change to lower values in plutons to the northwest could be related to increasing crustal contamination in areas of less voluminous magma generation. Our new isotopic data from Neoproterozoic - Cambrian igneous units support previous studies (e.g., Samson *et al.* 2000) which suggested that the boundary of the Avalon terrane coincides with the Caledonia

- Clover Hill fault. The data further suggest that the Brookville and New River terranes have different crustal components, but more complete study of units is needed in the New River terrane to further assess the significance of the difference.

DISCUSSION AND CONCLUSIONS

Models for building of the Appalachian orogen (and its continuation in the Caledonides of Europe) typically show details for Paleozoic tectonic activity in the central portion of the orogen (e.g. van Staal *et al.* 1998; Armstrong and Owen 2001), but infer that much of the outboard area (variously termed Avalon zone, Avalon composite terrane, Avalon microcontinent, or Avalonia), behaved as a single block in the Paleozoic. Some authors have explicitly or implicitly linked the components of the Avalon composite terrane by events in the Late Proterozoic (Dostal *et al.* 1996; Murphy *et al.* 1999; Keppie *et al.* 2000). The overlap in ages among igneous units in these areas, as illustrated for example in Fig. 4, makes it tempting to correlate broadly on the basis of overlapping or near-overlapping age. However, as demonstrated by the data compiled here, the relationships among various igneous components of the "Avalon composite terrane" of similar ages are by no means clear. Differences in rock assemblages and chemical features, in some cases subtle, suggest that such igneous activity may have been related to the positions of these areas on active continental margins in the late Neoproterozoic, but that these margins were on different continents.

The model of van Staal *et al.* (1998) depicted the Cambrian through Silurian evolution of the orogen through interaction of Laurentia with Ganderia and various intervening oceanic and volcanic arc elements. Van Staal *et al.* (1998) suggested that Ganderia travelled with the Avalonian terranes as one microcontinent, but implied that Ganderia is a crustal block different from Avalon. Armstrong and Owen (2001) followed a similar theme, and referred to this area as Avalonia

in the United Kingdom and Ireland. They showed several components in Avalonia, including Leinster -Lakesman, Monian terrane(s), and Avalon Terrane, the latter area most likely equivalent to the Avalon terrane *sensu stricto* of the present paper. They acknowledged that Avalonia may have had a complex Paleozoic history, but implied that at least the Monian terrane(s) and Avalon Terrane were together from the late Cambrian. However, the presence of Silurian arc-related igneous activity within the "Avalon composite terrane", such as in the Kingston terrane in southern New Brunswick, suggests a more complex history (Barr *et al.* 2002). Barr *et al.* (2002) suggested that the Kingston terrane and adjacent Pocologan metamorphic suite represent an arc and accretionary complex formed on the margin of Ganderia in the Silurian, presumably related to the docking of the Brookville terrane. The differences between Late Proterozoic to Early Cambrian magmatic histories in the Brookville and New River terranes support this interpretation, in the same way as differences between the Brookville and Caledonia terranes suggest that they too were separate, perhaps until the Silurian or Devonian (Barr and White 1996).

Viewing "Avalonia" as a composite of separate terranes that arrived sequentially and separately during the Silurian and Devonian, followed by the Meguma terrane (Fig. 9), helps to explain the long duration of the "Acadian orgeny" in Maine (Robinson *et al.* 1998; Tucker *et al.* 2001). This scenario implies that the juxtaposition of these outboard terranes or crustal blocks in the Silurian and Devonian was mainly by transcurrent motions, and such lateral adjustments, with local transtension and transpression, continued into the Carboniferous.

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