# Lower to Middle Ordovician evolution of peri-Laurentian arc and backarc complexes in Iapetus: Constraints from the Annieopsquotch accretionary tract, central Newfoundland

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## ABSTRACT

**The Annieopsquotch accretionary tract in Newfoundland is composed of a series of west-dipping structural panels, each containing remnants of ophiolitic and arc-backarc complexes of Laurentian affinity formed during the Ordovician closure of Iapetus. Panels were transferred from an upper-plate to a lower-plate setting during their Middle to Late Ordovician accretion to the Laurentian margin and become progressively younger eastward. Geochronological data indicate a complex and rapid history of generation and accretion of peri-Laurentian suprasubduction zone rocks. The rapid changes in tectonic environments and the complexity of the relationships are analogous to the complex arc-backarc relationships observed in the western Pacific today. The recognition of the peri-Laurentian provenance of these units based on stratigraphy, geochronology, isotopes, and geochemistry defines the position of the Red Indian Line, the fundamental suture zone in the northern Appalachians, but more importantly enables the development of a realistic tectonic model for the Annieopsquotch accretionary tract involving both thrust and sinistral transcurrent displacements.**

**The oldest and most inboard unit in the Annieopsquotch accretionary tract is the Annieopsquotch ophiolite belt (ca. 480 Ma), which marks the initiation of subduction outboard of the Laurentian margin. The Lloyds River ophiolite complex (ca. 473 Ma) preserves a fragment of younger, more mid-ocean-ridge–like backarc-oceanic crust than the adjacent, structurally overlying Annieopsquotch ophiolite belt. The Lloyds River ophiolite complex originated as a backarc to the Buchans Group (ca. 473 Ma) ensialic bimodal calc-alkaline arc. The panels containing the Annieopsquotch ophiolite belt and Lloyds River ophiolite complex were stitched and overlain by ensialic arc rocks of the Otter Pond Complex (ca. 468 Ma) immediately after their accretion to composite Laurentia together with the structurally underlying Buchans Group. The youngest, structurally lowest two panels comprise the elements of the Red Indian Lake group (465–460 Ma), which record the opening of a backarc basin and the subsequent establishment of a bimodal ensialic calc-alkaline arc sequence.**

**The observed relationships indicate that the Annieopsquotch accretionary tract was generated above a single west-dipping subduction zone outboard of the Laurentian margin over ~20 m.y. Accretion mainly took place in two stages at ca. 468 and 450 Ma, which correspond with the collision between Laurentia and the Dashwoods ribbon continent and the collision with the peri-Gondwanan Victoria Arc along the Red Indian Line, respectively. Both collisions form part of the Taconic orogeny. The latter, Late Ordovician collision terminated the relatively rapid closure of the main Iapetan tract. The proposed model is similar to the correlative tracts in the British and Irish Caledonides, and may encourage a new look at the New England Appalachians.**

**Keywords: Notre Dame subzone, accretion, trace elements, whole-rock geochemistry, Sm-Nd isotopes, U-Pb geochronology.**

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## INTRODUCTION

The Appalachian-Caledonian orogen is an example of a long-lived accretionary orogen, which formed in response to the Paleozoic closure of the Iapetus, Tornquist, and Rheic Oceans. Closure of these ocean basins that separated Laurentia, Gondwana, and Baltica from each other (van Staal et al., 1998; Cocks and Torsvik, 2002) generated a diverse set of arc terranes, microcontinents, and suprasubduction zone oceanic terranes that were accreted as single or composite terranes to Laurentia in multiple stages, forming a complex tectonic collage. Consequently, assessing Laurentia's growth requires a good understanding of the provenance and tectonic processes involved in the accretion of the various terranes. Another important aspect is the role of trench-parallel translation and dispersion of terranes during and after accretion. Some workers have speculated that this process may have been important, because critical elements of tectonic systems (e.g., forearc basins) are missing in many places (van Staal et al., 1998).

The Newfoundland Appalachians represent a critical element of the Appalachian-Caledonian orogen to evaluate terrane linkages between the North American and European segments. This particularly applies to the terranes accreted during the Ordovician closure of Iapetus's main oceanic tract (van Staal, 2005), because the zone of accreted terranes is wide, relatively well exposed, and generally of low metamorphic grade, and there is a detailed integration of seismic and geological data (e.g., Thurlow et al., 1992; van der Velden et al., 2004). This paper presents new data concerning the tectonic setting, age, and structural architecture of the various igneous and sedimentary units that have been recognized in the Annieopsquotch accretionary tract (van Staal et al., 1998; Zagorevski et al., 2003a, 2003b) of central Newfoundland, discusses the regional correlations with other known units in the Annieopsquotch accretionary tract, and finally presents a tectonic model. It will be shown that the Annieopsquotch accretionary tract comprises a series of Lower to Middle Ordovician peri-Laurentian oceanic and ensialic suprasubduction zone terranes that were assembled in west-dipping structural panels as a result of Ordovician sinistral-oblique accretion to Laurentia. Accretion terminated when the main Iapetean tract was closed and sutured with peri-Gondwanan elements along the Red Indian Line during the Late Ordovician (van Staal et al., 1998; van Staal, 2005).

The new interpretations of the Annieopsquotch accretionary tract support previous correlations with the Northern Belt of the Southern Uplands accretionary system of the British Caledonides, although, as discussed below in detail, there appear to be differences in the tectonic setting of the accreted terranes and the time when west-directed subduction of Iapetus started (Ryan and Dewey, 2004; Lissenberg et al., 2005a). Evidence of west-directed subduction in Newfoundland has ramifications for tectonic analyses of the northern Appalachians in New England and southern Quebec. Both the continuation of the Annieopsquotch accretionary tract and the Red Indian Line, as well as the evidence for west-directed subduction in general, are controversial themes in New England (e.g., Karabinos et al., 1998; Moench and Aleinikoff, 2003; Robinson et al., 1998), Hence, the data and interpretations presented herein may inspire a new look at the Ordovician tectonic evolution of the central part of the northern Appalachians in New England (e.g., Kim et al., 2003), where part of this history is masked by the extensive post-Ordovician cover sequences, largely absent in Newfoundland.

The tectonic architecture of the Annieopsquotch accretionary tract was established by detailed geological mapping (i.e., Lissenberg et al., 2005b; Rogers et al., 2005; van Staal et al., 2005a, 2005b, 2005c), combined with high-quality geochronology and geochemistry. This paper follows the stratigraphy developed during this mapping, which wherever possible took previously described units and expanded upon them, so that they were categorized and ranked in a form that is compliant with the strictures of the North American Stratigraphic Code (i.e., the Skidder basalts become the Skidder formation). Additionally, several new tectono-stratigraphic units (Lloyds River ophiolite complex, Mink Lake formation, and Red Indian Lake group) that were identified for the first time during this mapping, and so cannot be directly linked to any previously described entities, are described in detail in this paper. The unit names, ranks, and categories presented herein can be considered informal pending the release of the formalizing documentation for this region.

### Regional Geology

Williams (1979, 1995) originally subdivided the Northern Appalachians into the Humber, Dunnage, Gander, Avalon, and Meguma zones, with the Humber zone representing the remnants of the Laurentian passive margin and the Gander, Avalon, and Meguma zones accreted peri-Gondwanan terranes (Fig. 1). In this classification, the Dunnage zone combines the vestiges of the Cambrian-Ordovician peri-Laurentian (Notre Dame and Dashwoods subzones) and peri-Gondwanan (Exploits subzone) continental and oceanic arc-backarc and ophiolitic complexes that formed within the Iapetus Ocean. The peri-Laurentian and peri-Gondwanan subzones are differentiated on the basis of marked contrasts in stratigraphy, structure, fauna, and isotopic characteristics. The recognition of these differences over time led to the discovery of the Red Indian Line (Fig. 1; Williams et al., 1988), which was a major breakthrough in understanding Appalachian tectonics. The Red Indian Line represents a major crustal-scale fault that is clearly visible in seismic surveys as a reflector extending to at least 20 km, at which point it is truncated by a Devonian, wedging-related structure (van der Velden et al., 2004).

This study discusses the sequences that occur immediately to the west of the Red Indian Line and that constitute the most outboard units of the peri-Laurentian Notre Dame subzone (Fig. 1). The Notre Dame subzone is dominated by Taconic deformed and metamorphosed Ordovician volcanic and plutonic rocks of the Notre Dame Arc (Whalen et al., 1997; van Staal et al., 1998), which are locally unconformably overlain by Silurian red beds. The Ordovician Notre Dame Arc was largely built upon the Dashwoods ribbon microcontinent, which was rifted off Laurentia during the Early Cambrian (Waldron and van Staal, 2001).

### Annieopsquotch Accretionary Tract

The Annieopsquotch accretionary tract is bounded to the west by the Lloyds River fault–Hungry Mountain thrust system (Lissenberg and van Staal, 2002; Thurlow, 1981) and to the east by the Red Indian Line (Zagorevski et al., 2003a, 2004). Internally, the constituent units of the Annieopsquotch accretionary tract are juxtaposed along northwest-dipping oblique reverse shear zones, which appear to become progressively younger to the southeast, suggesting progressive accretion to the Laurentian margin.

The structural relationships between the units of the Annieopsquotch accretionary tract are well preserved in the Buchans area (Fig. 1), where an extensive south-southeast–directed thrust duplex system was recognized with the Hungry Mountain thrust as the roof and the Red Indian Line as the floor thrusts (Fig. 1; e.g., Calon and Green, 1987; Thurlow et al., 1992). Structural relationships are more complicated southwest of Buchans, where several phases of deformation have resulted in tight to isoclinal folding, steepening, and reactivation of the thrusts as steep, southeast-directed sinistral oblique reverse faults (Zagorevski and van Staal, 2002). In the studied area, the thrusts are overprinted by open to tight, moderately

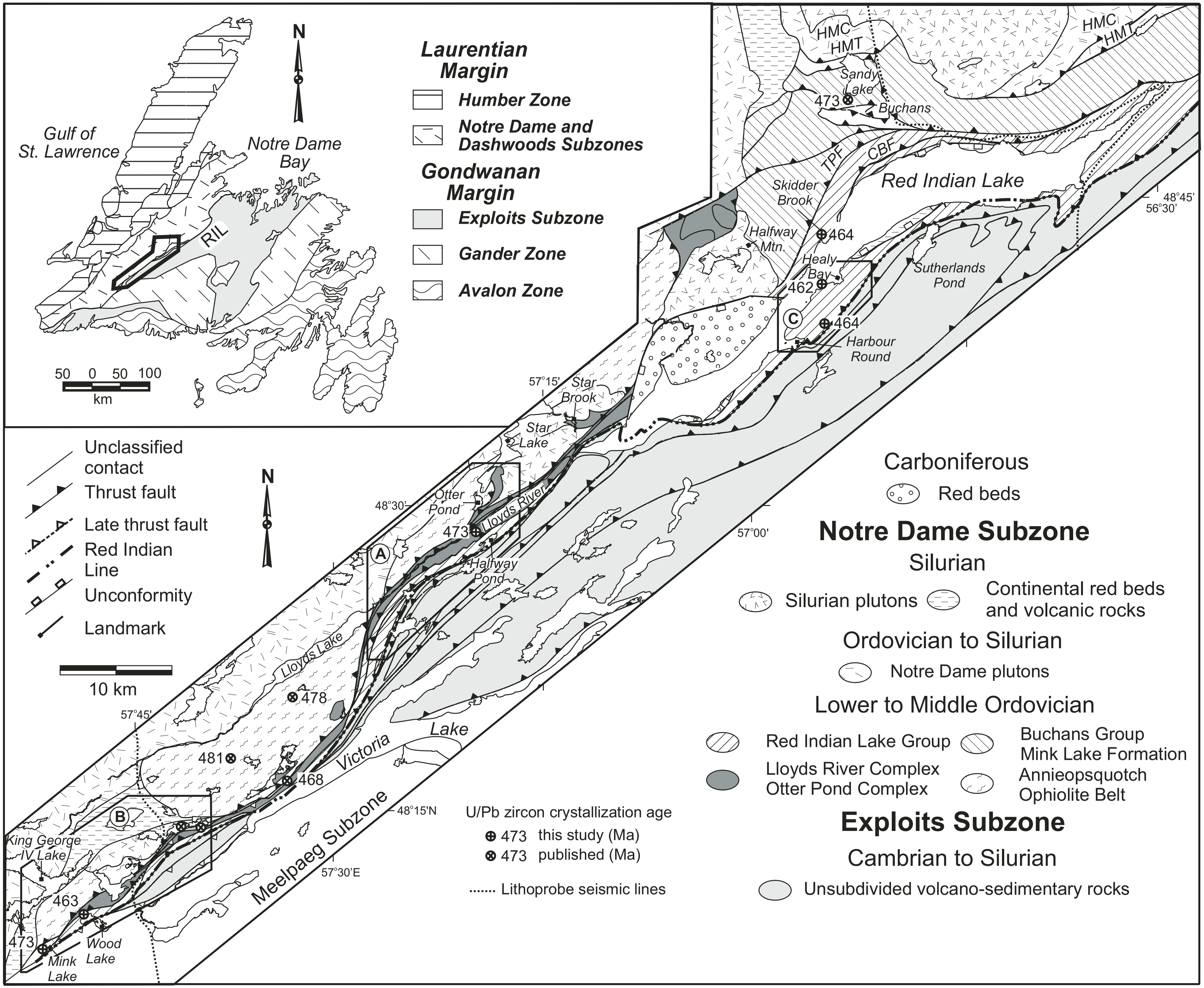


**Figure 1. Generalized geology of the Mink Lake–Red Indian Lake area showing the location of peri-Laurentian arc-backarc complexes (modified after Zagorevski et al., 2003b). CBF—Clench Brook fault; HMC—Hungry Mountain complex; HMT—Hungry Mountain thrust; RIL—Red Indian Line; TPF—Tilley's Pond fault. Inset: Tectono-stratigraphic zones of Newfoundland (modified after Williams, 1995).**

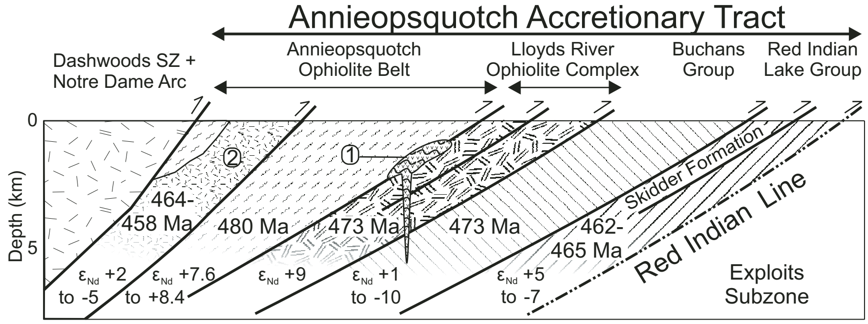


**Figure 2. Schematic composite cross section of the Annieopsquotch accretionary tract in central Newfoundland (modified from Lissenberg et al., 2005c). (1) Otter Pond Complex (468 ± 2 Ma; $\varepsilon_{Nd(468)}$ –1 to –6.8). (2) Pierre's Pond Intrusive Suite (Lissenberg et al., 2005c). SZ—subzone.**

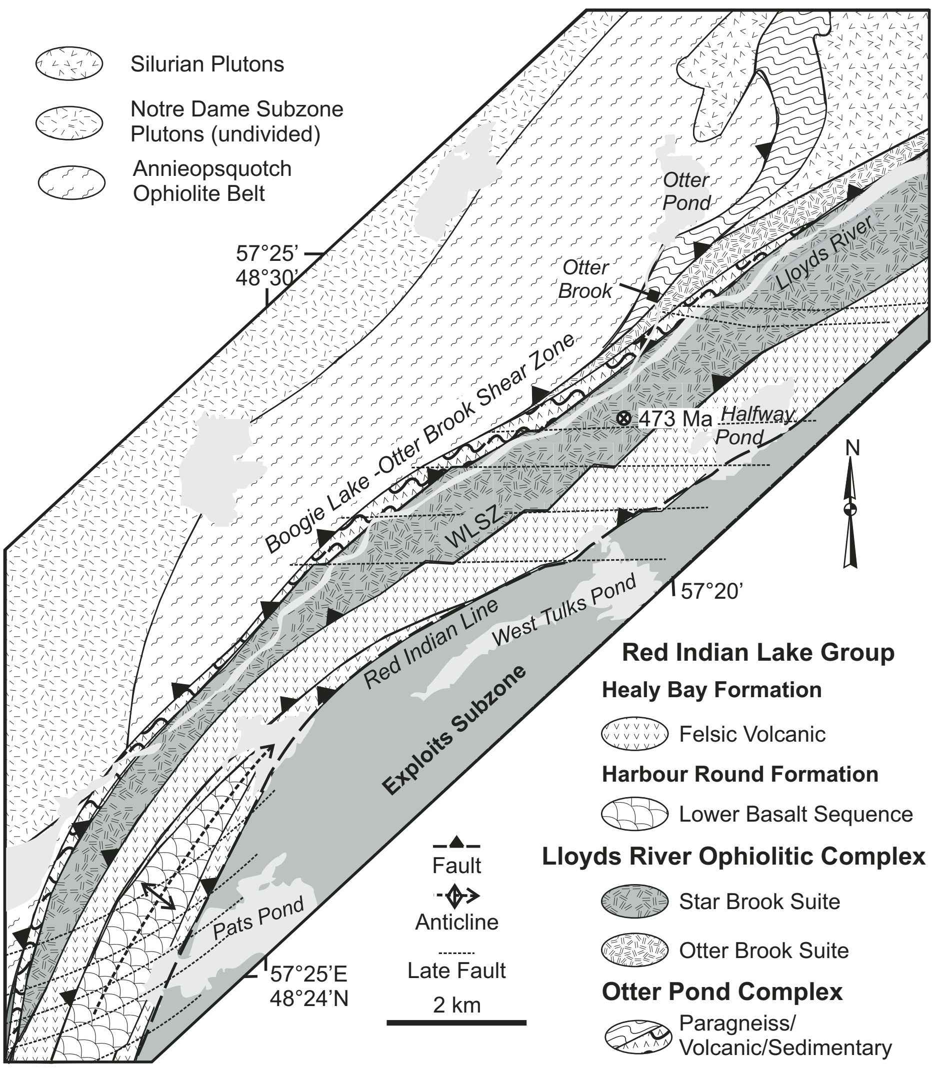


**Figure 3. Detailed geology of the Otter Pond area demonstrating tectono-stratigraphic relationships between fault-bounded units and Silurian intrusive rocks. WLSZ—Wood Lake shear zone.**

inclined folds and kinks related to Silurian to Devonian deformation, resulting in local overturning of the southeast-directed thrusts. Our interpretation of the original geometry of the Annieopsquotch accretionary tract relies in part on the geometrical reconstruction of the thrust duplex in the Buchans area (Calon and Green, 1987; Thurlow et al., 1992).

The Annieopsquotch accretionary tract contains the structural panels comprising the Annieopsquotch ophiolite belt (U/Pb zircon 477.5 +2.6/–2, 481 +4/–1.9 Ma; Dunning and Krogh, 1985), Lloyds River ophiolite complex (U/Pb zircon 473 ± 3.7 Ma; see following), Otter Pond Complex (468 ± 2 Ma; Lissenberg et al., 2005c), Buchans Group (U/Pb zircon 473 ± 1, 473 ± 2, 473 +3/–2, 473 ± 4 Ma; Dunning et al., 1987; Bostock, 1988; Kean, 1979a; Kerr and Dunning, 2003; Swinden et al., 1997; see following), and the Red Indian Lake group (U/Pb zircon 464.8 ± 3.5, 462 +2/–9, 465 ± 2, 463 ± 3 Ma: see following), respectively, which have a total structural thickness of 8–15 km (Fig. 1). The structural thickness of each panel individually varies significantly in the study area (0–5 km, ~2 km average), indicating partial to total excision of the lithostratigraphic units due to strike-slip and/or thrust faulting related to transfer from an upper-plate to lower-plate setting during accretion and subsequent deformation. The stratigraphy of each of these structural panels is addressed from the structurally highest (northwest) to the lowest (southeast), that is generally from old to young (Fig. 2). All units have been metamorphosed to (sub)-greenschist to amphibolite facies, with the grade of metamorphism generally increasing toward the west.

### *Annieopsquotch Ophiolite Belt*

Annieopsquotch ophiolite belt is composed of several related suprasubduction zone ophiolite complexes (Figs. 1, 3, and 4) that formed during the initiation of west-directed subduction outboard of the Dashwoods subzone (Lissenberg et al., 2005b). They preserve an early boninitic troctolite phase, along with later gabbro sill, sheeted dike, and pillow basalt zones (Dunning, 1984; Lissenberg et al., 2005b). The gabbro–sheeted dike–basalt sequence has a tholeiitic suprasubduction zone geochemical signature, although the stratigraphically highest basalts progressively develop more mid-ocean-ridge basalt (MORB)–like compositions and are cut by enriched backarc basalt (BAB)-like sheeted dikes (Lissenberg et al., 2005b). The Annieopsquotch ophiolite belt is separated from the structurally underlying Lloyds River ophiolite and Otter Pond complexes by the Otter Brook–Boogie Lake shear zone (Figs. 3 and 4).

***Lloyds River Ophiolite Complex***

Lloyds River ophiolite complex is exposed as an ~1-km-thick belt for over 100 km from Mink Lake to the town of Buchans, and is defined as a series of geochemically distinct ophiolitic panels that are younger than the structurally overlying Annieopsquotch ophiolite belt (Figs. 1, 3, and 4). Spectacular exposures of this ophiolite complex occur along the Lloyds River (Fig. 3). The Lloyds River ophiolite complex contains rocks that were previously correlated with the Annieopsquotch ophiolite belt, and locally with the Bay du Nord, Buchans, and Victoria Lake Groups (as defined by Kean, 1979b, 1982, 1983). Lloyds River ophiolite complex is intruded by felsic dikes typical of the Otter Pond Complex (Lissenberg et al., 2005c; see following) and is unconformably overlain by Upper Llandovery to Wenlock continental red beds and volcanic rocks (Dunning et al., 1990). The Lloyds River ophiolite complex is divided into two geochemically distinct suites that in the study area occur within distinct structural panels, but may occur together further to the north according to the geochemical database of Davenport et al. (1996) (Table 1; Fig. 5).

***Otter Brook suite.*** The ophiolitic Otter Brook suite, named after the exposure above the Otter Brook (Fig. 3), is composed of variably deformed gabbro, sheeted diabase (Fig. 6A), and pillow basalt. The diabase and basalt are vesicular and plagioclase phyric, whereas the gabbroic rocks display subophitic intergrowths between plagioclase and clinopyroxene. The clinopyroxene is frequently altered to hornblende and oxide assemblages. The Otter Brook suite is separated from the Annieopsquotch ophiolite belt and the Otter Pond Complex by the Boogie Lake–Otter Brook shear zone (Figs. 3 and 4).

***Star Brook suite.*** The ophiolitic Star Brook suite is composed of variably deformed gabbro, anorthosite, sheeted diabase, and pillow basalt (Fig. 6B). The gabbro grades into anorthositic gabbro and anorthosite, defining a continuous, but fault-dissected, anorthosite-rich lens along the Lloyds River valley. The gabbro sequence is locally cut by plagioclase porphyritic diabase, similar to the dikes in the sheeted diabase zone. The sheeted dikes grade into a pillow lava sequence that is locally associated with thinly bedded limestone. The relationships between sheeted diabase and basalt are well preserved in the type locality along Star Brook. An additional reference section is designated for this suite immediately north of the southwestern tip of Victoria Lake. This area preserves a 0.75-km-thick northwest-younging sequence of layered and isotropic gabbro (~500 m), diabase (~50 m), and pillow basalt (~200 m).

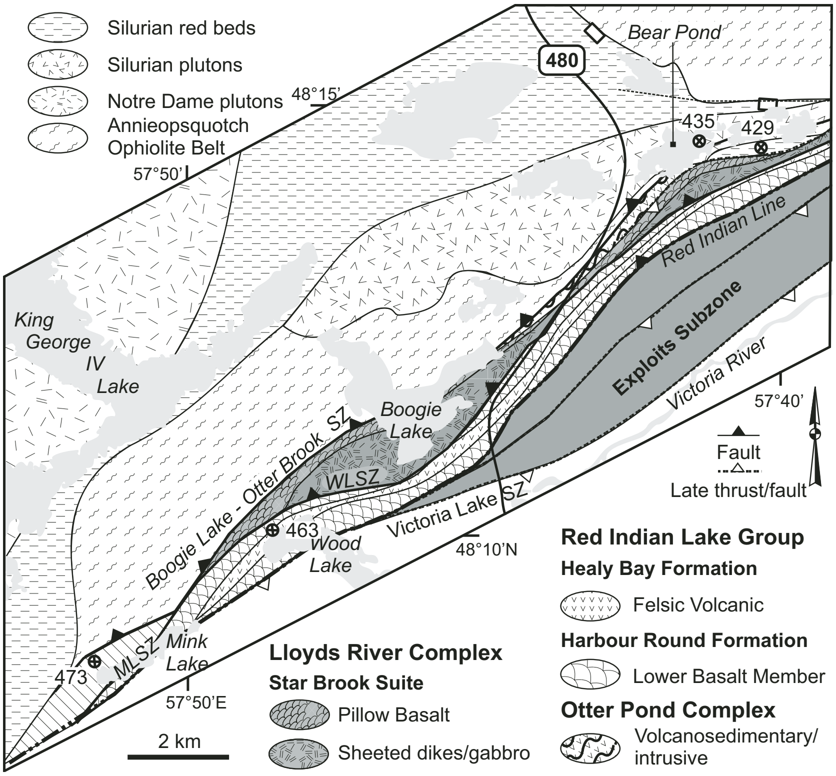


**Figure 4. Detailed geology of the Wood Lake area demonstrating tectono-stratigraphic relationships between Annieopsquotch ophiolite belt, Mink Lake formation, and Red Indian Lake group. MLSZ—Mink Lake shear zone, WLSZ—Wood Lake shear zone.**

***Otter Pond Complex***

The Otter Pond Complex (Lissenberg et al., 2005c; Figs. 1, 3, and 4) occurs in a relatively thin, highly deformed tectonite panel composed of rhyolite, amphibolite, metagabbro, mica, and graphitic schist that are tentatively interpreted to represent a sequence of interlayered rhyolitic tuff (Fig. 6C), basaltic flow and/or sill, pelite or altered felsic tuff, and carbonaceous sedimentary rocks. This tectonite panel largely defines the Boogie Lake–Otter Brook shear zone along ~150 km of its length (Figs. 3 and 4), which separates the Lloyds River ophiolite complex from the Annieopsquotch ophiolite belt. Northeast of Otter Pond, Silurian plutons intrude the Otter Pond Complex, which was here transformed into interlayered biotite-muscovite-garnet, quartzo-feldspathic and migmatitic paragneiss by the accompanying metamorphism (Fig. 6D). A magmatic link with the Annieopsquotch ophiolite belt is provided by the hornblende-phyric to oikiocrystic gabbro and diabase, typical of the Otter Brook Complex, that were intruded into the Annieopsquotch ophiolite belt. Chemistry of the Otter Pond Complex felsic and mafic rocks suggests formation in a calc-alkaline ensialic arc setting ($\varepsilon_{Nd}$ –1 to –6.8; Lissenberg et al., 2005c). Otter Pond Complex granodiorite intrudes along the Otter Brook–Boogie Lake shear zone and is interpreted to stitch the Annieopsquotch ophiolite belt, Lloyds River ophiolite complex, and Buchans Group (468 ± 2 Ma; Lissenberg et al., 2005c).

***Buchans Group***

The Buchans Group and correlative Roberts Arm Group are composed of ca. 473 Ma peri-Laurentian ensialic island-arc sequences that have an exposed combined strike length of ~200 km (Table 1; Fig. 5) (Bostock, 1988; Dunning et al., 1987; Nowlan and Thurlow, 1984; Swinden et al., 1997; Thurlow and Swanson, 1987). The herein-defined Mink Lake formation is included in the Buchans Group based on its age, geochemistry, Sm-Nd isotope characteristics, and similarity of structural position.

***Mink Lake formation.*** The Mink Lake formation is restricted to a small area southwest of Wood Lake and north of Mink Lake, which forms its type locality (Figs. 1 and 4). The Boogie Lake and Wood Lake shear zones separate it from the Annieopsquotch ophiolite belt and Lloyds River ophiolite complex to the north and northeast, respectively, whereas the Mink Lake

TABLE 1. SUMMARY OF CORRELATIVES OF HEREIN-PROPOSED TECTONO-STRATIGRAPHIC UNITS IN NEWFOUNDLAND, AND THEIR TECTONO-MAGMATIC AFFINITY

| U/Pb zircon age (Ma) | Characteristics | Tectonic setting‡ | Correlatives§ |
|---|---|---|---|
| Red Indian Lake Group† | | | |
| 460–465 | Healy Bay formation†: Felsic volcanic and epiclastic rocks (tuff, rhyolite, sandstone) locally interlayered with red shale and/or red chert.<br>Harbour Round formation†: Tholeiitic to calc-alkaline pillow basalt, diabase, and andesite locally containing interpillow limestone and interlayered with red chert and shale.<br>Skidder formation†: Tholeiitic pillow basalt and diabase locally associated with interpillow red chert and cut by fine-grained trondhjemite. | Ensialic arc and backarc | Gullbridge area: No known correlatives.<br>Roberts Arm area: Crescent Lake formation tholeiitic basalts and associated volcanic and epiclastic rocks (Bostock, 1988).<br>Notre Dame Bay: Early Llanvirn (ca. 465 Ma; G. Nolan, personal commun. in O'Brien, 2003) tholeiitic Mores Cove formation of the Cottrell's Cove Group (Dec et al., 1997; O'Brien, 2003).<br>Potentially Chanceport Group, as it lies in the same structural position as the Cottrell's Cove Group (Dec et al., 1997). |
| Otter Pond Complex | | | |
| 468 ± 2†† | Banded rhyolite interlayered with graphitic schist, mica schist, and amphibolite. | Ensialic arc | No known correlatives. |
| Buchans Group | | | |
| 473 ± 1<br>473 + 3/–2‡‡ | Bimodal calc-alkaline volcanic rocks locally associated with epiclastic rocks and chert (Thurlow and Swanson 1987; this study). | Ensialic arc | Gullbridge area: Tholeiitic volcanic rocks from Great Gull Lake to Lake Bond (Swinden and Sacks 1986; Pope et al., 1991), which although lie on-strike with the Buchans Group are atypical in their geochemical diversity (Davenport et al., 1996).<br>Roberts Arm area: Roberts Arm Group excluding Crescent Lake formation (473 ± 2, 473 ± 4 Ma; Bostock, 1988; Dunning et al., 1987; Kerr and Dunning, 2003).<br>Notre Dame Bay: Potentially Fortune Harbour formation of the Cottrell's Cove Group (Dec et al., 1997). Although an age of 484 ± 2 Ma has been obtained (Dec et al., 1997), the age is questionable due to multiple inheritance and lack of concordant analyses. |
| Lloyds River Ophiolite Complex† | | | |
| 473 ± 4 | Star Brook and Otter Brook suites†: Tholeiitic pillow basalt, sheeted diabase, gabbro with minor anorthosite and trondhjemite. Interpillow red chert and limestone are locally present. | Backarc | Buchans Area: Ophiolitic Harry's River Metabasite (Thurlow, 1991) equivalent to unit 2a of Lundberg Hill formation (Calon and Green, 1987). Potentially portions of the upper Buchans Subgroup (Thurlow, 1981).<br>Gullbridge and Roberts Arm areas: No known correlatives.<br>Notre Dame Bay: Potentially Cutwell Group on Pilley's and Triton Islands and Moreton's Harbour Group (Swinden, 1996). These groups occupy an identical structural position above the Roberts Arm Belt and have similar tectonic setting (Swinden, 1996), although they have not yet been reliably dated. |

†Tectono-stratigraphic unit proposed in this paper.
‡ Tectonic setting inferred herein from geochemical and geological characteristics; see text for discussion.
§See Figure 7.
††Lissenberg et al. (2006).
‡‡Dunning et al. (1987).

shear zone separates it from the Red Indian Lake group to the southeast. The Mink Lake formation is only gently folded and frequently appears largely undeformed macroscopically. It is dominated by hematized pillow basalt and breccia (Fig. 6E), with some massive basalt flows, diabase, felsic tuff, and jasper. Younging indicators suggest the felsic tuff occurs near the stratigraphically highest exposed level of the sequence, however, as neither the base nor the top of the formation are exposed, its true position within the Buchans Group stratigraphy cannot be resolved at present.

### *Red Indian Lake Group*

The herein defined Red Indian Lake group (Figs. 1, 3, 4, and 7), predominantly exposed along the shores of Red Indian Lake, is composed of rocks that were previously allocated to several informal units, such as the Healy Bay siltstone, Harbour Round basalt (Thurlow et al., 1992), Harbour Round formation (Kean and Jayasinghe, 1980), and Skidder basalt (Pickett, 1987). These are expanded herein to reflect the lithological characteristics in the type localities, and three revised units are proposed for the Red Indian Lake group: Harbour Round, Healy Bay, and Skidder formations. The Red Indian Lake group is separated from the structurally overlying Buchans Group by the Tilley's Pond fault (Thurlow et al., 1992) and correlative Mink Lake shear zone (Figs. 1 and 4); the Wood Lake shear zone separates it from the structurally overlying Lloyds River ophiolite complex (Fig. 4), whereas the Red Indian Line separates it from the structurally underlying peri-Gondwanan Victoria Lake Supergroup (Fig. 1; Evans and Kean, 2002). Internally within the Red Indian Lake group, the Clench Brook fault juxtaposes the Skidder formation with the structurally underlying Harbour Round and Healy Bay formations (Fig. 1). The Healy Bay formation is stratigraphically intertongued with the more-extensive Harbour Round formation.

The Red Indian Lake group is exposed in a 1–6-km-wide, imbricated belt for at least 150 km from Wood Lake to Red Indian Lake (Fig. 1). Although, the Red Indian Lake group has yet to be recognized northeast of Red Indian Lake, correlatives may exist in the Roberts Arm–Chanceport belt (Table 1; Fig. 5)

***Skidder formation.*** The Skidder formation, which is named after the previously defined Skidder basalt (Pickett, 1987), is a tholeiitic sequence of predominantly pillowed and massive amygdaloidal and variolitic basalt and pillow breccia (Fig. 6F), which locally host significant volcanogenic massive sulfide (VMS)-style mineralization (Skidder Prospect; Pickett, 1987). These basaltic rocks are associated with interstitial jasper, interflow hematitic siltstone and jasper, and are intruded by gabbroic dikes and pods of chemically related trondhjemite (Davenport et al., 1996; Pickett, 1987). The Skidder formation is well exposed in Skidder Brook, east of the Skidder Prospect, where pillow lava and breccia are cut by fine-grained trondhjemitic dikes. The absence of calc-alkaline basalt and felsic tuff distinguishes the Skidder formation from the upper basalt of the Harbour Round formation. However, it may be, in part, correlative to chemically similar basalt in the lower member of the Harbour Round formation (see following).

***Harbour Round formation.*** The Harbour Round formation is informally subdivided into the lower and upper basalt members (Figs. 4 and 6), with the lower basalt member dominating the southern portion of the formation's exposures and the upper basalt the northern part. All lithologies are intertongued with felsic tuff typical of the Healy Bay formation. The central portion of the formation, which occurs immediately north of Harbour Round, although structurally complex, preserves the stratigraphic relationships between these members, and as such, forms the type locality. The lower basalt member is composed predominantly of light-green pillow basalt associated with hematitic red shale, interstitial limestone, diabase, gabbro, iron formation, and felsic tuff.

The appearance of a polymictic volcanogenic conglomerate to breccia marks the base of the upper basalt member (Fig. 6G). The conglomerate ranges from clast- to matrix-supported, and thinly bedded to massive. The clasts are felsic volcanic, mafic volcanic, and jasper. In the stratigraphically higher levels, the conglomerate is associated with hematized pillow basalts, which are chemically distinct from the lower basalt member.

***Healy Bay formation.*** The Healy Bay formation is composed of mainly light-gray to white ash to crystal tuff locally associated with rhyolite, volcaniclastic sandstone, and shale. All lithologies are locally interlayered with red shale and/or hematitic chert (Fig. 6H). Bedded red shale can be abundant locally, with a thickness exceeding several meters.

## U-Pb GEOCHRONOLOGY[1]

Six new U-Pb zircon age determinations were conducted at the Geological Survey of Canada (Ottawa) utilizing, as appropriate, both thermal ionization mass spectrometry (TIMS) and sensitive high-resolution ion microprobe (SHRIMP II) methodologies. SHRIMP II analyses were conducted following the analytical procedures of Stern (1997), with standards and U-Pb calibration methods following Stern and Amelin (2003). The U-Pb TIMS analytical methods are outlined in Parrish et al. (1987), with treatment of analytical errors following Roddick et al. (1987). U-Pb SHRIMP II and TIMS analyses are presented in Tables 1 and 2, respectively, and are plotted in concordia diagrams with errors at the 2σ level (Fig. 8).

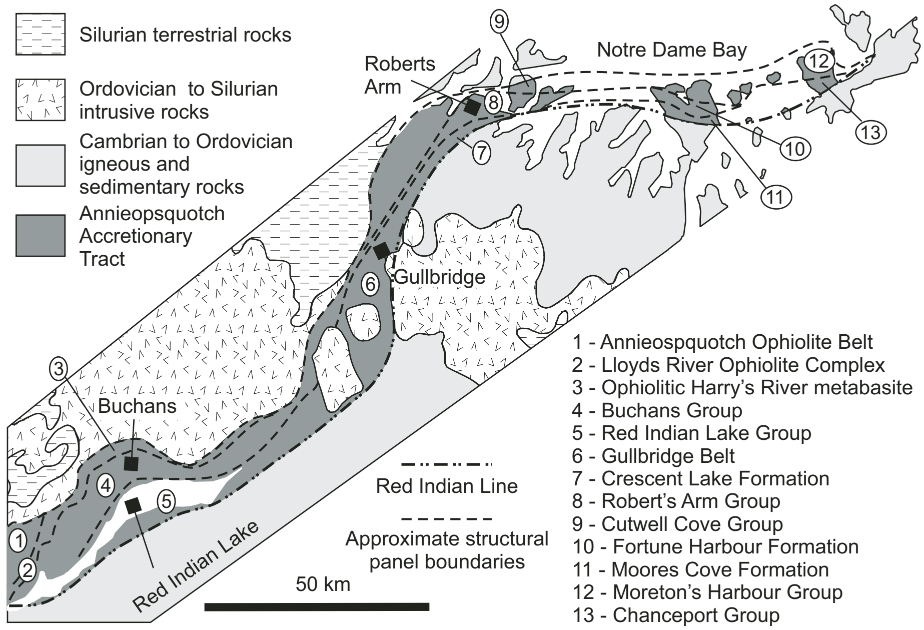


**Figure 5. Correlation of the herein described tectono-stratigraphic units to Notre Dame Bay.**

### Lloyds River Complex Leuco-Gabbro (VL02A178)

Sample VL02A178 consists of a white weathered leuco-gabbro that outcrops to the southeast of Lloyds River. This sample yielded a small amount of poor-quality zircon grains and fragments. All of the grains preserve some euhedral faces and igneous zoning; however, alteration patches are present in some grains. In total, 9 grains were analyzed with the SHRIMP II, producing a concordia age calculated to be 473.0 ± 3.7 Ma (mean square of weighted deviates [MSWD] of concordance and equivalence = 1.5) (Table 2; Fig. 8A). This age is interpreted to be the crystallization age of the Star Brook suite leuco-gabbro and therefore is also representative of the gabbro, sheeted dikes, and pillow lavas of Star Brook suite.

### Mink Lake Formation Felsic Tuff (VL01A097)

Sample VL01A097 was obtained from a buff weathered, jasper chip–bearing, bedded felsic tuff that directly overlies a basaltic flow. The sample yielded a small amount of variable-quality zircon with several distinct morphologies, including euhedral prisms, stubby prisms, and equant grains, as well as concoidal fragments derived from larger grains. Cores and inclusions were present in several grains. In addition, there were also presumably inherited slightly to strongly rounded prismatic to equant zircons and anhedral grains in the sample. Four fractions were selected for TIMS analysis (Table 3). Two fractions (E and F) are nearly concordant (0.2%), and together define a concordia age of 473.4 ± 1.2 Ma (MSWD of concordance and equivalence = 0.22) (Fig. 8B). Fraction C is 8.1% discordant and likely experienced recent Pb loss, whereas fraction B is interpreted to contain an inherited zircon component derived from an older crustal source. The age of 473.4 ± 1.2 Ma is interpreted to represent the crystallization age of the felsic tuff and the associated mafic volcanic rocks.

[1]GSA Data Repository item 2006043, analytical procedures and whole-rock geochemistry from the peri-Laurentian arc and backarc complexes in central Newfoundland, is available on the Web at http://www.geosociety.org/pubs/ft2006.htm. Requests may also be sent to editing@geosociety.org.

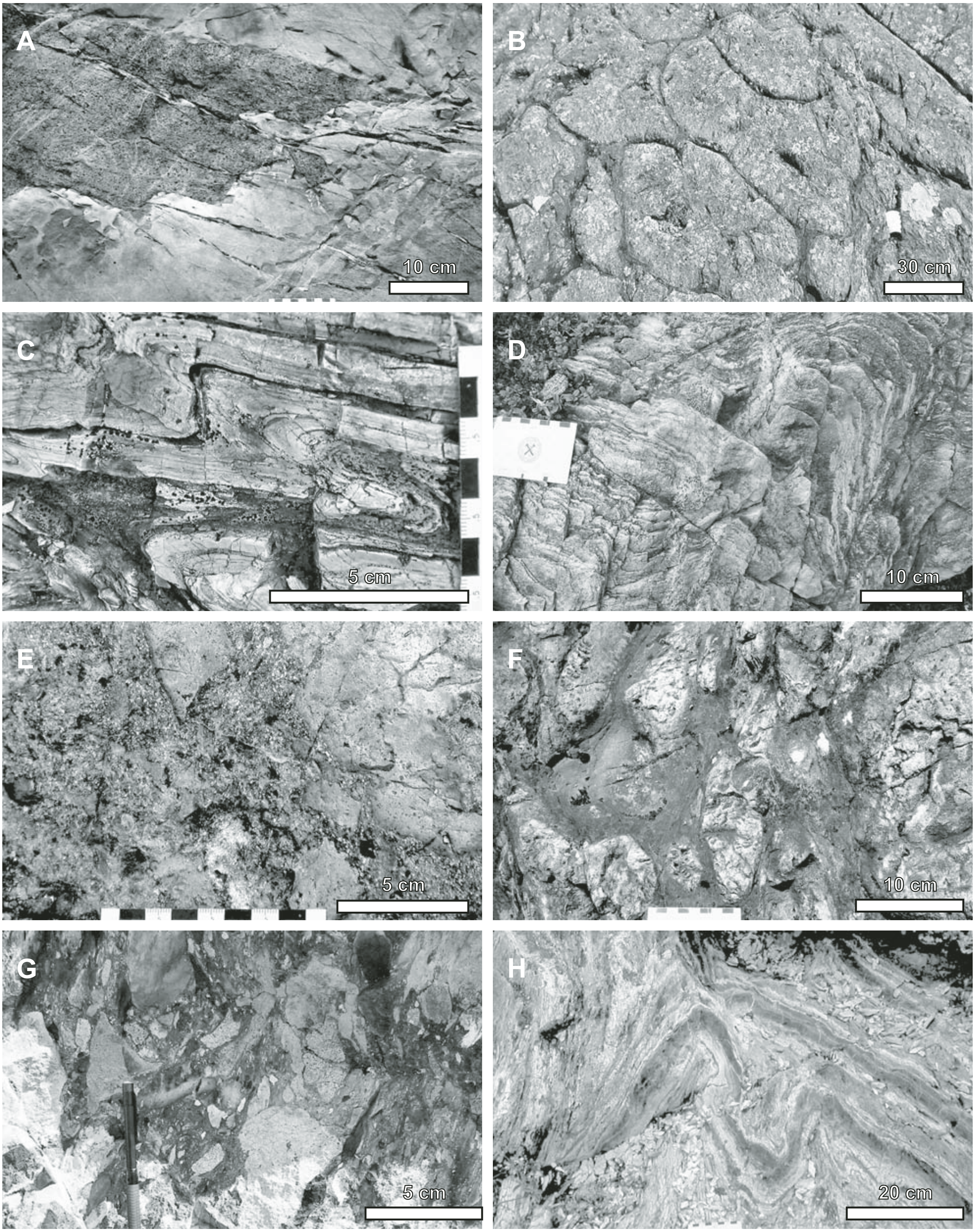


**Figure 6. Representative photographs of the rocks in the Red Indian Lake–Wood Lake area: (A) angular vesicular mafic enclave in sheeted diabase zone of the Otter Brook suite; (B) foliated Star Brook suite pillow basalt; (C) folded Otter Pond Complex rhyolite; (D) folded Otter Pond Complex garnet-biotite-muscovite gneiss; (E) extremely well-preserved basalt breccia immediately below the Mink Lake formation dated felsic tuff; (F) epidotized Skidder formation pillow basalt breccia immediately adjacent to the dated trondhjemite; (G) Healy Bay formation complexly folded interbedded red shale, jasper, and felsic tuff; and (H) Harbour Round formation conglomerate.**

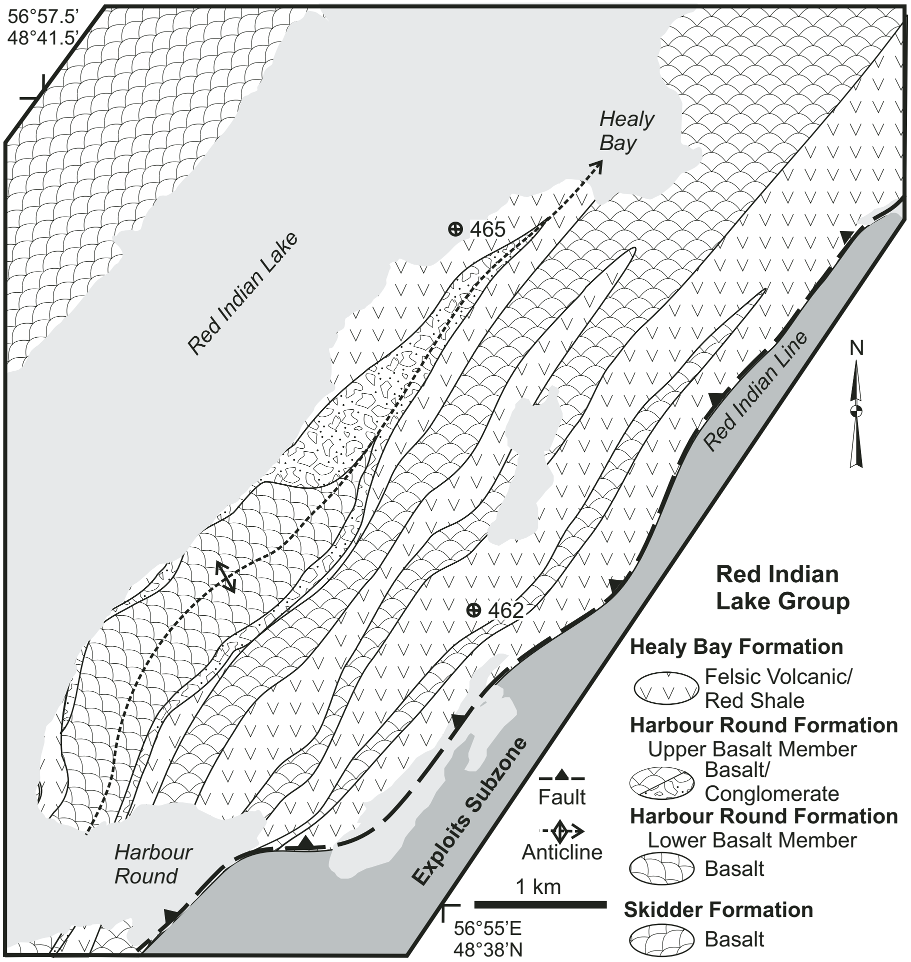


**Figure 7. Detailed geology of the Harbour Round area demonstrating tectono-stratigraphic relationships between formations in the Red Indian Lake group.**

### Skidder Formation Trondhjemite (VL02A294)

Sample VL02A294 was collected from a small body of fine-grained trondhjemite that intrudes epidotized pillow breccia east of the Skidder Prospect. The trondhjemite is locally extensively quartz veined. This sample yielded a small amount of poor-quality zircon grains and fragments. Most of the morphologies are interpreted to be magmatic in origin, with stubby prisms predominating. However, several rounded, presumably inherited zircons are also present. The dominant population of zircons from the trondhjemite, analyzed on the SHRIMP, has a concordia age calculated at 464.8 ± 3.5 Ma (MSWD of concordance and equivalence = 1.4, $n$ = 10) (Fig. 8C; Table 2). A second, younger population of zircons ($n$ = 6) has a calculated concordia age of 424.2 ± 4.2 Ma (MSWD of concordance and equivalence = 1.1) (inset of Fig. 8C). Presence of two distinct zircon populations makes the interpretation of the age of the trondhjemite somewhat problematic. The trondhjemite could have crystallized at 424 Ma and inherited the ca. 465 Ma population, however, there is no documented Silurian oceanic crust in the Annieopsquotch accretionary tract. The oceanic character of the Skidder formation (Pickett, 1987; Swinden et al., 1997) is inconsistent with Silurian magmatism, which is predominantly ensialic calc-alkaline and alkaline (Whalen et al., 2003). The Silurian age is best interpreted to either reflect hydrothermal zircon growth in a microscopic quartz vein or possibly igneous growth in a tonalitic veinlet related to the nearby, voluminous Silurian magmatism, the substance of which was accidentally not removed during sample preparation. The interpreted age of the trondhjemite, at 464.8 ± 3.5 Ma, also provides an age on the Skidder formation basaltic volcanism.

### Healy Bay Formation Tuff (RAX01-908; z7097)

Sample RAX01-908 (z7097) lies stratigraphically near the base of the Healy Bay formation. This sample contains abundant euhedral prismatic zircons. Four multigrain zircon fractions were analyzed by TIMS (Table 3). Three of these analyses are quite discordant (32%–60%) and are interpreted to contain significant inherited components (Fig. 8D). Fraction A2 is nearly concordant; the $^{206}Pb/^{238}U$ age of this fraction is 462.3 ± 1.3 Ma. Zircons from this tuff sample were also placed on a grain mount and analyzed by SHRIMP. Scanning electron microscope (SEM) imaging revealed numerous zircons with core-rim relationships, as well as entirely magmatic grains with sharp oscillatory zoning. Thirteen analyses were collected from oscillatory zoned rims and grains interpreted to be magmatic in origin (Table 4). The concordia age calculated from these analyses is 457.0 ± 3.7 Ma (MSWD of concordance and equivalence = 1.4) (Fig. 8E). SHRIMP analyses of zircon cores range in age from ca. 935 to 1845 Ma (Table 2; not plotted), revealing contributions from older crustal sources. The best interpretation for the age of this tuff is taken to be 462 +2/–9 Ma, to take into account the age of nearly concordant fraction A2 and the concordia age calculated from the SHRIMP analyses.

### Healy Bay Formation Tuff (RAX00-903; z6679)

Sample RAX00-903 (z6679) occurs stratigraphically above RAX01-908. This sample contains abundant euhedral zircon, ranging in morphology from equant grains to elongate crystals (Table 3). Six multigrain zircon fractions were analyzed by TIMS. Fraction A1 is concordant and has a $^{206}Pb/^{238}U$ age of 465.1 ± 1.2 Ma (Fig. 8F; Table 3). Fractions E1 and C1 are discordant and contain inherited components. A linear regression including fractions C1, E1, and A1 has an upper intercept at ca. 2.3 Ga and a lower intercept at 465 ± 1 Ma (MSWD = 0.02). Fractions B1, B2, and D1 are slightly discordant and may have undergone a minor amount of Pb loss. A weighted average of the $^{207}Pb/^{206}Pb$ ages of the most concordant analyses (A1, D1, B1) is 467.1 ± 2.9 Ma (MSWD = 0.19). The best interpretation for the age of the tuff is 465 ± 2 Ma and takes into account the error on all analyzed fraction combinations.

### Healy Bay Formation Felsic Tuff (RAX00-916; z6682)

Sample RAX00-916 (z6682) occurs in close association with the upper basalt member and

TABLE 2. U-Pb SHRIMP ANALYTICAL DATA

| Spot name | U (ppm) | Th (ppm) | Th/U | Pb* (ppm) | $^{204}Pb$ (ppb) | $^{204}Pb/^{206}Pb$ | ± $^{204}Pb/^{206}Pb$ | f(206)$^{204}$ | $^{208}Pb/^{206}Pb$ | ± $^{208}Pb/^{206}Pb$ | $^{207}Pb/^{235}U$ | ± $^{207}Pb/^{235}U$ | $^{206}Pb/^{238}U$ | ± $^{206}Pb/^{238}U$ | Corr. coeff | $^{207}Pb/^{206}Pb$ | ± $^{207}Pb/^{206}Pb$ | Ages (Ma)† $^{206}Pb/^{238}U$ | ± $^{206}Pb/^{238}U$ | Ages (Ma)† $^{207}Pb/^{206}Pb$ | ± $^{207}Pb/^{206}Pb$ | Ages (Ma)‡ $^{206}Pb/^{238}U$ | ± $^{206}Pb/^{238}U$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VL02A178 (Z7518): Star Brook Suite leuco-gabbro (UTM Zone 21 472808 5367792; NAD 83) | | | | | | | | | | | | | | | | | | | | | | | |
| 7518–10.1 | 265 | 173 | 0.675 | 21 | 0 | 0.000010 | 0.000010 | 0.0002 | 0.2114 | 0.0037 | 0.5770 | 0.0097 | 0.0736 | 0.0009 | 0.781 | 0.0569 | 0.0006 | 458 | 5 | 486 | 24 | 457 | 5 |
| 7518–9.1 | 323 | 438 | 1.397 | 32 | 1 | 0.000032 | 0.000054 | 0.0006 | 0.4450 | 0.0037 | 0.5949 | 0.0123 | 0.0753 | 0.0008 | 0.608 | 0.0573 | 0.0010 | 468 | 5 | 502 | 37 | 468 | 5 |
| 7518–18.1 | 211 | 239 | 1.167 | 20 | 5 | 0.000321 | 0.000164 | 0.0056 | 0.3524 | 0.0071 | 0.5814 | 0.0296 | 0.0776 | 0.0009 | 0.345 | 0.0544 | 0.0026 | 482 | 5 | 386 | 112 | 483 | 5 |
| 7518–19.1 | 56 | 101 | 1.870 | 6 | 2 | 0.000631 | 0.000254 | 0.0109 | 0.5907 | 0.0177 | 0.5764 | 0.0447 | 0.0756 | 0.0010 | 0.291 | 0.0553 | 0.0041 | 470 | 6 | 423 | 176 | 471 | 6 |
| 7518–20.1 | 66 | 63 | 0.988 | 6 | 3 | 0.000593 | 0.000219 | 0.0103 | 0.2993 | 0.0112 | 0.5627 | 0.0415 | 0.0753 | 0.0015 | 0.387 | 0.0542 | 0.0037 | 468 | 9 | 380 | 162 | 469 | 9 |
| 7518–4.1 | 77 | 60 | 0.801 | 7 | 1 | 0.000156 | 0.000173 | 0.0027 | 0.2648 | 0.0084 | 0.6320 | 0.0323 | 0.0762 | 0.0010 | 0.381 | 0.0602 | 0.0029 | 473 | 6 | 610 | 106 | 471 | 6 |
| 7518–5.1 | 476 | 501 | 1.088 | 45 | 3 | 0.000102 | 0.000073 | 0.0018 | 0.3337 | 0.0045 | 0.6137 | 0.0156 | 0.0784 | 0.0009 | 0.568 | 0.0568 | 0.0012 | 487 | 6 | 482 | 47 | 487 | 6 |
| 7518–7.1 | 275 | 401 | 1.505 | 28 | 3 | 0.000184 | 0.000069 | 0.0032 | 0.4665 | 0.0044 | 0.5918 | 0.0149 | 0.0769 | 0.0008 | 0.532 | 0.0558 | 0.0012 | 478 | 5 | 444 | 48 | 478 | 5 |
| 7518–2.1 | 260 | 456 | 1.815 | 28 | 4 | 0.000248 | 0.000067 | 0.0043 | 0.5700 | 0.0075 | 0.5910 | 0.0167 | 0.0759 | 0.0009 | 0.531 | 0.0565 | 0.0014 | 471 | 5 | 472 | 54 | 471 | 5 |
| VL02A294 (Z7522): Skidder formation trondhjemite (UTM Zone 21 506085 5397449; NAD 83) | | | | | | | | | | | | | | | | | | | | | | | |
| 7522–32.1 | 85 | 38 | 0.460 | 6 | 2 | 0.000399 | 0.000224 | 0.0069 | 0.1434 | 0.0115 | 0.4857 | 0.0382 | 0.0662 | 0.0009 | 0.297 | 0.0532 | 0.0040 | 413 | 6 | 339 | 181 | 414 | 5 |
| 7522–53.1 | 83 | 35 | 0.437 | 6 | 0 | 0.000010 | 0.000010 | 0.0002 | 0.1475 | 0.0035 | 0.5156 | 0.0125 | 0.0671 | 0.0009 | 0.670 | 0.0557 | 0.0010 | 419 | 6 | 440 | 41 | 419 | 6 |
| 7522–54.1 | 276 | 131 | 0.492 | 20 | 1 | 0.000037 | 0.000108 | 0.0007 | 0.1507 | 0.0046 | 0.5158 | 0.0185 | 0.0682 | 0.0008 | 0.454 | 0.0549 | 0.0018 | 425 | 5 | 408 | 74 | 425 | 5 |
| 7522–12.1 | 140 | 66 | 0.485 | 10 | 3 | 0.000339 | 0.000115 | 0.0059 | 0.1464 | 0.0051 | 0.5033 | 0.0200 | 0.0685 | 0.0009 | 0.431 | 0.0533 | 0.0019 | 427 | 5 | 340 | 84 | 428 | 5 |
| 7522–18.1 | 187 | 106 | 0.585 | 14 | 1 | 0.000079 | 0.000144 | 0.0014 | 0.1844 | 0.0060 | 0.5229 | 0.0240 | 0.0687 | 0.0008 | 0.375 | 0.0552 | 0.0024 | 428 | 5 | 420 | 99 | 429 | 5 |
| 7522–8.1 | 174 | 81 | 0.481 | 12 | 0 | 0.000010 | 0.000010 | 0.0002 | 0.1501 | 0.0024 | 0.5485 | 0.0141 | 0.0688 | 0.0008 | 0.530 | 0.0579 | 0.0013 | 429 | 5 | 525 | 49 | 427 | 5 |
| 7522–41.1 | 82 | 55 | 0.690 | 7 | 0 | 0.000043 | 0.000153 | 0.0007 | 0.2222 | 0.0070 | 0.6020 | 0.0276 | 0.0737 | 0.0009 | 0.379 | 0.0593 | 0.0025 | 458 | 5 | 577 | 96 | 457 | 5 |
| 7522–29.1 | 77 | 47 | 0.627 | 6 | 2 | 0.000383 | 0.000217 | 0.0066 | 0.1911 | 0.0091 | 0.5627 | 0.0379 | 0.0739 | 0.0010 | 0.310 | 0.0552 | 0.0036 | 460 | 6 | 422 | 151 | 460 | 5 |
| 7522–6.1 | 123 | 41 | 0.342 | 9 | 1 | 0.000077 | 0.000189 | 0.0013 | 0.1094 | 0.0074 | 0.5856 | 0.0326 | 0.0741 | 0.0009 | 0.338 | 0.0573 | 0.0030 | 461 | 5 | 503 | 121 | 460 | 5 |
| 7522–24.1 | 101 | 85 | 0.872 | 9 | 0 | 0.000010 | 0.000010 | 0.0002 | 0.2673 | 0.0048 | 0.6071 | 0.0171 | 0.0743 | 0.0014 | 0.769 | 0.0593 | 0.0011 | 462 | 9 | 577 | 40 | 460 | 9 |
| 7522–5.1 | 258 | 242 | 0.968 | 23 | 0 | 0.000016 | 0.000057 | 0.0003 | 0.3132 | 0.0035 | 0.5642 | 0.0132 | 0.0743 | 0.0009 | 0.610 | 0.0551 | 0.0010 | 462 | 5 | 414 | 42 | 463 | 5 |
| 7522–22.1 | 258 | 172 | 0.689 | 21 | 2 | 0.000099 | 0.000077 | 0.0017 | 0.2192 | 0.0046 | 0.5769 | 0.0169 | 0.0748 | 0.0009 | 0.520 | 0.0559 | 0.0014 | 465 | 5 | 450 | 57 | 465 | 5 |
| 7522–42.1 | 234 | 158 | 0.699 | 19 | 0 | 0.000010 | 0.000010 | 0.0002 | 0.2219 | 0.0025 | 0.5986 | 0.0092 | 0.0750 | 0.0008 | 0.793 | 0.0579 | 0.0005 | 466 | 5 | 526 | 21 | 465 | 5 |
| 7522–2.1 | 81 | 43 | 0.546 | 6 | 1 | 0.000266 | 0.000220 | 0.0046 | 0.1641 | 0.0095 | 0.5738 | 0.0391 | 0.0753 | 0.0011 | 0.340 | 0.0553 | 0.0036 | 468 | 7 | 423 | 151 | 469 | 7 |
| 7522–4.1 | 146 | 128 | 0.904 | 13 | 0 | 0.000010 | 0.000010 | 0.0002 | 0.2841 | 0.0048 | 0.5962 | 0.0109 | 0.0757 | 0.0009 | 0.719 | 0.0571 | 0.0007 | 470 | 5 | 496 | 29 | 470 | 5 |
| 7522–31.1 | 310 | 146 | 0.488 | 24 | 2 | 0.000099 | 0.000053 | 0.0017 | 0.1547 | 0.0028 | 0.5849 | 0.0125 | 0.0758 | 0.0008 | 0.602 | 0.0560 | 0.0010 | 471 | 5 | 452 | 39 | 471 | 5 |
| RAX01-908 (z7097): Healy Bay formation tuff (UTM Zone 21 506248 5392154; NAD 83) | | | | | | | | | | | | | | | | | | | | | | | |
| 7097–10.1 | 160 | 90 | 0.580 | 12 | 1 | 0.000115 | 0.000102 | 0.0020 | 0.1847 | 0.0056 | 0.5535 | 0.0195 | 0.0715 | 0.0010 | 0.485 | 0.0561 | 0.0018 | 445 | 6 | 457 | 71 | 445 | 6 |
| 7097–92.1 | 157 | 148 | 0.970 | 13 | 3 | 0.000295 | 0.000141 | 0.0051 | 0.3080 | 0.0069 | 0.5382 | 0.0252 | 0.0721 | 0.0010 | 0.399 | 0.0541 | 0.0023 | 449 | 6 | 376 | 100 | 450 | 6 |
| 7097–93.1 | 496 | 281 | 0.585 | 38 | 1 | 0.000041 | 0.000047 | 0.0007 | 0.1790 | 0.0024 | 0.5671 | 0.0108 | 0.0722 | 0.0008 | 0.654 | 0.0570 | 0.0008 | 449 | 5 | 491 | 32 | 449 | 5 |
| 7097–22.1 | 243 | 107 | 0.454 | 18 | 2 | 0.000105 | 0.000122 | 0.0018 | 0.1404 | 0.0052 | 0.5583 | 0.0216 | 0.0727 | 0.0009 | 0.417 | 0.0557 | 0.0020 | 452 | 5 | 441 | 81 | 452 | 5 |
| 7097–78.1 | 238 | 205 | 0.889 | 20 | 2 | 0.000102 | 0.000086 | 0.0018 | 0.2797 | 0.0077 | 0.5560 | 0.0210 | 0.0728 | 0.0015 | 0.658 | 0.0554 | 0.0016 | 453 | 9 | 428 | 65 | 453 | 9 |
| 7097–7.1 | 301 | 155 | 0.532 | 23 | 2 | 0.000093 | 0.000075 | 0.0016 | 0.1649 | 0.0035 | 0.5614 | 0.0154 | 0.0729 | 0.0008 | 0.504 | 0.0558 | 0.0013 | 454 | 5 | 446 | 54 | 454 | 5 |
| 7097–11.1 | 230 | 124 | 0.557 | 18 | 2 | 0.000137 | 0.000103 | 0.0024 | 0.1809 | 0.0045 | 0.5532 | 0.0193 | 0.0732 | 0.0009 | 0.461 | 0.0548 | 0.0017 | 456 | 5 | 404 | 71 | 456 | 6 |
| 7097–13.1 | 141 | 88 | 0.641 | 11 | 1 | 0.000079 | 0.000113 | 0.0014 | 0.2022 | 0.0056 | 0.5742 | 0.0220 | 0.0737 | 0.0010 | 0.469 | 0.0565 | 0.0019 | 458 | 6 | 473 | 77 | 458 | 6 |
| 7097–95.1 | 240 | 172 | 0.743 | 20 | 1 | 0.000096 | 0.000117 | 0.0017 | 0.2334 | 0.0051 | 0.5848 | 0.0213 | 0.0739 | 0.0008 | 0.424 | 0.0574 | 0.0019 | 460 | 5 | 506 | 75 | 459 | 5 |
| 7097–96.1 | 438 | 246 | 0.580 | 35 | 2 | 0.000084 | 0.000058 | 0.0015 | 0.1816 | 0.0027 | 0.5804 | 0.0127 | 0.0748 | 0.0008 | 0.602 | 0.0563 | 0.0010 | 465 | 5 | 463 | 39 | 465 | 5 |
| 7097–14.1 | 226 | 91 | 0.414 | 17 | 0 | 0.000029 | 0.000062 | 0.0005 | 0.1364 | 0.0040 | 0.5762 | 0.0142 | 0.0748 | 0.0009 | 0.581 | 0.0558 | 0.0011 | 465 | 5 | 446 | 46 | 465 | 5 |
| 7097–18.1 | 175 | 64 | 0.378 | 13 | 1 | 0.000082 | 0.000072 | 0.0014 | 0.1234 | 0.0035 | 0.6173 | 0.0163 | 0.0751 | 0.0009 | 0.561 | 0.0596 | 0.0013 | 467 | 5 | 590 | 49 | 465 | 6 |
| 7097–63.2 | 115 | 40 | 0.360 | 9 | 2 | 0.000288 | 0.000297 | 0.0050 | 0.1103 | 0.0121 | 0.5858 | 0.0509 | 0.0761 | 0.0010 | 0.276 | 0.0558 | 0.0047 | 473 | 6 | 446 | 199 | 473 | 7 |
| 7097–4.1 | 91 | 52 | 0.591 | 15 | 0 | 0.000028 | 0.000065 | 0.0005 | 0.2050 | 0.0038 | 1.5167 | 0.0360 | 0.1506 | 0.0020 | 0.648 | 0.0730 | 0.0013 | 904 | 11 | 1015 | 37 | | |
| 7097–6.1 | 538 | 231 | 0.444 | 86 | 2 | 0.000022 | 0.000018 | 0.0004 | 0.1362 | 0.0012 | 1.4830 | 0.0213 | 0.1532 | 0.0017 | 0.830 | 0.0702 | 0.0006 | 919 | 9 | 935 | 17 | | |
| 7097–31.1 | 54 | 34 | 0.645 | 9 | 0 | 0.000010 | 0.000010 | 0.0002 | 0.1964 | 0.0039 | 1.6083 | 0.0309 | 0.1576 | 0.0020 | 0.750 | 0.0740 | 0.0010 | 943 | 11 | 1042 | 26 | | |
| 7097–28.1 | 273 | 119 | 0.451 | 48 | 0 | 0.000005 | 0.000056 | 0.0001 | 0.1393 | 0.0034 | 1.7115 | 0.0345 | 0.1698 | 0.0021 | 0.701 | 0.0731 | 0.0011 | 1011 | 12 | 1017 | 30 | | |
| 7097–63.1 | 110 | 39 | 0.363 | 19 | 1 | 0.000084 | 0.000067 | 0.0015 | 0.1100 | 0.0032 | 1.7254 | 0.0409 | 0.1700 | 0.0023 | 0.669 | 0.0736 | 0.0013 | 1012 | 13 | 1031 | 36 | | |
| 7097–30.1 | 41 | 28 | 0.710 | 8 | 1 | 0.000094 | 0.000177 | 0.0016 | 0.2208 | 0.0078 | 1.9094 | 0.0785 | 0.1770 | 0.0023 | 0.429 | 0.0782 | 0.0029 | 1051 | 13 | 1153 | 76 | | |
| 7097–53.1 | 164 | 104 | 0.657 | 32 | 2 | 0.000095 | 0.000038 | 0.0017 | 0.1979 | 0.0024 | 1.8113 | 0.0371 | 0.1777 | 0.0024 | 0.733 | 0.0739 | 0.0010 | 1054 | 13 | 1040 | 29 | | |
| 7097–3.1 | 121 | 99 | 0.847 | 35 | 2 | 0.000067 | 0.000048 | 0.0012 | 0.2606 | 0.0029 | 3.4639 | 0.0650 | 0.2441 | 0.0036 | 0.843 | 0.1029 | 0.0011 | 1408 | 18 | 1677 | 19 | | |
| 7097–23.1 | 64 | 64 | 1.030 | 22 | 0 | 0.000010 | 0.000010 | 0.0002 | 0.3092 | 0.0070 | 3.9256 | 0.0763 | 0.2779 | 0.0045 | 0.886 | 0.1025 | 0.0009 | 1581 | 23 | 1669 | 17 | | |
| 7097–45.1 | 49 | 17 | 0.366 | 17 | 4 | 0.000268 | 0.000097 | 0.0047 | 0.1020 | 0.0043 | 4.9982 | 0.1238 | 0.3214 | 0.0052 | 0.738 | 0.1128 | 0.0019 | 1797 | 25 | 1845 | 31 | | |

*Note*: See Stern (1997). Uncertainties reported at 1σ (absolute) and are calculated by numerical propagation of all known sources of error; f206$^{204}$ refers to mole fraction of total $^{206}Pb$ that is due to common Pb, calculated using the $^{204}Pb$ method; common Pb composition used is the surface blank.

†204-corrected ages.

‡207-corrected ages (Stern 1997).

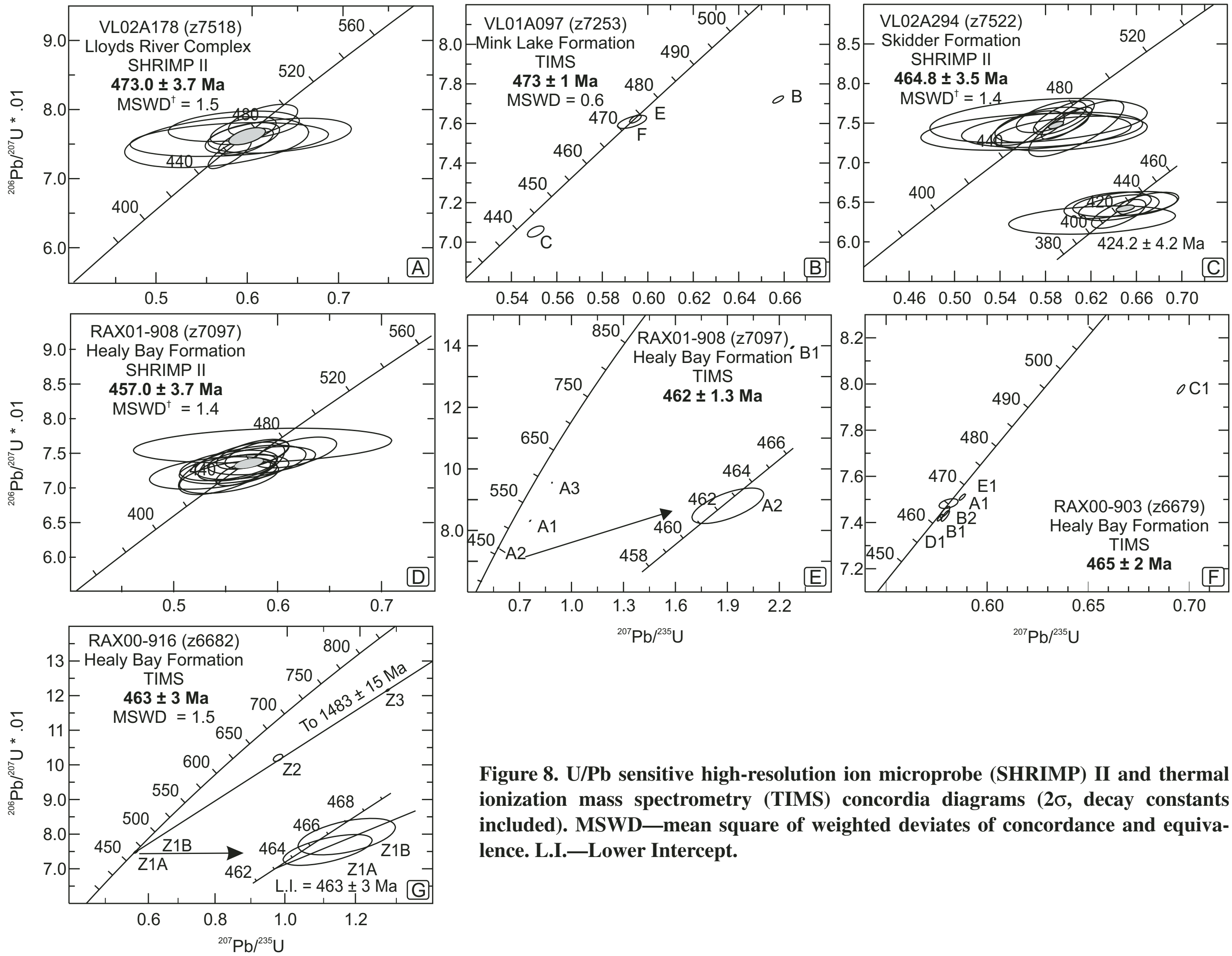


**Figure 8. U/Pb sensitive high-resolution ion microprobe (SHRIMP) II and thermal ionization mass spectrometry (TIMS) concordia diagrams (2σ, decay constants included). MSWD—mean square of weighted deviates of concordance and equivalence. L.I.—Lower Intercept.**

is interpreted to occupy a similar stratigraphic position as the other geochronology samples in the Healy Bay formation. The tuff contains a moderate amount of euhedral zircon, with minor inclusions ranging in morphology from stubby prismatic grains to elongate crystals (Table 4). Four multigrain zircon fractions were analyzed from this rock (Table 3). A linear regression utilizing all four TIMS analyses has an upper intercept of 1483 ± 15 Ma and a lower intercept of 463 ± 3 Ma (MSWD = 1.5) (Fig. 8G). Fractions Z2 and Z3A are quite discordant (33% and 35%, respectively) and are interpreted to contain inherited components. Fractions Z1A and Z1B are nearly concordant, and their $^{206}Pb/^{238}U$ ages are within error of the lower-intercept age. This date of 463 ± 3 Ma is interpreted to be the crystallization age of the tuff.

## GEOCHEMISTRY

The analytical methods employed for determination of major and trace elements and isotopic ratios are described in Rogers (2004). The analyses are listed in Table DR1 (see footnote one) and Table 4. The compositional variation between groups is graphically presented in Figures 9 and 10. Numerous studies (see Pearce, 1996, for references) have shown that the pervasive sub-greenschist to amphibolite facies metamorphic and metasomatic conditions that the rocks within this study have experienced result in some element mobility (e.g., Cs, Rb, Ba, K, Sr). Thus, the analysis of the data focuses on elements that are generally considered to be immobile under normal metamorphic conditions. Tholeiitic and calc-alkaline series were differentiated on the basis of trace-element chemistry (Cabanis and Lecolle, 1989). FeO and Mg# were calculated assuming a $Fe^{3+}/Fe^{2+}$ ratio of 0.1.

### Lloyds River Ophiolite Complex

#### *Otter Brook Suite*

The Otter Brook suite is dominated by high-Ti tholeiitic basaltic rocks ($TiO_2$ 1.3–3.1 wt%; FeO + MgO 16–20 wt%) that are characterized by enrichment in light rare earth element (LREE; average $La_n/Yb_n$ 2.6) and Th (average $La_n/Th_n$ 0.5), and a slight depletion in Nb (average $La_n/Nb_n$ 1.7). The diabase and basalt members of this chemical grouping are moderately to strongly fractionated, resulting in a Mg# of 35–60.

#### *Star Brook Suite*

The Star Brook suite is composed of three distinct geochemical types informally referred to herein as $SB_1$, $SB_2$, and $SB_3$. $SB_1$ consists of high-Ti tholeiitic rocks that outcrop as gabbro, diabase, and basalt and have a notable homogeneous basaltic chemistry ($TiO_2$ 1–2 wt%; FeO + MgO 13–21 wt%). This group is characterized by 0.8–2 times normalized (N)-MORB trace-element abundances, slight depletion to slight enrichment of LREE on N-MORB normalized spidergrams ($La_n/Yb_n$ 1.2), slight but consistent depletion in Zr ($Zr_n/Sm_n$ 0.9), slight enrichment of Th ($La_n/Th_n$ 0.7), negligible depletion of Nb ($La_n/Nb_n$ 1), and is primitive to moderately fractionated (Mg# 49–66). A sample of basalt was analyzed for Sm/Nd isotopes and yielded an $\varepsilon_{Nd(t=473)}$ value of 8.9.

$SB_2$ is also a high-Ti tholeiite ($TiO_2$ 1.33–1.72 wt%; FeO + MgO 10–18 wt%), but outcrops only as gabbro and diabase. This group is characterized by N-MORB-like trace-element abundances, slight depletion to slight enrichment of LREE ($La_n/Yb_n$ 1.3), depleted Zr ($Zr_n/Sm_n$ 0.6), strong depletion in Th ($La_n/Th_n$ 4.1), slight depletion to slight enrichment of Nb ($La_n/Nb_n$ 1.1), and is moderately fractionated (Mg# 58).

The $SB_3$ tholeiitic rocks ($TiO_2$ 0.23–1.3 wt%; FeO + MgO 13–21 wt%) outcrop as gabbro, diabase, and basalt. This group is heterogeneous, but has similar normalized profiles. The abundance of REE can be related to the fractionation index (Mg#). The group is characterized by strongly depleted LREE ($La_n/Yb_n$ 0.5; heavy [H] REE 0.4–1 times N-MORB), depleted Zr ($Zr_n/Sm_n$ 0.6), slight enrichment in Th ($La_n/Th_n$ 0.8), and moderate depletion of Nb ($La_n/Nb_n$ 2). The gabbro has a cumulate-derived composition (Mg# 71–79), whereas the diabase and basalt are primitive to moderately fractionated (Mg# 56–68).

## Buchans Group

### *Mink Lake Formation*

The Mink Lake formation contains felsic and mafic volcanic rocks that are informally referred to herein as $ML_1$ and $ML_2$, respectively. $ML_1$ is represented by a single sample of bedded rhyolitic tuff. This tuff is characterized by moderate LREE enrichment ($La_n/Yb_n$ 3.8), strong Th enrichment ($La_n/Th_n$ 0.2), and Nb depletion ($La_n/Nb_n$ 2.9). This sample was analyzed for Sm/Nd isotopes and yielded an $\varepsilon_{Nd}$ value of –4.0.

$ML_2$ is represented by transitional calc-alkaline to tholeiitic pillow basalts ($TiO_2$ 0.5–0.7 wt%; FeO + MgO 12–15 wt%), flows, and rare dikes. This group is characterized by moderate LREE enrichment ($La_n/Yb_n$ 3.3), Zr depletion ($Zr_n/Sm_n$ 0.7), strong Th enrichment ($La_n/Th_n$ = 0.3), and Nb depletion ($La_n/Nb_n$ = 5.5). Samples are moderately fractionated (Mg# 47–63). A sample of basalt was analyzed for Sm/Nd isotopes and yielded an $\varepsilon_{Nd(t=473)}$ value of 0.9.

TABLE 3. U-Pb THERMAL IONIZATION MASS SPECTROMETRY (TIMS) ANALYTICAL DATA

| Fract.† | Description‡ | Wt. (ug) | U (ppm) | Pb§ (ppm) | $^{206}Pb/^{204}Pb$# | Pb†† (pg) | Isotopic ratios‡‡ $^{208}Pb/^{206}Pb$ | $^{207}Pb/^{235}U$ | ±1SE Abs | $^{206}Pb/^{238}U$ | ±1SE Abs | Corr.§§ coeff. | $^{207}Pb/^{206}Pb$ | ±1SE Abs | Ages (Ma)## $^{206}Pb/^{238}U$ | ±2SE | $^{207}Pb/^{235}U$ | ±2SE | $^{207}Pb/^{206}Pb$ | ±2SE | % disc |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VLA01-097 (Z7253): Mink Lake formation felsic tuff (UTM Zone 21 436177 5332496; NAD 83) | | | | | | | | | | | | | | | | | | | | | |
| B (30) | Co,Clr,Eq,Eu,fIn,fFr,M1° | 7 | 483 | 38 | 5059 | 3 | 0.13 | 0.65738 | 0.00121 | 0.07721 | 0.00009 | 0.755 | 0.06175 | 0.00008 | 479.4 | 1.1 | 513.0 | 1.5 | 665.5 | 5.2 | 29.0 |
| C (32) | pBr,Clr,Eu,St,rFr,M1° | 7 | 264 | 19 | 1107 | 7 | 0.10 | 0.55070 | 0.00185 | 0.07054 | 0.00014 | 0.547 | 0.05662 | 0.00016 | 439.4 | 1.7 | 445.5 | 2.4 | 476.9 | 12.4 | 8.1 |
| E (41) | pBr,Clr,Eu,St,fIn,M3° | 14 | 297 | 23 | 2461 | 8 | 0.15 | 0.59456 | 0.00132 | 0.07623 | 0.00011 | 0.683 | 0.05656 | 0.00009 | 473.6 | 1.3 | 473.8 | 1.7 | 474.6 | 7.1 | 0.2 |
| F (14) | Co,Clr,Frag,M3° | 20 | 240 | 19 | 371 | 64 | 0.14 | 0.59307 | 0.00324 | 0.07608 | 0.00017 | 0.617 | 0.05653 | 0.00025 | 472.7 | 2.0 | 472.8 | 4.1 | 473.4 | 19.6 | 0.2 |
| RAX00-903 (Z6679): Healy Bay formation tuff (UTM Zone 21 515633 5394334; NAD 83) | | | | | | | | | | | | | | | | | | | | | |
| A1 (20) | Co,Clr,Eu,El,fIn,NM5° | 11 | 99 | 9 | 1310 | 4 | 0.28 | 0.58091 | 0.00237 | 0.07482 | 0.00010 | 0.446 | 0.05631 | 0.00021 | 465.1 | 1.2 | 465.0 | 3.0 | 464.5 | 16.2 | -0.1 |
| B1 (95) | Co,Clr,Eu,St,rIn,NM5° | 30 | 245 | 20 | 6765 | 5 | 0.21 | 0.57675 | 0.00073 | 0.07421 | 0.00007 | 0.848 | 0.05636 | 0.00004 | 461.5 | 0.9 | 462.4 | 0.9 | 466.8 | 3.0 | 1.2 |
| B2 (65) | Co,Clr,Eu,St,fIn,NM5° | 17 | 246 | 19 | 4262 | 5 | 0.18 | 0.57932 | 0.00104 | 0.07429 | 0.00012 | 0.838 | 0.05655 | 0.00006 | 462.0 | 1.5 | 464.0 | 1.3 | 474.2 | 4.4 | 2.7 |
| C1 (65) | Co,Clr,Eu,Eq,NM5° | 15 | 306 | 26 | 12345 | 2 | 0.17 | 0.69595 | 0.00095 | 0.07977 | 0.00010 | 0.827 | 0.06328 | 0.00005 | 494.7 | 1.2 | 536.4 | 1.1 | 717.6 | 3.3 | 32.3 |
| D1 (70) | Co,Clr,Eu,Pr,fIn,fFr,NM5° | 16 | 321 | 26 | 1304 | 18 | 0.20 | 0.57914 | 0.00126 | 0.07446 | 0.00012 | 0.799 | 0.05641 | 0.00007 | 463.0 | 1.4 | 463.9 | 1.6 | 468.5 | 5.8 | 1.2 |
| E1 (51) | Co,Clr,Eu,Pr,fIn,fFr,NM5° | 14 | 374 | 30 | 3275 | 8 | 0.19 | 0.58769 | 0.00081 | 0.07510 | 0.00007 | 0.837 | 0.05676 | 0.00004 | 466.8 | 0.8 | 469.4 | 1.0 | 482.2 | 3.5 | 3.3 |
| RAX00-916 (Z6682): Healy Bay formation felsic tuff (UTM Zone 21 440098 5335591; NAD 83) | | | | | | | | | | | | | | | | | | | | | |
| Z1A (1) | Co,Clr,Eu,St,fIn | 10 | 157 | 13 | 576 | 13 | 0.25 | 0.58236 | 0.00193 | 0.07474 | 0.00011 | 0.623 | 0.05651 | 0.00015 | 464.7 | 1.3 | 466.0 | 2.5 | 472.5 | 11.8 | 1.7 |
| Z2 (25) | Co,Clr,Eu,Pr,fIn | 7 | 160 | 17 | 1537 | 2 | 0.18 | 0.97470 | 0.00663 | 0.10203 | 0.00051 | 0.503 | 0.06928 | 0.00042 | 626.3 | 6.0 | 690.9 | 6.8 | 907.2 | 24.9 | 32.5 |
| Z3A (12) | Co,Clr,Eu,El,fIn | 7 | 173 | 22 | 1219 | 8 | 0.17 | 1.27630 | 0.00244 | 0.12156 | 0.00018 | 0.707 | 0.07615 | 0.00010 | 739.5 | 2.1 | 835.2 | 2.2 | 1099.0 | 5.4 | 34.6 |
| Z1B (2) | Co,Clr,Eu,St,fIn | 19 | 146 | 12 | 863 | 15 | 0.23 | 0.58402 | 0.00211 | 0.07493 | 0.00013 | 0.508 | 0.05653 | 0.00018 | 465.8 | 1.6 | 467.0 | 2.7 | 473.1 | 13.7 | 1.6 |

†All fractions are zircon and have been abraded following the method of Krogh (1982). Number in parentheses refers to the number of grains in the analysis.

‡Zircon descriptions: Co—colorless, pBr—pale brown, Clr—clear, fFr—few fractures, rFr—rare fractures, fIn—few inclusions, rIn—rare inclusions, El—elongate, Eq—equant, Eu—euhedral, Frag—fragment, Pr—prismatic, St—stubby prism, Dia—diamagnetic, M1—magnetic @1.8A, 1°SS, M3—magnetic @1.8A, 3°SS, NM5—nonmagnetic @1.8A, 5°SS.

§Radiogenic Pb.

#Measured ratio, corrected for spike and fractionation.

††Total common Pb in analysis corrected for fractionation and spike.

‡‡Corrected for blank Pb and U and common Pb, errors quoted are 1σ absolute standard error (SE); procedural blank values for this study ranged from 0.1 to 0.3 pg for U and 2 to 5 pg for Pb; Pb blank isotopic composition is based on the analysis of procedural blanks; corrections for common Pb were made using Stacey and Kramers (1975) compositions.

§§Correlation coefficient.

##Corrected for blank and common Pb; errors quoted are 2σ in Ma.

TABLE 4. Sm/Nd ISOTOPIC DATA

| Sample | Lithostratigraphic unit | Group | Age | Nd† | Sm† | $^{143}Nd/^{144}Nd$ | $^{147}Sm/^{144}Nd$ | $^{143}Nd/^{144}Nd_i$‡ | $\varepsilon_{Nd}(t)$‡ |
|---|---|---|---|---|---|---|---|---|---|
| VL01A057 | Star Brook suite | $SB_1$ | 473 | 12.17 | 4.48 | 0.513173 | 0.2226 | 0.5125 | 8.87 |
| VL01A097a | Mink Lake formation | $ML_2$ | 473 | 7.68 | 2.17 | 0.512605 | 0.1706 | 0.5121 | 0.93 |
| VL01A097b | Mink Lake formation | $ML_1$ | 473 | 16.67 | 4.41 | 0.512319 | 0.1601 | 0.5118 | –4.02 |
| RAX01059 | Skidder formation | $SK_1$ | 464 | 9.46 | 3.44 | 0.512931 | 0.2201 | 0.5123 | 4.33 |
| RAX01047 | Harbour Round fm. | $HR_2$ | 464 | 15.40 | 5.26 | 0.513064 | 0.2067 | 0.5124 | 7.73 |
| RAX01049 | Harbour Round fm. | $HRF_5$ | 464 | 18.18 | 4.14 | 0.512357 | 0.1377 | 0.5119 | –1.99 |
| RAX01051 | Healy Bay formation | | 464 | 19.67 | 3.65 | 0.512054 | 0.1123 | 0.5117 | –6.40 |
| VL01A360 | Healy Bay formation | | 464 | 19.23 | 3.88 | 0.512074 | 0.1221 | 0.5117 | –6.59 |
| VL02A283 | Healy Bay formation | | 464 | 19.53 | 4.39 | 0.512059 | 0.1357 | 0.5116 | –7.70 |
| VL02A295 | Healy Bay formation | | 464 | 22.57 | 5.02 | 0.512101 | 0.1343 | 0.5117 | –6.79 |

†Concentration in ppm from isotope dilution.
‡Calculated at age of formation.

## Red Indian Lake Group

### *Skidder Formation*

The Skidder formation contains two distinct basaltic units that are informally referred to herein as $SK_1$ and $SK_2$. $SK_1$ comprises tholeiitic basalt and pillow basalt ($TiO_2$ 0.7–1.1 wt%; FeO + MgO 10–19 wt%) characterized by slight LREE enrichment ($La_n/Yb_n$ 2.1), Zr depletion ($Zr_n/Sm_n$ 0.7), strong Th enrichment ($La_n/Th_n$ 0.3), and Nb depletion ($La_n/Nb_n$ 3.3). Samples are primitive to moderately fractionated (Mg# 57–69). A sample of basalt was analyzed for Sm/Nd isotopes and yielded an $\varepsilon_{Nd(t = 464)}$ value of 4.3. Previously published analyses have the same geochemical and isotopic ($\varepsilon_{Nd(t = 464)}$ of 5.2) characteristics as this group (Fig. 9; Davenport et al., 1996; Swinden et al., 1997).

$SK_2$ is represented by two analyses of a basalt and andesite ($TiO_2$ 1.2–1.6 wt%; FeO + MgO 9.4–20.8 wt%) and is characterized by moderate LREE enrichment ($La_n/Yb_n$ 3.7), strong Th enrichment ($La_n/Th_n$ 0.3), and slight Nb depletion ($La_n/Nb_n$ 1.7). This group shares similar chemical characteristics to previously analyzed Skidder formation trondhjemitic rocks (Davenport et al., 1996).

### *Harbour Round Formation*

The Harbour Round formation is divisible into five chemically distinct mafic volcanic units (informally referred to herein as $HR_1$ through $HR_5$). The $HR_1$ high-Ti tholeiites are a generally homogeneous package of predominantly basalt with minor diabase and gabbro ($TiO_2$ 0.8–2 wt%; FeO + MgO 12–19 wt%). This group is characterized by 0.5–2 times N-MORB trace-element abundances, slight depletion to slight enrichment of LREE on N-MORB normalized spidergrams ($La_n/Yb_n$ 1.1), slight but consistent depletion in Zr ($Zr_n/Sm_n$ 0.9), slight enrichment of Th ($La_n/Th_n$ 0.7), negligible depletion of Nb ($La_n/Nb_n$ 1.1), and is moderately fractionated (Mg# 52–66).

$HR_2$ is tholeiitic basalt to andesite ($TiO_2$ 1.3–1.9 wt%; FeO + MgO 15–17 wt%). This group is characterized by LREE enrichment ($La_n/Yb_n$ 2.1), enrichment of Th ($La_n/Th_n$ 0.5), slight depletion of Nb ($La_n/Nb_n$ 1.2), and is moderately fractionated (Mg# 48–60). One sample has yielded an $\varepsilon_{Nd(t = 464)}$ value of 7.7.

$HR_3$ includes several heterogeneous tholeiitic basalt analyses, which have chemistries similar to those of $SB_2$ Th-depleted tholeiite and $SB_3$ LREE-depleted tholeiite.

$HR_4$ is composed of tholeiitic basalt to andesite ($TiO_2$ 0.6–0.8 wt%; FeO + MgO to 12–17 wt%). This group is characterized by LREE enrichment ($La_n/Yb_n$ 2.9), depletion in Zr ($Zr_n/Sm_n$ 0.6), strong enrichment of Th ($La_n/Th_n$ 0.2), strong depletion of Nb ($La_n/Nb_n$ 4.7), and is variably fractionated (Mg# 56–73).

$HR_5$ consists of transitional tholeiitic to calc-alkaline basalt to andesite ($TiO_2$ 0.5–1.7 wt%; FeO + MgO 10–17 wt%). This group is characterized by strong LREE enrichment ($La_n/Yb_n$ 8.9), slight enrichment to modest depletion in Zr ($Zr_n/Sm_n$ 0.7), strong enrichment of Th ($La_n/Th_n$ 0.2), strong depletion of Nb ($La_n/Nb_n$ 4.2), and is variably fractionated (Mg# 43–72). One sample was analyzed for Sm/Nd isotopes and yielded an $\varepsilon_{Nd(t = 464)}$ value of –2.0.

### *Healy Bay Formation*

The volcanic rocks of the Healy Bay formation consist predominantly of felsic lithic tuff, which is characterized by strong LREE enrichment ($La_n/Yb_n$ 12.5), strong Th enrichment ($La_n/Th_n$ 0.1), and Nb depletion ($La_n/Nb_n$ 3.1). Analysis of Sm/Nd isotopes yielded distinctly negative $\varepsilon_{Nd(t = 464)}$ values of between –6.4 and –7.7.

## DISCUSSION

The data presented herein allow for a detailed reconstruction of the tectono-magmatic processes in the Iapetus Ocean near Newfoundland's Laurentian margin during the Ordovician. Our data indicate that the Annieopsquotch accretionary tract is composed of several tectonic panels that have been accreted to the Dashwoods margin along northwest-dipping thrust faults. The revised top-to-bottom tectono-stratigraphy of the Annieopsquotch accretionary tract consists of the Annieopsquotch ophiolite belt (ca. 480 Ma), Lloyds River ophiolite complex (ca. 473 Ma), ensialic arc rocks of the Buchans Group, including the Mink Lake formation (ca. 473 Ma), Otter Pond Complex (ca. 468 Ma), and Red Indian Lake group (ca. 464 Ma). The general age progression of the rocks in the panels from the most inboard and oldest to the most outboard and youngest suggests accretion of progressively younger tectonic fragments that formed above a single west-dipping subduction zone. In the following sections, the tectono-magmatic history for each tectonic panel will be discussed and a unified tectonic model presented.

### Magmatism in the Annieopsquotch Accretionary Tract

#### *Lloyds River Ophiolite Complex*

The ophiolitic Lloyds River ophiolite complex preserves the record of suprasubduction zone spreading with multiple source components. The Otter Brook suite is characterized by a prominent enrichment of LREE and Th and a depletion of Nb, which suggests a contribution of both enriched mantle and subduction components. The Star Brook suite is dominated by mafic rocks that are MORB-like on the basis of their flat MORB-normalized trace-element profiles and very juvenile isotopic characteristics ($SB_1$). Although the tectonic setting of the $SB_1$ rocks is by itself ambiguous (Fig. 10A), the association with the Th-depleted MORB-like $SB_3$ rocks and LREE-depleted, weak-arc signature $SB_2$ rocks provides a more reliable interpretation. A number of studies (e.g., Fretzdorff et al., 2002; Hawkins and Allan, 1994; Leat et al., 2000; Pearce et al., 1995) have demonstrated associations of chemical groups comparable to Lloyds River ophiolite complex in modern backarcs, such as the Lau Basin and East Scotia Ridge backarc basin. Thus, it is reasonable to conclude that the Lloyds River ophiolite complex formed in a backarc tectonic setting. Although the adjacent Annieopsquotch ophiolite belt is petrographically similar to the Lloyds River ophiolite complex, it does exhibit several important differences that distinguish it in regional studies. The chemical characteristics of the Lloyds River ophiolite complex mafic rocks are significantly different from those in the adjacent Annieopsquotch ophiolite belt (Figs. 9

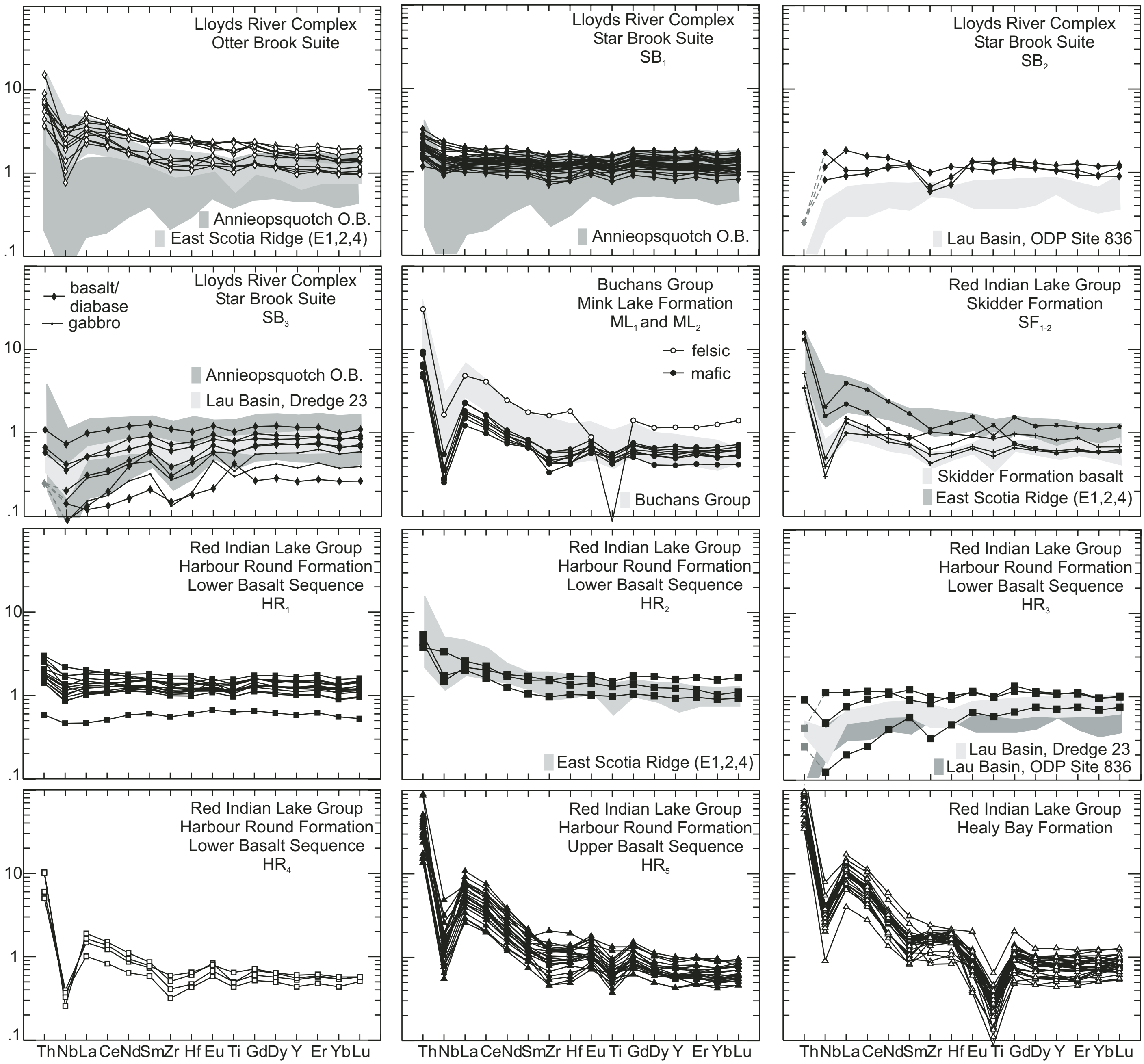


**Figure 9. Extended rare earth element (REE) spidergrams of the chemical groups defined in this study (N-MORB normalization values and order from Sun and McDonough, 1989; modified to exclude mobile trace elements). Shaded fields are basalt-sheeted dike range from Annieopsquotch ophiolite belt (O.B.); Skidder formation and Buchans Group basalt (Davenport et al., 1996); selected samples from back-arc East Scotia Sea Ridge (Fretzdorff et al., 2002; Leat et al., 2000); selected samples from Lau Basin Dredge 23 (Pearce et al., 1995); and selected samples from Site 836, Ocean Drilling Program (ODP) Leg 135 (Hawkins and Allan, 1994).**

and 11). In addition, the Lloyds River ophiolite complex (473 ± 3.7 Ma) is younger than the oldest age of the Annieopsquotch ophiolite belt (481 +4/–2 Ma: Dunning and Krogh, 1985). Despite the slight overlap of the 2σ errors, the Lloyds River ophiolite complex is also statistically younger ($p < 0.1$, one-sided t-test) than the youngest age obtained in the Annieopsquotch ophiolite belt on a late pegmatitic trondhjemite, which may or may not be representative of the crystallization age of the bulk of the unit (478 +3/–2 Ma; Dunning and Krogh, 1985). The geochronological data thus support the petrological evidence that the Annieopsquotch ophiolite belt and Lloyds River ophiolite complex represent two different segments of Iapetan oceanic crust.

### *Buchans Group*

Geochemistry, geochronology, and isotopic characteristics of the Mink Lake formation indicate eruption in a continentally influenced arc

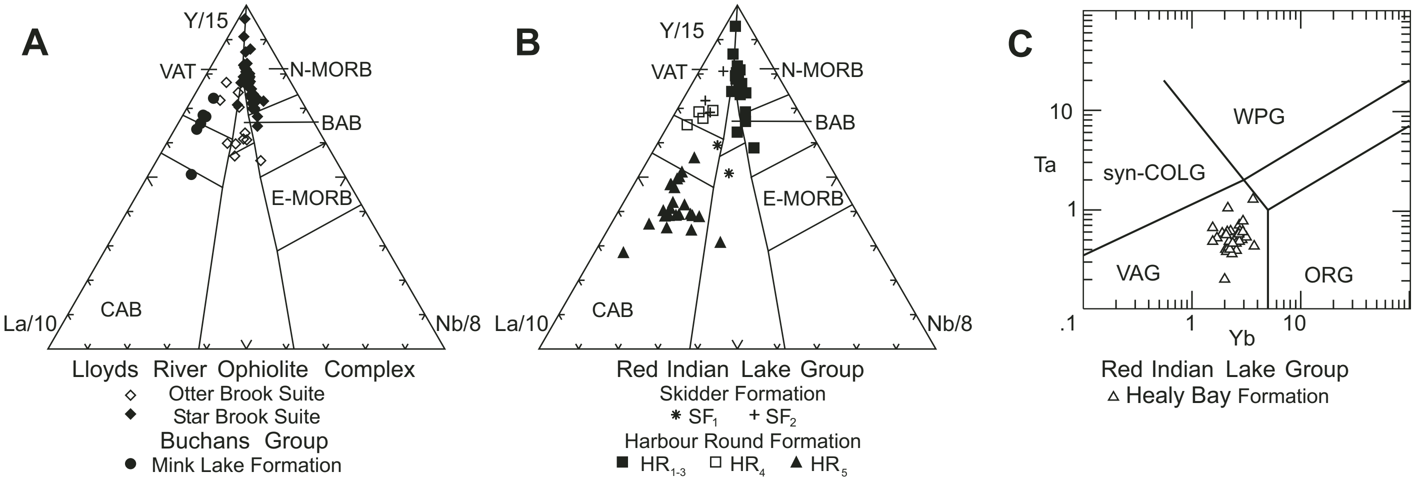


**Figure 10. La/10–Y/15–Nb/8 tectonic setting discrimination diagrams for (A) Lloyds River ophiolite complex and Mink Lake formation and (B) Red Indian Lake group mafic volcanic, shallow intrusive, and selected plutonic rocks (Cabanis and Lecolle, 1989); (C) Ta-Yb discrimination diagram for felsic volcanic rocks of the Healy Bay formation (Pearce et al., 1994). BAB—backarc basalt, CAB—calc-alkaline basalt, E-MORB—enriched mid-ocean-ridge basalt, N-MORB—normal mid-ocean-ridge basalt, ORG—ocean-ridge granite, syn-COLG—syncollisional granite, VAG—volcanic arc granite, VAT—volcanic arc tholeiite, WPG—within-plate granite.**

(Fig. 10A; Table 4). The depletion of Nb and Ti and enrichment of Th and LREE indicate an arc setting, whereas the low to negative $\varepsilon_{Nd}$ values and zircon inheritance indicate significant contribution of mature continental crust to both its felsic and mafic rocks. Although the Sm/Nd isotopic characteristics cannot uniquely discriminate between continental basement and subduction of continentally derived sediment, a comparison to the modern arc systems (Swinden et al., 1997) supports the presence of continental basement, consistent with abundant zircon inheritance. The Mink Lake formation is thus assigned to an ensialic arc setting, identical to the interpretations made of the coeval peri-Laurentian (Nowlan and Thurlow, 1984) Buchans and Roberts Arm Groups by Swinden et al. (1997). Since the Mink Lake formation occupies the same structural position in the thrust stack as the coeval Buchans Group, it has been included in this group. Although the Mink Lake formation does not appear to have any direct geochemical analogues in either the Buchans or Roberts Arm Groups (Fig. 9; Davenport et al., 1996), it may correspond to the Ski Hill Formation in the Buchans area (Thurlow and Swanson, 1987).

### *Red Indian Lake Group*

The presence of a strong Th/Nb anomaly and slight LREE enrichment in the Skidder formation ($SK_1$) argues for a volcanic arc setting (Fig. 10B). The Sm/Nd isotopic data tend to suggest a source that is typical for an intra-oceanic arc; however, a continental setting with minimal upper-crustal assimilation cannot be ruled out (Swinden et al., 1997). The $SK_2$ basalts exhibit enrichment in LREE and Th, but contain only a weak Th/Nb anomaly. These data suggest an enriched-mantle source with a minor subduction component, similar to that observed in the East Scotia Ridge backarc basin (Fretzdorff et al., 2002). The contemporaneous eruption of $SK_1$ and $SK_2$ lavas strongly indicates a transitional arc-backarc setting for the Skidder formation.

The lower basalt member of the Harbour Round formation is dominated by lavas that are similar to MORB and island-arc tholeiite (Fig. 10B; $HR_{1-3}$). The association of these chemical groups is similar to that observed for the Lloyds River ophiolite complex and Eastern Lau Basin spreading center (Fig. 9; Hawkins and Allan, 1994; Pearce et al., 1995) and suggests a juvenile spreading-arc or backarc setting for the lower basalt member. However, the contemporaneous eruption of the island-arc tholeiite-like, LREE- and Th-enriched and Nb-depleted $HR_4$ basalts points to a relatively immature arc setting for the lower basalt member. The transition to the upper basalt member of the Harbour Round formation is defined by an intraformational unconformity that is marked by a conglomeratic unit that is followed by the calc-alkaline $HR_5$ basalt (Fig. 10B). The prominent Th/Nb anomaly, LREE enrichment, and negative $\varepsilon_{Nd}$ value of the $HR_5$ indicate eruption in a continental arc setting. The felsic tuffs of the Healy Bay formation exhibit strong enrichment in Th and REE and depletion in Nb consistent with eruption in a volcanic arc setting (Fig. 10C), which together with the highly negative $\varepsilon_{Nd}$ values and zircon inheritance confirms formation in an ensialic arc setting. Although the ensialic basement is nowhere exposed, and there is no fossil control on the paleogeographic setting of the arc, the identification of inherited zircons in the ca. 935–1845 Ma age range (Table 2) but not in the ca. 500–800 Ma age range is more consistent with peri-Laurentian provenance (e.g., Cawood and Nemchin, 2001) rather than peri-Gondwanan (e.g., van Staal et al., 1996) provenance. Thus, the Red Indian Lake group originated in a Llanvirn peri-Laurentian ensialic arc complex.

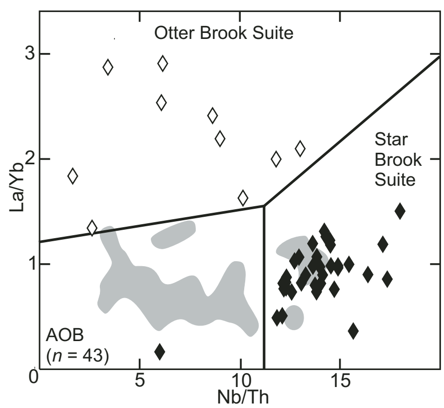


**Figure 11. La/Yb versus Nb/Th diagram comparing the chemical characteristics of the basalt and diabase of the Annieopsquotch ophiolite belt (AOB; shaded field; *n* = 43) and Lloyds River ophiolite complex and Otter Brook (open diamond) and Star Brook (filled diamond) Suites. Annieopsquotch forms a very distinct field with only minor overlap with Star Brook suite.**

### Implications for the Position of the Red Indian Line

Prior to this study, the position of the Red Indian Line was only roughly defined in the map area, mainly drawn along the easternmost extent of the Annieopsquotch ophiolite belt and Buchans Group (Fig. 1; e.g., Evans and Kean, 2002; Williams et al., 1988). However, Thurlow et al. (1992) concluded that such a position was inconsistent with the observed relationships in this part of Newfoundland and the definition of the Red Indian Line. Instead, they suggested a placement of the Red Indian Line further to the east, although they could not identify it. The peri-Laurentian provenance of the Red Indian Lake group supports their interpretation, and the Red Indian Line is herein defined to lie immediately to the east of the peri-Laurentian Red Indian Lake group (Fig. 1), where it is conveniently marked in several places by a highly tectonized black shale mélange along the eastern shore of Red Indian Lake (Fig. 2). Consequently, the Lloyds River ophiolite complex, Otter Pond Complex, and Red Indian Lake group lie to the west of the Red Indian Line and form part of the peri-Laurentian Notre Dame subzone, consistent with the original criteria that define the Red Indian Line, since they share the sub-Silurian unconformity and lack the Caradoc black shale cover typical of the Exploits subzone (Williams et al., 1988).

### Tectonic History of the Annieopsquotch Accretionary Tract (480–468 Ma)

The age progression of the panels, with progressively younger rocks occurring at the lower structural levels, combined with a provenance immediately outboard of the peri-Laurentian Dashwoods ribbon continent with its Notre Dame arc suprastructure, is most simply related to intermittent generation of arc-backarc complexes above a single west-dipping subduction zone that was continuously retreating to the east (present coordinates) due to slab rollback. These relationships appear to hold along the entire segment of the Annieopsquotch accretionary tract from central Newfoundland to Notre Dame Bay (Table 1; Fig. 5) and are generally supported by the correlatives of the Annieopsquotch accretionary tract outside Newfoundland. Initiation of west-directed subduction in the Newfoundland Annieopsquotch accretionary tract must have occurred shortly prior to ca. 480 Ma, as is evidenced by the suprasubduction zone Annieopsquotch ophiolite belt (Lissenberg et al., 2005b). Subsequently, an east-facing ensialic arc and oceanic backarc were generated further outboard, represented by the ca. 473 Ma Buchans Group and Lloyds River ophiolite complex, respectively (Fig. 12A).

The presence of peri-Laurentian continental arc magmatism outboard of the oceanic Annieopsquotch ophiolite belt, where subduction initiated, and the lack of a proto-Buchans remnant arc need to be explained in order for the rather simplified model presented herein to be more widely applicable. The presence of the ensialic Buchans arc outboard of the intra-oceanic Annieopsquotch ophiolite belt requires either accretion of an independent microcontinental sliver to the Annieopsquotch ophiolite belt or the introduction of a continental crustal flake into the arc-trench gap through trench-parallel strike-slip movements (forearc slivering). No direct evidence in the Newfoundland Annieopsquotch accretionary tract or correlative tracts requires that the Buchans Group should be built on another distinct microcontinent. In addition, accretion of such a microcontinent would require the step-back or initiation of another phase of subduction shortly after the subduction initiation responsible for the Annieopsquotch ophiolite belt. Although this possibility cannot be completely ruled out, there is ample evidence for sinistral oblique-slip southeast-directed faulting throughout the Ordovician in the Annieopsquotch accretionary tract (Lafrance and Williams, 1992; Lissenberg and van Staal, 2002; Thurlow, 1981; Zagorevski and van Staal, 2002), however, it is frequently overprinted by Silurian and younger dextral transpression (e.g., Lafrance and Williams, 1992; Williams et al., 1993). The correlatives of the Annieopsquotch accretionary tract outside Newfoundland, in the Northern Belt of the Southern Uplands terrane and South Connemara Group, have also experienced sinistral transpression in the Ordovician (e.g., Dewey and Shackleton, 1984; Elders, 1987; Ryan and Dewey, 2004), and forearc slivering accompanied by large trench-parallel movements have been invoked to explain the provenance of the conglomerates in the Northern Belt of the Southern Uplands terrane (Elders, 1987). Thus the position of the ensialic Buchans arc outboard of the Annieopsquotch ophiolite belt and Lloyds River ophiolite complex is probably most simply explained by forearc slivering. This model can also explain

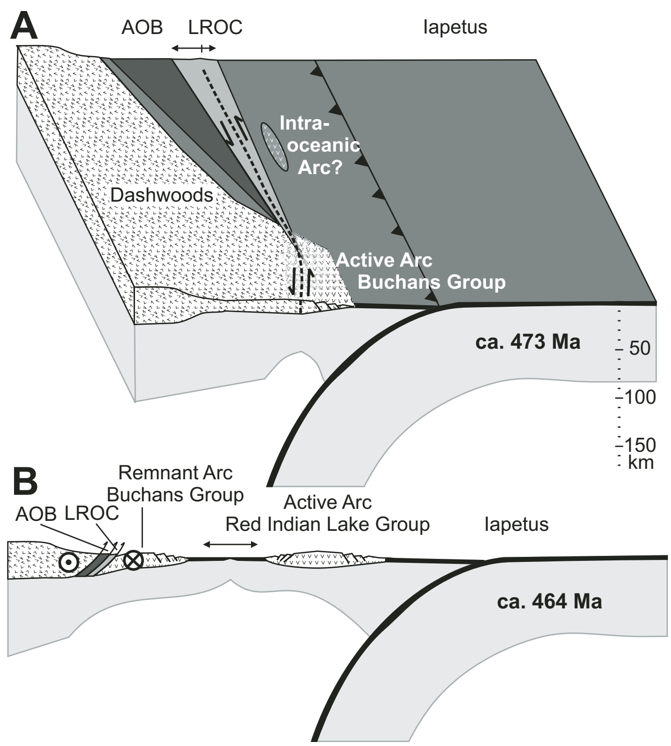


**Figure 12. Tectonic evolution of the Annieopsquotch accretionary tract. (A) Formation of Lloyds River ophiolite complex (LROC) outboard of the Dashwoods microcontinent is coeval with continentally influenced magmatism in the Buchans arc. An outline of a sinistral fault that juxtaposes the Buchans Group and Lloyds River ophiolite complex is shown. (B) Buchans arc rifts producing an intra-arc or small backarc basin and new active Red Indian Lake arc. Annieopsquotch ophiolite belt (AOB) and Lloyds River ophiolite complex are faulted inboard of Buchans arc.**

the lack of an identifiable Buchans remnant arc, as the whole Buchans crustal block could have experienced trench-parallel transport outboard of active Lloyds River ophiolite complex magmatism (Fig. 12).

The evolution of the Newfoundland portion of the Annieopsquotch accretionary tract is summarized in Figure 12. West-dipping subduction initiated outboard of the Dashwoods, probably in a re-entrant prior to ca. 480 Ma, with the Annieopsquotch spreading center having formed due to rapid hinge retreat of the downgoing slab (Lissenberg et al., 2005b). Although, the exact timing of the sinistral strike-slip translation of the Buchans arc outboard of Annieopsquotch ophiolite belt and Lloyds River ophiolite complex is poorly constrained at present (prior to ca. 468 Ma), we infer that the subduction under the Dashwoods margin generated the Buchans arc on its leading edge approximately coeval with spreading responsible for the Annieopsquotch ophiolite belt and Lloyds River ophiolite complex along-strike in the re-entrant. The propagation of the Annieopsquotch ophiolite belt–Lloyds River ophiolite complex spreading center into the adjacent promontory on the active Dashwoods microcontinent isolated a sliver of Dashwoods with its Buchans suprastructure. Alternatively, a new spreading center could have been initiated in a region far removed from the Annieopsquotch ophiolite belt that rifted the Buchans arc from the leading edge of Dashwoods, with subsequent unrelated strike-slip faulting bringing this crustal fragment outboard of the Annieopsquotch ophiolite belt. A compressional event, potentially triggered by the Laurentia-Dashwoods collision to the west (Waldron and van Staal, 2001), may have initiated underthrusting of the Annieopsquotch ophiolite belt, Lloyds River ophiolite complex, and the Buchans Group beneath the hot Notre Dame Arc along the Hungry Mountain thrust system (Thurlow, 1981) prior to or synchronous with the intrusion and eruption of the ca. 468 Ma stitching Otter Pond Complex (Lissenberg et al., 2005c).

### Tectonic History of the Annieopsquotch Accretionary Tract (Younger than 468 Ma)

The close spatial association and peri-Laurentian provenance of the Buchans and Red Indian Lake groups suggest that these were generated above the same west-dipping subduction zone (Fig. 12). Following the ca. 468 Ma event that led to the accretion of Annieopsquotch ophiolite belt, Lloyds River ophiolite complex, and Buchans Group, the accreted Buchans arc rifted due to renewed rollback of the west-dipping slab, leaving most of the exposed Buchans Group in a remnant arc position. Thus, the new Red Indian Lake ensialic arc and backarc basin were established by ca. 464 Ma to the east of this remnant arc. Similar Llanvirn-Caradoc tectonic development of the peri-Laurentian margin has been inferred in the Caledonides as well, where an accretionary prism was active outboard of the active continental arc (e.g., Ryan and Dewey, 2004).

The main tract of the Iapetus Ocean was closed at ca. 450 Ma, resulting in a collision between peri-Laurentian Red Indian Lake and peri-Gondwanan Victoria Lake arcs (van Staal et al., 1998), and incorporation of the Red Indian Lake arc-backarc into the Annieopsquotch accretionary tract. Caradoc closure of this portion of the Iapetus is consistent with along-strike correlatives in the peri-Laurentian portion of the Southern Uplands terrane, which start to contain characteristically peri-Gondwanan detritus during the Caradoc (Phillips et al., 2003).

During the collision, the Victoria Lake arc was thrust beneath the Annieopsquotch accretionary tract (van der Velden et al., 2004), forcing uplift and exhumation of the Annieopsquotch accretionary tract (McNicoll et al., 2001) that led to a widespread sub-Silurian unconformity (e.g., Williams et al., 1988). Silurian continental red beds and volcanic rocks were subsequently deposited, forming an overlap sequence coeval with intrusion of consanguineous Silurian plutons into all units of the Annieopsquotch accretionary tract.

### Correlatives of Annieopsquotch Accretionary Tract outside Newfoundland

The correlations of the Annieopsquotch accretionary tract into the New England Appalachians and British Caledonides are somewhat controversial. In the New England Appalachians, extensive post-Ordovician cover has obscured many of the relationships between units, leading to questions over their affinity (i.e., peri-Laurentian versus peri-Gondwanan). Since both peri-Laurentian and peri-Gondwanan terranes have experienced coeval, but unrelated arc-building events on opposite sides of the Iapetus Ocean, this has lead to a variety of conflicting models (e.g., Karabinos et al., 1998; Moench et al., 2000; Robinson et al., 1998; van Staal et al., 1998). Van Staal et al. (1998) proposed that the Annieopsquotch accretionary tract extends into New England and is represented by rocks of the Boil Mountain Complex, Jim Pond Formation (e.g., Coish and Rogers, 1987; Moench and Aleinikoff, 2003), and rocks in the Caucomgomoc inlier. This interpretation is consistent with the composite nature, age (477 ± 1, Kusky et al., 1997), and position of the Boil Mountain Complex and Jim Pond Formation outboard of the Chain Lakes Massif (Gerbi et al., 2005). The latter has been proposed to represent a portion of a Laurentian-derived microcontinent correlative to the Dashwoods in Newfoundland (Waldron and van Staal, 2001; Gerbi et al., 2005).

In the British Caledonides, van Staal et al. (1998) have proposed a correlation of the Annieopsquotch accretionary tract with the South Connemara Group in Ireland, which has recently been reinterpreted as a Middle to Late Ordovician accretionary complex that incorporated Early Ordovician seamounts above a north-dipping subduction zone (Ryan and Dewey, 2004). As the Northern Belt of the Southern Uplands terrane in Scotland is a direct correlative to the South Connemara Group (Ryan and Dewey, 2004; van Staal et al., 1998), it follows that these rocks should also be correlated to the Annieopsquotch accretionary tract. Clasts in the South Connemara Group place it immediately outboard of the composite Laurentian margin (Grampian Highlands; Ryan and Dewey, 2004), while the provenance of clasts in conglomerates of the Northern Belt of the Scottish Southern Uplands terrane suggests large trench-parallel translations of forearc material (Elders, 1987). A direct correlation between members of the Annieopsquotch accretionary tract and elements of the British Caledonides remains tenuous at present, because the well-preserved sedimentary sequences of the Southern Uplands are largely absent in the northern Appalachians, a feature that may reflect strike-slip excision.

## CONCLUSIONS AND TECTONIC IMPLICATIONS

Detailed mapping combined with geochronological, geochemical, and isotopic studies of the central Newfoundland Annieopsquotch accretionary tract has allowed: (1) the identification of the exact location of the Red Indian Line and the proposal of several new and previously unrecognized informal suprasubduction zone units of peri-Laurentian affinity, which has enabled the formulation of realistic reconstructions of the development of the peri-Laurentian arc; (2) the understanding of their assembly into structural panels involving both thrusting and sinistral strike-slip translations; and (3) the understanding of the rate of growth of the Laurentian margin. Our data indicate that the various arc-backarc systems evolved very rapidly, with major tectonic changes occurring on the time scale of about five million years. The ensialic Buchans arc was firmly established at least seven million years after the initiation of subduction and was accreted to the Dashwoods margin less than five million years later, approximately coeval with calc-alkaline magmatism in the Otter Pond Complex. Subsequently, this accreted arc was rifted, with the development of the Red Indian Lake arc and backarc basin within approximately five million years. Although the rate of tectonic changes observed in the Annieopsquotch accretionary tract is rapid and would be impossible to resolve without very detailed and accurate geochronology, it is consistent with the time frame of tectonic processes in recent arc systems, such as those of the southwest Pacific (e.g., Hall, 2002)

The results of our work presented herein highlight the complexity of the tectonic processes that took place in the Ordovician immediately outboard of the Dashwoods microcontinent during and after its final docking to Laurentia. They involve a protracted (~20 m.y.) period of arc-trench migration that led to repetitive arc-rifting and backarc basin formation and rapid trench-parallel translation of forearc slivers in the Newfoundland Appalachians and British Caledonides. This complexity is probably also present elsewhere in the northern Appalachians and British Caledonides, but a complex post-Ordovician tectonic history, including deposition of thick Silurian-Devonian cover sequences may prevent its elucidation. In particular, the identification of oblique accretion of complexes along the Laurentian margin may explain why parts of tectonic systems along the Laurentian margin appear to be missing in many places (van Staal et al., 1998). Accretion of large volumes of sedimentary rocks common to other Phanerozoic orogens (e.g., Alvarez-Marron et al., 2000; Şengör and Natal'in, 1996) does not appear to play a significant role in the development of the Newfoundland Annieopsquotch accretionary tract. The Middle Ordovician growth of the Laurentian margin along this portion of the Annieopsquotch accretionary tract appears to have been primarily accommodated by accretion of backarc crust and addition of juvenile material to the outboard ensialic magmatic arcs.

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