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LITHOSTRATIGRAPHIC STATUS OF THE HAMMERDOWN BASALT OF THE WESTERN NOTRE DAME BAY VOLCANIC BELT, KING'S POINT AREA (NTS MAP AREA 12H/9), NEWFOUNDLAND

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ABSTRACT

Located southwest of the Springdale Peninsula in Green Bay, the Hammerdown basalt separates two of the oldest tectonic constituents of the peri-Laurentian Western Notre Dame Bay volcanic belt. It forms a narrow map unit situated near the regional boundary between the Ordovician Catchers Pond Group and the Cambrian Lushs Bight Group.

Picrobasalt, basalt, basaltic andesite and andesite flows in the southwestern part of the Hammerdown volcanic belt comprise locally mineralized suites of tholeiitic and subordinate calc-alkalic rocks. Most Hammerdown pillow lavas and breccias, although not all of them, are geochemically similar to the Early Ordovician extrusive rocks found in the lowest observed part of the Catchers Pond Group. In particular, Hammerdown strata may be correlated with the mid-oceanic ridge basalt, back-arc basin basalt, transitional arc tholeiite and picrobasalt seen in the Indian Brook Formation. They are probably also the equivalent of part of the sequence of basaltic andesite, (normal and low-Ti) island-arc tholeiite, and dacitic crystal tuff that typifies the overlying Long Pond Formation. Such marine lavas comprise the depositional substrate of the felsic pyroclastic strata that dominate the middle and upper part of the Catchers Pond Group.

A precise 477.3 ± 1.3 Ma U–Pb crystallization age of a quartz–feldspar tuff from the middle Long Pond Formation indicates that some of the earliest felsic eruptions in the Catchers Pond Group occurred near the base of the Floian stage. Moreover, this implies that accumulation of the Indian Brook Formation had already begun by the latest Tremadoc. Magmatic zircons from a limestone-bearing crystal tuff give a new U–Pb age of 475 ± 1.4 Ma for Floian strata, located near the contact between the middle and upper divisions of the Catchers Pond Group. Situated near the early Arenig–middle Arenig boundary above all known fossil localities, this horizon is preserved in a tectonic window below the sole thrust of the Hammerdown basalt, which is observed to structurally overlie the Catchers Pond felsic volcanic rocks. The late Tremadocian–early Floian volcanic strata, including those present in the Hammerdown belt, are interpreted to be part of a cover succession that had once unconformably overlain the Cambrian basement rocks of the Lushs Bight Group.

Structural inversion of the Catchers Pond basin-fill was governed by a northeast-dipping, foliation-parallel thrust zone that had developed prior to the intrusion of a quartz–feldspar porphyry sheet dated herein at 474.7 ± 1.6 Ma. The southwest-directed fault movements were mainly focused on the Western Arm Group and the structurally underlying Catchers Pond Group, but they did also affect an allochthonous slice of the Lush Bight Group and the highly dismembered Early Ordovician strata immediately underlying these Cambrian rocks. Such orogen-parallel displacement, which occurred during a time interval of 3.3 Ma or less duration, is probably related to the main Taconic II accretion in the metamorphic hinterland of west-central Newfoundland.

The Hammerdown basalt is an arcuate tectonic collage of several Cambrian and Early Ordovician lithostratigraphic units. Nevertheless, it is mainly composed of structurally interleaved rocks derived, for the most part, from the two lowest formations of the Catchers Pond Group. The Hammerdown imbricate thrust stack is deformed by an upright train of dome-and-basin fold structures that are responsible for exposure of the Indian Brook and Long Pond formations in their type area near the Indian River.

INTRODUCTION TO THE WESTERN NOTRE DAME BAY VOLCANIC BELT

The Cambro-Ordovician rocks of the Western Notre Dame Bay volcanic belt occur in the Dunnage Zone of the Newfoundland Appalachians (Swinden *et al.*, 1997). They have been long considered to comprise an integral part of the Notre Dame Subzone of the Dunnage Zone (Williams *et al.*, 1988), as this particular volcanic belt has been interpreted to have developed on the peri-Laurentian margin of the Iapetus Ocean. As previously defined, the constituent stratified rocks have been assigned to the Middle Cambrian and/or Early Ordovician Lushs Bight Group and the Middle Ordovician and older Western Arm, Catchers Pond and Cutwell groups (*cf.* Kean *et al.*, 1995). The geographic location of the study area in northwestern Newfoundland is shown on the index map in Figure 1.

TECTONIC SETTING

The regional Green Bay Fault (Figure 1) is situated along the northwest margin of the Western Notre Dame Bay volcanic belt. Near the study area, it separates the Catchers Pond and Lushs Bight groups from the latest Cambrian ophiolite suites (*ca.* 489–487 Ma) that crop out on the eastern part of the Baie Verte Peninsula (Skulski *et al.*, 2010). Along parts of its southeast margin, the Western Notre Dame Bay volcanic belt is tectonically juxtaposed against the Early Ordovician (*ca.* 480 Ma) Annieopsquotch and coeval ophiolite suites and the younger rocks of the Buchans–Robert's Arm volcanic belt by the Lloyds River Fault (*e.g.*, Zagorevski *et al.*, 2006). Rocks of the Western Notre Dame Bay volcanic belt are also locally in direct contact with the terrestrial Silurian strata of two discrete cover basins that are situated southeast of the Lobster Cove Fault and northwest of the Green Bay Fault (Figure 1). Southwestward, the Catchers Pond and Lushs Bight groups are obscured by younger intrusive rocks (O'Brien, 2011).

Tectonic interpretations of the Cambrian sequence within the Western Notre Dame Bay volcanic belt have the contained infant arc and ultramafic rocks belonging to a primitive Lushs Bight oceanic tract (Swinden *et al.*, 1997). Unlike the younger Betts Cove ophiolite on the Baie Verte Peninsula, the Lushs Bight Group is deemed to have been generated outboard of a rifted peri-Laurentian microcontinent (*e.g.*, van Staal *et al.*, 2007).

The eruption of the Early and Middle Ordovician volcanic rocks in the Western Notre Dame Bay volcanic belt has been attributed to two discrete phases of continental-arc magmatism within the suprastructure of the convergent margin Notre Dame Arc (*i.e.*, *ca.* 482–475 Ma and *ca.* 469–459 Ma separated by a magmatic gap; *cf.* van Staal *et al.*, 2007). Such rocks are thereby tectonically contrasted with age-equivalent volcanic strata in the back-arc-related cover sequences that had accumulated above the *ca.* 489–487 Ma ophiolite suites during their initial obduction near the Humber continental margin (Skulski *et al.*, 2010; *e.g.*, the Snooks Arm and Glover groups of the Baie Verte oceanic tract). Although disposed within the Salinic–Scandian (earliest Silurian) hinterland of west-central Newfoundland, the Ordovician successions of the Western Notre Dame Bay volcanic belt are postulated to have been affected by two episodes of tectonism related to the main (second) phase of the Taconic Orogeny (*i.e.*, a post-483 Ma, pre-470 Ma increment and a post-470 Ma, pre-455 Ma increment; van Staal *et al.*, *ibid*).

REGIONAL GEOLOGY

As originally defined, the Ordovician Western Arm Group (Marten, 1971) contained an Early Arenigian brachiopod fauna (MacLean, 1947) near the bottom of the basal formation (Skeleton Pond Tuff). The conformably underlying sequence of magnetic pillow lava and ferruginous chert was placed in the uppermost part of the Lushs Bight Group and also assumed to be Ordovician.

In re-defining the Western Arm Group, Szybinski (1995) referred to the above-mentioned pillow lava formation as the Sugar Loaves Basalt and removed it from the Lushs Bight Group. From a lithostratigraphic perspective, he situated the Sugar Loaves Basalt at the base of his Western Arm Group, and assigned it and the conformably overlying Skelton Pond Tuff and Big Hill Basalt to the lower three formations of this redefined rock group. Moreover, Szybinski (1995) provided original evidence that all three formations of his lower Western Arm succession were crosscut by a late synkinematic to posttectonic suite of Late Cambrian lamprophyric dykes. In doing so, he disregarded the original biostratigraphic placement of the Early Ordovician (Arenigian) fossils to a position within the Skeleton Pond Tuff.

In contrast to the interpretations of earlier workers, the basal Sugar Loaves Basalt was thought to be everywhere faulted against the underlying undated strata of the Lushs Bight Group. Such rocks include the lowest formations of ultramafic, sheeted dyke and infant-arc (boninitic) rocks in the Lushs Bight Group (Kean *et al.*, 1995) as well as postulated correlatives of the Late Cambrian lamprophyric dykes.

Stratified pyroclastic rocks from the two highest formations of the Western Arm Group were absolutely dated (Szybinski, 1995) and confirmed to be Early and Middle Ordovician, respectively. The felsic volcanic and epiclastic sedimentary succession comprising much of the upper part of his Western Arm Group was thus distinguished from the

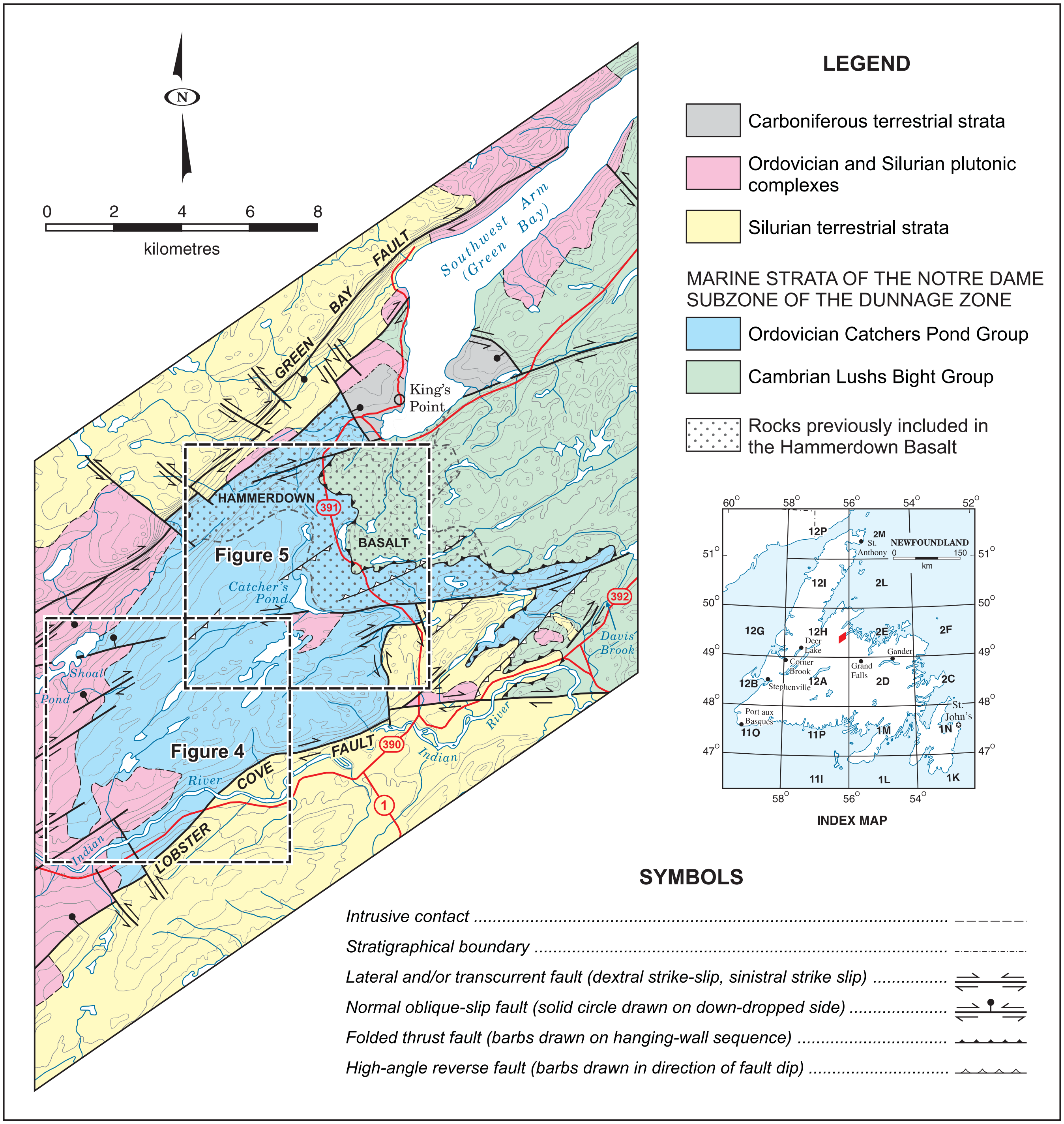


Figure 1. *Simplified regional geological map of the study area between the Green Bay Fault and the Lobster Cove Fault depicting the Cambro-Ordovician marine rocks of the Notre Dame Subzone of the Dunnage Zone and their relationships to younger terrestrial strata and plutonic complexes.*

Cambrian succession and, consequently, it was separated from the mafic volcanic strata that Szybinski (*op. cit.*) assigned to the lower part of the group. The oldest formation belonging to the upper Western Arm succession (Welsh Cove Tuff) was reported to unconformably overlie the Late Cambrian or older Big Hill Basalt on Triton Island.

Szybinski (1995) interpreted the Ordovician sequence in the upper part of the Western Arm Group as a correlative of the fossil-bearing strata previously recognized in the upper part of the Early Ordovician Catchers Pond Group and the uppermost part of the Middle Ordovician Cutwell Group (Figure 2). He considered the younger volcanic-arc

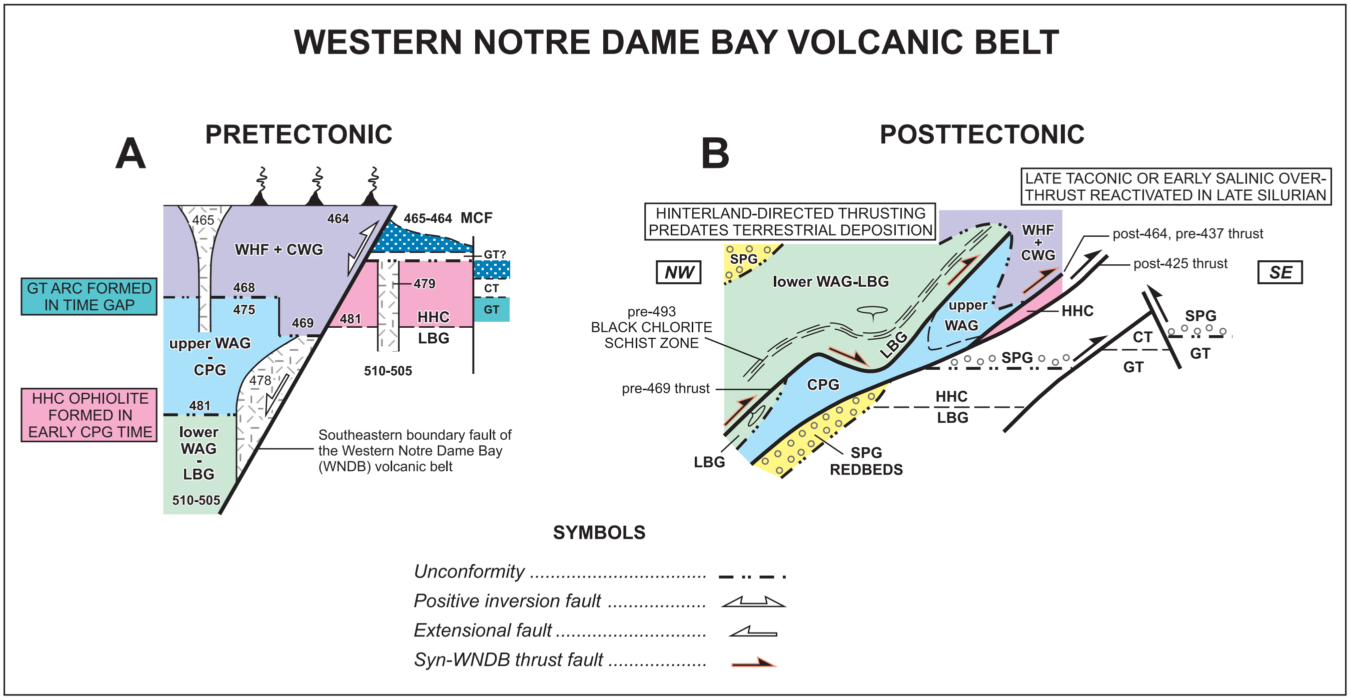


Figure 2. *Schematic palinspastic restoration and approximate structural section of the rock groups comprising the Western Notre Dame Bay (WNDB) volcanic belt. A) Postulated pretectonic configuration of the constituent Cambro-Ordovician rocks; some of the southeasterly adjacent rocks in the tectonic footwall sequence below the WNDB rocks are also illustrated; B) Northwest–southeast cross-section depicting the progressive evolution of the fold-and-thrust belt in the WNDB volcanic belt, including the terrestrial strata of the Silurian Springdale Group. LBG = Lushs Bight Group, WAG = Western Arm Group, CPG = Catchers Pond Group, CWG = Cutwell Group, WHF = Western Head Formation, SPG = Springdale Group. Selected units of the tectonically adjacent ophiolite suite and the Buchans–Robert's Arm volcanic belt are HHC = Hall Hill Complex, GT = Gullbridge Calc-Alkaline Tract, CT = Crescent Tholeiite Tract, MCF = Moores Cove Formation.*

sequence to have been deposited between *ca.* 485 Ma and *ca.* 465 Ma above a substrate composed of oceanic rocks from the lower Western Arm Group and the Lushs Bight Group (Figure 2). However, based on the isotopic and petrochemical signature of the younger suite of extrusive and intrusive rocks, the Ordovician stratigraphic succession of the upper Western Arm Group was interpreted by Szybinski (1995) and Swinden *et al.* (1997) to have been built up above an underlying block of unexposed Precambrian continental crust.

STRUCTURAL GEOLOGY

In places, a suite of peridotite, serpentinite and talc schist comprising the oldest ophiolitic part of the Lushs Bight Group lies structurally above island-arc-related volcanic rocks in younger parts of this rock group (*e.g.*, O'Brien, 2012). On Stag Island, arc-related pillow breccias are known to be crosscut by a *ca.* 506 Ma lamprophyric dyke (Szybinski, 1995), although the host rocks at this locality cannot be unequivocally assigned to the Lushs Bight Group. The earliest regional deformation and greenschist-facies metamorphism of the Lushs Bight Group produced chlorite schist zones (Figure 2) prior to the intrusion of a 493 ± 5 Ma body of gabbro hosted by the Sugar Loaves Basalt and underlying strata (Szybinski, 1995). Such dynamothermal structures possibly resulted from a Cambrian collision of the Lushs Bight oceanic tract with a microcontinental block of Paleoproterozoic crust (*cf.* van Staal *et al.*, 2007).

The Early Ordovician strata of the Catchers Pond Group were deposited at least 25 My after the Cambrian development of the black chlorite schist zones within the Lushs Bight Group, assuming that the relationships reported on Stag Island and near Sugar Loaves Hill are regionally applicable. Therefore, as seen in the pretectonic restoration of the Western Notre Dame Bay volcanic belt illustrated herein (Figure 2), the stratigraphical boundary separating the Catchers Pond and Lushs Bight groups is shown as an unconformity. Black chlorite schist zones have not been found in metamorphosed basalts in the type area of the Catchers Pond Group.

During the initial folding and faulting of the Catchers Pond Group, the chlorite schist zones near the southern margin of the Lushs Bight Group were preferentially reworked.

At this time, the strata of the Catchers Pond Group were underplated beneath the chlorite schists of the Lushs Bight Group along an arcuate thrust fault (Figure 1) and, as a result, the original basement-cover contact was tectonically modified (Figure 2). In the Western Notre Dame Bay volcanic belt, the oldest known group of northeast-trending ductile structures that crosscut the northeast-dipping overthrust separating the Catchers Pond and Lushs Bight groups, and overprint earlier structural features in both groups, are thought to be associated with the late syntectonic Taconian emplacement of a *ca.* 465 Ma suite of felsic–mafic sills and sheet-like intrusions (*e.g.*, the Coopers Cove or Colchester plutons stitching the upper Western Arm and Lushs Bight groups; Sayeed, 1970; Szybinski, 1995; Kean *et al.*, 1995).

The southeast-directed thrust fault that forms the lower tectonic boundary of the rock groups making up the Western Notre Dame Bay volcanic belt (Figure 2) is thought to have formed at a later time. Movement occurred in the Late Ordovician or Early Silurian, between *ca.* 464 and *ca.* 437 Ma, subsequent to the accumulation of the Cutwell Group and the cessation of volcanic activity in this late Middle Ordovician island arc (*see* Szybinski, 1995, Ritcey *et al.*, 1995; Whelan *et al.*, 2006; O'Brien, 2012). Related accretion resulted in inhomogeneous regional deformation of the variably metamorphosed strata below and above the sub-Cutwell unconformity (Figure 2).

Continued episodic displacement of the southeastern boundary fault of the Western Notre Dame Bay volcanic belt is witnessed by the structural incorporation of the Early Silurian red beds of the Springdale Group (SPG) and the Early Ordovician ophiolite of the Hall Hill Complex (HHC) into the regional footwall sequence (Figure 2). This occurred along the Lobster Cove Fault during Silurian or later movement, resulting in offset of the sub-Springdale unconformity that had developed above the basement rocks of the Lushs Bight Group (Davis Brook area in Figure 1).

EARLY ORDOVICIAN INTRUSIONS

Early Ordovician hypabyssal intrusions were emplaced into parts of the Lushs Bight, Western Arm and Catchers Pond groups during the late Tremadocian–early Floian interval. The oldest crosscutting gabbro–diorite intrusions (*ca.* 478 Ma) are associated with trondjhemite and quartz–feldspar porphyry (Figure 2). They are reported to have enclaves of ultramafic intrusive rocks sourced from the Lushs Bight Group and mafic volcanic rocks sourced from the Western Arm and Catchers Pond groups (Sybinski, 1995; Kean *et al.*, 1995).

Some of the Early Ordovician intrusive rocks in the Western Notre Dame Bay volcanic belt might conceivably be comagmatic feeders to certain mafic to intermediate extrusive rocks within the mid-upper part of the Catchers Pond Group. However, many intrusions of this age are too old to intrude the basal *ca.* 469–468 Ma rocks of the unconformity-bounded Cutwell Group (Figure 2) or equivalent and younger Middle Ordovician strata in the uppermost part of Szybinski's (1995) Western Arm Group. In this paper, they have been illustrated as sub-Cutwell plutonic basement.

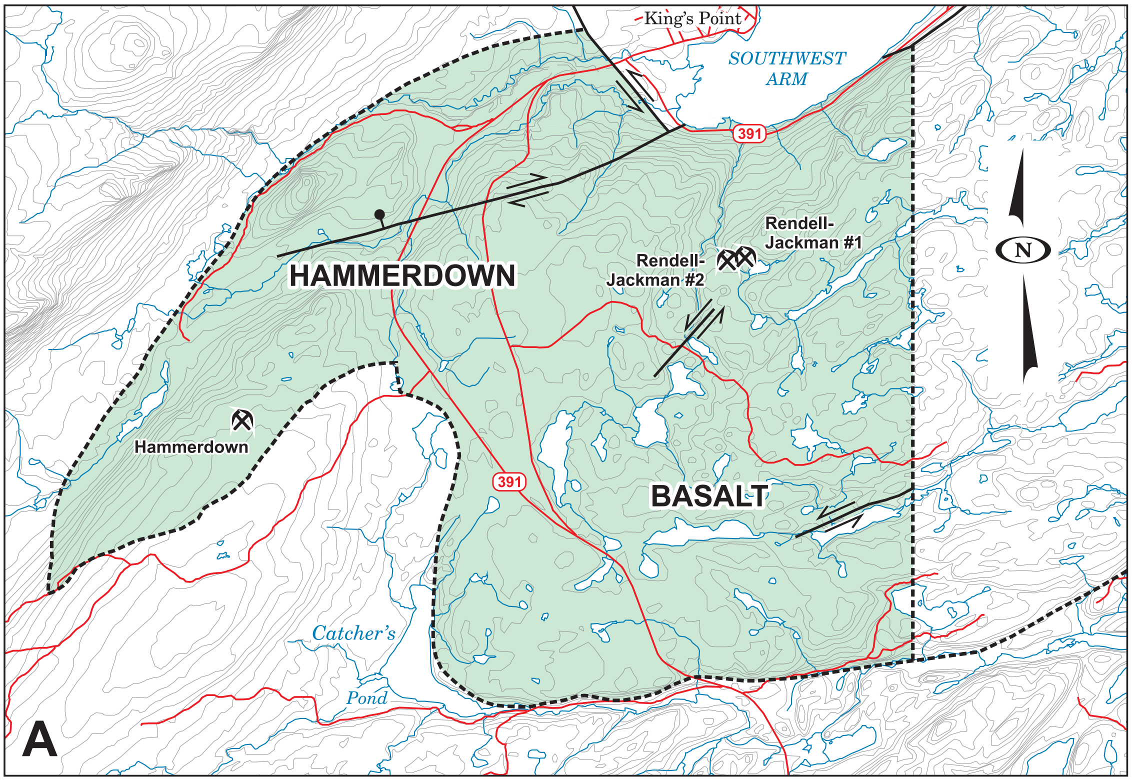
Early Ordovician intrusions observed in the older part of the Western Notre Dame Bay volcanic belt are postulated by one of the authors to have been nonconformably overlain by the *ca.* 464 Ma intermediate tuff and agglomerate of the Western Head Formation (WHF in Figure 2). They are possibly related to some of the *ca.* 479–477 Ma sheeted plutonic bodies (*e.g.*, Mansfield Cove igneous complex) seen farther southeast in the tectonically adjacent rocks. Host rocks include the *ca.* 480 Ma ophiolitic sequences of the Hall Hill igneous complex (HHC in Figure 2) and the Early Ordovician and/or older Moretons Harbour Group (Dunning *et al.*, 1987; Zagorevski *et al.*, 2006; Cutts *et al.*, 2012).

The oldest metamorphism and ductile shearing (Williams *et al.*, 1976) of the peri-Laurentian Cambrian Twillingate trondjhemite (Elliot *et al.*, 1991) and the older Sleepy Cove Group (Lushs Bight Group correlative; Swinden, 1996) are associated with subvertical fault structures that overlap in age with the Early Ordovician mafic–felsic intrusions.

DEFINITION OF THE HAMMERDOWN BASALT

The Hammerdown basalt is an informal term (*e.g.*, Mullen, 1994) for a strongly mineralized, mafic volcanic-dominant map unit (Figure 1) that occurs south of the town of King's Point near the Southwest Arm of Green Bay (Figure 3). From the perspective of the regional geology of the NTS 12H/9 map area (Kean *et al.*, 1995), it lies southwest of the main tract of the Lushs Bight and Western Arm groups on the Springdale Peninsula. Previous workers have restricted the distribution of the Hammerdown basalt to an outcrop belt located immediately northeast of the type area of the Catchers Pond Group (Figure 3A).

The Hammerdown basalt is host to several base-metal prospects, including the historic Rendell-Jackman copper deposit (Figure 3A). It is also known to contain numerous precious metal showings and, of these, the Muddy Shag, Wistaria and Rumbullion showings are some of the best studied in the area surveyed (Andrews and Huard, 1991; Ritcey *et al.*, 1995; Gaboury *et al.*, 1996). The Hammerdown gold deposit (Figure 3A) has proven to be commercially viable as a gold-only mining operation (Kahlert, 2011).



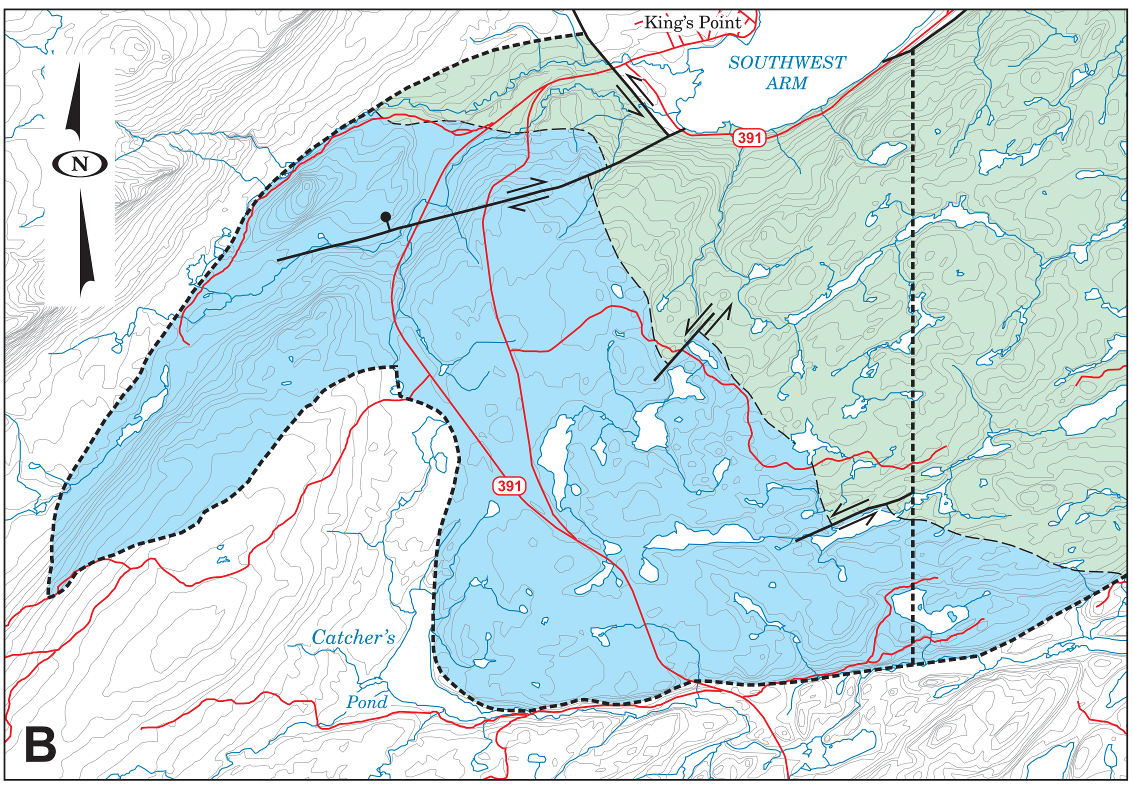


Figure 3. *Location of the Hammerdown Basalt and the Hammerdown volcanic belt within the south-central part of the NTS 12H/9 map area. A) Map illustrating the approximate extent of the Hammerdown Basalt of the Lushs Bight Group as defined by Moore* et al. *(2002); B) Map of the Hammerdown volcanic belt (*cf. *Andrews, 1991) showing the area of rocks correlated with the Lushs Bight Group (green) and the Catchers Pond Group (blue).*

Moore *et al.* (2002) assigned the Hammerdown basalt to an undetermined lithostratigraphic position within the Lushs Bight Group and restricted the Catchers Pond Group rocks to the region southwest of the Hammerdown basalt (Figure 3A). In contrast, Andrews (1991) correlated rocks in the northeastern part of the Hammerdown volcanic belt with those of the Lushs Bight Group but, in an alternative interpretation, he considered rocks in the southwestern part of the outcrop belt to represent an unspecified stratigraphic unit of the Catchers Pond Group (Figure 3B).

The northwest-trending suite of volcanic rocks previously assigned to the Hammerdown basalt form a regionally sinuous belt that is crossfolded and crossfaulted by northeast-trending structures (Figures 1 and 3). The unit is mainly composed of variably foliated greenschist-facies rocks that commonly preserve primary volcanological features but, in places, pass transitionally into northeast-dipping zones of metabasite and mafic mylonite.

Steeply southeast-dipping zones of schistose felsic porphyry intrude across the foliation developed in the mafic volcanic strata included in the Hammerdown basalt. In places, these northeast-trending intrusions are host rocks to deformed gold-bearing quartz veins. The mesothermal gold mineralization at the Hammerdown deposit is associated with a F–Cu–Pb–Zn metal enrichment, whose origin has been attributed to some of the Early Silurian magmatic rocks of the region (Andrews and Huard, 1991).

GEOCHEMICAL COMPARISON OF ROCKS IN THE LOWER CATCHERS POND GROUP AND THE HAMMERDOWN VOLCANIC BELT

Mafic and intermediate volcanic rocks from the lowest two formations of the Catchers Pond Group were sampled in the type areas of these units north of the Indian River (Figure 4). There are twelve (12) samples in total; seven (7) from the Indian Brook Formation and five (5) from the overlying Long Pond Formation collected from an area about 5–10 km southwest of the nearest exposure of the Hammerdown basalt.

Unmineralized mafic and intermediate volcanic rocks were also collected within the northwestern, south-central and southeastern parts of the Hammerdown volcanic belt (Figure 5). The entire suite of sixteen (16) rock specimens come from the southwestern part of this volcanic belt (Figure 3), and all of the sampled Hammerdown lava flows crop out to the north of the felsic pyroclastic strata typical of the middle and upper parts of the Catchers Pond Group (Figure 5).

Major- and trace-element data from the combined suite of twenty eight (28) analysed rock samples are presented herein (Table 1). These results have been augmented by previously published rare-earth element data from the type area of the Indian Brook Formation. Our purpose is to discern the geochemical nature of the mafic to intermediate volcanism, particularly as seen in the stratified rocks of the lower part of the Catchers Pond Group. Another aim of this paper is to compare and contrast the above record with that of the volcanic rocks found in the adjacent part of the Hammerdown volcanic belt.

METAMORPHISM AND ALTERATION

Rocks of the Catchers Pond and Lushs Bight groups contain secondary albite, quartz, actinolite, chlorite, sericite, carbonate, zoisite and titanite. However, this metamorphism and alteration is unlikely to have fractionated the immobile trace elements in these rocks, in particular the transition metals Ti, Zr, Nb, Y and V (*e.g.*, Merriman *et al.*, 1986). In the field, fresh lava samples were collected from pillow centres and, on the basis of a visual inspection, the least altered (non-vitric) rock slabs were selected for crushing. Geochemical alteration indices were not calculated for any of the analyzed volcanic rock samples.

The detection limits for elements analyzed at the Geological Survey's Howley Laboratory, Acme Analytical Limited and Bondar-Clegg Limited are shown in Table 1. However, analyses of the major elements and the transition metals were not repeated in other geochemical laboratories.

LITHOGEOCHEMISTRY OF THE INDIAN BROOK FORMATION

The Indian Brook Formation (Unit O:CPib) is well exposed in the high ground north of the Indian River along part of the southern margin of the Catchers Pond Group (Figure 4). Most of the mafic extrusive rocks sampled in the Indian Brook Formation comprise a tholeiite suite when plotted on a FeO/MgO *vs* SiO_2 diagram (Miyashiro, 1974), although sample 2540608 falls in the field of calc-alkaline rocks (Figure 6a).

Using the log Zr/Ti *vs* log Nb/Y ratio (Pearce, 1996), the seven samples collected in the type area of this lowest exposed subdivision belong to the subalkaline basalt group (Figure 6b), although some of these pillowed lavas would be considered basaltic andesite and andesite on a TiO_2% *vs* Zr diagram. A suite of magnetic iron-rich tholeiites (having Ti >9600 ppm) are represented by four of the subalkaline basalt samples collected from the type area.

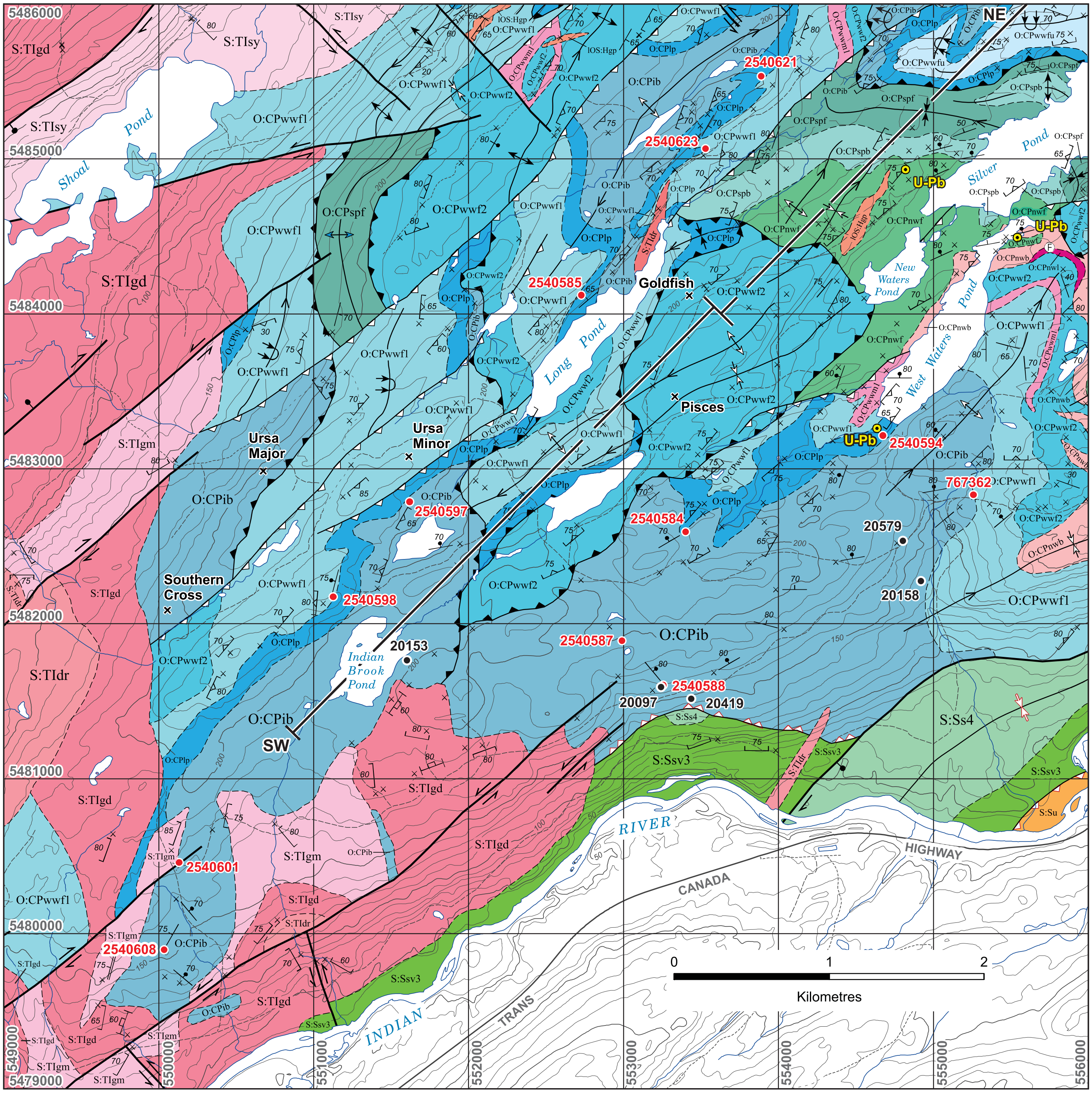


Figure 4. *Detailed geological map of part of the Catchers Pond Group and adjacent rock units showing the localities of the lithogeochemical specimens collected from the type area of the Indian Brook Formation (7 red samples; Unit O:CPib) and the type area of the Long Pond Formation (5 samples; Unit O:CPlp). Black numbers represent samples having REE data that come from the Indian Brook Formation. Informal names of mineral prospects are shown in bold font; position of north-east–southwest line of section is indicated. Legend for Figure 4 is appended following the References Section.*

All analyzed mafic volcanic rocks from the Indian Brook Formation plot as either mid-ocean ridge basalt (MORB) or back-arc basin basalt (BABB) on a Ti/1000–V geotectonic diagram (Shervais, 1982; Figure 6A). However, on this type of immobile element plot, three of the six samples [2540608, 2540597 and 2540584] are also seen to lie within the average range of calc-alkaline arc and shoshonitic rocks. In particular, sample 2540608 is probably a transitional calc-alkaline suite rock, as it lies within the mixed arc tholeiite–calc-alkaline arc field on a TiO_2 *vs* FeOt/MgO plot.

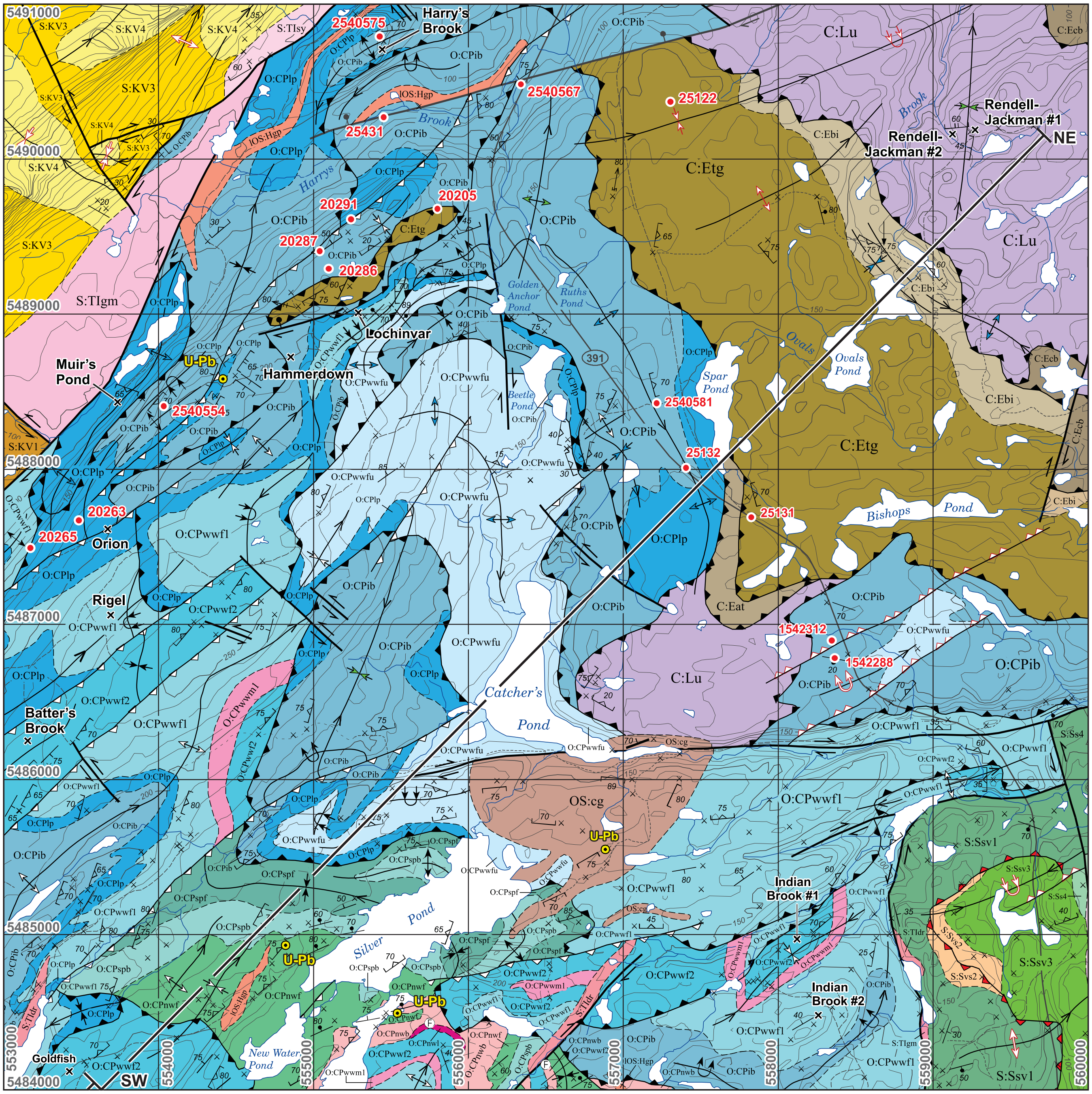


Figure 5. *Detailed geological map of rock units comprising the southwestern portion of the Hammerdown volcanic belt (*cf. *Figure 3) in the ground north of Beetle Pond, west of Lochinvar and east of Catcher's Pond. The localities of sixteen lithogeochemical specimens are plotted in this region. Informal names of mineral prospects are shown in bold font; position of northeast–southwest line of section is indicated. Legend for Figure 5 is appended following the References Section.*

In contrast, samples 2540587, 2540588 and 2540601 are magnetic Ti-rich tholeiitic basalts that are most probably of MORB-type.

Samples 2540584 and 767362 from the uppermost part of Unit O:CPib are classified as volcanic-arc basalt on the Ti/Y *vs* Nb/Y and the Zr/Y *vs* Zr discrimination diagrams or, alternatively, as convergent plate-margin basalt on the Zr/Y *vs* Ti/Y discrimination diagram. The former is probably an intermediate volcanic rock distinguished by the highest Fe/Mg ratio in the Indian Brook tholeiite suite (Table 1; Figure 6A); whereas, the latter is a tholeiitic picrobasalt of pos-

Table 1. Major-element and trace-element data obtained from rocks of the Indian Brook and Long Pond formations in the southwest of the study area, and selected rocks of the Hammerdown basalt located farther northeast. Analytical results for 20205-20291 inclusive (ICP-MS Aqua Regia and ICP-ES Borate Fusion-Acid Digestion in Moore *et al.*, 2002), 25122-25132 inclusive (ICP-AES, NA-DC Plasma and XRF in Andrews, 1991) and 1542288-2540623 inclusive (ICP-OES Borate Fusion-Acid Digestion by the Geological Survey laboratory reported herein). Limits of detection from Acme Analytical, Bondar-Clegg and the Howley laboratories are indicated

lab number	Unit of	Acme	20205	20263	20265	20286	20287	20291	25431	Bondar	25122	25131	25132	Howley	1542288	1542312
belt_unit	measure	Analytical	HD	HD	HD	HD	HD	HD	HD	Clegg	HD	HD	HD	Lab	HD	HD
E_UTM		detection	524323	553483	553214	555098	555042	555241	555452	detection	557302	557826	557408	detection	558365	558344
N_UTM		limit	5489679	5487670	5487493	5489291	5489405	5489610	5490270	limit	5490368	5487687	5488007	limit	5486780	5486895
SiO2	%	0.01%	48.14	44.22	46.82	47.66	45.56	43.21	51.82	0.01%	47.28	44.74	47.82	0.01%	48.450	49.670
Al2O3	%	0.01%	13.21	16.20	15.82	15.48	13.87	13.75	14.55	0.01%	17.29	14.14	15.17	0.01%	16.850	14.490
FeO	total %	0.04%	13.21	10.69	8.74	8.82	11.74	7.50	9.75	0.01%	9.16	10.65	11.29	0.01%	10.280	12.440
MgO	%	0.01%	7.01	7.74	5.51	8.01	7.26	8.30	8.46	0.01%	5.95	5.41	6.45	0.01%	6.240	6.840
CaO	%	0.01%	9.49	10.54	7.32	11.31	11.99	12.86	7.28	0.01%	8.22	12.54	10.61	0.01%	13.010	9.700
Na2O	%	0.01%	3.29	3.10	4.96	2.69	2.87	4.07	3.67	0.01%	4.22	1.86	2.83	0.01%	2.890	4.360
K2O	%	0.01%	0.39	0.14	0.61	0.09	0.06	0.13	0.01	0.01%	0.54	0.12	0.13	0.01%	0.210	0.140
TiO2	%	0.01%	1.85	1.39	1.40	0.72	1.88	0.51	0.34	0.01%	1.63	1.82	1.78	0.001%	1.750	2.020
P2O5	%	0.01%	0.11	0.06	0.10	0.05	0.13	0.02	0.03	0.01%	0.14	0.18	0.18	0.001%	0.150	0.160
MnO	%	0.01%	0.15	0.10	0.09	0.10	0.11	0.11	0.11	0.01%	0.11	0.16	0.18	0.01%	0.160	0.190
Cr2O3	%	0.002%	0.010	0.038	0.007	0.036	0.022	0.049	0.038		0.000	0.038	0.042			
LOI	%	0.10%	3.30	5.80	8.90	4.80	4.30	9.30	3.90	0.05%	5.49	8.48	3.61		2.520	5.540
Total	%		100.18	100.04	100.31	99.79	99.81	99.83	99.97		100.14	100.14	100.10			
Au	ppb	0.2 ppb	0.60	1.40	0.40	0.50	1.50	4.40	5.30	1000 ppm						
As	ppm	0.1 ppm	2.00	1.00	1.10	7.00	1.90	1.20	0.70	1 ppm				2 ppm		
Ba	ppm	1 ppm	60.00	28.00	132.00	12.00	14.00	23.00	9.00	15 ppm	75.00		15.00	1 ppm	48.00	64.00
Be	ppm													0.1 ppm		
Bi	ppm	0.02 ppm	0.01	0.01	0.01	0.01	0.01	0.01	0.01	2 ppm						
Cd	ppm	0.01 ppm	0.07	0.07	0.10	0.05	0.06	0.05	0.10	1 ppm				0.1 ppm		
Ce	ppm													1 ppm		
Co	ppm	0.1 ppm	31.70	32.40	28.50	29.80	25.80	25.50	26.50	1 ppm				1 ppm		
Cr	ppm	0.5 ppm	75.80	253.40	47.90	162.40	82.50	289.40	260.03			259.00	287.00	1 ppm	226.00	220.00
Cu	ppm	0.01 ppm	49.86	100.38	4.80	70.41	69.77	71.20	104.53	1 ppm	68.00	78.00	84.00	1 ppm	91.00	99.00
Dy	ppm													0.1 ppm		
La	ppm	0.1 ppm	4.40	3.60	8.50	1.90	4.80	1.40	1.60	1 ppm				1 ppm		
Li	ppm													0.1 ppm		
Mn	ppm	1 ppm	891.00	729.00	945.00	596.00	596.00	849.00	643.00	1 ppm				1 ppm		
Mo	ppm	0.01 ppm	0.11	0.31	0.20	0.18	0.33	0.12	0.16	1 ppm				1 ppm		
Nb	ppm	0.1 ppm	3.80	2.20	4.60	0.80	2.40	0.70	0.80		2.00	3.00	5.00	1 ppm	4.30	4.50
Ni	ppm	0.1 ppm	26.00	55.00	37.50	81.20	34.80	86.60	66.40	1 ppm				1 ppm	76.00	39.00
P	ppm													1 ppm		
Pb	ppm	0.1 ppm	0.73	1.81	0.86	0.96	0.45	0.43	0.18	2 ppm				1 ppm		
Rb	ppm													1 ppm		
Sc	ppm													0.1 ppm		
Sb	ppm	0.1 ppm	0.09	0.07	0.01	0.08	0.05	0.04	0.03	1 ppm						
Sr	ppm	0.5 ppm	218.80	212.00	206.50	129.90	321.50	161.00	93.30	1 ppm	268.00	261.00	228.00	1 ppm	298.00	148.00
Th	ppm	0.2 ppm	0.50	0.05	1.90	0.05	0.05	0.30	0.30	1 ppm						
Ti	ppm													1 ppm		
U	ppm	0.1 ppm	0.20	0.05	0.20	0.20	0.05	0.20	0.05	1 ppm						
V	ppm	8 ppm	336.00	254.00	195.00	229.00	312.00	172.00	234.00	1 ppm				1 ppm	264.00	357.00
Y	ppm	0.1 ppm	33.80	22.50	22.40	15.80	31.30	10.30	8.30		30.00	26.00	26.00	1 ppm	4.00	32.00
Zn	ppm	0.1 ppm	63.30	62.70	74.00	42.80	47.70	34.30	44.90	1 ppm	92.00	84.00	71.00	1 ppm	75.00	118.00
Zr	ppm	0.1 ppm	107.80	70.20	126.50	34.20	118.10	23.10	22.10		114.00	118.00	117.00	1 ppm	110.00	131.00

sible back-arc basin origin (Figure 6B; *see* below). Most mafic volcanic strata in the Indian Brook Formation have Zr/Y values greater than 3 and could thus be interpreted as rocks that erupted within a continental arc (Pearce, 1983).

Although there has been some secondary hematization and jasperitization of pyritic basalt in the upper part of the Indian Brook Formation, mineralized black chlorite–schist zones have not been recognized in the type area. Thus, some iron and silica may have been locally mobilized during alteration or metamorphism of this formation; however, the rare-earth element contents of the Indian Brook basalts (*see* below) were probably much less affected.

Rare-Earth Element Data for Volcanic Rocks from the Indian Brook Formation

Five samples of mafic volcanic rocks from the type area of the Indian Brook Formation of the Catchers Pond Group were previously analyzed for their rare-earth element (REE) content (Moore *et al.*, 2002; *see* Table 2). For comparison, a rock sample previously collected from the Lushs Bight Group northeast of the Rendell-Jackman copper prospect and having known REE values is included within this table (sample 1542237; Kean *et al.*, 1995).

Table 1. Continued

2540554	2540567	2540575	2540581	2540584	2540587	2540588	2540597	2540601	2540608	767362	2540585	2540594	2540598	2540621	2540623
HD	HD	HD	HD	IB	IB	IB	IB	IB	IB	IB	LP	LP	LP	LP	LP
554035	556341	555428	557217	553402	552992	553259	551621	550133	550036	555262	552729	554674	551126	553888	553529
5488407	5490481	5490790	5488426	5482591	5481889	5481602	5482786	5480457	5479894	5482831	5484120	5483213	5482173	5485533	5485066
47.02	49.23	47.56	58.85	55.49	48.71	47.75	51.79	53.22	56.68	44.68	62.33	49.63	55.37	49.75	48.95
17.99	15.43	13.76	15.80	13.08	15.01	13.66	16.29	14.09	16.37	15.10	14.64	14.74	15.29	16.76	19.10
13.20	9.94	12.78	8.15	7.91	11.50	12.92	7.71	11.60	8.82	10.26	6.69	9.89	10.38	10.07	12.82
5.66	8.62	6.38	3.16	2.30	6.76	6.81	4.30	3.99	4.17	6.03	2.67	7.49	7.51	5.51	5.67
8.24	9.56	5.18	3.81	6.74	5.43	11.19	5.63	4.79	4.44	7.30	1.42	4.57	0.14	3.79	2.39
2.60	3.26	3.75	4.54	5.87	5.24	3.01	6.90	5.98	6.75	4.83	4.82	4.85	5.05	6.12	5.43
0.06	0.06	0.04	0.52	0.03	0.12	0.16	0.03	0.03	0.12		1.88	0.17	0.02	0.60	1.03
0.953	0.835	1.230	0.995	1.129	1.800	1.740	0.962	1.758	0.989	0.950	0.770	0.892	0.395	0.862	0.994
0.118	0.053	0.087	0.165	0.139	0.148	0.143	0.149	0.167	0.123	0.100	0.209	0.072	0.014	0.138	0.090
0.197	0.135	0.160	0.143	0.159	0.185	0.205	0.218	0.209	0.109	0.380	0.106	0.203	0.143	0.217	0.221
3.83	2.71	7.76	3.32	5.98	3.56	1.41	6.17	4.68	1.74	10.15	3.03	7.23	4.85	5.52	3.47
99.86	99.83	98.70	99.44	98.82	98.48	99.01	100.15	100.51	100.31	99.79	98.57	99.74	99.16	99.34	100.16
3	3	4	4	6	3	2	3	3	3		3	5	6	4	4
17	19	15	135	20	36	29	45	30	54		268	41	13	85	169
				0.4	0.1		0.3	0.3	0.8		0.8	0.1	0.2	0.4	0.2
0.8	0.4	0.6	0.3	0.4	0.5	0.6	0.5	0.4	0.3		0.2	0.5	0.5	0.5	0.4
				9	11	9	9	11	23		27	6	3	12	14
31	39	41	26	14	47	48	25	32	24	66	14	34	20	32	34
8	229	40	8	2	174	137	11	22	4	65	3	75	99	20	7
35	11	41	12	31	4	56	16		4		5	135	69	133	80
				4.8	5.6	5.7	3.1	5.6	2.9		2.7	2.8	0.3	3.1	3.0
4	1		13	4	4	3	6	5	8		12	3		6	6
				4.1	7.3	4.3	5.1	3.4	2.4		5.9	8.3	4.0	9.7	11.0
1355	983	1168	1078	1157	1327	1432	1559	1481	821		857	1456	1085	1573	1579
										3					
9	7	9	11	7	10	9	7	11	8		9	8	9	10	12
9	52	17	4	2	33	29	6	8	3			16	17	11	5
				606	622	589	626	711	524		920	307	68	591	389
3													3		
					9	9	7	8	5		29	7	4	9	14
				24.2	46.0	48.0	31.7	32.2	28.1		22.1	35.9	46.8	34.2	40.2
341	150	94	221	92	148	184	124	92	179	84	111	179	50	103	169
				6739	9628	9866	5759	9630	5631		3741	5328	1761	5210	6130
371	261	340	162	204	310	313	218	276	225		87	253	329	248	327
15	17	19	30	28	30	31	16	30	17	18	16	15	2	17	15
98	58	107	77	79	66	92	76	62	31	223	95	131	432	163	94
50	37	58	168	83	102	105	71	129	88	53	114	50	25	69	65

The concentrations of the suite of REEs from La to Yb have been normalized to primitive mantle (*cf.* Sun and McDonough, 1989) and presented along with the normalized values of the incompatible trace elements Th and Ti and the transition metals Nb, Zr and Y. Their relative abundances are illustrated in the extended REE plot shown in Figure 7. In this paper, most of the heavy rare-earth elements (HREE) Tb, Dy, Ho, Er, Tm, Yb and Lu are plotted with Y on the right side of the diagram; whereas, most of the light rare-earth elements (LREE) La, Ce, Pr, Nd, Pm, Sm, Eu and Gd are plotted from the left in order of increasing atomic number, excluding Sc.

As seen on the diagram in Figure 7, rocks from the Indian Brook Formation display a relatively flat slope through the HREE and a flat to slightly positive slope from Gd to Eu. These parts of the REE patterns are similar to those of island-arc tholeiite (IAT) or normal mid-ocean ridge basalt (N-MORB). They do not show the distinctive Eu to La LREE enrichment that is characteristic of calc-alkaline basalt (CAB) nor the overall positive REE slope of ocean-island basalt (OIB).

Located in the type area of the Indian Brook Formation near Indian Brook Pond, sample 20153 shows a relatively strong LREE-depleted pattern and a prominent negative slope from La to Th. It is generally similar to Sun and McDonough’s (1989) modern example of a normal mid-ocean ridge basalt (average N-MORB; Figure 7). Other samples from the Indian Brook Formation illustrate variably developed positive Th and negative Nb anomalies relative to La, and thus indicate a weak volcanic island-arc signal in the extended REE plot.

Sample 20419 displays a slightly negative LREE slope, a very weak Th–Nb anomaly, and a ratio of Th/La much less

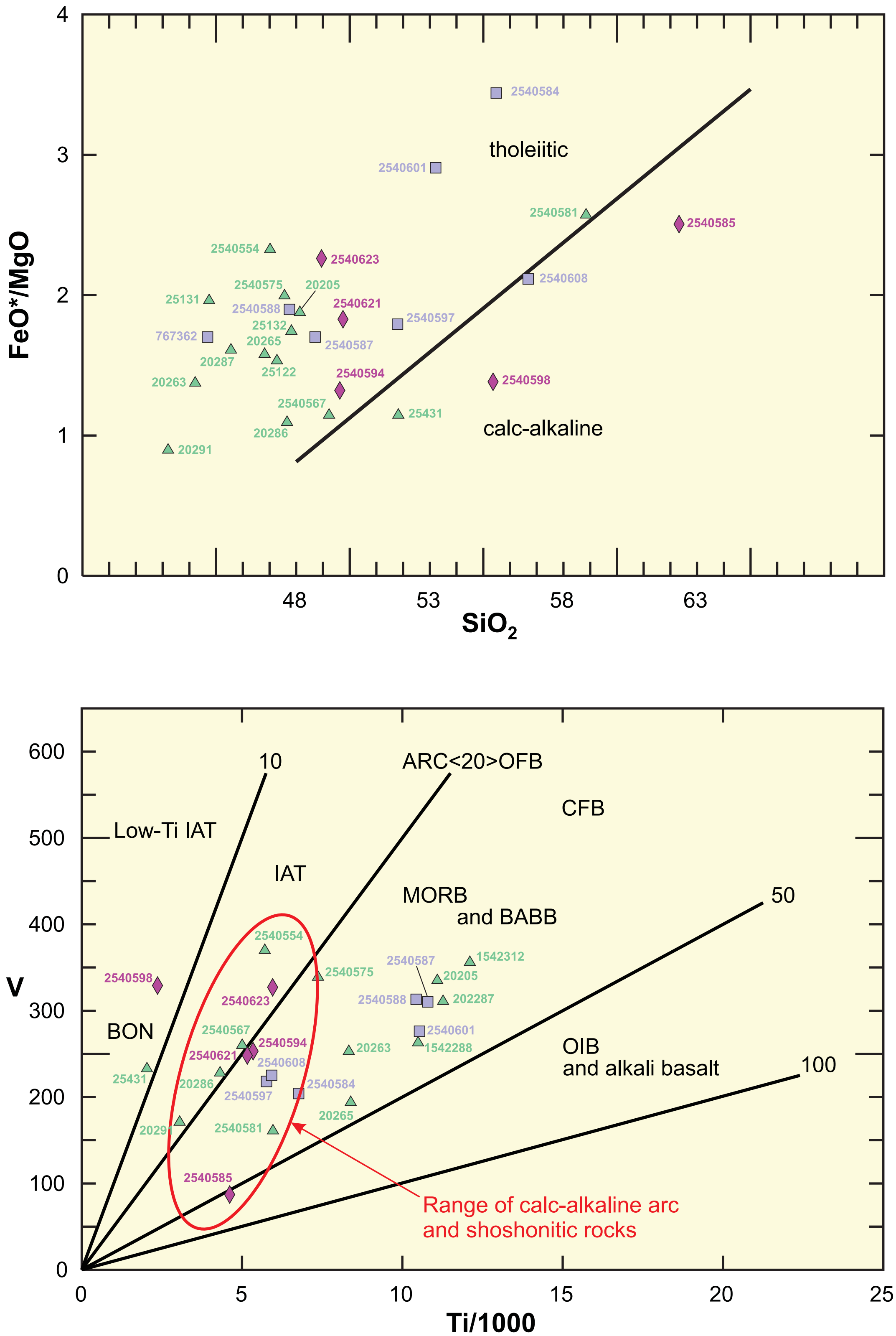


Figure 6A. *Classification plot showing the FeO* (total Fe)/MgO ratio* versus *SiO_2 (weight percent) diagram of Miyashiro (1974) and a geotectonic discrimination diagram by Shervais (1982) employing the V* versus *Ti/1000 ratio. Sample numbers from rocks of the Indian Brook and Long Pond formations of the Catchers Pond Group are blue and purple, respectively. The green sample numbers represent rocks from the Hammerdown volcanic belt.*

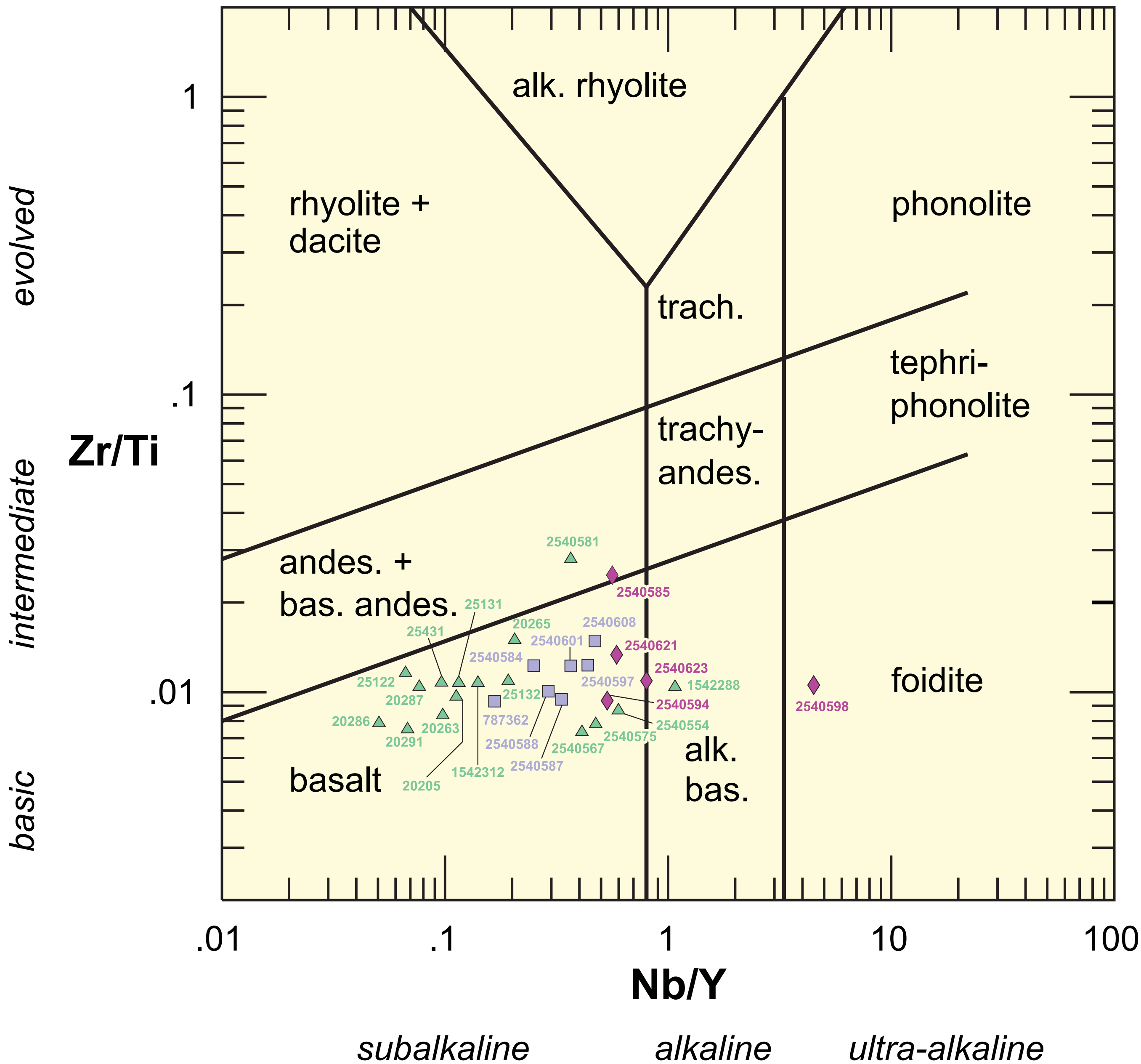


Figure 6B. *The log Zr/Ti versus log Nb/Y lithogeochemical classification plot, as modified by Pearce (1996), showing the sample numbers of rocks from the Hammerdown volcanic belt in green. These are plotted together with samples from the Indian Brook Formation (blue) and the Long Pond Formation (purple).*

than one. It may be an example of BABB that is transitional to MORB.

Other Indian Brook lavas having a volcanic-arc signal (negative Nb anomaly and ratio of Th/La>1) and displaying a flat to slightly negative LREE slope may represent island-arc tholeiites (IAT). Whereas sample 20097 is a typical island-arc tholeiite, sample 20579 may represent IAT lava that is transitional to a calc-alkaline rock. Containing 57.67% SiO_2 by weight, sample 20579 could be interpreted as a tholeiitic andesite or arc tholeiite from the upper part of the Indian Brook Formation. The postulated Indian Brook IAT flows are relatively LREE-enriched in comparison to the Zr-poor island-arc tholeiite from the Lushs Bight Group (sample 1542237).

LITHOGEOCHEMISTRY OF THE LONG POND FORMATION

Northeast and southwest of Long Pond, the Indian

Table 2. Rare-earth element and Th, Nb, Zr, Ti and Y data obtained from rocks in the type area of the Indian Brook Formation of the Catchers Pond Group. Data re-tabulated from Moore *et al.* (2002). Limits of detection for ICP-MS and ICP-ES analyses are indicated with the exception of elemental Ti (ppm), which was calculated from the value of the weight-percent oxide. Non-determined = n-d

lab number **E_ UTM** **N_UTM**	**detection** **limit** **(ppm)**	**20153** **551605** **5481766**	**20097** **553248** **5481595**	**20419** **553434** **5481515**	**20579** **554795** **5482527**	**20158** **554921** **5482275**	**1542237** **560254** **5490225**
Th	0.2	0.2	0.6	0.4	0.8	0.6	0.28
Nb	0.1	2.5	2.5	2.9	2.4	1.9	1
La	0.1	4.5	3.8	5.8	3.6	3.2	1.91
Ce	0.1	14.2	12.9	16.9	10.7	8.3	5.6
Pr	0.02	2.58	2.13	2.56	1.63	1.41	0.88
Nd	0.3	12.8	11.3	14.9	8.2	6.6	4.75
Pm		n-d	n-d	n-d	n-d	n-d	n-d
Sm	0.05	4.3	3.5	3.6	1.9	2.2	1.84
Zr	0.1	114.8	99.1	135.8	64.8	56.7	27
Eu	0.02	1.81	1.5	1.68	0.82	0.95	0.76
Ti		11331	10791	11331	5815	6475	5216
Gd	0.05	5.96	4.8	6.02	3	2.83	2.57
Tb	0.01	0.95	0.84	1.01	0.47	0.5	0.52
Dy	0.05	6.44	6.02	6.91	3.28	3.32	3.82
Y	0.1	35.9	31.2	38.9	18.8	18.4	21
Ho	0.02	1.42	1.33	1.44	0.76	0.77	0.87
Er	0.03	4.37	3.76	4.17	2.05	2.25	2.46
Tm	0.01	0.65	0.57	0.63	0.3	0.31	0.35
Yb	0.05	3.93	3.36	4.27	2.17	2.03	2.43
Lu	0.01	0.58	0.5	0.65	0.35	0.32	0.36

Brook Formation is observed to be succeeded by a distinctive sequence of basaltic, andesitic, dacitic and rhyolitic flows and related pyroclastic strata. These have been assigned to the Long Pond Formation (O:CPlp), which comprises a relatively thin but widespread marker unit in the western and southern parts of the Catchers Pond Group.

The mafic to intermediate volcanic rocks sampled in the type area of the Long Pond Formation comprise lavas of tholeiitic and calc-alkaline affinity (Miyashiro, 1974; Figure 6A). Subalkaline basalt and basaltic andesite are represented (Pearce, 1996; Figure 6B). Sample 2540594 is a tholeiitic basalt flow located near the site of a quartz–feldspar crystal tuff that provides the new U/Pb zircon age for the Long Pond Formation reported herein.

Sample 2540598 is a Fe-poor intermediate volcanic rock that falls in the field of island-arc tholeiite (low-Ti IAT) on the V–Ti/1000 geotectonic diagram (Shervais, 1982; Figure 6A). Moreover, this rock would also plot in the field of low-K arc tholeiite on a Ti *vs* Zr diagram. Sample 2540585 is one of two calc-alkaline rocks collected from the Long Pond Formation (Figure 6A). It is a basaltic andesite (Figure 6B) that has a ratio of Nb/Y higher than the older Indian Brook lavas but similar to the other analyzed rocks from this part of the Catchers Pond Group. When plotted on the V–Ti/1000 diagram (Figure 6A), sample 2540585 occurs within the overlapping fields of the ocean-floor basaltic rocks (OFB) and the calc-alkaline arc and shoshonitic rocks.

Samples 2540623, 2540621 and 2540594 are subalkaline basalts of tholeiitic affinity from the Long Pond Formation (Figures 6A and 6B). Sample 2540623 is a Fe-rich island-arc tholeiite (normal IAT; Figure 6A) that is generally similar to Szybinski's (1995) Type A-2e group of medium-K arc tholeiites from the Catchers Pond Group. Samples 2540594 and 2540621 are tholeiitic basalts that appear to be transitional between MORB or BABB and IAT. However, without corroborative REE data for the Long Pond Formation, it should be emphasized that, given a similar Ti value, the highly varying V and Si content of the interstratified basaltic and andesitic lavas permits certain IAT to fall within the BABB–MORB field and allows other within-plate tholeiites to plot as transitional alkali basalt.

LITHOGEOCHEMISTRY OF THE HAMMERDOWN VOLCANIC BELT

On Miyashiro's (1974) FeO*/MgO–SiO_2 diagram, thirteen rocks in the Hammerdown volcanic belt fall in the

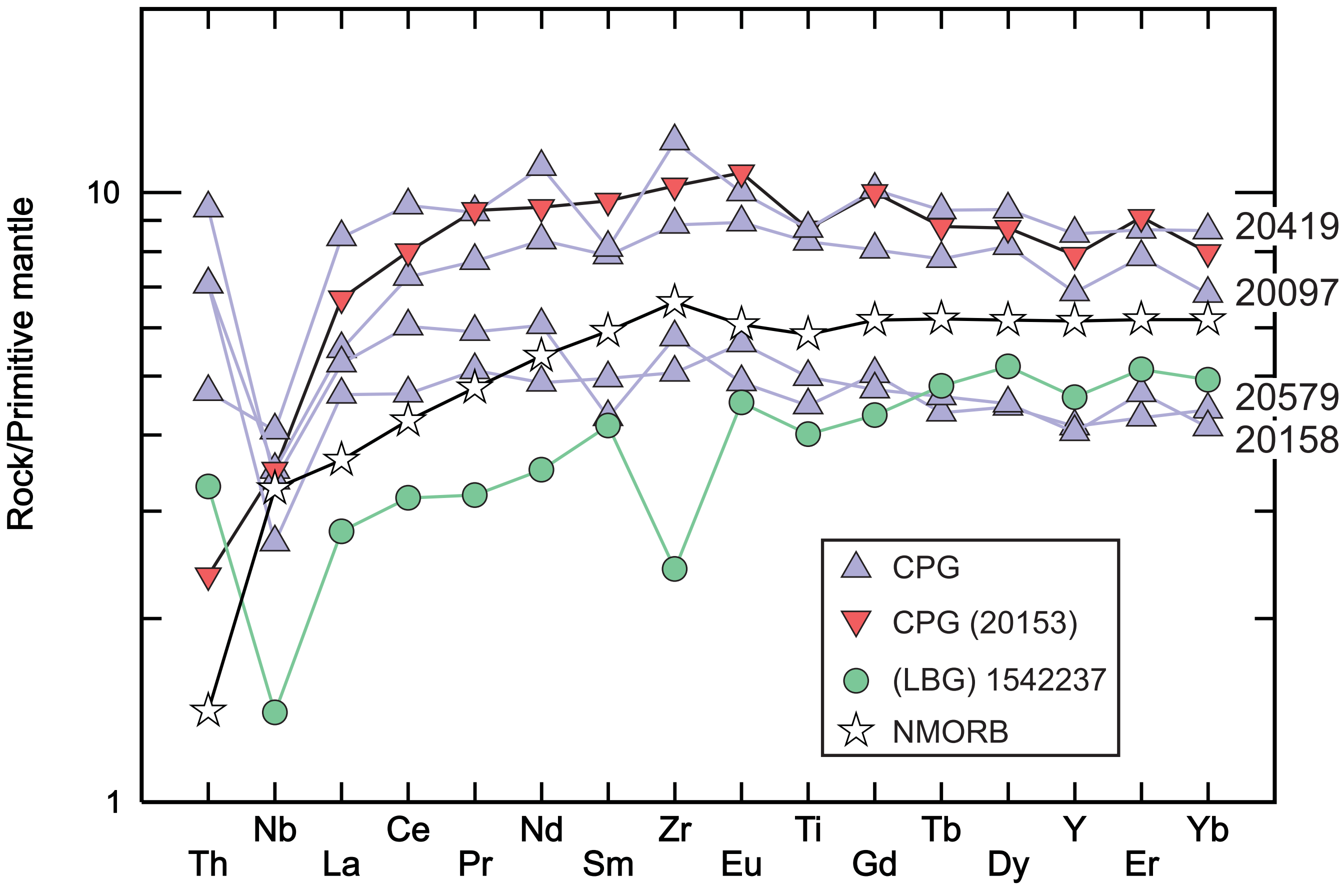


Figure 7. *Extended rare-earth element plot having concentration values normalized to primitive mantle (*cf. *Sun and McDonough 1989; Table 2). Samples 20419, 20097, 20579, 20158 and 20153 come from the type area of the Indian Brook Formation (Figure 4); pattern in open black stars is average N-MORB from Sun and McDonough (1989). A rock sample (green) from the Lushs Bight Group (situated northeast of the Rendell-Jackman prospect) is included for comparison.*

tholeiite field and most of them make up a relatively Fe-rich volcanic suite (Figure 6A). However, one of the constituent basalts (sample 25431) appears to be calc-alkaline in character and is richer than most in Mg. Samples 20263 and 20291 are probably tholeiitic picrobasalts (Table 1), situated northwest of mineralized Catchers Pond felsic volcanic rocks at the Rigel and Lochinvar prospects. On the geological map of the Indian River–King's Point area (O'Brien, 2012), such volcanic strata have been assigned to various lithostratigraphic subdivisions of the Catchers Pond Group and the Western Arm Group (Figure 5).

Subalkaline basalts, which comprise the majority of rocks that were sampled in the southwestern part of the Hammerdown volcanic belt, have been identified in this report solely on the basis of the presumed constant ratios of the immobile trace elements Zr, Ti, Nb and Y (Figure 6B). One subalkaline flow of basaltic andesite (sample 2540581) is also discriminated using this classification diagram; the unit in which the sample occurs lies structurally above the mineralized felsic volcanic strata (O:CP wwfu) outcropping near Beetle Pond (Figure 5). One outlier sample (1542288) plots in the alkali basalt field on Figure 6B due to an unusually low Y value, although this sample would also plot as subalkaline basalt on a SiO_2 versus Zr/TiO_2 diagram.

The above-mentioned basaltic andesite in the Hammerdown volcanic belt plots within the field of MORB and BABB lavas on Figure 6A; it also falls in the range of calc-alkaline arc-related rocks. In addition to this rock, other basalts in the Hammerdown suite might be also classified as transitional IAT–MORB rocks (*e.g.*, *see* samples 2540567 and 20286 on both illustrations in Figure 6A). Such lavas are discriminated as back-arc basin basalts on other geotectonic diagrams (*e.g.*, Cabinis and Lecolle, 1989).

One pillowed subalkaline flow (sample 25431) of Ti-poor island-arc tholeiite (low-Ti IAT) was recognized along Harry's Brook within the Hammerdown volcanic belt. Geochemically similar rocks have been previously recognized in the northern (Cambrian) part of the Lushs Bight Group (Szybinski, 1995) and in the southern (Ordovician) part of the Catchers Pond Group, although there they are generally more V-rich (*e.g.*, sample 2540598 in Figure 6A; *also* Jenner and Szybinski, 1987). Several normal island-arc tholeiites (normal IAT) in the Hammerdown volcanic belt (samples 2540554, 2540567, 20286 and 20291) are seen to overlap with those from the type area of the Long Pond Formation of the Catchers Pond Group.

Most Hammerdown tholeiites plot as MORB or BABB on a V–Ti/1000 geotectonic diagram; many of these rocks overlap with the Ordovician tholeiitic lavas from the Indian Brook Formation on this illustration (Figure 6A). Certain high-iron tholeiitic basalts in the Hammerdown volcanic belt are also relatively enriched in titanium (*e.g.*, >11 000 ppm Ti in sample 20205). Such rocks are notably magnetic over several kilometres of strike length and demarcate subunits of the Western Arm Group.

GEOCHEMICAL COMPARISON

On the geotectonic plot illustrated in Figure 6A, analytical results of eleven samples from the southern part of the Catchers Pond volcanic belt were superposed with those of thirteen samples from the Hammerdown volcanic belt. On this diagram, sixteen samples of the stratified rocks fall within the combined field of MORB and BABB, which are equally represented in both belts. Basalt samples from the Hammerdown volcanic belt display a tholeiitic trend on a TiO_2 *versus* FeO*/MgO diagram.

Most basalt and andesite flows in the structurally lowest portion of the Hammerdown volcanic belt and the stratigraphically lower part of the Catchers Pond Group overlap in the tholeiite field (22 samples in Figure 6A). Some of these tholeiites are within-plate basalts, especially the N-MORB pillow breccias in the Indian Brook Formation. However, arc tholeiites (normal and low-Ti IAT) are also present in several places within the Hammerdown volcanic belt (5 samples) and in the type area of the Long Pond Formation (2 samples). Those in the Hammerdown volcanic belt have relatively low Zr/Ti ratios and appear to form two populations on the Pearce diagram (Figure 6b).

One group distinguished by relatively low Nb/Y ratios, and including normal IAT lavas, samples 20286 and 20291 (*see* Figure 6A), does not show any overlap with samples from the Catchers Pond Group. A second group, having higher Nb/Y ratios and including normal IAT lavas, samples 2540567 and 2540554, illustrates significant overlap with the Ordovician rocks. In particular, the basalt exposure in the Indian Brook Formation labelled as providing samples 2540588 and 20097 (Figure 4) displays an extended REE pattern typical of island-arc tholeiite (Figure 7) and belongs to the second group.

Subalkaline basalts from the Long Pond Formation display Nb/Y ratios that are generally higher than those in the Hammerdown belt or the Indian Brook Formation. However, basaltic andesite from the Long Pond Formation has a similar Zr/Ti ratio as the sample from the Hammerdown volcanic belt.

Island-arc-related lavas are thought to characterize the 'less refractory' arc tholeiite sequence developed in the mid to upper part of the Lush Bight Group (Figure 25A of Kean *et al.*, 1995), although the depositional age of this particular sequence is contentious. Most of the iron-rich tholeiitic basalts and island-arc tholeiites found in the Hammerdown volcanic belt have FeO* values and FeO*/MgO ratios that are distinct from the low-K, low-Ti, LREE-depleted arc tholeiite sequence present in the older parts of the Lushs Bight Group (*e.g.*, LOTI lavas; Kean *et al.*, 1995).

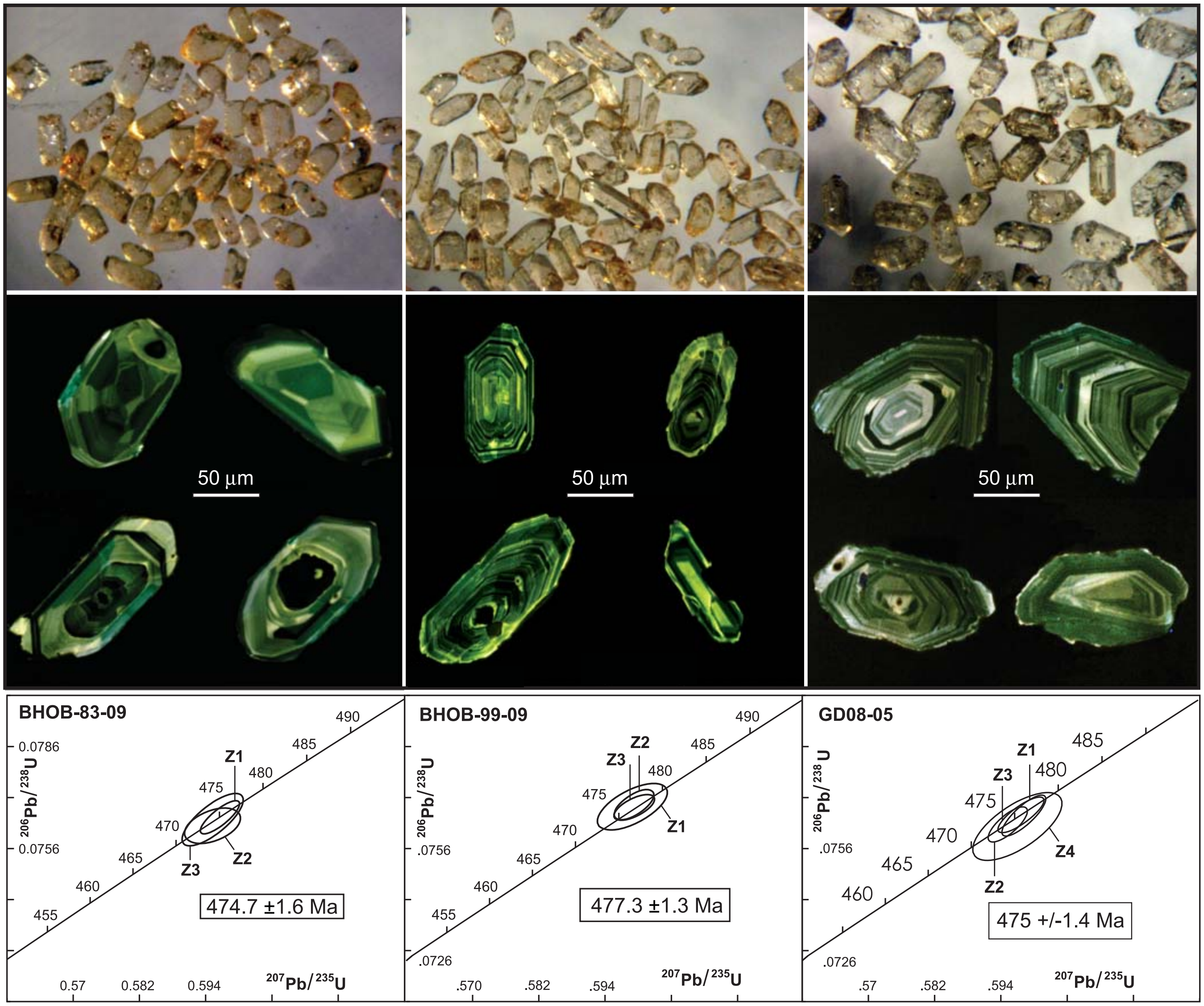
The Hammerdown basalt flows discussed herein probably correspond to two of the lithotectonic divisions previously recognized near the Hammerdown gold deposit (Gaboury *et al.*, 1996). These are a relatively extensive unit of high-Mg pillowed lavas of IAT composition and a structurally underlying mafic volcanic unit of petrochemically-related pyroclastic strata, mainly composed of normal mid-ocean ridge basalt (fragmental N-MORB).

U–Pb CA–TIMS GEOCHRONOLOGY

The U–Pb ages were determined for three samples using the chemical abrasion thermal ionization mass spectrometry method (Figure 8, Table 3); 1 – a stratified felsic extrusive rock (BHOB-99-09) from the Catchers Pond Group near West Waters Pond bottom, 2 – a crosscutting felsic intrusive rock (BHOB-83-09) hosted by the Catchers Pond Group (and the Lushs Bight Group) near Catcher's Pond, and 3 – the youngest dated felsic extrusive rock (GD-08-05) in the Catchers Pond Group, which contains limestone blocks in the vicinity of Silver Pond. In addition, the age of the previously published 480 +4/-3 Ma felsic tuff collected near the Hammerdown trenches [E554417 N5488581, Ritcey *et al.*, 1995] was reassessed, re-calculated as the weighted average of the $^{207}Pb/^{206}Pb$ ages.

Samples were crushed and processed through mineral separation using standard procedures with heavy liquids and a Frantz magnetic separator. The coarse-grained zircon in these samples contains well-developed igneous growth zoning, with layers of high and low luminescence that suggest some complexity in the crystallization history, possibly due to new magma influxes (Figure 8).

Zircon grains were selected for analysis according to criteria of mineral clarity, euhedral form and lack of inclu-



CATCHERS VALLEY GRANITE
[Unit Os:cg]: quartz-feldspar porphyry

Upper LONG POND FM.
[Unit Os:CPlp]: crystal tuff

Upper NEW WATERS POND FM.
[Unit O:CPnwf]: crystal-lithic tuff

Figure 8. *Concordia diagrams illustrating plots of U/Pb isotopic ratios determined by the CA-TIMS method. Data obtained from zircons in samples BHOB-83-09 [E556885 N5485549], BHOB-99-09 [E554637 N5483260] and GD-08-05 [E554821 N5484931] from Early Ordovician rocks in the Catchers Pond Group. Photographs of zircon grains were taken under natural light (top) and thermoluminescence (middle). Bar scale is 50 microns (50 µm) long.*

sions. All grains were annealed at 950°C for 36 hours, and then subjected to chemical abrasion in concentrated HF acid at 200°C to remove radiation-damaged domains, following the procedure of Mattinson (2005).

FELSIC CRYSTAL TUFF SOUTH OF WEST WATERS POND (BHOB-99-09; E554637 N5483260)

This sample contains zircon with straightforward obvious simple igneous growth zoning, and the data are simple; 3 concordant overlapping points yield an age of 477.3 ± 1.3 Ma (95% Confidence Interval (CI), MSWD= 0.059).

QUARTZ–FELDSPAR PORPHYRY SOUTH OF CATCHERS POND (BHOB-83-09; E556885 N5485549)

Three overlapping concordant points from analysis of 3 or 4 zircon grains yield a weighted average ^{206}Pb–^{238}U age of 474.7 ± 1.6 Ma (95% CI, MSWD= 0.38).

FELSIC CRYSTAL-LITHIC TUFF WEST OF SILVER POND (GD08-05; E554821 N5484931)

Zircon grains in this sample are of high quality, with fine-scale growth zones, with some zones corroded and new

Table 3. U–Pb data for a felsic crystal tuff from the Long Pond Formation (Unit *O:CPlp*) south of West Waters Pond (BHOB-99-2009), a felsic crystal-lithic tuff from the New Waters Pond Formation (Unit *O:CPnwf*) west of Silver Pond (GD-08-05), and a quartz–feldspar porphyry intrusion from the Catchers Valley Granite (Unit *OS:cg*) south of Catcher's Pond (BHOB-83-09)

		Concentration		**Measured**		**Corrected Atomic Ratios ***							**Age [Ma]**		
Fraction	**Weight [mg] (a)**	**U [ppm]**	**Pb rad [ppm] (b)**	**total common Pb [pg]**	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	**+/-**	$\frac{^{207}Pb}{^{235}U}$	**+/-**	$\frac{^{207}Pb}{^{206}Pb}$	**+/-**	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$
OB-99-09 Crystal tuff from the upper Long Pond Formation (E554637 N5483260)															
Z1 5 clr 3:1 prm	0.007	489	38.6	12	1444	0.1376	0.07683	56	0.5989	52	0.05654	40	477	477	474
Z2 4 clr 3:1 prm	0.006	924	72.4	9.1	2941	0.1286	0.07689	36	0.5992	30	0.05652	22	478	477	473
Z3 2 clr 3:1 euh prm	0.003	789	62.3	5.3	2189	0.1368	0.07681	30	0.5993	30	0.05659	22	477	477	476
OB-83-09 Quartz-feldspar porphyry from the Catchers Pond Granite (E556885 N5485549)															
Z1 4 sml 3:1 prm	0.004	468	40.2	2.8	3281	0.2472	0.07652	40	0.5966	28	0.05655	18	475	475	474
Z2 4 sml 3:1 prm	0.004	227	18.6	3.3	1349	0.1964	0.07627	42	0.5952	42	0.05660	38	474	474	476
Z3 3 sml prm	0.003	697	59.9	3.2	3162	0.2501	0.07645	62	0.5953	46	0.05647	32	475	474	471
GD08-05 Crystal-lithic tuff from the upper New Waters Pond Formation (E554821 N5484931)															
Z1 3 med prms	0.004	305	23.8	1.6	4084	0.1273	0.07659	42	0.5976	34	0.05659	20	476	476	476
Z2 5 med prm	0.007	255	19.9	0.9	9906	0.1328	0.07631	42	0.5952	30	0.05657	20	474	474	475
Z3 5 prm	0.007	442	34.6	1.2	13676	0.1323	0.07657	50	0.5981	32	0.05665	22	476	476	478
Z4 3 prm	0.004	193	15.0	1.9	2165	0.1315	0.07625	82	0.5970	66	0.05678	50	474	475	483

Notes: Z=zircon, 2, 3=number of grains, clr=clear, prm =prism, euh=euhedral, sml =small.
All zircon was chemically abraded (cf. Mattinson, 2005). (a)Weights were estimated, (b)radiogenic lead.
* Atomic ratios corrected for fractionation, spike, laboratory blank of 1-2 picograms of common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 0.5-1 picogram U blank. Two sigma uncertainties are reported after the ratios and refer to the final digits.

zones overgrowing them, as is common in rhyolite. Four analyses are all concordant and mutually overlapping and yield a weighted average ^{206}Pb–^{238}U age of 475 ± 1.4 Ma (95% CI, MSWD= 0.038).

FELSIC TUFF WEST OF HAMMERDOWN (SV-2, E554417 N5488581)

The result of this sample was published in 1995 with an age calculated by linear regression as 480 +4/-3 Ma with a lower intercept of 30 ± 30 Ma. As the line goes through zero, it is reasonable to re-calculate the age, using ISOPLOT, as the weighted average of the ^{207}Pb/^{206}Pb ages of the 6 clustered co-linear analyses. This gives 479 ± 2 Ma (95% CI, MSWD=0.32), which should replace the previously published age as the best estimate of the age of eruption of this unit.

BIOSTRATIGRAPHIC AND CHRONOSTRATIGRAPHIC AGE OF THE MIDDLE CATCHERS POND GROUP (NEW WATERS POND FORMATION)

In the area north of the Indian River, the rocks of the Indian Brook and Long Pond formations are succeeded by volcanic and sedimentary strata belonging to the ignimbrite- and argillite-bearing West Waters Pond Formation (Unit O:CP ww) and the crystal ash tuff- and carbonate-bearing New Waters Pond Formation (Unit O:CP nw) of the middle Catchers Pond Group (O'Brien, 2012; Figure 5). The youngest exposed strata in the Catchers Pond succession have been assigned to the overlying Silver Pond Formation (Unit O:CP sp).

In the type section along the shore of Silver Pond (Figure 5), strata in the uppermost preserved part of the Catchers Pond Group are observed to be crosscut by an intrusion of Early Ordovician quartz–feldspar porphyry that has been dated herein. Felsic pyroclastic breccias lying above the ferruginous chert and andesite of the Silver Pond Formation contain outsized epiclastic blocks derived from several underlying formations within the middle part of the Catchers Pond Group.

All of the known fossil localities in the Catchers Pond Group are situated in the middle part of the stratigraphic column, occurring within the New Waters Pond Formation well above the underlying strata of the West Waters Pond Formation. Such fossil-bearing horizons have yielded abundant early to mid Arenigian trilobites, brachiopods and conodonts (Dean, 1970; Boucot, 1973; O'Brien and Szybinski, 1989). The fossils in the New Waters Pond Formation are found in discontinuous carbonate lenticules within the oldest member of andesite and pillowed basalt (Unit O:CP nwb), within an intermediate member of bedded bioclastic limestone (Unit O:CP nwl), and within ribboned limestone lying immediately below a laminated iron formation and the uppermost member of quartz–feldspar tuff (Unit O:CP nwf).

Several of the New Waters Pond limestone beds contain identifiable conodont species that belong to two successive biostratigraphic zones (O'Brien and Szybinski, 1989). These authors confirmed the local presence of the Lower Ordovician *Prioniodus elegans* Zone (early Arenig or Moridunian; Fortey *et al.*, 1995) and the Middle Ordovician *Oepikodus evae* Zone (mid Arenig or Whitlandian; Fortey *et al.*, *ibid*). The older conodont biozone has recently been interpreted to have an absolute age range between 477.5 and 474.8 Ma; whereas, the younger biozone is thought to extend from 474.8 to 471.8 Ma (Sadler *et al.*, 2009). However, in the Catchers Pond Group, *O.evae* Zone strata cannot be any younger than the quartz–feldspar porphyry dated at 474.7 ± 1.6 Ma.

The Tremadocian–Arenigian boundary, situated at the base of the *Tetragraptus approximatus* graptolite biozone (Fortey *et al.*, 1995), has been considered to have an absolute age at 478.6 ± 1.7 Ma; it is slightly older than the suggested base of the *P. elegans* Zone at 477.5 Ma (Gradstein and Finney, 2007). In the study area, this stratigraphic boundary lies within the lower part of the Catchers Pond Group well below the New Waters Pond Formation (*see* below).

VOLCANISM AND DEFORMATION OF EARLY ORDOVICIAN AGE IN ROCKS OF THE CATCHERS POND GROUP

AGE CONSTRAINTS ON VOLCANISM

In the study area, the oldest known felsic pyroclastic strata occur in the Long Pond Formation of the Catchers Pond Group. The quartz–feldspar tuff (BHOB-99-2009) sampled near the southern end of West Waters Pond (Figure 4) is located in the middle-upper part of this formation and has an igneous zircon crystallization age of 477.3 ± 1.3 Ma (Figure 8; Table 3). The maximum depositional age range for this rock is from 478.6 to 476.0 Ma (95% confidence interval).

A crystal-rich felsic tuff (sample SV-2) from the lower part of the Long Pond Formation (Figure 5) is seen to be interstratified with mafic tuff in exploration trenches west of the Hammerdown deposit. It was collected during an earlier study by the second author and has an igneous zircon crystallization age of 480 +4/-3 Ma (as reported in Ritcey *et al.*, 1995). This age has been recalculated to 479 ± 2 Ma using ISOPLOT and, therefore, 481 to 477 Ma is the maximum allowable period for this pyroclastic eruption.

The youngest stratified volcanic rock in the Catchers Pond Group dated herein is located in the upper part of the New Waters Pond Formation on the west side of Silver Pond (Figures 5 and 6). There, a felsic crystal-lithic tuff (GD-08-05) marked by large limestone blocks has an igneous crystallization age of 475 ± 1.4 Ma (Figure 8; Table 3). The maximum age range of deposition for this rock is from 476.4 to 473.6 Ma, although statistically the time span is likely to be much narrower.

STRATIGRAPHIC IMPLICATIONS

The two dated tuffs from the Long Pond Formation bracket some of the earliest felsic volcanism recorded in the lower Catchers Pond Group. These eruptions were restricted to a time period between *ca.* 481 and 476 Ma. Moreover, the dated tuffs demonstrate that rocks of this broad age and stratigraphic position are found in the northeastern and southwestern parts of the Catchers Pond Group.

As ratified by the International Committee on Stratigraphy, the base of the global Dapingian Stage defines the Middle Ordovician–Early Ordovician boundary. Accepting the absolute age of the Lower Ordovician Tremadocian–Floian boundary at 477.7 ± 1.4 Ma and the base of the Dapingian at 470.0 ± 1.4 Ma (Cooper and Sadler, 2012), Early Ordovician accumulation of the strata comprising the Catchers Pond Group began in the latest Tremadocian–earliest Floian in the Long Pond Formation and possibly earlier in the Indian Brook Formation. The revised Tremadocian–Arenigian boundary of the British Series may, in places, reside within the younger of these two formations.

Within the stratigraphically higher divisions of the Catchers Pond Group, deposition continued throughout the interval between the early and mid-Floian. Generally, this is in agreement with the relatively imprecise age of a felsic crystal tuff reported to be in depositional contact with limestone and basalt of the Catchers Pond Group (479.2 ± 3.6 Ma U/Pb TIMS age on igneous zircon; Silver Pond tuff bed; Szybinski, 1995).

Considering the error limits, the Silver Pond Tuff could be as young as 476.2 Ma. Therefore, though most probably belonging to the Moridunian Stage, it is just possible that this particular horizon in the New Waters Pond Formation may be too young to be correctly assigned to the early Arenigian *P. elegans* Zone. However, based on the suggested *ca.* 475 Ma age (Gradstein and Finney, 2007) for the base of the *O.evae* conodont biozone, it is more likely that the overlying limestone-bearing felsic tuff (475 ± 1.4 Ma) lies within the earliest part of the middle Arenig succession.

Thus, the chronostratigraphic record of deposition within the middle and upper parts of the Catchers Pond Group is, in part, biostratigraphically constrained and corresponds approximately to the time period between the early Moridunian and earliest Whitlandian stages of the Arenig. The accumulation of this Floian succession must have ceased prior to 473.1 Ma, assuming the youngest possible crystallization age for the quartz–feldspar porphyry intrusion. This may be partially corroborated by the precise geochronological age of the youngest dated tuff in the upper part (basal *O. evae* Zone) of the New Waters Pond Formation.

EARLY DEFORMATION OF THE CATCHERS POND GROUP

The youngest preserved strata in the Catchers Pond Group are exposed in a tectonic window lying structurally below several overriding thrust sheets that carry the older rocks of the Catchers Pond Group (Figure 5). This particular window was formed by erosion of a secondary antiformal structure that has an upright to steeply inclined axial surface. The fold, which may have originally been gently northwest plunging in the vicinity of Silver Pond, is portrayed on the northeast–southwest cross-section illustrated in Figure 9.

Rocks assigned to the lower Catchers Pond Group were thrust toward the southwest, structurally imbricated to form a tectonic collage of right-side-up and inverted strata, and emplaced above the rocks of the upper Catchers Pond Group. A regional northwest-trending domal structure is responsible for the open folding of one of the major thrust faults and allied fold nappes within the Catchers Pond Group (Figure 9). On the southwest flank of the tectonic window (secondary antiform) at Silver Pond, the thrust surface changes from its original northeastward dip to being southwesterly inclined.

This fault attitude is prevalent north of the Indian River in the southwestern part of the Catchers Pond Group (Figure 9). There, several internally right-way-up tectonic panels comprise a regionally upside-down lithotectonic sequence in which strata from the lower Catchers Pond Group structurally overlie strata from the middle Catchers Pond Group. This is consistent with the overall tectonic dip of the thrust-bounded horses located between the Pisces and Ursa Minor base-metal prospects (Figure 4). The first author wishes to clarify that, on certain previously published cross-sections of this area (*e.g.*, section BB' *in* O'Brien, 2009; section AA' *in* O'Brien, 2010), the regional sense of thrust displacement

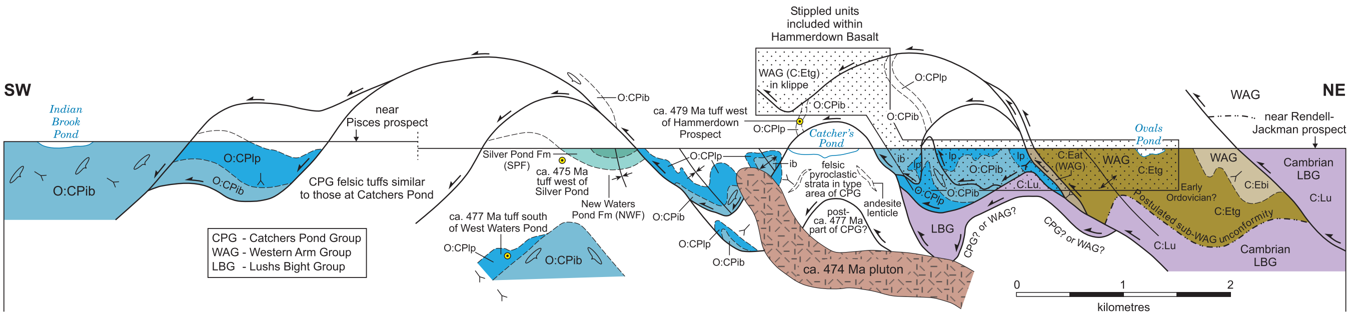


Figure 9. *Northeast–southwest cross-section emphasizing the regional structural disposition of the Indian Brook and Long Pond formations of the lower Catchers Pond Group and their interpreted relationship to rocks of the Western Arm and Lushs Bight groups. Also indicated in the folded imbricate thrust stack are the positions of the youngest exposed formation of the Catchers Pond Group and the various rock units that comprise the Hammerdown volcanic belt. The line of section is shown on Figures 4 and 5. Horizontal scale of the cross-section is identical to that of the accompanying geological maps; vertical scale is exaggerated.*

was incorrectly illustrated on the hanging-wall plate of the early formed fault structures.

The rocks of the Indian Brook Formation occur at depth within the above-mentioned tectonic window and are situated in the core of the same antiform that disposes the felsic tuffs dated herein by U–Pb CA–TIMS (Figures 4 and 9). The type area of the Long Pond Formation occurs slightly northwest of the line of section. However, such strata lie stratigraphically above the N-MORB pillow lavas of the Indian Brook Formation that crop out at Indian Brook Pond and that are illustrated at the southwestern limit of the cross-section. Most of the lithogeochemical samples from the Long Pond Formation are located on the limb of a syncline whose hinge zone was displaced by a thrust fault (Figure 4).

STRUCTURAL SETTING OF THE HAMMERDOWN BASALT

Northeast of the tectonic window near Silver Pond, the overlying folded imbricate thrust stack is thought to root downward into the Hammerdown basalt and the Lushs Bight Group (Figure 9). Northwest-trending antiforms and synforms, similar in scale as the open Silver Pond structure or tighter and smaller in size, are fundamental in controlling the disposition of the various thrust sheets and klippe making up the Hammerdown volcanic belt (Figure 5). Constituent rocks include volcanic strata from the lower Catchers Pond Group, the Western Arm Group and the Lushs Bight Group (Figure 9), some of which have been analyzed and discussed in this report.

These secondary folds caused tectonic depression or uplift of the structural footwall sequence lying beneath the Hammerdown basalt. Erosion of the refolded gently plunging antiform underlying Catchers Pond, for example, facilitated surface exposure of the felsic pyroclastic strata and intercalated andesite lenticles present within the type area of the Catchers Pond Group. It also geographically isolated the folded klippe of the Western Arm Group located northwest of the Lochinvar prospect from the main tract of this rock group, as it simultaneously created a window through the tectonic overburden of the Cambrian Lushs Bight Group.

The thrust fault that lies directly above the rocks of the upper Catchers Pond Group at the northern end of Silver Pond (*see* map view in Figure 5) is interpreted to merge with the sole thrust of the Hammerdown belt (*see* cross-section of stippled rocks in Figure 9). An underlying imbricate fault is also thought to extend beneath the succession of the middle Catchers Pond Group exposed at Catchers Pond and to be folded at depth by the Catchers Pond antiform. If correct, displacement on all these faults must have postdated the accumulation of the dated *ca.* 475 Ma tuff outcropping west of Silver Pond. However, geochronological data are not yet available from metamorphic phyllosilicates in the thrust-related mylonite and associated phyllonite zones to directly determine the age of fault movement.

AGE CONSTRAINTS ON EARLY DEFORMATION

The quartz–feldspar porphyry intrusion dated at 474.7 ± 1.6 Ma south of the Catchers Pond valley is mapped to crosscut some of the early formed thrust faults and fold nappes that are disposed within the antiformal windows at Catchers Pond and Silver Pond (Figures 5 and 9). This porphyry is thus interpreted to constrain the age of the earliest regional deformation of the Catchers Pond Group as well as the initial structural juxtaposition of the Early Ordovician and Cambrian rocks within the Hammerdown volcanic belt.

Considering the age range incorporating errors for the youngest deformed tuff (475 ± 1.4 Ma) and the crosscutting plutonic sheet (474.7 ± 1.6 Ma), the initial southwest-directed movement in the imbricate thrust stack was likely shortlived, occurring during a time interval that was 3.3 Ma or less in duration. This age range is in agreement with the suggested *ca.* 475 Ma age of the main pulse of Taconian II accretion in the metamorphic hinterland of west-central Newfoundland (*cf.* van Staal *et al.*, 2007).

THE LITHOSTRATIGRAPHIC AFFILIATION DEBATE

The original stratigraphic position of the Hammerdown basalt relative to the Cambrian mafic volcanic rocks of the Lushs Bight Group and the Early Ordovician mafic volcanic rocks of the Western Arm and Catchers Pond groups has long been debated. Several interpretations have been previously postulated.

Summarized below, these explanations include: a) Cambrian rocks of the Lushs Bight Group being restricted to the northeast part of the Hammerdown volcanic belt and younger strata of the Catchers Pond Group being disposed farther southwest within the same belt (Andrews, 1991; Figure 3B); b) Ordovician mafic volcanic and sedimentary rocks restricted to the southwest part of the Hammerdown volcanic belt and tentatively correlated with the Catchers Pond Group rather than the underlying Western Arm Group (Unit Ov and Unit Ot of Kean and Evans, 1994); c) Cambrian basalt flows from the lower Western Arm Group (*cf.* Szybinski, 1995) comprising the southwestern part of the Hammerdown volcanic belt together with mafic volcanic rocks assigned to an undated part of his Catchers Pond sequence of the Western Arm Group (Mistaken Pond Panel; *ibid*); d) small allochthonous slices of the Lushs Bight Group situated near the southwestern boundary of the Hammerdown volcanic belt being thrust-faulted above the regionally upside-down rocks of the Western Arm Group (Szybinski, 1995); e) a major tectonic boundary near the Hammerdown gold deposit separating the Cambrian Lushs Bight Group in the northwestern part of the Hammerdown volcanic belt from underlying exotic slices of calc-alkaline basalt locally present along the southeast boundary of the belt (Gaboury *et al.*, 1996); and f) all mafic extrusive and intrusive rocks in the Hammerdown volcanic belt situated northeast of the presumed Ordovician felsic pyroclastic strata (and andesite lenticles) in the vicinity of Catchers Pond being assigned to the Cambrian Lushs Bight Group (Moore *et al.*, 2002; Figure 3A).

IMPLICATIONS OF PURPORTED STRATIGRAPHIC CORRELATION

Correlation of most volcanic rocks present in the Hammerdown volcanic belt with those observed in the Indian Brook and Long Pond formations of the Catchers Pond Group is supported by the precise geochronology, lithogeochemical fingerprint and structural disposition of these Ordovician lava flows (Figure 5). A corollary of this assertion is that some rocks in the southern part of the Lushs Bight Group are probably Early Ordovician rather than being Late Cambrian or older in age (*cf.* Kean *et al.*, 1995). In the study area, such strata may be found in some or all of the local subunits of the Western Arm Group, parts of which could have once conformably underlain the Indian Pond Formation.

An allochthonous thrust slice of the Lushs Bight Group is located within the Hammerdown volcanic belt immediately east of Catchers Pond (Figures 5 and 9). Andrews (1991) indicated that a narrow tract of the Lushs Bight Group also occurred immediately west of the fault bounding the Carboniferous strata near King's Point (compare Figures 1 and 3B). Because the well-exposed section of chlorite schists from the Lushs Bight Group south of King's Point does not display a characteristic electrical conductivity or unique aeromagnetic signature, it is possible that such rocks crop out beneath the thick glacial deposits in the valley between Paddy's Brook and Harry's Brook and extend discontinuously south to the vicinity of Muir's Pond.

On regional considerations, any outcrop of Cambrian strata in this part of the Hammerdown volcanic belt would likely represent a small outlier of the Lushs Bight Group lying above the younger rocks of the Indian Brook or Long Pond formations and be comparable to the nearby klippe carrying the mafic volcanic rocks of the Western Arm Group.

TECTONIC INTERPRETATION OF THE CATCHERS POND GROUP

The youngest observed strata in the Catchers Pond Group, now preserved in the tectonic window at Silver Pond, are disposed in a synclinorium that had an original northwest–southeast trend (O'Brien, 2012). This regional structural feature probably reflects low-strain Taconic shortening of an original depositional basin located within an extended Early Ordovician island-arc–back-arc basin complex. Such a depocentre, filled by thick pyroclastic and epiclastic deposits, may have possibly been the site of a felsic volcanic caldera that evolved above a substrate of basaltic andesite and island-arc tholeiite from the Long Pond Formation.

Structural telescoping of the original margin of this Early Ordovician volcano-sedimentary basin was associated with orogen-parallel displacement along arcuate ductile faults, although such translation predated a similar kind of lateral offset described by Lin *et al.* (2013). Southwestward tectonic movement of the oldest preserved part of the Catchers Pond Group occurred along a thrust above a structural footwall sequence that contained younger mineralized parts of the same rock group. The felsic and intermediate volcanic succession observed immediately below the Hammerdown overthrust sheet is host to the Lochinvar and Indian Brook base-metal deposits (Figure 5).

An overriding tectonic control on the nature of basin closure within the Catchers Pond Group and, more particularly, the structural development of the Hammerdown volcanic belt may have been the remobilization of the original boundary separating Ordovician cover from Cambrian basement and the resultant incomplete positive inversion of the Catchers Pond basin fill (Figure 9).

CONCLUSIONS

Within the rock formations comprising the middle and upper part of the Early Ordovician Catchers Pond Group, Floian deposition of felsic pyroclastic strata probably ceased around 475 My ago near the boundary separating the early Arenig (Moridunian) and middle Arenig (Whitlandian) stages. The older limit of deposition of strata in the Catchers Pond Group is unknown, although the mafic volcanic rocks observed in the oldest exposed formation had probably already been erupted by the late Tremadoc.

A comparison of the geochronological, geochemical and structural data presented from the southwest and northeast parts of the study area supports correlation of the majority of the stratified rocks underlying the extreme southwest part of the Hammerdown volcanic belt with basaltic and andesitic lava flows typical of the two lowest formations of the Catchers Pond Group. Such rocks structurally overlie the Floian felsic volcanic rocks that uniquely characterize the Catchers Pond Group.

Thrust-imbricated lithotectonic panels derived from several Early Ordovician and Cambrian stratigraphic units comprise the accretionary collage previously referred to as the Hammerdown Basalt (Figure 9). Strata exposed near the Indian River in the type area of the Indian Brook and Long Pond formations are linked by folded faults to the regionally upside-down and parautochthonous rocks of the Catchers Pond Group situated within the Hammerdown thrust stack.

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LEGEND FOR FIGURES 4 AND 5

Note: All uncoloured units in the legend do not occur in Figures 4 and 5. Legend is taken from O'Brien (2012).

POST-METAMORPHIC COVER

LATE MISSISSIPPIAN?

SOUTHWEST COVE SEQUENCE

MS:mc Variably indurated, red and grey sedimentary rocks

MS:mc

Mainly a redbed molasse in its lower part, including polymictic conglomerate distinguished by rounded clasts of plutonic, volcanic, hypabyssal and metamorphic rocks; massive boulder conglomerate beds locally having scoured bases grading to crossbedded pebbly sandstone; in its middle part, red and grey sandstone intercalated with reddish-brown arkose and subordinate conglomerate; in its upper part, reddish-brown siltstone having abundant nodules or concretions and displaying desiccation cracks; dark grey mudstone and light green argillite hosting secondary lenses of podiform carbonate near reduction–oxidation boundaries; in the middle and upper parts of the Southwest Cove sequence, calcrete and silcrete developed as stratabound and transgressive bodies and forming replacement zones on the metre scale and zoned veins on the centimetre scale; silcrete, predominantly grey chalcedony and orange jasper surrounded by a pale green halo of glauconitic clay and reduced mudstone, locally crosscutting calcrete; minor goethite-bearing ferricrete and hematitic clay-rich duricrusts; the outcrop pattern has been modified from Unit Cs on Map 94-226 (Kean and Evans, 1994); outlier possibly equivalent to parts of the Rocky Brook and Humber Falls formations of the Deer Lake Group in the Carboniferous Deer Lake sub-basin or the Little Pond Brook Formation of the Deer Lake Group in the Carboniferous Grand Lake sub-basin

Note 1: Detrital clasts of riebeckite-bearing tuff and syenite are found in polymictic conglomerate near the base of Unit *MS:mc* and are similar to certain Early Silurian magmatic rocks outcropping in the tectonically adjacent King's Point Complex. In the middle part of the Southwest Cove sequence, calcrete and jasper are observed as detrital grains in red and grey sandstone.

Note 2: The lower part of Unit *MS:mc* is probably correlative with redbeds in the Indian Pond–Black Brook area previously assigned to Unit MI:sc (O'Brien, 2011). Although Unit MI:sc has been interpreted as a possible outlier of the Mississippian Deer Lake Group *(ibid)*, Colman-Sadd and Crisby-Whittle (2005) have assigned the strata in Unit *MS:mc* to the Mississippian–Pennsylvanian Barachois Group based on the work of Kean and Evans (1994).

INTRUSIVE ROCKS

POSTTECTONIC INTRUSIVE ROCKS

EARLY TO LATE SILURIAN?

TOPSAILS IGNEOUS SUITE

S:TI Topsails Intrusive Suite

S:TIsy

Mainly red and light pink, medium- to fine-grained, porphyritic to equigranular bodies of isotropic quartz syenite, potassium feldspar-phyric syenite, quartz-phyric granite, quartz–feldspar porphyry and granophyre; maroon, variably jasperitized, biotite-bearing syenite and hematized granophyre crosscut by composite dykes of fresh diabase; light pink, feldspar-phyric stocks and minor intrusions of Unit *S:TIsy* having disseminations of dusty hematite throughout the matrix or having deep red, silicious alteration zones arranged bilaterally about systematic joint surfaces; abundant chlorite–hematite–jasper–quartz veinlets in purplish-red, fine-grained syenite sheets; cataclastite zones in syenite, granite and stratified host rocks injected by minor intrusions, such as pyritic felsic microporphyries, fractured aplite dykes and pinnate quartz veins; widespread conjugate dykes of porphyritic and aphanitic diabase

S:TIdr

Mainly isotropic bodies of light grey, medium-grained equigranular diorite and subordinate, dark grey, coarse-grained quartz gabbro; minor porphyritic diorite having intratelluric plagioclase laths replaced by hematite, carbonate and sericite; pyroxene phenocrysts altered to actinolite and magnetite; rarely, cupriferous diorite porphyry showing uniquitous disseminations of pennitic chlorite, ferroan carbonate, epidote and jasper throughout the diorite matrix; near faults, kink-banded and drag-folded stringers of quartz, calcite and sericite within silicified diorite sheets and adjacent country rocks; jasper-cemented tuffisite pipes intruding ferroan carbonate alteration zones in pyritic bodies of Unit *S:TIdr* diorite

S:TIgm

Mainly light grey, equigranular to slightly porphyritic, hornblende-bearing microgranite and biotite-bearing granophyre; subordinate, light grey, fine-grained, saussuritized quartz–feldspar porphyry and quartz porphyry crosscut by tuffisite pipes, diabase dykes and aplite veins; near the Indian River, buff-weathered graphic granite and associated carbonate-altered microporphyry hosting cataclastite zones and swarms of sigmoidally foliated mafic dykes; chalcopyrite-bearing intrusive breccia composed of variably jasperitized fragments of Unit *S:TIgm* microgranite and Ordovician country rock basalt; composite intrusions made up of silicified granophyre from Unit *S:TIgm* and chloritized diorite from Unit *S:TIdr*, particularly along the faulted margin of the Silurian Springdale Group; Unit *S:TIgm* may include correlatives of Unit eS:TImh of Whalen and Currie (1988)

S:TIgd

Mainly light grey, isotropic hornblende–biotite granodiorite, locally displaying discontinuous glomeracrystic aggregates of very coarse plagioclase; in places, medium-grained equigranular granodiorite hosting diabase intrusions having chilled margins back veined by granite or having zones of partially assimilated mafic dykes; coarse hornblende granodiorite preserving relict trains of cognate xenoliths rich in brown biotite; mafic dykes co-mingled with granodiorite and illustrating folded flow-foliation, particularly around joint abuttments in Unit *S:TIgd* host rocks; silicified granodiorite showing diffuse gradational boundaries with patches of light pink, fine-grained biotite granite or light grey quartz-phyricporphyry bodies; flow-layered intrusive sheets of felsic microporphyry associated with granodiorite-hosted swarms of porphyritic diabase dykes distinguished by a margin-parallel foliation defined by neocrystallized chlorite; near strike-slip faults, highly fractured, light green granodiorite containing a propylitically-altered matrix and illustrating subhorizontal hematite–chlorite slickenlines; epidotized, sericitized or carbonitized granodiorite having a feldspar-depleted sucrose matrix and locally intruded by quartz–pyrite–chalcopyrite veins or, more rarely, molybdenite–chalcocite–bornite veinlets; Unit *S:TIgd* includes locally reddened and jasperitized granodiorite previously assigned to Unit Tg of the Topsails intrusive suite (O'Brien, 2009); may also include K-feldspar porphyritic granite and two-feldspar quartz syenite previously assigned to Unit eS:TIsa of the Topsails intrusive suite (Whalen and Currie, 1988; Coyle, 1992)

Note 1: In the Indian Brook–King's Point map area, plutonic and hypabyssal rocks assigned to the Topsails intrusive suite were locally offset by rectilinear faults before, and after, the presumed Carboniferous deposition of the Southwest Cove sequence. In places, some of these intrusive rock units are hosted by both the Cambro-Ordovician rocks of the Notre Dame Subzone of the Dunnage Zone and the Silurian rocks of the terrestrial overlap sequences.

Note 2: Unit *S:TIgm* forms the cupola of several bosses emplaced into Unit *O:CPib* basalt of the Ordovician Catchers Pond Group and older Silurian parts of the Topsails intrusive suite. It also comprises subvertical intrusive sheets near the tectonic boundary that separates the Silurian King's Point Complex from basement rocks of the Catchers Pond and Lushs Bight groups.

Note 3: Unit *S:TIsy* and Unit *S:TIgm* are mapped to crosscut regional fold structures that affect the stratified rocks of the King's Point Complex. Unit *S:TIdr* is mapped to crosscut fault structures that cause tectonic excision of the basal stratigraphy of the Springdale Group.

SYN-TECTONIC TO POSTTECTONIC INTRUSIVE ROCKS

LATE ORDOVICIAN TO EARLY SILURIAN?

BURLINGTON GRANODIORITE

lOS:B Burlington granodiorite

lOS:BU

Mainly light grey to pink, isotropic, coarse-grained, porphyritic, hornblende–biotite granodiorite; light grey to greenish grey, isotropic, medium-grained, equigranular, hornblende–biotite granodiorite transitional to sheeted quartz–feldspar porphyry; epidotized or chloritized granodiorite passing into strongly hematized and silicified granodiorite; massive amphibole-rich granodiorite commingling with the chilled margin of an isotropic gabbro; rectangular boudins of diabase dykes enclosed by granodiorite illustrating a plutonic flow foliation. Unit *lOS:BU* may include subordinate quartz dioritic, monzonitic and granitic rocks assigned to Unit eS:BU by Hibbard (1983)

Note 1: On the Baie Verte Peninsula, various phases of the Burlington granodiorite are known to range in age from the Late Ordovician to the Early Silurian (Skulski *et al.*, 2010). Parts of Unit *lOS:BU* are probably also correlative with the Early Silurian Glovers Island granodiorite (Unit eS:GI of Cawood and van Gool, 1998).

Note 2: North of Kitty's Pond, Unit *lOS:BU* includes younger granodiorite bodies previously assigned to Unit eS:BU of Hibbard (1983) and Unit S:TIgd of O'Brien (2011).

SYN-TECTONIC INTRUSIVE ROCKS

LATE ORDOVICIAN TO EARLY SILURIAN?

RAINY LAKE COMPLEX

lOS:H Harry's Brook gabbro – felsic porphyry

lOS:Hgp

Mainly folded intrusive sheets of medium grained, equigranular to porphyritic gabbro and diorite hosted by Early Ordovician rocks of the Catchers Pond Group; isotropic gabbro transitional to chalcopyrite-bearing greenschist and phyllonite; co-mingling diorite and quartz–feldspar porphyry crosscut by foliated porphyritic gabbro; sheeted quartz–feldsparporphyry bodies containing country rock xenoliths displaying a bed-parallel foliation; sulphidic, silicified and chloritized metagabbro and associated quartz–feldspar porphyry carrying late syntectonic arrays of quartz–chlorite–ferroan carbonate–pyrite–arsenopyrite veins; boudinaged diorite sheets and pinch-and-swell diabase dykes displaying crenulation folding of the country rock schistosity in the boudin neck of the intrusions; openly folded diabase dykes crosscutting penetrative foliation within quartz–feldspar porphyry veins; steeply dipping bodies of quartz–feldspar porphyry intruded into fold hinge zones outlined by a bed-parallel foliation in Ordovician country rocks; nested gabbroic bodies and composite diabase dykes emplaced, in places, across early-formed regional folds and having a foliation parallel to their intrusive margins deformed by later fold structures

Note 1: Many of the deformed quartz–feldspar porphyries (*cf.* Andrews and Huard, 1991;Gaboury *et al.*, 1996) assigned to Unit *lOS:Hgp* are similar to the Early Silurian (*ca.*437 Ma) quartz–feldspar porphyry that was dated in an isotopic study of mineralized rocks near the former Hammer Down Gold Mine (Ritcey *et al*., 1995).

Note 2: Unit *lOS:Hgp* comprises a sheeted intrusive complex–dyke swarm that is possibly correlative with parts of Unit SO:RL of Whalen and Currie (1988) or Unit OS:SR of Colman-Sadd and Crisby-Whittle (2005) in the Topsails igneous terrane. Amphibole-rich mafic intrusions (*ca.*438 Ma) within Unit SO:RL are hosted by Unit O:GV volcanic rocks of the Early Ordovician Glover Group (Whalen and Currie, 1988).

Note 3: Some of the intrusive rocks assigned to Unit *lOS:Hgp* in the Indian River–King's Point area are possibly older than Late Ordovician–Early Silurian and could thereby document a pre-Rainy Lake Complex phase of tectonism in the Catchers Pond Group. In particular, the Late Middle Ordovician episode of schistosity development that had affected the late kinematic (*ca* 465 Ma) Coopers Cove granodiorite (and older chlorite schists) in the northerly adjacent Cambrian rocks of the Lushs Bight Group (Szybinski, 1995) may have also affected the Ordovician strata of the Catchers Pond Group.

ORDOVICIAN OR SILURIAN?

CATCHERS VALLEY GRANITE

OS:c Catchers Valley granite – felsic porphyry

OS:cg

Mainly fine-grained, equigranular, biotite microgranite and graphic granite; subordinate quartz–feldspar porphyry intruded by aplite veins, diabase dykes and striated quartz veins; zones of secondary jasper, hematite, ferroan carbonate and bornite; in places, microgranite illustrating hematized potassium feldspar phenocrysts set in a carbonate-rich siliceous matrix and showing chlorite pseudomorphs after biotite; possibly related to the granitic phases of the Coopers Cove pluton (Unit Occg of Kean and Evans, 1994)

Note: The granite and felsic porphyry phases of Unit *OS:cg* are generally isotropic but are strongly fractured and regionally altered, particularly in the vicinity of late brittle faults. Pyritic quartz-feldspar porphyry and later diabase dykes are truncated along a major east northeast-trending, steeply-dipping fault structure in the type area of the Catchers Valley granite (see also DeGrace, 1971). However, near the south shore of Catchers Pond, a microgranite in the Unit *OS:cg* pluton carries a localized sericite foliation and displays a tectonic alignment of podiform quartz–chlorite–sericite veinlets.

STRATIFIED ROCKS

POST-ORDOVICIAN AND PRE-CARBONIFEROUS TERRESTRIAL OVERLAP SEQUENCES

MIDDLE SILURIAN AND OLDER?
S:K KING'S POINT COMPLEX
S:KV Volcanic rocks of the King's Point Complex

S:KV4

Mainly red, pink and greyish-pink, flow-layered porphyritic rhyolite and hematized welded tuff ; massive, crystal-lithic felsic tuff passing upward into compacted flow-layered tuff; partially welded tuff containing fragments of aphanitic rhyolite, quartz–feldspar porphyry and resorbed quartz crystals set in a maroon vitric matrix; crystal-rich felsic tuff locally displaying thin bedding, internal lamination, fine-grained banding and chaotic flow folding; conchoidally fractured black obsidian having concentric perlitic cracks; dark red, hematized flows of feldspar-phyric rhyolite intercalated with ignimbrite; selective epidote replacement along flow bands within layered ash tuffs and adjacent ignimbrite; tuffaceous strata illustrating a jasper-rich sucrose matrix, particularly where well-stratified and preferentially altered; rare, well-bedded red sandstone grading upward from size-graded sedimentary breccia and underlying massive debrite marked by a large textural variety of felsic volcanic clasts; probably in part correlative with the Upper Volcanic Rocks of the King's Point Complex and possibly equivalent to Unit 6B of Miller and Abdel-Rahman (2003) or Unit eS:KVue (Colman-Sadd and Crisby-Whittle, 2005)

S:KV3

Mainly light pink, generally massive, felsic lapilli tuff, felsic ash tuff and felsic crystal tuff; in places, thickly stratified intervals of medium-grained lithic tuff and coarse-grained volcanic breccia preferentially hosting pyritic gossan zones; minor, light grey and light pink interbeds of well-layered but variably hematized potassium feldspar–quartz tuff; pyrolusite–graphite films on folded and striated systematic joints in felsic lapilli tuff; where heavily fractured, dark grey pseudomorphs of chlorite, sericite and pyrite after primary feldspar crystals; disseminated hematite, arsenopyrite and pyrite cubes near quartz vein arrays; probably in part correlative with the Upper Volcanic Rocks of the King's Point Complex and possibly equivalent to Unit 6A of Miller and Abdel-Rahman (2003) or Unit eS:KVup (Colman-Sadd and Crisby-Whittle, 2005)

S:KV2

Mainly light grey to reddish-grey ash flow tuff, crystal-poor ignimbrite and minor aphanitic rhyolite; conspicuous flow-banded aphyric rhyolite blocks within an eutaxitically foliated matrix; probably, in part, correlative with the Middle Volcanic Rocks of the King's Point Complex and possibly equivalent to Unit 4 of Miller and Abdel-Rahman (2003) or Unit eS:KVm (Colman-Sadd and Crisby-Whittle, 2005)

S:KV1

Unseparated felsic volcanic strata, including subcroppings of purplish-red and red crystal tuff and fine-grained, lithic ash tuff having outsized fragments of aphyric rhyolite; relative stratigraphic position unknown due to lack of exposure

Note 1: In the northwestern part of the Indian Brook–King's Point area, intrusive rock units of presumed Silurian age have been previously included in the Early Silurian King's Point Complex. Many of these rocks are herein removed from the King's Point Complex and assigned to the Topsails intrusive suite because they are contiguous with posttectonic plutonic rocks assigned to the S:TI divisions of this suite in the Sheppardville map area (O'Brien, 2011).

Note 2: North of the map area, and southeast of Strugglers Pond on the Baie Verte Peninsula, a basal sedimentary breccia in the oldest known stratified rock unit of the King's Point Complex (Miller and Abdel-Rahman, 2003) may lie above a nonconformity separating the breccia and overlying felsic volcanic strata from an earliest Silurian or older granodiorite within Unit *IOS: BU*.

TOPSAILS IGNEOUS SUITE
EARLY TO MIDDLE SILURIAN
S:S SPRINGDALE GROUP
Sedimentary (S:Ss) and volcanic (S:Sv) rocks

S:Su

Unseparated sedimentary, volcanic and hypabyssal rocks previously assigned to the Springdale Group (Coyle, 1992), including felsic volcanic flows and pyroclastic strata, red cobble conglomerate and crossbedded sandstone, and quartz–feldspar porphyry

S:Sv6

Mainly a massive to thick stratified sequence of dark grey basalt flows; dark green aphanitic basalt marked by a regional chlorite–epidote alteration

S:Svs5

Mainly purplish-red mafic volcanic strata enriched in hematite or jasper; commonly, porphyritic basalt displaying a flow-top breccia infilled by fine-grained red sandstone and grey laminated argillite; discontinuous lenticle of cobble conglomerate rich in locally derived intraclasts of purplish-red basalt and succeeded by purplish-red basalt intruded by gabbro sills; sequential chlorite-chalcedonic quartz-ferroan carbonate-pyrite alteration in strongly amygdaloidal basalt flows

S:Ss4

Mainly red, crossbedded granular sandstone and minor pebbly sandstone; sandstone beds containing rip-up clasts of red argillite and being locally scoured by size-graded conglomerate; conglomeratic sandstone having detrital clasts of quartz–feldspar porphyry; pebbly sandstone within Unit *S:Ss4* illustrating rounded clasts of mafic and felsic volcanic rocks similar to those found in lower parts of the local Springdale Group sequence; Unit *S:Ss4* supersedes Unit S:Ss of O'Brien, 2011; Unit *S:Ss4* is possibly partially correlative with certain redbeds in Unit 9 of Coyle (1992) or Unit S:SS (Colman-Sadd and Crisby-Whittle, 2005)

S:Ssv3

Mainly clast-supported polymictic conglomerate interstratified with subordinate matrix-supported pebble conglomerate and succeeded by vesicular grey basalt and minor andesite; purplish-red, plagioclase-rich basalts intercalated with basaltic breccia and mafic tuff; in places, basalt breccias being made up entirely of red hematized blocks of vesicular lava and also containing isolated fragments of mafic tuff completely replaced by jasper; mafic pyroclastic strata having angular grey clasts of flow-layered rhyolite present in addition to the more common clasts of dark green scoraceous basalt; near the base of the subunit, very thick stratified, red and grey conglomerate containing rare, well-rounded extrabasinal clasts of granite and gabbro, minor cobbles of grey ignimbrite and orange rhyolite, and ubiquitous purplish-red boulders of variably hematized basalt; massive to thick stratified sedimentary breccia characterized by basalt clasts displaying internal hematite-rich spherical bands and having concentric leached zones in the granular matrix surrounding them; medium-bedded red sandstone and grey pebbly sandstone showing irregular zones of hematite locally replacing the sedimentary matrix; in other localities, pre-incorporation liesegang rings and randomly oriented redox bands within basalt boulders; yellowish-grey, parallel laminated interbeds of fine-grained palagonitic sandstone within a fining-upward succession of red sandstone; open-spaced veins of chlorite–hematite–calcite–quartz near joint sets in conglomerate and sandstone; crosscutting epidote–carbonate–chlorite alteration zones in light green vesicular basalt and amygdaloidal gabbro sills, especially near faults; prominent jasper–hematite–pyrite–quartz veinlets along feathered joints in reddish-grey basalt; *Unit S:Ssv3* supersedes Unit S:Sm of O'Brien (2011); possibly correlative, in part, with Unit S:SVm4 (Colman-Sadd and Crisby-Whittle, 2005); possibly also equivalent to the volcanic-derived conglomerate in Unit 9 of Coyle (1992) or Unit S:SSc (Colman-Sadd and Crisby-Whittle, 2005)

S:Svs2

Mainly light grey and pink, felsic volcanic and pyroclastic strata, including welded ash flow tuff, crystal-lithic lapilli tuff, pumiceous vitric tuff and felsic agglomerate having large blocks of flow-banded rhyolite; in the lowest exposed part of the subunit, massive flows of porphyritic rhyolite having quartz and potassium feldspar phenocrysts set in a microlite-rich matrix; intercalated with light pink, feldspar-porphyritic and aphanitic rhyolite showing flow banding and flow folding; coarse volcanic breccia marked by jasper-rimmed fragments of emerald green pumice and pink spherulitic rhyolite; succeeded by a size-graded polylithic breccia containing ubiquitous felsic ash tuff, minor basalt and rare laminated argillite; thick-bedded tuff and lithic breccia having abundant outsized blocks of potassium-feldspar-bearing orange rhyolite and dark red aphyric rhyolite; volcanic conglomerate and fanglomerate having outsized felsic and mafic volcanic clasts; minor sand-matrix debrite, parallel-laminated grey sandstone and slump-folded argillite; light grey, felsic lithic-crystal tuff distinguished by the presence of rare mafic lapilli; massive crystal tuff dominantly composed of resorbed quartz grains and euhedral feldspar prisms set in a purplish-red ash matrix; in correlative units elsewhere in the Springdale Group, reports of exotic clasts of the local Ordovician basement (*cf.* Coyle, 1992); Unit *S:Svs2* supersedes Unit S:Sf of O'Brien (2011); possibly correlative, in part, with units 2 and 6 of Coyle (1992) or units S:SVx and S:SVf2 (usage of Colman-Sadd and Crisby-Whittle, 2005)

S:Ssv1

Mainly red boulder conglomerate and purplish-red silicified andesite comprising several interstratified lenticles of volcanic and sedimentary rocks (monomictic conglomerate in lowest preserved lenticle); clast-supported conglomerate marked by variably hematized boulders of plagioclase porphyritic and glomeracrystic andesite; red conglomerate illustrating well-rounded cobbles of parallel-laminated quartzose sandstone; intraformational grey sandstone showing jasper concretions and containing distinctive pebbles of hematitic andesite and jasper; dark grey, light green and purplish-red amygdaloidal basalt flows and mafic pyroclastic rocks comprising two lenticles of Unit *S:Ssv1* volcanic strata; massive amygdaloidal andesite flows intercalated with coarse volcanic breccia displaying bombs selectively replaced by jasper; polylithic mafic tuff having a chloritic matrix replaced by hematite and quartz; Unit *S:Ssv1* is possibly correlative with units 3 and 5 of Coyle (1992) or units S:SVif and S:SVm2 (Colman-Sadd and Crisby-Whittle, 2005)

Note 1: North of the intersection of routes 390 and 391, red boulder conglomerate overlying felsic pyroclastic strata in the lower part of Unit *S:Ssv3* of the Springdale Group contains granite and gabbro extraclasts together with ignimbrite and basalt intraclasts, all set in a sandstone matrix locally enriched in yellowish-green palagonite. The sub-Springdale Group nonconformity documented by McGonigal (1970) may possibly relate to this episode of basement uplift.

Note 2: The terrestrial volcanosedimentary strata that have been assigned to Unit S:Su probably represent rocks that are generally younger than those observed within the anticline–syncline pair located immediately northwest of the Indian River.

EARLY SILURIAN?
eS:M MICMAC LAKE GROUP
eS:MU Volcanic rocks of the Upper Sequence?

eS:MUm

Mainly dark grey to purplish-red basalt breccia, reddish-grey, plagioclase-porphyritic magnetic andesite, and purplish-red, very coarse-grained, highly amygdaloidal basalt in subcrop near Kitty's Pond; locally, very large blocks of red scoraceous basalt and hematitic vesicular basalt in glacial till

ROCKS FORMED IN THE IAPETUS OCEAN (NOTRE DAME SUBZONE OF THE DUNNAGE ZONE)

EARLY ORDOVICIAN
CATCHERS POND GROUP
O:CP Volcanic and sedimentary rocks

O:CPsp Silver Pond Formation

O:CPspf

Upper felsic volcanic member: Mainly light grey to light pink volcanic breccia and quartz-rich crystal tuff; at the base of the member, felsic breccia lying in sharp contact with a basaltic andesite flow from Unit *O:CPspb*; thin-bedded volcanic breccia gradational to felsic lapilli tuff and felsic ash tuff; succeeded by medium-grained, thick-bedded felsic crystal tuff, having abundant resorbed quartz prisms and displaying small bombs of quartz-phyric porphyry and quartz–feldspar porphyry; overlain by a polymictic felsic volcanic breccia distinguished by large volcanic fragments derived from older formations of the Catchers Pond Group; capped by fine-grained felsic, lithic–crystal tuff

O:CPspb

Lower mafic volcanic and chert member: Mainly mafic volcanic flows, hemipelagic chert and epiclastic turbidites; at the base of the member, a relatively thin, well stratified sequence of vesicular pillow lava illustrating interstitial red chert passing gradationally upwards into highly vitric pillow breccia; succeeding light grey beds of graded pebbly wacke, massive feldspathic sandstone and laminated siltstone turbidite fining upward into dark grey siliceous argillite; dark green ferruginous chert bands intercalated with subordinate lava flows; overlying basalt breccia interbedded with aquagene tuff; vesicular basalt and basaltic andesite characterized by chlorite–quartz–jasper–carbonate alteration

Note 1: Lithic wackes scoured into Unit *O:CPspb* siltstone typically display detrital clasts of intraformational chert and basalt, and they are commonly observed to have rip-up clasts of laminated argillite, particularly in the lower part of the member. In contrast, some coarse-grained granular wackes in the upper part of Unit *O:CPspb* begin to show felsic volcanic extraclasts derived from strata other than within the Silver Pond formation.

Note 2: Felsic volcanic breccia in the middle–upper part of the younger member of the Silver Pond formation illustrates outsized blocks of very coarse, quartz–feldspar crystal tuff similar to those seen within the limestone block-bearing marker horizon in the underlying New Water Pond formation. This *O:CPspf* breccia also contains angular blocks of aphanitic and porphyric rhyolite similar to those found in the older West Waters Pond formation.

O:CPnw New Waters Pond Formation

O:CPnwf

Upper argillite and felsic volcanic member: Mainly thin-bedded argillaceous jasperite, felsic pyroclastic strata (associated with rhyolite flows and intrusions), and a marker horizon of subaqueous quartz–feldspar tuff; at the base of the member, red to pink, hematized felsic crystal tuff, jasperitized siltstone turbidite, and ferruginous replacement chert comprising laterally continuous beds draped on the tops of mafic lava flows distinguished by limestone inclusions; succeeded by interbedded red laminated argillite, green siliceous argillite and maroon graded siltstone and by minor sandstone turbidite displaying abundant rip-up clasts of dark grey laminated argillite; sharply overlain by a fining-upward interval of felsic pyroclastic strata, including course volcanic breccia composed of angular fragments of aphanitic rhyolite, potassium feldspar-phyric rhyolite, flow-banded rhyolite and eutaxitically foliated ignimbrite, and capped by lithic tuff made up of microlitic or vitric felsite bombs and clast-rotated bedded blocks; a very coarse-grained crystal tuff forming a marker horizon in Unit *O:CPnwf* and being characterized by large blocks of fossil-bearing clastic limestone together with angular fragments made up of size-graded beds of crystal tuff; near the bottom of the marker unit, smaller subangular clasts of hematized felsic crystal tuff, ferruginous chert and jasper supported by large fractured phenocrysts of resorbed quartz; locally, at the top of the member, massive feldspathic wacke, rhyolite-derived wacke and basalt-derived wacke

O:CPnwl

Limestone member: Mainly well-bedded fossiliferous limestone yielding a trilobite, brachiopod and conodont fauna (Dean, 1970; O'Brien and Szybinski, 1989) and comprising a relatively thin sequence directly above coherent andesitic sheet flows; laterally discontinuous lenses of bioclastic carbonate interstratified with smooth-surface autobreccias of basaltic andesite

O:CPnwb

Lower mafic volcanic member: Mainly a localized and variably thick sequence of marine mafic to intermediate volcanic rocks and subordinate subvolcanic sills; dominantly highly vesicular calc-alkaline basalt, transitional calc-alkaline basalt–island-arc tholeiite, basaltic andesite and andesite (Moore *et al.*, 2002); comprising sheet flows or autobreccias intercalated with biogenic carbonate or, more rarely, fine-grained, thin-bedded quartz-feldspar crystal tuff; in places, carbonate-altered pillow lavas transitional to silicified pillow breccias

Note: Primary coherent rhyolite extrusions have not been observed within the stratigraphical succession of the New Waters Pond formation. It is unknown if they occur in the subsurface.

O:CPww West Waters Pond Formation

O:CPwwfu

Unseparated felsic volcanic strata: Mainly thin-bedded chloritic lithic tuff, fine-grained quartz-feldspar crystal tuff, subordinate silicified volcanic breccia, and pyritic gossan; all transitional to quartz-sericite schist; minor phyllite and dark grey argillite

Note: Unit *O:CPwwfu* may include rocks that are elsewhere assigned to Unit *O:CPwwf1* and possibly Unit *O:CPwwf2*. The felsic volcanic rocks at the Lochinvar prospect (Froude *et al.*,1996) are included in Unit *O:CPwwfu*.

O:CPwwf2

Upper rhyolite and mudstone member: Mainly rhyolite flows, rhyolite breccias and felsic volcanic-derived sedimentary rocks; at the base of the member, a coherent rhyolite lava showing synvolcanic folds of flow layering crosscut by marginally banded or massive dykes of quartz–feldspar porphyry; flow-banded rhyolite forming laterally discontinuous *in situ* lobes gradational with jigsaw-fit hyaloclastite; succeeded by felsic volcanic breccia made up of fragments of porphyritic, aphyric and spherulitic rhyolite; overlying stratiform rhyolite bodies display aphyric, quartz-phyric, pumiceous or scoriaceous textures and are capped by feldspar-phyric crystal tuff; at the top of the member, tuffaceous wacke gradational to laminated mudstone

Note: Based on their lateral extent and thickness, the rhyolite lavas in the upper member of the West Waters Pond formation probably comprise parts of kilometre-scale coulée-type extrusive bodies. Some of the overlying coarse pyroclastic strata possibly represent autoclastic breccias that are locally augened by a eutaxitic flow foliation.

O:CPwwm2

Upper pillowed basalt member: Mainly a very localized but notably thick sequence of basalt and andesite; throughout most of the member, vesicular basalt flows having abundant matrix-disseminated carbonate and vein carbonate; near the structural top of the unit, pillow lava and pillow breccia transitional to chlorite schist; near its faulted contact with the Springdale Group, sucrose basalt from Unit *O:CPwwm2* hosting open-spaced, fibred and slickenlined veins of quartz, calcite, hematite, ferroan carbonate, chlorite, clinozoisite, epidote, chalcopyrite and pyrite

Note: Restricted to the east of the map area, Unit *O:CPwwm2* may be, in part, a lateral facies variant of Unit *O:CPwwm1*, although the former is significantly thicker than the latter. The stratigraphical base of the upper pillowed basalt member is not exposed.

O:CPwwm1

Lower mafic volcanic member: Mainly mafic volcanic flows and mafic intrusions; at the base of the member, spectacular intervals of dark grey pillow lava having variolitic glassy rims, radial structure and interstitial green chert; extensively altered pillow breccia net-veined by iron carbonate; succeeded by vesicular basalt flows intruded by coarse-grained gabbro sills, both locally displaying a completely silicified matrix; at the top of the member, highly amygdaloidal andesite flows progressively replaced by chlorite, hematite and jasper ascending the volcanic sequence

Note: Relatively thin but laterally persistent, Unit *O:CPwwm1* is well developed in the type area of the West Waters Pond formation and farther west. However, it is also interpreted to be present to the north of Unit *O:CPwwm2* near the Indian Brook copper prospects.

O:CPwwf1

Lower felsic volcanic member: Mainly fine-grained felsic pyroclastic strata forming the most widespread unit of felsic volcanic rocks in the Catchers Pond Group; at the base of the member, thin-bedded to laminated, very fine-grained, crystal-lithic tuff; succeeded by finely laminated ash tuff and lapilli tuff intercalated, in places, with banded siliceous argillite; overlying quartz-phyric tuff and quartz–feldspar crystal tuff commonly altered by ferroan carbonate and weathered to pitted limonite; locally, chalcopyrite-bearing tuff having disseminated sulphide grains rimmed by secondary hematite or extensively replaced by jasper; pretectonic sills of pyritic gabbro and multiple diabase dykes

Note: In places, the lowest member of the West Waters Pond formation contains outsized blocks of dacitic tuff typical of those that characterize the underlying Long Pond formation as well as ferruginous chert and jasper clasts similar to those occurring in the uppermost part of the Indian Brook formation.

O:CPlp Long Pond Formation

Mainly mafic extrusive and intermediate pyroclastic strata; at the base of the formation, thin sulphidic or jasperitized interbeds of dark to light green, fine-grained, highly vitric, plagioclase-phyric dacitic crystal tuff and light grey, size-graded, felsic lithic-crystal tuff distinguished by rounded quartz eyes set in a lapilli-rich chloritic matrix; amygdaloidal dykes and sills of porphyritic diabase and equigranular gabbro; dark green, carbonate-altered basalt and epidotized pillow breccia (having conspicuous fragments of red chert and orange jasper) interstratified with buff-weathered, plagioclase-and/or quartz-phyric crystal tuff; light green, silicified, mafic–felsic breccia containing plagioclase-porphyritic mafic bombs (displaying vesicular chloritic cores and leached sericitized rims) and minor outsized blocks of felsic lapillistone (illustrating notched or hot-indented margins adjacent to mafic clasts and preserving a eutaxitically foliated or spherulitic matrix)

In the middle part of the Long Pond formation, a well stratified interval of polylithic tuff having conspicuous fragments of light-green dacitic vitroclasts (perlitically fractured, obsidian-rich pumice and quench-textured ejecta characterized by compacted chilled selvages and minute chloritic amygdules) together with clasts of light-pink rhyolitic glass (porphyritic ash composed of embayed quartz phenocrysts set in a dark-grey matrix of contorted shards); minor, flow-layered welded tuff passing gradationally into devitrified bands made up of isolated spherulites and agate-bearing lithophysae; light-grey, coarse-grained, clast-rotated felsic breccias displaying sharp boundaries with interstratified horizons of fine-grained, medium-bedded mafic tuff

At the top of the Long Pond formation, extensively carbonate-altered and highly silicified basalt flows capping glassy intermediate tuff and jasperitized felsic tuff; the above-mentioned bimodal pyroclastic strata hosting laterally discontinuous stratabound zones of massive jasper and crosscutting zones of hematite-bearing quartz veinlets

Unit *O:CPlp* tuff is locally transitional to sericitic, chloritic or carbonaceous schist; in places, the subdivision is host to zones of disseminated chalcopyrite and sphalerite in volcanic schist, to arrays of chlorite–quartz–pyrite–hematite veins, to stringers made up of jasper, hematite, sericite and feldspar, and to spotted aggregates composed of ferroan carbonate and pyrite grains

O:CPib Indian Brook Formation

Mainly pillowed basalt, pillow breccia, interflow chert and subvolcanic intrusions; throughout most of Unit *O:Cib*, dark green, well stratified, medium- to fine-grained pillowed basalt intercalated with massive, medium- to coarse-grained flows of plagioclase-porphyritic andesite; abundant gabbroic sills and multiple diabase dykes having variolitic edges or chilled margins; pillow lava intervals displaying pipe vesicles, glassy selvages, interstitial grey-green chert, monomictic mafic breccia and hyaloclastite; in places, polylithic basaltic breccia and grey mafic tuff made up of thoroughly silicified and relatively pristine volcanic fragments; minor pyrite–chalcopyrite mineralization in gossans present along contacts between mafic breccia and massive flows; widespread propylitically altered basalt illustrating chlorite pseudomorphs after clinopyroxene, having ubiquitous amygdules filled by chlorite and carbonate, and being crosscut by numerous chlorite–epidote–titanite–quartz stringers; in places, folded pyrite–sericite–quartz veinlets in silicified basalt; in the upper part of the Indian Brook formation, and especially near its boundary with the Long Pond Formation, red jasperitized basalt having abundant matrix-disseminated carbonate, and displaying purple-red interbeds of parallel-laminated chert, and hosting transgressive sheets of quartz–feldspar porphyry

CAMBRIAN TO EARLY ORDOVICIAN?
C:E WESTERN ARM GROUP?

C:Ecb

Maroon and red, hematitic, ribboned chert; dark green, siliceous, parallel-laminated argillite; light grey, thin-bedded sandstone turbidite; dark grey, magnetic basalt flows, tholeiitic pillow lava and porphyritic gabbro sills; locally, hematized jasper-rich basalt, black chlorite schist and light green epidosite; possibly correlative with Early Ordovician parts of the upper Skeleton Pond Tuff and the overlying Big Hill Basalt [Unit wOs and Unit wOb of Kean and Evans (1994)] or, alternatively, Unit LCOpb at the stratigraphical top of the Cambro-Ordovician Lushs Bight Group (*cf.* Kean and Evans, 1994)

C:Eat

Banded argillite, ferruginous chert and mafic crystal tuff in subcrop and drill core; possibly correlative with strata found in the upper part of the Skeleton Pond Tuff (Marten, 1971) of the basal Western Arm Group (*cf.* Kean *et al.*, 1995)

C:Ebi

Massive flows of light grey plagioclase-porphyritic basalt; light green, non-magnetic basalt enriched in disseminated epidote; arsenopyrite-bearing quartz veins in silicified basalt; porphyroblastic chalcopyrite in mafic greenschist; thin horizons of sulphide-bearing banded iron formation; possibly correlative with Cambrian strata located near the Sugar Loaves Basalt–Skeleton Pond formation transition (*cf.* Szybinski, 1995)

C:Etg

Highly magnetic tholeiitic basalt and tholeiitic gabbro sills (Jenner and Szybinski, 1987; Szybinski, 1995), including island-arc tholeiite (Gaboury *et al.*, 1996); massive aphyric mafic flows, minor pillow breccia and aquagene tuff, particularly in the klippe made up of Unit *C:Etg* rocks; dark grey, plagioclase-porphyritic vesicular basalt and variolitic pillowed basalt transitional to sulphide-bearing, black chlorite schist; equigranular to schistose gabbro carrying folded quartz–chlorite–carbonate veins displaying bilateral pyrite–arsenopyrite mineralization; along the southern margin of Unit C:Etg, banded mylonite, talc schist and chlorite schist; possibly correlative with the Late Cambrian or older Sugar Loaves Basalt (*cf.* Szybinski, 1995) or, alternatively, the Big Hill Basalt (*cf.* Szybinski, 1995) within the pre-Ordovician part of the Western Arm Group (Colman-Sadd and Crisby-Whittle, 2005)

Note 1: A brachiopod-bearing argillite within the type area of the Skeleton Pond Tuff of the Western Arm Group has been previously determined to be Early Ordovician (MacLean, 1947).

Note 2: According to Szybinski (1995), the Sugar Loaves Basalt of the Western Arm Group is Late Cambrian or older on the basis of a crosscutting *ca.* 493 Ma (Furongian) lamprophyric dyke. Equivalent to Kean and Evans' (1994) Unit LCOpb in the uppermost Lushs Bight Group, the Sugar Loaves Basalt has been interpreted by Szybinski (1995) as being Cambrian and comprising the basal formation of the Cambro-Ordovician Western Arm Group.

Note 3: The banded siliceous argillite and magnetite-rich mafic tuff herein assigned to Unit *C:Eat* of the Western Arm Group had been previously placed in Unit C1T (Andrews, 1991) or Unit Ot (Kean and Evans, 1994) and included in the Catchers Pond Group rather than the Lushs Bight Group. They have been tentatively correlated with similar strata in the Ordovician Skeleton Pond Tuff in the type area of the Western Arm Group (Kean *et al.*, 1995).

Note 4: In the vicinity of Spar Pond, the basalt flows, gabbro sills and mafic mylonite herein assigned to Unit *C:Etg* of the Western Arm Group were previously included in Unit C1F of the Catchers Pond Group (Andrews, 1991). If correct, they are possibly partial equivalents of some of the Ordovician mafic volcanic strata observed in Unit O:CPib of the Catchers Pond Group rather than being Cambrian and correlative with the Sugar Loves Basalt or the Big Hill Basalt of Szybinski (1995).

LATE CAMBRIAN OR OLDER?
C:L LUSHS BIGHT GROUP

C:Lu

Unseparated mafic volcanic rocks and associated subvolcanic intrusions belonging to the southwestern part of the Lushs Bight Group (cf. DeGrace, 1971); includes the basaltic pillow lava, pillow breccia, hyaloclastite, chlorite schist, gabbro sills and sheeted diabase dykes of the Cambrian and/or Early Ordovician Lushs Bight Group (*cf.* Kean and Evans, 1994); non-magnetic extrusive and intrusive rocks having numerous chalcopyrite-rich gossans and hosting alteration zones marked by polymineralic veins

C:Liu

Altered ultramafic rocks, including ophiolitic peridotite, serpentinite and talc schist [part of Unit LCOu (Colman-Sadd and Crisby-Whittle, 2005)] and thus representing the oldest exposed part of the Lushs Bight Group as defined by Kean and Evans (1994); possibly correlative with part of the Cambrian Indian Head–Indian Beach complex (Szybinski, 1995)

Note 1: In the area immediately northeast of Catchers Pond, rocks herein assigned to Unit *C:Lu* include massive basaltic flows, subordinate pillow lava and a gabbro sill complex, all of which are thought to be older than the adjacent faulted body of quartz–feldspar porphyry. They are possibly correlative with Unit LCOpd in the lower sequence of the Lushs Bight Group (Kean and Evans, 1994) or they may represent part of the Cambrian Little Bay Basalt (Szybinski, 1995).

Note 2: Most of the rocks shown within the main tract of Unit *C:Lu* were presumed to have comprised the northern and central units of a local south-facing Early Ordovician succession of the Lushs Bight Group, and to have occupied the inverted limb of a southerly-overturned fold nappe (DeGrace, 1971).

Note 3: In the southwesternmost tectonic panel of Unit *C:Lu*, certain extrusive rocks have been excluded from DeGrace's (1971) Lushs Bight Group and, in an alternative interpretation by Andrews (1991), were included in the Ordovician Catchers Pond Group. These comprise part of Unit C1T of Andrews (1991).