

Petrology, age, and tectonic setting of The Wolves Pluton: implications for Appalachian terranes in the western Bay of Fundy region

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ABSTRACT

The islands known as The Wolves are located in the Bay of Fundy, approximately 10 km offshore from mainland southwestern New Brunswick. They are underlain by monzodiorite, gradational to diorite, quartz diorite, and quartz monzodiorite, and minor units of tonalite and quartz monzonite, herein termed collectively The Wolves Pluton. Finer grained dioritic xenoliths are abundant in all the units. Rare syenite dykes and scattered mafic dykes intrude the pluton. Samples from the monzodiorite unit have silica concentrations ranging from 47.6% to 59.6% (average 54.5%), whereas tonalite samples have higher SiO₂ from 65.4% to 73.3% (average 69.6%) and two quartz monzonite samples have about 69% SiO₂. Although finer grained, the xenoliths are generally similar in mineralogy and chemical composition (49.2–54.7% SiO₂) to the dioritic part of the monzodiorite unit. Based on continuity and similarity of chemical trends and patterns, the monzodiorite, tonalite, and quartz monzonite, as well as the dioritic xenoliths, are interpreted to be co-magmatic. They constitute a calc-alkalic, I-type granitoid suite that likely formed in a subduction zone. A sample of monzodiorite from East Wolf Island yielded an Early Silurian U-Pb age of 436.4 ± 1.2 Ma, showing that The Wolves Pluton is not related to the Late Neoproterozoic to Early Cambrian plutonic rocks of the Caledonia, Brookville, and New River terranes, or of Grand Manan Island. They are older than Late Silurian-Devonian plutons of the Coastal Maine Magmatic Province. The best match in age is with Lower Silurian volcanic and granitic units of the Kingston terrane, although the rocks of The Wolves Pluton differ petrologically from the mainly fine-grained granite typically exposed in the Kingston terrane. Nevertheless, the similarity in age and inferred tectonic setting, as well as their similar positive epsilon Nd signatures, suggest that The Wolves Pluton might represent a deeper part of the Kingston volcanic arc. If so, the location of The Wolves Pluton apparently necessitates sinistral offset of the Kingston terrane to the southeast.

RÉSUMÉ

Les îles appelées The Wolves sont situées dans la baie de Fundy, à une dizaine de kilomètres au large de la partie intérieure du Sud-Ouest du Nouveau-Brunswick. Elles reposent sur une unité de jotunite passant graduellement à de la diorite, de la diorite quartzique et de la jotunite quartzique, accompagnée d'une unité secondaire de tonalite et d'adamellite, collectivement appelées dans le présent résumé *le pluton The Wolves*. Les xénolites dioritiques à grains plus fins sont abondants dans toutes les unités. De rares dykes syénitiques et des dykes mafiques dispersés pénètrent le pluton. Les échantillons de l'unité de jotunite renferment des concentrations de silice variant entre 47,6% et 59,6% (en moyenne 54,5%), tandis que les échantillons de tonalite comportent des concentrations supérieures de SiO₂ variant entre 65,4% et 73,3% (en moyenne 69,6%) et que deux échantillons d'adamellite renferment environ 69% de SiO₂. Même si les xénolites présentent des grains plus fins, ils ont généralement une composition minéralogique et chimique similaire (49,2 à 54,7% de SiO₂) à la partie dioritique de l'unité de jotunite. S'appuyant sur la continuité et la similarité des tendances et des configurations chimiques, on interprète la jotunite, la tonalité et l'adamellite, tout comme les xénolites dioritiques, en tant qu'éléments comagmatiques. Ils constituent un cortège granitique de type intrusif, calco-alkalin, qui s'est probablement formé dans une zone de subduction. Un échantillon de jotunite de l'île East Wolf a donné par datation U-Pb un âge du Silurien précoce de 436,4 ± 1,2 Ma, ce qui révèle que le pluton The Wolves n'est pas apparenté aux roches plutoniques du Néoprotérozoïque tardif au Cambrien précoce des terranes de Caledonia, de Brookville et de New River ni à l'île Grand Manan. Les îles sont plus âgées que les plutons du Silurien

tardif au Dévonien de la province magmatique de la côte du Maine. Le meilleur jumelage possible selon l'âge est celui avec les unités volcaniques et granitiques du Silurien inférieur du terrane de Kingston, même si les roches du pluton The Wolves diffèrent du point de vue pétrologique du granite essentiellement à grains fins typiquement dénudé dans le terrane de Kingston. La similarité de l'âge et le cadre tectonique présumé, ainsi que leurs signatures epsilon Nd positives similaires, laissent supposer que le pluton The Wolves pourrait représenter une partie plus profonde de l'arc volcanique de Kingston. Le cas échéant, l'emplacement du pluton The Wolves nécessite apparemment un décalage senestre du terrain de Kingston vers le sud-est.

[Traduit par la rédaction]

INTRODUCTION

The Wolves are a group of small rocky islands located in the Bay of Fundy, approximately 10 km offshore from southwestern New Brunswick (Fig. 1). Alcock (1948) described the rocks on the islands as "reddish granite", whereas Ritchie (1985) mapped the largest island (East Wolf) as medium-grained, pinkish hornblende-biotite granodiorite. A positive aeromagnetic anomaly extends ~500 m offshore from the islands and closely follows the shape of the island group (Geological Survey of Canada 1965a, b), suggesting that the granitoid rocks outcropping on the island are part of a larger pluton with an area of about 75 km².

The Wolves are located in an area where the Caledonia, Brookville, and Kingston terranes of southern New Brunswick extend into the offshore, and where major terrane-bounding faults, including the offshore extension of the Cobequid-Chedabucto fault zone between Avalonia and Meguma, appear to converge (Fig. 1). Barr *et al.* (2001) included The Wolves in the Brookville terrane, based on their location on trend with that terrane (Fig. 1) and on a reconnaissance examination of the rocks on the islands which suggested that they are similar to the ca. 555–525 Ma granitoid rocks typical of the Brookville terrane. Barr *et al.* (2001) used the inferred correlation to justify extending the Brookville terrane an additional 30 km into the Bay of Fundy. However, a preliminary U-Pb age of ca. 440 Ma subsequently reported by Barr *et al.* (2003a) indicated that some, if not all, of the plutonic rocks on The Wolves are Silurian, and hence unlikely to be linked to the Neoproterozoic-Cambrian plutons of the Brookville terrane.

In this paper we report the results of a petrochemical study of the granitoid rocks, herein named The Wolves Pluton, which make up The Wolves, and confirm the preliminary U-Pb age cited by Barr *et al.* (2003a). We use these data to infer a terrane affiliation for The Wolves Pluton and discuss implications for terrane configuration in the Bay of Fundy.

FIELD RELATIONS AND PETROGRAPHY

Outcrops and field relationships on The Wolves were observed during three one-day mapping and sampling boat excursions in 2000, 2004, and 2005. Most of the islands consist of grey to pink, medium- to coarse-grained granitoid rocks that are assigned here to a compositionally variable unit in which monzodiorite is the main component (Fig. 2). Two other rock

units form small areas on the islands: tonalite on the southern third of South Wolf Island and on a small promontory on the southeastern shore of East Wolf Island, and quartz monzonite on Spruce Island (Fig. 2). All three units contain abundant dioritic xenoliths. A swarm of small syenitic dykes up to ~1 m in width occur in monzodiorite on Green Rock, and scattered mafic dykes up to 5 m wide were observed mainly on the southern coast of East Wolf Island.

Based on modal analysis of twenty samples, the monzodiorite unit varies from diorite through quartz diorite, monzodiorite, and quartz monzodiorite (Fig. 3). The rocks locally show magmatic layering that results from alternating changes in the proportion of felsic and mafic minerals, a feature especially well developed in some outcrops on the northwestern shore of East Wolf Island (Fig. 4a). The layering trends approximately east-west, and dips steeply to the south; cross-cutting relations suggest that the top of the pluton may be to the south, but data are too localized to attach much significance to that observation. Plagioclase, biotite, and amphibole are the most abundant minerals in the monzodiorite unit (Figs 5a, 6a). Interstitial quartz and potassium feldspar (orthoclase) form up to 30%. The amphibole commonly contains relict cores of clinopyroxene. Accessory minerals include abundant apatite, magnetite, zircon, and large sub- to euhedral grains of titanite. On the southern islands, the rocks are more altered, with feldspars increasingly saussuritized and sericitized, and the mafic minerals increasingly altered to chlorite, epidote, and actinolite.

Based on electron microprobe analyses tabulated in Wolczanski (2006), plagioclase compositions in the monzodiorite unit vary from labradorite to oligoclase (An₅₆ to An₂₀). Biotite is intermediate in composition between phlogopite and annite, with Fe/(Fe+Mg) of about 0.4 to 0.5. On the MgO-FeO-Al₂O₃ ternary discrimination diagram of Abdel-Rahman (1992), the biotite compositions plot in the field of biotite in calc-alkaline orogenic suites. Amphibole is mainly magnesiohornblende to actinolitic hornblende (classification of Leake *et al.* 1997). Relict clinopyroxene cores in the amphibole include both low-Ca (augite) and high-Ca (diopside) varieties, both with Fe to Mg ratio of about 0.2 to 0.3.

The tonalite on East Wolf and South Wolf islands consists of plagioclase, quartz, and interstitial biotite with little to no amphibole or K-feldspar (Figs. 3, 5b, 6b). The tonalite differs in texture from the monzodiorite in that it is coarse grained, and quartz is not interstitial but instead forms large anhedral crystals (Fig. 5b, 6b). The contact between monzodiorite and tonalite on East Wolf Island is not exposed, but on the west-

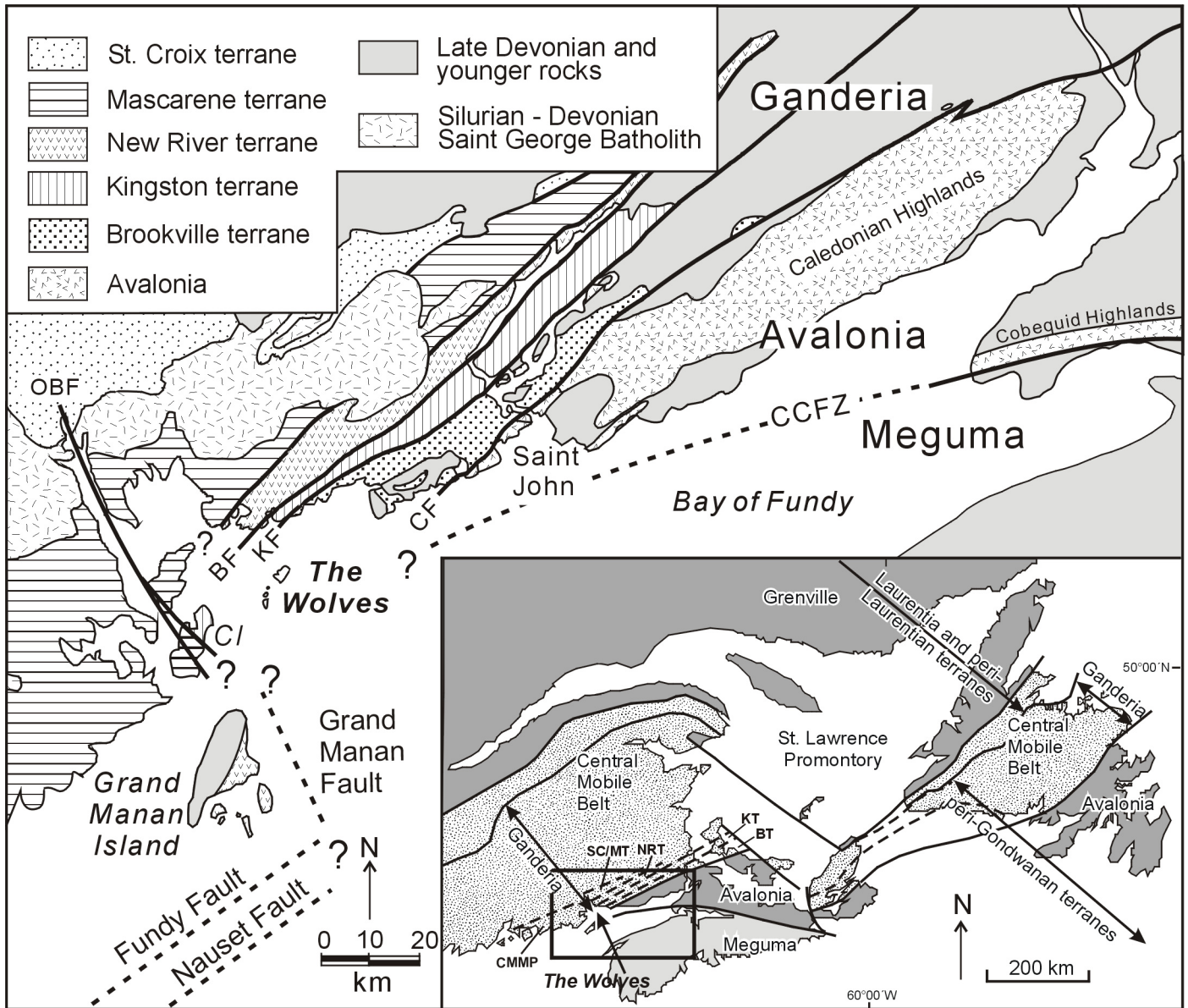


Fig. 1 Terranes in the Bay of Fundy region (after Hibbard *et al.* 2006) showing the location of The Wolves. Abbreviations: BF, Belleisle Fault; BT, Brookville terrane; CCFZ, Cobequid-Chedabucto fault zone; CF, Caledonia Fault; CI, Campobello Island; CMMP, Coastal Maine magmatic province; KF, Kennebecasis Fault; KT, Kingston terrane; NRT, New River terrane; OBF, Oak Bay Fault; PB, ; SC/MT, St. Croix and Mascarene terranes.

ern shore of South Wolf Island the relationship appears to be gradational, with a southward increase in grain size and quartz content from the monzodiorite to tonalite over a distance of several tens of metres.

The third unit on The Wolves, quartz monzonite, was mapped along the western part of Spruce Island and, based on reconnaissance views from the boat, appears to form the whole island. The quartz monzonite is pink and coarse grained (Fig. 5c) and consists of plagioclase, microcline, interstitial quartz, biotite, and hornblende with augite cores (Fig. 3, 6c). The plagioclase has been saussuritized and the biotite displays alteration to chlorite. Accessory phases include apatite, titanite, and magnetite. At one location on the west side of Spruce Island,

the quartz monzonite has been intruded by a ~ 5 m-wide dyke of monzodiorite (Fig. 4b). The contact between the two units is sharp but irregular, and rounded xenoliths of quartz monzonite are present in the monzodiorite dyke. These relationships suggest that the quartz monzonite may not have been completely crystallized when intruded by the monzodiorite magma. Both units also contain abundant and similar dioritic xenoliths.

The monzodiorite and tonalite units on South Wolf Island have locally developed foliation defined by alignment of mafic minerals and/or elongate quartz grains. The foliation trends northeast to east with mainly steep dips to the southeast and south. Localized brittle shear zones occur on all the islands and generally trend east-northeast with varying dips from shallow

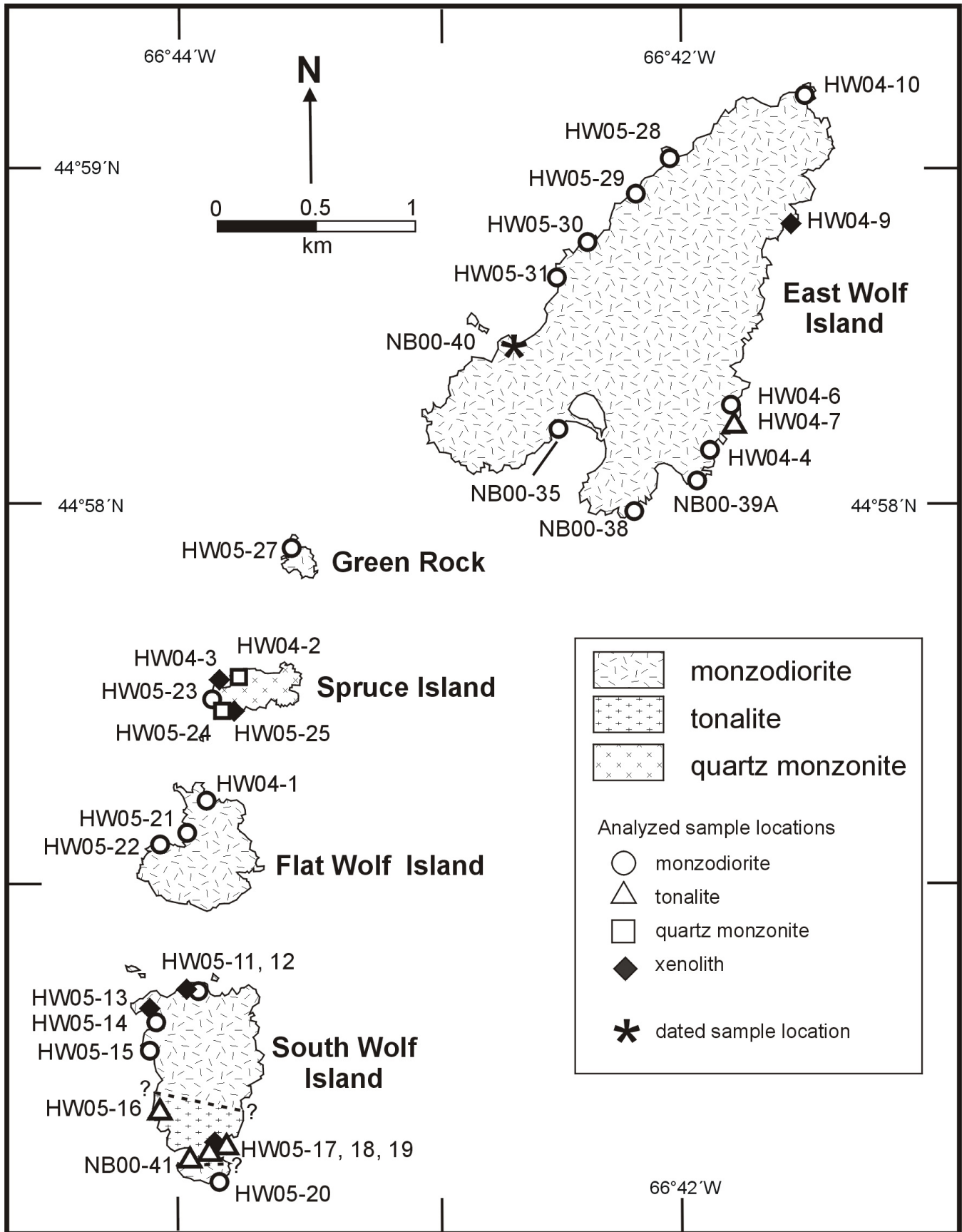


Fig. 2 Geological map of The Wolves based on the present study. Sample locations are indicated by symbols.

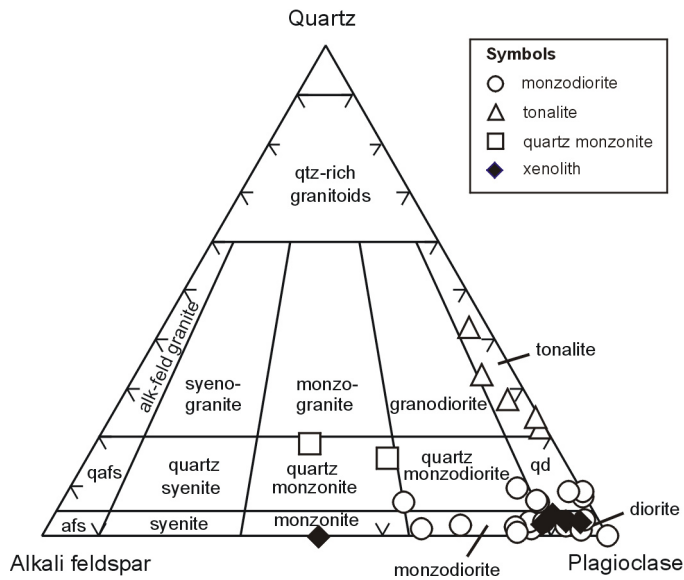


Fig. 3 Modal mineralogy of samples from The Wolves plotted on the Q (quartz) - A (alkali feldspar) - P (plagioclase) ternary diagram with fields from Streckeisen (1976). Data were obtained by counting of approximately 200 points on slabs etched in hydrofluoric acid and stained for K-feldspar following the method of Hutchinson (1974), combined with visual estimates of fine-grained components in thin section.

to steep. No evidence for south-dipping thrust or normal faults as seen in southern New Brunswick (King and Barr 2004; Nance 1987; Park 2001) and in offshore seismic reflection profiles (Keen *et al.* 1991) was observed on the island.

Dark grey xenoliths are common in the monzodiorite, tonalite, and quartz monzonite units. They are commonly ovoid and ~15–20 cm long, although at one location on South Wolf Island some xenoliths are more than 1 m across. Texture is fine- to very fine-grained, hypidiomorphic inequigranular to granular (Figs. 5d, 6d). The xenoliths consist of plagioclase, biotite, magnesio-hornblende with relict cores of clinopyroxene, and interstitial quartz and potassium feldspar (Fig. 6d). They range from diorite to monzodiorite, with the exception of one sample (HW04-09), which has a higher K-feldspar content and is a monzonite (Fig. 3). Compared to the monzodiorite unit, the xenoliths are finer grained and tend to have a higher proportion of mafic minerals.

The syenite dykes in monzodiorite on Green Rock consist mostly of microcline and plagioclase with minor quartz, and sparse biotite, hornblende, and opaque minerals. As a whole, the rock has allotriomorphic inequigranular texture. Plagioclase occurs as smaller, equigranular crystals along grain boundaries of larger K-feldspar grains. Irregular patches of coarse-grained K-feldspar are also present. The mafic dykes are gabbroic, with fine-grained intergranular texture of plagioclase and mainly altered pyroxene.

Magnetic susceptibility was measured in the field using a KT-9 Kappameter (manufactured by Geoploration Ltd.). Between 4 and 10 readings were taken at each of about 25 out-

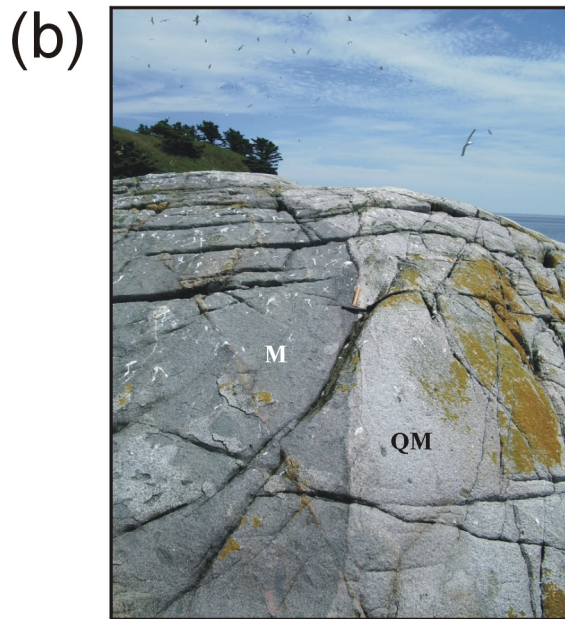


Fig. 4 (a) Outcrop of monzodiorite showing cumulate layering on the northern shore of East Wolf Island. (b) Monzodiorite dyke (M) in quartz monzonite (QM), western shore of Spruce Island.

crops around the islands (Wolczanski 2006). Average readings ranged from lows of less than 1 to a high of 19, but averaged about 7.0×10^{-3} SI units. The xenoliths generally gave lower values than their host rocks. One mafic dyke yielded a value of 12.3. These readings are moderate to high in comparison to other rock units in southern New Brunswick (King and Barr 2004) and are consistent with the pluton being the cause of the positive aeromagnetic anomaly in the area of The Wolves (Geological Survey of Canada 1965a, b).

Major- and Trace-Element Geochemistry

Whole-rock chemical data were obtained for thirty-two samples, focusing on the main monzodiorite unit (Table 1). Six of

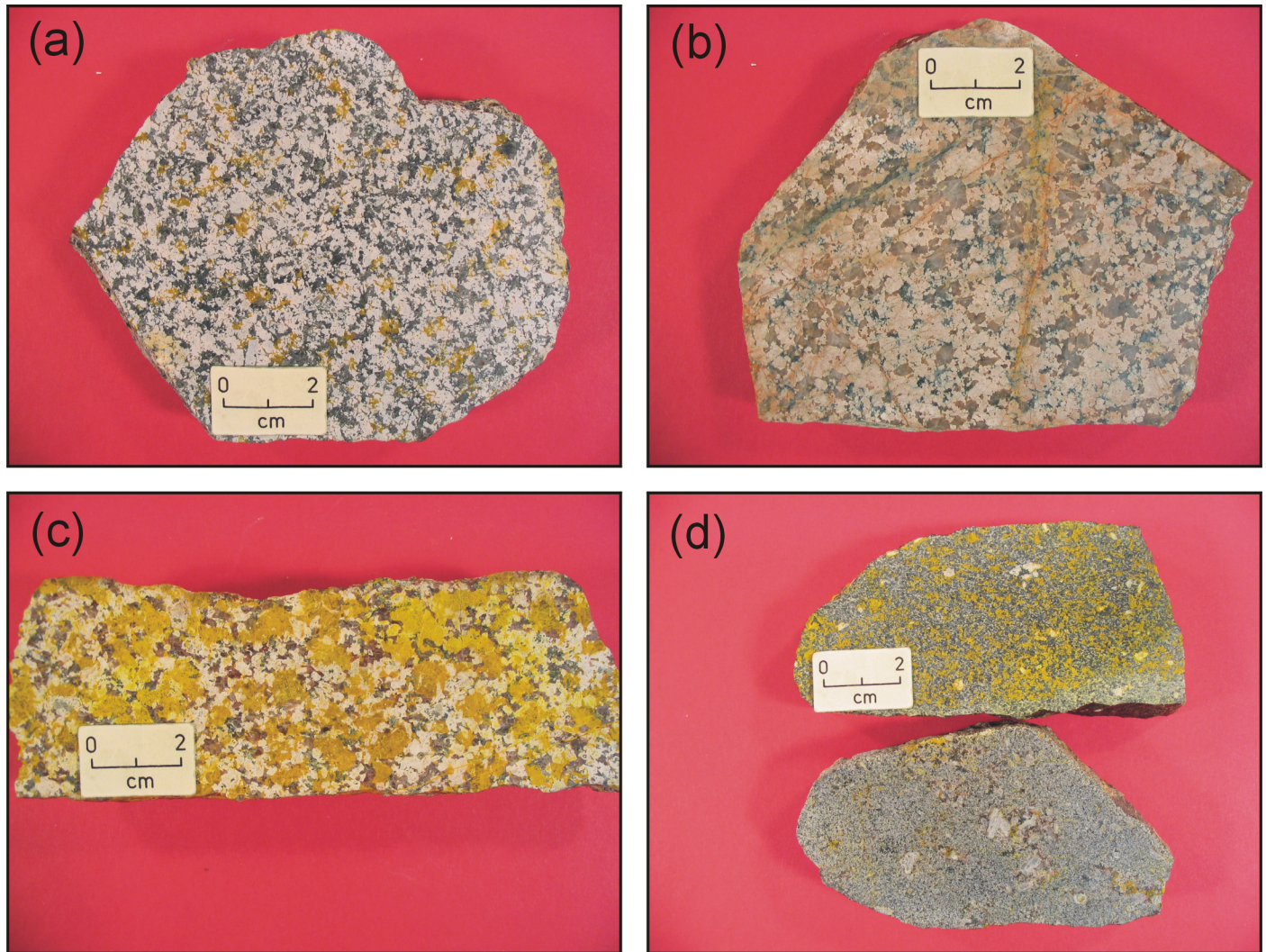


Fig. 5 Hand specimen slabs of representative samples, etched and stained for K-feldspar (yellow) using the technique of Hutchinson (1974). (a) Monzodiorite (sample HW05-31). (b) Tonalite (sample HW05-19). (c) Quartz monzonite (sample HW04-2). (d) Xenoliths (samples HW04-9 (top) and HW04-3 (bottom)).

those samples were analyzed also for rare-earth elements (Table 2). The silica concentrations in the twenty analyzed monzodiorite unit samples range from 47.6% to 59.6% (average 54.5%), whereas the five tonalite and two quartz monzonite samples have higher SiO_2 (average 69.6% and 69.0%, respectively). A silica gap of about 6% separates the most silicic monzodiorite sample from the least silicic tonalite sample. The five dioritic xenolith samples have SiO_2 contents ranging from 49.2% to 54.7%, overlapping those in the low- SiO_2 monzodiorite unit samples.

Major element oxide data from both monzodiorite and xenolith samples show scatter but TiO_2 , Fe_2O_3 , MnO , MgO , CaO , and P_2O_5 generally have negative correlation with SiO_2 whereas Na_2O tends to show positive correlation and Al_2O_3 and K_2O little correlation with SiO_2 (Fig. 7). Trace elements (Fig. 8) show even less well developed trends against SiO_2 than the major-element oxides. However, the similarity in compositional varia-

tion between the xenoliths and the monzodiorite supports a co-magmatic relationship. The xenoliths may represent earlier formed cumulate material disrupted by subsequent magma movement.

In spite of the poorly developed chemical trends and the silica gap between the monzodiorite and the tonalite and quartz monzonite units, the cumulate-type layering (e.g., Fig. 4a) and textures observed in the monzodiorite unit in particular suggest that crystal fractionation was a major process in magma evolution. Major element oxide variations are consistent with feldspar and mafic mineral fractionation (Fig. 7, 8). Co-variations between TiO_2 and Fe_2O_3 (Fig. 9a) and $\text{V-Fe}_2\text{O}_3$ (Fig. 9b) suggest that fractionation of Ti- and V-bearing biotite and magnetite may have produced those trends. Microprobe analyses indicate TiO_2 contents up to 3–4 % in biotite in the monzodiorite unit (Wolczanski 2006). Strong correlation between P_2O_5 and TiO_2 (Fig. 9c), as well as P_2O_5

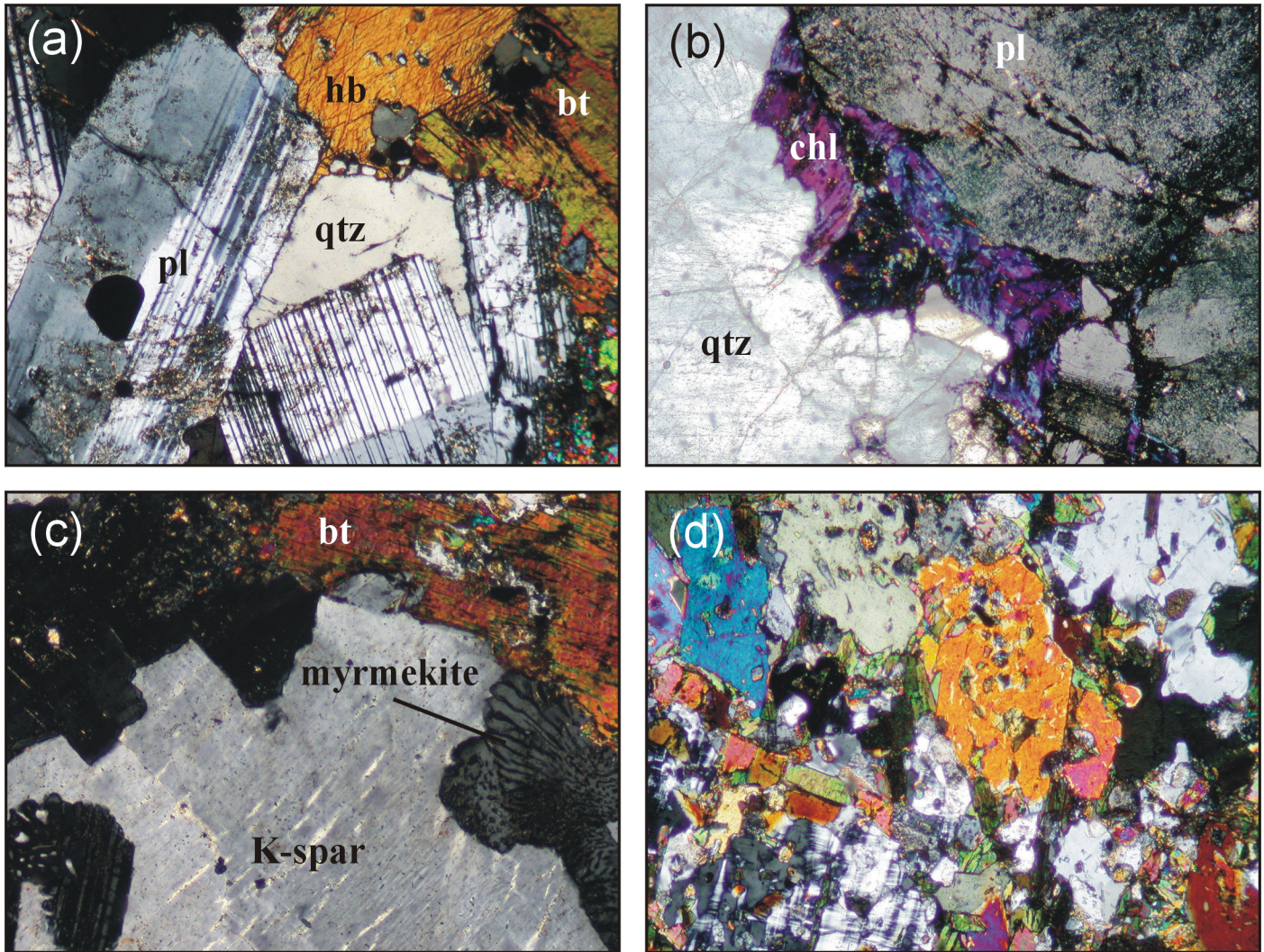


Fig. 6 Photomicrographs of typical samples in thin section under crossed polars. Field of view is about 1 mm wide. (a) Monzodiorite (sample HW05-28). (b) Tonalite (sample HW05-19). (c) Quartz monzonite (sample HW04-2). (d) Xenolith (HW04-9). Abbreviations: bt, biotite; chl, chlorite; hb, hornblende; K-spar, potassium feldspar; pl, plagioclase; qtz, quartz.

and Zr (Fig. 9d), suggest that other accessory phases (titanite, apatite, and zircon) were also involved, perhaps as inclusions in the fractionating biotite. All of these accessory minerals are relatively abundant in the monzodiorite and rare or absent in the tonalite and quartz monzonite samples.

Samples show a calc-alkalic trend on the AFM diagram (Fig. 10a), consistent with the biotite compositions noted above. Although commonly used tectonic setting discrimination diagrams are probably not reliable for these cumulate rocks, a multi-element spider diagram, normalized to N-MORB, reveals that samples from The Wolves Pluton have depletions in Ta, Nb, P and Ti (Fig. 10b), all characteristics of origin in a subduction zone setting.

Rare-Earth Element Data

All six samples analyzed for rare-earth elements (REE) (Table 2) show light-REE enrichment (Fig. 11). The three mon-

zodiorite samples show similar patterns of enrichment in light REE and a steady decrease in middle REE, with a low, flat, heavy REE pattern. One monzodiorite sample (NB00-39A) shows a slight negative Eu anomaly, indicative of feldspar fractionation, and a flatter REE pattern that crosses the patterns of the other monzodiorite samples. The pattern for the xenolith sample is similar to those for the monzodiorite samples, consistent with a co-magmatic relationship as indicated by the petrographic and other chemical data. Such REE patterns are like those derived from melting of mafic sources (e.g., Hanson 1980).

The quartz monzonite sample shows a steeper REE pattern, and more depletion in the heavy REE, consistent with having experienced more mafic and accessory mineral fractionation. This saddle-shaped heavy REE pattern is much more pronounced in the tonalite sample, which has lower REE than any of the other samples. It also displays a positive Eu anomaly, consistent with plagioclase accumulation in the rock. Crystal fractionation models (e.g., Hanson 1980; Gromet and Silver

Table 1. Chemical data for samples from The Wolves Pluton.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ ^t	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Total	Ba	Rb	Sr	Y	Zr	Nb	Th	Pb	Ga	Zn	Cu	Ni	V	Cr	Co	U	
<i>Monzodiorite</i>																													
HW04-01	55.45	1.39	18.48	6.18	0.09	2.12	4.84	4.29	3.92	0.49	1.60	98.85	485	83	772	23	472	24	10	19	21	79	40	<3	78	<4	31	3	
HW04-04	59.56	0.67	17.45	6.72	0.14	2.40	5.93	3.21	1.93	0.16	1.41	99.57	187	67	385	19	129	3	<2	7	17	76	43	<3	46	<4	43	2	
HW04-10	53.14	0.97	22.09	5.26	0.07	2.55	7.32	4.11	1.86	0.39	1.97	99.73	286	54	1330	15	216	7	3	19	24	62	63	<3	57	<4	30	<1	
HW05-12	52.38	1.62	18.75	8.47	0.16	3.74	5.36	4.10	2.84	0.47	2.47	100.35	777	76	614	20	275	24	10	15	22	111	44	17	198	<5	40	2	
HW05-14	55.41	0.98	19.73	6.15	0.11	2.66	4.85	4.96	2.81	0.42	2.05	100.14	1204	93	1050	35	528	16	12	19	20	79	92	17	150	6	34	3	
HW05-15	51.82	1.32	17.17	8.95	0.14	5.14	6.53	3.15	2.58	0.33	2.66	99.78	602	65	670	19	221	15	10	13	21	86	80	54	210	39	49	2	
HW05-20	49.83	0.82	16.56	10.76	0.19	6.61	10.04	2.02	0.83	0.11	3.10	100.87	286	19	364	17	81	4	5	12	16	92	404	61	227	102	52	1	
HW05-21	54.38	1.39	19.30	6.54	0.11	2.49	4.74	4.71	3.67	0.56	1.66	99.54	1081	86	744	30	436	23	6	15	20	88	<4	9	162	<5	30	3	
HW05-22	54.76	1.43	19.49	6.82	0.13	2.32	5.37	4.86	3.55	0.56	0.76	100.05	992	83	935	33	490	27	<2	19	23	93	13	8	168	19	31	2	
HW05-23	53.26	1.46	19.22	7.86	0.13	3.47	6.38	4.53	2.65	0.61	0.92	100.49	895	78	1032	31	362	18	<2	10	23	118	13	22	191	16	38	2	
HW05-27	57.83	1.00	17.49	6.29	0.10	3.23	4.73	4.09	3.81	0.31	0.93	99.81	616	108	716	28	325	18	7	23	17	72	44	39	141	42	34	2	
HW05-28	50.28	1.39	21.92	6.70	0.08	2.89	8.68	3.79	1.53	0.56	1.70	99.52	392	66	1394	33	179	9	<2	9	22	68	33	10	175	<5	34	2	
HW05-29	47.63	1.86	20.67	8.59	0.13	4.59	6.81	3.36	3.10	0.73	1.87	99.33	1713	126	1407	28	175	10	<2	30	19	94	16	6	229	10	32	1	
HW05-30	53.46	1.08	22.16	5.44	0.08	2.57	7.12	4.15	2.40	0.39	1.84	100.69	586	92	1390	34	201	11	2	11	24	61	119	14	148	8	32	3	
HW05-31	57.36	0.94	17.42	6.65	0.11	3.78	5.43	3.88	3.01	0.31	1.12	100.01	549	91	762	27	239	11	10	15	19	87	14	44	141	39	43	2	
NB00-35	57.80	1.04	17.34	6.15	0.13	3.19	4.60	3.96	3.68	0.35	1.30	99.54	838	93	706	22	292	18	13	18	19	101	8	17	152	23	45	1	
NB00-38	53.87	0.67	17.61	8.61	0.16	5.16	8.25	2.86	1.47	0.14	1.69	100.50	179	46	460	19	88	2	2	7	17	74	99	18	169	52	54	1	
NB00-39A	55.74	0.67	17.67	8.50	0.16	3.81	7.48	2.93	1.47	0.15	1.12	99.71	303	50	360	22	85	4	3	3	17	79	90	11	161	23	58	1	
NB00-40	57.27	0.97	17.82	7.02	0.12	3.85	5.37	3.77	2.81	0.31	1.46	100.77	599	81	817	19	232	12	12	19	20	95	9	25	160	22	59	<1	
<i>Quartz monzonite</i>																													
HW04-02	69.16	0.44	15.57	2.80	0.05	0.95	1.73	4.17	4.80	0.18	0.79	100.64	373	103	525	11	267	5	11	26	17	51	<4	<3	26	<4	40	3	
HW05-24	68.87	0.44	15.96	2.78	0.05	0.92	1.97	4.53	4.26	0.19	0.66	100.63	540	126	483	31	264	18	20	26	16	32	13	21	59	<5	42	4	
<i>Tonalite</i>																													
HW04-07	72.23	0.29	14.42	2.50	0.05	1.16	1.56	4.80	2.14	0.08	1.41	100.64	228	63	219	11	131	<1	<2	31	14	35	39	<3	22	<4	48	2	
HW05-16	66.82	0.61	15.62	4.63	0.07	1.43	3.19	4.18	1.68	0.16	1.54	99.93	323	85	445	33	286	7	14	19	16	37	22	23	78	<5	40	4	
HW05-17	65.40	0.49	16.80	4.36	0.08	1.84	2.73	4.74	1.79	0.16	1.56	99.95	415	97	381	28	110	4	14	31	15	54	48	27	78	6	42	5	
HW05-19	71.62	0.25	15.03	2.34	0.05	0.91	1.93	4.80	1.74	0.09	1.30	100.06	423	89	352	29	139	6	17	25	14	28	57	23	44	<5	36	6	
NB00-41	73.26	0.23	14.53	1.93	0.03	0.65	1.80	4.90	1.48	0.05	1.09	99.96	1258	52	279	10	132	1	9	10	13	26	7	85	40	<4	62	2	
<i>Xenoliths</i>																													
HW04-03	54.74	1.09	17.89	6.68	0.13	3.80	6.12	4.80	2.23	0.32	0.84	98.64	259	68	705	21	331	15	10	13	21	71	14	4	62	23	38	1	
HW04-09	50.43	1.19	13.38	7.92	0.23	9.99	6.85	1.81	5.30	0.47	1.39	98.96	749	93	560	17	491	18	14	6	18	91	46	245	73	376	43	2	
HW05-11	50.03	1.17	13.27	7.83	0.14	11.23	7.44	2.21	3.46	0.81	2.92	100.51	1124	67	696	22	583	17	5	3	15	95	51	395	171	640	42	2	
HW05-13	49.28	1.41	18.36	9.19	0.18	5.25	6.48	3.48	2.41	0.63	3.49	100.14	764	85	1058	29	418	18	13	20	26	172	57	45	204	15	48	2	
HW05-18	50.03	0.81	18.74	9.05	0.19	5.88	6.56	3.33	2.58	0.18	2.59	99.94	721	68	439	20	80	5	4	9	19	163	18	56	156	42	42	2	
HW05-25	49.21	1.97	19.29	9.12	0.14	3.83	6.31	4.70	2.60	0.89	1.63	99.69	1095	74	1051	31	421	22	<2	9	24	111	76	17	239	9	36	2	

Notes: Analyses were done by X-ray Fluorescence at the Regional Geochemical Centre, Saint Mary's University, Halifax, Nova Scotia. Major elements and some trace elements were measured using fused glass disks and other trace elements were measured using pressed powder pellets (see http://www.stmarys.ca/academic/science/geology/rgv/reg_home.htm for description of the methodology, and accuracy/precision information). Analytical error is generally less than 5% for major elements and 2-10% for trace elements. Fe₂O₃^t is total Fe as Fe₂O₃. LOI is loss on ignition at 1000°C.

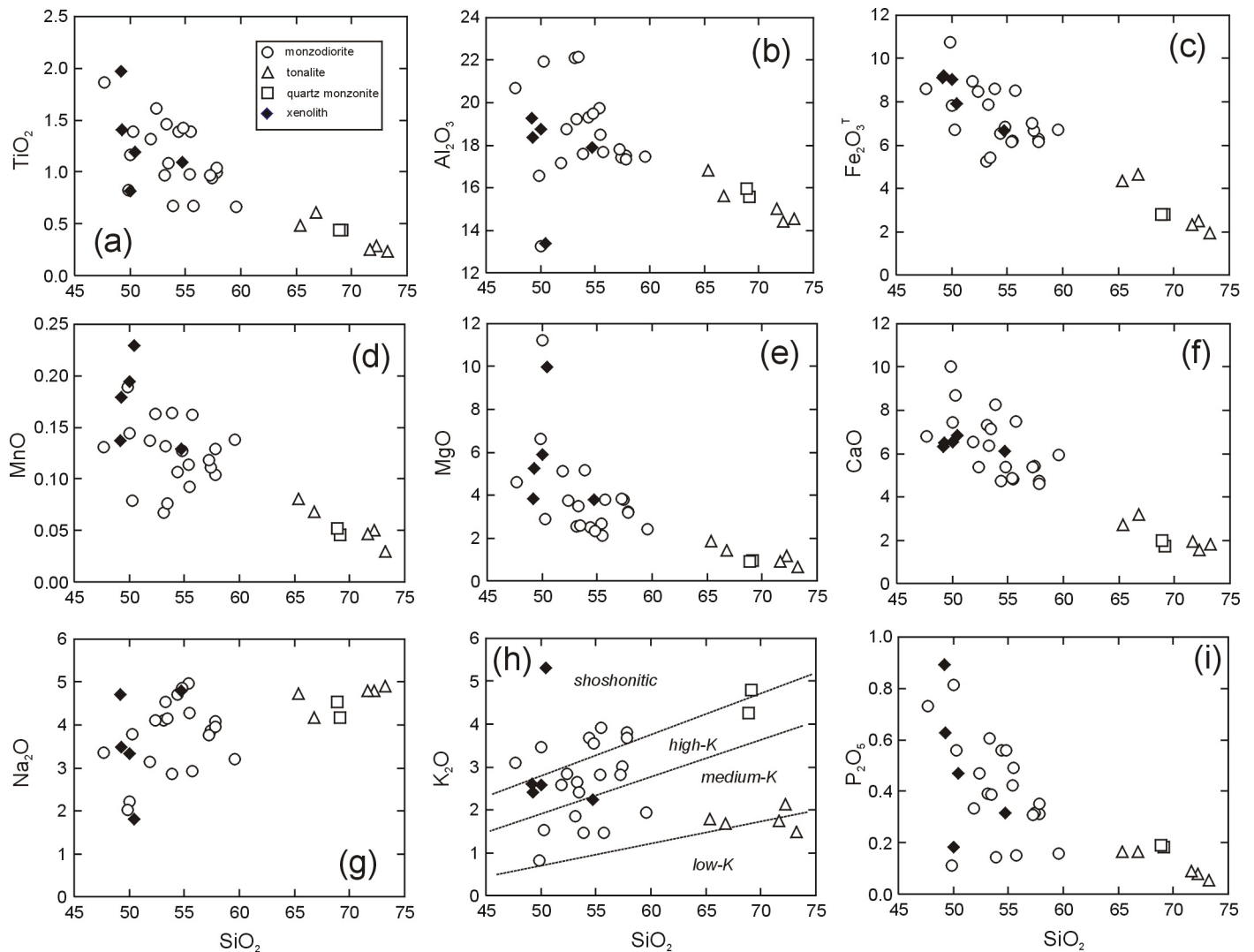


Fig. 7 Plots of major element oxides against SiO_2 (all in weight %) to illustrate chemical variation in The Wolves Pluton. Chemical data are from Table 1. Fields in (h) are after Middlemost (1975).

1987) show that fractionation of hornblende is a likely cause of saddle-shaped heavy REE patterns, although accessory mineral removal is also needed to lower the total REE abundance to that seen in the tonalite sample.

U-Pb Dating

U-Pb zircon dating of monzodiorite sample NB00-40 (Fig. 2) was done at the University of North Carolina-Chapel Hill Isotope Geochemistry Laboratory. Zircon grains were separated from the ca. 25 kg sample 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. Detailed analytical procedures are described in Miller *et al.* (2006). Data reduction followed Ludwig (1989) using the unpublished program PbMacDat

(D. Coleman, University of North Carolina) with the plotting and regression algorithms of Ludwig (1990; 1998). Data are presented in Table 3 and on concordia diagram (Fig. 12) at the 2-sigma uncertainty level.

Zircon grains separated from sample NB00-40 were mainly large prisms with relatively high U and radiogenic Pb concentrations, allowing for the analysis of single- and two-grain fractions. One analyzed grain was brown and slightly metamict. This grain contained very high U and radiogenic Pb concentrations and is highly discordant due to geologically recent Pb-loss (Fig. 12). Seven other fractions consisted of single prismatic grains, or fragments of prismatic grains. One concordant analysis is slightly older than the rest; its exclusion from the regression line reduces the uncertainty but does not significantly affect the age. The upper intercept of a regression line that includes all eight analyses is 436.4 ± 1.2 Ma, which we interpret as the time of crystallization of the monzodiorite.

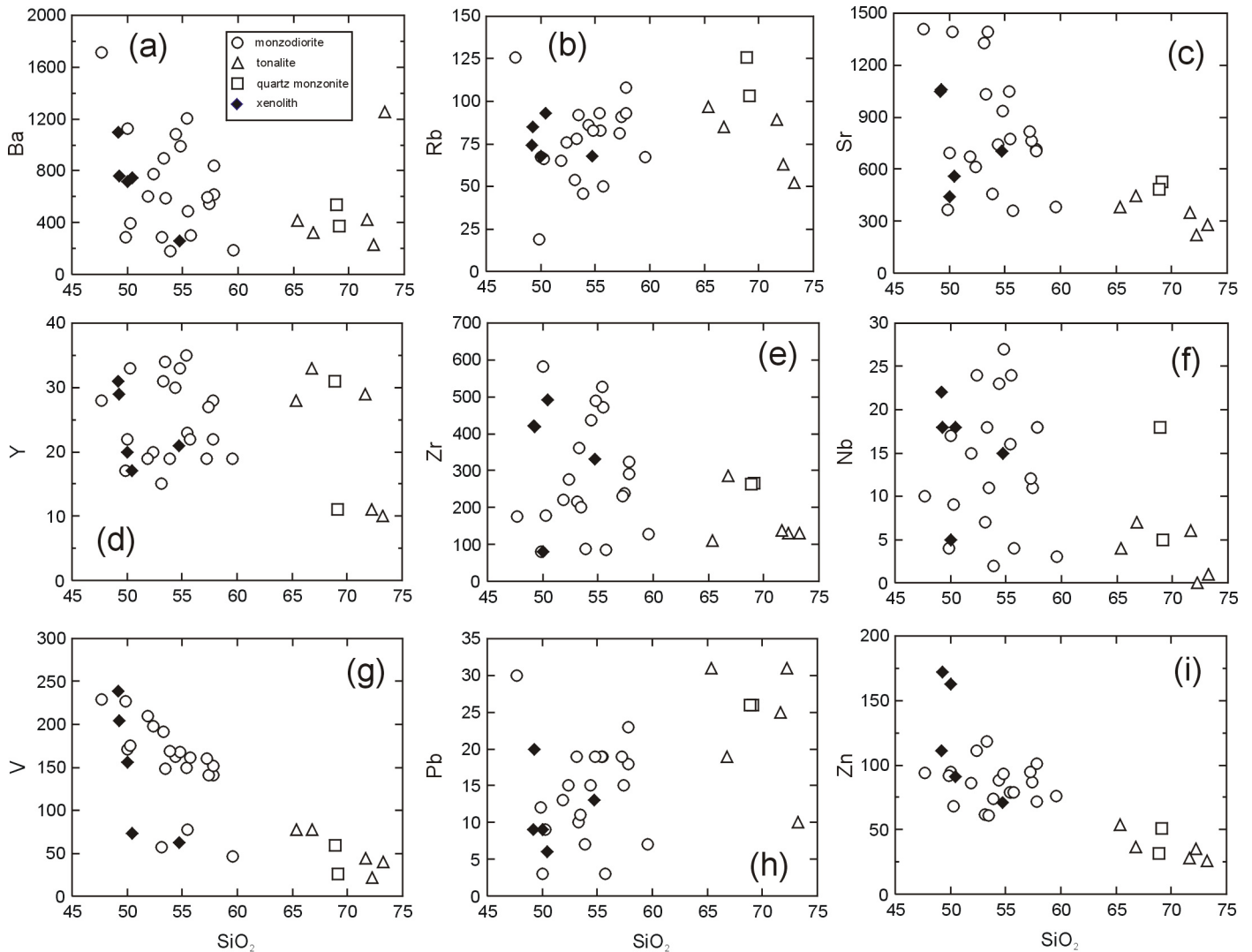


Fig. 8 Plots of (a) Ba, (b) Rb, (c) Sr, (d) Y, (e) Zr, (f) Nb, (g) V, (h) Pb, and (i) Zn (in ppm) against SiO₂ (in weight %) to illustrate chemical variation in The Wolves Pluton.

Sm-Nd Isotopic Data

Samarium and Nd isotopic data were obtained for three samples representing the monzodiorite, tonalite, and quartz monzonite units (Table 4). The ϵ_{Nd} values (calculated to the U-Pb age, 436 Ma) are closely clustered at 3.8, 3.6, and 2.7, with depleted mantle model ages between 671 and 779 Ma. The similarity in ϵ_{Nd} is consistent with a co-magmatic origin for the three granitoid units on The Wolves. The parent magma may have been a mantle-derived melt that experienced some crustal contamination to lower the ϵ_{Nd} from typical depleted mantle values of ca. 7 (Fig. 13). Alternatively, the magma may have been derived by partial melting of juvenile, mafic mantle-derived rocks in the lower crust. The latter origin is more consistent with the REE patterns described above.

DISCUSSION

The Wolves are on strike with the Brookville terrane (Fig. 1), and the granitoid rocks exposed on these islands are petrologically similar to some of the abundant granitoid rocks of the Brookville terrane (Barr *et al.* 2001; White *et al.* 2002). However, the petrological similarities are likely the result of the plutons having formed in similar subduction zone settings, because the Brookville terrane plutons have ages between 555 and 527 Ma (White *et al.* 2002), and hence can have no direct link with the 436 Ma rocks in The Wolves Pluton. If The Wolves Pluton is located in the Brookville terrane, then it is the only Silurian pluton known in that belt, which has been well studied in the onshore part (White *et al.* 2002). Furthermore, plutons in the Brookville terrane, even those of Devonian age, have mainly negative or only slightly positive epsilon Nd values,

Table 2. Rare-earth element, Hf, and Ta data* for samples from The Wolves Pluton.

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta
<i>Monzodiorite</i>																
HW05-22	48.36	105.03	13.11	53.16	8.87	2.37	6.72	0.87	4.85	0.90	2.45	0.33	2.13	0.32	11.32	1.18
NB00-39A	12.28	28.72	3.73	16.10	3.64	1.00	3.68	0.55	3.41	0.71	2.10	0.31	2.03	0.31	2.21	0.64
NB00-40	33.86	70.14	8.53	33.32	5.63	1.67	3.99	0.53	3.01	0.59	1.62	0.24	1.57	0.24	4.87	1.81
<i>Quartz Monzonite</i>																
HW04-02	30.65	55.84	6.02	21.66	3.19	0.98	2.26	0.30	1.63	0.30	0.85	0.13	0.88	0.14	5.02	1.29
<i>Tonalite</i>																
HW05-19	9.44	17.21	1.95	7.16	1.32	0.65	1.12	0.13	0.67	0.13	0.39	0.06	0.42	0.08	2.83	0.52
<i>Xenolith</i>																
HW04-03	33.55	72.59	8.80	34.30	6.23	1.69	4.78	0.67	3.78	0.73	2.05	0.29	1.90	0.28	7.02	1.09

*Analyses at Memorial University of Newfoundland by ICP-MS, using the Na₂O₂ sinter method (Longerich et al. 1990).

Table 3. U-Pb isotopic data for monzodiorite sample NB00-40 (sample location UTM 680400E, 4982650N; Grid Zone 19T).

Fraction (number of grains)	weight (mg) ¹	Total ¹ U (ng)	Total ¹ Pb (pg)	Total ¹ Com.Pb (pg)	U (ppm)	Pb (ppm)	Atomic Ratios										Ages (Ma)			
							$\frac{^{206}\text{Pb}^2}{^{204}\text{Pb}}$		$\frac{^{206}\text{Pb}^3}{^{238}\text{U}}$		$\frac{^{207}\text{Pb}^3}{^{235}\text{U}}$		$\frac{^{206}\text{Pb}}{^{238}\text{U}}$		$\frac{^{207}\text{Pb}}{^{235}\text{U}}$		$\frac{^{206}\text{Pb}}{^{238}\text{U}}$		$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	
							%	Error ⁴	%	Error ⁴	%	Error ⁴	%	Error ⁴	%	Error ⁴	%	Error ⁴		
largest brown metamict (1)	0.004	23.47	1502.4	2.30	5868	376	42394	11.475	0.06513	0.065	0.49980	0.089	0.05566	0.060	406.7	411.6	438.7	0.74		
medium clear prisms (2)	0.002	4.42	361.1	3.37	2208	181	5777	3.140	0.06909	0.156	0.53028	0.201	0.05566	0.127	430.7	432.0	439.0	0.77		
square prism fragments (2)	0.002	4.62	391.3	9.48	2312	196	2202	2.921	0.07027	0.158	0.53893	0.181	0.05562	0.088	437.8	437.7	437.3	0.88		
large prism (1)	0.003	4.64	393.1	2.69	1857	157	7725	2.867	0.06998	0.120	0.53609	0.145	0.05556	0.079	436.0	435.8	434.9	0.84		
smaller prism (1)	0.002	1.25	105.1	2.46	833	70	2280	2.920	0.06984	0.105	0.53537	0.185	0.05560	0.146	435.2	435.2	436.3	0.62		
medium clear prism (1)	0.002	2.13	176.7	3.71	1419	118	2571	3.100	0.06985	0.354	0.53549	0.368	0.05560	0.095	435.3	435.4	436.3	0.97		
large prism (1)	0.002	4.46	362.7	2.47	2229	181	8015	3.336	0.06970	0.085	0.53434	0.126	0.05560	0.093	434.3	434.7	436.6	0.67		
prism fragment (1)	0.002	5.32	419.7	2.88	2662	210	8169	3.746	0.06922	0.053	0.53039	0.076	0.05558	0.054	431.4	432.1	435.5	0.71		

Notes: 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 2 sigma. ⁵ Correlation coefficient of Ludwig (1989) for ²⁰⁷Pb/²³⁵U - ²⁰⁶Pb/²³⁸U.

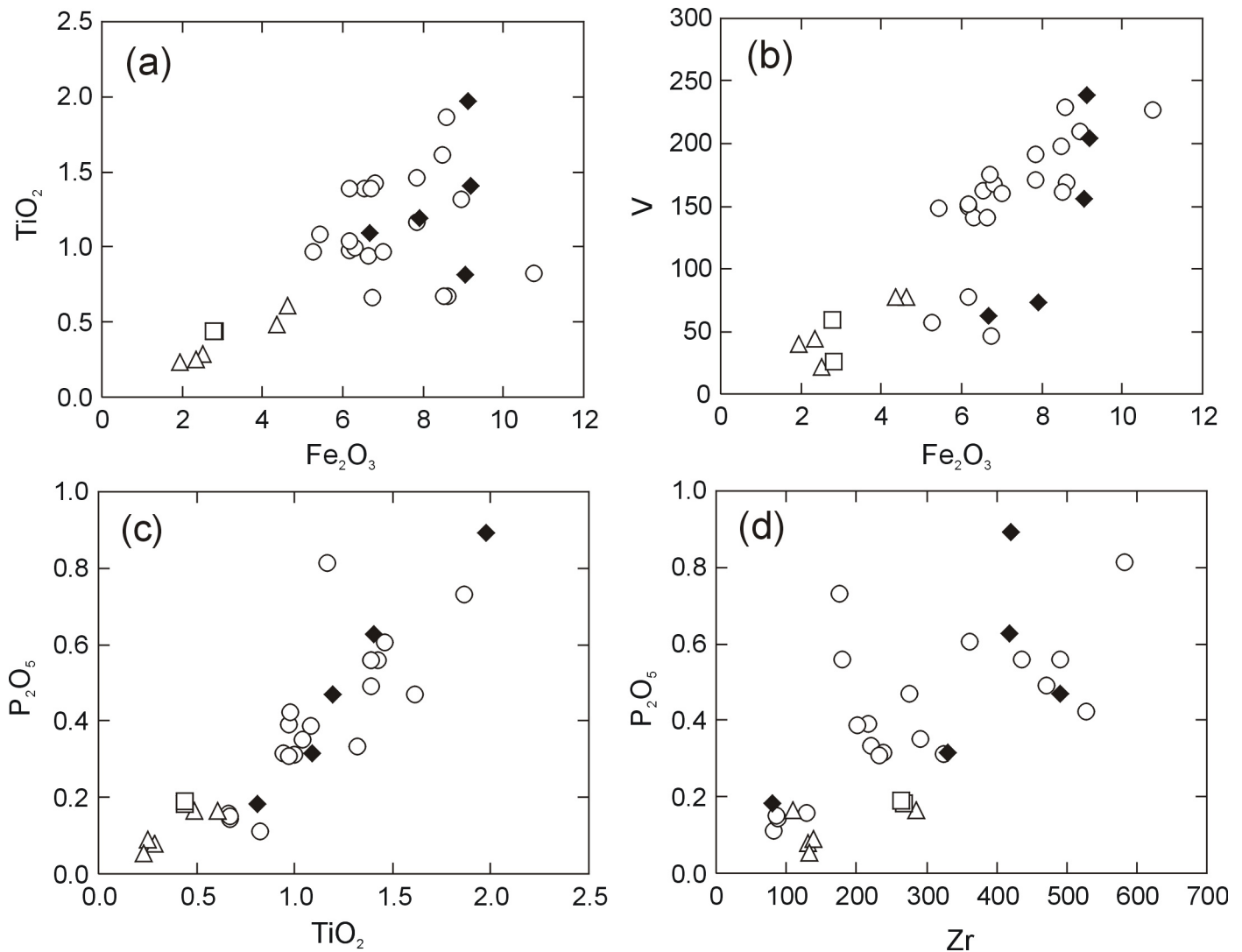


Fig. 9 Plots of (a) TiO_2 - Fe_2O_3 , (b) V - Fe_2O_3 , (c) P_2O_5 - TiO_2 , and (d) P_2O_5 - Zr to illustrate chemical trends in The Wolves Pluton.

and hence the terrane seems unlikely to generate rocks with the positive epsilon Nd values like those measured in samples from The Wolves Pluton (Fig. 13).

The Caledonia terrane in southern New Brunswick, part of Avalonia (Hibbard *et al.* 2006), also includes abundant granitoid rocks (Barr and White 1999; Barr *et al.* 2003b). However, their ages of ca. 620 and ca. 550 Ma are too old to be directly related to The Wolves Pluton. No plutons with ages of ca. 436 Ma are known in Caledonia terrane, or in the Cobequid Highlands of northern mainland Nova Scotia, which is also part of Avalonia (e.g., Pe-Piper and Piper 2002). Interpretations of seismic reflection profiles in the Bay of Fundy in the vicinity of The Wolves place the islands well to the north of the normal fault system that separates Meguma terrane rocks from Avalonia (e.g., Wade *et al.* 1996; Keen *et al.* 1991). In any case, the age and petrological characteristics of The Wolves Pluton are not compatible with an origin in crust of the Meguma terrane, which has yielded mainly peraluminous granitoid rocks (e.g., Clarke *et al.* 1997).

In terms of age, The Wolves Pluton is a good match with volcanic and plutonic rocks of the Kingston terrane, which have yielded ages of 442–435 Ma (Barr *et al.* 2002). This narrow fault-bounded belt of Silurian calc-alkaline rocks has been interpreted to represent a continental-margin arc terrane formed on the Ganderian New River terrane. According to Barr *et al.* (2002), subduction in the Kingston arc culminated in a collision between the New River terrane and the Brookville terrane, and an ensuing extensional setting in the Late Silurian, related to transpressive motion, resulted in the emplacement of abundant tholeiitic mafic dykes.

Although of similar age, the Kingston terrane rocks are not similar petrologically to The Wolves Pluton. Plutonic rocks in the Kingston terrane are mainly fine-grained aphyric to porphyritic granite with granophyric textures and other features indicative of high-level emplacement, and they are intimately associated with co-magmatic, mainly felsic, pyroclastic rocks (Barr *et al.* 2002). These rocks are markedly different from the medium- to coarse-grained rocks on The Wolves, none

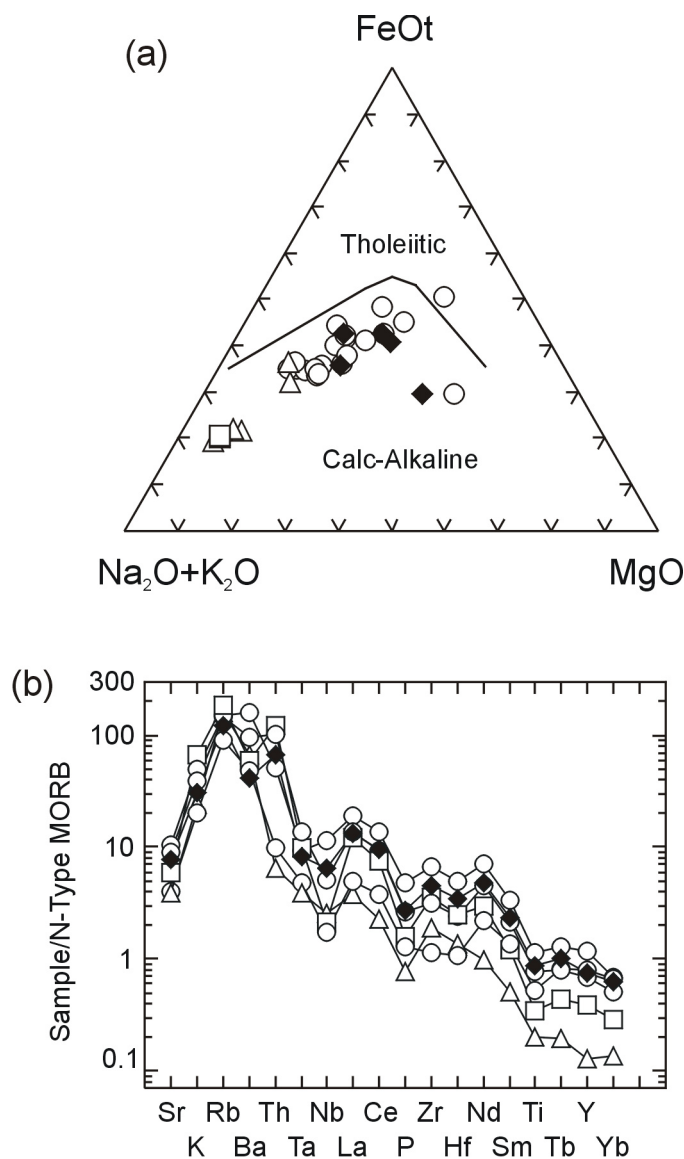


Fig. 10 (a) AFM ternary diagram (tholeiitic-calc-alkaline dividing line from Irvine and Baragar 1971), and (b) multi-element variation diagram for selected samples, normalized against N-MORB (normalizing values from Sun and McDonough 1989).

of which is granite *sensu stricto*. However, minor medium- to coarse-grained monzodiorite and diorite occur near the margins of two of the plutons in the Kingston terrane (Barr *et al.* 2002), and it is possible that the granitoid rocks on The Wolves represent deeper parts of the Kingston arc. If so, The Wolves escaped much of the pervasive mafic dyke-emplacment event that characterizes the Kingston terrane, as well as subsequent deformation and accompanying amphibolite-facies metamorphism (Barr *et al.* 2002). However, evidence for that metamorphic event is less pronounced in the southwestern part of the terrane on Campobello Island (McLeod and Rast 1988; McLeod *et al.* 2001). Samples from both the Kingston

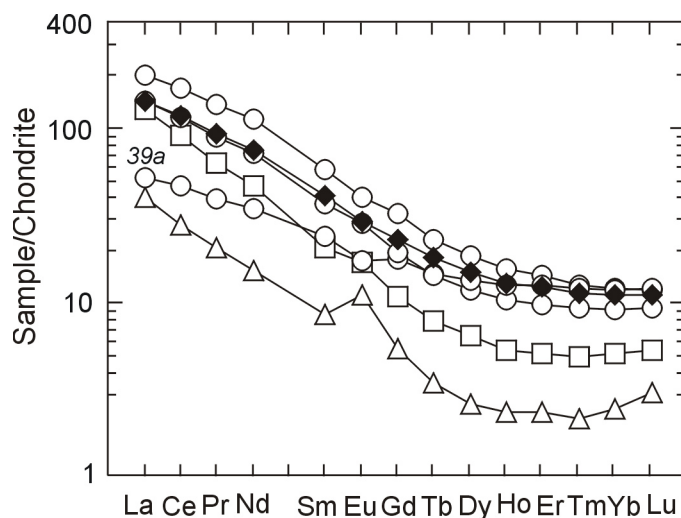


Fig. 11 Chondrite-normalized REE diagrams samples from The Wolves Pluton. Data are from Table 2. Chondrite-normalizing values are from Sun and McDonough (1989).

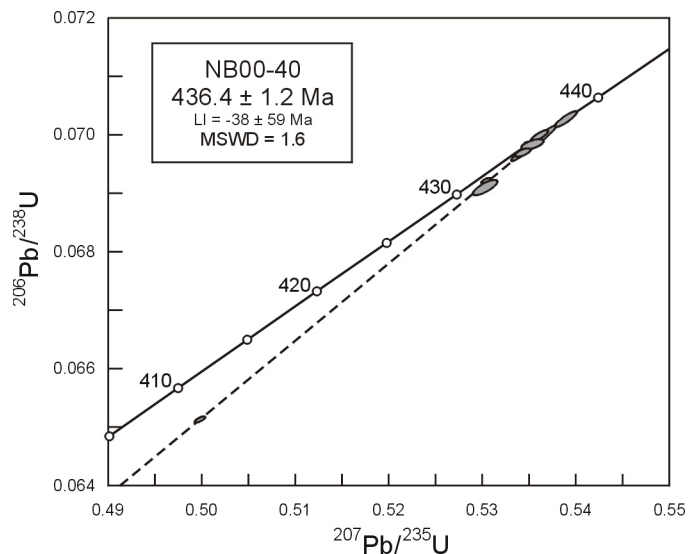


Fig. 12 Concordia diagram for dated sample NB00-40. LI is the lower intercept of the regression line with Concordia. Data are from Table 3.

terrane and The Wolves Pluton are characterized by similar positive ϵ_{Nd} values between 2.5 and 4 (Fig. 13). Furthermore, a prominent magnetic signature is characteristic of the Kingston terrane (e.g., King and Barr 2004), an attribute also associated with The Wolves.

Volcanic rocks of early Silurian age are also present in the more inboard Mascarene terrane in southern New Brunswick (Fyffe *et al.* 1999; Miller and Fyffe 2002). However, they are mainly rift-related rhyolite and no plutonic rocks of similar age are known in the area; their distance from The Wolves also makes a direct link unlikely. Plutonic rocks make up much of the Coastal Maine Magmatic Province and continue into south-

Table 4. Sm-Nd isotopic data for samples from The Wolves Pluton.

Sample	Age (t)	Nd (ppm)	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2 sigma	$\epsilon_{\text{Nd}(0)}$	$\epsilon_{\text{Nd}(t)}$	$T_{(\text{DM})}$
Monzodiorite (NB00-40)	436	32.10	5.448	0.1026	0.512563	0.000006	-1.5	3.8	671
Quartz monzonite (HW04-02)	436	22.38	3.417	0.0923	0.512520	0.000010	-2.3	3.6	642
Tonalite (HW05-19)	436	7.378	1.389	0.1138	0.512539	0.000006	-1.9	2.7	779

Notes: Sm and Nd concentrations and Nd isotopic compositions were analyzed at Université du Québec à Montréal (NB00-40) or at Memorial University of Newfoundland (HW04-02,19). Errors on Nd isotopic compositions are <0.002% and errors on the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio are estimated to be lower than 0.1%. The epsilon Nd values are calculated using $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ values for the present day chondrite uniform reservoir (CHUR). ^{147}Sm decay constant is 6.54 10⁻¹² y⁻¹ (Steiger and Jäger 1977), $T_{(\text{DM})}$ is calculated with respect to the DePaolo (1988) mantle model.

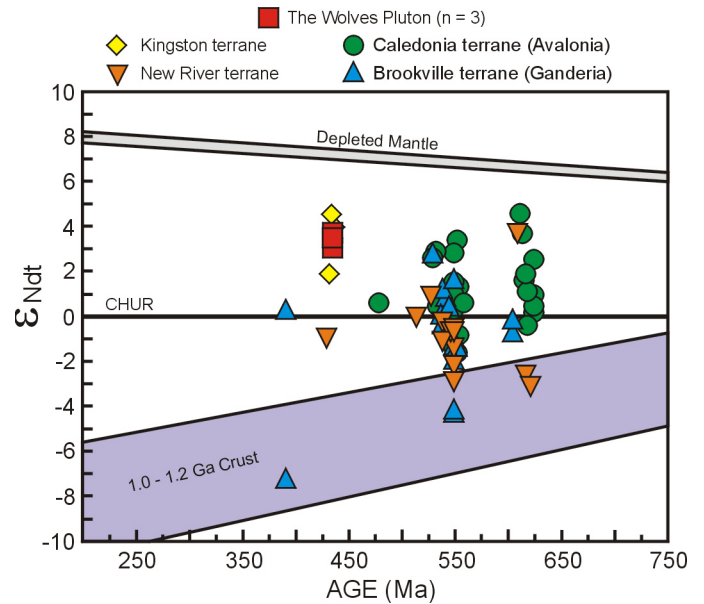


Fig. 13 Epsilon Nd data (calculated at 436 Ma) plotted against unit age. Data are from Samson *et al.* (2000), Barr *et al.* (2003b), and Table 4.

ern New Brunswick as the Saint George Batholith (Fig. 1), but they are Late Silurian to Devonian in age (Hogan and Sinha 1989; McLaughlin *et al.* 2003). The Early Silurian (436 Ma) age of The Wolves Pluton precludes a direct link with those voluminous plutons, the oldest of which seems to be ca. 425 Ma.

Looking farther offshore for possible correlations, Grand Manan Island to the south of The Wolves consists mainly of Mesozoic rocks. Plutonic rocks are only a minor component, and all that are exposed have been dated and yielded Neoproterozoic to early Cambrian ages (Miller *et al.* in press). Associated volcanic and sedimentary rocks have a similar age range, and it is not clear that any Silurian rocks are present on Grand Manan Island.

In summary, granitoid rocks on The Wolves appear to be geological orphans that have no directly correlative rocks in adjacent land areas. Based on the arguments presented above, the best correlation seems to be with the Kingston terrane. Assignment of The Wolves Pluton to the Kingston terrane implies apparent sinistral offset of the terrane to the southeast by 5–10 km relative to its position on the mainland (Fig. 14). Magnetic coverage in the critical areas is limited, but reveals some evidence for an east-trending structure that could be a fault (Fig. 14). This fault may also offset other terrane-bounding faults (Belleisle, Kennebecasis, Caledonia, Cobequid-Chedabucto), and could be one of a series of faults that offset southern New Brunswick terranes and terrane boundaries outboard to beyond Grand Manan Island (e.g., McCutcheon and Robinson 1987; Hibbard *et al.* 2006). This interpretation is consistent with the proposed correlation of rocks on Grand Manan Island with the New River and Mascarene terranes (Miller *et al.* in press). However, it is difficult to reconcile with the apparent continuity of the Kingston terrane through

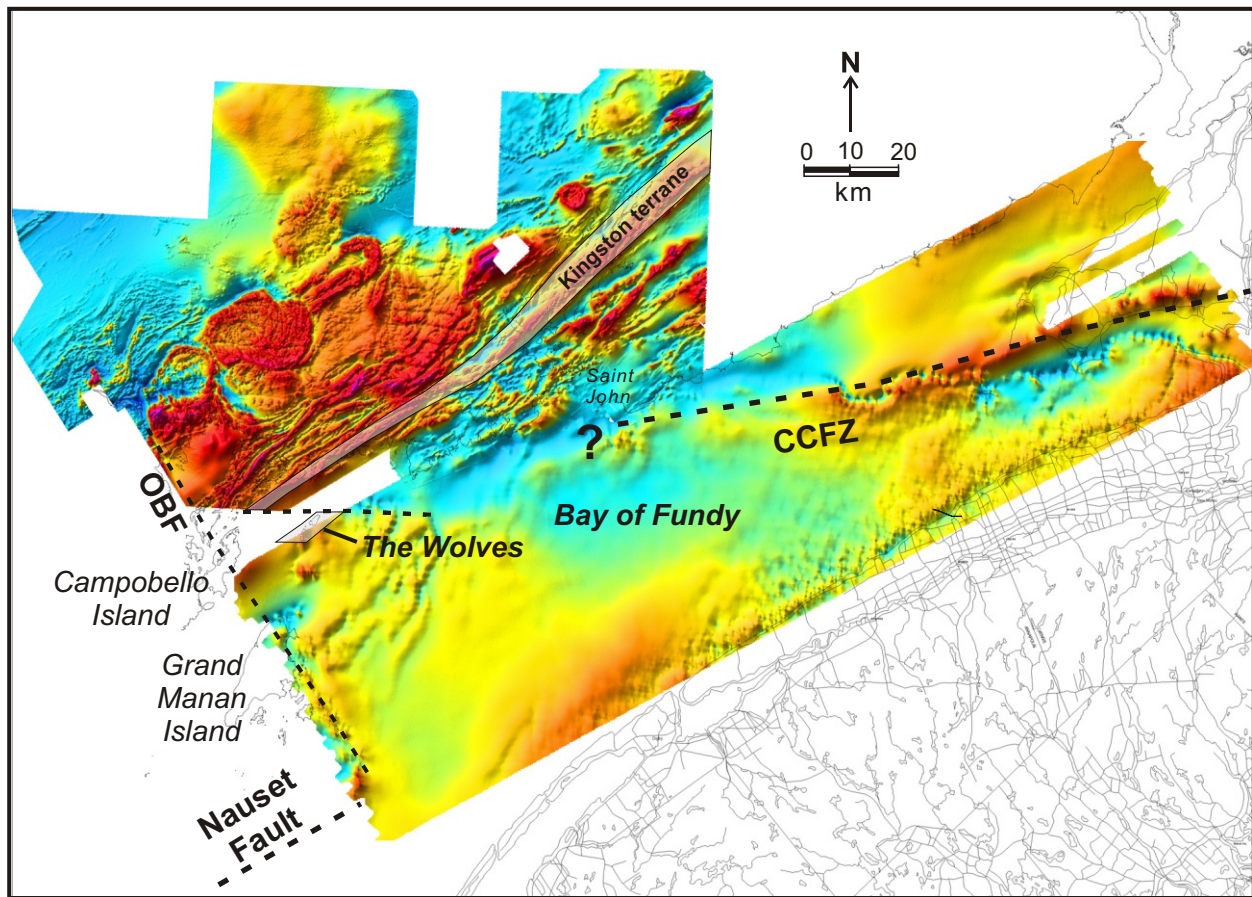


Fig. 14 Magnetic total field map of data from onshore and offshore magnetic surveys in the Bay of Fundy area, as compiled by M.S. King (unpublished data, 2005). The area shown is approximately the same as in Figure 1. The postulated east-trending fault between The Wolves and the onshore Kingston terrane (shaded) is indicated by the black dashed line north of The Wolves. Abbreviations: CCFZ, Cobequid-Chedabucto Fault Zone; OBF, Oak Bay Fault. The Nauset Fault marks the inferred boundary between Avalonia and Meguma (Hutchinson *et al.* 1988; Hibbard *et al.* 2006).

Campobello Island and into Maine (McLeod and Rast 1988; McLeod *et al.* 2001). The geological enigmas associated with these terrane boundaries might be resolved by more detailed aeromagnetic data in the western Bay of Fundy between The Wolves, Grand Manan Island, and the mainland.

ters by a fault trending approximately east-west with apparent sinistral offset. Other terranes and terrane-bounding faults in the western part of the Bay of Fundy may be similarly offset, as part of a series of offsets stepping southern New Brunswick terranes outboard to Grand Manan Island and beyond.

CONCLUSIONS

The Wolves Pluton is composed mainly of monzodiorite gradational to diorite, quartz diorite, and quartz monzodiorite, with minor units of tonalite and quartz monzonite. Dioritic to monzodioritic xenoliths are mineralogically and chemically similar to the monzodiorite unit, and are interpreted to represent a deeper, less evolved part of the pluton. The Wolves Pluton has relatively high magnetic susceptibility and likely coincides in extent with a positive magnetic anomaly, suggesting that the pluton has an area of about 75 km². The pluton is calc-alkalic and likely formed in a volcanic-arc setting. It may be a deeper part of the Silurian Kingston arc, offset a few kilome-

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