Tectono-stratigraphic setting of the Moreton's Harbour Group and its implications for the evolution of the Laurentian margin: Notre Dame Bay, Newfoundland[1]

J.A. Cutts, A. Zagorevski, V. McNicoll, and S.D. Carr

Abstract: The Moreton's Harbour Group lies along the Red Indian Line, the fundamental Iapetus suture that separates rocks of peri-Laurentian affinity with rocks of peri-Gondwanan affinity in the Newfoundland Appalachians. Characterization of age and environment of formation of the Moreton's Harbour Group is an important constraint on evolution of the Laurentian margin during Ordovician closure of Iapetus Ocean and associated marginal basins. The Moreton's Harbour Group comprises a fault-bounded ophiolitic sequence of layered gabbro, sheeted diabase, pillow basalt, and felsic intrusive rocks. It is offset by high-angle shear zones that were contemporaneous with a 477.4 ± 0.4 Ma syn-tectonic and syn-magmatic suite of trondhjemite and tonalite. Trace element data from the felsic suite indicate formation in a supra-subduction zone setting, although isotopic data from the felsic intrusive rocks ($\varepsilon_{\mathrm{Nd}}$ (–5.02) to (–10.53), T_{dm} 1200–1800 Ma) indicate a significant amount of contamination from Mesoproterozoic or older continental crust. The age and tectonic setting of the Moreton's Harbour Group suggest that it is the northernmost extent of the ca. 480 Ma Annieopsquotch Ophiolite Belt. We present a model in which the Moreton's Harbour Group formed in response to propagation of the Annieopsquotch Ophiolite Belt spreading centre into the Dashwoods microcontinent. This ridge propagation model supports the formation of the Annieopsquotch Ophiolite Belt immediately outboard of Dashwoods and explains its rapid accretion to the composite Laurentian margin.

Résumé : Le Groupe de Moreton's Harbour est situé le long de la ligne Red Indian, la suture fondamentale Iapetus qui sépare les roches d'affinité péri-laurentienne des roches d'affinité péri- gondwanienne dans les Appalaches de Terre-Neuve. La caractérisation de l'âge et de l'environnement de formation du Groupe de Moreton's Harbour représente une contrainte importante pour l'évolution de la bordure de Laurentia durant la fermeture, à l'Ordovicien, de l'Océan Iapetus et des bassins marginaux associés. Le Groupe de Moreton's Harbour comprend une séquence ophiolitique de gabbro lité, de feuillets de diabase, de basaltes en coussins et de roches intrusives felsiques, limitée par des failles. La séquence est décalée par des zones de cisaillement à angle élevé qui étaient contemporaines d'une suite syntectonique et synmagmatique de trondhjémite et de tonalite âgée de 477,4 ± 0,4 Ma. Des données d'éléments traces de la suite felsique indiquent une formation dans un environnement de zone de supra-subduction, bien que les données isotopiques des roches intrusives felsiques (εNd (–5,02) à (–10,53), T_{dm} 1200–1800 Ma) indiquent une quantité significative de contamination à partir de la croûte continentale mésoprotérozoïque ou plus ancienne. Selon l'âge et l'environnement tectonique du Groupe de Moreton's Harbour, il s'agirait de l'étendue la plus septentrionale de la ceinture ophiolitique d'Annieopsquotch, ~480 Ma. Nous présentons un modèle dans lequel le Groupe de Moreton's Harbour s'est formé en réponse à une propagation de l'étalement de la ceinture ophiolitique d'Annieopsquotch au centre du microcontinent de Dashwoods. Ce modèle de propagation de la crête supporte la formation de la ceinture ophiolitique d'Annieopsquotch immédiatement au large de Dashwoods et explique son accrétion rapide à la bordure composite laurentienne.

[Traduit par la Rédaction]

Received 8 October 2010. Accepted 22 February 2011. Published at www.nrcresearchpress.com/cjes on 18 November 2011.

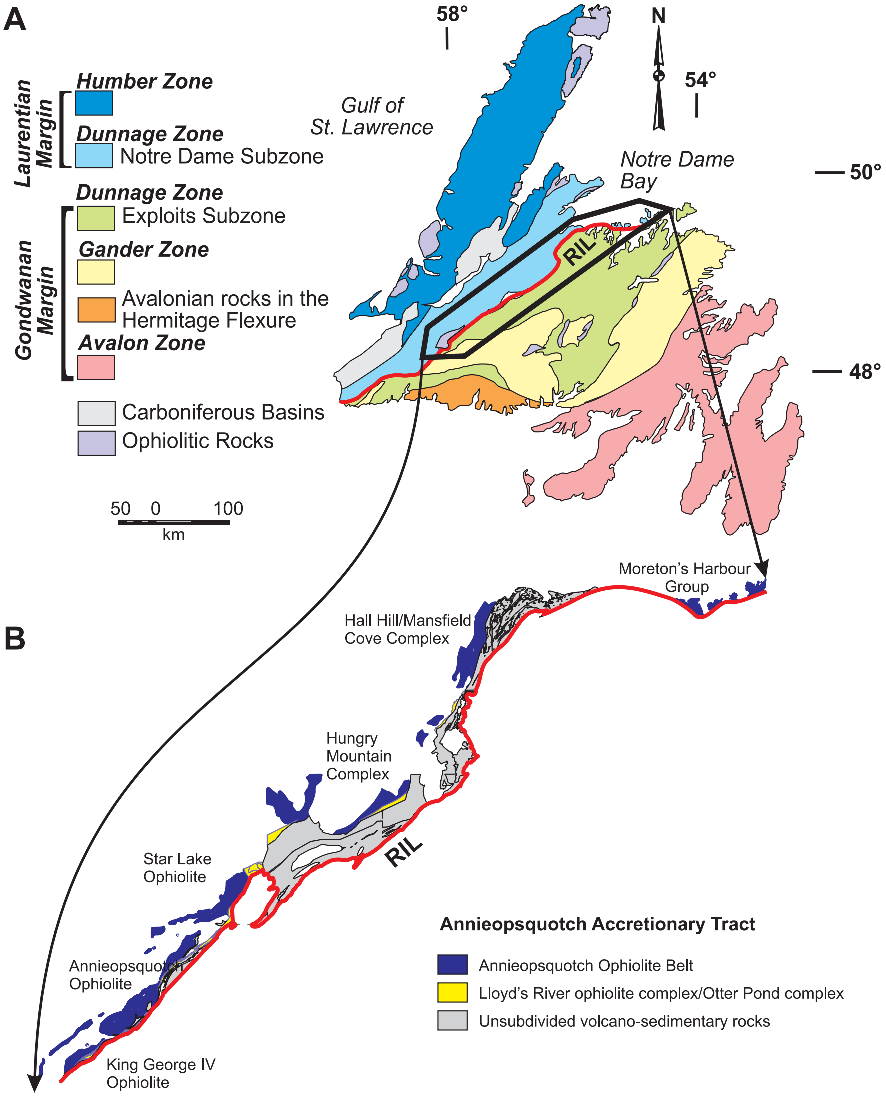
Paper handled by Associate Editor B. Murphy.

J.A. Cutts and S.D. Carr. Ottawa-Carleton Geoscience Centre, Department of Earth Sciences, Carleton University, 2125 Herzberg Building, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada.
A. Zagorevski and V. McNicoll. Geological Survey of Canada, 601 Booth St., Ottawa, ON K1A 0E8, Canada.

Corresponding author: J.A. Cutts (e-mail: jcutts@connect.carleton.ca).

[1] This article is one of a series of papers published in this *CJES Special Issue: In honour of Ward Neale* on the theme of Appalachian and Grenvillian geology.

Fig. 1. Generalized geology of the Red Indian Line region of the Newfoundland Appalachians. (A) Tectono-stratigraphic zones and subzones of Newfoundland (Modified after Williams 1995*a*; Williams 1995*b*). (B) The constituent elements of the Annieopsquotch Accretionary Tract (modified after Zagorevski et al. 2009). HMT, Hungry Mountain Thrust; LRF, Lloyd's River Fault; RIL, Red Indian Line.



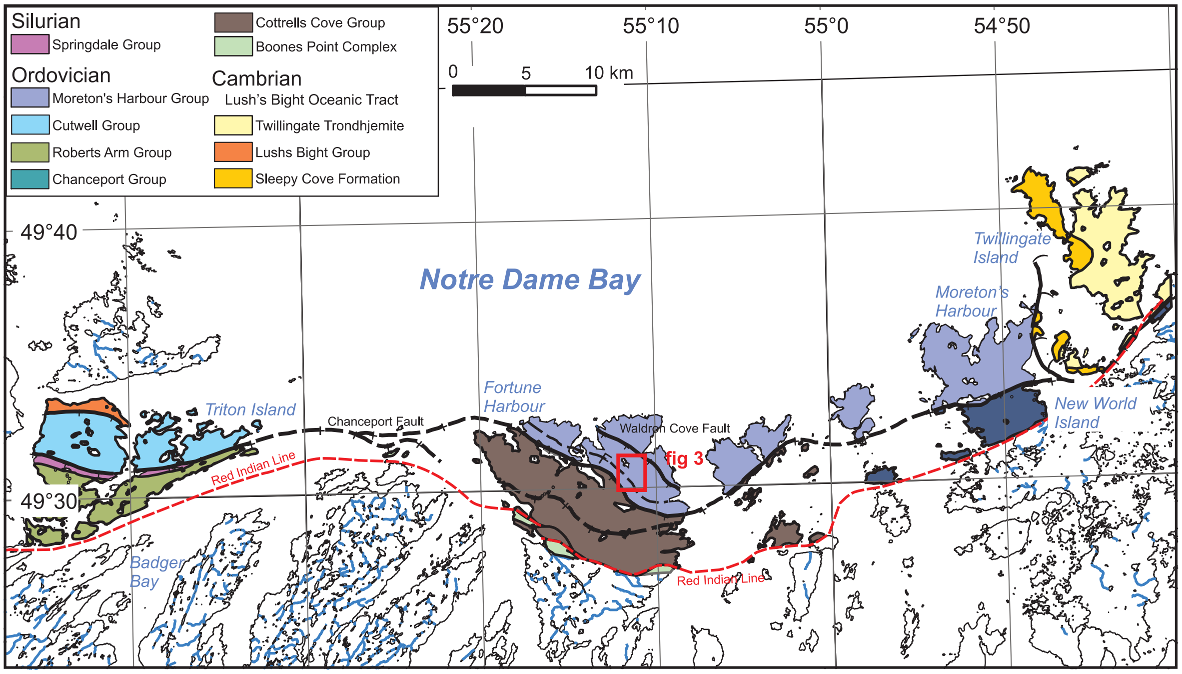
Introduction

The development of the allocthon as a model for the formation of the Appalachians (Rodgers and Neale 1963) was a major breakthrough in understanding Newfoundland geology. Since its development, an allocthton model has been the paradigm for the closure of the Iapetus, and related accretion of micro-continents, intra-oceanic and continental arcs, basins, and ophiolites (e.g., van Staal et al. 1998; Williams and Hatcher 1983, and references therein). Ophiolites commonly occur in proximity to major suture zones and are interpreted as remnants of oceanic crust separating crustal blocks; therefore, their study is essential to understanding the evolution of the Laurentian margin (van Staal et al. 1998). Being located at the northern end of the Iapetus suture in the Newfoundland Appalachians (Fig. 1), the ophiolitic rocks of the Moreton's Harbour Group occupy a key position for the understanding of the closure of Iapetus.

Owing to the proximity of ophiolites to continental margins or arcs during their formation and rapid accretion, the study of ophiolites provides important information on the evolution of these environments (Dilek 2003; Pearce 2003). Models of ophiolite formation have evolved significantly and they are now known to form in subduction initiation, pericollisional, and backarc settings (Bedard et al. 1998; Cawood and Suhr 1992; Dilek 2003; Harris 1992; Pearce 2003). Ophiolites are commonly associated with suites of felsic rocks that can provide constraints on the tectonic setting, age, and timing of accretion of the ophiolite sequences (e.g., Rollinson 2009).

Previous field work by O'Brien (2003*b*) and geochemical studies by Swinden (1996) demonstrated that the Moreton's Harbour Group formed in a supra-subduction zone oceanic setting. The paleo-latitude of the Moreton's Harbour Group (11° S) is indistinguishable from that of the Laurentian margin (Johnson et al. 1991); hence, understanding of the gene-

Fig. 2. Generalized geology of Notre Dame Bay highlighting units of the Notre Dame Subzone and demonstrating the proximity of the Moreton's Harbour Group to the Red Indian line (modified after O'Brien 2003*b*). Red box indicates the location of Fig. 3.



sis of the Moreton's Harbour Group will help constrain the tectonic evolution of the active Ordovician Laurentian margin. This study characterizes and constrains the age and origin of the Moreton's Harbour Group through detailed field mapping, U–Pb zircon geochronology, Sm/Nd isotope geochemistry and trace element geochemistry studies. We correlate the Moreton's Harbour Group with the northern-most extension of the Annieopsquotch Ophiolite Belt (Dunning 1981; Lissenberg et al. 2005*b*), the oldest and structurally highest component of the Annieopsquotch Accretionary Tract (Lissenberg et al. 2005*b*; van Staal et al. 1998). Furthermore, our data on felsic rocks in the Moreton's Harbour Group provides important spatial and temporal links between the formation of the Annieopsquotch Accretionary Tract and the Dashwoods microcontinent (Waldron and van Staal 2001).

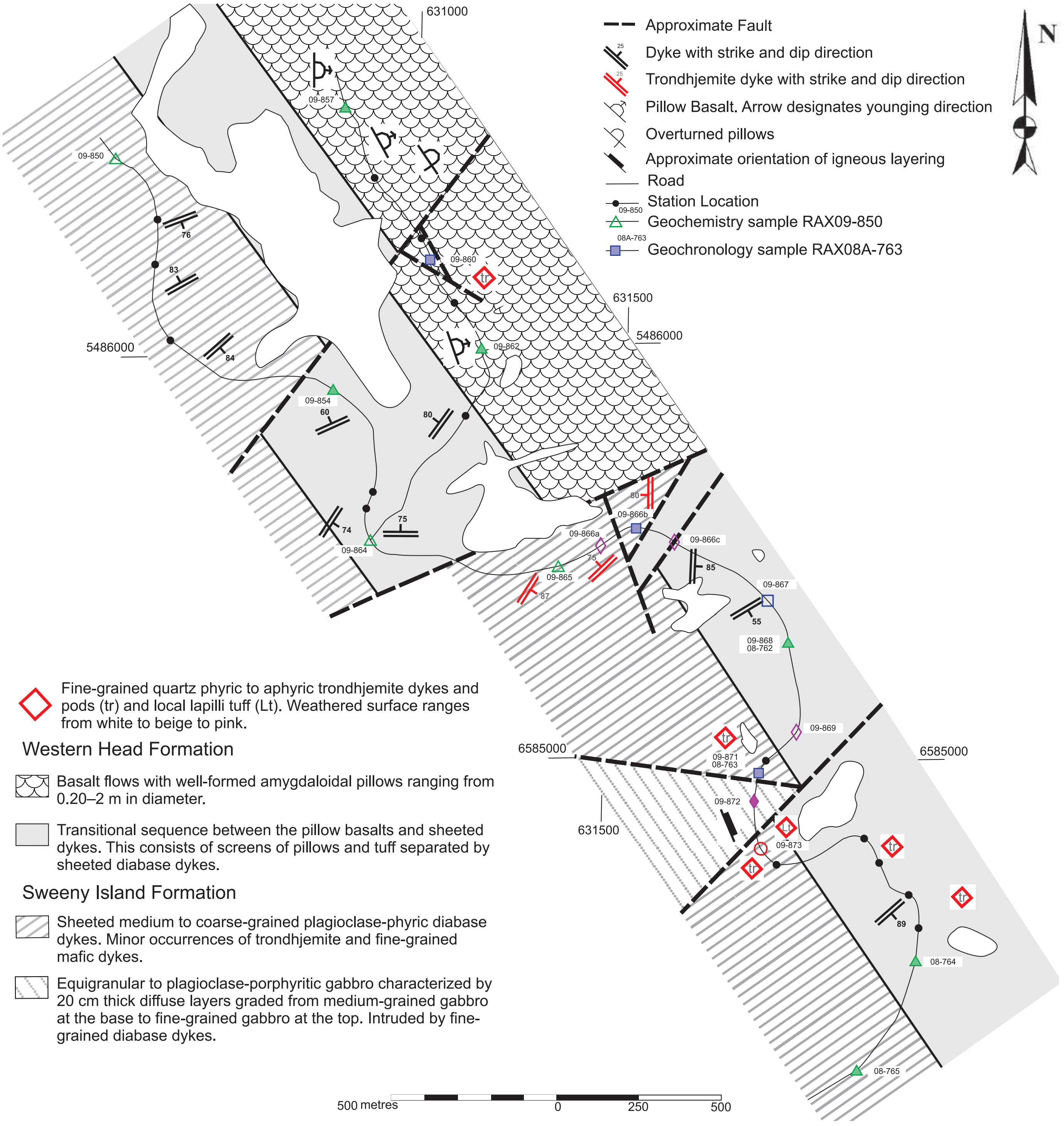
Geologic and tectonic setting

The Newfoundland Appalachians are subdivided into four zones on the basis of paleogeographic and geological histories (Williams 1995*a*; inset, Fig. 1). The study area is within the Dunnage zone that comprises oceanic arcs, continental arcs, back-arc basins, and ophiolites originating in the Iapetus Ocean (van Staal et al. 1998; Williams 1995*b*). The Dunnage Zone is further subdivided into the peri-Laurentian Notre Dame Subzone and the peri-Gondwanan Exploits Subzone, separated by the Red Indian Line, the principal Iapetus suture zone (Williams 1995*b*; Williams et al. 1988; Fig. 1). The Notre Dame Subzone encompasses volcanic and plutonic rocks of the Notre Dame Arc (van Staal et al. 2007; Whalen et al. 1997), ophiolites and arc–back-arc complexes (van Staal et al. 1998). These include the Lushs Bight Oceanic Tract, the Baie-Verte Oceanic Tract, and Annieopsquotch Accretionary Tract (van Staal et al. 1998).

Over the past 10 years, significant advances in understanding the evolution of the composite Laurentian margin in the Late Cambrian – Early Ordovician have placed the component elements in a modern tectonic context.

The Lushs Bight Oceanic Tract (Fig. 2) comprises lower to middle Cambrian (ca. 508–501 Ma: Szybinski 1995) ophiolitic rocks that formed in a marginal basin called the Humber Seaway (Waldron and van Staal 2001) that separated the peri-Laurentian Dashwoods microcontinent from Laurentia (Waldron and van Staal 2001). The obduction of the Lushs Bight Oceanic Tract onto Dashwoods represents the earliest period of orogenic activity identified in the Notre Dame Subzone and was followed by the formation of the ca. 489–484 Ma Baie-Verte Oceanic Tract (Cawood et al. 1996; Dunning and Krogh 1985). Closure of the Humber Seaway led to the formation of the Notre Dame Arc on the Dashwoods microcontinent (van Staal et al. 2007; Whalen et al. 1997). The collision of Dashwoods with Laurentia and obduction of the Baie-Verte Oceanic Tract culminated in subduction step-back into the main tract of the Iapetus. Initiation of west-dipping subduction outboard of the composite Laurentian margin (Lissenberg et al. 2005*a*, 2005*b*; Waldron and van Staal 2001) induced the multiple arc–back-arc complexes (ca. 480–460 Ma) that constitute the Annieopsquotch Accretionary Tract (Dunning and Krogh 1985; Lissenberg et al. 2005*a*, 2005*b*; Zagorevski et al. 2006; Fig. 1). The Annieopsquotch Accretionary Tract is an east-verging thrust stack of ophiolites, and arc–back-arc complexes (van Staal et al. 1998) that includes the Annieopsquotch Ophiolite Belt (King George IV, Annieopsquotch, and Star Lake ophiolites) and the Hall Hill/Mansfield Cove Complexes (Fig. 1B). Tectonic models put forward by Lissenberg et al. (2005*a*, 2005*b*) suggest that accretion of the Annieopsquotch Accretionary Tract

Fig. 3. Geology of the Moreton's Harbour Group locality on Fortune Harbour Peninsula, Notre Dame Bay, Newfoundland. Sample numbers are preceded by RAX in table, i.e., 08-857 = RAX08-857 and denoted by the geochemical symbol used in Figs. 6, 7, 8.

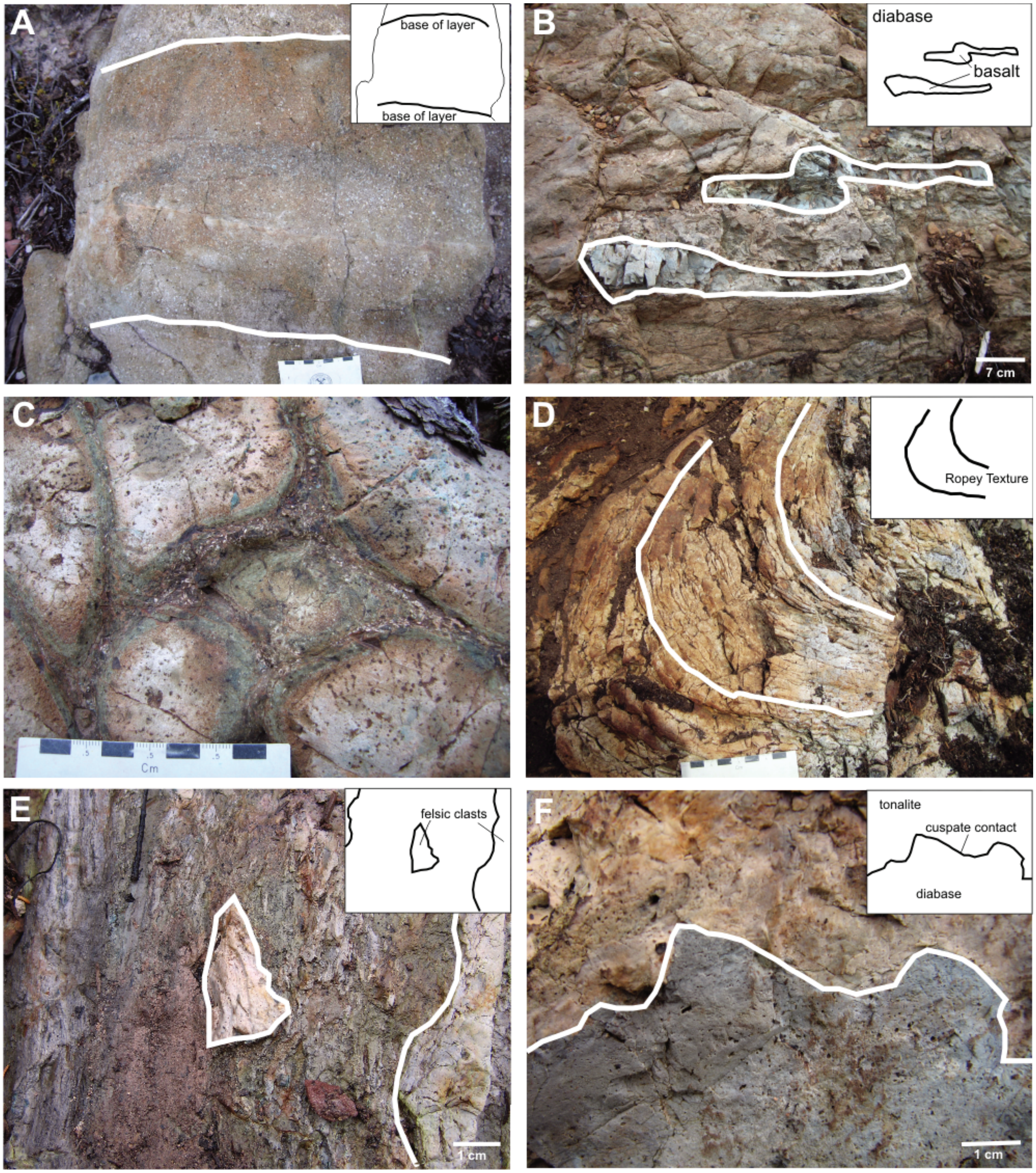


to the composite Laurentian margin occurred within 5–10 million years of its formation above a west-dipping subduction zone.

Recent studies have highlighted the geochemical dissimilarity between the boninitic rocks which characterize the Cambrian Lush's Bight Oceanic Tract and the tholeiitic rocks of the Moreton's Harbour Group (Swinden 1996). This geochemical dissimilarity with the Lushs Bight Oceanic Tract and a tectonic position for the Moreton's Harbour Group proximal to the Red Indian Line suggest the possibility of its inclusion in the Annieopsquotch Accretionary Tract (Zagorevski et al. 2006). This would place the Moreton's Harbour Group in a similar structural position as the Annieopsquotch Ophiolite Belt and Hall Hill complexes (Fig. 1B).

The Annieopsquotch Ophiolite Belt (477.5 +2.6/–2.0,

Fig. 4. Representative photographs of rocks from the Moreton's Harbour Group on Fortune Harbour Peninsula: (A) layered gabbro of the Sweeny Island Formation; (B) En-echelon tension gashes of basalt in diabase host; (C) well-preserved pillow basalts of the Western Head Formation; (D) "Ropy wrinkle" surface traction texture in the pillow basalts of the Western Head Formation; (E) Sheared trondhjemite clast aligned within a steep shear zone; (F) cuspate magma mingling contact between the chilled margin of a diabase dyke and a trondhjemite pod.



481 +4.0/–1.9 Ma, U/Pb zircon: Dunning and Krogh 1985) comprises three ophiolite massifs that share a common stratigraphy that includes gabbro sills with enclaves of boninitic troctolite, a sheeted dyke complex, and pillow basalt (Lissenberg et al. 2005*a*). The Annieopsquotch Ophiolite Belt has a tholeiitic suprasubduction-zone geochemical signature, although MORB like geochemistry is also seen in the upper pillow basalts (Lissenberg et al. 2005*a*).

Table 1. Sample RAX08A-763 U–Pb ID–TIMS analytical data.

							Isotopic Ratios [f]			
Fraction[a]	Description[b]	Wt. (µg)	U (ppm)	Pb (ppm)[c]	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$[d]	Pb (pg)[e]	$\frac{^{208}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	±1SE Abs	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
RAX08A-763 (Z9874)										
A1a (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, Nm1°, Pa 4.5 h	11	166	13	4880	2	0.12	0.60114	0.00079	0.07687
A2A (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, Nm1°, Pa 4.5 h	6	136	11	1536	3	0.14	0.60270	0.00113	0.07681
B1a (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, M1°, Pa 4.5 h	5	169	13	3628	1	0.13	0.60029	0.00088	0.07665
C1 (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, Nm1°, L12 h, Ca	8	109	8	2196	2	0.10	0.60277	0.00096	0.07702
C2 (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, Nm1°, L12 h, Ca	12	112	9	5170	1	0.12	0.60172	0.00079	0.07683
C3 (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, Nm1°, L12 h, Ca	6	113	9	3976	1	0.11	0.59964	0.00098	0.07687
C4 (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, Nm1°, L18 h, Ca	5	198	16	2921	1	0.15	0.60744	0.00101	0.07680
C5 (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, Nm1°, L18 h, Ca	5	192	15	3395	1	0.14	0.60151	0.00081	0.07681
C6 (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, Nm1°, L18 h, Ca	4	143	11	2160	1	0.13	0.60330	0.00103	0.07700

[a] Z, zircon. Number in brackets refers to the number of grains in the analysis.

[b] Fraction descriptions: Co, Colourless; Clr, Clear; Eu, Euhedral; Pr, Prismatic, rFr, Rare Fractures; –rIn, rare inclusions; Nm1°, non-magnetic@1.8A 1° SS; Pa, physically abraded, Ca, chemically abraded; L, leaching.

[c] Radiogenic Pb.

[d] Measured ratio, corrected for spike and fractionation.

[e] Total common Pb in analysis corrected for fractionation and spike.

[f] Corrected for blank Pb and U and common Pb, errors quoted are 1 sigma absolute; procedural blank values for this study ranged from <0.1- 0.1 pg for U and 1 pg for Pb; Pb blank isotopic composition is based on the analysis of procedural blanks; corrections for common Pb were made using Stacey–Kramers compositions.

[g] Correlation Coefficient.

[h] Corrected for blank and common Pb, errors quoted are 2σ in Ma.

Lissenberg et al. (2005*a*) correlated the Annieopsquotch Ophiolite Belt with the Hall Hill – Mansfield Cove complexes (Fig. 1B; 479 ± 3 Ma: Bostock 1988; Dunning et al. 1987). The Hall Hill complex comprises extensive sheeted diabase and screens of pillow basalt intruded by gabbro and the Mansfield Cove Complex diorite, tonalite, and granodiorite. Recent work indicates that the Hall Hill Complex is a composite lithostratigraphic unit containing components of both the Annieopsquotch Ophiolite Belt and the Lloyd's River ophiolite complex (c. 473 Ma: Zagorevski et al. 2006; Zagorevski and McNicoll, unpublished data).

Moreton's Harbour Group

The Moreton's Harbour Group is herein interpreted to represent an incomplete ophiolite sequence on the basis of a pseudo-stratigraphy primarily comprising cummulate gabbro, sheeted diabase dykes, and pillow basalts (Anonymous 1972; Dilek 2003). The Moreton's Harbour Group is located in Notre Dame Bay and extends along strike for 40 km from Fortune Harbour Peninsula to New World Island (Fig. 2). The geology of the Moreton's Harbour Group thus far has been based primarily on mapping that has been focussed on Fortune Harbour Peninsula (O'Brien 2003*a*). The Moreton's Harbour Group is generalized as being part of an oceanic crustal sequence comprising the mafic intrusive and hypabyssal rocks of the Sweeny Island Formation, and mafic volcanic rocks of the Western Head Formation (Dean and Strong 1977; O'Brien 2003*a*).

The study area is located on the northern tip of the Fortune Harbour Peninsula and contains steeply dipping, relatively undeformed volcanic, sedimentary and plutonic rocks that were metamorphosed at prehnite-pumpellyite facies conditions. These rocks occur in a fault-bounded panel, confined by the NW–SE striking, vertical Chanceport Fault to the south and the roughly parallel Waldron Cove Fault to the north (Fig. 2). Within this structural panel, the rocks are folded in an overturned, tight anticline that plunges gently to the southeast (Dean and Strong 1977; O'Brien 2003*a*). Faults within this structural panel strike approximately perpendicular to the Chanceport and Waldron Cove Faults and result in the fault blocks shown in Fig. 3. Rocks preserved in the study area include ~250 m of cumulate gabbro, ~500 m of sheeted diabase, ~500 m of diabase with screens of pillow breccia, and ~500 m of pillow basalt flows (Fig. 3).

Sweeny Island Formation

The Sweeny Island Formation (O'Brien 2003*a*) occurs at the base of the Moreton's Harbour Group and comprises

				Ages (Ma)[h]						
±1SE Abs	Corr. Coeff.[g]	$\frac{^{207}\mathrm{Pb}}{^{206}\mathrm{Pb}}$	±1SE Abs	$\frac{^{206}\mathrm{Pb}}{^{238}\mathrm{U}}$	±2SE	$\frac{^{207}\mathrm{Pb}}{^{235}\mathrm{U}}$	±2SE	$\frac{^{207}\mathrm{Pb}}{^{206}\mathrm{Pb}}$	± 2SE	%Disc.
0.00008	0.885	0.05672	0.00004	477.4	1.0	478.0	1.0	480.5	2.8	0.7
0.00008	0.781	0.05691	0.00007	477.1	1.0	478.9	1.4	488.0	5.4	2.3
0.00008	0.809	0.05680	0.00005	476.1	0.9	477.4	1.1	483.6	3.9	1.6
0.00009	0.754	0.05676	0.00006	478.3	1.1	479.0	1.2	482.1	4.6	0.8
0.00008	0.791	0.05680	0.00005	477.2	0.9	478.3	1.0	483.9	3.5	1.4
0.00012	0.779	0.05658	0.00006	477.4	1.4	477.0	1.2	475.2	4.6	–0.5
0.00010	0.720	0.05736	0.00007	477.0	1.2	481.9	1.3	505.5	5.1	5.8
0.00007	0.825	0.05680	0.00004	477.1	0.8	478.2	1.0	483.6	3.5	1.4
0.00008	0.734	0.05683	0.00007	478.2	1.0	479.3	1.3	484.8	5.2	1.4

equigranular cumulate gabbro and sheeted diabase dykes. The gabbro, which is exposed in one fault bounded block (Fig. 3), is cut by diabase dykes. The gabbro is clinopyroxene rich, plagioclase phyric and is characterized by repeating ~20 cm thick diffuse layers grading from medium-grained at the base to fine-grained at the top (Fig. 4A). The sheeted diabase is plagioclase-phyric, amygdaloidal, and displays subophitic intergrowths of plagioclase and clinopyroxene. In proximity to inferred faults, the diabase hosts en-echelon tension gashes filled with basalt, suggesting syn-kinematic emplacement (Fig. 4B).

Western Head Formation

The Western Head Formation (O'Brien 2003*a*) is predominantly composed of pillow basalt with lobes ranging from 0.2–2.0 m in diameter (Fig. 4C) and minor occurrences of jasperite, cross-bedded sandstone and mafic tuff. The basalt is characterized by the presence of prehnite/pumpellyite amygdules and subophitic intergrowths between plagioclase and acicular clinopyroxene. Plagioclase has a skeletal habit including "swallow tails". Jasperite is confined to inter-lobate regions of the pillow basalts. Cross-bedded sandstone was observed in one locality underlying a basalt flow displaying "ropy-wrinkle" texture at the base (Fig. 4D).

Trondhjemite-tonalite suite

The trondhjemite and tonalite dykes and pods of the Moreton's Harbour Group range between 0.1–3.0 m in thickness and are plagioclase rich with minor micro-lithic quartz. They are commonly flow banded, have a very granular weathered texture and are concentrated in or proximal to 1–2 m thick shear zones. These felsic dykes and pods primarily occur within one of the fault blocks in the study area (Fig. 3). The felsic dykes are commonly cross-cut by the shear zones and to be elongated and brecciated within the shear zones, although some dykes were observed to cut across the shear zone foliation (Fig. 4E). These relationships are interpreted to represent syn-tectonic emplacement of the felsic suite. Similarly, the felsic dykes cut across the sheeted diabase and were in turn cross-cut by them. Cuspate magma-mingling textures were observed between diabase and tonalite (Fig. 4F). These mutually cross-cutting relationships are interpreted as coeval emplacement of the felsic suite and the sheeted diabase.

U–Pb geochronology

A U–Pb geochronology study of a trondhjemite dyke (RAX08A-763) was conducted at the Geological Survey of

Fig. 5. (A) U/Pb concordia diagram with ID–TIMS zircon data obtained from trondhjemite dyke RAX08A-763. Error ellipses are displayed at the 2σ level. Shaded ellipses are fractions that underwent physical abrasion, and unfilled ellipses are fractions that underwent chemical abrasion. MSWD, mean square of weighted deviates. (B) CL and BSE–SEM images of zircons from the trondhjemite that show the euhedral morphology of the analyzed zircons and the preserved igneous zoning.

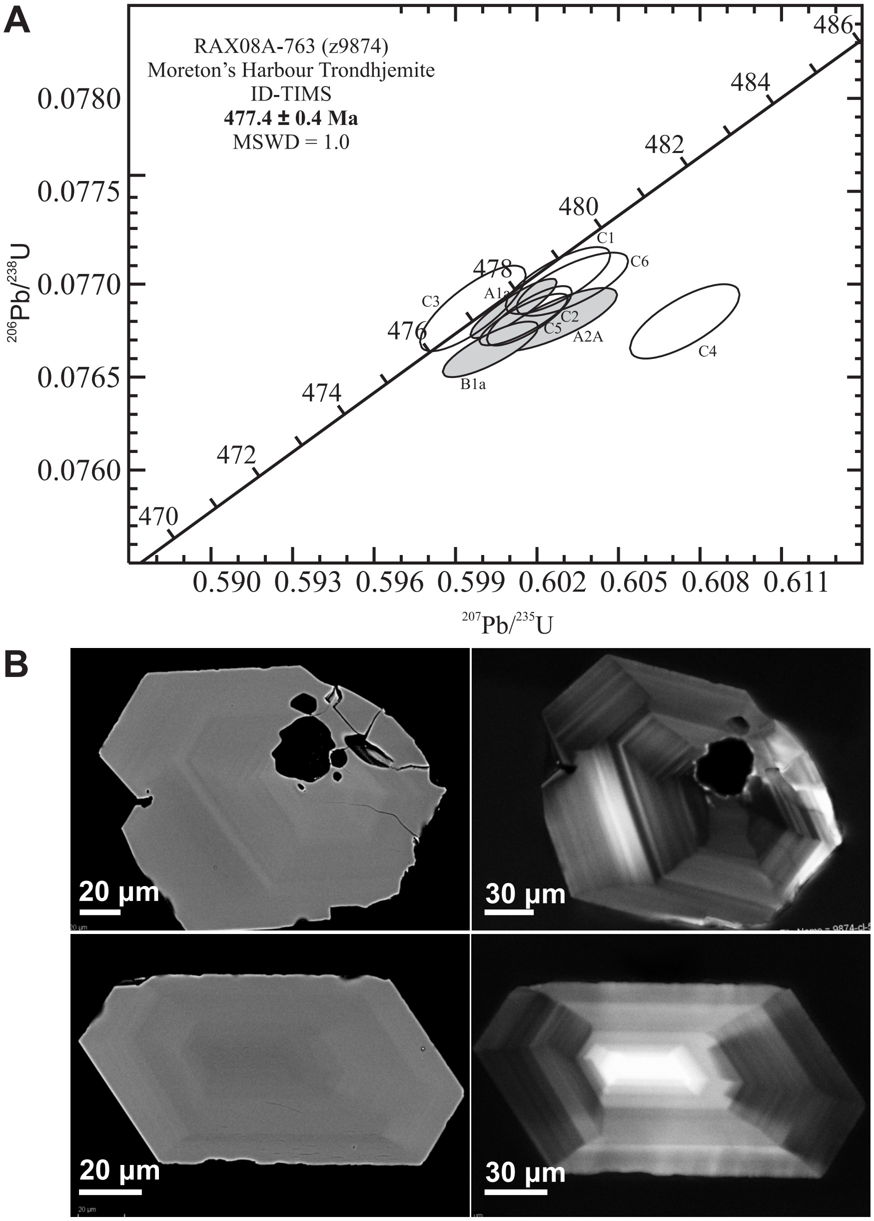


Table 2. Sm/Nd isoptopic data.

Sample	Rock Type	Age (Ma)	Nd*	Sm*	^{143}Nd/^{144}Nd	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd$_i$**	ε_{Nd} (t)	T_{dm}
RAX08A-763	Trondhjemite	477.4	22.55	5.78	0.512684	0.1551	0.512199	3.45	1114
RAX09-860	Trondhjemite	477.4	23.87	4.36	0.511966	0.1103	0.51162	–7.85	1686
RAX09-866A	Tonalite	477.4	33.28	5.74	0.511810	0.1043	0.511483	–10.53	1810
RAX09-866B	Trondhjemite	477.4	7.09	1.81	0.512436	0.1542	0.511953	–1.35	1728
RAX09-869	Tonalite	477.4	13.04	2.97	0.512197	0.1378	0.511765	–5.02	1832

*Concentration in ppm from isotope dilution.

**Calculated at age of formation.

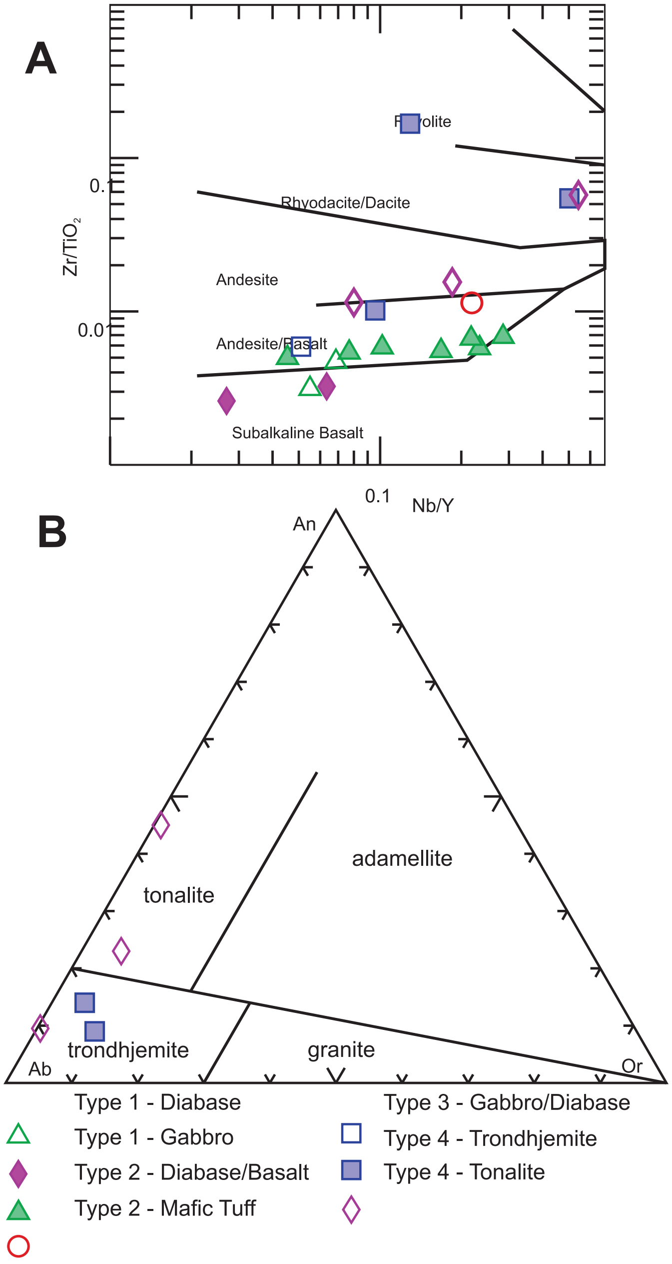


Fig. 6. (A) Zr/Ti_2O–Nb/Y rock discrimination diagram for volcanic rocks (Winchester and Floyd 1977) of the Moreton's Harbour Group on Fortune Harbour Peninsula (this study). (B) Rock discrimination diagram for felsic rocks (O'Connor 1965) of the Moreton's Harbour Group on Fortune Harbour Peninsula (this study). Ab, albite; An, anorthite; Or, orthoclase.

Canada in Ottawa, using isotope dilution – thermal ionization mass spectrometry (ID–TIMS). A heavy mineral concentrate was prepared using crushing, grinding, Wilfley™ table, and heavy liquid techniques, followed by sorting of the zircon by magnetic susceptibility using a Frantz™ isodynamic separator. Analyzed zircon underwent physical abrasion using methods after Krogh (1982) or chemical abrasion using methods modified after Mattinson (2005) to reduce discordance in U–Pb results (Table 1). U–Pb analytical techniques are modified after Parrish et al. (1987) with treatment of the analytical errors following Roddick et al. (1987). U–Pb ID–TIMS analyses are presented in Table 1, and plotted on a concordia diagram (Fig. 5) with errors at the 2σ level.

Trondhjemite dyke (RAX08A-763)

The geochronology sample was collected from a quartz phyric trondhjemite that intruded sheeted diabase of the Sweeny Island Formation (Fig. 3). The sample yielded a large population of gem-quality zircon grains that were mainly euhedral, well-faceted, clear, colourless and preserved their igneous zoning (Fig. 5). In total, nine single zircon grains were analyzed, three which were physically abraded and six that were chemically abraded (Table 1). Most of the analyses overlap, and the ages are interpreted as concordant or near-concordant. A weighted average $^{206}Pb/^{238}U$ age obtained from the seven most concordant analyses (<1.6% discordant, Table 1) is calculated to be 477.4 ± 0.4 Ma (mean square of weighted deviates (MSWD) = 1.0), which is interpreted as the crystallization age. Two discordant analyses (B2a, C4, 2.0% discordant, Table 1) are excluded in the age calculation.

Whole rock geochemistry

Major and trace elements were analyzed for 19 samples at ActLabs in Ancaster, Ontario, using the package "4lithores – Metaborate/Tetraborate Fusion – ICP/ICP–MS". ICP and ICP–MS data are presented in Appendix Table A1. Analyzed samples included two gabbros, five diabase, six pillow basalts, six felsic dykes, and one mafic tuff. In the study area, six principal geochemical types were identified through variations in the trace element geochemistry. Only those trace elements considered to be relatively immobile under normal sub- to greenschist-facies metamorphic and hydrothermal conditions were used to define the geochemical types (Pearce 1996). Sm/Nd isotopic compositions were also analyzed from trondhjemite and tonalite samples at Carleton University (Table 2).

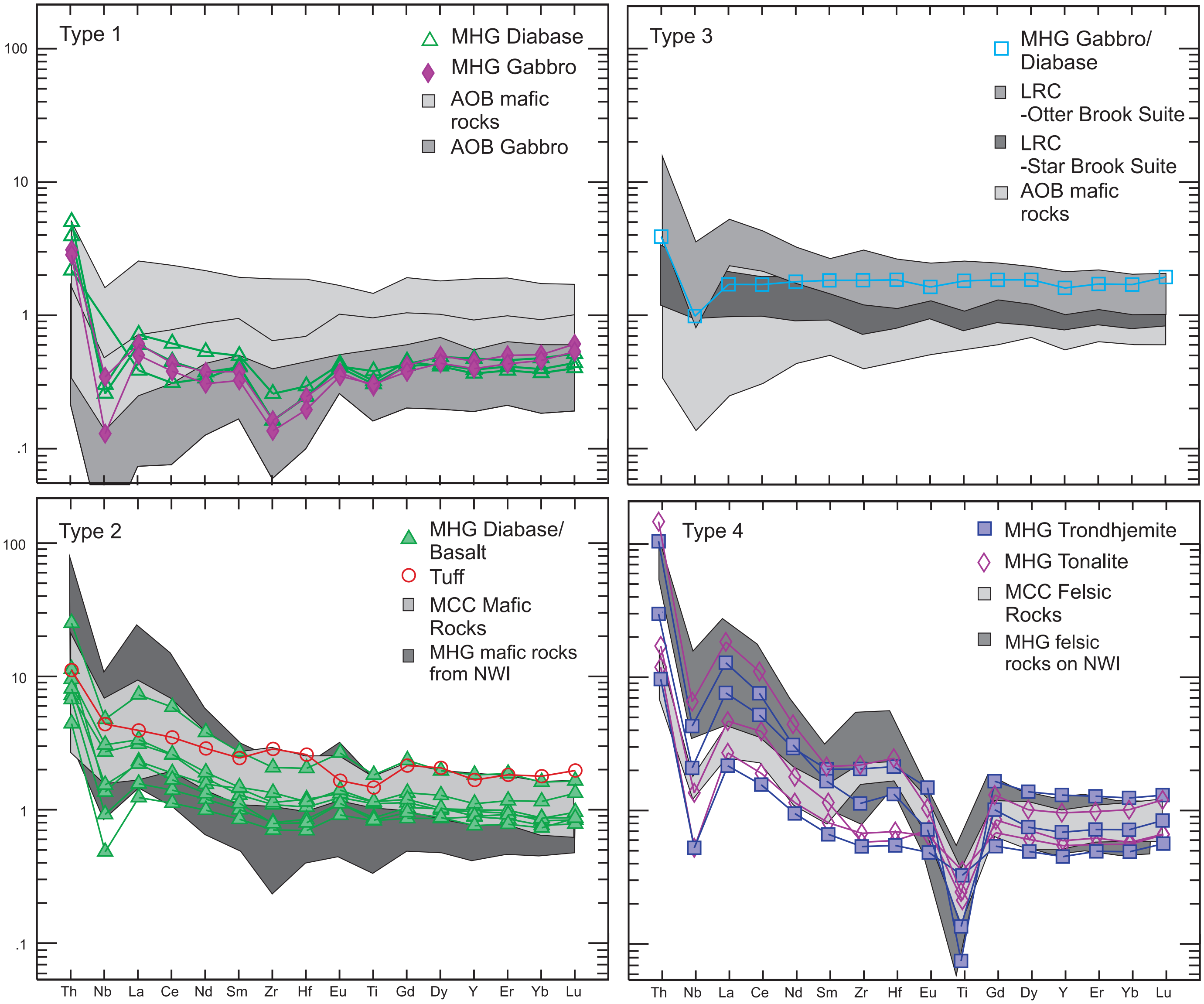
Type 1 – Depleted mafic rocks

Type 1 mafic rocks are represented by two diabase samples (RAX09–850, 864, 865) and two gabbro samples (RAX09–872a, 872b). They are characterized by high TiO_2 (0.3–0.4 wt.%) and plot in the andesite/basalt and subalkaline basalt field on the Winchester and Floyd (1977) rock discrimination plot (Fig. 6A). On an normal mid-ocean ridge (N-MORB) normalized extended trace element plot (Fig. 7) these samples are characterized by an overall depletion with respect to MORB with an enrichment in the light rare earth elements (LREE) (average La/Yb 1.08 not normalized), a strong enrichment in Th (average La/Th 3.53) and depletions in Nb (average La/Nb 2.78) and Zr (average La/Zr 0.11). Type 1 mafic rocks plot in the volcanic arc tholeiite (VAT) field on standard tectonic discrimination plots for mafic rocks (Fig. 8).

Type 2 – Island-arc tholeiite mafic rocks

Type 2 mafic rocks are represented by two diabase sample (RAX08A-765, RAX09-854), five pillow basalts (RAX08-762, 764, 766B, RAX09-857, 862), and one mafic tuff (RAX09-873). They are characterized by relatively high TiO_2 (1.0–2.2 wt.%) and plot in the andesite/basalt field on

Fig. 7. Extended trace element plots for the geochemical groups in this study (N-MORB normalization values and order from Sun and McDonough (1989); modified to exclude mobile trace elements). Shaded fields are gabbro, basalt/diabase dyke, and trondhjemite ranges from the Annieopsquotch Ophiolite Belt (AOB) and Lloyd's River Complex (LRC) (Lissenberg et al. 2004, 2005*a*); selected samples from the Mansfield Cove/Hall Hill Complex (MCC) (Zagorevski 2008); selected samples from the Moreton's Harbour Group on New World Island (MHG on NWI).



the Winchester and Floyd (1977) rock discrimination plot (Fig. 6A). On an N-MORB normalized extended trace element plot (Fig. 7) these samples are characterized by LREE enriched profiles (average La/Yb 2.34) with slight Nb depletion (average La/Nb 1.62).They plot in the VAT–BAB-continental field on standard tectonic discrimination plots for mafic rocks (Fig. 8A).

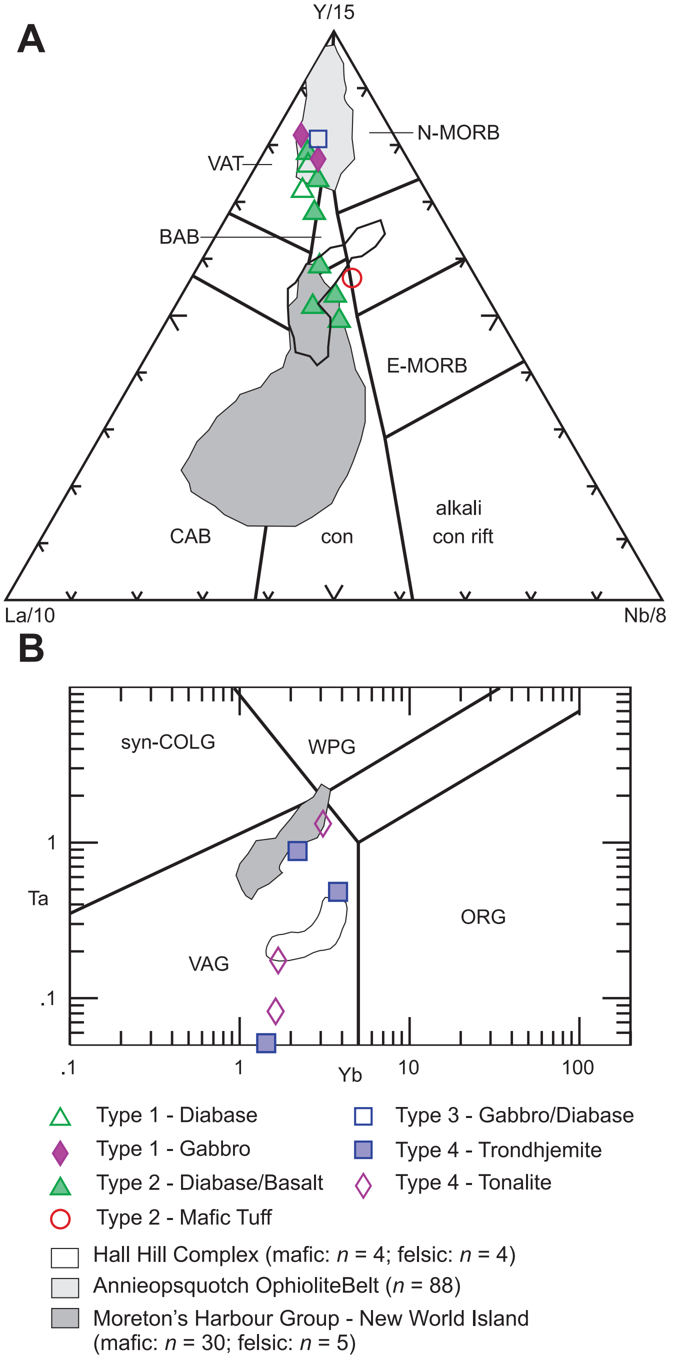
Type 3 – Diabase/gabbro

Type 3 is represented by a single sample of a diabase/gabbro (RAX09-867). It plots in the andesite/basalt field on the Winchester and Floyd (1977) rock discrimination diagram (Fig. 6A) and is characterized by relatively high TiO_2 (2.3 wt.%). On an N-MORB normalized extended trace element plot (Fig. 7) the sample is characterized by a relatively flat profile (La/Yb 0.82 that is slightly enriched with respect to MORB. The sample also shows enrichment in Th (La/Th 9.11) and depletion in Nb (La/Nb 1.86) and plots in the VAT field on standard tectonic discrimination diagrams for mafic rocks (Fig. 8A).

Type 4 – Felsic rocks

Type 4 felsic rocks are represented by three trondhjemite samples (RAX08-763, RAX09-860, 866B) and three tonalite samples (RAX09-866A, 866C, 869). They plot in the trondhjemite and tonalite fields, respectively, on the O'Connor

Fig. 8. (A) La/10-Y/15-Nb/8 tectonic setting discrimination diagram for mafic rocks (Cabanis and Lecolle 1989) of the Moreton's Harbour Group on Fortune Harbour Peninsula (this study), Moreton's Harbour Group on New World Island (Swinden 1996), Annieopsquoch Ophiolite Belt (Lissenberg et al. 2004, 2005*a*), and Hall Hill Complex (Zagorevski 2008). (B) Ta–Yb discrimination diagram (Pearce et al. 1984) for felsic rocks of the Moreton's Harbour Group on Fortune Harbour Peninsula. BAB, backarc basalt; CAB, calc-alkaline basalt; E-MORB, enriched mid-ocean-ridge basalt; N-MORB, normal mid-ocean-ridge basalt; ORG, ocean-ridge granite; syn-COLG, syn-collisional granite; VAG,- volcanic arc granite; VAT, volcanic arc tholeiite; WPG, within-plate granite.



(1965) discrimination plot for felsic rocks (Fig. 6B). On a N-MORB normalized extended trace element plot (Fig. 7), the samples are characterized by strong LREE enrichment (average La/Yb 8.14) and depletions in Nb (average La/Nb 3.97) and Ti (0.1–0.4 wt.%). These samples yielded primitive to strongly contaminated εNd values ranging from 3.45 to –10.53 and plot in the VAG field on standard tectonic discrimination plots for felsic rocks (Fig. 8B).

Discussion

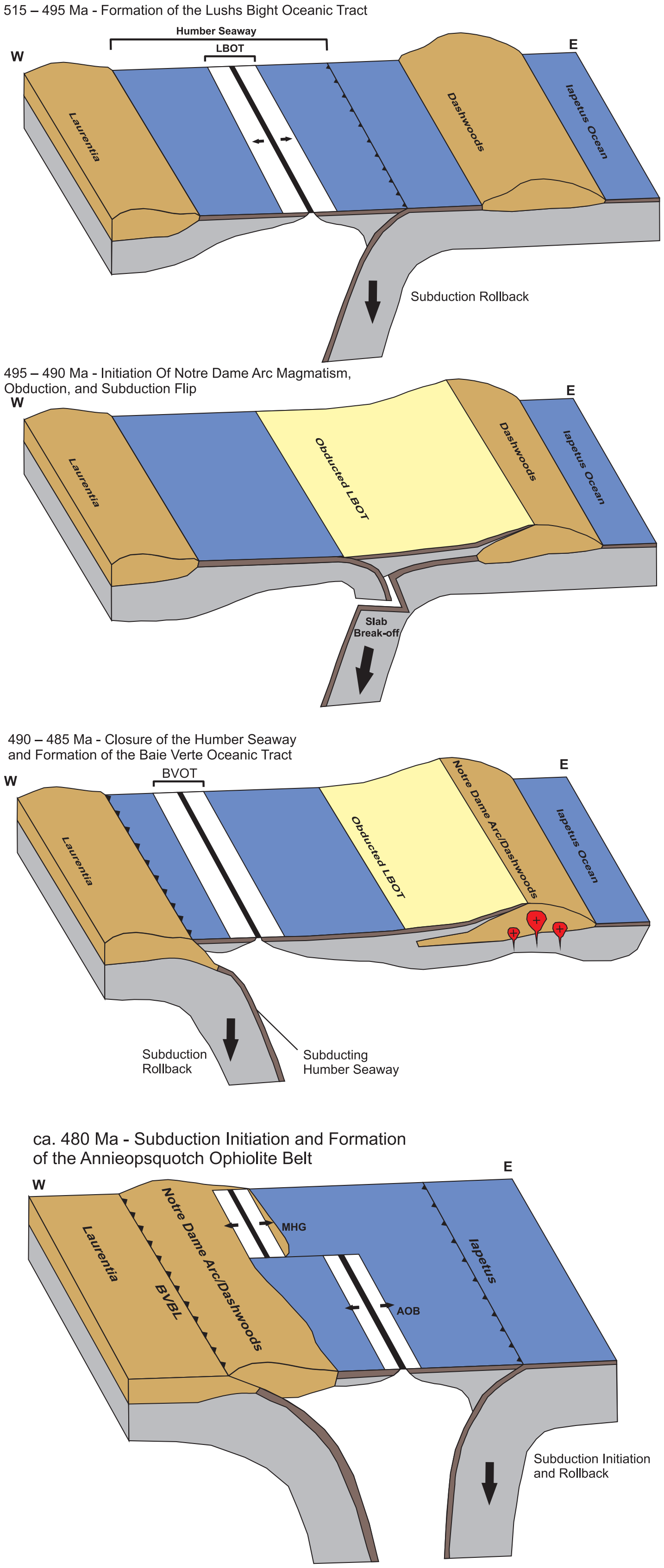
The field relationships between the felsic plutonic rocks, diabase dykes and shear zones indicate that the dated trondhjemite dyke was syn-magmatic with respect to ophiolite formation and thus its 477.4 ± 0.4 Ma crystallization age is taken to represent the age of the Moreton's Harbour Group. The four principal geochemical types of the Moreton's Harbour Group have distinct trace element geochemical profiles. Field evidence of cross-cutting relationships between the various magma-suites is lacking and relative age between the geochemical types is not apparent. In general, the trace element profiles of mafic rocks show enrichment in LREE and Th, with prominent depletions in Nb (Fig. 7). This suggests that the magmas have been influenced by both enriched mantle and a subduction component. This is consistent with formation of a nascent arc in a back-arc tectonic setting typical of supra-subduction zone ophiolites. One sample of trondhjemite has juvenile isotopic characteristics ($\varepsilon_{\mathrm{Nd}}$ + 3.45) consistent with the primitive nature of the ophiolites and intra-oceanic island arcs (Swinden et al. 1997). Other felsic rocks have highly contaminated isotopic signatures ($\varepsilon_{\mathrm{Nd}}$ –1.35 to –10.53) indicative modest to significant involvement of Mesoproterozoic ($T_{\mathrm{d/m}}$ 1200–1800 Ma) or older continental crust in their genesis.

Comparison of the Moreton's Harbour Group to other ophiolites

The ca. 477 Ma Moreton's Harbour Group is coeval with other ophiolitic units that formed along the composite Laurentian margin, including the ca. 480 Ma Annieopsquotch Ophiolite Belt (477.5 +2.6/–2.0, 481 +4.0/–1.9 Ma: Dunning and Krogh 1985) and the 479 ± 3 Ma Hall Hill – Mansfield Cove complexes (Dunning et al. 1987). The Annieopsquotch Ophiolite Belt and Hall Hill Complex are interpreted to have formed in a nascent arc setting following initiation of subduction and consequent back-arc extension (Lissenberg et al. 2005*a*, 2005*b*). This tectonic setting is consistent with the Moreton's Harbour Group geochemical data (this study; Swinden 1996). Given the similar structural position, age of formation and tectonic setting of the Annieopsquotch Ophiolite Belt, Mansfield Cove/Hall Hill Complex, and the Moreton's Harbour Group, we conclude that they are correlative with each other.

Lissenberg et al. (2005*a*, 2005*b*) proposed that the Annieopsquotch Ophiolite Belt formed close to the Dashwoods margin and was rapidly accreted (5–10 million years after formation). Paleomagnetic data presented by Johnson et al. (1991) places the Moreton's Harbour Group at 11° S during formation, which is consistent with the position of the composite Laurentian margin at the time (van Staal et al. 1998). Given the Moreton's Harbour Group association with the An-

Fig. 9. Tectonic model for the formation of the Moreton’s Harbour Group and the Annieopsquotch Ophiolite Belt where the spreading centre propagates onto Dashwoods continental crust (Modified after Lissenberg et al. 2005*a*; van Staal et al. 1998; Zagorevski and Van Staal in press). AOB, Annieopsquotch Ophiolite Belt; BVBL, Baie-Verte-Brompton Line; BVOT, Baie-Verte Oceanic Tract; LBOT, Lushs Bight Oceanic Tract; MHG, Moreton’s Harbour Group.



nieopsquotch Ophiolite Belt, this suggests the Annieopsquotch Ophiolite Belt formed in proximity to the composite Laurentian margin and by inference that the Newfoundland portion of the Humber Seaway was closed and the Dashwoods ribbon microcontinent (Waldron and van Staal 2001) was already accreted to Laurentia by ca. 477 Ma.

Along Strike Variations in the Annieopsquotch Ophiolite Belt and Tectonic Implications

Comparison of the correlative ophiolites along strike to the Moreton's Harbour Group (i.e., King George IV, Annieopsquotch, Star Lake, Hall Hill Complex, and the Moreton's Harbour Group on New World Island: Fig. 1, 2) indicates significant differences in both trace element and isotopic signatures. Trace element discrimination diagrams of mafic rocks from the Annieopsquotch Ophiolite Belt indicate the rocks originated in a primitive arc setting (Fig. 8; Lissenberg et al. 2005*a*). In contrast, the Moreton's Harbour Group on New World Island shows significant variation in the geochemistry. Swinden (1996) suggested that New World island rocks were derived from melts that had been modified by continental lithosphere in a back-arc rifting environment. The extended trace element plots (Fig. 7) for New World Island rocks show similar geochemical types to those from Fortune Harbour Peninsula; however, as suggested by Swinden (1996), trace element tectonic discrimination diagrams indicate continental rift affinity (Fig. 8: Swinden 1996). The Moreton's Harbour Group rocks from Fortune Harbour Peninsula and rocks from the Hall Hill Complex lie between the continental rift and volcanic arc fields on the tectonic discrimination diagram (Fig. 8). The transition from the juvenile to continental rift-like setting, combined with the ophiolitic character of the Annieopsquotch Ophiolite Belt and Moreton's Harbour Group can be accounted by propagation of the intra-oceanic Annieopsquotch Ophiolite Belt spreading centre into the Dashwoods microcontinent. Rifting of the Dashwoods microcontinent resulted in rocks typical of continental rifts in the Moreton's Harbour Group (Fig. 9). Rifting likely allowed anatexis of Dashwoods crust with significant Mesoproterozoic component and formation of strongly contaminated felsic rocks. Subsequent closure of this oceanic basin outboard of Dashwoods (e.g., Lissenberg et al. 2005*b*; Zagorevski et al. 2009) juxtaposed the remnants of the Dashwoods microcontinent with para-autochtonous ophiolites of the Annieopsquotch Accretionary Tract.

Conclusions

The Moreton's Harbour Group occupies an important stratigraphic position in the Newfoundland Appalachians at the northern end of the Dunnage Zone along the fundamental Iapetus suture marked by the Red Indian Line. Prior to this study, knowledge of the age and tectonic framework of the Moreton's Harbour Group was uncertain. Detailed field mapping, and results from geochronology, trace-element geochemistry and isotopic geochemistry studies of rocks from the Moreton's Harbour Group presented here, have established that: (1) The Moreton's Harbour Group is an incomplete ophiolite, consisting of a sequence dominated by cumulate gabbro, sheeted dykes, and pillow basalts with extensive felsic dyke intrusions, and is ca. 477 Ma in age; (2) The Moreton's Harbour Group formed in a supra-subduction zone setting proximal to continental crust; (3) The Moreton's Harbour Group is correlative to the Annieopsquotch Ophiolite Belt (and Hall Hill Complex); and (4) Along-strike variations in the Annieopsquotch Ophiolite Belt refine the tectonic model for subduction initiation outboard of the Early Ordovician Dashwoods margin. This study provides new insights into the Early Ordovician evolution of the composite Laurentian margin by presenting a model whereby the Annieopsquotch Ophiolite Belt spreading centre propagated into the Dashwoods terrane, forming the Moreton's Harbour Group.

Acknowledgements

This paper is a result of work completed for J.A. Cutts' B. Sc. Honours thesis at Carleton University. The manuscript is a contribution to the Buchans — Robert`s Arm component of the Geological Survey of Canada Targeted Geoscience Initiative 3: Appalachians (2005–2010). Julie Peressini, Linda Cataldo, and Carole Lafontaine in the Geochronology lab at the Geological Survey of Canada assisted with the generation of the U–Pb data. Additional funding was also provided through an Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant to S. Carr. The authors would also like to thank the associate editor B. Murphy and reviewers S. Swinden, J.A. Winchester, and N. Rogers for their constructive comments that greatly improved the final manuscript.

References

Anonymous, . 1972. Penrose field conference on ophiolites. Geotimes, **17**(12): 22–24.

Bedard, J.H., Lauziere, K., Tremblay, A., and Sangster, A. 1998. Evidence for forearc seafloor-spreading from the Betts Cove Ophiolite, Newfoundland; oceanic crust of boninitic affinity. Tectonophysics, **284**(3–4): 233–245. doi:10.1016/S0040-1951(97)00182-0.

Bostock, H.H. 1988. Geology and petrochemistry of the Ordovician volcano-plutonic Robert's Arm Group, Notre Dame Bay, Newfoundland. Geological Survey of Canada.

Cabanis, B., and Lecolle, M. 1989. Le diagramme La/10-Y/15-Nb/8; un outil pour la discrimination des series volcaniques et la mise en evidence des processus de melange et/ou de contamination crustale. The La/10-Y/15-Nb/8 diagram; a tool for distinguishing volcanic series and discovering crustal mixing and/or contamination. Comptes Rendus de l'Academie des Sciences, Serie 2, Mecanique, Physique, Chimie, Sciences de l'Univers. Sciences de la Terre, **309**(20): 2023–2029.

Cawood, P.A., and Suhr, G. 1992. Generation and obduction of ophiolites; constraints for the Bay of Islands Complex, western Newfoundland. Tectonics, **11**(4): 884–897. doi:10.1029/92TC00471.

Cawood, P.A., van Gool, J.A.M., and Dunning, G.R. 1996. Geological development of eastern Humber and western Dunnage zones: Corner Brook–Glover Island region, Newfoundland. Canadian Journal of Earth Sciences, **33**(2): 182–198. . doi:10.1139/e96-017.

Dean, P.L., and Strong, D.F. 1977. Folded thrust faults in Notre Dame Bay, central Newfoundland. American Journal of Science, **277**(2): 97–108. doi:10.2475/ajs.277.2.97.

Dilek, Y. 2003. Ophiolite concept and its evolution. Geological Society of America. Special Paper, **373**: 1–16. doi:10.1144/GSL.SP.2003.218.01.01.

Dunning, G.R. 1981. The Annieopsquotch ophiolite belt, southwest Newfoundland. Current Research — Geological Survey of Canada, Report, 81–1B, pp. 11–15.

Dunning, G.R., and Krogh, T.E. 1985. Geochronology of ophiolites of the Newfoundland Appalachians. Canadian Journal of Earth Sciences, **22**(11): 1659–1670. doi:10.1139/e85-174.

Dunning, G.R., Kean, B.F., Thurlow, J.G., and Swinden, H.S. 1987. Geochronology of the Buchans, Roberts Arm, and Victoria Lake groups and Mansfield Cove Complex, Newfoundland. Canadian Journal of Earth Sciences, **24**(6): 1175–1184. doi:10.1139/e87-113.

Harris, R.A. 1992. Peri-collisional extension and the formation of Oman-type ophiolites in the Banda Arc and Brooks Range. *In* Ophiolites and their modern oceanic analogues. *Edited by* L. M. Parson, B. J. Murton, and P. Browning. Geological Society, London. pp. 301–325.

Johnson, R.J.E., van der Pluijm, B.A., and Van der Voo, R. 1991. Paleomagnetism of the Moreton's Harbour Group, northeastern Newfoundland Appalachians; evidence for an Early Ordovician island arc near the Laurentian margin of Iapetus. Journal of Geophysical Research, **96**(B7), 11689–11701.

Krogh, T.E. 1982. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abasion technique. Geochimica et Cosmochimica Acta, **46**(4): 637–649. doi:10.1016/0016-7037(82)90165-X.

Lissenberg, C.J., Bedard, J.H., and van Staal, C.R. 2004. The structure and geochemistry of the gabbro zone of the Annieopsquotch Ophiolite, Newfoundland; implications for lower crustal accretion at spreading ridges. Earth and Planetary Science Letters, **229**(1–2): 105–123. doi:10.1016/j.epsl.2004.10.029.

Lissenberg, C.J., van Staal, C.R., Bedard, J.H., and Zagorevski, A. 2005*a*. Geochemical constraints on the origin of the Annieopsquotch ophiolite belt, Newfoundland Appalachians. Geological Society of America Bulletin, **117**(11–12): 1413–1426. doi:10.1130/B25731.1.

Lissenberg, C.J., Zagorevski, A., McNicoll, V.J., van Staal, C.R., and Whalen, J.B. 2005*b*. Assembly of the Annieopsquotch accretionary tract, Newfoundland Appalachians; age and geodynamic constraints from syn-kinematic intrusions. The Journal of Geology, **113**(5): 553–570. doi:10.1086/431909.

Mattinson, J.M. 2005. Zircon U-Pb chemical abrasion ("CA-TIMS") method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. Chemical Geology, **220**(1-2): 47–66. doi:10.1016/j.chemgeo.2005.03.011.

O'Brien, B.H. 2003*a*. Geology of the central Notre Dame Bay region (Parts of NTS areas 2E/3,6,11) northestern Newfoundland. Newfoundland Department of Energy and Mines, Geological Survey Branch, Department of Mines and Energy.

O'Brien, B.H. 2003*b*. Geology of the central Notre Dame Bay region (Parts of NTS areas 2E/3,6,11) northestern Newfoundland. *In* Report 03–03. Newfoundland Department of Energy and Mines, Geological Survey Branch, Department of Mines and Energy.

O'Connor, J.T. 1965. A classification for quartz-rich igneous rock based on feldspar ratios. USGS. Professional Paper, **535B**: B79–B84.

Parrish, R.R., Roddick, J.C., Loveridge, W.D., and Sullivan, R.W. 1987. Uranium-lead analytical techniques at the geochronology laboratory, Geological Survey of Canada. Radiogenic age and isotope studies, Report 1: Geological Survey of Canada Paper, **87–2**: 3–7.

Pearce, J.A. 1996. A user's guide to basalt discrimination diagrams. *In* Trace element geochemistry of volcanic rocks: Application for massive sulphide exploration. *Edited by* D. A Wyman. Geological Association of Canada, Short Course Notes. pp. 79–113.

Pearce, J.A. 2003. Supra-subduction zone ophiolites: The search for modern analogues. Geological Society of America. Special Paper, **373**: 269–293.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology, **25**(4): 956–983.

Roddick, J.C., Loveridge, W.D., and Parrish, R.R. 1987. Precise U/Pb dating of zircon at the sub-nanogram Pb level. Chemical Geology. Isotope Geoscience Section, **66**(1–2): 111–121. doi:10.1016/0168-9622(87)90034-0.

Rodgers, J., and Neale, E.R.W. 1963. Possible "Taconic" klippen in western Newfoundland. American Journal of Science, **261**(8): 713–730. doi:10.2475/ajs.261.8.713.

Rollinson, H. 2009. New models for the genesis of plagiogranites in the Oman ophiolite. Lithos, **112**(3–4): 603–614. doi:10.1016/j.lithos.2009.06.006.

Sun, S.S., and McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts; implications for mantle composition and processes. Geological Society Special Publications, **42**(1): 313–345. doi:10.1144/GSL.SP.1989.042.01.19.

Swinden, S. 1996. Geochemistry of volcanic rocks in the Moreton's Harbour-Twillingate area, Notre Dame Bay. Current Research (1996) Newfoundland Department of Mines and Energy Geological Survey, Report 96–1, pp 207–226.

Swinden, H.S., Jenner, G.A., and Szybinski, Z.A. 1997. Magmatic and tectonic evolution of the Cambrian-Ordovician Laurentian margin of Iapetus; geochemical and isotopic constraints from the Notre Dame Subzone, Newfoundland. Memoir. Geological Society of America, **191**: 337–365.

Szybinski, Z.A. 1995. Paleotectonic and structural setting of the western Notre Dame Bay area, Newfoundland Appalachians. Memorial University of Newfoundland, St. John's, Newfoundland, Canada.

van Staal, C.R., Dewey, J.F., Mac Niocaill, C., and McKerrow, W.S. 1998. The Cambrian-Silurian tectonic evolution of the Northern Appalachians and British Caledonides; history of a complex, west and southwest Pacific-type segment of Iapetus. *In* Lyell: the Past is the Key to the Present. *Edited by* D.J. Blundell, and A.C. Scott. Geological Society, London. pp. 199–242.

van Staal, C.R., Whalen, J.B., McNicoll, V.J., Pehrsson, S., Lissenberg, C.J., Zagorevski, A., van Breemen, O., and Jenner, G.A. 2007. The Notre Dame Arc and the Taconic Orogeny in Newfoundland *In* 4-D Framework of continental crust. *Edited by* R.D. Hatcher Jr., M.P. Carlson, J.H. McBride, and J.R. Martinez Catalan. pp. 511–552.

Waldron, J.W.F., and van Staal, C.R. 2001. Taconian Orogeny and the accretion of the Dashwoods Block; a peri-Laurentian microcontinent in the Iapetus Ocean. Geology (Boulder), **29**(9): 811–814. doi:10.1130/0091-7613(2001)029<0811:TOATAO>2.0.CO;2.

Whalen, J.B., Jenner, G.A., Longstaffe, F.J., Gariepy, C., and Fryer, B.J. 1997. Implications of granitoid geochemical and isotopic (Nd, O, Pb) data from the Cambrian-Ordovician Notre Dame Arc for the evolution of the central mobile belt, Newfoundland Appalachians. Memoir . Geological Society of America, **191**: 367–395.

Williams, H. 1995*a*. Chapter 2: Temporal and spatial divisions. *In* Geology of the Appalachian-Caledonian orogen in Canada and Greenland. *Edited by* Harold Williams. Geological Survey of Canada. pp. 23–42.

Williams, H. 1995*b*. Chapter 3: Dunnage Zone — Newfoundland. *In* Geology of the Appalachian-Caledonian orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada. pp. 142–166.

Williams, H., and Hatcher, R.D., Jr. 1983. Appalachian suspect terranes. Memoir. Geological Society of America, **158**: 33–53.

Williams, H., Colman-Sadd, S.P., and Swinden, H.S. 1988. Tectonic-stratigraphic subdivisions of central Newfoundland. Paper. Geological Survey of Canada **88–1B**: 91–98.

Winchester, J.A., and Floyd, P.A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology, **20**(4): 325–343. doi:10.1016/0009-2541(77)90057-2.

Zagorevski, A. 2008. Preliminary Geochemical Database of the Buchans-Robert's Arm Belt, central Newfoundland. Geological Survey of Canada Open File 5986, 1 [CD-ROM].

Zagorevski, A., and Van Staal, C. in press. The record of Ordovician arc-arc and arc-continent collisions in the Canadian Appalachians during the closure of Iapetus. *In* Arc-continent collisions, Frontiers in Earth Science. *Edited by* D. Brown, and P.D. Ryan. Springer.

Zagorevski, A., Rogers, N., van Staal, C.R., McNicoll, V., Lissenberg, C.J., and Valverde-Vaquero, P. 2006. Lower to Middle Ordovician evolution of peri-Laurentian arc and back-arc complexes in the Iapetus: Constrains from the Annieopsquotch Accretionary Tract, central Newfoundland. Geological Society of America Bulletin, **118**(3–4): 324–342. doi:10.1130/B25775.1.

Zagorevski, A., Lissenberg, C.J., and van Staal, C.R. 2009. Dynamics of accretion of arc and backarc crust to continental margins: Inferences from the Annieopsquotch Accretionary Tract, Newfoundland Appalachians. Tectonophysics, **479**(1–2): 150–164. doi:10.1016/j.tecto.2008.12.002.

Appendix A

Appendix Table A1 follows.

Table A1. Whole-rock geochemistry of the Moreton's Harbour Group (NAD83 UTM Zone 21). Negative numbers indicate that the element

Sample:	RAX08A762	RAX08A763	RAX08A764	RAX08A765	RAX08A766B	RAX09A850	RAX09A854	RAX09A857	RAX09A860	RAX09A862
Rock Type:	pillow basalt	trondjhemite	pillow basalt	diabase	pillow basalt	diabase dyke	diabase dyke	pillow basalt	felsic dyke	pillow basalt
UTM Easting:	632026	631956	632395	632244	631812	630145	630768	630794	631027	631171
UTM Northing:	5485277	5484907	5484409	5484111	5483781	5486600	5485949	5486711	5486300	5486064
SiO2	51.33	78.67	49.03	49.82	48.56	47.26	48.43	44.97	75.54	47.67
TiO2	1.376	0.097	1.079	2.264	1.027	0.481	1.41	1.423	0.176	1.035
Al2O3	19.25	10.43	15.17	14.64	15.76	17.78	14.86	16.27	12.53	14.66
MnO	0.088	0.035	0.191	0.218	0.229	0.124	0.208	0.13	0.063	0.142
MgO	3.35	1.7	7.25	3.76	10.32	7.01	6.39	4.32	0.72	5.91
CaO	7.63	0.43	9.93	6.78	6.11	13.19	7.58	14.73	1	11.58
Na2O	5.9	4.67	2.85	5.19	3.97	1.6	3.55	3.58	5.14	4.35
K2O	0.34	0.03	0.84	0.03	0.52	1.86	1.51	0.03	0.77	0.04
P2O5	0.26	0.01	0.11	0.44	0.09	0.03	0.16	0.24	0.07	0.14
LOI	4.33	1.47	3.46	2.44	4.8	3.65	3.08	5.63	1.22	5.39
Fe2O3t	7.1	3.31	10.82	14.34	9.29	7.48	12.54	9.12	3.31	9.98
Total	100.9	100.9	100.7	99.93	100.7	100.5	99.73	100.4	100.5	100.9
Ba	58	17	251	21	70	383	531	11	130	25
Co	43	2	42	33	38	32	43	39	3	42
Cr	270	–20	120	–20	270	320	70	200	30	250
Cs	–0.1	–0.1	0.9	–0.1	0.8	0.6	0.5	–0.1	0.2	–0.1
Cu	30	10	70	30	80	80	70	70	20	50
Ga	18	14	15	21	15	13	15	18	10	14
Hf	2.1	4.5	1.7	4.1	1.4	0.5	2.4	2.3	2.8	1.6
Nb	6.2	5	2.1	10.9	1.1	–1	3.1	7	10.3	3.5
Ni	90	–20	40	–20	70	90	70	130	–20	140
Pb	–5	5	–5	7	–5	–5	–5	–5	21	–5
Rb	3	–1	17	–1	12	39	17	–1	8	–1
Sb	4	2.9	3.2	4.5	4.4	–1	–1	–1	–1	–1
Sc	36	11	39	31	43	33	39	34	6	36
Sr	138	64	166	128	204	177	156	112	99	77
Ta	0.44	0.47	0.09	0.72	0.04	–0.01	0.19	0.49	0.86	0.21
Th	0.85	3.68	0.79	2.95	0.52	0.26	1.33	1.12	12.9	0.95
Tl	0.17	0.08	0.15	–0.05	0.09	0.07	0.13	0.07	0.1	–0.05
U	1.36	0.99	0.18	0.59	0.08	0.04	0.34	0.65	3.25	0.39
V	369	6	304	324	291	193	356	341	35	291
Y	26.5	37.6	27.3	50.1	24.2	13.2	30.4	24.5	19.8	20.8
Zn	90	30	80	160	70	50	100	80	–30	90
Zr	79	156	58	150	51	12	82	97	86	57
La	7.61	19.6	3.83	17.8	3.02	0.96	5.64	8.2	33	5.4
Ce	18.9	40.2	10.3	43.2	8.22	2.32	13.8	19.1	58.4	12.3
Pr	2.86	5.5	1.73	6.4	1.39	0.43	2.26	3	6.99	1.97
Nd	12.3	22.1	8.57	27.2	7.08	2.45	11.1	13.6	23.3	9.46
Sm	3.32	5.52	2.58	7	2.18	1.09	3.72	3.79	4.49	2.87
Eu	1.23	1.56	1.12	2.66	0.91	0.42	1.32	1.4	0.755	1.11
Gd	4.07	6.28	3.73	8.46	3.1	1.58	4.82	4.3	3.84	3.43
Tb	0.71	1.07	0.7	1.43	0.58	0.33	0.92	0.78	0.63	0.62
Dy	4.41	6.47	4.53	8.73	3.83	2.21	5.71	4.58	3.51	3.89
Ho	0.93	1.3	0.96	1.8	0.82	0.45	1.15	0.9	0.74	0.8
Er	2.74	3.91	2.88	5.41	2.48	1.36	3.4	2.67	2.2	2.26
Tm	0.395	0.596	0.417	0.782	0.367	0.213	0.5	0.395	0.328	0.323
Yb	2.46	3.9	2.59	4.81	2.28	1.45	3.44	2.57	2.25	2.18
Lu	0.374	0.61	0.387	0.733	0.348	0.233	0.592	0.427	0.394	0.385

is below the detection limit

RAX09A864	RAX09A865	RAX09A866A	RAX09A866B	RAX09A866C	RAX09A867	RAX09A869	RAX09A872A	RAX09A872B	RAX09A873
mafic dyke	mafic dyke	felsic dyke	felsic dyke	felsic dyke	diabase	felsic dyke	gabbro	gabbro	tuff
630876	631391	631490	631490	631490	631972	632056	631940	631940	631954
5485533	5485471	5485543	5485543	5485543	5485387	5485030	5484839	5484839	5484708
48.41	47.56	59.3	65.62	60.19	47.38	73.26	48.56	47.71	58.99
0.406	0.385	0.319	0.406	0.439	2.308	0.264	0.37	0.384	1.822
21.48	17.53	19.35	14.05	14.53	13.57	7.73	15.99	15.99	19.13
0.131	0.125	0.055	0.061	0.072	0.256	0.059	0.15	0.152	0.062
6.88	8.82	2.32	3.37	3.63	5.6	2.86	9.2	9.28	2.22
8.9	11.65	3.79	1.67	2.92	9.91	2.86	11.13	11.41	1.87
2.69	1.52	7.96	5	4.93	3.63	1.8	2.63	2.34	5.17
1.84	2.11	0.06	0.42	0.56	0.07	0.05	0.78	0.84	2.51
0.08	0.04	0.09	0.12	0.1	0.18	0.1	0.05	0.05	0.22
3.15	3.62	2.25	2.57	3.3	2.44	3.28		3.47	3.5
6.78	6.93	4.44	6.73	7.78	14.45	8.56	8.44	8.44	4.3
100.7	100.3	99.93	100	98.45	99.79	100.8	100.8	100.1	99.04
597	596	23	104	111	25	14	268	342	457
31	37	10	17	21	40	15	40	41	21
240	280	–20	40	20	80	–20	280	380	50
0.8	2.2	–0.1	–0.1	–0.1	–0.1	–0.1	1.5	1.8	1.2
60	120	–10	50	80	70	40	110	110	50
13	11	15	12	13	19	11	12	12	24
0.6	0.5	5.2	1.1	1.4	3.8	1.2	0.5	0.4	5.2
0.7	0.6	15.7	1.2	1.2	2.3	3.1	0.8	0.3	10
130	130	–20	–20	20	80	–20	130	140	40
–5	–5	–5	6	11	–5	7	–5	–5	–5
29	42	–1	4	4	–1	–1	13	15	43
0.4	–1	–1	–1	0.2	–1	–1	–1	0.3	0.2
27	37	12	24	22	42	12	40	39	47
214	142	322	153	174	55	243	179	168	173
0.03	0.04	1.29	0.05	0.08	0.18	0.17	0.03	0.03	0.62
0.6	0.47	18.1	1.14	1.4	0.47	2.02	0.37	0.34	1.31
0.14	0.21	–0.05	–0.05	–0.05	–0.05	–0.05	0.09	0.11	0.27
0.15	0.09	3.98	0.64	0.87	0.15	1.05	0.1	0.09	1.65
152	178	86	175	184	392	167	220	227	324
10.2	10.9	27.7	12.4	15	45.1	16.3	12.6	11.1	45.8
70	40	30	90	80	140	–30	60	70	70
19	12	167	39	49	136	42	12	10	207
1.78	1.5	47.3	5.32	6.65	4.28	11.5	1.52	1.25	9.64
4.59	3.36	85.2	11.5	14	12.8	28.9	3.26	2.84	25.6
0.79	0.53	9.88	1.58	1.9	2.41	3.05	0.54	0.46	4.24
3.86	2.72	33.3	6.81	8.21	13.1	12.8	2.73	2.23	20.6
1.3	1.07	5.78	1.71	2.09	4.83	2.96	0.99	0.85	6.28
0.436	0.412	1.09	0.485	0.641	1.67	0.717	0.378	0.355	1.65
1.65	1.53	4.95	1.95	2.46	6.81	3.07	1.54	1.38	7.72
0.31	0.31	0.79	0.36	0.44	1.34	0.51	0.32	0.29	1.46
1.88	1.94	4.75	2.2	2.71	8.44	3.17	2.25	1.98	9.17
0.38	0.4	1.01	0.47	0.56	1.77	0.63	0.49	0.42	1.86
1.14	1.22	3	1.44	1.62	5.12	1.81	1.48	1.28	5.31
0.168	0.178	0.452	0.218	0.252	0.759	0.267	0.229	0.2	0.789
1.12	1.2	3.18	1.47	1.67	5.21	1.73	1.54	1.39	5.33
0.182	0.199	0.562	0.252	0.294	0.885	0.297	0.276	0.242	0.877