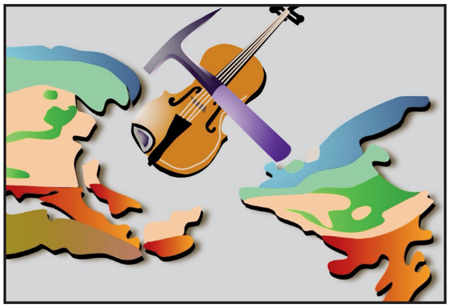
HAROLD WILLIAMS SERIES



From Large Zones to Small Terranes to Detailed Reconstruction of an Early to Middle Ordovician Arc – Backarc System Preserved Along the Iapetus Suture Zone: A Legacy of Hank Williams

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SUMMARY

The Annieopsquotch accretionary tract (AAT) comprises a thrust stack of Lower to Middle Ordovician arc and backarc terranes that were accreted to the composite Laurentian margin of Iapetus during the Middle to Late Ordovician. Geological relationships suggest that the constituent terranes of the AAT initially formed outboard of the composite Laurentian margin in an extensional arc that underwent multiple rifting episodes prior to its accretion. The initiation of AAT magmatism led to the development of Tremadocian to Floian supra-subduction zone ophiolites (481 to 477 Ma) with organized ridges indicated by the presence of well-developed sheeted dyke complexes. This spreading centre propagated through a fragment of Laurentian crust and separated it from the composite Laurentian margin. This Laurentian crust fragment then formed the basement to subsequent Floian to Darriwilian AAT arc magmatism. The Floian arc (473 to 468 Ma) underwent extensive rifting indicated by organized spreading in the Lloyds River backarc basin, which was floored by juvenile backarc ophiolitic crust (472 Ma). The establishment of the Darriwilian arc (467 to 462 Ma) was in part coeval with yet another stage of rifting. Darriwilian magmatism is characterised by significant along-strike variability, ranging from continental to primitive calc-alkaline arc to tholeiitic backarc-like magmatism. The diversity of Darriwilian magmatism can be attributed to fragmentation and magmatic reworking of Laurentian-derived basement along strike in the same arc undergoing disorganized spreading. The development of the AAT is interpreted to be similar to that of the modern Izu – Bonin – Mariana arc in the western Pacific.

SOMMAIRE

La bande d'accrétion d'Annieopsquotch (AAT) est constituée d'un empilement de chevauchements de l'Ordovicien précoce à moyen, et de terranes d'arc et d'arrière-arc qui se sont accrétés à la marge composite laurentienne japétienne à l'Ordovicien moyen à tardif. Les faits géologiques relevés portent à penser que les terranes constitutifs de l'AAT se sont constitués à l'extérieur de la marge laurentienne dans un arc d'extension qui a subi de multiples épisodes de rifting avant son accrétion. L'initiation du magmatisme de l'AAT a mené au développement de zones d'ophiolites de supra-subduction du Trémadocien au Floien (481 Ma à 477 Ma), avec des crêtes ordonnées mises en évidence par la présence de complexes de tapis de dikes bien développés. Ce centre d'extension s'est propagé à travers un fragment de la croûte laurentienne, et l'a ultimement séparé de la marge composite laurentienne. Et, du Floien au Darriwilien, ce fragment de croûte laurentienne a servi de substratum au magmatisme d'arc de l'AAT. Au Floien (473 Ma à 468 Ma), cette zone d'arc a subi un important rifting, comme l'indique la distension ordonnée du bassin d'arrière-arc de Lloyds River, lequel a servi de semelle à une croûte ophiolitique d'arrière-arc (472 Ma). La mise en place de l'arc au Darriwilien (467 Ma à 462 Ma) a coexisté pour un temps avec un autre épisode de rifting. Le magmatisme darriwilien

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est caractérisé par une variabilité de composition importante parallèlement à sa direction, passant d'une composition d'arc continental à celle d'arrière-arc primitif calco-alcalin jusqu'à une composition de magmatisme de type tholéiitique d'arrière-arc. La diversité du magmatisme darriwilien peut être attribuée à la fragmentation et au remaniement magmatique de la croûte d'origine laurentienne parallèlement à la direction d'un même arc subissant une distension désordonnée. Nous proposons que le développement de l'AAT a été similaire à celui de l'arc moderne Izy-Bonin-Marianne du Pacifique occidental.

INTRODUCTION

Comprehensive terrane analysis is the principal tool for understanding and reconstructing the tectonic evolution of complex orogens. Harold (Hank) Williams applied the concept of suspect terranes (as per Coney et al. 1980) to the Appalachian orogen (Williams and Hatcher 1982, 1983), ultimately defining four major composite suspect terranes (Dunnage, Gander, Avalon and Meguma; Fig. 1). The suspect terrane framework was updated and revised over time (Williams et al. 1988; Williams 1995a) but in general it has endured the test of over 30 years of research. Williams and Hatcher (1982) advocated scale-dependent treatment of suspect terranes and recognized that "those inclined to emphasize similarities among rock groups in large areas are likely to define fewer terranes than those who emphasize differences in local areas" (Williams and Hatcher 1983, p. 34). The scale-dependent treatment of terranes and willingness to emphasize the differences proved to be extremely important for furthering our understanding of the tectonic processes responsible for forming the Appalachian orogen. For example, detailed investigations of the oceanic Dunnage terrane or Dunnage Zone (Williams 1995a, b) revealed significant geological contrasts within it, leading to its subdivision into peri-Laurentian Notre Dame and peri-Gondwanan Exploits subzones separated by the Red Indian Line, the main Iapetus suture (Fig. 1; Williams 1995a, b). Furthermore, there were clear indications that the subzones were, in themselves, composite suspect terranes.

The peri-Laurentian Notre Dame subzone contains several distinct and unrelated ophiolite belts (e.g. Dunning and Krogh 1985; Zagorevski and van Staal 2011), indicating that it is a composite terrane. On the basis of age, structure, and tectonic setting, van Staal et al. (1998) grouped the easternmost units of the Notre Dame subzone, including the Annieopsquotch ophiolite belt (Dunning 1987; Dunning et al. 1987), into the Annieopsquotch accretionary tract (AAT), a southeast facing accretionary complex composed of slivers of arc and backarc rocks (Fig. 1; e.g. Pickett 1987; Bostock 1988; Swinden et al. 1989). Subsequent detailed investigations of the AAT, focusing on the differences and/or changes in tectonic setting and structure over time between different areas, implied a greater complexity, as each one of these slivers, in essence, was shown to constitute a discrete terrane (Fig. 1; Bostock 1988; Zagorevski et al. 2006, 2009, 2010a; Zagorevski and Rogers 2009).

In this contribution, we present new geochronological (6 U–Pb and 1 $^{40}Ar/^{39}Ar$) and isotopic (29 Sm–Nd) data and summarize previously published whole-rock geochemical data on Floian to Darriwilian volcanic and plutonic rocks within the AAT; (note that geochronological and isotopic data are presented in appendix tables A1 to A3 and are available at GAC's open source GC Data Repository at http://www.gac.ca/wp/?page_id=306). We review the development of the arc – backarc complexes preserved in the AAT (Fig. 1) and subdivide it into smaller, mappable, fault-bounded terranes. Although the preservation and exposure of these terranes is fragmentary, we interpret them to represent the fundamental building blocks of a single peri-Laurentian Ordovician arc system. Tectonic analysis of these fundamental building blocks allows recognition and reconstruction of supra-subduction zone (SSZ) spreading centres, remnant arc, arc, forearc, and accretionary prism settings. The preserved elements of the arc system are remarkably similar to many aspects of modern arc systems, such as Tonga – Kermadec and Izu –Bonin – Mariana arcs of the western Pacific (e.g. Taylor 1992; Wright et al. 1996). These subdivisions allow us to make inferences concerning the tectonic development of this arc system, including transition from Early Ordovician organized spreading to Middle Ordovician disorganized spreading, subduction erosion, seamount accretion and the nature of the forearc basement. Ultimately, these in turn contribute to our knowledge of the paleogeography of Iapetus and impose important constraints on the overall tectonic processes active during the Ordovician.

GEOLOGICAL SETTING OF THE DUNNAGE ZONE

The Dunnage Zone is a large composite (super)terrane that comprises supra-subduction zone ophiolites, arc-backarc complexes and sedimentary basins of diverse ages that formed within the Iapetus Ocean (Fig. 1). Williams et al. (1988) utilized structure, stratigraphy, geophysics, fauna and the lead isotopic signatures of volcanogenic massive sulphide deposits to highlight the geological contrasts in Newfoundland and subsequently divided the Dunnage Zone into the Notre Dame and Exploits subzones (Fig. 1; Williams 1995b). These subzones correspond to the peri-Laurentian and peri-Gondwanan Iapetan realms of Hibbard et al. (2006) and are separated by the Red Indian Line (Williams 1995b), the suture zone along which the main tract of Iapetus must have closed. The identification of the contrasting subzones within the Dunnage Zone was a major breakthrough in understanding the development of the northern Appalachians, because it recognized that two unrelated but coeval arc systems were active along opposing margins of the Iapetus Ocean (Fig. 2).

To the east of the Red Indian Line, the peri-Gondwanan Early to Middle Ordovician Popelogan – Victoria arc was built on an older Cambrian to Early Ordovician arc – backarc (Penobscot) system and pre-Cambrian Gander Zone basement (Rogers et al. 2006; Zagorevski et al. 2010b and references therein). To the west of the Red Indian Line, elements of the Early to Middle Ordovician AAT arc – backarc complex were in part built on Laurentian basement (Swinden et al. 1997; Zagorevski et al. 2006, 2008; see

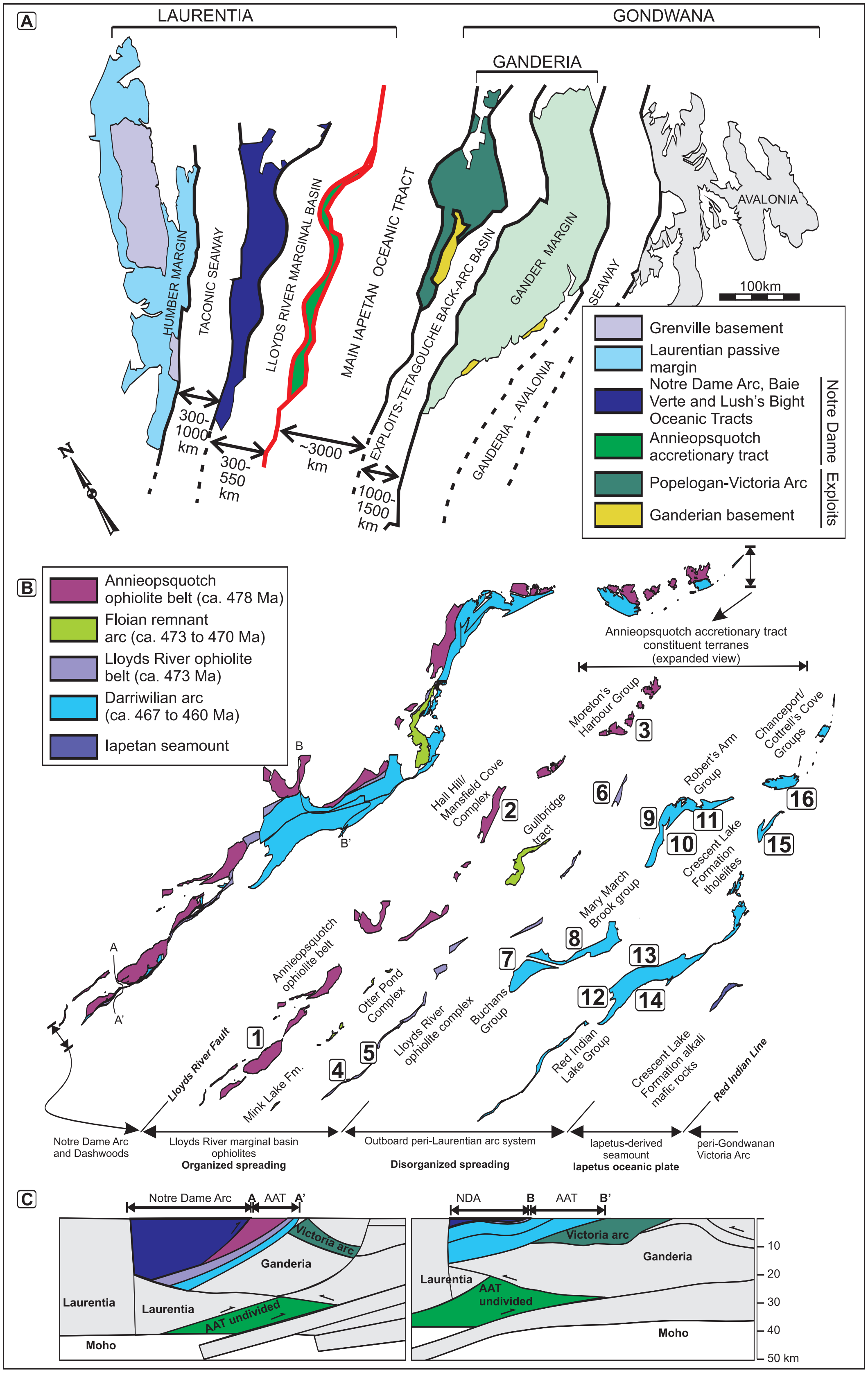

Figure 1. A. Tectono-stratigraphic subdivisions of Newfoundland expanded to show seaways that occurred outboard of Laurentian margin (modified from Zagorevski and van Staal 2011). B. Expanded view of Annieopsquotch accretionary tract (AAT) constituent terranes highlighting the various stages of development. Moreton's Harbour, Cottrell's Cove and Chanceport groups have been rotated counterclockwise. Numbers are keyed to schematic stratigraphic sections in Figures 3 and 9. C. Simplified cross-sections based on seismic reflection studies showing disposition of the AAT (modified from van der Velden et al. 2004).

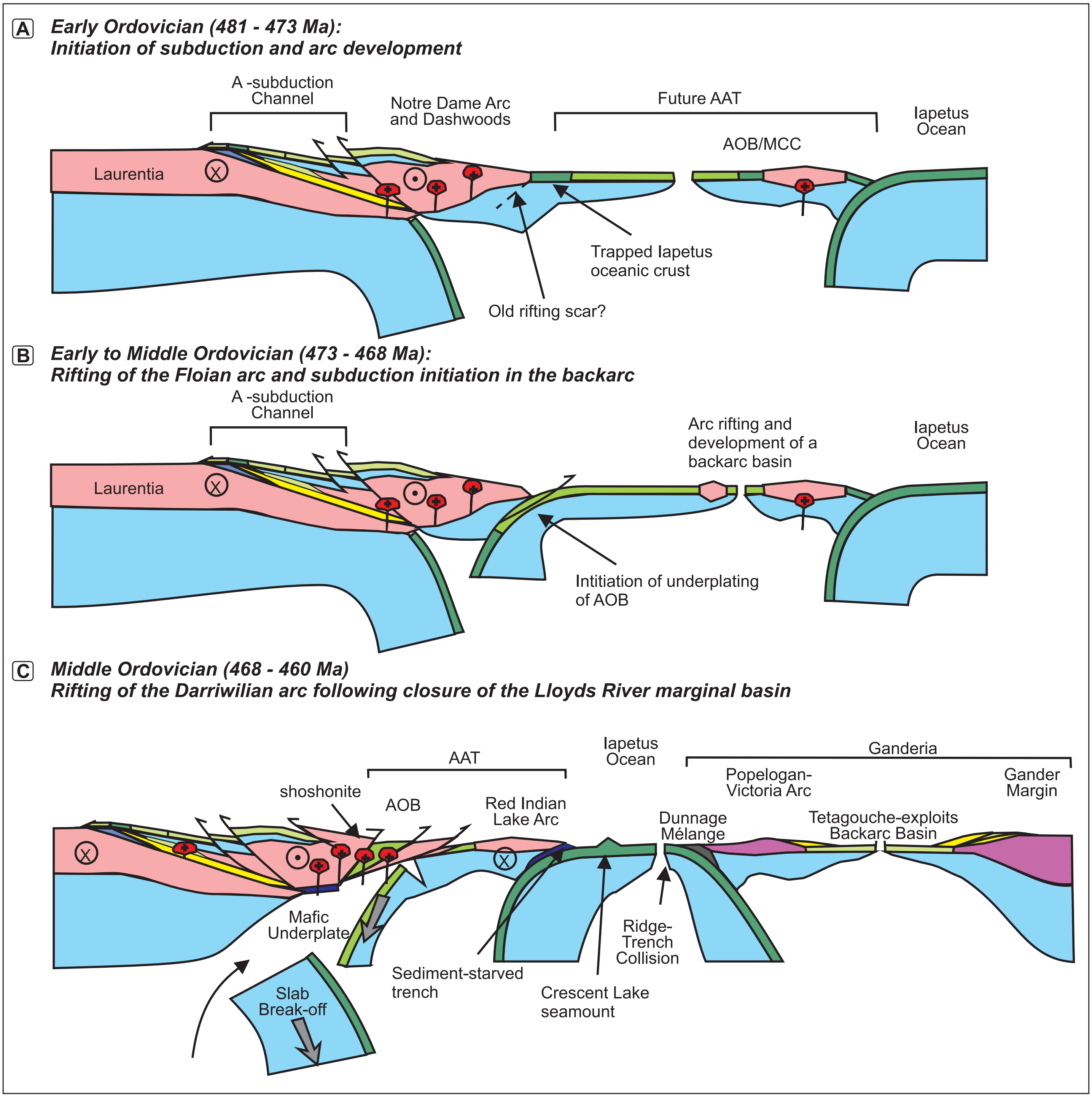

Figure 2. Early to Middle Ordovician tectonic evolution of the Humber margin and outboard peri-Laurentian terranes (from Zagorevski and van Staal 2011). A. Formation of the Annieopsquotch ophiolite belt (AOB) and Mansfield Cove Complex (MCC) is followed by development of extensional arc outboard of Dashwoods (Zagorevski et al. 2006) synchronous with on-going collision in the Taconic Seaway. B. Floian arc rifts, producing a backarc basin represented by the Lloyds River ophiolite complex. On-going convergence in the Taconic Seaway places Lloyds River marginal basin under compression, initiating subduction at an old rifting scar at the Dashwoods – Iapetus oceanic crust interface. Lloyds River marginal basin terranes are underplated beneath Dashwoods, forming an accretionary tract (Lissenberg et al. 2005b). C. The Floian arc (Mink Lake Formation, Gullbridge Tract) is accreted to the composite Laurentian margin accompanied by slab break-off and stitching magmatism in the Annieopsquotch accretionary tract (AAT). The Darriwilian arc (Red Indian Lake, Buchans, Mary March and Robert's Arm groups) continues to be active following a short magmatic gap, unconformity and syn-tectonic sedimentation. It undergoes disorganized spreading that is marked by development of coeval constructive and rift segments.

following). The two arc systems collided at ca. 455 Ma following bi-vergent subduction of the Iapetus Ocean plate (Fig. 2; van Staal et al. 1998; Zagorevski et al. 2008; Zagorevski and McNicoll 2012). The overall evolution is interpreted to be similar to the Molucca Sea collision zone (e.g. Bader et al. 1999; Pubellier et al. 1999). The collision led to termination of arc volcanism above both subduction zones, loading and black shale transgression on the Popelogan – Victoria arc, and major uplift and exhumation of the AAT and adjacent hinterland (Williams 1995b; Zagorevski et al. 2008). These stratigraphic relationships, combined with structural and seismic reflection studies, indicate that the Popelogan – Victoria arc became the lower plate following the onset of arc – arc collision and was, at least in part, underthrust and sutured beneath the AAT and the Red Indian Line (van der Velden et al. 2004; Zagorevski et al. 2007, 2008).

ANNIEOPSQUOTCH ACCRETIONARY TRACT

The Annieopsquotch accretionary tract (AAT) comprises a southeast verging thrust stack of peri-Laurentian Early to Middle Ordovician arc – backarc terranes (Fig. 1) that, before their tectonic assembly, were situated immediately outboard of the west-facing Early Ordovician Notre Dame arc (Lissenberg et al. 2005a; Zagorevski et al. 2006). The Notre Dame arc was built upon the Dashwoods microcontinent, which is a rifted segment of Laurentia (Waldron and van Staal 2001). The Notre Dame arc and its Dashwoods microcontinent basement started to collide diachronously with Laurentia between 480 and 470 Ma (van Staal et al. 2007, 2013), forming a composite Laurentia. This collision led to initiation of a new, northwest-dipping subduction zone, which progressively rolled back eastwards and formed a series of arc and backarc terranes on its upper plate adjacent to the Dashwoods microcontinent (Fig. 2). The terranes of the AAT were fully assembled and accreted to the composite Laurentian margin during the Middle Ordovician Taconic orogeny (Thurlow et al. 1992; van Staal et al. 1998; van der Velden et al. 2004; Lissenberg et al. 2005b; Zagorevski et al. 2007, 2009; Zagorevski and Rogers 2009). Accretion involved an independent northwest-dipping subduction zone situated in the backarc region of the progressively east-migrating arc (Fig. 2). Partial closure of the backarc basin led to underplating of the Tremadocian – Dapingian infant arc and backarc terranes beneath composite Laurentia between ca. 473 and 468 Ma (Lissenberg et al. 2005b). This was followed by addition and imbrication of Darriwilian arc terranes during collision with the peri-Gondwanan Popelogan – Victoria arc. The structure and development of the individual terranes has been described in detail in other publications (Bostock 1988; Kerr 1996; Dec et al. 1997; O'Brien 2003, 2007; Zagorevski et al. 2006, 2010a; Zagorevski and Rogers 2009). In the following sections, we present new isotopic and geochronological data on Tremadocian, Floian and Darriwilian arc components and synthesize the tectonic development of the AAT through a comparison to modern arc systems, notably the Izu – Bonin – Mariana arc and its remnant ridges in the western Pacific region (e.g. Oakley et al. 2009).

Tremadocian – Floian Remnant Infant Arc (481 to 477 Ma)

The oldest AAT arc magmatism is preserved in the 481 – 477 Ma supra-subduction zone (SSZ) ophiolites that form the structurally highest units in the AAT. These include the King George IV Complex, Annieopsquotch Complex, Star Lake Complex, Hall Hill – Mansfield Cove Complex and the Moreton's Harbour Group (Fig. 1; Williams and Payne 1975; Dunning 1987; Dunning et al. 1987; Szybinski 1995; Swinden 1996; O'Brien 2003; Lissenberg et al. 2005c; Cutts et al. 2012). Collectively, these are interpreted as a remnant infant arc. The ophiolites are characterized by typical ophiolitic stratigraphy that includes layered to isotropic gabbro, tonalite to trondhjemite, well-developed sheeted diabase dykes, pillow basalt and minor sedimentary rocks (Figs. 3, 4). The overall arc setting is supported by the Mansfield Cove Complex (Figs. 1, 3) a hornblende – biotite granodiorite to monzogranite pluton that is coeval with gabbro of the Hall Hill Complex (Fig. 4A; Bostock 1988).

Throughout the belt, the primary ophiolitic stratigraphy is locally disrupted by high-angle intra-oceanic faults that acted as the locus for emplacement of felsic intrusive rocks (Fig. 3; Dunning 1987; van Staal et al. 2005; Cutts et al. 2012). Despite their similar ages, these ophiolitic complexes display systematic along-strike geochemical variation (Fig. 5). Mafic rocks range from light rare-earth (LREE)-depleted island arc tholeiite (IAT) in the southwestern King George IV and Annieopsquotch complexes (Lissenberg et al. 2004, 2005) to continental rift basalt and andesite in the northeastern Moreton's Harbour Group (Swinden 1996; Cutts et al. 2012). The felsic rocks, although volumetrically minor overall, exhibit similar variations in geochemical characteristics. They range from primitive trondhjemite in the southwest to rhyolite derived by melting of continental crust in the northeast (Fig. 5; Rogers 2004; Cutts et al. 2012; Whalen 2012).

The presence of well-developed sheeted dyke complexes suggests that the late Tremadocian phase (481 – 477 Ma) of arc development was characterized by formation of an organized (single-rift spreading mode of Tamaki 1985), magma-rich (Robinson et al. 2008) spreading centre. Rare boninitic troctolite enclaves occur within the gabbro zone of the Annieopsquotch Complex and indicate that magmatism evolved from boninitic to tholeiitic (IAT) in the southwest (Lissenberg et al. 2005a). The extent of the early boninitic substrate is impossible to estimate as it is only locally preserved and, in general, appears to have reacted with younger percolating tholeiitic melts (Lissenberg et al. 2005a; Bédard 2014). Lissenberg et al. (2005a) proposed that the supra-subduction zone spreading centre responsible for the Annieopsquotch Complex and coeval, along-strike ophiolite complexes formed during initiation of the northwest-dipping subduction zone (see above), analogous with the intra-oceanic Izu – Bonin – Mariana arc (Stern and Bloomer 1992).

In contrast with the intra-oceanic Izu – Bonin – Mariana arc, the AAT spreading centre formed in close proximity to continental crust, because

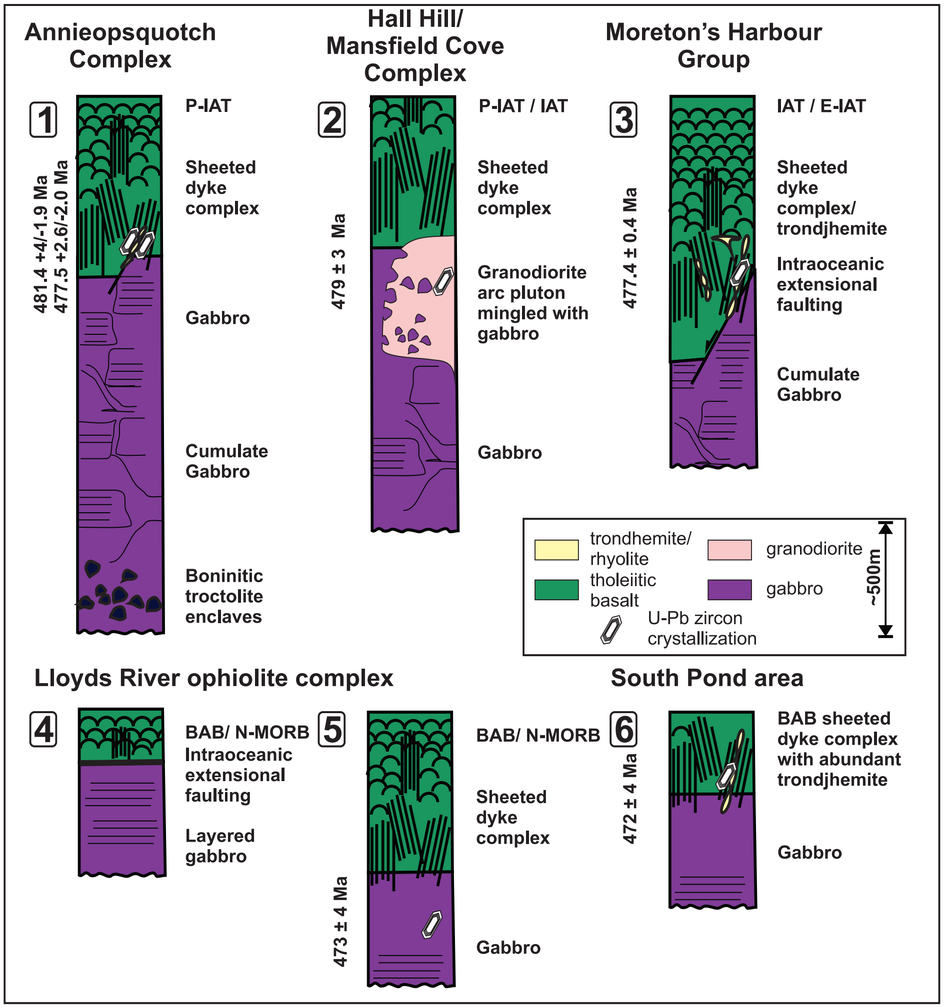

Figure 3. Schematic pseudo-stratigraphy of Tremadocian and Floian ophiolitic rocks in the Annieopsquotch accretionary tract, at the locations shown in Figure 1B. 1. Annieopsquotch ophiolite (Dunning 1987). 2. Hall Hill – Mansfield Cove Complex (Dunning et al. 1987). 3. Moretons Harbour Group, Fortune Harbour Peninsula (Cutts et al. 2012). 4. Lloyds River ophiolite complex, Victoria Lake area (Zagorevski et al. 2006). 5. Lloyds River ophiolite complex, Lloyds River area (Zagorevski et al. 2006). 6. Lloyds River ophiolite complex, South Pond area (see Appendix 2). P-IAT – primitive island arc tholeiite, E-IAT – enriched island arc tholeiite, BAB – backarc basalt; N-MORB – normal mid-ocean ridge basalt.

it was underthrust beneath the Notre Dame arc and its microcontinental basement (Dashwoods subzone of Williams et al. 1988) within 10 to 5 m.y. of its formation. This followed accretion of the Notre Dame arc to Laurentia, which together formed a composite margin (Lissenberg et al. 2005a; van Staal et al. 2007). Proximity to continental margins has been documented in many ophiolite belts; however, in contrast to most ophiolites, the Annieopsquotch belt was structurally underplated beneath the composite margin of Laurentia rather than obducted (Figs. 1, 2; Lissenberg et al. 2005b). The changes in chemistry and isotopic characteristics along strike suggest that this supra-subduction zone spreading centre actually propagated into Laurentian continental crust farther to the north at the latitude of Moreton's Harbour Group (Fig. 1; Cutts et al. 2012). This is further supported by the presence, in the younger AAT terranes, of inherited zircon from the Lush's Bight Group (ca. 510 Ma; e.g. Jenner et al. 1991) and the first phase of Notre Dame arc volcanism (ca. 488 Ma; van Staal et al. 2007 and references therein).

AAT magmatism is, in part, similar in age and character to some parts of the Notre Dame arc (e.g. O'Brien and Dunning 2014). This can be attributed to the tectonic position of the Notre Dame arc above a southeast-dipping subduction zone in the closing Taconic Seaway, and above a newly-initiated, northwest-dipping subduction zone within Iapetus (Fig. 2). This tectonic position is similar to present day Mindanao in the western Pacific (Sajona et al. 2000). Existing data are insufficient to determine the exact geometry of the AAT subduction initiation and the orientation of the spreading centre with respect to the trend of the composite Notre Dame arc and Laurentia. The spreading centre may have been oblique to the composite Laurentian margin or may have propagated into a promontory situated along it (Zagorevski et al. 2006; Cutts et al. 2012). The relationship between an ophiolitic spreading centre and continental crust is rarely documented in ancient ophiolite belts (see de Wit and Stern 1981; van Staal et al. 1996; Furnes et al. 2012; Hollis et al. 2012, 2013 for exceptions); however, there is some similarity to the Izu – Bonin – Mariana arc, where Cretaceous basement was transected during Eocene subduction initiation-related spreading (Ishizuka et al. 2011).

Floian Arc and Backarc (473 to 470 Ma)

The Floian remnant arc and its backarc elements are principally preserved as tectonic slivers structurally below the Tremadocian Annieopsquotch belt (Fig. 1; Zagorevski et al. 2006) and as detritus in the younger Darriwilian arc sequences (see following). In the Mink Lake area (Fig. 1), situated southwest of the King George IV ophiolite, a preserved segment of the Floian arc comprises transitional tholeiitic to calc-alkaline pillow basalt, minor felsic tuff and jasperite, which yielded an age of 473 ± 4 Ma (Zagorevski et al. 2006). In the structurally complex Gullbridge area (Fig. 1), another segment of this arc is preserved in several thin thrust panels comprising dominantly coeval felsic, mafic or bimodal volcanic rocks having geochemical characteristics ranging from mid-oceanic ridge-like basalt and IAT to calc-alkaline basalt (Figs. 6A-D, 7, 8A; Pope et al. 1991;

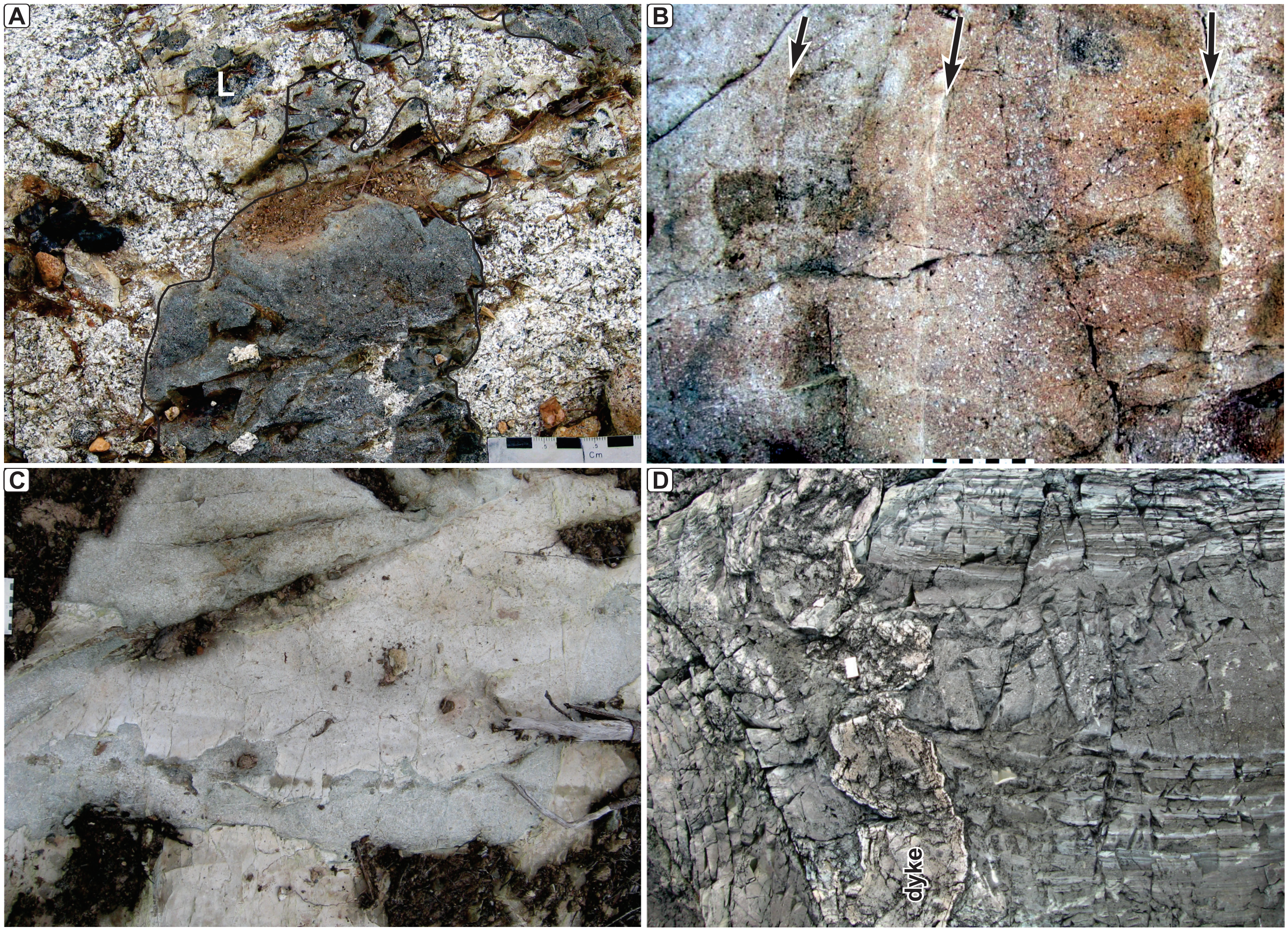

Figure 4. Representative photographs of Tremadocian ophiolitic rocks in the Annieopsquotch accretionary tract. A. Gabbro-granodiorite mingling on the margin of the Mansfield Cove Complex. L – false mingling texture produced by lichen. B. Layered gabbro formed by injection of multiple differentiated gabbro sills, Moreton's Harbour Group on Fortune Harbour Peninsula. C. Sheeted dyke complex with scalloped contacts between dykes that suggest repeated injection of magma into crystal mush, Moreton's Harbour Group on Fortune Harbour Peninsula. D. Semi-consolidated submarine mafic tuff cut by mafic feeder dyke, Moreton's Harbour Group on New World Island.

O'Brien 2009), including a felsic tuff dated at 472 ± 4 Ma (Fig. 8A, Table A1). The structural complexity and paucity of data make the stratigraphic reconstruction of the Gullbridge area very difficult. In the Buchans area (Fig. 1), Floian volcanic rocks (ca. 471 Ma; Dunning et al. 1987; G. Dunning, personal communication 2012) occur within Darriwilian (Whalen et al. 2013) debris flows that host volcanogenic massive sulphide deposits (e.g. Thurlow and Swanson 1987). This suggests that Floian arc basement was locally exhumed along rift and/or caldera walls during subsequent Darriwilian arc development (Whalen et al. 2013). In the Robert's Arm area, evidence for Floian arc activity is mainly preserved as detritus in conglomerates locally exposed at the stratigraphic base of the Darriwilian arc (Fig. 8B; Table A1).

The presence of inherited zircon in felsic volcanic rocks (Fig. 8A; Zagorevski et al. 2006), detritus in associated sedimentary rocks (Fig. 8B), and low ε_{Nd} values in both mafic (0.9) and felsic (– 4.0 to –10.2) volcanic rocks (Table A3; Swinden et al. 1997; Zagorevski et al. 2006) indicate that the Floian arc was also built on a continental substrate. Although zircon inheritance data are limited, ca. 1.0, 1.20 – 1.25, 1.7 – 1.8 and >2.6 Ga ages (Table 1) are consistent with major peaks of magmatism in Laurentia, including the Grenville orogeny, Mezoproterozoic convergent margin magmatism, Paleoproterozoic Laurentian assembly, and Archean craton assembly (e.g. Cawood and Nemchin 2001), as well as Ediacaran rift magmatism associated with the opening of the Iapetus Ocean (Cawood et al. 2001; van Staal et al. 2013).

The Floian arc was subjected to significant extension, as evidenced by the presence of coeval transitional tholeiitic to calc-alkaline arc and bimodal volcanic rocks, and consanguineous ophiolite complexes. The latter are best revealed in the narrow, but regionally extensive ca. 473 Ma Lloyds River ophiolite belt (Figs. 1, 3, 6E, F;

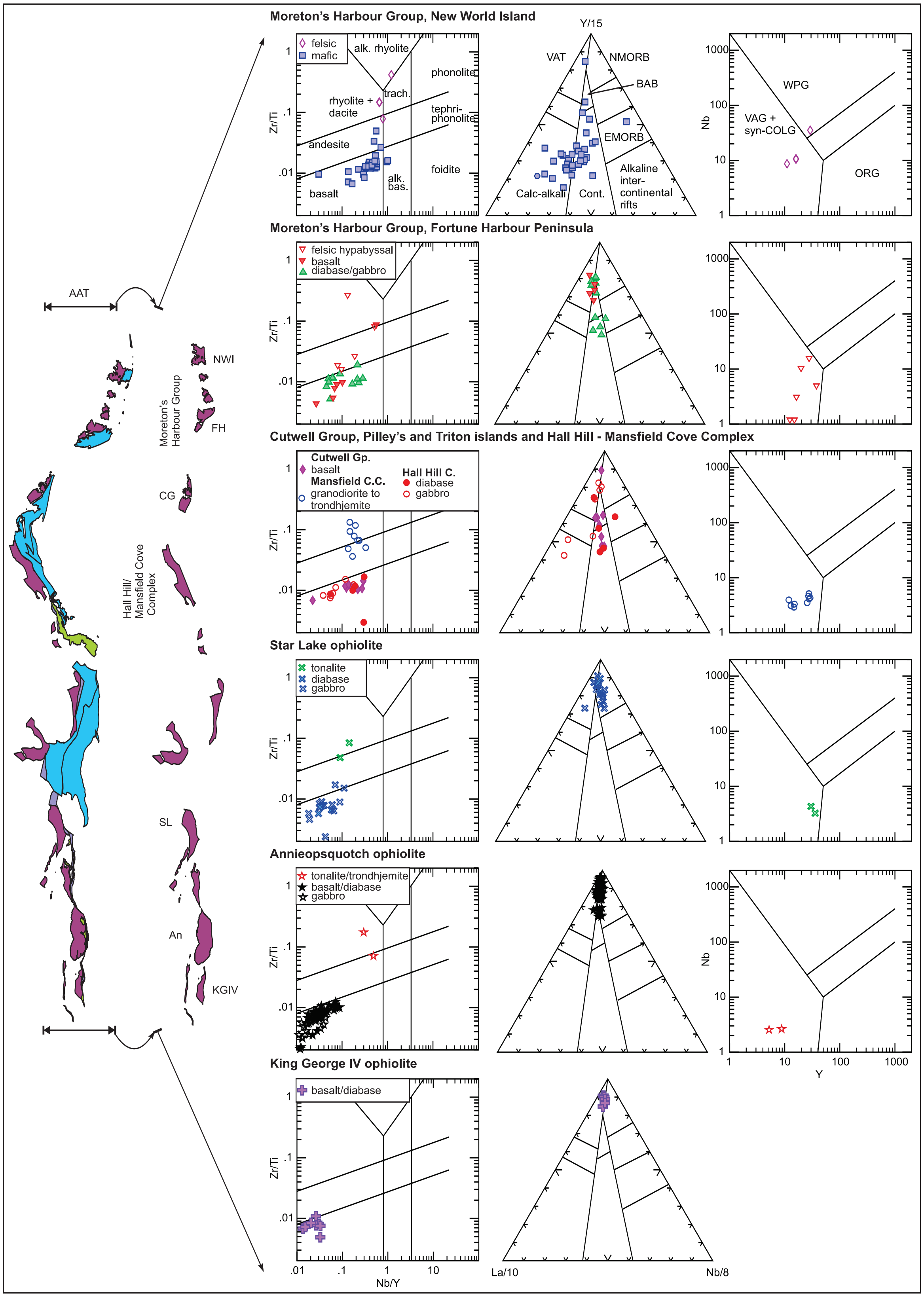

Figure 5. Geochemical characteristics of the Annieopsquotch ophiolite belt. Discrimination plots, from left to right: Nb/Y vs. Zr/Ti (Pearce 1996); La–Nb–Y ternary plot (Cabanis and Lecolle 1989); Nb vs. Y (Pearce et al. 1984). Data sources: Dec and Swinden 1994; Davenport et al. 1996; Swinden 1996; Dec et al. 1997; Rogers 2004; Zagorevski and Rogers 2011; Cutts et al. 2012; Whalen 2012). Geochemistry of felsic rocks in the King George IV ophiolite is not available. AAT – Annieopsquotch accretionary tract; AN – Annieopsquotch ophiolite; CG – Cutwell Group; FH – Fortune Harbour peninsula; KGIV – King George IV ophiolite; NWI – New World Island; SL – Star Lake.

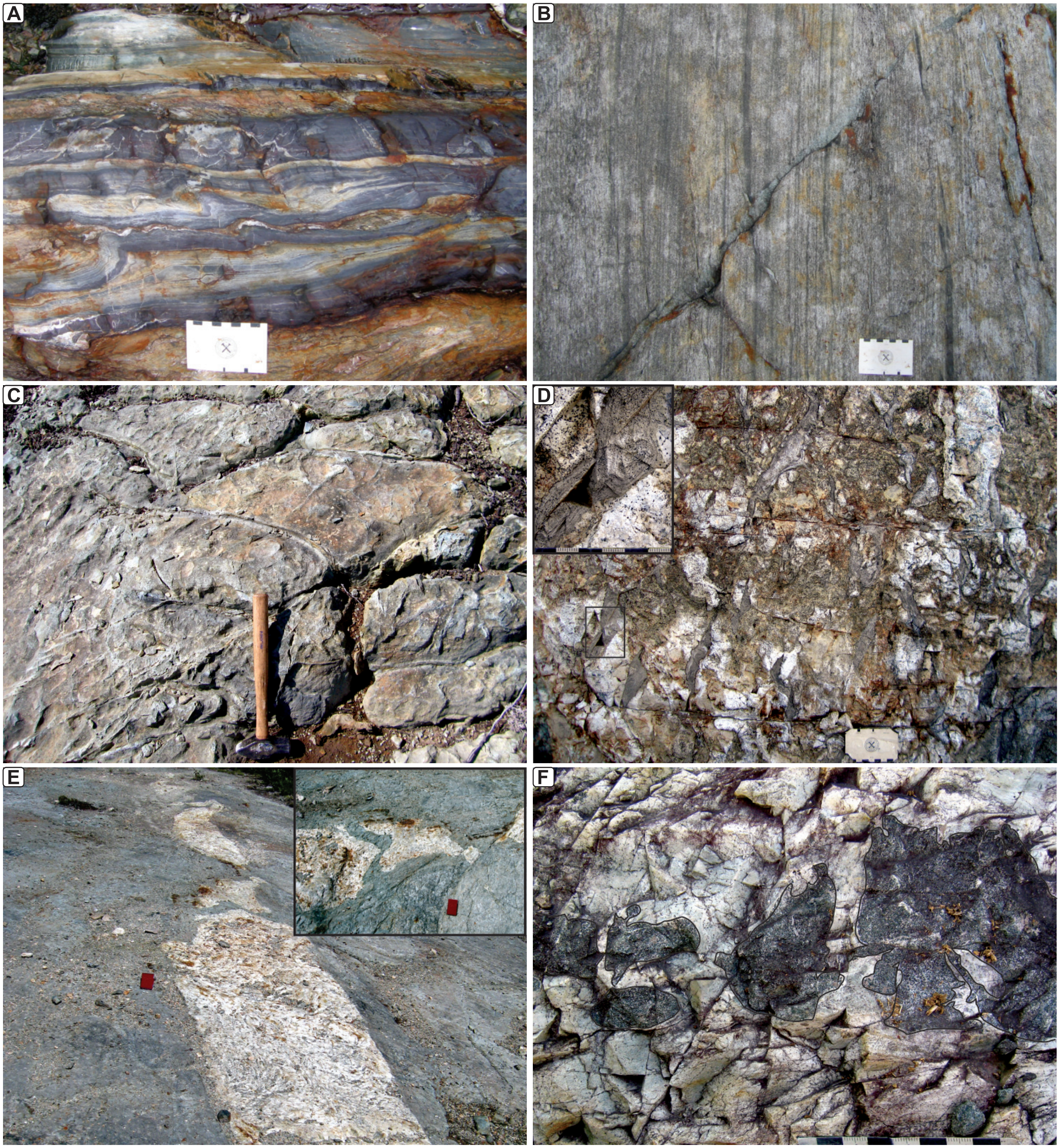

Figure 6. Representative photographs of Floian ophiolitic and arc rocks in the Annieopsquotch accretionary tract. A. Interbedded jasperite and felsic epiclastic tuff near the Gullbridge VMS deposit, Robert's Arm Group. This sequence is contact metamorphosed by the Silurian Hodges Hill batholith. B. The ca. 472 Ma bedded and foliated felsic lapilli tuff near the Gullbridge VMS deposit, Robert's Arm Group; U–Pb geochronological data are shown in Figure 8A. C. Pillow basalt in bimodal felsic – mafic sequence, Dawes Pond area, Robert's Arm Group. D. Rhyolite breccia containing finely flow-banded, spherulitic fragments (inset), Dawes Pond area, Robert's Arm Group. E. Boudinaged ca. 472 Ma trondhjemite dyke in the sheeted dyke complex of the Lloyds River ophiolite complex, South Pond area. Inset: Detail of boudin neck filled with and cut by fine-grained gabbro. F. Disaggregated gabbro sheet (dark, outlined in black) in lighter-coloured diabase, Lloyds River ophiolite complex, South Pond area. Such interaction, documented in the gabbro and cumulate zones of ophiolites (e.g. Lissenberg et al. 2004; Bédard 2014), likely also results in hybridization of different batches of magma in the sheeted dyke complexes.

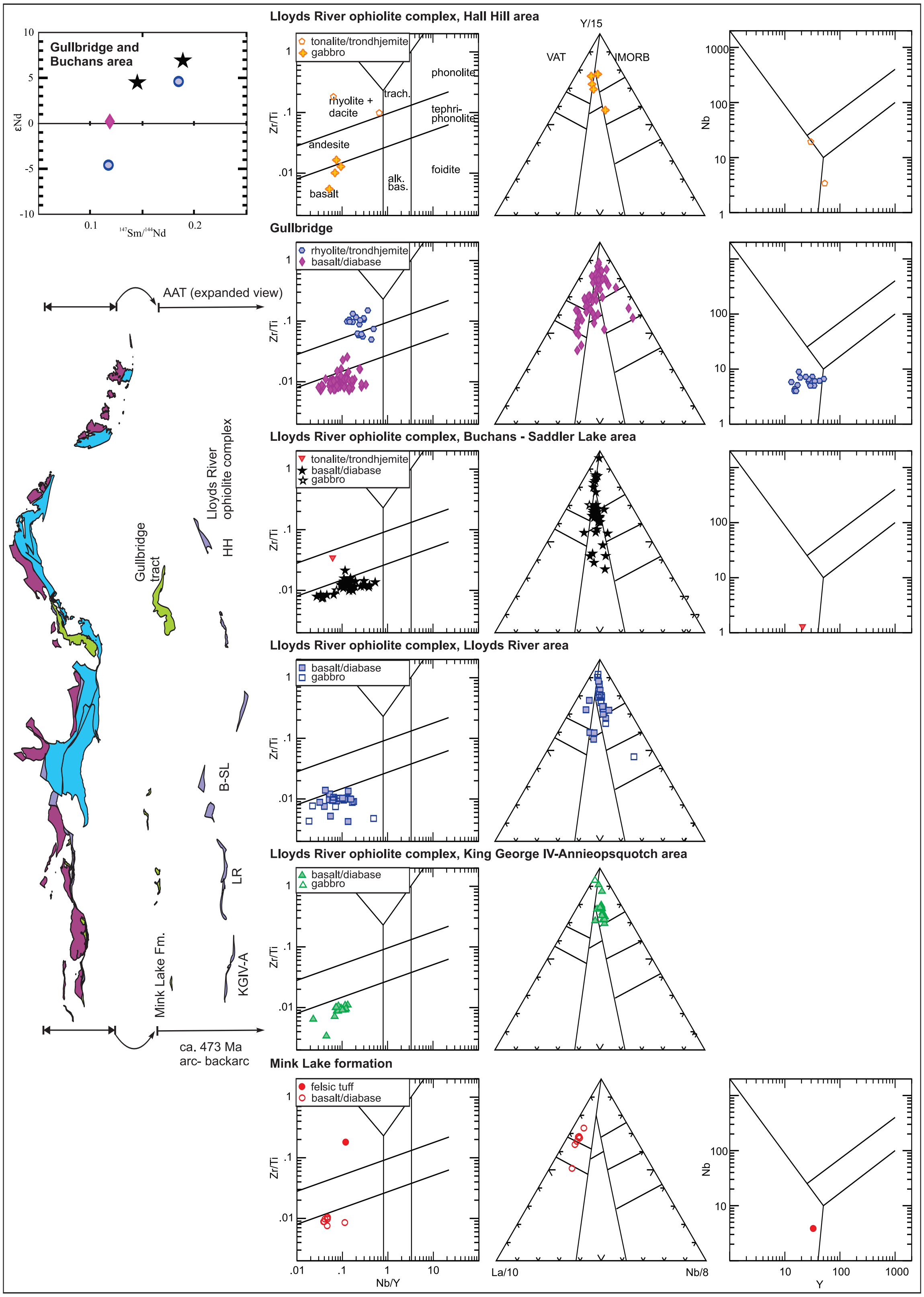

Figure 7. Geochemical characteristics of the Floian arc and backarc. Discrimination plots, from left to right: Nb/Y vs. Zr/Ti (Pearce 1996); La–Nb–Y ternary plot (Cabanis and Lecolle 1989); Nb vs. Y (Pearce et al. 1984). Data sources: Dec and Swinden 1994; Davenport et al. 1996; Swinden 1996; Dec et al. 1997; Rogers 2004; Zagorevski and Rogers 2011; Cutts et al. 2012; Whalen 2012). AAT – Annieopsquotch accretionary tract; KGIV-A – King George IV–Annieopsquotch area; LR – Lloyds River area; B-SL – Buchans and Star Lake areas; HH – Hall Hill – South Pond area. Felsic analyses are not available for the Lloyd's River ophiolite complex in the King George IV–Annieopsquotch and Lloyds River areas. Top left: Sm–Nd isotopic characteristics of the Lloyds River ophiolite complex and Gullbridge area volcanic rocks (see Table A3).

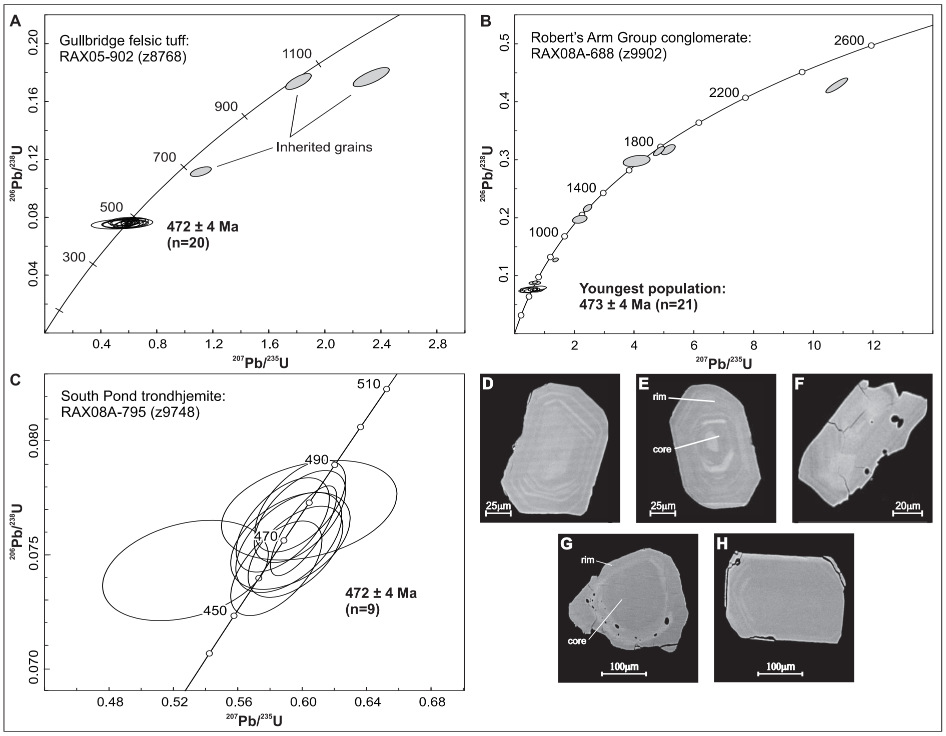

Figure 8. U–Pb concordia diagrams and backscatter (BSE) scanning electron microscope (SEM) images of zircon grains; see also Appendix 2 and Table A1. A. U–Pb concordia diagram of zircon analyses from a Gullbridge felsic tuff. B. U–Pb concordia diagram of detrital zircon analyses from a Robert's Arm Group conglomerate. C. U–Pb concordia diagram of zircon analyses from the South Pond trondhjemite (see Fig. 6E for sampled locality). D. Magmatic zircon grain displaying growth zoning, from the Gullbridge felsic tuff (RAX05-902). E. Zircon grain showing a small apparent core, from the Gullbridge felsic tuff (RAX05-902). F. Zircon grain showing growth zoning, from the South Pond trondhjemite (RAX08A-795). G. Detrital zircon grain displaying a magmatic rim on an inherited core, Boot Harbour conglomerate, Robert's Arm Group (RAX08A-688). H. Euhedral zircon grain showing faint growth zoning, from the Boot Harbour conglomerate (RAX08A-688).

Zagorevski et al. 2006). The Lloyds River ophiolite belt preserves variably deformed layered and isotropic gabbro, sheeted dykes, pillow basalt, trondhjemite (Fig. 6E), and minor sedimentary rocks. Correlatives of the Lloyds River ophiolite belt are present in the Gullbridge area (Gull Pond basalt; Pope et al. 1991), and continues into the Robert's Arm area, where a unit that includes gabbro, sheeted dykes and trondhjemite (Fig. 6E, F) yielded a 472 ± 4 Ma age (Fig. 8C). The presence of a well-developed sheeted dyke complex implies that some of the extension was accommodated by formation of an organized, magma-rich spreading centre, suggesting that arc extension led to formation of a discrete backarc basin hosting a spreading centre(s).

The Lloyds River ophiolite belt is internally more structurally disrupted than the adjacent Annieopsquotch ophiolite belt and this disruption involved both intra-oceanic and syn- to post-accretionary structures. For example, local juxtaposition of the upper sheeted dyke complex (i.e., sheeted dykes with abundant pillow basalt screens) with layered gabbro (Fig. 3) suggests excision of ophiolite stratigraphy by extension, probably by formation of shallowly dipping intra-oceanic detachments. The latter are typical of relatively magma-poor, slow-spreading centres and/or oblique spreading centres (e.g. Ohara et al. 2003). Floian ophiolitic rocks are characterized by LREE-enriched continental rift and backarc basalt, as well as by normal mid-ocean-ridge basalt compositions consistent with an overall backarc basin setting (Fig. 7; Zagorevski et al. 2006, 2010a).

The preservation of Floian arc rocks both inboard and outboard of the Lloyds River ophiolite belt suggests that the arc rifting occurred near to, or along the magmatic front. This led to formation of an inactive remnant arc ridge preserved inboard (Mink Lake and parts of the Gullbridge belt; Fig. 1) and an active arc segment (Buchans and Robert's Arm groups; Figs. 8B, C, 9, 10A; Dunning et al. 1987; Whalen et al. 2013) that became basement to subsequent Darriwilian arc magmatism. This style of complex arc – backarc development is similar to the relationships observed in the Izu – Bonin – Mariana and Tonga – Kermadec arcs. In the Izu – Bonin – Mariana arc, opening of both the Parece – Vela and West Mariana backarc basins occurred along the magmatic front, leading to development of remnant arc ridges (Palau – Kyushu Ridge and West Mariana; e.g. Taylor 1992). The extension in these backarc basins was accommodated by development of a spreading centre or centres and intra-oceanic detachments, such as observed in modern backarc basins (e.g. Ohara et al. 2003). The development of such detachments may indicate moderate magma supply during extension (Tucholke et al. 2008) or may represent a switch to a magma-poor rift system (MacLeod et al. 2009). A similar history is preserved in the northern Tonga – Kermadec arc, where opening of the Lau basin led to development of a remnant Lau arc, several overlapping spreading centres and the active Tofua arc (e.g. Smith and Price 2006).

Darriwilian Arc (468 to 460 Ma)

Elements of the Darriwilian arc phase are preserved in several units, each characterized by a discrete volcano-stratigraphic anatomy, indicative of rapid changes in tectonic setting along strike (Fig. 9). They have been dispersed along the Red Indian Line and will be described below from southwestern Newfoundland to northeastern Notre Dame Bay (Fig. 1). The Darriwilian arc units are generally better preserved than most of the Floian arc – backarc complexes (Fig. 1). This is to be expected in highly extensional arc

Table 1: Isotopic and inheritance characteristics of Darriwilian rocks in the Annieopsquotch Accretionary Tract

	Age (Ma)	$\varepsilon_{Nd(465\ Ma)}$	T_{DM} (Ga)	Inherited/ detrital zircon (Ga)	Tectonic setting
Red Indian Lake group: *King George IV - south shore of Red Indian Lake*	460-465	-7.7 to 7.7	1.1 to 2.1	0.9 to 1.8, ca. 1.5 and 2.3 upper intercepts	Continental arc/ Back-arc
Otter Pond Complex: *King George IV - Red Indian Lake*	468±2	-6.8 to -0.9	1.3 to 1.7	0.473	Stitching/overlap continental arc
Red Indian Lake group: *north shore of Red Indian Lake*	464.8±3.5; 465±4; 464±4; <467±4 *Darriwilian*[1]	-11.2 to 5.2	1.0 to 2.2	0.5 to 2.8	Continental arc/ back-arc
Buchans Group: *north shore of Red Indian Lake*	462±4; 463±4; 465±4; 465±4; ca. 471	-3.8 to -1.8	1.3 to 1.7	0.5 to 3.4	Continental arc
Mary March Brook group: *north shore of Red Indian Lake*	461.5±4; 461.5±4	-5.8 to 6.0	1.0 to 2.4	0.6	Continental arc – intra-arc rift/back arc
Robert's Arm Group, Notre Dame Bay	ca. 473-464	-2.2 to 4.3	1.0 to 1.8	0.5 to 2.7	Continental arc
Crescent Lake Terrane, Ghost Pond sequence: *Notre Dame Bay*	467±3; 466±3	-6.3 to 6.7	1.1 to 1.9	0.48 to 2.6	Continental arc – intra-arc rift/back arc
Cottrell's Cove – Group: *Notre Dame Bay*	ca. 466; *possibly Darriwilian*[1]	-10.4	1.9	0.56 to 2.6, ca. 2.5 upper intercept	Continental arc - backarc
Chanceport Group: *Notre Dame Bay*	Correlated with CCG and RAG	–	–	–	Continental arc - backarc

[1]fossil age constraints

Sources of data: Dunning et al. (1987); Nowlan (1996); Nowlan and Thurlow (1987); Dec et al. (1997); Nowlan (1997); Swinden et al. (1997); O'Brien (2003); Zagorevski et al., (2006); O'Brien (2008; 2009); Zagorevski and Rogers (2011); van Staal and Zagorevski (2012); Coombs et al. (2012); Zagorevski and McNicoll (2012); Whalen et al., (2013); Willner et al. (2014); Zagorevski et al. (unpublished data); F. Cordey, unpublished data

systems, as remnant arc ridges are typically narrow and thin (e.g. Calvert 2011) and lack sufficient size and buoyancy for good preservation during accretion (Cloos 1993). In addition, Darriwilian arc – backarc complexes escaped the pre-Darriwilian deformation history that affected the Floian arc – backarc complexes (ca. 470 Ma; Lissenberg et al. 2005b).

In the southwestern and central parts of the AAT, the Darriwilian arc is represented by the Red Indian Lake Group, which comprises continental calc-alkaline volcanic rocks that were deposited on top of a juvenile tholeiitic oceanic backarc-like basement (Figs. 1, 9; Zagorevski et al. 2006). Sheeted dykes are locally preserved but, in general, poorly exposed. The tholeiitic basement comprises IAT to backarc basin pillow basalt and minor felsic volcanic rocks, suggesting a rifted arc or backarc setting (Fig. 11; Zagorevski et al. 2006). The transition from tholeiitic basement to calc-alkaline volcanism is in many places marked by deposition of polymictic conglomerates that were derived from coeval volcanic rocks and a slightly older continental andesitic arc – backarc complex (467 ± 4 Ma; Coombs et al. 2012).

Farther to the northwest, the Mary March, Buchans and Red Indian Lake groups form three distinct and, in part, coeval Darriwilian volcanic sequences that were structurally juxtaposed, mainly by thrust faulting, in the Buchans area (Figs. 1, 9, 12; Thurlow et al. 1992; Zagorevski and Rogers 2008, 2009; Zagorevski et al. 2010a). The structurally highest Mary March Group is predominantly characterized by tholeiitic bimodal volcanism (Fig.

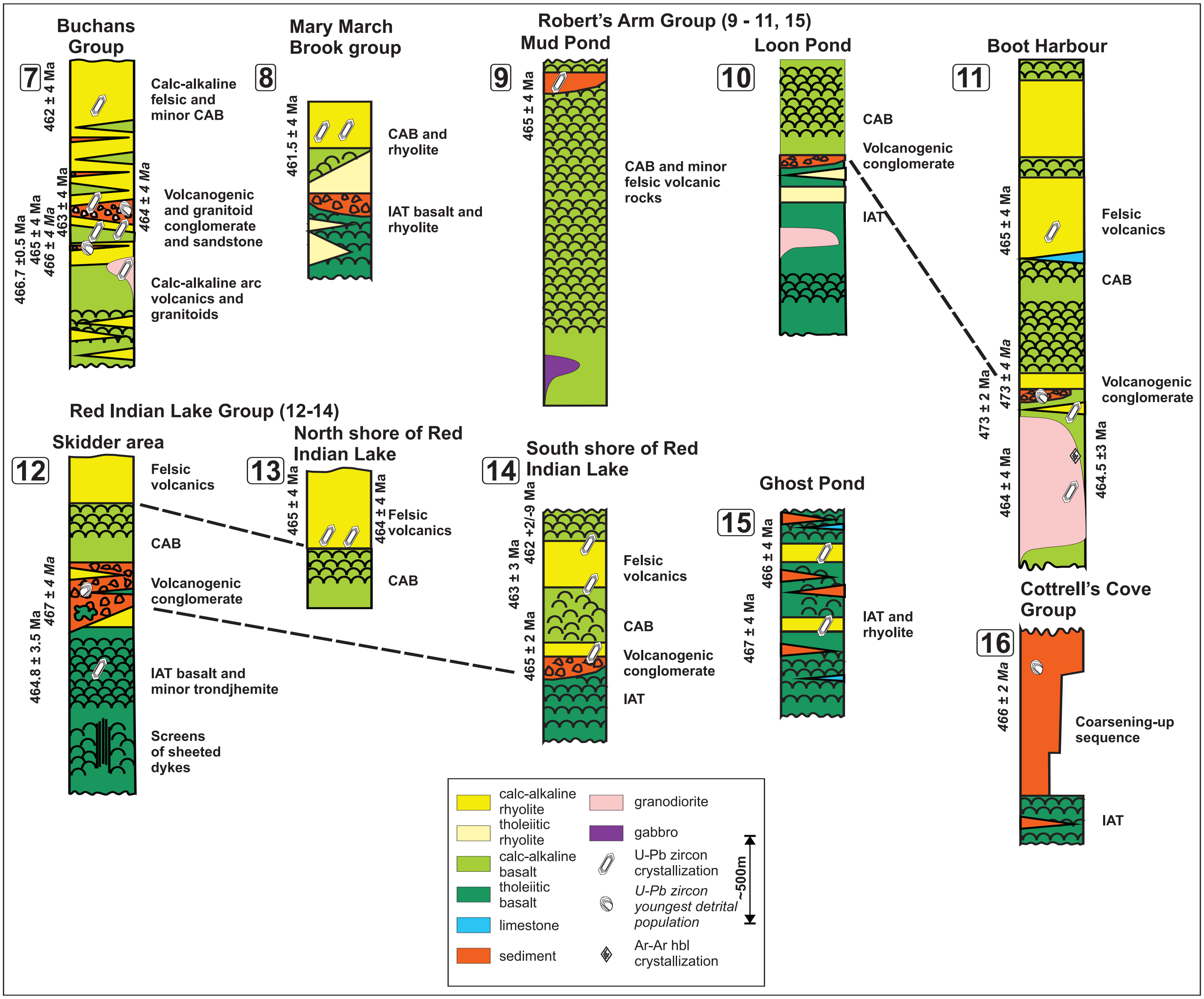

Figure 9. Schematic stratigraphy of Darriwilian rocks in the Annieopsquotch accretionary tract. 7. Buchans Group (Thurlow and Swanson 1987; van Hees et al. 2012; Whalen et al. 2013). 8. Mary March Brook Group (Zagorevski and Rogers 2008, 2009). 9. Mud Pond assemblage, Robert's Arm Group. 10. Loon Pond assemblage, Robert's Arm Group. 11. Boot Harbour assemblage, Robert's Arm Group (Dunning et al. 1987; Bostock 1988; Kerr 1996). 12–14. Red Indian Lake Group (Zagorevski et al. 2006; Zagorevski and Rogers 2009). 15. Ghost Pond assemblage, Robert's Arm Group (Zagorevski and McNicoll 2012). 16. Moore's Cove Formation, Cottrell's Cove Group (Dec et al. 1997; Willner et al. 2014).

11; Zagorevski and Rogers 2009). Tholeiitic rhyolite cryptodomes were emplaced coevally with pillow basalts having IAT compositions, leading to rapid facies changes (Zagorevski and Rogers 2009). Eruption of these volcanic rocks was accompanied by emplacement of polymictic debris flows and locally, pervasive hydrothermal alteration and VMS mineralization, all indicative of an extensional environment. Collectively, these characteristics suggest a backarc or intra-arc rift setting. The primitive tholeiitic bimodal sequence is conformably overlain by more evolved, continentally contaminated rhyolite. Both tholeiitic and calc-alkaline sequences yielded indistinguishable U–Pb zircon ages of 462 ± 4 Ma (Fig. 9; Zagorevski et al. unpublished data).

The structurally underlying Buchans Group comprises calc-alkaline basaltic and rhyolitic rocks of continental arc affinity, along with locally abundant granitoid-bearing conglomerate and debris flows, constituting the Lundberg, Ski Hill and Buchans River formations, respectively (Thurlow and Swanson 1987; van Hees et al. 2012). New geochronological data indicate that volcanism occurred between 465 ± 4 to 463 ± 4 Ma (Zagorevski et al. unpublished data). These rocks are structurally underlain by felsic crystal tuff, arkose and conglomerate of the stratigraphically younger Sandy Lake Formation (Thurlow and Swanson 1987) which yielded a 462 ± 4 Ma age

Figure 10. Representative photographs of Darriwilian arc and forearc rocks in the Annieopsquotch accretionary tract. A. Felsic volcanic-dominated Boot Harbour conglomerate containing well-rounded cobbles; sandstone intercalated with these rocks yielded ca. 473 Ma zircons (Fig. 8B). Base of the Darriwilian arc volcanic sequence, Robert's Arm Group, Robert's Arm area. B. Polymictic conglomerate of the Boot Harbour assemblage, dominated here by felsic volcanic clasts and angular jasperite 'bricks', Robert's Arm Group, Robert's Arm area. C. Consanguineous Woodfords Arm monzogranite and diorite (ca. 465 Ma). Diorite is outlined for clarity. D. Flow-aligned pipe vesicles in Hayward's Bight rhyolite, Robert's Arm Group. E. Cherty felsic tuff at the top of the Mud Pond assemblage, Robert's Arm Group. F. Cleaved forearc basin sediments, Fortune Harbour Formation, Cottrell's Cove Group. G. Strongly deformed turbiditic sandstone and siltstone along the forearc basement – accreted Tommy's Arm River (seamount) sequence boundary, Crescent Lake composite terrane. H. Mafic-derived conglomerate and sandstone of the Tommy's Arm River seamount assemblage, Crescent Lake composite terrane.

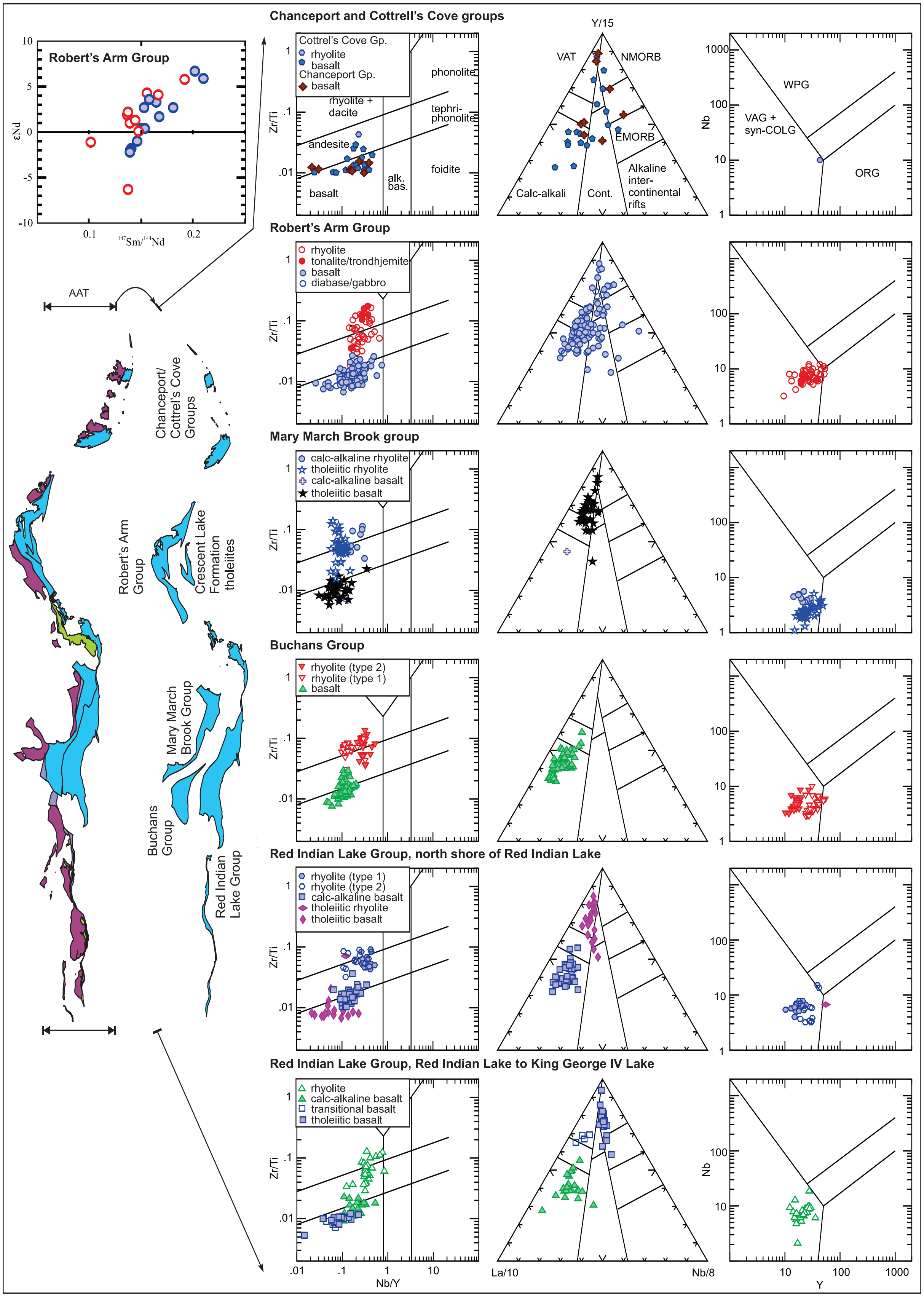

Figure 11. Geochemical characteristics of the Darriwilian arc and backarc. Discrimination plots, from left to right: Nb/Y vs. Zr/Ti (Pearce 1996); La–Nb–Y ternary plot (Cabanis and Lecolle 1989); Nb vs. Y (Pearce et al. 1984). Data sources: Dec and Swinden 1994; Davenport et al. 1996; Swinden 1996; Dec et al. 1997; Rogers 2004; Zagorevski and Rogers 2011; Cutts et al. 2012; Whalen 2012). Top left: Sm–Nd isotopic characteristics of the Robert's Arm Group (see Table A3).

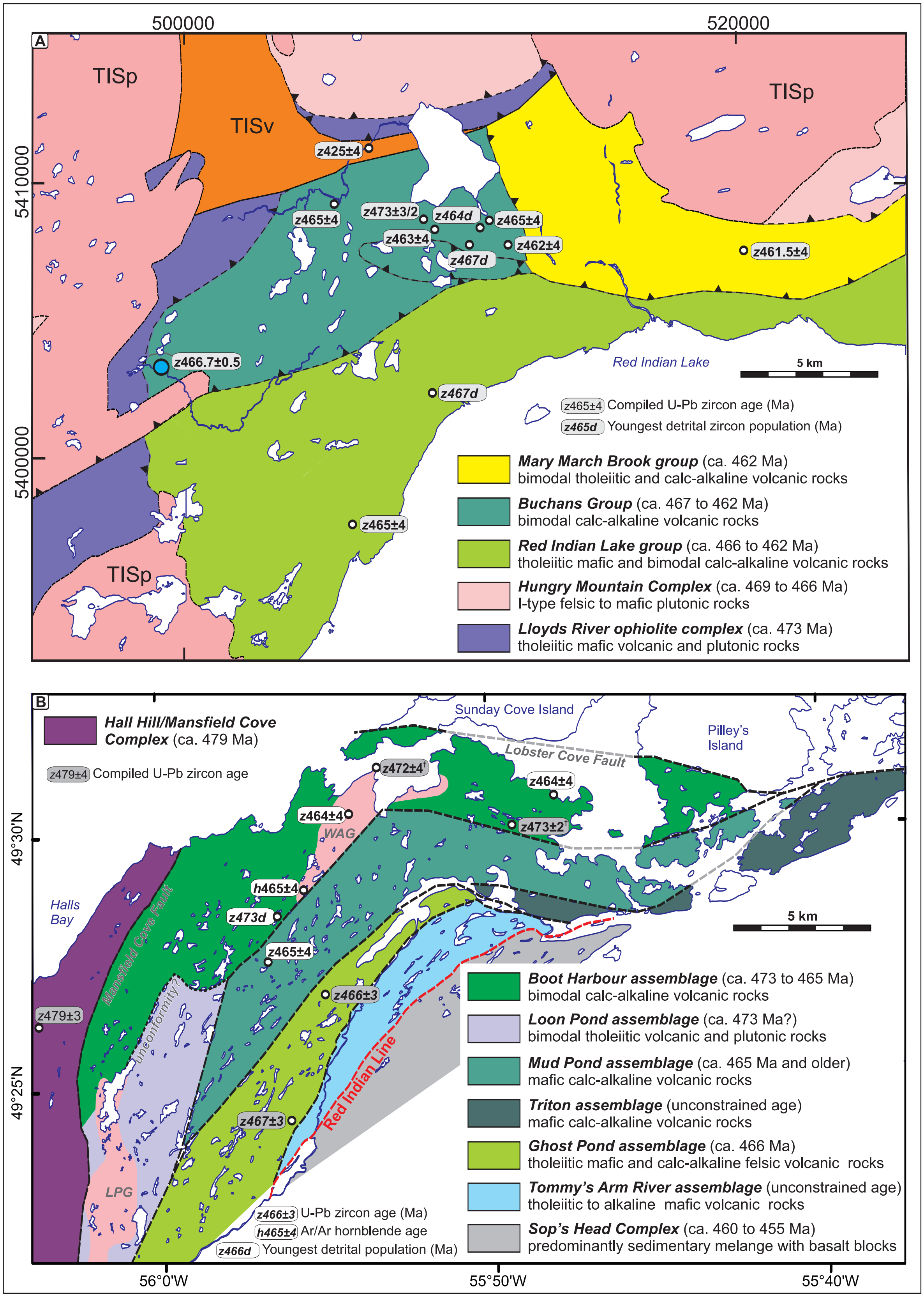

Figure 12. Simplified geology of the Buchans (A) and Robert's Arm (B) areas (geology modified from Whalen et al. (2013) and Bostock (1988), respectively). Geochronology is compiled from Dunning et al. 1987; Kerr and Dunning 2003; Zagorevski et al. 2006; Coombs et al. 2012; Whalen et al. 2013 and this paper (see Appendix 2). LPG – Loon Pond granite; TISp – Topsails Igneous Suite plutonic rocks; TISv – Topsails Igneous Suite volcanic rocks; WAG – Woodfords Arm monzogranite; "d" refers to the youngest detrital zircon population in the dated sample.

(Zagorevski et al. unpublished data). Granitoid-bearing conglomerate within the Buchans River Formation has zircon provenance and granitoid clast crystallization ages (466 ± 4 Ma; Whalen et al. 2013) that indicate derivation from a slightly older and/or broadly coeval volcanic sequence, whereas some of the debris flows contain volcanic blocks derived from the underlying Floian arc (473 +3/–2 Ma; Dunning et al. 1987; G. Dunning, personal communication 2012). Stratigraphic relationships with this inferred Floian basement are not exposed or are not preserved.

The most extensive Darriwilian volcanic sequences are exposed north of Buchans in the Notre Dame Bay area (Figs. 1, 12) and are assigned to the Robert's Arm Group, which is similarly complex in its tectono-stratigraphy and comprises volcanic sequences having tholeiitic and calc-alkaline affinities preserved in several structural panels (Bostock 1988; Kerr 1996; Zagorevski and McNicoll 2012). Contacts between these panels are now generally marked by late brittle-ductile and brittle faults. These generally north and northwest facing structural panels were termed *terranes* by Bostock (1988) and Kerr (1996); however, the relationship between some of these *terranes* may be stratigraphic. To differentiate this broader definition of *terrane* from tectonic terranes used elsewhere in the manuscript, we will informally use *'assemblage'* to identify mappable stratigraphic units. The Mud Pond, Boot Harbour and Triton assemblages (terranes of Bostock 1988; Figs. 1, 9, 11, 12) predominantly comprise calc-alkaline volcanic rocks, including thick pillow basalt sequences. The adjacent tholeiitic mafic and calc-alkaline felsic volcanic rocks were grouped into the Crescent terrane by Bostock (1988) on the basis of chemistry, although it was recognized that it was composed of several distinct tectono-stratigraphic sequences.

The Boot Harbour assemblage preserves the most diverse stratigraphic sequence (Figs. 9, 12). The base of the Boot Harbour assemblage contains a felsic volcanic-derived conglomerate containing 473 ± 4 Ma zircons (Figs. 8B, 9; Dunning et al. 1987). The provenance of the conglomerate indicates that the Darriwilian volcanic arc rocks of the Robert's Arm Group were, at least in part, also built on top of an older Floian arc substrate. The stratigraphic contact with Floian basement is probably preserved in the southwestern Boot Harbour assemblage, where polymictic and jasper-rhyolite cobble to boulder conglomerate (Figs. 10B, 12) marks the contact between Darriwilian volcanic rocks and the underlying tholeiitic rocks (herein termed the Loon Pond assemblage: Fig. 12). Bostock (1988) included these tholeiitic rocks in the Crescent terrane; however, they lie along strike with the 472 ± 4 Ma Gullbridge belt (Fig. 8A) and South Pond trondhjemite (Figs. 8C, 9), suggesting that they form part of the Floian arc – backarc complex. A significant angular discordance across the contact with the overlying conglomerate (Bostock 1988) suggests that the Floian and Darriwilian arc phases are separated here by an angular unconformity. Further to the northeast, Dunning et al. (1987) obtained a 473 ± 2 Ma age from a breccia (Fig. 12), suggesting that either the basement or detritus derived from it are present along most of the base of the Boot Harbour assemblage.

The sedimentary and associated volcaniclastic rocks are overlain by a thick sequence of submarine basalt and andesite. These rocks range from massive flows and sills to spatially extensive sequences of amygdaloidal pillow lavas, minor pillow breccia, and mafic-derived epiclastic sediments. Felsic volcanic rocks are common near the stratigraphic top of the Boot Harbour assemblage, and consanguineous granodiorite and gabbro bodies of the Woodfords Arm pluton intrude the lower stratigraphic levels (Figs. 10C, D, 12; Bostock 1988). Volcanic rocks yielded 465 ± 4 Ma age whereas the Woodfords Arm pluton yielded U–Pb and Ar–Ar ages of 464 ± 4 and 464.5 ± 3.0 Ma, respectively (Fig. 13A–C; Table A1).

The associated Mud Pond and Triton assemblages (Fig. 12) are dominated by submarine calc-alkaline mafic volcanic rocks, and in a broad sense may be stratigraphic equivalents of the Boot Harbour assemblage. The only age constraints on these rocks come from bedded, siliceous tuff at the top of the Mud Pond assemblage, which yielded an age of 465 ± 4 Ma (Figs. 10E, 13D; Table A1), indicating that it was in part contemporaneous with Boot Harbour assemblage magmatism. Without additional age constraints it is difficult to discern the exact stratigraphic relationships between the assemblages in the Robert's Arm Group.

The Crescent Lake composite terrane is divided into two distinct sequences, the Ghost Pond arc and Tommy's Arm River seamount assemblages, both representing tectonic terranes (Fig. 12). The Ghost Pond assemblage is characterized by IAT basalt, calc-alkaline rhyolite (466 ± 4 and 467 ± 4 Ma), red shale, and jasperite (Zagorevski and McNicoll 2012). The latter rocks are locally abundant and a distinctive feature of this unit. Rhyolite contains abundant zircon inheritance (0.5, 0.85, 1.1, 1.4, 1.6, 2.6 Ga; Zagorevski and McNicoll 2012), similar to rocks that define the Floian arc (Table A1) and the Laurentian margin (Cawood and Nemchin 2001). The abundant IAT suggests a tectonic environment akin to a rifted arc or backarc forming within attenuated continental crust (Zagorevski and McNicoll 2012). The Tommy's Arm River assemblage comprises an accreted seamount characterized by geochemically distinctive ocean island basalt (Bostock 1988; Zagorevski and McNicoll 2012).

To the east of the Robert's Arm Group, the correlative Cottrell's Cove Group displays similar stratigraphic and geochemical complexity (Fig. 1; Dec et al. 1997; Swinden et al. 1997; O'Brien 2003). The Cottrell's Cove Group is divided into the volcanic-dominated Fortune Harbour Formation and the predominantly sedimentary Moore's Cove Formation (Dec et al. 1997; O'Brien 2003). We interpret the Moore's Cove Formation as part of the forearc basin attached to the Darriwilian arc (see following). The Fortune Harbour Formation comprises the most northeasterly component of the Darriwilian arc, and contains both calc-alkaline and tholeiitic basalt and locally abundant rhyolite. The tholeiitic chemistry of basalts, olistostromes, and abundant volcaniclastic rocks in the Fortune Harbour Formation suggest a

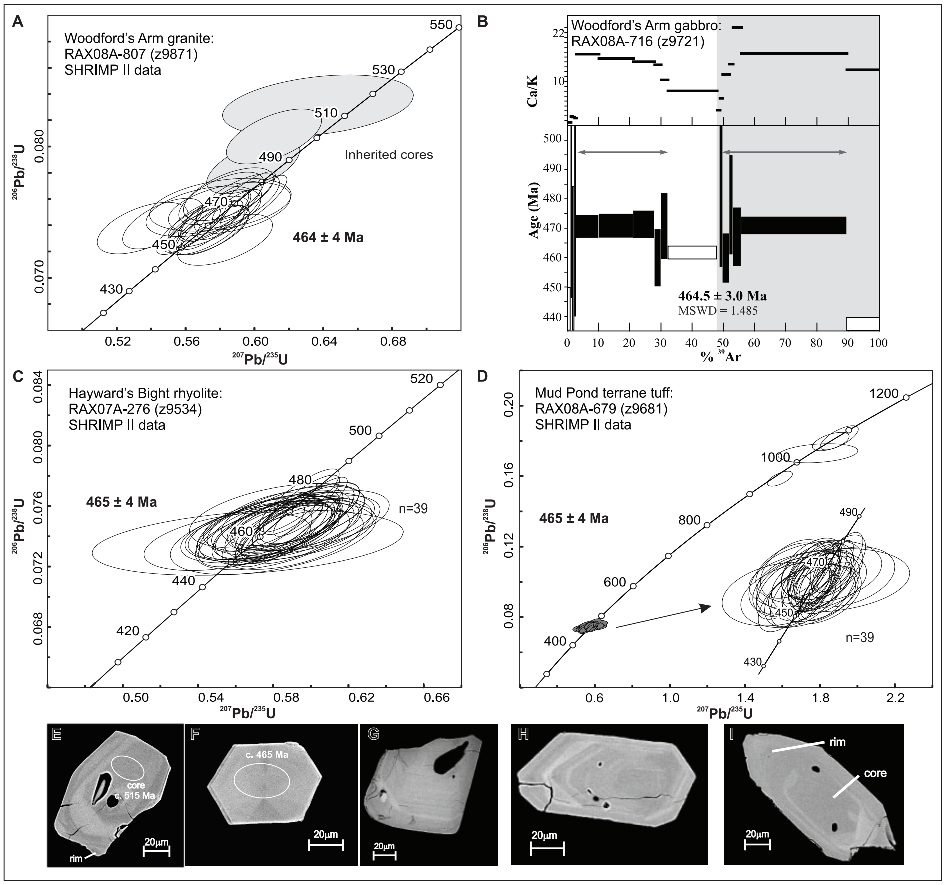

Figure 13. U–Pb concordia diagrams, $^{40}Ar/^{39}Ar$ spectra and backscatter (BSE) scanning electron microscope (SEM) images of zircon grains; see also Appendix 2 and Tables A1 and A2. A. U–Pb concordia diagram of zircon analyses from the Woodfords Arm monzogranite, Robert's Arm Group. B. $^{40}Ar/^{39}Ar$ gas release spectra for hornblende in Woodfords Arm hornblende diorite, Robert's Arm Group. C. U–Pb concordia diagram of zircon analyses from the Hayward's Bight rhyolite, Robert's Arm Group. D. U–Pb concordia diagram of zircon analyses from felsic tuff of the Mud Pond assemblage, Robert's Arm Group. E. Zircon from the Woodfords Arm monzogranite, showing an inherited core (RAX-08A-807; analysis 9871.39, Table A1). F. Magmatic zircon with sector zoning from the Woodfords Arm monzogranite (RAX-08A-807; analysis 9871.12, Table A1). G. Magmatic zircon showing faint growth zoning, from the Hayward's Bight rhyolite (RAX-07A-276; analysis 9534-2, Table A1). H. Magmatic zircon showing growth zoning, from the Mud Pond assemblage tuff (RAX-08A-679; analysis 9681-45.1, Table A1). I. Zircon showing an inherited core from the Mud Pond assemblage tuff (RAX-08A-679; analysis 9681-26, Table A1).

transition from a continental arc to a backarc or intra-arc basin tectonic setting (Dec et al. 1997). Dec et al. (1997) obtained a lower intercept U–Pb TIMS age of 484 ± 2 Ma on the basis of three out of five discordant fractions. This age is herein considered erroneous because of the lack of concordant analyses, complex zircon inheritance, and its significantly older age compared to the correlative Robert's Arm Group. Instead, preliminary radiolarian fossil determinations suggest an Arenig to Llanvirn age (F. Cordey, personal communication 2009; between 477.7 and 458.4 Ma: Cohen et al. 2013). Although the exact timing of magmatism remains to be established, isotopic characteristics and zircon inheritance indicate that the Cottrell's Cove Group was built on continental crust (ca. 0.56 to 2.60 Ga inheritance in figure 9 of Willner et al. 2014; ca. 2.6 Ga inheritance in Dec et al. 1997; rhyolite ε_{Nd} = 10.2 in Swinden et al. 1997).

As described above, the Darriwilian arc is characterized by non-systematic variations in arc stratigraphy, geochemistry and isotopic characteristics along and across strike (Figs. 9, 11). This suggests that continental calc-alkaline arc, bimodal tholeiitic intra-arc rift, and tholeiitic backarc basins all formed during the same stage of arc development. In several localities, the arc rift and backarc basin-related volcanic rocks are directly overlain by continental calc-alkaline volcanic rocks (Zagorevski et al. 2006; Coombs et al. 2012; Zagorevski and McNicoll 2012). The stratigraphic continuity between tholeiitic ophiolite sequences containing poorly developed sheeted dyke complexes and overlying continentally contaminated calc-alkaline volcanic arc sequences (e.g. Skidder Formation; Pickett 1987; Zagorevski et al. 2006; Zagorevski et al. unpublished data) suggests that discrete spreading centres, akin to the Parece – Vela basin or West Mariana trough, did not develop. Rather, these various arc-backarc segments may have formed in a tectonic setting more similar to either a) the disorganized spreading occurring in the Havre trough, where constructive volcanic centers are separated by discontinuous rift sectors along the magmatic front (e.g. Wright et al. 1996; Wysoczanski et al. 2010), or b) the early stages of arc rifting prior to development of a spreading centre such as inferred for the inception of the Mariana trough (e.g. Taylor 1992; Oakley et al. 2009).

FOREARC BASIN AND BASEMENT

The Red Indian Line represents the terminal suture zone of the main Iapetan tract (Zagorevski et al. 2008) and therefore broadly represents the site of the paleo-trench of the peri-Laurentian arc system, now represented by the AAT. The rocks immediately adjacent to this fault have geochemical characteristics that mainly suggest formation in a rifted arc or backarc basin setting (Bostock 1988; Dec et al. 1997; Zagorevski et al. 2006), suggesting that the arc-trench gap is largely missing. The missing arc-trench gap can be explained by strike-slip excision (e.g. Elders 1987), subduction of the forearc block (Boutelier et al. 2003; McIntosh et al. 2005; Zagorevski et al.

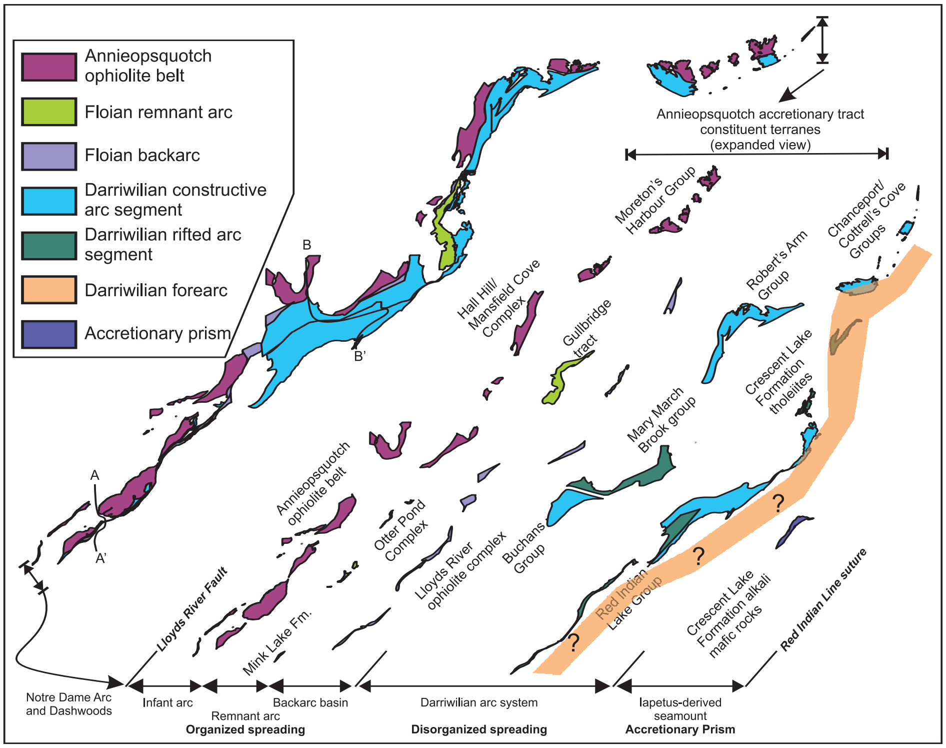

Figure 14. Schematic distribution of the infant arc spreading centre, remnant arc ridge, backarc basin spreading centre, active arc, forearc basin and accretionary prism in the Darriwilian Annieopquotch accretionary tract. The distribution of the forearc basin strata is poorly constrained. The accretionary prism is only preserved in the Robert's Arm area.

2008), subaerial erosion following syn-collisional uplift (e.g. Williams 1995b; Waldron et al. 2012) or misidentification of the tectonic setting of arc-proximal sedimentary rocks and underlying basin. Of these, strike-slip excision, forearc subduction and syn-collisional erosion are the most plausible mechanisms. However, several rock units discussed in more detail below may represent surviving remnants of the forearc environment. Previous misidentification of these rocks as foredeep or backarc-related deposits may have been a result of the ambiguous characteristics of the arc front that formed as a result of disorganized spreading. Also, sedimentary rocks deposited in the forearc, trench slope and backarc basin settings are lithologically similar and are difficult to discriminate in the absence of other tectonic setting indicators (e.g. Dickinson 1995; Clift et al. 2009). We focus specifically on the volcaniclastic and sedimentary rocks of the Ghost Pond sequence in the Crescent Lake terrane (Fig. 12; Bostock 1988; Zagorevski and McNicoll 2012) and Moores Cove Formation of the Cottrell's Cove Group (Dec et al. 1997). Both of these units occur immediately adjacent to the Red Indian Line and are overlain by sequences of arc-derived, turbiditic epiclastic rocks and associated deep water sediments (radiolarian chert, jasperite, red shale) that may represent forearc or trench slope deposits.

The sediment-dominated, >1200 m thick, Moores Cove Formation overlies the volcanic-dominated Fortune Harbour Formation of the Cottrell's Cove Group (Figs. 9, 10F; Dec et al. 1997). Limestone within the lower part of the Moores Cove Formation yielded Floian to Darriwilian (late Arenig to early Llanvirn) conodonts (Nowlan 1996, 1997) and radiolaria (F. Cordey, personal communication 2009), consistent with the 466 ± 2 Ma youngest detrital zircon population in sandstone of the Moores Cove Formation (Willner et al. 2014). Dec et al. (1997) interpreted a change in the sedimentary environment from pelagic sedimentation in a lower slope – basin floor setting to a coarsening turbidite sequence deposited in a prograding deep-sea fan. The transition from the Fortune Harbour Formation to Moores Cove Formation was formerly inferred to represent a change from backarc basin to deep-water flysch basin sedimentation related to emplacement of Taconic allochthons onto the Laurentian margin (Dec et al. 1997). However, the position of the Cottrell's Cove Group along the Red Indian Line, and not in the Taconic seaway (van Staal et al. 2009; Zagorevski and van Staal 2012), precludes the interpretation of these rocks as the foreland basin to the Taconic orogen. The location along the Red Indian Line suture zone, and the sedimentology and provenance of the Moores Cove Formation, are more consistent with deposition in a shallowing-upward forearc basin (e.g. Dickinson 1995) that was deposited onto slightly older arc basement (Fig. 9). The backarc-like character of parts of this basement (Fig. 11; Dec et al. 1997) is probably related to the disorganized nature of spreading in the Darriwilian arc (Fig. 14), such that rift sectors along the magmatic front are characterized by backarc-like rocks (Wysoczanski et al. 2010).

The sedimentary rocks of the Ghost Pond sequence (Fig. 12) are correlative with the Moores Cove Formation (O'Brien 2003), but their sedimentology has not been studied in detail. These rocks are similarly dominated by interbedded turbiditic sandstone (Fig. 10G), siltstone, shale, chert and jasperite that overlie volcanic basement composed of tholeiitic basalt and calc-alkaline rhyolite (e.g. Bostock 1988; O'Brien 2003; Zagorevski and McNicoll 2012). Turbiditic rocks have a volcanic provenance (Bostock 1988). The Ghost Pond sequence is structurally juxtaposed to the east against an accreted seamount, supporting its position close to the trench (see following; Bostock 1988; Zagorevski and McNicoll 2012). Thus, although these sedimentary rocks overlie tholeiitic, ca. 466 Ma rifted arc or backarc basin-like volcanic rocks (Bostock 1988; Zagorevski and McNicoll 2012), they are best interpreted to have been deposited in a forearc basin. A similar tectonic setting may be also be applicable to parts of the Red Indian Lake Group, in which volcaniclastic and epiclastic deposits are locally abundant above backarc-like basement along the Red Indian Line (Rogers et al. 2005; Zagorevski et al. 2006).

The basement to the forearc basin strata is young relative to the inception of AAT arc magmatism, which occurred ca. 14 m.y. earlier. This is analogous to the earliest history of the Izu – Bonin – Mariana and Tonga – Kermadec forearcs, where the oldest strata are Oligocene, and only marginally younger than the underlying Eocene igneous basement (e.g. Bloomer et al. 1994; Clift and MacLeod 1999; Taylor et al. 2005; Stern 2010). The deposition of forearc strata on only marginally older volcanic basement can be explained in several ways: 1) Forearc basin strata can be intercalated with volcanic rocks formed along the arc front (Dickinson 1995; Draut and Clift 2013); as such, the preserved AAT forearc basin may have been proximal to the arc front. 2) The Darriwilian volcanic front was characterized by disorganized spreading and rifted arc and backarc basin-like rocks, resulting in deposition of the forearc strata on a backarc-like volcanic substrate. 3) Magmatism may have extended into the forearc (e.g. Marlow et al. 1992). 4) The forearc region may have been very narrow and similar in dimensions to intra-oceanic arc systems that are undergoing active subduction erosion (Clift and Vannucchi 2004; Stern 2010). 5) Subduction of a seamount or seamount chain, such as is preserved in the Tommy's Arm River sequence (Zagorevski and McNicoll 2012), may have caused forearc block subduction or enhanced subduction erosion (Ballance et al. 1989; Clift and Vannucchi 2004).

ACCRETIONARY PRISM

Remnants of accetionary prisms related to subduction of oceanic slabs of the Iapetus Ocean plate appear to be largely absent in Newfoundland, on both sides of the suture zone (Zagorevski et al. 2006, 2012; Zagorevski and van Staal 2011). Abundant late Middle to Late Ordovician sedimentary rocks and mélange occur along the Red Indian Line; however, these rocks were mainly deposited in syn-collisonal basins and became imbricated during the subsequent increments of arc-arc collision (McConnell et al. 2002; Zagorevski et al. 2008, 2012; Waldron et al. 2012). Hence, in general, these rocks do not represent remnants of the oceanic accretionary complexes. The lack of an accretionary prism can be explained by the same mechanisms as those discussed in the context of the forearc environment, such as strike-slip excision, subduction of the forearc, and tectonic burial by collision-generated overthrusts. Alternatively, the trenches were starved of clastic sediments and hence, no prism ever developed.

The only readily identifiable remnant of the down-going Iapetus Ocean plate is the Tommy's Arm River assemblage (Figs. 1, 10H; Zagorevski and McNicoll 2012), which forms part of the Crescent terrane of Bostock (1988). The rocks interpreted to represent an oceanic seamount mainly comprise a distinct sequence of gabbro, diabase, pillow basalt and minor sediment. The basalts have a very distinctive ocean island basalt chemistry (Zagorevski and McNicoll 2012), locally contain interpillow chert and jasper, and are mantled by mafic-derived sandstone, conglomerate, and minor limestone. The make-up of this sequence is typical of ocean-floor stratigraphy and supports the seamount setting. The seamount was thrust beneath the Darriwilian arc volcanic rocks (ca. 466 Ma; Zagorevski and McNicoll 2012) without a noticeable intervening accretionary prism. Many modern intraoceanic trenches are starved of clastic sediments and associated accretionary prisms are poorly developed (e.g. Taylor 1992; von Huene and Ranero 2003; Clift and Vannucchi 2004; von Huene et al. 2004; Scholl and von Huene 2007). In addition, such arc-trench systems are commonly undergoing active subduction erosion, as indicated by subsidence of the forearc block and narrowing of the arc-trench gap in areas of seamount collision. Therefore, we conclude that the trench associated with Darriwilian arc sequences was sediment starved and that seamount subduction caused a period of enhanced subduction erosion. Thus, the lack of an accretionary prism in the Newfoundland sector of the Darriwilian arc is likely a primary feature of the arc system, rather than a product of post-accretionary processes (Zagorevski and McNicoll 2012).

CONCLUSIONS

The scale-dependent treatment of suspect terranes by Hank Williams (Williams and Hatcher 1982, 1983; Williams et al. 1988; Williams 1995a, b) provided a critical framework that guided subsequent studies of the northern Appalachians. Emphasis on differences in local areas, particularly by focusing on the detailed volcanic evolution in space and time, allows further subdivision of the peri-Laurentian rocks along the Red Indian Line into regional terranes that form the fundamental building blocks of a complex, southeast-facing Tremadocian to Darriwilian arc – forearc system (Fig. 14). The overall similarities in volcanic history and tectonic setting of these regional terranes, and comparisons with modern analogues, suggests that the Tremadocian to Darriwilian peri-Laurentian arc system formed above a west-dipping subduction zone in Iapetus (e.g. van Staal et al. 1998; Zagorevski et al. 2006). This composite arc – backarc system was very similar to the modern intra-oceanic Izu – Bonin – Mariana and Tonga – Kermadec arc systems. Supra-subduction magmatism was initiated as an ophiolitic infant arc immediately outboard of a peri-Laurentian microcontinent. Subsequently, the arc rapidly evolved into an extensional arc system, presumably due to rollback of the down-going slab. Extension was accommodated by development of extensive supra-subduction zone ophiolite belts (Fig. 14), suggesting that the Tremadocian to Floian phase of this arc was accompanied by organized spreading.

In contrast, the subsequent Darriwilian phase of arc magmatism was characterized by disorganized spreading and highly variable magmatism similar to what is observed in the Havre Trough (Fig. 14). This phase of arc development produced disparate sectors alternating between constructive arc magmatic chains and rift segments that eventually became distinct terranes when the system was disrupted internally as a result of oblique thrusting related to Middle Ordovician arc – arc collision. The Darriwilian arc was associated with small and spatially restricted forearc basins, and an accretionary prism was either poorly developed because of starving of the trench, or was subsequently removed during tectonic processes such as subduction erosion. Studies of modern forearcs indicate that they are very useful for tracking the evolution of the adjacent arc systems (e.g. Clift et al. 1994, 1998; Clift and MacLeod 1999; Clift and Hartley 2007). The sedimentology of the preserved forearc basins in the AAT has been investigated to only a limited extent (Dec et al. 1997), and not with the purpose of studying forearc basin evolution. This remains one of the most interesting avenues for future research.

Modern intra-oceanic arcs are commonly cited to be natural laboratories in which to study evolution of magmas and generation of felsic melts, unencumbered by continental basement. However, geochemical and isotopic similarity of the arc basement and mantle-derived melts in modern arcs leads to a lack of distinction between differentiation versus crustal melt models. The morphological character of the peri-Laurentian arc system, dominantly comprising submarine volcanic rocks, spreading ridges and intra-arc rift sectors, is akin to the development of intra-oceanic arc systems; however, all phases of the AAT appear to have been built on a continent-derived substrate. This is indicated by common zircon inheritance and low ε_{Nd} values in mafic and felsic volcanic rocks (Table 1). This in turn indicates that the continental basement and its influence on arc magmatism can persist despite extensive rift-related fragmentation and magmatic recycling. This contrasts with the Mariana arc, where the Cretaceous basement has been documented only along the Eocene magmatic front (Ishizuka et al. 2011). In addition, AAT terranes behaved as intra-oceanic arcs but had attenuated continental basement to provide an isotopic marker. As such they represent a natural laboratory to study silicic melts in intra-oceanic settings. Isotopic and zircon inheritance evidence indicates that silicic melts in the AAT were demonstrably derived by melting of arc crust and basement (cf. Smith et al. 2003).

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REFERENCES

Bader, A.G., Pubellier, M., Rangin, C., Deplus, C., and Louat, R., 1999, Active slivering of oceanic crust along the Molucca ridge (Indonesia-Philippine): implication for ophiolite incorporation in a subduction wedge?: Tectonics, v. 18, p. 606–620, http://dx.doi.org/10.1029/1999TC900004.

Ballance, P.F., Scholl, D.W., Vallier, T.L., Stevenson, A.J., Ryan, H., and Herzer, R.H., 1989, Subduction of a Late Cretaceous seamount of the Louisville Ridge at the Tonga Trench: A model of normal and accelerated tectonic erosion: Tectonics, v. 8, p. 953–962, http://dx.doi.org/10.1029/TC008i005p00953.

Bédard, J.H., 2014, Ophiolitic magma chambers; a perspective from the Canadian Appalachians, *in* Charlier, B., Namur, O., Latypov, R., Tegner, C., *eds.*, Layered Intrusions: Springer Verlag, in press.

Bloomer, S.H., Ewart, A., Hergt, J.M., and Bryan, W.B., 1994, Geochemistry and origin of igneous rocks from the outer Tonga forearc (Site 841), *in* Hawkins, J., Parson, L., Allan, J., et al., *eds.,* Proceedings of the Ocean Drilling Program, Scientific Results, Leg 135, College Station, TX, p. 625–646, http://dx.doi/org/10.2973/odp.proc.sr.135.129.1994.

Bostock, H.H., 1988, Geology and petrochemistry of the Ordovician volcano-plutonic Robert's Arm group, Notre Dame Bay, Newfoundland: Geological Survey of Canada, Bulletin 369, 84 p.

Boutelier, D., Chemenda, A., and Burg, J.-P., 2003, Subduction versus accretion of intra-oceanic volcanic arcs; insight from thermo-mechanical analogue experiments: Earth and Planetary Science Letters, v. 212, p. 31–45, http://dx.doi.org/10.1016/S0012-821X(03)00239-5.

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, v. 309, p. 2023–2029.

Calvert, A.J., 2011,The seismic structure of island arc crust, *in* Brown, D., and Ryan, P.D., *eds.,* Arc-Continent Collision, Frontiers in Earth Sciences: Springer-Verlag Berlin Heidelberg, p. 87–119, http://dx.doi.org/10.1007/978-3-540-88558-0_4.

Cawood, P.A., and Nemchin, A.A., 2001, Paleogeographic development of the east Laurentian margin: Constraints from U–Pb dating of detrital zircons in the Newfoundland Appalachians: Geological Society of America Bulletin, v. 113, p. 1234–1246, http://dx.doi.org/10.1130/0016-7606(2001)113<1234:PDOTEL>2.0.CO;2.

Cawood, P.A., McCausland, P.J.A., and Dunning, G.R., 2001, Opening Iapetus: Constraints from the Laurentian margin in Newfoundland: Geological Society of America Bulletin, v. 113, p. 443–453, http://dx.doi.org/10.1130/0016-7606(2001)113<0443:OICFTL>2.0.CO;2.

Clift, P.D., and Hartley, A.J., 2007, Slow rates of subduction erosion and coastal underplating along the Andean margin of Chile and Peru: Geology, v. 35, p. 503–506, http://dx.doi.org/10.1130/G23584A.1.

Clift, P.D., and MacLeod, C.J., 1999, Slow rates of subduction erosion estimated from subsidence and tilting of the Tonga forearc: Geology, v. 27, p. 411–414, http://dx.doi.org/10.1130/0091-7613(1999)027<0411:SROSEE>2.3.CO;2.

Clift, P., and Vannucchi, P., 2004, Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust: Reviews of Geophysics, v. 42, RG2001, http://dx.doi.org/10.1029/2003RG000127.

Clift, P.D., Bednarz, U., Bøe, R., Rothwell, R.G., Hodkinson, R.A., Ledbetter, J.K., Pratt, C.E., and Soakai, S., 1994, Sedimentation on the Tonga forearc related to arc rifting, subduction erosion, and ridge collision: a synthesis of results from Sites 840 and 841, *in* Hawkins, J., Parson, L., Allan, J., et al., *eds.,* Proceedings of the Ocean Drilling Program, Scientific Results, Leg 135: College Station, TX, p. 843–855, http://dx.doi.org/10.2973/odp.proc.sr.135.164.1994.

Clift, P.D., MacLeod, C.J., Tappin, D.R., Wright, D.J., and Bloomer, S.H., 1998, Tectonic controls on sedimentation and diagenesis in the Tonga Trench and forearc, southwest Pacific: Geological Society of America Bulletin, v. 110, p. 483–496, http://dx.doi.org/10.1130/0016-7606(1998)110<0483:TCOSAD>2.3.CO;2.

Clift, P.D., Carter, A., Draut, A.E., Long, H.V., Chew, D.M., and Schouten, H.A., 2009, Detrital U–Pb zircon dating of lower Ordovician syn-arc-continent collision conglomerates in the Irish Caledonides: Tectonophysics, v. 479, p. 165–174, http://dx.doi.org/10.1016/j.tecto.2008.07.018.

Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737, http://dx.doi.org/10.1130/0016-7606(1993)105<0715:LBACOS>2.3.CO;2.

Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J.-X., 2013, The ICS International Chronostratigraphic Chart: Episodes, v. 36, p. 199–204.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329–333, http://dx.doi.org/10.1038/288329a0.

Coombs, A.M., Zagorevski, A., McNicoll, V., and Hanchar, J.M., 2012, Preservation of terranes during the assembly of the Annieopsquotch accretionary tract: Inferences from the provenance of a Middle Ordovician ophiolite to arc transition, central Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 49, p. 128–146, http://dx.doi.org/10.1139/e11-042.

Cousens, B.L., 1996, Magmatic evolution of Quaternary mafic magmas at Long Valley Caldera and the Devils Postpile, California: Effects of crustal contamination on lithospheric mantle-derived magmas: Journal of Geophysical Research, v. 101, p. 27673–27689, http://dx.doi.org/10.1029/96JB02093.

Cutts, J.A., Zagorevski, A., McNicoll, V., and Carr, S., 2012, Tectono-stratigraphic setting of the Moreton's Harbour Group and its implications for the evolution of the Laurentian Margin: Notre Dame Bay, Newfoundland: Canadian Journal of Earth Sciences, v. 49, p. 111–127, http://dx.doi.org/10.1139/e11-040.

Davenport, P.H., Honarvar, P., Hogan, A., Kilfoil, G., King, D., Nolan, L.W., Ash, J.S., Colman-Sadd, S.P., Hayes, J.P., Liverman, D.G.E., Kerr, A., and Evans, D.T.W., 1996, Digital Geoscience Atlas of the Buchans-Robert's Arm Belt, Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey, Open File NFLD/2611 (1996) version 1.0, CD-ROM (1 disk)

Dec, T., and Swinden, H.S., 1994, Lithostratigraphic model, geochemistry and sedimentology of the Cottrells Cove Group, Buchans-Roberts Arm volcanic belt, Notre Dame Subzone: Report - Government of Newfoundland and Labrador Department of Mines and Energy, Geological Survey, Report: 94-1, p. 77–100.

Dec, T., Swinden, H.S., and Dunning, R.G., 1997, Lithostratigraphy and geochemistry of the Cottrells Cove Group, Buchans-Roberts Arm volcanic belt: new constraints for the paleotectonic setting of the Notre Dame Subzone, Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 34, p. 86–103, http://dx.doi.org/10.1139/e17-008.

de Wit, M.J., and Stern, C.R., 1981, Variations in the degree of crustal extension during formation of a back-arc basin: Tectonophysics, v. 72, p. 229–260, http://dx.doi.org/10.1016/0040-1951(81)90240-7.

Dickinson, W.R., 1995, Forearc basins, *in* Busby, C.J., and Ingersoll, R.V., *eds.*, Tectonics of sedimentary basins: Blackwell Science, p. 221–261.

Draut, A.E., and Clift, P.D., 2013, Differential preservation in the geologic record of intraoceanic arc sedimentary and tectonic processes: Earth-Science Reviews, v. 116, p. 57–84, http://dx.doi.org/10.1016/j.earscirev.2012.11.003.

Dunning, G.R., 1987, Geology of the Annieopsquotch Complex, southwest Newfoundland: Canadian Journal of Earth Sciences, v. 24, p. 1162–1174, http://dx.doi.org/10.1139/e87-112.

Dunning, G.R., and Krogh, T.E., 1985, Geochronology of ophiolites of the Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 22, p. 1659–1670, http://dx.doi.org/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, v. 24, p. 1175–1184, http://dx.doi.org/10.1139/e87-113.

Elders, C.F., 1987, The provenance of granite boulders in conglomerates of the Northern and Central Belts of the Southern Uplands of Scotland: Journal of the Geological Society, v. 144, p. 853–863, http://dx.doi.org/10.1144/gsjgs.144.6.0853.

Furnes, H., Dilek, Y., and Pedersen, R.B., 2012, Structure, geochemistry, and tectonic evolution of trench-distal backarc oceanic crust in the western Norwegian Caledonides, Solund-Stavfjord Ophiolite (Norway): Geological Society of America Bulletin, v. 124, p. 1027–1047, http://dx.doi.org/10.1130/B30561.1.

Hibbard, J., van Staal, C., Rankin, D.W., and Williams, H., 2006, Lithotectonic map of the Appalachian orogeny (South), Canada - United States of America: Geological Survey of Canada Map 02096A, scale 1:1,500,000, 2 sheets.

Hollis, S.P., Roberts, S., Cooper, M.R., Earls, G., Herrington, R., Condon, D.J., Cooper, M.J., Archibald, S.M., and Piercey, S.J., 2012, Episodic arc-ophiolite emplacement and the growth of continental margins: Late accretion in the Northern Irish sector of the Grampian-Taconic Orogeny: Geological Society of America Bulletin, v. 124, p. 1702–1723, http://dx.doi.org/10.1130/B30619.1.

Hollis, S.P., Cooper, M.R., Roberts, S., Earls, G., Herrington, R., Condon, D.J., and Daly, J.S., 2013, Evolution of the Tyrone ophiolite, Northern Ireland, during the Grampian-Taconic orogeny: a correlative of the Annieopsquotch Ophiolite Belt of central Newfoundland?: Journal of the Geological Society, v. 170, p. 861–876, http://dx.doi.org/10.1144/jgs2012-103.

Ishizuka, O., Taylor, R.N., Yuasa, M., and Ohara, Y., 2011, Making and breaking an island arc: A new perspective from the Oligocene Kyushu-Palau arc, Philippine Sea: Geochemistry, Geophysics, Geosystems, v. 12, Q05005, http://dx.doi.org/10.1029/2010GC003440.

Jenner, G.A., Dunning, G.R., Malpas, J., Brown, M., and Brace, T., 1991, Bay of Islands and Little Port complexes, revisited: age, geochemical and isotopic evidence confirm suprasubduction-zone origin: Canadian Journal of Earth Sciences, v. 28, p. 1635–1652, http://dx.doi.org/10.1139/e91-146.

Kerr, A., 1996, New perspectives on the stratigraphy, volcanology, and structure of island-arc volcanic rocks in the Roberts Arm Group, Notre Dame Bay: Newfoundland Department of Natural Resources, Geological Survey Branch, Current Research Report 96-1, p. 283–311.

Kerr, A., and Dunning, G.R., 2003, A note on the U–Pb zircon age of the Woodford's Arm granite, and its relationship to the Roberts Arm Group, Central Newfoundland (NTS2E/12): Newfoundland Department of Mines and Energy, Geological Survey Branch, Current Research Report 03-1, p. 47–50.

Kerr, A., and Wardle, R.J., 1997, Definition of an Archean – Proterozoic crustal suture by isotopic studies of basement intersections from offshore wells in the southern Labrador Sea: Canadian Journal of Earth Sciences, v. 34, p. 209–214, http://dx.doi.org/10.1139/e17-017.

Lissenberg, C.J., Bédard, 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, v. 229, p. 105–123, http://dx.doi.org/10.1016/j.epsl.2004.10.029.

Lissenberg, C.J., van Staal, C.R., Bédard, J.H., and Zagorevski, A., 2005a, Geochemical constraints on the origin of the Annieopsquotch ophiolite belt, Newfoundland Appalachians: Geological Society of America Bulletin, v. 117, p. 1413–1426, http://dx.doi.org/10.1130/B25731.1.

Lissenberg, C.J., Zagorevski, A., McNicoll, V.J., van Staal, C.R., and Whalen, J.B., 2005b, Assembly of the Annieopsquotch accretionary tract, Newfoundland Appalachians: Age and geodynamic constraints from syn-kinematic intrusions: The Journal of Geology, v. 113, p. 553–570, http://dx.doi.org/10.1086/431909.

Lissenberg, C.J., Zagorevski, A., Rogers, N., van Staal, C.R., and Whalen, J.B., 2005c, Geology, Star Lake, Newfoundland and Labrador (NTS 12A/11): Geological Survey of Canada, Open File 1669, 1 sheet, 1 CD-ROM, http://dx.doi.org/10.4095/221288.

MacLeod, C.J., Searle, R.C., Murton, B.J., Casey, J.F., Mallows, C., Unsworth, S.C., Achenbach, K.L., and Harris, M., 2009, Life cycle of oceanic core complexes: Earth and Planetary Science Letters, v. 287, p. 333–344, http://dx.doi.org/10.1016/j.epsl.2009.08.016.

Marlow, M.S., Johnson, L.E., Pearce, J.A., Fryer, P.B., Pickthorn, L.G., and Murton, B.J., 1992, Pleistocene volcanic rocks in the Mariana forearc revealed by drilling at Site 781, *in* Fryer, P., Pearce, J.A., Stokking, L.B., et al., *eds.,* Proceedings of the Ocean Drilling Program, Scientific Results, v. 125, College Station, TX, p. 293–310, http://dx.doi.org/10.2973/odp.proc.sr.125.501.1992.

McConnell, B.J., O'Brien, B.H., and Nowlan, G.S., 2002, Late Middle Ordovician olistostrome formation and magmatism along the Red Indian Line, the Laurentian Arc-Gondwanan Arc boundary, at Sops Head, Newfoundland: Canadian Journal of Earth Sciences, v. 39, p. 1625–1633, http://dx.doi.org/10.1139/e02-084.

McIntosh, K., Nakamura, Y., Wang, T.-K., Shih, R.-C., Chen, A., and Liu, C.-S., 2005, Crustal-scale seismic profiles across Taiwan and the western Philippine Sea: Tectonophysics, v. 401, p. 23–54, http://dx.doi.org/10.1016/j.tecto.2005.02.015.

Nowlan, G.S., 1996, Report on two samples from lower Paleozoic strata of the Point Leamington Area, Northern Newfoundland collected and submitted for conodont analysis by Dr. T. Dec (Consultant) and Brian O'Brien (Newfoundland Department Of Mines And Energy); NTS 002E/06; Con# 1487: Geological Survey of Canada, Paleontological Report, v. 006-GSN-1996, p. 3.

Nowlan, G.S., 1997, Report on three samples from Bay Of Exploits Area, North Central Newfoundland, submitted for microfossil analysis by Dr. Brian O'Brien, Newfoundland Department Of Mines and Energy; NTS 2E/06; Con # 1501: Geological Survey of Canada, Paleontological Report, v. 001-GSN-1997, p. 4.

Nowlan, G.S., and Thurlow, J.G., 1984, Middle Ordovician conodonts from the Buchans Group, central Newfoundland, and their significance for regional stratigraphy of the Central Volcanic Belt: Canadian Journal of Earth Sciences, v. 21, p. 284–29, http:dx.doi.org/10.1139/e84-031.

Oakley, A.J., Taylor, B., Moore, G.F., and Goodliffe, A., 2009, Sedimentary, volcanic, and tectonic processes of the central Mariana Arc: Mariana Trough back-arc basin formation and the West Mariana Ridge: Geochemistry, Geophysics, Geosystems, v. 10, Q08X07, http://dx.doi.org/10.1029/2008GC002312.

O'Brien, B.H., 2003, Geology of the Central Notre Dame Bay region (Parts of NTS areas 2E/3,6,11) Northeastern Newfoundland: Newfoundland and Labrador Department of Mines and Energy, Geological Survey Report 03-03, 147 p.

O'Brien, B.H., 2007, Geology of the Buchans-Roberts Arm volcanic belt, near Great Gull Lake: Current Research - Newfoundland Geological Survey Branch, Report 07-1, p. 85–102.

O'Brien, B.H., 2008, Preliminary tectonic map showing the dispositon of the main structural tracts comprising the southern part of the Robert's Arm volcanic Belt [NTS areas 12H/1, 12A/16] west-central Newfoundland: Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Open File NFLD/2974, Map 2008-17, scale 1:25,000.

O'Brien, B.H., 2009, Geology of the Little Joe Glodes Pond - Catamaran Brook Region with emphasis on the Roberts Arm volcanic belt (Parts of NTS 12H/1 and 12A/16), west-central Newfoundland: Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Open File NFLD/3035, Map 2009–28, scale 1:25,000.

O'Brien, B.H., and Dunning, G.R., 2014, Lithostratigraphic status of the Hammerdown Basalt, of the western Notre Dame Bay volcanic belt, King's Point area (NTS map area 12H/9), Newfoundland: Current Research (2014), Newfoundland and Labrador Department of Natural Resources Geological Survey, Report 14-1, p. 155–188.

Ohara, Y., Fujioka, K., Ishii, T., and Yurimoto, H., 2003, Peridotites and gabbros from the Parece Vela backarc basin: Unique tectonic window in an extinct backarc spreading ridge: Geochemistry, Geophysics, Geosystems, v. 4, 8611, http://dx.doi.org/10.1029/2002GC000469.

Pearce, J.A., 1996, A user's guide to basalt discrimination diagrams, *in* Wyman, D.A., *ed.,* Trace element geochemistry of volcanic rocks: Applications for massive-sulphide exploration: Geological Association of Canada, Short Course Notes 12, p. 79–113.

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, v. 25, p. 956–983, http://dx.doi.org/10.1093/petrology/25.4.956.

Pickett, J.W., 1987, Geology and geochemistry of the Skidder Basalt, *in* Kirkham, R.V., *ed.,* Buchans Geology, Newfoundland: Geological Survey of Canada Paper 86-24, p. 195–218.

Pope, A.J., Calon, T.J., and Swinden, H.S., 1991, Stratigraphy, structural geology and mineralization in the Gullbridge area, central Newfoundland, *in* Swinden, H.S., Evans, D.T.W., and Kean, B.F., *eds.*, Metallogenic framework of base and precious metal deposits, central and western Newfoundland (Field Trip 1): Geological Survey of Canada, Open File 2156, p. 93–100.

Pubellier, M., Bader, A.G., Rangin, C., Deffontaines, B., and Quebral, R., 1999, Upper plate deformation induced by subduction of a volcanic arc: the Snellius Plateau (Molucca Sea, Indonesia and Mindanao, Philippines): Tectonophysics, v. 304, p. 345–368, http://dx.doi.org/10.1016/S0040-1951(98)00300-X.

Robinson, P.T., Malpas, J., Dilek, Y., and Zhou, M.-F., 2008, The significance of sheeted dike complexes in ophiolites: GSA Today, v. 18, p. 4–11, http://dx.doi.org/10.1130/GSATG22A.1.

Rogers, N., 2004, Red Indian Line geochemical database: Geological Survey of Canada, Open File 4605, 1 CD-ROM, http://dx.doi.org/10.4095/215123.

Rogers, N., van Staal, C.R., McNicoll, V.J., Squires, G.C., Pollock, J., and Zagorevski, A., 2005, Geology, Lake Ambrose and part of Buchans, Newfoundland and Labrador (NTS 12A/10 and part of 12-A/15): Geological Survey of Canada, Open File 4544, 1 sheet, 1 CD-ROM, http://dx.doi.org/10.4095/221289.

Rogers, N., van Staal, C.R., McNicoll, V., Pollock, J., Zagorevski, A., and Whalen, J., 2006, Neoproterozoic and Cambrian arc magmatism along the eastern margin of the Victoria Lake Supergroup: A remnant of Ganderian basement in central Newfoundland?: Precambrian Research, v. 147, p. 320–341, http://dx.doi.org/10.1016/j.precamres.2006.01.025.

Sajona, F.G., Maury, R.C., Pubellier, M., Leterrier, J., Bellon, H., and Cotten, J., 2000, Magmatic source enrichment by slab-derived melts in a young post-collision setting, central Mindanao (Philippines): Lithos, v. 54, p. 173–206, http://dx.doi.org/10.1016/S0024-4937(00)00019-0.

Scholl, D.W., and von Huene, R., 2007, Crustal recycling at modern subduction zones applied to the past—Issues of growth and preservation of continental basement crust, mantle geochemistry, and supercontinent reconstruction: Geological Society of America Memoirs, v. 200, p. 9–32, http://dx.doi.org/10.1130/2007.1200(02).

Smith, I.E.M., and Price, R.C., 2006, The Tonga–Kermadec arc and Havre–Lau back-arc system: Their role in the development of tectonic and magmatic models for the western Pacific: Journal of Volcanology and Geothermal Research, v. 156, p. 315–331, http://dx.doi.org/10.1016/j.jvolgeores.2006.03.006.

Smith, I.E.M., Worthington, T.J., Stewart, R.B., Price, R.C., and Gamble, J.A., 2003, Felsic volcanism in the Kermadec arc, SW Pacific: crustal recycling in an oceanic setting: Geological Society, London, Special Publications, v. 219, p. 99–118, http://dx.doi.org/10.1144/GSL.SP.2003.219.01.05.

Stern, R.J., 2010, The anatomy and ontogeny of modern intra-oceanic arc systems, *in* Kusky, T.M., Zhai, M.-G, and Xiao, W., *eds.*, The Evolving Continents: Understanding Processes of Continental Growth: Geological Society, London, Special Publications, v. 338, p. 7–34, http://dx.doi.org/10.1144/SP338.2.

Stern, R.J., and Bloomer, S.H., 1992, Subduction zone infancy: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs: Geological Society of America Bulletin, v. 104, p. 1621–1636, http://dx.doi.org/10.1130/0016-7606(1992)104<1621:SZIEFT>2.3.CO;2.

Swinden, H.S., Jenner, G.A., Kean, B.F., and Evans, D.T.W., 1989, Volcanic rock geochemistry as a guide for massive sulphide exploration in central Newfoundland: Current Research (1989), Geological Survey of Newfoundland, Report 89-1, p. 201–219.

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, *in* Sinha, A.K., Whalen, J.B., and Hogan, J.P., *eds.*, The Nature of Magmatism in the Appalachian Orogen: Geological Society of America Memoirs, v. 191, p. 337–365, http://dx.doi.org/10.1130/0-8137-1191-6.337.

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, p. 207–226.

Szybinski, Z.A., 1995, Paleotectonic and structural setting of the western Notre Dame Bay area, Newfoundland Appalachians: Unpublished PhD thesis, Memorial University of Newfoundland, St. John's, NL, 340 p.

Tamaki, K., 1985, Two modes of back-arc spreading: Geology, v. 13, p. 475–478, http://dx.doi.org/10.1130/0091-7613(1985)13<475:TMOBS>2.0.CO;2.

Taylor, B., 1992, Rifting and the volcanic-tectonic evolution of the Izu-Bonin-Mariana Arc: Proceedings of the Ocean Drilling Program, Scientific Results, v. 126, College Station, TX, p. 627–651.

Taylor, F.W., Mann, P., Bevis, M.G., Edwards, R.L., Cheng, H., Cutler, K.B., Gray, S.C., Burr, G.S., Beck, J.W., Phillips, D.A., Cabioch, G., and Recy, J., 2005, Rapid fore-arc uplift and subsidence caused by impinging bathymetric features: Examples from the New Hebrides and Solomon arcs: Tectonics, v. 24, TC6005, http://dx.doi.org/10.1029/2004TC001650.

Thurlow, J.G., and Swanson, E.A., 1987, Stratigraphy and structure of the Buchans Group, *in* Kirkham, R.V., *ed.,* Buchans Geology, Newfoundland: Geological Survey of Canada, Paper 86-24, p. 35–46.

Thurlow, J.G., Spencer, C.P., Boerner, D.E., Reed, L.E., and Wright, J.A., 1992, Geological interpretation of a high resolution reflection seismic survey at the Buchans mine, Newfoundland: Canadian Journal of Earth Sciences, v. 29, p. 2022–2037, http://dx.doi.org/10.1139/e92-159.

Tucholke, B.E., Behn, M.D., Buck, W.R., and Lin, J., 2008, Role of melt supply in oceanic detachment faulting and formation of megamullions: Geology, v. 36, p. 455–458, http://dx.doi.org/10.1130/G24639A.1.

van der Velden, A.J., van Staal, C.R., and Cook, F.A., 2004, Crustal structure, fossil subduction, and the tectonic evolution of the Newfoundland Appalachians: Evidence from a reprocessed seismic reflection survey: Geological Society of America Bulletin, v. 116, p. 1485–1498, http://dx.doi.org/10.1130/B25518.1.

van Hees, G., Zagorevski, A., and Hannington, M., 2012, Volcanology and Stratigraphy of the Lundberg Zone, Buchans, Newfoundland: Current Research (2012) Newfoundland Department of Mines and Energy Geological Survey, Report 12-1, p. 147–166.

van Staal, C.R., and Zagorevski, A., 2012, Accreted terranes of the Appalachian Orogen in Newfoundland: In the footsteps of Hank Williams: Geological Association of Canada, Guidebook Trip A1, 99 p.

van Staal, C.R., Sullivan, R.W., and Whalen, J.B., 1996, Provenance of tectonic history of the Gander Zone in the Caledonian/Appalachian Orogen: Implications for the origin and assembly of Avalon, *in* Nance, R.D., and Thompson, M.D., *eds.,* Avalonian and related peri-Gondwanan terranes of the Circum-North Atlantic: Geological Society of America Special Papers, v. 304, p. 347–367, http://dx.doi.org/10.1130/0-8137-2304-3.347.

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* Blundell, D.J., and Scott, A.C., *eds.*, Lyell: The Past is the Key to the Present: Geological Society, London, Special Publications, v. 143, p. 199–242, http://dx.doi.org/10.1144/GSL.SP.1998.143.01.17.

van Staal, C.R., Lissenberg, C.J., Pehrsson, S., Zagorevski, A., Valverde-Vaquero, P., Herd, R.K., McNicoll, V.J., and Whalen, J.B., 2005, Geology, Puddle Pond, Newfoundland and Labrador (NTS 12-A/05): Geological Survey of Canada, Open File OF1664, scale 1:50,000.

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* Hatcher, R.D., Jr., Carlson, M.P., McBride, J.H., and Martínez Catalan, J.R., *eds.*, 4-D Framework of Continental Crust: Geological Society of America Memoirs, v. 200, p. 511–552, http://dx.doi.org/10.1130/2007.1200(26).

van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N., 2009, Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians, *in* Murphy, J.B., Keppie, J.D., and Hynes, A.J., *eds.*, Ancient Orogens and Modern Analogues: Geological Society, London, Special Publications, v. 327, p. 271–316, http://dx.doi.org/10.1144/SP327.13.

van Staal, C.R., Chew, D.M., Zagorevski, A., McNicoll, V., Hibbard, J., Skulski, T., Castonguay, S., Escayola, M.P., and Sylvester, P.J., 2013, Evidence of Late Ediacaran Hyperextension of the Laurentian Iapetan Margin in the Birchy Complex, Baie Verte Peninsula, Northwest Newfoundland: Implications for the Opening of Iapetus, Formation of Peri-Laurentian Microcontinents and Taconic – Grampian Orogenesis: Geoscience Canada, v. 40, p. 94–117, http://dx.doi.org/10.12789/geocanj.2013.40.006.

von Huene, R., and Ranero, C.R., 2003, Subduction erosion and basal friction along the sediment-starved convergent margin off Antofagasta, Chile: Journal of Geophysical Research, v. 108, 2079, http://dx.doi.org/10.1029/2001JB001569.

von Huene, R., Ranero, C.R., and Vannucchi, P., 2004, Generic model of subduction erosion: Geology, v. 32, p. 913–916, http://dx.doi.org/10.1130/G20563.1.

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, v. 29, p. 811–814, http://dx.doi.org/10.1130/0091-7613(2001)029<0811:TOATAO>2.0.CO;2.

Waldron, J.W.F., McNicoll, V.J., van Staal, C.R., 2012, Laurentia-derived detritus in the Badger Group of central Newfoundland: deposition during closing of the Iapetus Ocean: Canadian Journal of Earth Sciences, v. 49, p. 207–221, http:dx.doi.org/10.1139/e11-030.

Whalen, J.B., 2012, Geochemical and isotopic (Nd, O, Pb and Sr) data from igneous rocks of the Notre Dame Subzone and adjacent tectonostratigraphic zones, western and central Newfoundland: Geological Survey of Canada, Open File 7202, 16 p.

Whalen, J., Zagorevski, A., McNicoll, V.J., and Rogers, N., 2013, Geochemistry, U–Pb geochronology, and genesis of granitoid clasts in transported volcanogenic massive sulfide ore deposits, Buchans, Newfoundland: Canadian Journal of Earth Sciences, v. 50, p. 1116–1133, http://dx.doi.org/10.1139/cjes-2013-0040.

Williams, H., 1995a, Chapter 2: Temporal and spatial divisions, *in* Williams, H., *ed.,*Geology of the Appalachian-Caledonian orogen in Canada and Greenland: Geological Survey of Canada, p. 23–42, http://dx.doi.org/10.4095/205242.

Williams, H., 1995b, Chapter 3: Dunnage Zone – Newfoundland, *in* Williams, H., *ed.,*Geology of the Appalachian-Caledonian orogen in Canada and Greenland: Geological Survey of Canada, p. 142–166, http://dx.doi.org/10.4095/205242.

Williams, H., and Hatcher, R.D., Jr., 1982, Suspect terranes and accretionary history of the Appalachian orogen: Geology, v. 10, p. 530–536, http://dx.doi.org/10.1130/0091-7613(1982)10<530:STAAHO>2.0.CO;2.

Williams, H., and Hatcher, R.D., Jr., 1983, Appalachian suspect terranes: Geological Society of America Memoirs, v. 158, p. 33–53, http://dx.doi.org/10.1130/MEM158-p33.

Williams, H., and Payne, J.G., 1975, The Twillingate granite and nearby volcanic groups: An island arc complex in northeast Newfoundland: Canadian Journal of Earth Sciences, v. 12, p. 982–995, http://dx.doi.org/10.1139/e75-090.

Williams, H., Colman-Sadd, S.P., and Swinden, H.S., 1988, Tectonic-stratigraphic subdivisions of central Newfoundland: Geological Survey of Canada, Paper88-1B, p. 91–98.

Willner, A.P., Gerdes, A., Massonne, H.-J., van Staal, C.R., and Zagorevski, A., 2014, Crustal Evolution of the Northeast Laurentian Margin and the Peri-Gondwanan Microcontinent Ganderia Prior to and During Closure of the Iapetus Ocean: Detrital Zircon U–Pb and Hf Isotope Evidence from Newfoundland: Geoscience Canada, v. 41, p. 345–364, http://www.dx.doi.org/10.12789/geocanj.2014.41.046.

Wright, I.C., Parson, L.M., and Gamble, J.A., 1996, Evolution and interaction of migrating cross-arc volcanism and backarc rifting: An example from the southern Havre Trough (35°20'–37°S): Journal of Geophysical Research, v. 101, p. 22071–22086, http://dx.doi.org/10.1029/96JB01761.

Wysoczanski, R.J., Todd, E., Wright, I.C., Leybourne, M.I., Hergt, J.M., Adam, C., and Mackay, K., 2010, Backarc rifting, constructional volcanism and nascent disorganised spreading in the southern Havre Trough backarc rifts (SW Pacific): Journal of Volcanology and Geothermal Research, v. 190, p.

39–57, http://dx.doi.org/10.1016/j.jvolgeores.2009.04.004.

Zagorevski, A., and Rogers, N., 2008, Stratigraphy and structural geology of the Ordovician volcano-sedimentary rocks in the Mary March Brook area: Current Research (2008) Newfoundland Department of Mines and Energy Geological Survey, Report 08-01, p. 111–123.

Zagorevski, A., and Rogers, N., 2009, Geochemical characteristics of the Ordovician volcano-sedimentary rocks in the Mary March Brook area: Current Research (2009), Newfoundland Department of Mines and Energy, Geological Survey Report 09-01, p. 271–288.

Zagorevski, A., and Rogers, N., 2011, Geochemical data of the Buchans-Robert's Arm Belt and adjacent units in central Newfoundland and Notre Dame Bay regions: Geological Survey of Canada, Open File 6728, 2011, 13 p., 1 CD-ROM, http://dx.doi.org/10.4095/288698.

Zagorevski, A., and van Staal, C.R., 2011, The record of Ordovician arc–arc and arc–continent collisions in the Canadian Appalachians during the closure of Iapetus, *in* Brown, D., and Ryan, P.D., *eds.,* Arc-Continent Collision, Frontiers in Earth Sciences: Springer-Verlag Berlin Heidelberg, p. 341–371, http://dx.doi.org/10.1007/978-3-540-88558-0_12.

Zagorevski, A., and McNicoll, V., 2012, Evidence for seamount accretion to a peri-Laurentian arc during closure of Iapetus: Canadian Journal of Earth Sciences, v. 49, p. 147–165, http://dx.doi.org/10.1139/e11-016.

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 backarc complexes in Iapetus: Constraints from the Annieopsquotch accretionary tract, central Newfoundland: Geological Society of America Bulletin, v. 118, p. 324–342, http://dx.doi.org/10.1130/B25775.1.

Zagorevski, A., van Staal, C.R., and McNicoll, V.J., 2007, Distinct Taconic, Salinic and Acadian deformation along the Iapetus suture zone, Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 44, p. 1567–1585, http://dx.doi.org/10.1139/E07-037.

Zagorevski, A., van Staal, C.R., McNicoll, V., Rogers, N., and Valverde-Vaquero, P., 2008, Tectonic architecture of an arc-arc collision zone, Newfoundland Appalachians, *in* Draut, A.E., Clift, P.D., and Scholl, D.W., *eds.*, Formation and Applications of the Sedimentary Record in Arc Collision Zones: Geological Society of America Special Papers, v. 436, p. 309–333, http://dx.doi.org/10.1130/2008.2436(14).

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, v. 479, p. 150–164, http://dx.doi.org/10.1016/j.tecto.2008.12.002.

Zagorevski, A., Rogers, N., and Haslam, R., 2010a, Geology and significance of the Harry's River mafic volcanic rocks, Buchans area, Newfoundland: Current Research (2010), Newfoundland Department of Mines and Energy Geological Survey, Report 10-1, p. 373–384.

Zagorevski, A., van Staal, C.R., Rogers, N., McNicoll, V.J., and Pollock, J., 2010b, Middle Cambrian to Ordovician arc-backarc development on the leading edge of Ganderia, Newfoundland Appalachians, *in* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., *eds.*, From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoirs, v. 206, p. 367–396, http://dx.doi.org/10.1130/2010.1206(16).

Zagorevski, A., van Staal, C.R., McNicoll, V.J., Hartree, L., and Rogers, N., 2012, Tectonic evolution of the Dunnage Mélange tract and its significance to the closure of Iapetus: Tectonophysics, v. 568–569, p. 371–387, http://dx.doi.org/10.1016/j.tecto.2011.12.011.

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