

Insights into tectonostratigraphic zone identification in southwestern Newfoundland based on isotopic (Nd, O, Pb) and geochemical data*

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Plutonic and supracrustal rocks sampled from various tectonostratigraphic divisions in southwestern Newfoundland exhibit a large range in SiO₂ (49 to 77 wt.%), K₂O (0.9 to 4.2 wt.%), ε_{Nd} (T) (-9.2 to +8.1), δ¹⁸O (+6.3 to +12.7‰), and Pb isotopic ratios. In general, isotopic plus geochemical data are either compatible with, or substantiate, structurally and lithologically based correlations between southwestern Newfoundland and the Central Mobile Belt farther north. Such data can thus represent a robust terrane identification tool in highly telescoped or segmented portions of orogenic belts, such as southwestern Newfoundland, and can also provide significant insights into orogen evolution. For example, the Port aux Basques granite (tonalite), which is characterized by MORB-like ε_{Nd} (+8.1) and δ¹⁸O (+7.5‰) and radiogenic Pb (²⁰⁷Pb/²⁰⁴Pb = 15.818), is interpreted as a Late Ordovician partial-melt of a juvenile source added to the Gander Zone during Early Ordovician opening of the Exploits back-arc basin. Strongly negative ε_{Nd} (T), mantle-like δ¹⁸O, variable Pb isotopic ratios and metaluminous characteristics of Ordovician plutonism in the Notre Dame arc suggest derivation from Paleoproterozoic or older infracrustal sources. The data indicate formation in an Andean-type continental arc formed on the edge of the Laurentian margin.

Les roches plutoniques et supracrustales échantillonnées de divers secteurs tectonostratigraphiques dans le sud-ouest de Terre-Neuve affichent de vastes écarts dans les rapports isotopiques du SiO₂ (49 à 77 % pds), du K₂O (0,9 à 4,2 % pds), du ε_{Nd} (T) (-9,2 à +8,1), du δ¹⁸O (+6,3 à 12,7 ‰) et du Pb. En général, les données isotopiques et géochimiques sont compatibles avec les corrélations structurales et lithologiques entre le sud-ouest de Terre-Neuve et la zone orogénique centrale plus au nord, ou elles les corroborent. De telles données peuvent par conséquent représenter un solide outil de caractérisation dans les parties fortement étagées ou segmentées des ceintures orogéniques, comme dans le sud-ouest de Terre-Neuve; elles peuvent en outre fournir des renseignements déterminants sur l'évolution de l'orogène. Par exemple, le granite de Port aux Basques (tonalite), caractérisé par un ε_{Nd} (+8,1) de type MORB, du δ¹⁸O (+7,5 ‰) et du Pb radiogénique (²⁰⁷Pb/²⁰⁴Pb = 15,818), est interprété comme du liquide de fusion partiel de l'Ordovicien tardif provenant d'une source juvénile qui s'est ajoutée à la zone de Gander au cours de l'ouverture de l'Ordovicien précoce du bassin arrière-arc d'Exploits. Les rapports isotopiques variables du Pb de type mantellique δ¹⁸O de ε_{Nd} (T) fortement négatifs et les caractéristiques métalumineuses du plutonisme ordovicien de l'arc de Notre Dame laissent supposer qu'il provient de la période paléo-protérozoïque ou de sources infracrustales plus anciennes. Les données révèlent que la formation présente dans un arc continental de type andin s'est formée sur le bord de la marge laurentienne.

[Traduit par la rédaction]

INTRODUCTION

Southwestern Newfoundland, an area where the Humber, Dunnage and Gander zones of Williams (1979) converge (Fig. 1), has been interpreted as a product of Silurian collision between promontories on the margins of Laurentia and Gondwana (Lin *et al.*, 1994). High-grade metamorphism, complex deformation, and a series of major faults with extended structural histories render tectonostratigraphic zone

identification difficult in this area (van Staal *et al.*, 1991, 1992; Burgess *et al.*, 1992).

Extensive studies of Appalachian granites in New Brunswick (Whalen *et al.*, 1989; Ayuso and Bevier, 1991; Whalen, 1993; Whalen *et al.*, 1994a; Whalen *et al.*, 1996a,b), and other regional investigations in Newfoundland (Fryer *et al.*, 1992; Kerr *et al.*, 1995; Whalen *et al.*, 1997) and Cape Breton Island (Barr and Hegner, 1992), have shown

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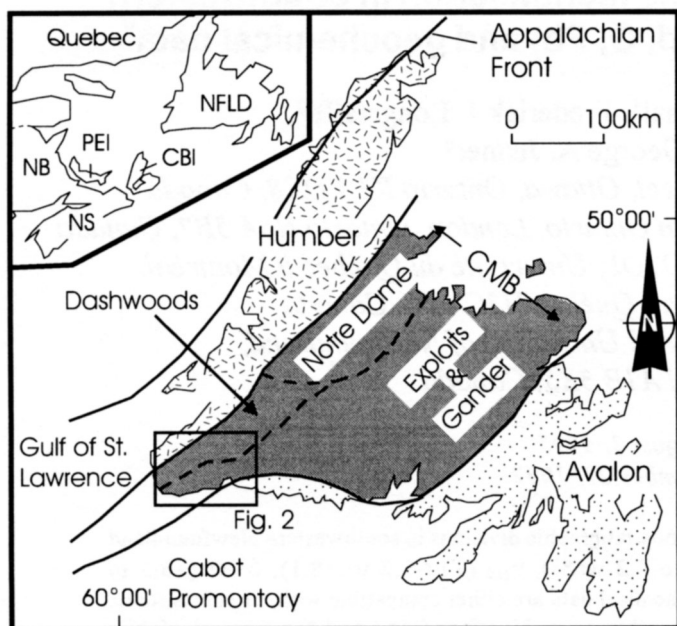


Fig. 1. Tectonostratigraphic zones and subzones of the Newfoundland Appalachians (modified after Williams *et al.*, 1988; Piasecki *et al.*, 1990). CMB is Central mobile belt. In insert, NB is New Brunswick, NS is Nova Scotia, PEI is Prince Edward Island, CBI is Cape Breton Island, and NFLD is Newfoundland.

that significant geochemical and isotopic contrasts exist among plutons emplaced into the different Appalachian tectonostratigraphic zones and that such signatures can be useful for terrane identification. Herein, we present new isotopic (Nd, O, Pb) and geochemical data from geological units in southwestern Newfoundland and evaluate the usefulness of these data as an aid to, and a check on, structural and tectonic interpretations of this complex continental collisional zone (Figs. 1, 2; Table 1).

TECTONIC AND GEOLOGICAL CONTEXT

The Canadian Appalachian Orogen contains the vestiges of the Early Paleozoic Iapetus Ocean which formerly separated the Laurentian and Gondwanan continents. The western margin (Humber Zone), a Late Neoproterozoic to Early Ordovician passive margin sequence deposited on the edge of Laurentia, was obducted by a Late Cambrian-Early Ordovician suprasubduction-zone oceanic terrane during the Early Ordovician (Cawood and Suhr, 1992). The obduction was followed by formation of a magmatic arc (Notre Dame arc) which contains significant volumes of well preserved, but tectonically disrupted, arc-type plutonic and volcanic rocks in its northern part (Notre Dame subzone) (Fig. 1) (Williams *et al.*, 1988; Whalen *et al.*, 1997). In contrast, the southern part of the Notre Dame arc (Dashwoods subzone) is underlain mainly by high grade supracrustal rocks and penetratively deformed arc-type plutonic rocks, which contain abundant rafts and lenses of dismembered ophiolite and screens of paragneiss (Dunning and Chorlton, 1985; Piasecki *et al.*, 1990; Hall *et al.*, 1994). To the east, the Exploits subzone

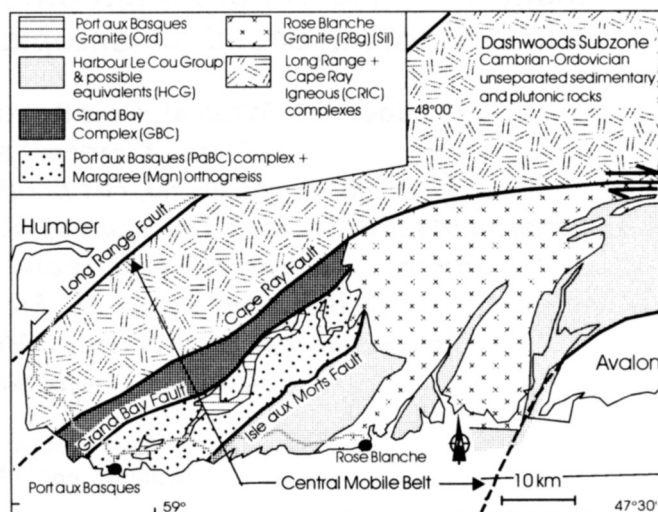


Fig. 2. Map of southwestern Newfoundland with the distribution of tectonic divisions and structures (modified after van Staal *et al.*, 1992; Lin *et al.*, 1994). Division abbreviations as in Tables 1, 3 and 4.

of the Dunnage Zone, dominated by oceanic and arc-type supracrustal rocks, has been interpreted to represent the remnants of Cambrian to Middle Ordovician arc and back-arc basins (Swinden *et al.*, 1990; Jenner and Swinden, 1993; Winchester and van Staal, 1995).

Final closure of oceanic elements in Iapetus is thought to have taken place by westward-directed subduction in Late Ordovician to Early Silurian time (e.g., van Staal, 1994). This closure resulted in collision of the Gander Zone, a continentally derived sedimentary wedge deposited on the edge of Gondwana (van Staal *et al.*, 1996b; Whalen *et al.*, 1996b), plus previously accreted remnants of the Exploits arc plus back arc basin, with the composite Laurentian margin. Collision occurred first in southwestern Newfoundland and Cape Breton Island between promontories on both margins (Lin *et al.*, 1994). The present day crustal structure beneath southwestern Newfoundland is interpreted to comprise a subsurface extension of the Gondwanan continent, which is structurally overlain at higher crustal levels, successively, by attenuated Laurentian crust and a veneer of Dunnage plus Gander zone rocks (Quinlan *et al.*, 1992). These features have been interpreted by Lin *et al.* (1994) to reflect delamination and tectonic wedging that accompanied the Laurentian-Gondwanan continental collision during the Silurian.

GENERAL GEOLOGY OF SOUTHWESTERN NEWFOUNDLAND

A cross section of the Central Mobile Belt is well exposed in coastal sections east and west of Port aux Basques. These rocks have been subdivided into different lithological and/or tectonic packages, and tectonostratigraphic zone correlations have been made (see van Staal *et al.*, 1991, 1992) (Fig. 2). Pertinent features of these subdivisions and some of the justification for the correlations are outlined below, from

Table 1. Characteristics of sampled units in southwest Newfoundland.

Name	Sampled Lithology	Unit Abbreviation	Division/Zone or Subzone	Mafics	Deformation	Age (Ma)+ Method	References for Ages
Cape Ray	granodiorite (tonalite)	CRgd	CRIC/DWsZ	b	mod+alt	469±2 ¹	Dubé <i>et al.</i> (1996)
Cape Ray	porphyritic granodiorite	CRpgd	CRIC/DWsZ	b,h	mod+alt	488±3 ¹	Dubé <i>et al.</i> (1996)
Red Rocks	granite	RRg	CRIC/DWsZ	b,m	sl	420 ¹	Dubé <i>et al.</i> (1996)
Grand Bay	granodiorite	GBgd	GBC/EsZ	b	mod to int	470 ³	van Staal <i>et al.</i> (1994)
Port aux Basques	amphibolite dyke	PaBamp	PaBC/GZ	h	sl	470 ³	van Staal <i>et al.</i> (1994)
Port aux Basques	paragneiss	PaBgn	PaBC/GZ	b	rc	<500 ³	van Staal <i>et al.</i> (1994)
Port aux Basques	granite (tonalite)	PaBg	PaBC/GZ	b,h	rc	453±3 ¹	van Staal <i>et al.</i> (1994)
Margaree Orthogneiss	diorite to tonalite	Mgn	PaBC/GZ	h,b	mod	470 ¹	van Staal <i>et al.</i> (1994)
Rose Blanche	granite	RBg	HCG/EsZ	b,m	sl	420-414 ²	van Staal <i>et al.</i> (1994)

Abbreviations: Mafic minerals: b = biotite, h = amphibole, m = muscovite. Deformation: sl = slight, mod = moderate, int = intense, alt = altered, rc = recrystallized. Divisions: CRIC = Cape Ray igneous complex, GBC = Grand Bay complex, PaBC = Port aux Basques complex, HCG = Harbour le Cou Group. Zones: DWsZ = Dashwoods subzone, EsZ = Exploits subzone, GZ = Gander Zone. Age methods: 1. U-Pb zircon; 2. Pb-Pb monazite; 3. estimated based on structural relationships; U-Pb ages without errors are preliminary.

west to east. The reader is referred to the above cited sources for a comprehensive treatment. Major characteristics of plutons or units sampled for this study, including rock type, mafic mineral content, deformation state, and age are summarized in Table 1.

Cambrian to Middle Ordovician ophiolitic rocks (Long Range Complex), variably deformed intermediate to felsic plutonic rocks (Cape Ray Igneous Complex; e.g., Cape Ray granodiorite in Table 1), and local paragneisses occur between the Long Range and Cape Ray faults. The Cape Ray Igneous Complex also includes Silurian to Lower Devonian plutons (e.g., Red Rocks granite in Table 1; Dubé *et al.*, 1996). These rocks form the southern part of the Dashwoods subzone, with the Cambro-Ordovician rocks representing remnants of the Notre Dame arc.

The Grand Bay complex, located between the Cape Ray and Grand Bay faults zones, consists of amphibolite-facies paragneiss and mafic and felsic orthogneiss, which includes the Grand Bay granodiorite. On the basis of the lithological correspondence along strike of sedimentary rocks, the Grand Bay complex is correlated with rocks of the Exploits subzone (Chorlton and Knight, 1983; van Staal *et al.*, 1996a).

The Port aux Basques Complex, located between the Grand Bay and Isle aux Morts faults (Fig. 2), consists mainly of paragneiss, intruded by Upper Ordovician (U-Pb zircon of 453 ± 3 Ma; van Staal *et al.*, 1994 and unpublished data) gneissic granitoid sheets (Port aux Basques granite), and abundant amphibolite dikes and sills. The Ordovician (U-Pb zircon of c. 470 Ma; van Staal *et al.*, 1994 and unpublished data) Margaree orthogneiss, a mixed mafic and felsic unit, is exposed on the coast east of Channel Port aux Basques

(Fig. 2). Field relationships suggest an originally intrusive relationship between Margaree orthogneiss and the Port aux Basques paragneiss. Deformed amphibolite dykes and sheets, which cut the Margaree orthogneiss, have been interpreted as consanguinous with similar dikes and sills cutting the Port aux Basques paragneiss (Schofield *et al.*, 1993, in press; van Staal *et al.*, 1994). The Port aux Basques Complex is interpreted to represent a structural inlier of Gander Zone rocks that occurs between two segments of Exploits subzone rocks, represented by the Grand Bay complex and the Harbour Le Cou Group. Similar inliers of Gander Zone rocks within Exploits subzone rocks have been mapped and described farther north (e.g., Williams *et al.*, 1988).

The Harbour Le Cou Group, located east of the Isle aux Morts fault, consists of monotonous paragneiss with minor amphibolite. These rocks are interpreted as correlative with the Early to Middle Ordovician Bay du Nord Group of the Exploits subzone. They are intruded by the Late Silurian (Pb-Pb monazite age of ca. 420 to 414; van Staal *et al.*, 1994 and unpublished data) muscovite-garnet-bearing Rose Blanche granite.

REGIONAL ND, O AND PB ISOTOPIC CONTEXT

The range in Nd isotopic compositions, expressed as ϵ_{Nd} at 430 Ma, and $\delta^{18}O_{\text{‰}}$ (SMOW) obtained from basement, sedimentary and granitoid rocks from interior parts of various Canadian Appalachian tectonostratigraphic zones (Fig. 1) are summarized in Table 2, together with the data sources. Because they may provide 'mixed' signatures (cf. Whalen *et al.*, 1996a), isotopic data from plutons immediately adjacent

Table 2. Ranges in ϵ_{Nd} at 430 Ma and $\delta^{18}\text{O}\text{‰}$ (SMOW) of various units within Canadian Appalachian tectonostratigraphic zones and subzones.

Group	Humber Zone	Dunnage Zone			Gander Zone	Avalon Zone
		Notre Dame Subzone	Dashwoods Subzone	Exploits Subzone		
Precambrian Granitoids	(-12/-1) ^{1,8} (+7/+12‰) ^{1,8}				(-8) ⁵	(-2/+6) ^{2,4} (+2/+8‰) ^{1,4}
>470 Ma Sedimentary rocks	(-11) ¹	(-16/-11) ^{1,8} (+6‰) ⁸			(-8/-7) ⁴ (+10/+14‰) ¹	
510-440 Ma Granitoids		(-14/+2) ⁸ (+5/+9‰) ⁸	(-10/-6) ⁸ (+8/+9‰) ⁸	(-2/+6) ^{1,4} (+8/+9‰) ¹	(-7/0) ^{4,6} (+8/+10‰) ^{1,6}	
<440 Ma Granitoids	(-8/+5) ^{1,3} (+6/+10‰) ^{1,3}	(-2/+4) ^{9,10} (+4/+8‰) ^{9,10}	(-10/+3) ¹⁰ (+7/+10‰) ¹⁰	(-2/+5) ^{1,4} (+7/+10‰) ^{1,3}	(-8/+1) ^{4,7} (+6/+10‰) ^{1,7}	(+1/+5) ^{2,4} (+5/+10‰) ^{1,4}

Sources: ¹Fryer *et al.* (1992); Whalen *et al.* ²(1994a), ³(1994b); ⁴Kerr *et al.* (1995); ⁵van Staal *et al.* (1996); Whalen *et al.* ⁶(1996a), ⁷(1996b), ⁸(1997), ⁹(1996c), ¹⁰(unpublished data). Data from the Brookville terrane in New Brunswick and from adjacent to zone boundaries excluded.

to zone boundaries are not included. Data summarized in Table 2 are sparse for units such as Early Paleozoic metasedimentary rocks but extensive for Paleozoic granites.

Ayuso and Bevier (1991) showed that Paleozoic plutons emplaced into the Laurentian and Gondwanan sides of the northern Appalachian orogen in the U.S.A. and New Brunswick are characterized by contrasting non-radiogenic (Laurentia) versus radiogenic (Gondwana) Pb isotopic signatures. The authors interpreted these signatures to reflect their presumed Precambrian Grenvillian and Avalonian basement rocks, respectively. Although Ordovician Notre Dame arc plutons mainly display 'Grenville-like' Pb isotopic compositions, their large range in ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁶Pb/²⁰⁴Pb ratios overlaps that of Avalonian basement rocks (Whalen *et al.*, 1997); i.e., the mainland Appalachian-based Pb-isotopic terrane signatures of Ayuso and Bevier (1991) may not be directly applicable to Newfoundland.

As interpretations of the reasons for, and significance of, these isotopic variations are complex and not unequivocal, the reader is referred to detailed discussions within sources listed below Table 2 and also to Ayuso and Bevier (1991). Herein, we attempt to employ these isotopic ranges as 'fingerprints' of different tectonostratigraphic zones for the purpose of terrane identification. Their petrogenetic or tectonic implications will be discussed only as regard to our data set from southwestern Newfoundland.

GEOCHEMISTRY

Major and trace element compositional data are presented in Table 3 and summarized in Figures 3 and 4; only geochemical features relevant to terrane correlation are discussed in the next section. Isotopic data and UTM co-ordinates for the samples are given in Table 4. Analytical techniques, precision and errors are the same as presented in Whalen *et al.* (1996b; 1997). Initial ¹⁴³Nd/¹⁴⁴Nd isotopic ratios are reported as ϵ_{Nd} values (DePaolo, 1988) and O isotopic analyses are reported in parts per thousand (‰) using the normal δ -notation relative to V-SMOW (Vienna Standard Mean Ocean Water) (Baertschi, 1976).

Based on Sm/Nd isotopic data, expressed as ϵ_{Nd} , the samples can be grouped into those with values ≤ -5 and > 0 (Table 3, Fig. 5). Those with $\epsilon_{\text{Nd}} \leq -5$ (Cape Ray Igneous Complex and Port aux Basques paragneiss) were derived from a reservoir(s) or source(s) with a history of long-term LREE enrichment, such as old continental crust. Those with $\epsilon_{\text{Nd}} > 0$ (Grand Bay granodiorite, Margaree orthogneiss, Port aux Basques granite and amphibolite) were derived from a reservoir(s) with a history of slight to strong LREE depletion. The Port aux Basques granite, whose value lies in the range of depleted mantle (DM), was analyzed in duplicate to confirm its strongly positive character.

The $\delta^{18}\text{O}$ values of the samples range from +6.3 to +12.7‰.

Table 3. Geochemical analyses from units in southwest Newfoundland.

Division	CRIC	CRIC	CRIC	GBC	GBC	GBC	PaBC	PaBC	PaBC	PaBC	PaBC	PaBC	HCG
Unit	CRgd	CRpgd	RRg	GBgd	GBgd	GBgd	PaBamp	PaBgn	PaBgn	PaBg	Mgn	Mgn	RBg
WXNF#	31	32	28	166	167	168	30a	30c	30b	29	170	169	171
SiO ₂ (wt.%)	70.02	57.43	71.92	70.01	73.72	60.59	51.80	76.32	76.84	75.38	49.03	65.79	71.19
TiO ₂	0.36	0.67	0.20	0.57	0.30	0.80	1.97	0.73	0.97	0.26	0.89	0.83	0.30
Al ₂ O ₃	13.51	16.29	14.81	15.10	13.30	16.20	14.51	10.85	9.89	13.31	17.76	16.20	15.30
Fe ₂ O ₃	1.83	3.10	0.71	0.97	0.71	2.25	5.55	1.36	1.16	1.00	2.91	1.51	0.76
FeO	1.43	2.43	0.53	1.90	0.80	2.50	7.67	2.07	1.93	0.60	5.30	2.30	1.15
MnO	0.07	0.13	0.04	0.07	0.08	0.17	0.25	0.09	0.09	0.04	0.15	0.05	0.09
MgO	1.08	2.87	0.52	1.06	0.97	2.68	4.41	1.30	1.05	0.31	7.89	1.41	0.64
CaO	3.39	4.87	1.90	2.36	1.63	2.85	8.21	0.93	2.35	1.43	10.96	3.09	1.59
Na ₂ O	3.19	3.25	3.86	5.54	4.32	4.07	2.28	2.07	2.83	6.43	2.94	4.27	4.75
K ₂ O	1.65	3.91	4.24	1.64	3.48	3.90	0.59	2.32	0.88	0.55	0.76	3.32	3.17
P ₂ O ₅	0.06	0.43	0.06	0.14	0.06	0.22	0.35	0.11	0.18	0.05	0.08	0.25	0.11
LOI	3.47	3.63	0.62	0.33	0.30	3.90	0.85	1.06	0.54	0.17	0.70	0.57	0.68
Total	100.05	99.00	99.42	99.69	99.66	100.12	98.44	99.19	98.71	99.53	99.36	99.59	99.72
Rb (ppm)	50	118	128	39	80	101	11	87	43	8	9	93	94
Ba	475	10	1732	5	1586	1684	111	397	169	36	77	1537	3
Sr	155	1168	724	263	148	220	343	111	267	215	185	398	312
Ga	<3	10	4	16	15	16	12	<3	<3	15	16	19	18
Ta	1.3	1.3	2.2	3.0	2.7	1.4	1.0	1.5	2.7	4.8	1.0	2.9	3.1
Nb	5.4	14.2	6.9	9.4	11.4	9.1	6.4	11.8	16.0	52.1	1.7	16.5	15.2
Hf	1.7	7.3	3.4	8.0	5.7	7.8	4.6	5.9	17.6	5.4	1.7	10.8	5.9
Zr	63	278	114	300	162	275	162	246	654	213	54	445	203
Y	5	16	5	18	19	24	37	23	37	37	20	17	9
Th	1.4	21.2	13.8	16.5	16.9	10.2	3.8	8.8	14.5	15.6	0.8	30.2	14.8
U	<4	8	5	<4	<4	<4	<4	<4	4	5	<4	<4	<3
La	9.1	92.9	33.0	23.3	35.9	22.4	15.1	29.9	38.9	42.2	3.2	84.6	61.9
Ce	16.2	184.4	60.5	54.1	67.4	48.1	34.6	63.8	83.3	82.5	8.0	159.5	117.1
Pr	1.6	20.2	6.3	5.3	7.4	5.7	4.4	7.3	9.9	9.0	1.2	16.6	12.0
Nd	5.6	68.5	20.0	19.0	26.7	22.4	18.9	27.7	36.9	30.6	6.2	56.6	38.8
Sm	0.99	9.74	2.64	3.81	4.57	4.69	4.82	5.33	7.41	5.90	2.08	9.33	5.61
Eu	0.63	2.02	0.54	0.96	0.91	1.52	1.63	1.10	1.37	0.74	0.85	1.80	1.22
Gd	0.81	5.50	1.20	3.00	3.80	4.61	5.45	4.66	6.06	4.77	3.05	6.21	3.50
Tb	0.10	0.63	0.12	0.49	0.59	0.70	0.89	0.71	0.95	0.79	0.48	0.79	0.41
Dy	0.68	3.26	0.73	3.42	3.67	4.70	5.68	4.31	5.85	5.07	3.67	4.36	2.33
Ho	0.14	0.56	0.13	0.71	0.70	0.91	1.22	0.86	1.20	1.02	0.75	0.72	0.39
Er	0.39	1.45	0.37	2.00	2.06	2.69	3.46	2.42	3.56	3.07	2.06	1.81	1.05
Tm	0.06	0.19	0.05	0.30	0.28	0.00	0.50	0.33	0.52	0.47	0.31	0.23	0.15
Yb	0.33	1.19	0.35	2.15	1.85	2.65	3.22	2.22	3.60	3.20	1.96	1.41	0.91
Lu	0.06	0.18	0.06	0.35	0.29	0.42	0.51	0.33	0.58	0.47	0.31	0.19	0.15
Cr	20	43	11	16	20	18	33	56	70	11	290	32	16
Ni	<4	12	<4	27	31	30	10	16	10	<4	130	35	32
Sc	14	14	<7	10	<7	15	38	<7	11	9	38	<7	<7
V	61	135	15	50	<6	92	439	55	42	<6	212	72	9
Cu	9	<3	<3	35	22	<3	47	8	31	<3	65	43	4
Pb	10	24	29	19	11	9	15	12	15	<4	<4	11	23
Zn	21	63	<10	20	<10	51	123	20	<10	<10	59	62	40
S	124	34	14	118	127	89	506	175	534	21	549	267	98
F	82	995	390	825	298	233	625	320	155	215	623	1080	278
Cl	35	63	44	<20	23	70	<20	<20	28	23	102	100	219
ASI	1.02	0.88	1.03	1.00	0.96	1.01	0.75	1.43	1.00	0.97	0.69	1.00	1.08

Notes: Pluton names corresponding to pluton# codes in Table 1; locations of divisions given in Figure 2. LOI = loss on ignition; ASI = aluminium saturation index (mol. proportion Al/(Ca+Na+K)).

Samples between +6 and +8‰ (Cape Ray Igneous Complex, Grand Bay granodiorite and Port aux Basques granite) overlap the range of juvenile or mantle-derived magmas (Fig. 5).

Almost all other samples, including one Port aux Basques paragneiss sample, fall in the range exhibited by granitoid plutons derived from mixed supracrustal-mantle sources (i.e.,

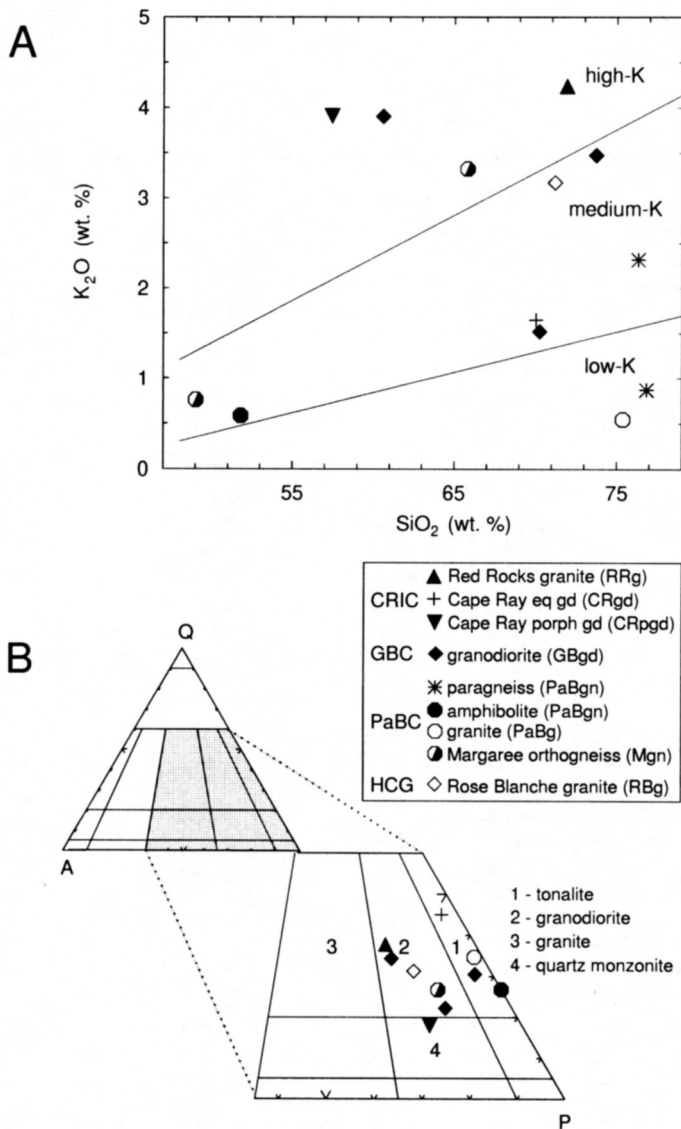


Fig. 3. (A) Silica versus potassium plot for units in southwestern Newfoundland (after Middlemost, 1985); (B) Mesonormative quartz-plagioclase-K-feldspar granite classification diagram; diagrams modified after Le Maitre (1989). Key to symbols given beside diagrams.

+8 to +10‰) (Taylor, 1978, 1988). The elevated $\delta^{18}\text{O}$ value (+12.7‰) of Grand Bay granodiorite sample 168 is attributed to intense deformation accompanied by extensive low-temperature sericite and carbonate alteration (see loss on ignition (LOI) values in Table 3).

Feldspar Pb isotopic data, which are available for only four granitoid samples, are shown in Figure 6 on conventional Pb-Pb plots. K-feldspars from the Cape Ray Igneous Complex and the Rose Blanche granite exhibit similar, somewhat radiogenic compositions. In contrast, albite from the Port aux Basques granite is remarkably radiogenic, indicating input from old crustal material. Duplicate residue and leachate analyses from this sample yielded similar radiogenic results. No obvious correlations exist between $\delta^{18}\text{O}$, ϵ_{Nd} or Pb isotopic values and whole rock chemistry.

TECTONOSTRATIGRAPHIC ZONE IDENTIFICATION AND ITS IMPLICATIONS

Isotopic and geochemical comparisons between tectonic divisions in southwest Newfoundland and various Appalachian tectonostratigraphic zones and subzones are discussed below, starting from the northwest:

1. Cape Ray Igneous Complex

The Cape Ray Igneous Complex forms part of the Dashwoods subzone (Fig. 2) and contains remnants of the Cambro-Ordovician Notre Dame arc. Support for this interpretation is given by the fact that its Ordovician plutons are low-K (Fig. 3A), metaluminous (Table 3), and have ϵ_{Nd} , $\delta^{18}\text{O}$ and K-feldspar Pb isotopic signatures within the ranges exhibited by similar age plutons in the northern Dashwoods and Notre Dame subzones (Figs. 5, 6). Like almost all other Notre Dame arc plutons, the strongly negative ϵ_{Nd} (0.43 Ga), mainly juvenile or mantle-like $\delta^{18}\text{O}$, and metaluminous characteristics of the Cape Ray granitoids indicate major contributions from old (>1.2 Ga; based on T_{DM} ages in Table 4) infracrustal sources.

2. Grand Bay complex

Based mainly on metasedimentary rock characteristics, the Ordovician Grand Bay complex has been equated with rocks of the western Exploits subzone (van Staal *et al.*, 1992). The positive ϵ_{Nd} values of the Grand Bay granodiorite samples are distinct from the negative values characteristic of contemporaneous Gander Zone plutons in Newfoundland and New Brunswick (Table 2; Fig. 5). Although they overlap the upper range of Ordovician Notre Dame arc plutons, ϵ_{Nd} values of those plutons are almost all strongly negative (mean ϵ_{Nd} (0.43 Ga) = -7 ± 3) (Whalen *et al.*, 1997). The positive ϵ_{Nd} values of the Grand Bay granodiorite are what would be expected of plutons emplaced within a relatively juvenile arc setting. Except for petrographically strongly altered sample 168, $\delta^{18}\text{O}$ values (+6.3 to +6.5‰) lie in the range of granites derived from juvenile or mantle-like sources, but are somewhat lower than other Exploits subzone plutons (Table 2). Overall, these results are compatible with the Grand Bay complex representing a sliver of the Exploits subzone.

3. Port aux Basques Complex

The Port aux Basques Complex, from which we have analyzed a variety of units, has been equated to the Gander Zone. The ϵ_{Nd} (0.43 Ga) signatures of Gander margin sediments (-8 to -7) are distinct from the more negative values (i.e., ~ -11 ; Table 2) obtained for sediments of equivalent age deposited on the Laurentian margin (Fryer *et al.*, 1992) or in the Notre Dame subzone (Whalen *et al.*, 1997). Thus, the ϵ_{Nd} (0.43 Ga) values (-8.5) obtained from Port aux Basques paragneiss are in keeping with its interpretation as part of the Gander

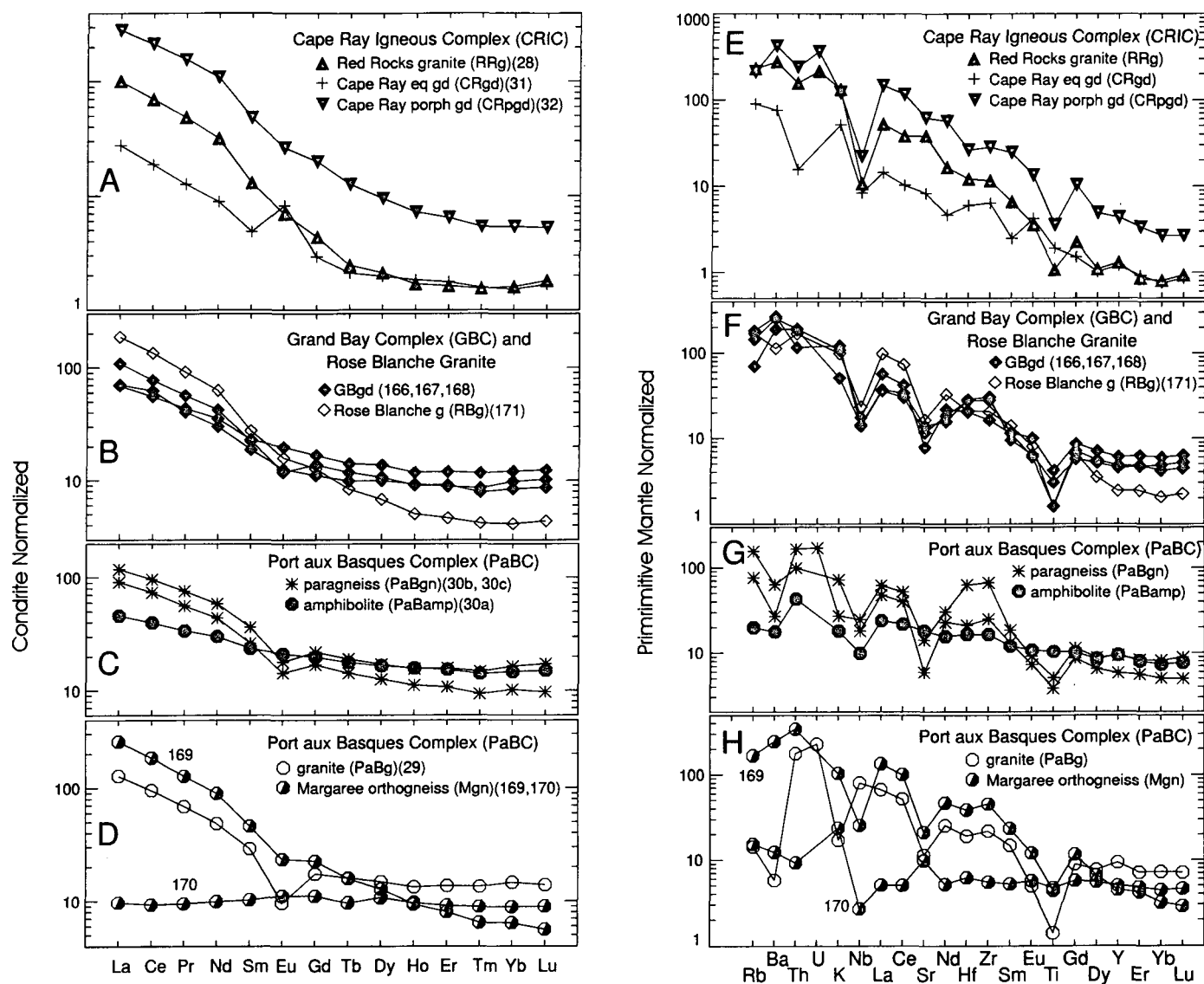


Fig. 4. Chondrite-normalized rare earth (A to D) and primitive mantle normalized extended element (E to H) plots for units in southwestern Newfoundland. Normalizing values for chondrite and primordial mantle from Sun (1982) and Taylor and McLennan (1985). Units are subdivided by the tectonic division within which they occur (for division locations, see Figure 1).

Zone. Its somewhat low $\delta^{18}\text{O}$ values (+9.8 to +10.1‰) may reflect Port aux Basques Complex sediments being more immature or less pelitic (Fig. 5) (cf. Longstaffe and Schwarcz, 1977). The pre-Neoproterozoic basement source sampled by Gander Zone trailing margin-type sandstones, such as the Port aux Basques paragneiss, was probably the composite Archean to Mesoproterozoic Amazonian craton (van Staal *et al.*, 1996b), which consists of older crust that is exposed in the Avalon Zone (see Avalon Zone ϵ_{Nd} (0.43 Ga) values in Table 2) (Whalen *et al.*, 1996b).

The ϵ_{Nd} and $\delta^{18}\text{O}$ values of an amphibolite sheet (+2.4 and +8.8‰) and a Margaree orthogneiss granodiorite (+1.1 and +9.5‰), interpreted by Schofield *et al.* (1993) to be consanguineous at 470 Ma, may reflect mixing between a depleted mantle-derived magma ($\epsilon_{\text{Nd}} \sim +8$; $\delta^{18}\text{O} \sim +6$ –8‰) and melts derived from Port aux Basques paragneiss ($\epsilon_{\text{Nd}} \sim -8$; $\delta^{18}\text{O} \sim +10$ ‰), which both intrude. If so, the negative Nb anomalies exhibited by these units (Fig. 4G,H) reflect crustal

contamination rather than volcanic-arc affinity. The positive ϵ_{Nd} signature and dioritic to granodioritic composition of the Margaree orthogneiss is distinct from Ordovician Gander Zone plutons in Newfoundland (Kerr *et al.*, 1995) and New Brunswick (Whalen, 1993; Whalen *et al.*, 1996b) (Table 2). Compositionally, the Margaree orthogneiss resembles similar age Notre Dame arc plutons, but almost all these plutons have negative ϵ_{Nd} (0.43 Ga) signatures. It does, however, resemble plutons of this age within the Exploits subzone (Table 2). This is compatible with the Margaree orthogneiss plus the Port aux Basques amphibolite dykes being interpreted as related to the opening of the Tetagouche-Exploits back-arc basin during the late Arenig to Llanvirn (Schofield *et al.*, 1993; van Staal, 1994; van Staal *et al.*, 1994). Granodiorites within the Grand Bay complex were emplaced at the same time as these units.

The Late Ordovician, early-syntectonic Port aux Basques granite (actually of low-K tonalitic composition; see Fig.

Table 4. Isotopic analyses and sample locations for units in southwestern Newfoundland.

Division	CRIC	CRIC	CRIC	GBC	GBC	GBC	PaBC	PaBC	PaBC	PaBC	PaBC	PaBC	HCG
Unit	CRgd	CRpgd	RRg	GBgd	GBgd	GBgd	PaBamp	PaBgn	PaBgn	PaBg	Mgn	Mgn	RBg
WXNF#	31	32	28	166	167	168	30a	30c	30b	29	170	169	171
$\delta^{18}\text{O}$ (‰)	+6.8	+8.7	+8.7	+6.3	+6.5	+12.7	+8.8	+10.1	+9.8	+7.5	-	+9.5	+9.5
$^{206}\text{Pb}/^{204}\text{Pb}$	-	18.652	18.410	-	-	-	-	-	-	20.044	-	-	18.244
$^{207}\text{Pb}/^{204}\text{Pb}$	-	15.596	15.692	-	-	-	-	-	-	15.818	-	-	15.609
$^{208}\text{Pb}/^{204}\text{Pb}$	-	38.098	38.072	-	-	-	-	-	-	39.986	-	-	38.067
$^{143}\text{Nd}/^{144}\text{Nd}_m$	0.511864	0.512056	0.511999	0.512441	0.512484	0.512485	0.512638	0.511979	0.511984	0.512809	-	0.512388	0.512388
$^{147}\text{Sm}/^{144}\text{Nd}_m$	0.0984	.0867	0.0803	0.1158	0.1037	0.1281	0.1568	0.1167	0.1168	0.1144	-	0.0971	0.0843
$^{143}\text{Nd}/^{144}\text{Nd}_i$	0.511549	0.511779	0.511778	0.512084	0.512165	0.512091	0.512155	0.511620	0.511624	0.512470	-	0.512089	0.512157
Age (Ma)	469	488	420	470	470	470	470	>500	>500	453	470	470	418
ϵ_{Nd} (T)	-9.2	-4.5	-6.2	+1.0	+2.6	+1.1	+2.4	-	-	+8.1	-	+1.1	+1.1
ϵ_{Nd} (0.43 Ga)	-9.7	-5.3	-6.1	+0.6	+2.1	+0.8	+2.2	-8.5	-8.4	+7.9	-	0.0	+1.3
T_{DM} (Ga)	1.7	1.3	1.3	1.1	0.9	1.2	1.4	1.8	1.8	0.5	-	1.0	0.9
Locations													
NTS Sheet	110/11	110/11	110/11	110/11	110/11	110/11	110/11	110/11	110/11	110/11	110/11	110/11	110/10
UTM Zone	21	21	21	21	21	21	21	21	21	21	21	21	21
Northing	52791	52766	52826	52729	52744	52764	52722	52722	52722	52728	52702	52702	52739
Easting	3323	3268	3271	3338	3366	3327	3389	3389	3389	3413	3464	3464	3713

Notes: Pluton names correspond to pluton abbreviations in Table 1; locations of divisions given in Figure 2. Subscripts i and m denote initial and measured, respectively.

3), which was probably generated during the early stages of closure of the Tetagouche-Exploits back-arc basin (van Staal, 1994; van Staal *et al.*, 1994), was previously interpreted as representing partial melts of its host paragneiss (Chorlton and Knight, 1983). Its depleted-mantle-like ϵ_{Nd} plus mantle-like $\delta^{18}\text{O}$ (+7.5‰) isotopic signatures make the Port aux Basques granite distinct from other granites emplaced into the Gander margin in Newfoundland (Kerr *et al.*, 1995) and New Brunswick (Whalen, 1993; Whalen *et al.*, 1996b) (Table 2), and dictate derivation from a juvenile depleted-mantle-like source. However, with respect to Pb, this granite is more radiogenic than either Paleozoic Gander Zone plutons (Whalen *et al.*, 1996b) or Precambrian Avalonian basement in New Brunswick (Fig. 6). Our Nd isotopic results (Fig. 5) suggest very little input to this granite from its paragneissic wall-rocks. However, a less positive ϵ_{Nd} (0.47 Ga) value of +2 reported from this granite by Fryer *et al.* (1992), its radiogenic or 'old crustal' Pb signature (Fig. 6), and the relatively low $\delta^{18}\text{O}$ value (+9.8‰) obtained from a Port aux Basques paragneiss are compatible with variable input from paragneiss to the granite sheets. If so, zoning in ϵ_{Nd} may be present within individual granite sheets, i.e., most positive in the centre of a sheet, the location from which our sample was collected.

4. Rose Blanche granite

The Silurian Rose Blanche granite has been interpreted as a syn-collisional, syn-peak-temperature metamorphism

pluton which formed as a result of westward-directed subduction and underthrusting by the Gander margin (Dunning *et al.*, 1991; Burgess *et al.*, 1995; van Staal *et al.*, 1994). This peraluminous granite petrographically resembles some Gander Zone granites, but its normalized geochemical pattern is not similar to those of Gander plutons (see Whalen *et al.*, 1996b), more closely resembling the Silurian Red Rock pluton of the Cape Ray Igneous Complex (Fig. 4). More significantly, its positive ϵ_{Nd} (0.43 Ga) signature is distinct from Gander Zone plutons (Table 1). These characteristics resemble most plutons in the Exploits subzone (Table 2) (Fryer *et al.*, 1992; Whalen *et al.*, 1994b). Also, its Pb isotopic signature, which is less-radiogenic than Gander Zone plutons in New Brunswick (Whalen *et al.*, 1994a,b), overlaps Pb isotopic compositions displayed by the 'Central Group' of Ayuso and Bevier (1991) (Fig. 6), plutons emplaced into the Dunnage Zone of New Brunswick and Maine. The peraluminous petrographic characteristics, positive ϵ_{Nd} and somewhat elevated $\delta^{18}\text{O}$ (+9.5‰) of the Rose Blanche granite could be attributed to derivation from immature arc-type volcanoclastic sediments (cf., Longstaffe and Schwarcz, 1977). A gradual increase in the volume of metatexite and stromatic *in situ* leucosome in the Harbour Le Cou Group migmatites toward their contact with this pluton suggests a significant input by partial melting of the Harbour Le Cou Group and supports this petrogenetic model. Also, this model may explain why this syn-collisional pluton has geochemical and isotopic characteristics similar to pre-collisional Exploits subzone plutons.

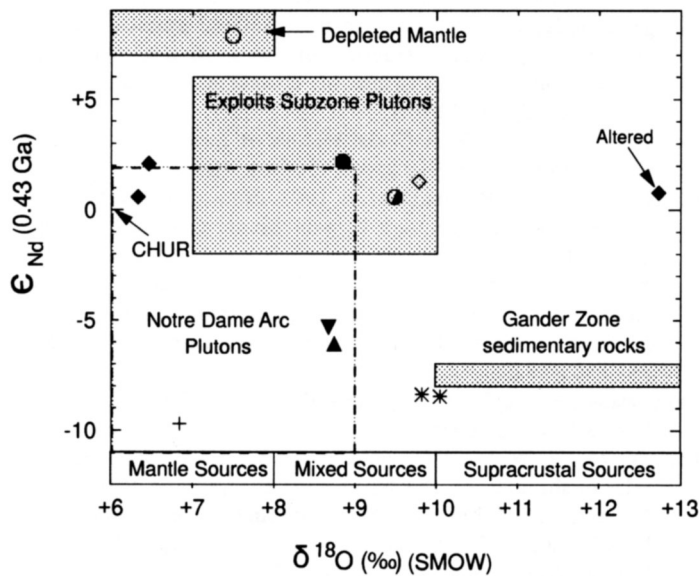


Fig. 5. ϵ_{Nd} (0.43 Ga) vs. $\delta^{18}O$ (SMOW) for units in southwestern Newfoundland; symbols as in Figures 2 and 3. Also shown are the fields of Ordovician Notre Dame arc and Exploits Paleozoic plutons from Table 2 and the ranges in $\delta^{18}O$ (SMOW) exhibited by various sources (bottom of diagram) from Taylor (1978, 1988).

DISCUSSION

This reconnaissance study suggests that isotopic plus geochemical analyses can be a useful aid in terrane identification in highly deformed portions of orogenic belts. In general, results obtained in this study are compatible with or support previous correlations which were arrived at following careful stratigraphic, structural, metamorphic and geochronological studies. In addition, this study has provided some new insights about the evolution of this area.

(1) Based on its unexpected isotopic characteristics, the Late Ordovician Port aux Basques granite (tonalite) formed either via fractionation from a MORB-like magma or by partial melting of recently formed (i.e., juvenile), depleted-mantle-derived, hydrous crust. In the second preferred option, a depleted mantle-derived underplate or intraplate may have formed at the time (ca. 470 Ma) of the opening of the Tetagouche-Exploits back-arc basin, at which time the Port aux Basques amphibolite dykes and Margaree orthogneiss were emplaced. The thermal conditions necessary to generate the Port aux Basques granite at 453 Ma by partial melting of such a juvenile underplate may have been generated during subduction of a spreading ridge (van Staal *et al.*, in review).

(2) The isotopic characteristics of Ordovician Notre Dame arc plutons suggest generation within an Andean-type continental arc which formed on the Laurentian margin; hence a subduction polarity reversal must have taken place after the Early Ordovician obduction of the suprasubduction zone oceanic tract (van Staal *et al.*, in review).

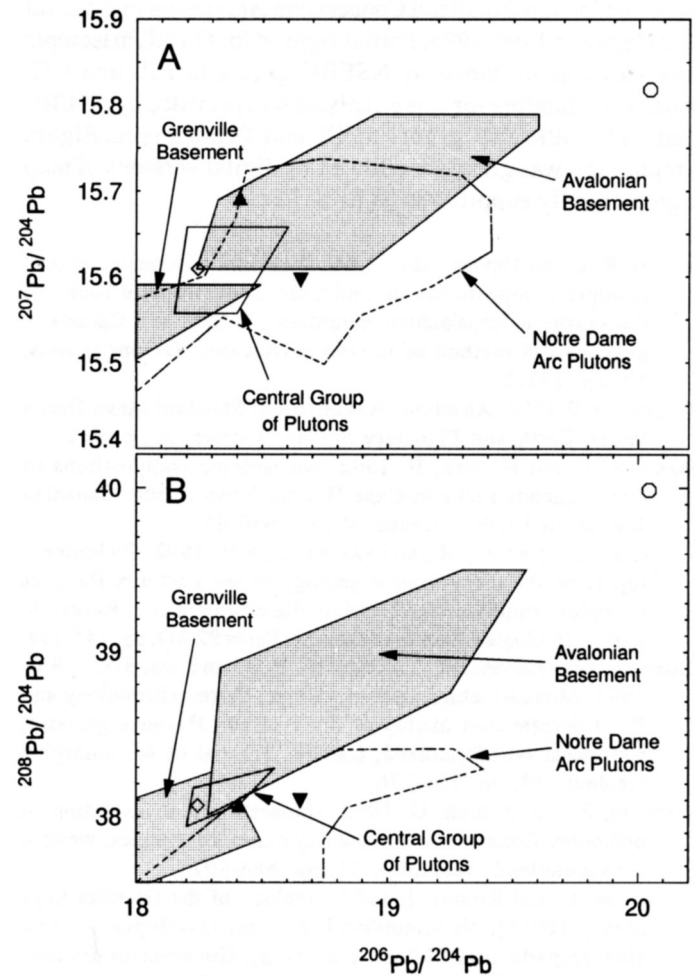


Fig. 6. Plot of $^{206}Pb/^{204}Pb$ versus (A) $^{207}Pb/^{204}Pb$, and (B) $^{208}Pb/^{204}Pb$ for feldspars from southwestern Newfoundland granitoid samples; comparison fields for Grenville basement, Precambrian Avalon Zone granitoid rocks and the 'Central Group' of plutons (after Ayuso and Bevier, 1991) and Ordovician Notre Dame arc plutons (after Whalen *et al.*, 1997) are also shown. Data of this study were recalculated to 400 Ma using $\mu = 10$ and $^{238}Th/^{238}U = 3.5$, the values that Ayuso and Bevier (1991) use for their 'Central Group' of plutons.

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