Current Research (2007) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 07-1, pages 103-116

TECTONOSTRATIGRAPHIC RELATIONSHIPS IN THE BUCHANS AREA: A COMPOSITE OF ORDOVICIAN AND SILURIAN TERRANES?

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ABSTRACT

The Buchans Group comprises a thrust imbricated peri-Laurentian continental-arc sequence that hosts the world-class Buchans VMS ore bodies. The overall structure of the Buchans Group is more complex than the simple Ordovician antiformal thrust stack that has been proposed in the literature, to date. Re-evaluation of the regional geology, outside of the mine area, suggests it is a composite terrane comprising several tectonically juxtaposed, but unrelated units, and that it has a complex structural history under sub-greenschist- to upper-amphibolite-facies conditions. The footwall of the Hungry Mountain thrust, which separates the Buchans Group from Notre Dame arc plutons, is marked by an amphibolite-facies ophiolite belt, herein termed the Harry's River ophiolite complex. Other units that should perhaps be excluded from a redefined Buchans Group include the volcanic rocks, herein termed the Seal Pond formation and Mary March Brook formation. The Ken's Brook formation, traditionally included in the Buchans Group, more closely resembles Silurian volcanic rocks associated with the Topsails Igneous Suite. If the Ken's Brook formation is indeed of Silurian age, its involvement in the thrusting suggests that the structure of the Buchans Group results from the superposition of Taconic and Salinic south–southeast-directed thrust and fold belts, consistent with the regional tectonic history of this part of the Newfoundland Appalachians.

INTRODUCTION

The Buchans mining camp produced 16.2 million tonnes of ore at an average grade of 14.5% Zn, 7.6% Pb, 1.3% Cu, 126 g/t Ag and 1.37 g/t Au, from 1928 until mining operations ceased in 1984. The ore was predominantly mined from five main orebodies thought to represent a single stratigraphic horizon within the Buchans Group (Thurlow and Swanson, 1987). Subsequent to mine closure, the understanding of the stratigraphy and structure of the Buchans Group within the immediate vicinity of the ore deposits was improved through structural investigations (*e.g.*, Calon and Green, 1987; Thurlow and Swanson, 1987) and seismic surveys (Thurlow *et al.*, 1992). The revised stratigraphy (Thurlow and Swanson, 1987) successfully predicted repetitions of ore horizons and related rocks by thrust faults hundreds of metres below the MacLean Orebody and allowed accurate constraints on the displacements of faults (J.G. Thurlow, personal communication, 2006).

Despite this, it has proved difficult to apply the existing mine-scale stratigraphy outside of the main mineralized blocks, and geochemical data indicate problems with suggested correlations (Jenner, 2002). Also, several structural panels outside the mine area have been assigned to several different formations over the past several decades and hence need to be re-examined. Reconciling these problems will hopefully allow delineation of prospective horizons within the Buchans area beyond the historic mining camp, and aid in the establishment of a consistent stratigraphic and structural framework for the Buchans–Roberts Arm belt.

This paper presents preliminary results of surface mapping and limited drill-core investigations carried out in 2006 as part of the Targeted Geoscience Initiative 3, Appalachians Project. The study area covers parts of the Star Lake, Lake Ambrose, Buchans, and Badger map areas (NTS 12A/10, 11, 15 and 16). The research approach of this study differs from previous investigations in that the rock units outside of the immediate vicinity of the mines are treated independently, rather than interpreted in terms of the stratigraphic sequence defined in the latter area. This avoids the problem of imposing mine stratigraphy on contemporaneous units that have a dissimilar stratigraphy, or completely unrelated

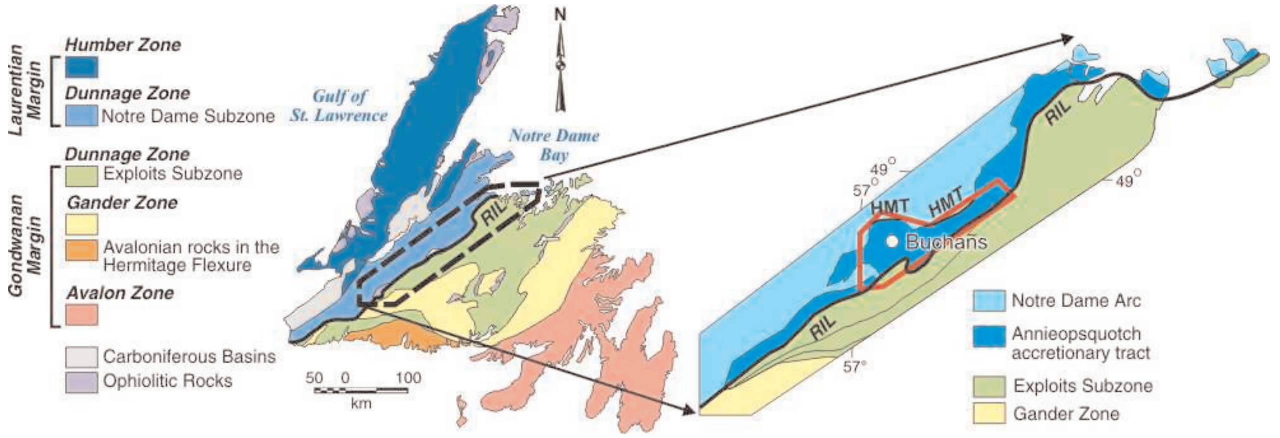

Figure 1. *Tectonostratigraphic zones of the Newfoundland Appalachians (modified after Williams* et al.*, 1988) and subdivision of the Notre Dame Subzone into the Notre Dame Arc and Annieopsquotch accretionary tract. HMT - Hungry Mountain Thrust, RIL - Red Indian Line (modified from van Staal* et al.*, 1998). Location of the study area indicated by the red polygon.*

volcanic sequences. The provisional lithostratigraphic units and correlations presented here are based predominantly on field mapping and petrographic similarities. However, these will be further evaluated later by the acquisition of geochemical, geochronological, and Sm–Nd isotopic data.

GEOLOGICAL SETTING

The Notre Dame Subzone (Williams *et al.*, 1988) in the study area is represented by the Notre Dame arc (Whalen *et al.*, 1997) and the Annieopsquotch accretionary tract (Figure 1; van Staal *et al.*, 1998). The current model for the development of the Middle Ordovician Notre Dame (continental magmatic) arc suggests that it formed above an east-dipping subduction zone in the Humber Seaway (Waldron and van Staal, 2001), immediately outboard of the Laurentian margin. Following the Middle Ordovician collision of the Notre Dame arc with the Laurentian margin, a new, west-dipping subduction zone was established outboard of the Notre Dame arc (van Staal *et al.*, 1998; Waldron and van Staal, *op. cit.*). The arc–back-arc complexes formed in response to this subduction are collectively referred to as the Annieopsquotch accretionary tract (Figure 1; van Staal *et al., op. cit.*).

The tectonostratigraphy of the Annieopsquotch accretionary tract has been recently redefined to the southwest and southeast of the study area (Lissenberg *et al.*, 2005a; Zagorevski *et al.*, 2006). From the northwest to the southeast, the Annieopsquotch accretionary tract comprises the Annieopsquotch Ophiolite Belt (ca. 480 Ma: Dunning and Krogh, 1985), Lloyds River ophiolite complex (ca. 473 Ma: Zagorevski *et al.*, 2006), Mink Lake formation (ca. 473 Ma: Zagorevski *et al.*, 2006), Otter Pond complex (ca. 468 Ma: Lissenberg *et al.*, 2005a), the Buchans Group (ca. 473-462 Ma: Dunning *et al.*, 1987; McNicoll *et al.*, unpublished data, 2007), and the Red Indian Lake group (ca. 465-460 Ma: Zagorevski *et al.*, 2006). The relationships of the other tectonostratigraphic units, within the Annieopsquotch accretionary tract, to the Buchans Group are uncertain, however the potential exists that the Buchans Group, in the broad sense, actually comprises several unrelated tectonostratigraphic units, some of which might correlate with those defined to the southwest. Here, a distinction is made between this loose usage of the term Buchans Group, and a more rigorous definition in the type locality (Buchans Group, s.s.), which applies only to a small area southwest of Sandy Lake (Figure. 2). Formal redefinition of the stratigraphic nomenclature is deferred to when geochemical, isotopic and geochronological data are more complete. This paper is concerned largely with areas that lie within the Buchans Group in the broad sense but outside the Buchans Group (s.s.).

The Notre Dame Subzone is unconformably overlain by the Silurian Springdale Group (ca. 427 Ma: Chandler *et al.*, 1987; Dunning *et al.*, 1990) and correlative rocks. The Springdale Group comprises continental bimodal volcanic rocks, red sandstone, conglomerate and mudstone (Chandler *et al.,* 1987). Genetically related plutonic rocks of the Topsails Igneous Suite and equivalents (Whalen, 1989; Whalen *et al.*, 2006) intrude into all units of the Notre Dame Subzone and commonly stitch regional shear zones (*e.g.*, Thurlow, 1981; Zagorevski and van Staal, 2002; Whalen *et al.*, 2006; Zagorevski, 2006).

ROCK UNITS AND RELATIONSHIPS

HUNGRY MOUNTAIN COMPLEX

The Hungry Mountain Complex lies structurally above the Buchans Group and is exposed to the north and north-

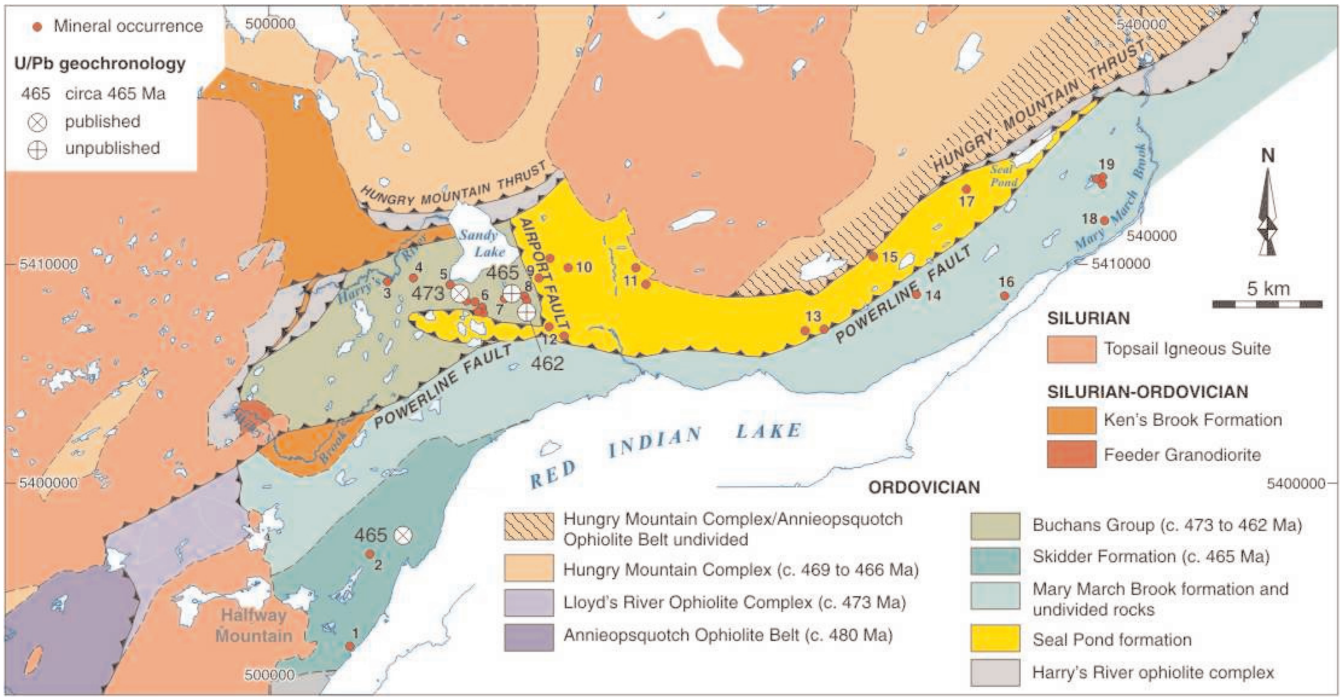

Figure 2. *Simplified geology of the Buchans Group and surrounding area (modified from Thurlow and Swanson, 1981; Whalen and Currie, 1988; Thurlow* et al.*, 1992; Davenport* et al.*, 1996; Lissenberg* et al.*, 2005b; Rogers* et al.*, 2005; geochronology compiled from Dunning* et al.*, 1987; Zagorevski* et al.*, 2006). Coordinates are UTM Zone 21, NAD83. Mineral occurrences: 1-Halfway Mountain; 2-Skidder; 3-Clementine; 4-Clementine Au; 5-MacLean; 6-Rothemere, Level Two, Lucky Strike; 7-Old Buchans; 8-Oriental; 9-Sandfill; 10-Middle Branch; 11-Woodmans Brook; 12-Power House; 13-Little Sandy; 14-Connel Option; 15-Mary March Property; 16-Mary March Zone; 17-Seal Pond; 18-Buchans Junction North; 19-Beaver Pond, Buchans Junction North.*

west of Buchans (Figure 2). It comprises massive to weakly foliated tonalite, granodiorite (Plate 1A), diorite and gabbro containing locally abundant enclaves of paragneiss, orthogneiss and amphibolite (Figure 2). The granodiorite has been imprecisely dated at 467 ± 8 Ma (Whalen *et al.*, 1987), and related rocks have been dated at 469 ± 1 and 466 ± 2 Ma (Whalen *et al.*, 1997). The amphibolite has been dated at 480 ± 3 Ma (Whalen *et al.*, 1997) suggesting the latter is a correlative of the Annieopsquotch Ophiolite Complex (ca. 480 Ma: Dunning and Krogh, 1985). The plutonic rocks become progressively deformed and mylonitized (Plate 1A) in a narrow zone near the Hungry Mountain thrust (Figure 2), which emplaces the Hungry Mountain Complex above the Buchans Group.

BUCHANS GROUP

The original definition of the Buchans Group includes all of the low metamorphic grade volcano-sedimentary rocks underlying the Hungry Mountain thrust north of Red Indian Lake (Thurlow and Swanson, 1981). To the northeast, the Buchans Group is continuous, and was presumed to be correlative with the Roberts Arm Group (northeastern Annieopsquotch accretionary tract in Newfoundland, Figure 1), from which it is arbitrarily separated along the NTS 12A/12H map-sheet boundary. To the south, the Buchans Group is in fault contact with the Skidder Formation of the Red Indian Lake Group (Figure 2; Pickett, 1987; Rogers *et al.*, 2005; Zagorevski *et al.*, 2006).

The stratigraphy of the Buchans Group underwent significant revision prior to, and following, the mine closure. Recognition of numerous significant thrust faults allowed simplification of the stratigraphic relationships (Thurlow and Swanson, 1987; Thurlow *et al.*, 1992). The most recent stratigraphy of the Buchans Group is primarily based on relationships established in the mineralized fault-bound blocks that host the Oriental and McLean orebodies, and it was from the Oriental block that the Lundberg Hill, Ski Hill, Buchans River (Plate 1A) and Sandy Lake formations were defined (Table 1; Thurlow and Swanson, 1987). Buchans has been dated at ca. 473 Ma (Dunning *et al.*, 1987); however, recently obtained U/Pb zircon ages suggest that volcanism in the Buchans Group was also occurring at ca. 465-462 Ma (V.J. McNicoll, unpublished data, 2007).

Extension of the Buchans Group formations outside of the mine area is difficult because of the very poor outcrop,

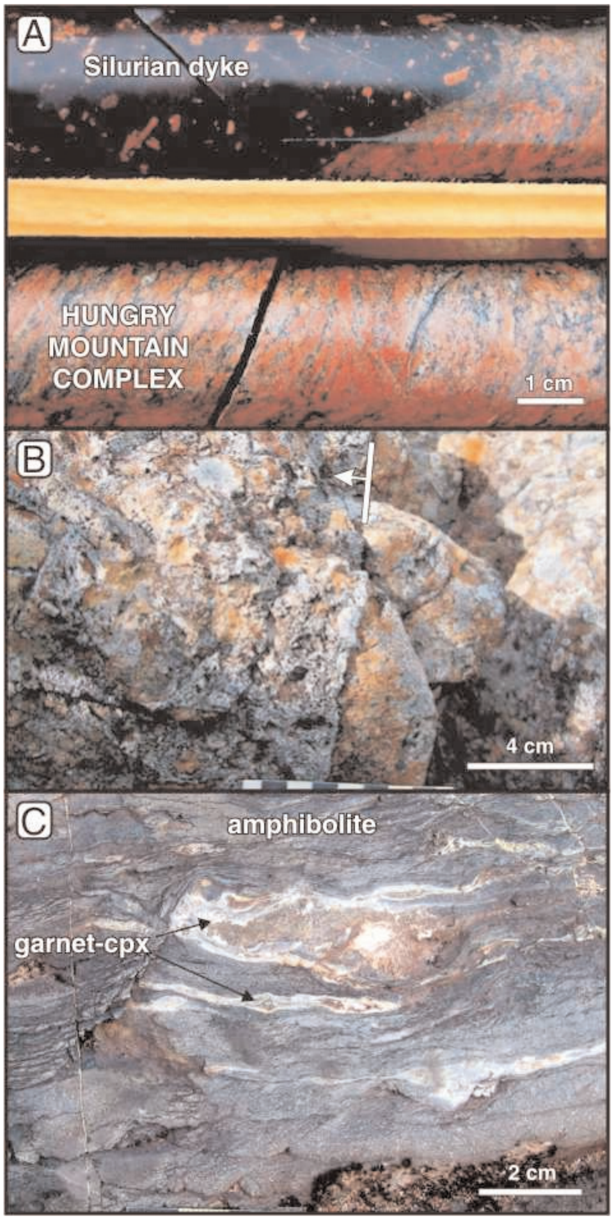

Plate 1. *Representative photographs of surface outcrops and DDH: A. Sheared Hungry Mountain complex cut by undeformed feldspar porphyritic Silurian dyke. B. Steeply south-facing Buchans River Formation east of Ski Hill. C. Harry's River ophiolite complex amphibolite with garnet–clinopyroxene lenses.*

and their distributions and relationships are mainly based on cores from diamond-drill hole (DDH), which becomes sparse, away from the main deposits. Consequently, areas have changed designation several times and/or acquired informal names (*e.g.*, Harry's River metabasite, Ken's Brook volcanics). In the following section, the nature of rocks on the margins of the Buchans Group will be discussed with the goal of separating those that are not in stratigraphic continuity with rocks of the Buchans Group (s.s.).

HARRY'S RIVER OPHIOLITE COMPLEX

The Harry's River ophiolite complex (formerly Harry's River metabasite: Thurlow *et al.*, 1992) is the northernmost unit in the Buchans Group, immediately below the Hungry Mountain thrust (Figure 2). It was initially designated as part of the Lundberg Hill Formation (Thurlow and Swanson, 1987). Pervasive epidote–amphibolite-facies metamorphism in the unit led Thurlow (1981) to suggest hot emplacement of the Hungry Mountain Complex over the Buchans Group along the Hungry Mountain thrust. Calon and Green (1987) suggest that the metabasite is a far-travelled isolated horse in the footwall of the Hungry Mountain thrust. As such, the Harry's River ophiolite complex was subsequently separated from the Buchans Group (Thurlow *et al.*, 1992).

The metabasite has a limited aerial extent with the surface exposure restricted to outcrops in Harry's River. It is predominantly composed of mylonitic interleaved diabase and gabbro. Mutual intrusive relationships observed during this study between diabase and gabbro preserved in low-strain pods suggest that they represent a dismembered ophiolitic sheeted dyke complex in the footwall of the Hungry Mountain thrust. Although the majority of the Harry's River ophiolite complex is epidote–amphibolite to amphibolite-facies, it commonly contains garnet–clinopyroxene lenses (Plate 1C), suggesting an earlier phase of high-pressure eclogite-facies metamorphism. To the east of Sandy Lake, mylonitic amphibolite has been identified in several DDHs, significantly expanding the extent of the metabasite. Mapping suggests that the regional extent of the metabasite is much larger than previously thought; similar rock types occur to the west and northeast of the town of Buchans in the western Harry's River and Mary March Brook areas (Figure 2).

Western Harry's River Area

A thick pile of greenschist- or sub-greenschist-facies mafic volcanic rocks associated with a prominent high positive magnetic anomaly (Figure 3 inset; Coyle, 2006) occurs to the west of the Buchans Group (s.s.). This was considered to be separated from the Harry's River ophiolite complex by a fault in the interpretation of Thurlow *et al.* (1992). This sequence was originally included in the Footwall arkose (Thurlow and Swanson, 1981); and later into the Sandy Lake and Lundberg Hill formations (Thurlow and Swanson, 1987). Subsequently, Thurlow (1991) separated this unit from the Buchans Group (s.s.) and suggested a correlation with the Skidder basalt (Pickett, 1987). The western exposure of the metabasite is characterized by fine-grained diabase dykes that, at least locally, have a sheeted appearance in outcrops and in DDH cores. 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 character-

Table 1. Stratigraphy of the Buchans Group (from Thurlow and Swanson, 1987)

Formation	Rock Types	Former Stratigraphic Names
Sandy Lake Formation	Basaltic pillow lava, pillow breccia intertonguing with coarse-grained, redeposited clastic rocks of felsic volcanic derivation (arkosic conglomerate, arkose, wacke, siltstone); local abundant tuff, breccia, polylithic pyroclastic breccia and tuffaceous sedimentary rocks	Sandy Lake Basalt, Upper Arkose, Lake Seven Basalt, Footwall Arkose, Footwall Basalt, part of Prominent Quartz sequence
Buchans River Formation	Felsic tuff, rhyolite breccia, pyritic siltstone, wacke, polylithic breccia-conglomerate, granite boulder conglomerate, high-grade in situ and transported sulphide orebodies	Lucky Strike Ore Horizon sequence, Oriental Ore Horizon sequence; parts of Intermediate Footwall
Ski Hill Formation	Basaltic to andesitic pyroclastic rocks, breccia, pillow lava, massive flows; minor felsic tuff	Ski Hill sequence, parts of Intermediate Footwall, Oriental Intermediate
Lundberg Hill Formation	Felsic pyroclastic rocks, coarse pyroclastic breccia, rhyolite, tuffaceous wacke, siltstone, lesser basalt, minor chert and magnetic iron-formation	Part of Prominent Quartz sequence, Wiley's Prominent Quartz sequence, Little Sandy sequence (?)

ized by diabase and medium-grained gabbro. The association of gabbro, diabase, sheeted dykes, and basalt is suggestive of an incomplete ophiolite sequence. This is supported by geochemical data, which suggest that these have normal to enriched mid-oceanic ridge basalt (N- to E-MORB) chemical affinities (Davenport *et al.*, 1996). The western margin of this unit is intruded by Silurian red granite and diabase. The contacts with the Ken's Brook formation (*see below)* to the north and Buchans Group (s.s.) to the southeast are inferred to be faults.

Mary March Brook Area

A metabasite unit in the Mary March Brook area north of Buchans Junction occurs in the immediate footwall of the Hungry Mountain thrust (Figure 2). It has been previously included in the undivided Buchans Group and Sandy Lake Formation (Davenport *et al.*, 1996). This metabasite unit is characterized by pillow basalt, diabase, gabbro and trondhjemite metamorphosed to epidote–amphibolite or amphibolite facies, but like the Harry's River ophiolite complex it is also commonly associated with garnet–clinopyroxene lenses and veins. The lithological association is suggestive of an ophiolite complex, consistent with E-MORB chemical affinities in DDH (Davenport *et al.*, 1996). The strain generally increases toward the Hungry Mountain Complex, and the northern margin of the metabasite rocks is marked by a well-developed amphibolite mylonite.

SEAL POND FORMATION

The Seal Pond formation is a provisionally proposed unit that consists of rocks that have been previously included in the Little Sandy Sequence (Thurlow and Swanson, 1981) and Lundberg Hill Formation (Thurlow and Swanson, 1987; Davenport *et al.*, 1996). It forms the structural footwall to the Hungry Mountain Complex and Harry's River ophiolite complex and is characterized by quartz glomeroporphyritic to megacrystic rhyolite at the structural base. The rest of the Seal Pond formation generally comprises finely quartz ± feldspar porphyritic felsic volcanic rocks including grey to brown flow-banded rhyolite (Plate 2A) and orange tuff to tuff breccia. Locally, significant amounts of magnetite-bearing mafic volcanic and intrusive rocks are present. Volcanic rocks of the Seal Pond formation are strongly deformed and transformed into phyllonite (Plate 2B) along contacts with the Mary March Brook formation (*see* next section) to the southeast, Buchans Group (s.s.) to the west, and Hungry Mountain Complex to the north (Figure 2).

The quartz megacrystic rhyolite is locally strongly altered with the groundmass completely transformed into phyllosilicates or containing high proportions of iron oxides that are possibly the result of deuteric oxidation of pyrite. The Seal Pond formation felsic volcanic rocks are host to the Mary March and Middle Branch VMS prospects, as well as the Woodman's Brook and Seal Pond showings (Figure 2).

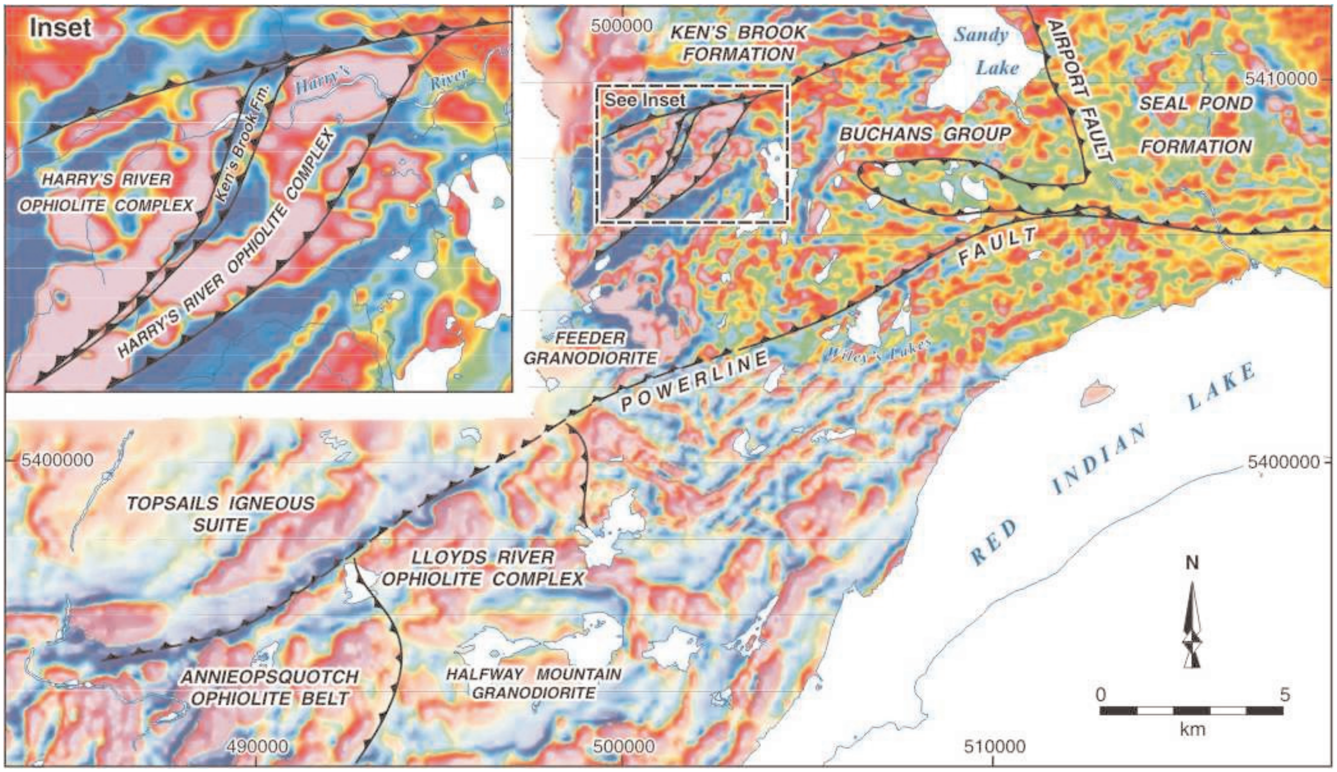

Figure 3. *Overlay of the major and some minor thrust faults on the first vertical derivative of the magnetic field. The lower intensity colour in the geophysical base map reflects old compilation (southwest: Oneschuk* et al.*, 2002), wheras the higher intensity corresponds to the recently reprocessed magnetic data (northeast: Coyle, 2006). Coordinates are UTM Zone 21, NAD83.*

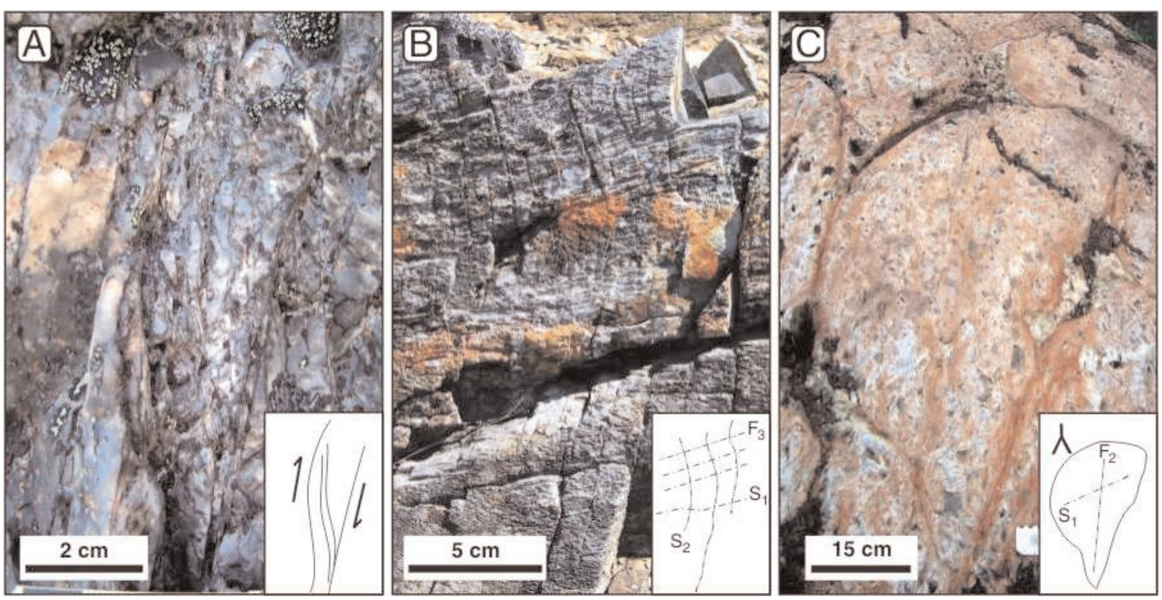

Plate 2. *Representative photographs of surface outcrops. A. Seal Pond formation rhyolite with brittle southeast vergent duplex. B. Poly-deformed phyllonite marking the Airport thrust (?) east of town of Buchans. C. Northeast-facing Skidder Formation pillow basalt in a hinge of an F_2 fold.*

MARY MARCH BROOK FORMATION

The Mary March Brook formation is a provisionally proposed unit of volcanic rocks that are best exposed in the highlands to the west of Mary March Brook (Figure 2). They comprise a bimodal volcanic sequence previously included in the Sandy Lake Formation (Davenport *et al.*, 1996) or correlated to the Skidder basalt (Thurlow and Swanson, 1981). Rare observations of younging directions in the Mary March Brook formation volcanic rocks suggest that although this belt is tightly internally folded, it predominantly has a north–northwest-facing direction. The strain increases to the northwest accompanied by development of phyllonite. The Mary March Brook formation volcanic rocks consist dominantly of white-weathering, black to orange to grey fresh, quartz-phyric, quartz-feldspar-phyric, and feldspar glomeroporphyritic rhyolite flows and (crypto) domes. The margins of the flows/domes are commonly strongly vesicular and are associated with rhyolite breccia, lapilli tuff and bedded, laminated, fine-grained felsic tuffs, epiclastic rocks and minor chert. The rhyolite is intimately intercalated with mafic to andesitic pillows, pillow breccia and minor mafic tuff breccia, indicating coeval andesitic-felsic magmatism. This is also supported by the presence of petrographically similar andesitic and felsic dykes and sills that cut rhyolite and andesite flows as well as magma mingling textures, east of Mary March Brook. Preliminary geochemical analyses (Rogers, 2004) suggest a calc-alkaline arc chemistry for the andesitic rocks. Felsic pyroclastic and epiclastic rocks become more abundant to the southwest and are associated with emerald green, grey, black and red cherts. Mafic to andesitic sills commonly intrude the pyroclastic rocks.

Mary March Brook formation volcanic rocks show local evidence of hydrothermal alteration. Rhyolite and rhyolite dykes are locally sulphidized and contain disseminated pyrite. Pillowed andesites are locally converted into epidosite. This unit appears to be highly prospective and is host to the Connel Option and Little Sandy Lake prospects, as well as Beaver Pond Zinc and Silver, and Buchans Junction North showings (Figure 2).

KEN'S BROOK FORMATION

The Ken's Brook formation (previously referred to as the Ken's Brook volcanics; *e.g.*, Thurlow *et al.*, 1992) is a provisionally proposed unit that occurs, in part, to the northwest of the Buchans Group (s.s.; Figure 2). These rocks predominantly outcrop as red to beige coarsely amygdaloidal flow-banded rhyolite (Plate 3A) and welded tuff. Although originally included in the Buchans Group, they have been suggested to overstep the Hungry Mountain thrust (Thurlow *et al.*, 1992) and form part of the Topsails Igneous Suite

Plate 3. *Representative photographs of surface outcrops and DDH. A. Ken's Brook formation coarsely amygdaloidal rhyolite. Note both red and black zones in the rhyolite. B. Rhyolite breccia in the footwall of the Powerline fault, Wiley's River. C. Amoeboid mafic inclusion in red rhyolite in the footwall of the Hungry Mountain thrust. D. Coarsely amygdaloidal rhyolite in the footwall of the Hungry Mountain thrust.*

(Whalen *et al.*, 1987; Whalen, 1989) or Springdale Group (Chandler *et al.*, 1987). Several potentially correlative units occur to the south in the West Harry's River and Wiley's Brook areas (Figure 2). These are provisionally separated from the Buchans Group because the typical Buchans Group rock types such as highly amygdaloidal andesite are absent, and the characteristic brick-red rhyolite is not present elsewhere in the Buchans Group (s.s.).

Wiley's Brook Area

Felsic and mafic volcanic and intrusive rocks previously included in the Lundberg Hill and Sandy Lake formations (*i.e.*, footwall arkose and prominent quartz sequence: Stewart, 1983) are exposed to the east of Wiley's Lake, predominantly along Wiley's River. Felsic rocks include coarse-grained quartz and fine-grained feldspar-phyric rhyolite and rhyolite breccia (Plate 3B), columnar jointed rhyolite, and bedded tuff. The quartz-phyric rhyolite breccia bears strong resemblance to the Feeder granodiorite (*see below*). The mafic rocks comprise fine-grained amygdaloidal massive basalt flows or sills. One such sill displays pepperitic contacts with grey to black chert and siliceous mudstone.

Harry's River Area

In the Harry's River area, the formation is characterized by brick-red flow-banded rhyolite, beige columnar-jointed rhyolite, orange, beige and light-green tuff, and grey chert exposed in the immediate footwall of the Hungry Mountain thrust. This sequence is intruded by numerous amygdaloidal mafic sills. The red rhyolite is in part extrusive and can be clearly seen to contribute fragments to the overlying lapilli tuff, although portions of it appear to be intrusive and display mutual crosscutting relationships with the mafic sills. The rhyolite is compositionally heterogeneous and contains reddish-grey zones that appear to be intermediate in composition. These zones contain brick-red felsic and green mafic amoeboid inclusions (Plate 3C), suggesting that the intermediate zones may represent hybridized mafic–felsic magma. This unit is predominantly exposed along Harry's River, however several DDHs to the east and west display similar rock types including coarsely amygdaloidal rhyolite (Plate 3D), grey chert, and felsic tuff with minor jasper intruded by abundant amygdaloidal mafic sills or flows. The sill contacts commonly appear to be pepperitic.

West Harry's River Area

A thin sliver of felsic volcanic rocks bisects the Harry's River ophiolite complex (Figure 3 inset). It comprises beige, orange and red rhyolite, flow-banded rhyolite, and rhyolite breccia that were previously included in the Wiley prominent quartz sequence (Thurlow and Swanson, 1981) and Lundberg Hill Formation (Davenport *et al.*, 1996). Rhyolite is sparsely but very coarsely vesicular, with individual vesicles commonly attaining diameters of 1 to 2 cm.

INTRUSIVE ROCKS

Feeder Granodiorite

The so-called Feeder granodiorite is fine to medium grained and quartz-phyric. The feldspars are commonly hematized resulting in an orange to red appearance on both fresh and weathered surfaces, although it commonly displays white- to pink-weathering. The Feeder granodiorite comprises the main intrusion along Wiley's River and several smaller intrusions to the east of Buchans (Little Sandy Lake intrusions; not shown). It may form a subvolcanic intrusion to the Buchans Group volcanics on the basis of its lithological similarity with the prominent quartz rhyolite (Lundberg Hill Formation) and granitoid boulders in the Buchans River Formation (Thurlow, 1981; Stewart, 1987; Thurlow and Swanson, 1987). The granodiorite intrudes the prominent quartz rhyolite (*i.e.*, Lundberg Hill Formation; Stewart, 1983; Thurlow and Swanson, 1987) as well as footwall arkose (*i.e.*, Sandy Lake Formation; Stewart, 1983). However, the Feeder granodiorite bears a closer resemblance to the Halfway Mountain granodiorite 5 km to the south, which is white- to pink-weathered, biotite ± amphibolite granite to granodiorite containing up to 1 cm quartz aggregates and/or phenocrysts. Feldspars on the fresh surface are hematized, resulting in either pink or brick red appearance. The Halfway Mountain granodiorite was correlated to the Silurian Puddle Pond intrusive suite by Whalen *et al.* (2006).

Silurian Dykes

Dykes of presumed Silurian age were observed to intrude most of the units in the Buchans Group (*cf.,* Thurlow, 1981). Purplish-red rhyolitic dykes that have locally flow-banded margins intrude into the Hungry Mountain Complex, Harry's River ophiolite complex and cut across the foliation in these units (Plate 1A). These are petrographically identical to the flow-banded rhyolite in the Ken's Brook formation. A suite of pink alkali-feldspar granite dykes intrudes the sheared Harry's River ophiolite complex. Locally, these dykes are strongly deformed and show strong north-plunging lineations identical to that seen in the surrounding Harry's River ophiolite complex mylonitic amphibolites. The same suite of dykes intrudes the Feeder granodiorite.

STRUCTURE

The initial structural assessment of the Buchans Group identified two deformation episodes (Thurlow, 1981). D_1 deformation was thought to result in formation of a Silurian south–southeast-directed thrust stack followed by Devonian open F_2 folds, which formed a broad syncline in the Buchans Group and were associated with the formation of steeply northeast-trending spaced S_2 cleavage (Thurlow, 1981). The early maps of the Buchans Group (Thurlow and Swanson, 1981; Kean, 1979) suggested a type-3 fold interference pattern. The presence of Silurian mafic sills outlining the structure suggests that at least the latest phase of folding was Silurian or later.

Recognition of thrust faulting within the Buchans Group resulted in reinterpretation of the structure as an Ordovician D_1 antiformal thrust stack with a passively folded roof thrust (Calon and Green, 1987; Thurlow and Swanson, 1987). Thurlow (1981) recognized several regionally important thrust faults including the Hungry Mountain thrust, Powerline fault and Airport thrust. The maximum age of thrusting was constrained by hot emplacement of the Ordovician Hungry Mountain Complex over the Buchans Group, while the minimum age limit is constrained by the Silurian Topsails igneous suite intrusive rocks that intrude along pre-existing shear zones (*e.g.*, Thurlow, 1981). The previously recognized F_2 folds were probably attributed to the D_1 passive folding and largely neglected in the later studies.

HUNGRY MOUNTAIN THRUST

The Hungry Mountain thrust has been the subject of several studies despite very limited surface exposure (*e.g.*, Thurlow, 1981; Calon and Green, 1987). The granodiorite and amphibolite mylonites marking the Hungry Mountain thrust are gently north-dipping and have steeply raking well-developed lineation. Shear sense markers such as asymmetrical porphyroclasts and S-C shear bands clearly indicate south-directed thrust motion (*cf.,* Thurlow, 1981; Calon and Green, 1987).

AIRPORT THRUST

The surface trace of the Airport thrust predominantly lies in areas of no surface exposure. Hence it has been predominantly studied in DDH (*e.g.*, Calon and Green 1987). To the east of Sandy Lake, the Airport thrust is marked by F_2 (?) folded phyllonite (*e.g.*, DDH-2845). Farther to the southeast, a belt of multiple-deformed S_1 phyllonite is exposed at surface (Plate 2B). At present it is unclear whether this phyllonite marks the Airport thrust (for which the surface trace is indicated 2 km to the west by Thurlow *et al.*, 1992) or an unrecognized, structurally higher thrust. However, considering that S_1 has a very shallow dip in this area, the areas of no exposure are likely underlain by a continuous phyllonite belt. The Airport thrust merges with the Powerline fault to the south and continues to the northeast as the tectonic boundary between the Seal Pond and Mary March Brook volcanic rocks.

POWERLINE FAULT

The Powerline fault (Figures 2 and 3) marks the structural base of the known Buchans-style mineralization. Thurlow *et al.* (1992) recognized it as a significant out-of-sequence thrust marked by broken formation and mélange (*e.g.*, DDH-1878). Unlike many thrusts in the area it does not appear to be folded (Thurlow *et al.*, 1992). The Powerline fault coincides with a major geophysical lineament that truncates the "Clementine Trend" of the Buchans River Formation (Figure 3; Thurlow *et al.*, 1992). The geophysical lineament continues to the southwest (Oneschuk *et al.*, 2002; Coyle, 2006), where it marks the southern boundary of the Feeder granodiorite (Thurlow and Swanson, 1981). Farther to the southwest, this geophysical anomaly truncates the northerly trending Lloyds River Ophiolite Complex and Annieopsquotch ophiolite belt and defines the southern boundary of Silurian plutonic rocks (Figure 3; Lissenberg *et al.*, 2005b). Although this boundary contains amphibolite mylonites of the Lloyds River Fault (ca. 470 Ma Ar/Ar: Lissenberg *et al.*, 2005a), it is also extensively quartz veined, suggesting shearing at low-metamorphic grade (C.J. Lissenberg, personal communications, 2003).

The geophysical anomaly also continues to the northeast of Buchans where the Powerline fault has been interpreted to merge with the Airport thrust (Thurlow *et al.*, 1992). Where observed, this thrust is marked by phyllonite. The relationship between the Powerline fault and Airport thrust is unclear at present. Thurlow *et al.* (1992) suggested that the Powerline fault truncates the Airport thrust to the south of the town of Buchans (Figure 14 *in* Thurlow *et al.*, 1992). However, continuation of the Powerline fault to the northeast is truncated by the Airport thrust (Figure 2 in Thurlow *et al.*, 1992) suggesting the opposite relationship. Considering the well-documented out-of sequence motion on the Powerline fault (Thurlow *et al.*, 1992) and the apparent lack of folding which would suggest that Powerline fault is younger than the Airport thrust. As such, the boundary between the Seal Pond and Mary March Brook formations is the Powerline fault (Figure 2).

OTHER D_1 TECTONITES

In the immediate area surrounding Buchans, the structural panels are commonly weakly internally deformed and metamorphosed to low sub-greenschist-facies conditions represented by pumpellyite, prehnite(?), chlorite and white mica. Cleavage development is generally poor and much of the structure was accommodated by brittle deformation. For example, Seal Pond formation rhyolite west of the Airport thrust exhibits small-scale, D_1(?) brittle thrust duplex development (Plate 2A), consistent with the interpreted thrust-stack structure of the Buchans mining camp (Calon and Green, 1987; Thurlow and Swanson, 1987; Thurlow *et al.*, 1992).

To the northeast, volcanic rocks of the Seal Pond and Mary March Brook formations are heterogeneously deformed within the structural panels. The style of deformation is characterized by alternating areas of weakly deformed rocks, S-tectonites and L-tectonites. The L-tectonites are characterized by steeply north-plunging lineations, whereas the S-tectonites are defined by steeply north–northwest-dipping foliations. L-tectonites are especially spectacular in some areas and commonly appear undeformed where outcrops form horizontal surfaces oriented roughly perpendicular to the lineation.

The intensity of D_1 deformation and foliation development increases toward Red Indian Lake in the Skidder Formation (Rogers *et al.*, 2005). S_1 is a continuous to spaced foliation formed at greenschist facies defined by chlorite and actinolite. Where S_1 foliation development is weak, it is locally marked by flattening of vesicles in the pillow basalts.

F_2 DEFORMATION

Structural mapping of the Hungry Mountain and Airport thrusts indicate that they are affected by shallowly northeast-plunging upright F_2 folds (Plate 2B). F_2 folding is accompanied by development of steeply spaced north–northwest-dipping S_2 crenulation cleavage (Plate 2B). The S_2, in the Harry's River amphibolite mylonite, is associated with low-temperature minerals indicating retrograde metamorphic conditions. The map-scale structure of the Buchans Group with structural windows and has been attributed to erosional removal of upper thrust systems structurally overlying the thrust duplexes (Calon and Green, 1987). The clear presence of shallowly plunging F_2 folds in areas adjacent to the mine site suggests that the structural window geometry is, in part, attributable to shallowly plunging upright F_2 folds, rather than solely early thrusting history. The F_2 folds in the Skidder Formation are moderately northeast plunging and clearly deform an earlier S_1 fabric (Plate 2C).

F_3 AND LATER DEFORMATION

Phyllonitic rocks in the Skidder, Seal Pond, and Mary March Brook formations are commonly folded by shallowly plunging recumbent F_3 folds and kink bands (Plate 2B). F_3 can be clearly seen to overprint the F_2 cleavage to the east of the town of Buchans. In addition, several sets of later (?) moderately to steeply plunging folds have also been observed.

DISCUSSION

HARRY'S RIVER OPHIOLITE COMPLEX

The similarity in structural position, metamorphic history, and lithology between the Harry's River ophiolite complex and the metabasites in the Mary March Brook area suggest a strong correlation, despite the lack of structural continuity. This suggests that the Buchans Group (s.s.) is separated from the Hungry Mountain Complex by a thin belt of strongly deformed ophiolite. The structural patterns (up to four phases of deformation) and metamorphic grade (predominantly amphibolite) in the metabasites suggest that they experienced a distinctly different history from the Buchans Group (s.s.; *cf.,* Calon and Green, 1987). The complex structural relationships, as well as the presence of intrusive and supracrustal rocks suggest that Harry's River ophiolite complex is the most appropriate stratigraphic nomenclature.

The suggested ophiolitic character of the metabasites in the western Harry's River area prevent its 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 unlikely, as the latter occurs only below the Powerline fault (Thurlow *et al.*, 1992) and the very limited chemistry is inconsistent with this correlation (Davenport *et al.*, 1996; Zagorevski *et al.*, 2006). The much lower degree of deformation and lower metamorphic grade of the part of the complex west of Buchans indicate some differences, however whether these differences are significant remains to be tested.

SEAL POND AND MARY MARCH BROOK FORMATIONS

Seal Pond formation volcanic rocks are generally poorly exposed and inadequately sampled, preventing a detailed interpretation at present. Several DDH geochemical analyses have been previously taken to the east of Buchans (Swinden *et al.*, 1997; Jenner, 2002); however, their significance is difficult to ascertain at present because the Airport thrust is very shallowly dipping in this area and the samples may have been collected from the Buchans Group (s.s.) below it. Although the petrographic characteristics of the felsic volcanic rocks are similar to both the Mary March Brook formation and Buchans Group (s.s.), the Seal Pond formation appears to be distinct from the both of these units (*cf.,* Thurlow and Swanson, 1981; Thurlow *et al.*, 1992).

The Mary March Brook formation occupies the largest surface area of the Buchans Group. Continuation of this unit along the Powerline fault to the Skidder Formation (Figure 2) is implied by Thurlow and Swanson (1981). The contact between the tholeiitic rocks of the Skidder Formation (Pickett, 1987; Zagorevski *et al.*, 2006) and the calc-alkaline rocks (Rogers, 2004) to the northeast appears to be stratigraphic. It is marked by the appearance of polylithic felsic pyroclastic breccia that contains fragments of rhyolite, andesite, altered basalt, chert and minor oxide-facies iron formation. The altered basalt fragments are very similar to the Skidder Formation.

The Skidder Formation has been dated at 465 Ma (Zagorevski *et al.*, 2006) while the calc-alkaline sequence to the north (herein referred to as the Mary March Brook formation) has yielded abundant Whiterockian conodonts (DDH-2933; ca. 462-468 Ma: Nowlan and Thurlow, 1984; Okulitch, 2002). A similar transition has been described in the adjacent Red Indian Lake Group between the lower and upper basalt members of the Harbour Round Formation (ca. 460-465 Ma: Zagorevski *et al.*, 2006). The similarity in age and geochemical stratigraphy suggests a link in tectonic setting between these sequences. Despite the similarities, the stratigraphy of the Mary March Brook formation is unique, especially in the predominance of rhyolites at Mary March Brook. The relationship between the Mary March Brook formation and the Red Indian Lake Group is unclear at present and will be subject of future investigations.

KEN'S BROOK FORMATION

The Ken's Brook formation volcanic rocks in the Harry's River and Wiley's Brook areas share remarkable lithological similarity, especially the presence of coarsely amygdaloidal flow-banded red rhyolite. In addition, abundant mafic sills/flows and columnar jointed rhyolites occur in Harry's River and Wiley's Brook belts. The coarsely amygdaloidal rhyolite is petrographically similar to the Ken's Brook formation volcanic rocks in their type area (Plate 3A, D). Other rock types resemble Silurian volcanic rocks known elsewhere in the region. For example, the Wiley's Brook purplish red rhyolite breccia (Plate 3B) is lithologically indistinguishable from the Springdale Group lahars; the flow-banded red rhyolites are similar to posttectonic dykes that cut mylonitized Harry's River ophiolite complex (Plate 1A); and the red rhyolite exposed in the Harry's River area exhibits magma mingling and hybridization textures that are common in the Silurian Topsails Igneous Terrane (Plate 3C; Whalen and Currie, 1984).

The unique characteristics of the Ken's Brook formation suggest this is a separate unit and should be excluded from the Buchans Group. Petrographic characteristics of the volcanic rocks suggest a correlation to the Topsails Igneous Suite and Springdale Group. This is, in part, supported by preliminary geochemistry that suggests Zr >300 ppm in some samples consistent with Silurian volcanic rocks elsewhere (Whalen *et al.*, 1987). Despite the petrographic similarities, some very important differences are readily apparent. The Wiley's Brook and Central Harry's River belts both contain cherts, indicative of a subaqueous environment, whereas most of the Silurian volcanic rocks in Newfoundland are subaerial. If the Ken's Brook formation volcanic rocks are indeed temporal equivalents to the Springdale Group, it would imply that marine conditions locally persisted in the Silurian. This is not inconsistent with the regional geology as the Silurian volcanic rocks in the King George IV Lake area, for example, do contain some pillowed andesite flows.

FEEDER GRANODIORITE

Field and map relationships suggest that the Feeder granodiorite intrudes both the Lundberg Hill and Sandy Lake formations (Table 1; Thurlow and Swanson, 1981; Davenport *et al.*, 1996; Figure 1 *in* Thurlow and Swanson, 1987) in the Wiley's Brook area, although the intrusive contacts are not exposed (Stewart, 1983). This, combined with the known 10 m.y. age span of the Buchans Group (473-462 Ma; Dunning *et al.*, 1987; McNicoll *et al.*, unpublished data, 2007), suggests that a temporal and genetic link between the Feeder granodiorite and the volcanic rocks of the Lundberg Hill and Buchans River formations is doubtful and in need of further testing. In addition the Lundberg Hill and Sandy Lake formations in the Wiley's Brook area are very poorly exposed and the DDH control is also very poor. Hence, the potential for misclassification of the rocks in this area is high and the intrusive relationships may be restricted to the Lundberg Hill Formation (Table 1) only.

TIMING OF DEFORMATION

The Hungry Mountain thrust mylonitic amphibolites are cut by both posttectonic and syn-tectonic Silurian rhyolitic and alkali feldspar granite dykes indicating both Ordovician and Silurian movement (*see* previous). If the Ken's Brook formation does consist of Silurian volcanic rocks, their position in the footwall of the Hungry Mountain thrust supports its reactivation in the Silurian. The Powerline fault may display a similar tectonic history. The presence of mélange/broken formation along portions of the Powerline fault, typical for Ordovician terrane boundaries in central Newfoundland (*e.g.*, Rogers and van Staal, 2002), suggests Ordovician movement on this fault zone. Continuation of the Powerline fault along the geophysical anomaly to the southeast requires Silurian reactivation as the anomaly marks the sheared southern boundary of Silurian plutonic rocks (Figure 3). The geophysical anomaly joins the Lloyds River Fault (Lissenberg *et al.*, 2005b), a proven Ordovician structure with Silurian overprint (Lissenberg and van Staal, 2006). This suggests that the Silurian thrusts reused pre-existing and favourably oriented Ordovician structures, while forming new fault surfaces where the orientation was less favourable for such reactivation.

Evidence for formation of entirely new Silurian thrusts/reverse faults may be preserved in the Harry's River ophiolite complex, which is bisected by a lens of Ken's Brook formation in the West Harry's River area (Figure 3 inset). Foliation development is very poor in this area; however it appears that the pillow basalts are repeated on either side of the Ken's Brook formation suggesting formation of a Silurian thrust fault.

The presented evidence suggests that the structure of the Buchans Group formed as a result of superposition of Ordovician and Silurian south–southeast-directed thrust and fold belts. Ordovician assembly of the Buchans Group is required by the ubiquitous presence of Silurian plutonic rocks in all units and tectonic boundaries, consistent with the rest of the Notre Dame Subzone (*e.g.*, Williams, 1995; van Staal *et al.*, 1998; Lissenberg *et al.*, 2005a). Silurian reactivation/formation of new thrusts is required by the involvement of Silurian supracrustal and syn-tectonic plutonic rocks. Similar kinematic significance of the Ordovician and Silurian deformation, largely a product of similar convergence geometry during the Ordovician to Silurian closure of the Iapetus, makes the separation of the generations of thrusts difficult. In addition, the presence of distinct F_2 folds and S_2 cleavage in the Ordovician thrusts (*e.g.*, Airport thrust: Plate 2B) require a re-evaluation of thrust ramp geometry presented in Calon and Green (1987).

The proposed structural history involving Ordovician and Silurian south–southeast-directed thrust and fold belts contrasts with previous interpretations of the Buchans Group; however, it is much more consistent with a regional tectonostratigraphic framework in which many Ordovician shear zones have been reactivated in the Silurian. Examples include the Lloyds River Fault (Lissenberg and van Staal, 2006), Otter Brook Shear Zone (Lissenberg *et al.*, 2005a; Zagorevski, 2006), and the Victoria Delta Fault (Zagorevski, 2006). In addition, it may explain the out-of-sequence movement of the Powerline fault and apparent out-of-sequence movement on the thrust below the Harry's River ophiolite complex, which cuts out the Airport thrust (Figures 1 and 3 *in* Thurlow *et al.*, 1992).

CONCLUSIONS

Application of the Buchans mine stratigraphy on a regional scale as was done in the past is inconsistent with the observed lithological relationships and has caused problems in correlations. Notably, the Lundberg Hill Formation, predominantly felsic by definition (Table 1), has been used to describe units ranging from possible Silurian volcanic rocks (Ken's Brook formation) to Ordovician ophiolitic rocks (Harry's River ophiolite complex). In addition, several lithostratigraphic units have continuously switched formation names throughout their history, indicating the need for modification of the definition of formations or addition of new lithostratigraphic units. We informally propose four new provisional lithostratigraphic units: the Harry's River, Seal Pond, Mary March Brook, and Ken's Brook formations. The utility of the proposed lithostratigraphic units in the Buchans Group will be evaluated by acquisition of geochemical, geochronological, Sm–Nd isotopic data, and by correlation with regional tectonostratigraphic units (*e.g.*, Lloyds River Ophiolite Complex, Red Indian Lake Group, Springdale Group, etc.). The identification of an ophiolite belt(s) and possible Silurian rocks on the margin of the Buchans Group further restricts the aerial extent of the Buchans Group (s.s.); however, improved understanding of the regional tectonostratigraphy should allow for more targeted mineral exploration.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contribution of the Geological Survey of Newfoundland and Labrador for their assistance and support in conducting the research behind this paper. In particular we would like to thank Drs. Andy Kerr, Richard Wardle and Brian O'Brien for their help. Angela Buchanan, Ian Kerr and Monica Escayola are also thanked for their assistance in conducting field studies in the summer of 2006. The scope of this manuscript has been improved through reviews by Drs. J. Hinchey, A. Kerr, and T. Skulski. This work was supported by the Geological Survey of Canada under the Government of Canada TGI 3 Program (GSC contribution # 10060599).

REFERENCES

Calon, T.J. and Green, F.K.
1987: Preliminary results of a detailed structural analysis of the Buchans Mine area. Geological Survey of Canada, Paper 86-24, pages 273-288.

Chandler, F.W., Sullivan, R.W. and Currie, K.L.
1987: The age of the Springdale Group, western Newfoundland, and correlative rocks; evidence for a Llandovery overlap assemblage in the Canadian Appalachians. Transactions of the Royal Society of Edinburgh. Earth Sciences, Volume 78, No. 1, pages 41-49.

Coyle, M.
2006: Integration of two aeromagnetic surveys: first vertical derivative of the magnetic field, southwestern area of Buchans sheet (NTS 12 A/15), Newfoundland and Labrador. Geological Survey of Canada, Open File 5187.

Davenport, P.H., Honarvar, P., Hogan, A., Kilfoil, G., King, D., Nolan, L.W., Ash, J.S., Colman-Sadd, S.P., Hayes, J.P., Liverman, D.G.E., Kerr, A. and Evans, D.T.W.
1996: Digital geoscience atlas of the Buchans-Robert's Arm belt, Newfoundland Newfoundland Geological Survey Branch.

Dunning, G.R., Kean, B.F., Thurlow, J.G. and Swinden, H.S.
1987: Geochronology of the Buchans, Roberts Arm, and Victoria Lake groups and Mansfield Cove Complex, Newfoundland. Canadian Journal of Earth Sciences, Volume 24, No. 6, pages 1175-1184.

Dunning, G.R. and Krogh, T.E.
1985: Geochronology of ophiolites of the Newfoundland Appalachians. Canadian Journal of Earth Sciences, Volume 22, No. 11, pages 1659-1670.

Dunning, G.R., O'Brien, S.J., Colman-Sadd, S.P., Blackwood, R.F., Dickson, W.L., O'Neill, P.P. and Krogh, T.E.
1990: Silurian orogeny in the Newfoundland Appalachians. Journal of Geology, Volume 98, No. 6, pages 895-913.

Jenner, G.A.
2002: Geochemistry of the Buchans - Roberts Arm Belt, Notre Dame Subzone: implications for stratigraphy, tectonic setting and metallogeny. Newfoundland and Labrador Geological Survey, Assessment File 12A/1008, 2002, 131 pages.

Kean, B.F.
1979: Buchans map area (12A/15), Newfoundland. *In* Report of Activities, 1979. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 79-1, pages 18-24.

Lissenberg, C.J. and van Staal, C.R.
2006: Feedback between deformation and magmatism in the Lloyds River Fault Zone, an example of episodic fault reactivation in an accretionary setting, Newfoundland Appalachians. Tectonics, Volume 25, TC4004.

Lissenberg, C.J., Zagorevski, A., McNicoll, V.J., van Staal, C.R. and Whalen, J.B.
2005a: Assembly of the Annieopsquotch accretionary tract, Newfoundland Appalachians; age and geodynamic constraints from syn-kinematic intrusions. Journal of Geology, Volume 113, No. 5, pages 553-570.

Lissenberg, C.J., Zagorevski, A., Rogers, N., van Staal, C.R., Whalen, J.B. and McNicoll, V.
2005b: Geology, Star Lake, Newfoundland (NTS 12-A/11). Geological Survey of Canada, Open File OF1669.

Nowlan, G.S. and Thurlow, J.G.
1984: Middle Ordovician conodonts from the Buchans Group, central Newfoundland, and their significance for regional stratigraphy of the Central Volcanic Belt. Canadian Journal of Earth Sciences, Volume 21, No. 3, pages 284-296.

Okulitch, A.V.
2002: Geological time chart: Geological Survey of Canada, Open-File Report 3040, 1 sheet.

Oneschuk, D., Tod, J. and Kilfoil, G.
2002: Red Indian Line Airborne Geophysics Compilation (Part 2), Central Newfoundland. Geological Survey of Canada, Open File 4254, CD-ROM.

Pickett, J.W.
1987: Geology and geochemistry of the Skidder Basalt. Geological Survey of Canada, Paper 86-24, pages 195-218.

Rogers, N.
2004: Red Indian Line geochemical database. Geological Survey of Canada, Open File 4605.

Rogers, N. and van Staal, C.R.
2002: Toward a Victoria Lake Supergroup; a provisional stratigraphic revision of the Red Indian to Victoria lakes area, central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 02-1, pages 185-195.

Rogers, N., van Staal, C.R., Pollock, J. and Zagorevski, A.
2005: Geology, Lake Ambrose and part of Buchans, Newfoundland (NTS 12-A/10 and part of 12-A/15). Geological Survey of Canada, Open File OF4544.

Stewart, P.W.
1983: Granitoid clasts in boulder breccias of MacLean Extension Orebody, Buchans, Newfoundland. Geological Survey of Canada, Paper 83-1A, pages 321-324.

1987: Geology and genesis of granitoid clasts in the MacLean Extension transported orebody. Geological Survey of Canada, Paper 86-24, pages 149-176.

Swinden, H.S., Jenner, G.A. and Szybinski, Z.A.
1997: Magmatic and tectonic evolution of the Cambrian-Ordovician Laurentian margin of Iapetus; geochemical and isotopic constraints from the Notre Dame Sub-

zone, Newfoundland. Geological Society of America, Memoir 191, pages 337-365.

Thurlow, J.G.
1981: The Buchans Group; its stratigraphic and structural setting. Geological Association of Canada, Special Paper 22, pages 79-89.

1991: Geology of the Buchans orebodies; a 1990 summary. *In* Metallogenic Framework of Base and Precious Metal Deposits, Central and Western Newfoundland. Field Trip 1,. pages 84-92.

Thurlow, J.G., Spencer, C.P., Boerner, D.E., Reed, L.E. and Wright, J.A.
1992: Geological interpretation of a high resolution reflection seismic survey at the Buchans Mine, Newfoundland. Canadian Journal of Earth Sciences, Volume 29, No. 9, pages 2022-2037.

Thurlow, J. G. and Swanson, E. A.
1981: Geology and ore deposits of the Buchans area, central Newfoundland. *In* The Buchans Orebodies: Fifty Years of Geology and Mining. *Edited by* E.A. Swanson, D. F. Strong and J. G. Thurlow. Geological Association of Canada, Special Paper 22, pages 113-142.

1987: Stratigraphy and structure of the Buchans Group. Geological Survey of Canada, Paper 86-24, pages 35-46.

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

Waldron, J.W.F. and van Staal, C.R.
2001: Taconian Orogeny and the accretion of the Dashwoods Block; a peri-Laurentian microcontinent in the Iapetus Ocean. Geology (Boulder), Volume 29, No. 9, pages 811-814.

Whalen, J.B.
1989: The Topsails igneous suite, western Newfoundland; an Early Silurian subduction-related magmatic suite? Canadian Journal of Earth Sciences, Volume 26, No. 12, pages 2421-2434.

Whalen, J.B. and Currie, K.L.
1984: The Topsails igneous terrane, western Newfoundland; evidence for magma mixing. Contributions to Mineralogy and Petrology, Volume 87, No. 4, pages 319-327.

1988: Geology, Topsails Igneous Terrane, Newfoundland. Geological Survey of Canada, "A" Series Map, 1680A.

Whalen, J.B., Currie, K.L. and van Breemen, O.
1987: Episodic Ordovician-Silurian plutonism in the Topsails igneous terrane, western Newfoundland. Transactions of the Royal Society of Edinburgh, Earth Sciences, Volume 78, No. 1, pages 17-28.

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

Whalen, J.B., McNicoll, V.J., van Staal, C.R., Lissenberg, C.J., Longstaffe, F.J., Jenner, G.A. and van Breemen, O.
2006: Spatial, temporal and geochemical characteristics of Silurian collision-zone magmatism: an example of a rapidly evolving magmatic system related to slab break-off. Lithos, Volume 89, Nos. 3-4, pages 377-404.

Williams, H.
1995: Chapter 2: Temporal and spatial divisions. *In* Geology of the Appalachian-Caledonian Orogen in Canada and Greenland. Geological Survey of Canada, pages 23-42.

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

Zagorevski, A.
2006: Tectono-magmatic evolution of peri-Laurentian and peri-Gondwanan arc - backarc complexes along the Red Indian Line, central Newfoundland Appalachians. Ph.D. thesis, University of Ottawa, Ottawa, 304 pages.

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

Zagorevski, A. and van Staal, C.R.
2002: Structures associated with the Red Indian Line in southwestern Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 02-1, pages 211-218.