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GEOLOGY AND SIGNIFICANCE OF THE HARRY'S RIVER MAFIC VOLCANIC ROCKS, BUCHANS AREA, NEWFOUNDLAND

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ABSTRACT

The Harry's River area is located immediately north and west of the former Buchans Mine and thus occupies an important area for testing the tectonostratigraphy of the Buchans–Robert's Arm belt. Detailed outcrop investigations indicate that the Harry's River area is underlain by vent-proximal mafic volcanic and hypabyssal rocks that do not form part of the mine stratigraphy. Lithogeochemical data presented here highlight differences in chemical characteristics and tectonic setting between the calc-alkaline Buchans Group and the backarc basin basalts of the Harry's River ophiolite complex. The identification of this distinct geochemical fingerprint, combined with its structural position and apparent lack of relationship to the Buchans Group, suggests a correlation to the regionally extensive Lloyds River ophiolite complex and has important implications for the distribution of mineral-deposit-bearing terranes in the Buchans–Robert's Arm belt.

INTRODUCTION

The Ordovician Buchans–Robert's Arm belt forms part of a tectonic collage of arc and backarc terranes that were accreted to the Laurentian margin during the Middle and Late Ordovician (Figure 1: *e.g.*, van Staal *et al.*, 1998; Lissenberg *et al.*, 2005) and subsequently deformed during the Salinic Orogeny (*e.g.*, Dunning *et al.*, 1990). Detailed studies of the Buchans–Robert's Arm belt have delineated multiple fault-bound volcanic tracts that possess individual stratigraphic and tectonic histories (*e.g.*, Bostock, 1988; Pope *et al.*, 1991; Kerr, 1996; Swinden *et al.*, 1997; O'Brien, 2003; Zagorevski *et al.*, 2006; O'Brien, 2007; Zagorevski and Rogers, 2009), warranting their interpretation as separate terranes. Regional correlation of these terranes is often tenuous, as they are commonly incompletely characterized and many of their features resemble those of adjacent terranes.

In this contribution, the volcanology and geochemical characteristics of the mafic volcanic and hypabyssal rocks, which are exposed west of the town of Buchans along Harry's River (Figure 2), are examined. This study demonstrates that these rocks are volcanologically and geochemically distinct from the adjacent Buchans Group volcanic rocks, but resemble the Harry's River metabasites of Thurlow (1981) and Thurlow and Swanson (1987) near Sandy Lake; the metabasites are included in the Harry's River ophiolite complex (Figure 2; *e.g.*, Zagorevski and Rogers, 2008, 2009). The geochemical fingerprint suggests that the Harry's River ophiolite complex erupted in an environment, such as a backarc or an intra-arc rift. This tectonic setting has been previously suggested for ophiolitic rocks that occupy a similar structural position to the Harry's River ophiolite complex (Zagorevski *et al.*, 2006). Although the Harry's River ophiolite complex remains undated, they are here correlated with the regionally extensive Lloyds River ophiolite complex (Zagorevski *et al.*, 2006). The occurrence of distinctly different volcanic rocks in the Buchans area suggests a complex volcanic and tectonic history. This has significant implications for mineral exploration in the Buchans–Robert's Arm belt as the Buchans Mine stratigraphy cannot be extrapolated to, and applied across, it.

HARRY'S RIVER OPHIOLITE COMPLEX

A sequence of sub- to greenschist-facies mafic volcanic and hypabyssal rocks associated with a prominent high, positive magnetic anomaly occurs to the west of the town of Buchans (Coyle, 2006; Zagorevski *et al.*, 2007). These volcanic rocks are well-exposed along Harry's River; however, in other areas, the bedrock is predominantly covered by glacial, deltaic deposits. The western exposure of the metabasite is characterized by fine-grained diabase dykes that, at

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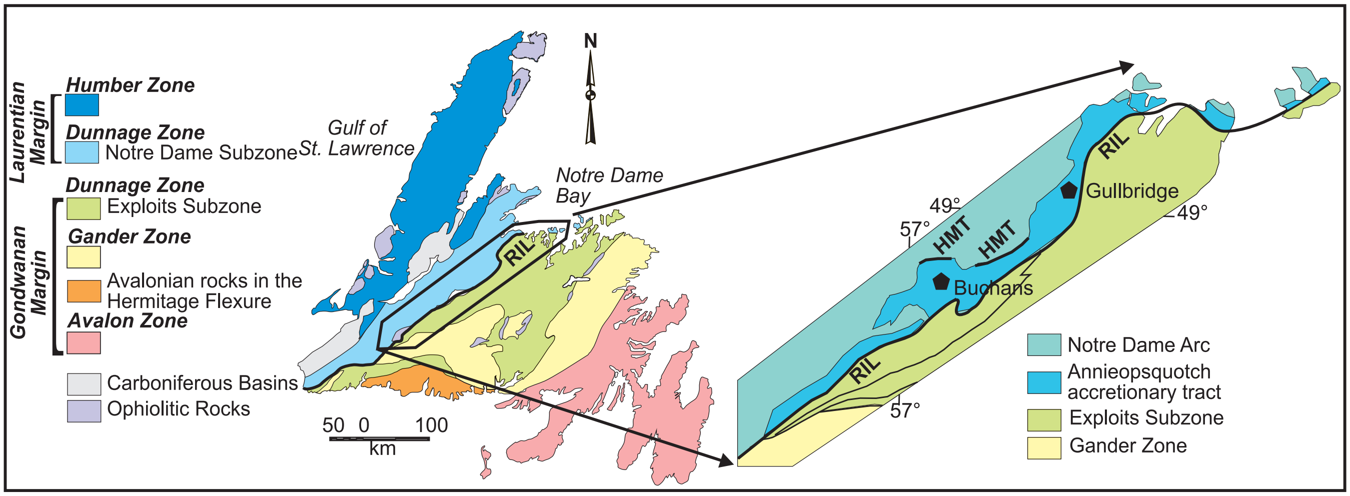

Figure 1. *Tectonostratigraphic zones of the Newfoundland Appalachians (modified after Williams* et al.*, 1988 and van Staal* et al.*, 1998).*

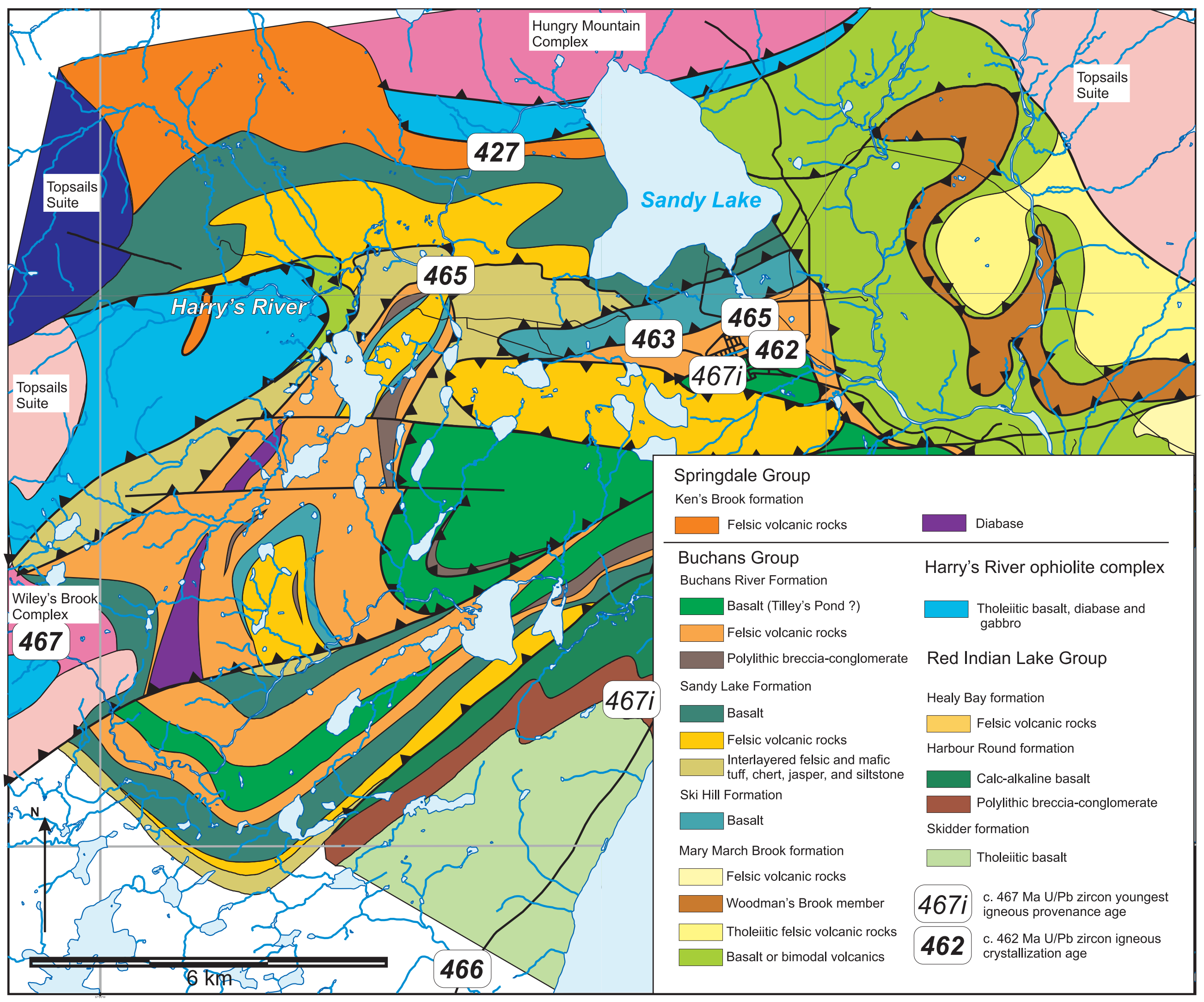

Figure 2. Geology of the Buchans Group (modified from Zagorevski *et al.*, 2009).

least locally, have a sheeted appearance in outcrop and drillholes. To the east, sheet flows and pillow basalts become dominant and the unit attains a gently east-dipping attitude. To the south, this unit is characterized by diabase and medium-grained gabbro. This sequence was originally included in the Footwall arkose unit of Thurlow and Swanson (1981), but subsequently was linked as part of the Sandy Lake and Lundberg Hill formations (Calon and Green, 1987; Thurlow and Swanson, 1987). Thurlow (1991) separated this unit from the Buchans Group and suggested a correlation with the Skidder basalt (Pickett, 1987).

Zagorevski *et al.* (2007) noted that the geochemical characteristics and predominance of mafic rock types in the western Harry's River area prevent their inclusion into the Lundberg Hill formation, which is dominated by arc-related (Jenner, 2002) felsic pyroclastic rocks (Thurlow and Swanson, 1987). Correlation with the Skidder basalt is equally unlikely, as the latter occurs below the Powerline fault (Thurlow *et al.*, 1992) and the whole-rock geochemistry is inconsistent with this correlation (Davenport *et al.*, 1996; Zagorevski *et al.*, 2006). Hence, the mafic volcanic rocks in the western Harry's River area were tentatively correlated to the Harry's River metabasite of Thurlow *et al.* (1992) and/or Lloyds River ophiolite complex of Zagorevski *et al.* (2006). The contact with the Ordovician Buchans Group to the southeast is inferred to be tectonic (Figure 2).

VOLCANIC FEATURES

The basaltic rocks in the Harry's River area display several distinct morphologies – bulbous pillows, flattened pillows and/or sheet flows, pillow fragment breccia and hyaloclastite; the bulbous pillows (Plate 1) generally range from 30 cm to 2 m in diameter. They have a well-defined bulbous morphology with rounded cross-sections. The surfaces of the pillows are, locally, finely corrugated (Plate 1B) and this likely relates to submarine eruption and vertical pillow growth (*e.g.*, Ballard and Moore, 1977). Internally, the pillows are commonly vesicular and locally display well-developed, cooling related, radial fractures.

Unlike the bulbous pillows, the flattened pillows form large mats (~0.3 by >2 m) with a gently undulating surface (Plate 2A). The size of the pillows is difficult to estimate because of the shallow dip and limited exposure. The upper surface of the flattened pillows is commonly broken, exposing a cavity (Plate 2A-C). In modern volcanic rock sequences, this texture has been related to the drainage of pillows and formation of hollows with shelves (also known as drain-back cavities) as a result of flow advancement during limited magma supply (Figure 3A, B; Ballard and Moore, 1977). The cavities are floored by ropey-textured lava (Plate 2A-C). Although the ropey texture is akin to subaerial pahoehoe lava (Fink and Fletcher, 1978), the presence of pillows in the same outcrop suggests that these flows formed in a submarine environment. The curvature of the ropey texture, in the Harry's River area, formed in response to different flow directions in the same flow unit, suggesting that lava spread out laterally from a source (Figure 3C). Some pahoehoe textures may decorate the top surfaces of sheet flows akin to some modern submarine sheet flows (Plate 2D; *e.g.*, Lonsdale, 1977; Chadwick *et al.*, 1999).

The transition between pillow flows and fragmental rocks is exposed in several localities. The pillow flows locally produce pillow buds that intrude into adjacent hyaloclastite (Plate 3A). The buds also become disconnected from the pillows forming small, rounded pillows in the hyaloclastite, attesting to contemporaneity of hyaloclastite formation and extrusion of pillow basalts (Plate 3A-C). The hyaloclastite grades into pillow fragment breccia set in hyalo-

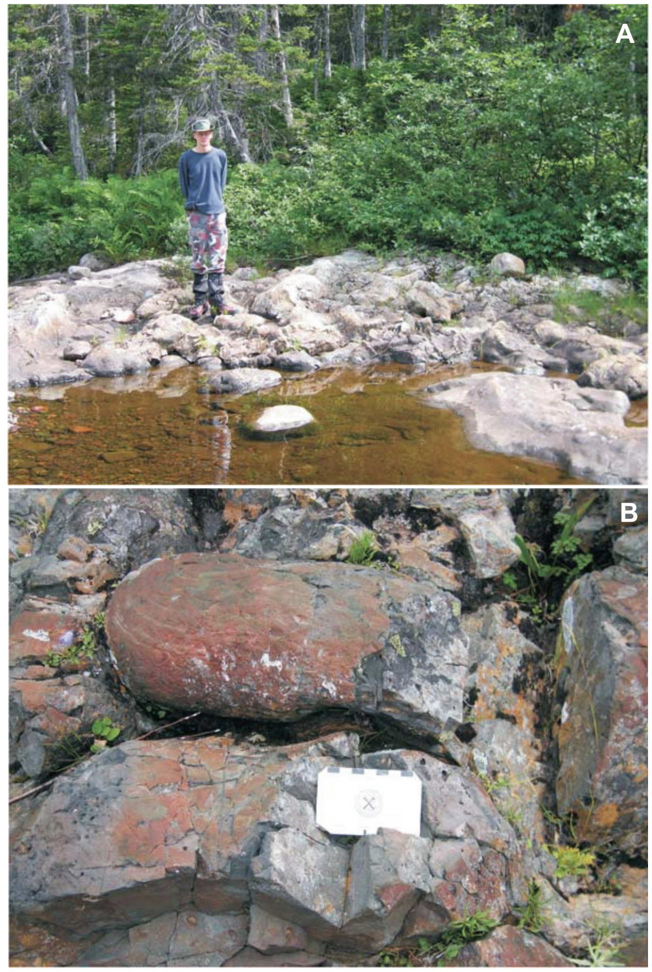

Plate 1. *Representative exposures of Harry's River pillow basalt. A) Small bulbous pillows; R. Haslam for scale. B) Well-formed vesicular bulbous pillow with fine paleo-horizontal surface corrugations.*

Plate 2. *Representative exposures of submarine basalt. A) Flattened pillow or sheet flow with exposed drain-back cavity (or cavities) floored by ropey-textured basalt. Inset outlines the location of ropey texture in Plates B and C as well as interpreted flow directions. B-C) Detail of pahoehoe in cavity. D) Detail of pahoehoe at the top of a sheet flow.*

clastite matrix (Plate 3D). This breccia locally contains haematized pillow fragments.

GEOCHEMICAL CHARACTERISTICS

Complete geochemical data, analytical procedures and elemental accuracies for the samples collected, as part of the Buchans component of the Geological Survey of Canada Targeted Geoscience Initiative 3 Program, are presented in Zagorevski (2008). A subset of this database is utilized in this contribution (Table 1; Figures 4–6) and includes 17 samples of the Harry's River ophiolite complex basalt, diabase and fine-grained gabbro, as well as 2 samples of intermediate volcanic rocks interpreted to be part of a structurally juxtaposed sequence, and 5 samples of rhyolite from adjoining units.

Harry's River Metabasite

All of the samples plot in the basalt–andesite field of the Winchester and Floyd (1977) diagram (Figure 5). Based on the Nb/Y and La/Y ratios, the samples can be divided into two suites (Figure 6A, B), although they may be entirely transitional. Tectonic discrimination plots of diabase and basalt suggest a backarc basin tholeiite and continental-rift tectonic setting of eruption for the two suites (Figure 5), consistent with their LREE-enriched trace-element profiles and minor Th–Nb–La anomalies. The presence of the Th–Nb–La anomalies in some of the samples could be explained by either contribution of subduction-zone or of arc and/or continental crust components.

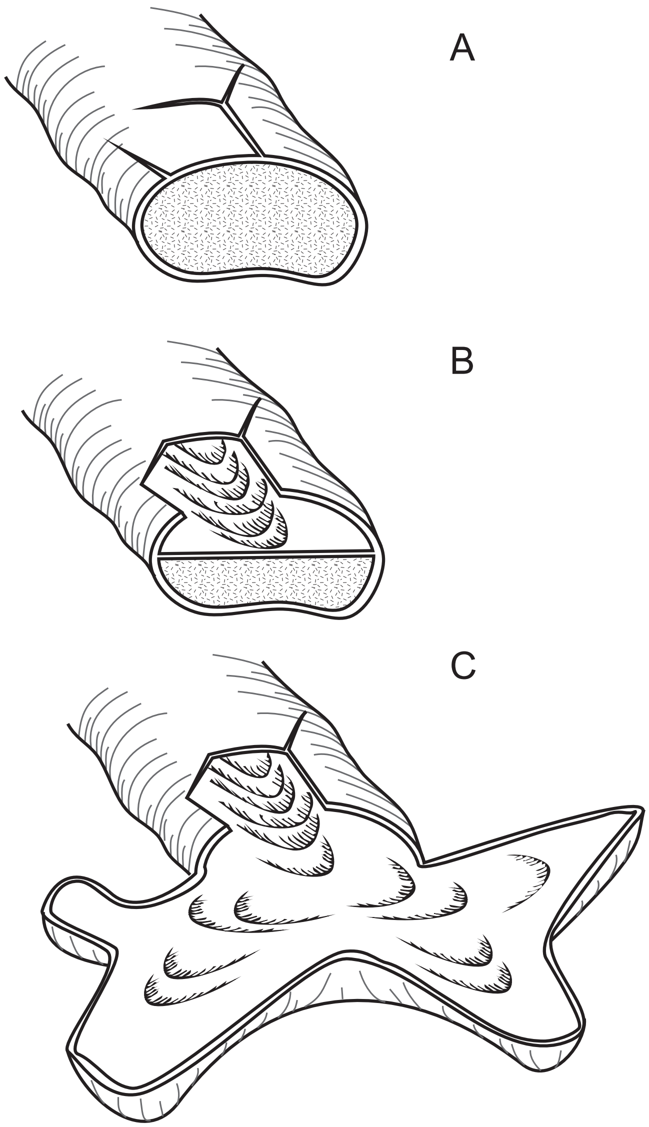

Figure 3. *Formation of ropey texture in submarine flows. Pillow tube or lobe filled with fluid lava (A) drains to produce a cavity allowing formation of a ropey texture (B) (modified from Ballard and Moore, 1977). Multiple drain directions allow formation of multiple directions of ropey texture in a single flattened pillow or lobe (C). Note that the top of the pillow is only partially shown in B and C.*

ISLAND-ARC THOLEIITES

Two samples of tholeiitic andesite are exposed in what is interpreted to be structural contact with the Harry's River ophiolite complex. These are characterized by a slight Nb and Ti depletion on N-MORB normalized extended trace-element diagrams (Figure 6C).

RHYOLITE

Two types of rhyolite have been observed in the Harry's River area. The first type of rhyolite (Ken's Brook formation in Figures 5 and 6D) occurs in structural or stratigraphic contact with the Harry's River metabasite. Its outcrops are characterized by abundant large amygdales (Plate 3A in Zagorevski *et al.*, 2007). This rhyolite is characterized by very high Zr/TiO_2 and Nb/Y ratios. It plots near the boundary between volcanic arc, with-in plate and orogenic granites on tectonic discrimination diagrams (not shown). The second rhyolite (Clementine West rhyolite in Figures 5 and 6D) occurs in fault contact to the south of the Harry's River metabasite, where it is associated with the Clementine West volcanic-hosted massive sulphide mineralization. This rhyolite is characterized by lower Zr/TiO_2 and Nb/Y ratios. It plots in the volcanic-arc fields on the tectonic discrimination diagrams (not shown).

DISCUSSION

The presence of abundant pillow basalt with only minor hyaloclastite and no volcanogenic sedimentation in the Harry's River area suggests that the exposed volcanic rocks formed in proximity to a high-volume basaltic volcanic vent. Comparison to modern settings indicates that flattened pillows and sheet flows are very widespread near high-volume volcanic centres along the Mid-Atlantic ridge, where they are interpreted to form by rapid growth and lateral spreading of pillows, while still plastic (Ballard and Moore, 1977). Although the presence of pahoehoe textures is commonly thought of as a subaerial feature, ropey textures, such as those observed (in this study) on the surface of submarine flows and pillow lobes, and in the collapse pits of abyssal basalts have been observed and documented in the Galapagos Rift (Lonsdale, 1977; Ballard *et al.*, 1979) and in other ancient volcanic fields (Yamagishi, 1991; Chadwick *et al.*, 1999). Analogue modelling of submarine flows suggests that the morphology of the flows is related to the lava extrusion rate (*e.g.*, Griffiths and Fink, 1992). Pillows form at low extrusion rates whereas the formation of ropey sheet flows is related to high extrusion rates (Griffiths and Fink, 1992). Hence, the co-existence of pillows and ropey flows reflects the waxing and waning of a submarine volcanic eruption(s).

High extrusion rates lead to rapid growth and lateral spreading of sheet flows resulting in the subsidence of still molten lava in the flows, forming extensive, partially collapsed, drainage cavities (Figure 3; *e.g.*, Ballard and Moore, 1977; Ballard *et al.*, 1979). The local preservation of radial-

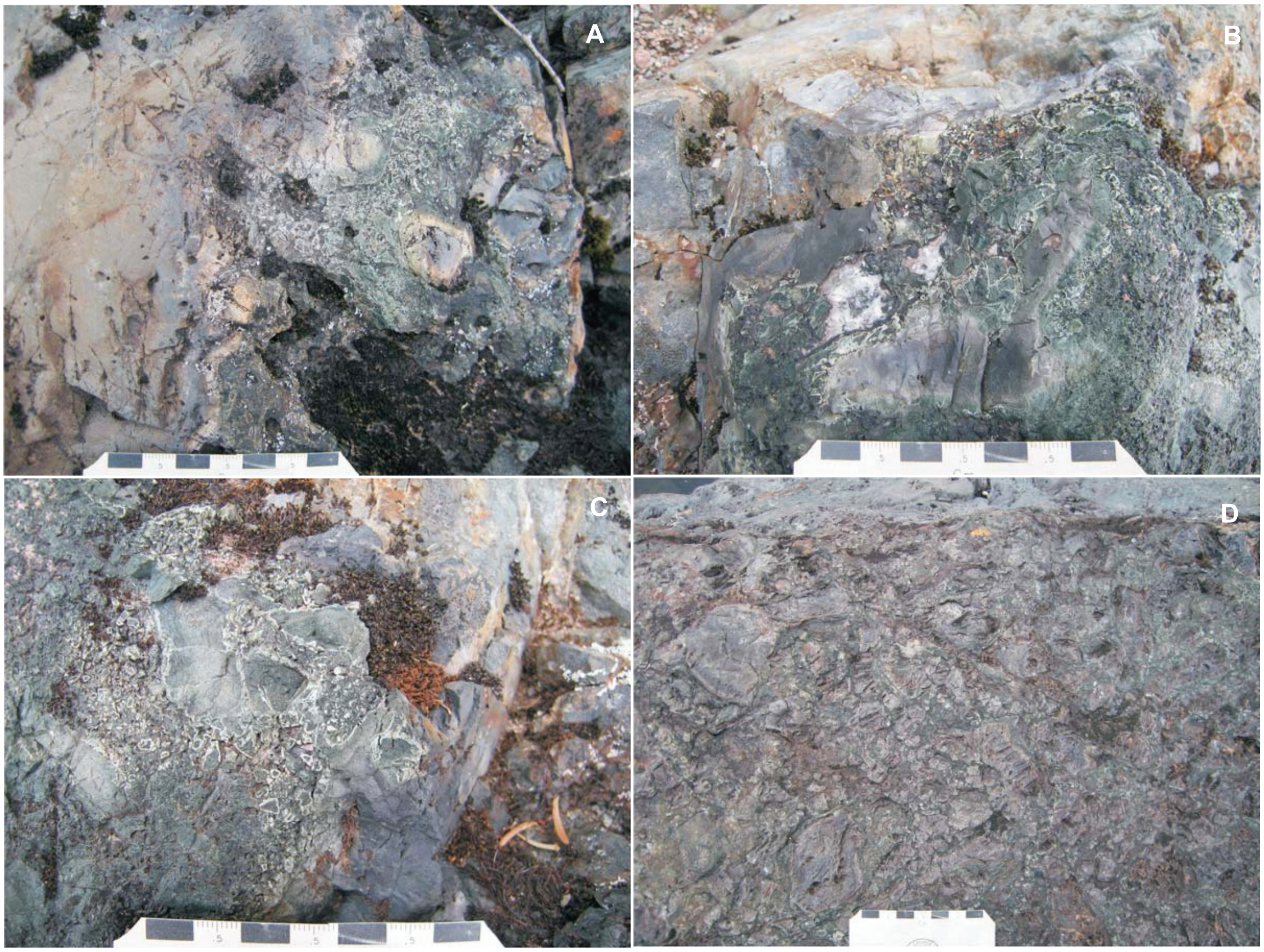

Plate 3. *Representative photographs of fragmental basalt. A) Pillow buds intrude hyaloclastite. B-C) Pillow fragment breccia with interstitial hyaloclastite; hyaloclastite fragments are outlined by alteration rims. D) Pillow fragment breccia.*

ly distributed pahoehoe flow directions in the drainage cavities of Harry's River sheet flows suggests that lateral spreading of flows was an important mechanism for pahoehoe development. Thus, the observed pahoehoe is the submarine equivalent of the on-land tube-fed pahoehoe.

GEOCHEMICAL CHARACTERISTICS

The tholeiitic backarc basin or continental rift-like geochemistry of the Harry's River ophiolite complex is distinctly different from the Buchans Group calc-alkaline mafic volcanic rocks (Figure 6). The lack of any Buchans-like calc-alkaline feeder dykes in the sampled hypabyssal rocks argues that Harry's River metabasites do not form the basement to the Buchans Group. Hence, the assignment to the stratigraphically lowest Lundberg Hill formation of the Buchans Group (Calon and Green, 1987; Thurlow and Swanson, 1987) is not supported. A direct correlation with the basalt of the Skidder formation (Zagorevski *et al.* 2006) is also not supported, because the Harry's River ophiolite complex is geochemically distinct and lies in the wrong structural position.

The association of gabbro, diabase, sheeted dykes, and basalt is suggestive of an incomplete ophiolite or seamount sequence. Zagorevski *et al.* (2007) tentatively correlated the Harry's River ophiolite complex to the Harry's River metabasite of Thurlow *et al.* (1992) and/or Lloyds River ophiolite complex of Zagorevski *et al.* (2006). Comparison of the geochemical characteristics of these units suggests a strong case for correlation with the Otter Brook and Star Brook formations of the Lloyds River ophiolite complex, Harry's River metabasite of Thurlow *et al.* (1992; Figure 6) and the ophiolitic rocks below the Hungry Mountain Thrust in the Mary March Brook area (Harry's River ophiolite complex of Zagorevski and Rogers, 2009). Hence, these metabasites are interpreted to comprise a slice of the regional-scale Lloyds River ophiolite complex (Zagorevski *et al.*, 2006).

Table 1. Locations of geochemical samples (NAD83, UTM Zone 21)

Sample	Unit	Easting	Northing	DDH	Rock Type
RAX06A048A	HR_1	500562	5408713		diabase
RAX06A050	HR_2	501112	5408509		pillow basalt
RAX06A052A	HR_1	507083	5412016		diabase
RAX06A063	HR_2	501339	5408566		basalt
RAX06A064	KB	501676	5408645		rhyolite
RAX06A066	KB	501762	5408732		rhyolite
RAX06A067	HR_2	501922	5408689		basalt
RAX06A069	HR_1	502493	5408958		pillow basalt
RAX06A070	HR_2	502985	5409037		pillow basalt
RAX06A183	HR_1	501369	5407179		diabase
RAX06A500	HR_1	502683	5408738	H2870	mafic dyke
RAX06A501	HR_2	502683	5408738	H2870	pillow basalt
RAX06A502	HR_2	502683	5408738	H2870	basalt
RAX07A058	HR_2	503470	5408237		pillow basalt
RAX07A115	CW	502450	5406562		rhyolite
RAX07A510	MM	504085	5408646	H2805	intermediate
RAX07A515	MM	504384	5408812	H1905	intermediate
RAX07A516	CW	502607	5406711	H1994	rhyolite
RAX07A517	CW	502607	5406711	H1994	rhyolite
RBH06H2825J	HR_2	501448	5408784	H2825	basalt
RBH06H2867AB	HR_1	502073	5408738	H2867	mafic
RBH06H2867F	HR_2	502073	5408738	H2867	mafic
RBH06H2867K	HR_2	502073	5408738	H2867	mafic
RBH06H2867V	HR_1	502073	5408738	H2867	mafic
RBH06H2870F	HR_2	502683	5408738	H2870	basalt

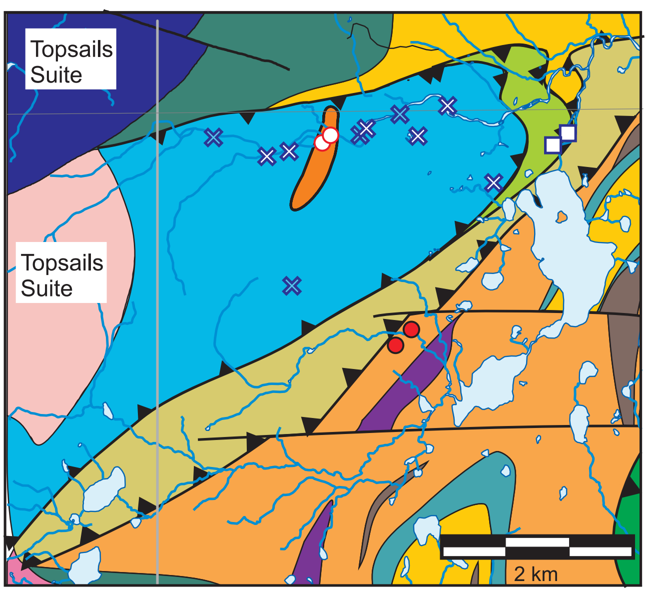

Figure 4. *Distribution of the geochemical sample localities.* See *Figure 2 for geology legend and Figure 5 for identification of geochemical types.*

The Lloyds River ophiolite complex exhibits backarc basin tectonic affinities along its entire length (*ca.* 473 Ma: Zagorevski *et al.*, 2006; Zagorevski and Rogers, 2009), suggesting that it formed a backarc to an outboard Early to Middle Ordovician peri-Laurentian arc (*ca.* 473 Ma: Zagorevski *et al.*, 2006). Both the arc and ophiolite were accreted to the Notre Dame Arc (van Staal *et al.*, 2007) during the Middle Ordovician assembly of the Annieopsquotch Accretionary Tract (Lissenberg *et al.*, 2005).

The volcanic arc tholeiitic rocks occupy an ambiguous structural–stratigraphic position immediately east–northeast of the adjacent Harry's River metabasites (Mary March Brook formation basalt in Figures 2 and 4). They are distinctly different from the Buchans Group calc-alkaline rocks and hence cannot form part of the mine sequence (Figure 6C). The arc tholeiite chemistry is geodynamically compatible with the back-arc-like chemistry observed in the Harry's River metabasite and could be related to complex interactions between arc and backarc magmatism, such as observed in modern backarc spreading centres (*e.g.*, Hawkins and Allan, 1994; Fretzdorff *et al.*, 2002). Alternatively, these rocks may form part of the island-arc tholeiite-dominated Mary March Brook formation (Figure 2; Zagorevski and Rogers, 2009).

The rhyolitic rocks that occur above the Harry's River metabasites have steep trace-element profiles that are unlikely to be produced through differentiation of the tholei-

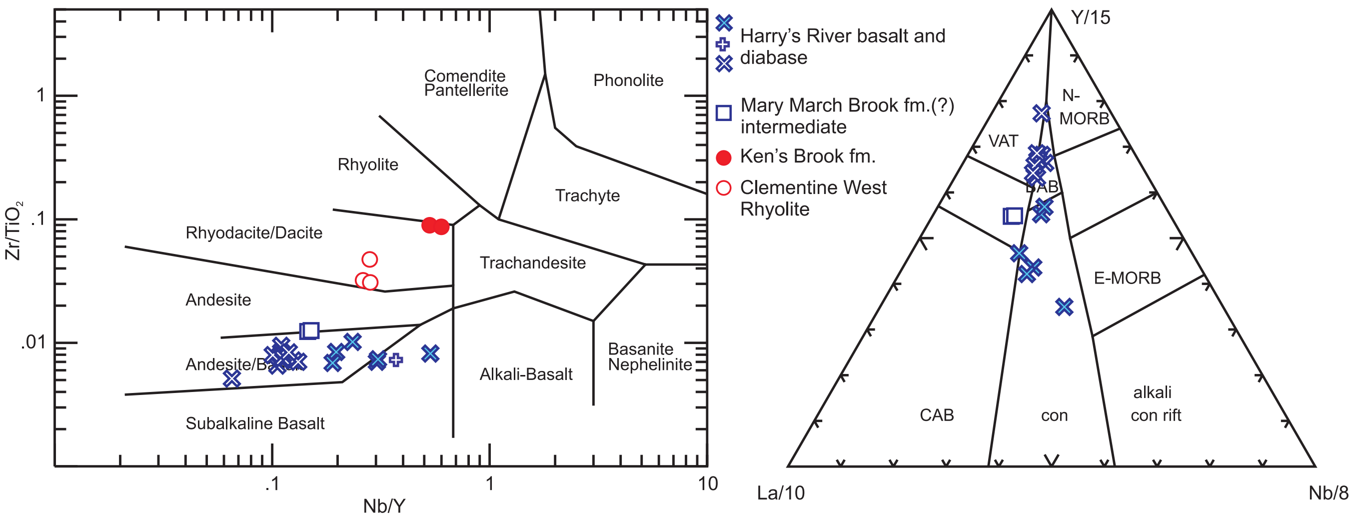

Figure 5. *Geochemical characteristics of the Harry's River area (discrimination plots after Winchester and Floyd, 1977 and Cabanis and Lecolle, 1989). BAB – backarc basalt, CAB – calc-alkaline basalt, con – continental, E-MORB – enriched mid-ocean ridge basalt, N-MORB – normal mid-ocean ridge basalt, VAT – volcanic arc tholeiite.*

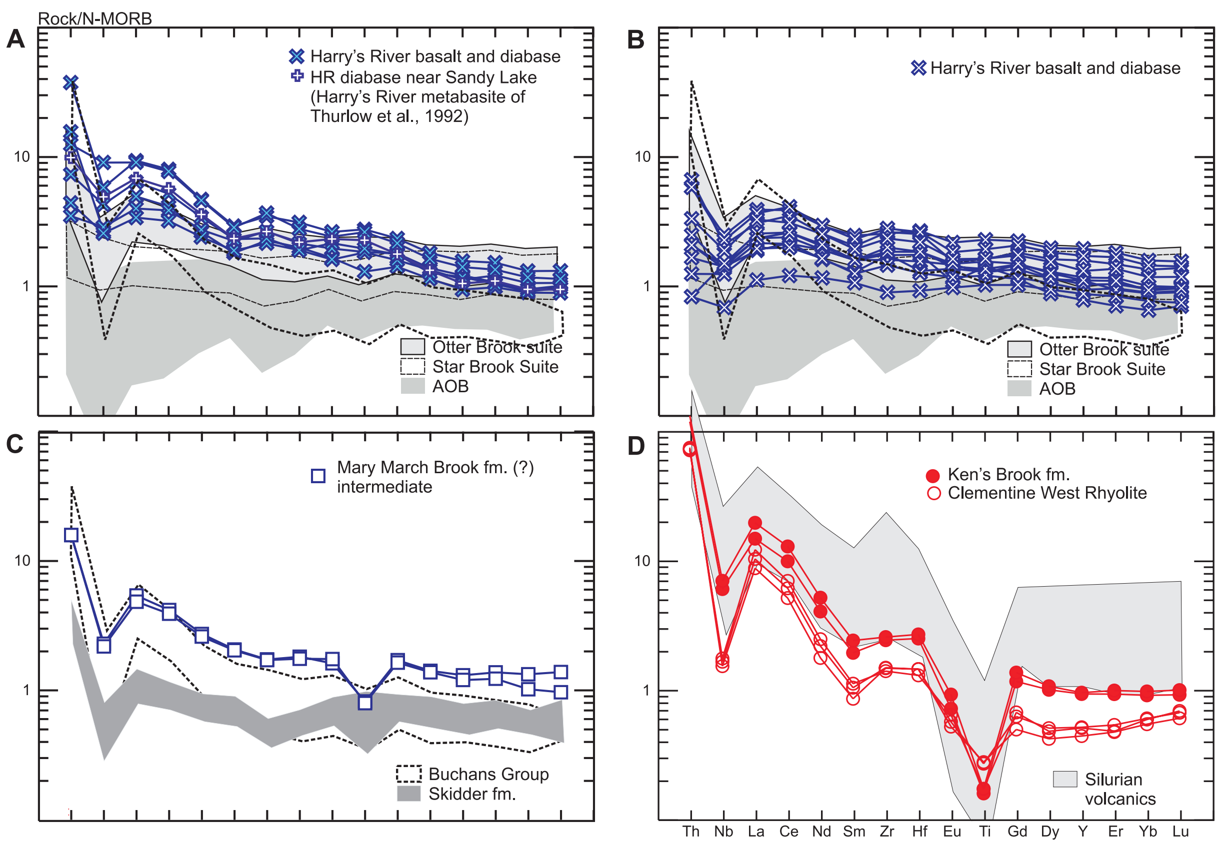

Figure 6. *Extended rare-earth element (REE) spidergrams of the chemical groups defined in this study (N-MORB normalization factors after Sun and McDonough, 1989). A and B) Harry's River ophiolite complex basalt and diabase. C) Mary March Brook formation tholeiitic rocks. D) Felsic volcanic rocks from the Buchans Group compared to Silurian(?) felsic volcanic rocks on top of Harry's River ophiolite complex. Comparison fields compiled from Annieopsquotch Ophiolite Belt (AOB: Lissenberg* et al., *2004), Otter Brook and Star Brook suites of the Lloyds River ophiolite complex (Zagorevski* et al., *2006), Buchans Group (Zagorevski, 2008), Buchans Group mafic rocks (Davenport* et al., *1996, Zagorevski, 2008), Skidder formation of the Red Indian Lake Group (Zagorevski* et al., *2006), and Silurian Topsails igneous suite volcanic rocks (Whalen, 1989).*

itic mafic magma (Figure 6D). They are also distinctly different from the Buchans Group rhyolite and rhyodacite that are associated with the Clementine West, Lundberg Zone, Oriental and McLean VMS mineralization (Zagorevski, 2008; van Hees *et al.*, 2009; Figure 6D). Zagorevski *et al.* (2007) suggested that these rhyolites may form part of the Silurian volcano-sedimentary overlap on the Notre Dame Subzone. The geochemical characteristics are distinctly different from some of the commenditic rhyolite (Zagorevski, 2008) in the adjacent Ken's Brook formation (Zagorevski *et al.*, 2007, 2009); however, similar Silurian rhyolites do occur in the Notre Dame Subzone (*e.g.*, Whalen *et al.*, 1987; Case and Zagorevski, 2009; Figure 6D). Hence, these rhyolites are tentatively interpreted as Silurian.

CONCLUSIONS

Harry's River ophiolite complex forms a distinct sequence of volcanic rocks in the Buchans area that are not correlative to the VMS-mineralized volcanic rocks of the Buchans Group or the Skidder formation (Zagorevski *et al.*, 2006). The Harry's River ophiolite forms a vent-proximal volcanic facies erupted above a basaltic volcanic setting in a backarc or continental-rift setting. It most likely represents a fragment of a backarc basin seamount that was incorporated into the Annieopsquotch Accretionary Tract during the Ordovician Taconic Orogeny (*e.g.*, Lissenberg *et al.*, 2005). Broadly correlative rocks of the Moreton's Harbour Group in the Notre Dame Bay area have yielded paleomagnetic inclinations indicative of close proximity to the Laurentian margin (Johnson *et al.*, 1991; Cutts *et al.*, 2010); however, exact tectonic reconstructions of the peri-Laurentian Iapetus Ocean are difficult to elicit due to the scarcity of suitable paleomagnetic sites (*e.g.*, van der Voo *et al.*, 1991). The remarkable preservation of original volcanic textures within the Harry's River metabasite and thus presumably accurate paleo-horizontal indicators, and low metamorphic grade make these rocks amenable for detailed paleomagnetic studies. Such a study would facilitate an improved paleogeographic reconstruction and understanding of the evolution of Iapetus Ocean.

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