Geoscience Canada
Journal of the Geological Association of Canada
Journal de l'Association Géologique du Canada

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Volume 41, numéro 4, 2014

URI : https://id.erudit.org/iderudit/1062258ar
DOI : https://doi.org/10.12789/geocanj.2014.41.053

Éditeur(s)

The Geological Association of Canada

ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

Citer cet article

Schoonmaker, A., Kidd, W., DeLong, S. & Bender, J. (2014). Lawrence Head Volcanics and Dunnage Mélange, Newfoundland Appalachians: Origin by Ordovician Ridge Subduction or in Back-Arc Rift? *Geoscience Canada*, *41*(4), 523–556. https://doi.org/10.12789/geocanj.2014.41.053

Résumé de l'article

Cet article passe en revue le contexte géologique et présente de nouvelles données géochimiques d'éléments traces des roches volcaniques ordoviciennes de Lawrence Head (LHV) et des filons-couches de gabbro sous-jacents du Groupe Exploits. Considérant la combinaison des données d'analyse publiées et des datations de ces roches, les roches volcaniques et les filons-couches sont indiscernables tant en composition qu'en âge, et les données sont compatibles avec l'hypothèse selon laquelle ils représentent le même événement magmatique (principalement E-MORB) du Darriwilien précoce à moyen (~465 ± 2 Ma). Les LHV ainsi que les strates de l'encaissant renferment des indices régionaux qui montrent : 1) que le volume et la granulométrie des matériaux volcanoclastiques d'arc diminuent vers le haut dans l'intervalle supérieur des strates de turbidites sédimentaires sous les LHV; 2) que le changement vers des milieux marins peu profonds localement vers la fin de l'événement des LHV a été suivi immédiatement par une subsidence importante, et 3) qu'il n'existe pas d'indices d'apports clastiques à gros grains, non plus que de formation de failles normales, durant ou immédiatement après le magmatisme des LHV. L'interaction crête-fosse (subduction de la crête) au lieu d'un système de subduction concorde avec toutes ces caractéristiques et la répartition spatiale des éléments reliés, alors qu'une origine de crête (arrière-arc) au-dessus d'une zone de subduction ne peut expliquer que les compositions et qu'elle est incompatible avec l'évidence géologique. Le Dunnage Mélange (DM) a été interprété soit comme un olistostome dans un bassin d'arrière-arc en développement, ou comme un prisme d'accrétion de subduction. Les intrusions hyperalumineuses dans le mélange (Porphyre Coaker — CP), s'explique plus facilement par une subduction de crête, et un âge de datation sur zircon de (469 ± 4 Ma) correspond à l'âge des LHV et des filons-couche de gabbro, aussi interprétés comme produits d'une subduction de crête. La localisation du CP dans la portion orientale du DM, et de la majeure partie des grands blocs volcaniques dérivés des LHV de la portion ouest du DM, suggère un âge légèrement plus jeune, et peut-être un mécanisme différent, pour l'origine de la portion ouest du DM.

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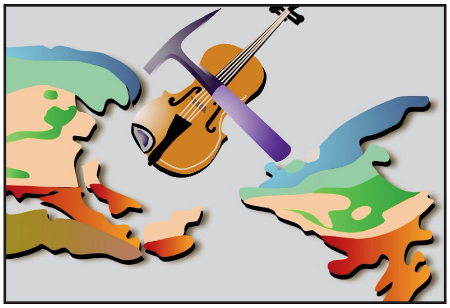

Lawrence Head Volcanics and Dunnage Mélange, Newfoundland Appalachians: Origin by Ordovician Ridge Subduction or in Back-Arc Rift?

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SUMMARY

This paper reviews the geological setting and reports new geochemical trace element data from the Ordovician Lawrence Head Volcanics (LHV) and the underlying gabbro sills in the Exploits Group. In combination with existing published analyses and ages of these rocks, the volcanic rocks and sills are indistinguishable in composition and age, and the data are consistent with the hypothesis that they represent the same (mostly E-MORB composition) magmatic event in the early–mid Darriwilian (~465 ± 2 Ma). The LHV and their enclosing strata show regional evidence for: 1) upward decline of volume and grain size of arc-derived volcaniclastic materials over the uppermost interval of turbidite sedimentary strata below the LHV; 2) change to shallow marine conditions locally by the end of the LHV event, followed immediately by significant subsidence, and 3) no evidence of coarse-grained clastic input, nor of normal faulting, during or immediately after LHV magmatism. Ridge–trench interaction (ridge subduction) at a subduction system is consistent with all of these features and spatial distribution of related elements, but a rift (back-arc) origin over a subduction zone can only accommodate the compositions, and is inconsistent with the geological evidence. The Dunnage Mélange (DM) has been interpreted either as olistostromal in a developing back-arc rift basin, or as a subduction accretionary prism. Peraluminous intrusions in the mélange (Coaker Porphyry — CP) are more readily explained by ridge subduction, and a previously reported zircon age (469 ± 4 Ma) is consistent with the age of the LHV and gabbro sills, also interpreted as products of ridge subduction. Localization of the CP in the eastern area of DM, and of most of the large LHV-derived volcanic blocks in the western DM, suggests a slightly younger age, and perhaps a different mechanism, for the origin of the western DM.

SOMMAIRE

Cet article passe en revue le contexte géologique et présente de nouvelles données géochimiques d'éléments traces des roches volcaniques ordoviciennes de Lawrence Head (LHV) et des filons-couches de gabbro sous-jacents du Groupe Exploits. Considérant la combinaison des données d'analyse publiées et des datations de ces roches, les roches volcaniques et les filons-couches sont indiscernables tant en composition qu'en âge, et les données sont compatibles avec l'hypothèse selon laquelle ils représentent le même événement magmatique (principalement E-MORB) du Darriwilien précoce à moyen (~465 ± 2 Ma). Les LHV ainsi que les strates de l'encaissant renferment des indices régionaux qui montrent : 1) que le volume et la granulométrie des matériaux volcanoclastiques d'arc diminuent vers le haut dans l'intervalle supérieur des strates de turbidites sédimentaires sous les LHV; 2) que le changement vers des milieux marins peu profonds localement vers la fin de l'événement des LHV a été suivi immédiatement par une subsidence importante, et 3) qu'il n'existe pas d'indices d'apports clastiques à gros grains, non plus que de formation de failles normales, durant ou immédiatement après le magmatisme des LHV. L'interaction crête-fosse (subduction de la crête) au lieu d'un système de

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Geoscience Canada, v. 41, http://dx.doi.org/10.12789/geocanj.2014.41.053

subduction concorde avec toutes ces caractéristiques et la répartition spatiale des éléments reliés, alors qu'une origine de crête (arrière-arc) au-dessus d'une zone de subduction ne peut expliquer que les compositions et qu'elle est incompatible avec l'évidence géologique. Le Dunnage Mélange (DM) a été interprété soit comme un olistostome dans un bassin d'arrière-arc en développement, ou comme un prisme d'accrétion de subduction. Les intrusions hyperalumineuses dans le mélange (Porphyre Coaker — CP), s'explique plus facilement par une subduction de crête, et un âge de datation sur zircon de (469 ± 4 Ma) correspond à l'âge des LHV et des filons-couche de gabbro, aussi interprétés comme produits d'une subduction de crête. La localisation du CP dans la portion orientale du DM, et de la majeure partie des grands blocs volcaniques dérivés des LHV de la portion ouest du DM, suggère un âge légèrement plus jeune, et peut-être un mécanisme différent, pour l'origine de la portion ouest du DM.

INTRODUCTION

The Exploits Group, part of the Dunnage Zone in the Bay of Exploits–New Bay area of north-central Newfoundland (Fig. 1), is composed of volcanic, volcaniclastic, and sedimentary rocks of early to medial Ordovician age that formed during closure of part of the Cambrian to Silurian ocean termed proto-Atlantic (Wilson 1966; Dewey and Bird 1971), Protacadic (Kay 1972), Iapetus (McKerrow and Ziegler 1972), or Appalachian (Kidd et al. 1978) Ocean, in the peri-Gondwanan part of that ocean (van Staal et al. 1998). These strata are adjacent and related to the Dunnage Mélange, a unit proposed by some to be associated with subduction of, or within, the Iapetus Ocean (Dewey and Bird 1971; Kay 1972, 1976; Williams 1979; Nelson and Casey 1979; O'Brien et al. 1997; van Staal et al. 2009). A series of volcanic flows and related rocks that have volcanic arc chemical affinities form the base of the Exploits Group (O'Brien et al. 1997; Penobscot Arc of Zagorevski et al. 2007, 2010). Sedimentary rocks of the middle section of the Exploits Group are largely volcaniclastic turbidite and lesser debris flow deposits of a deep marine setting, intruded abundantly by gabbro sills, and are overlain by a thick volcanic sequence, the Lawrence Head Volcanics (Helwig 1969); Lawrence Head Formation of some later authors, but we use Helwig's original designation in this paper. The sedimentary rocks and the Lawrence Head Volcanics have been interpreted either as deposits of a fore-arc basin/arc–trench gap setting (Dewey and Bird 1971; Kay 1972, 1976) or as an extensional basin related to intra-arc or back-arc rifting (Nelson and Casey 1979; O'Brien et al. 1997; Zagorevski et al. 2007, 2010), above a subduction zone interpreted respectively as either northwest-dipping, or southeast-dipping. The volcanic section, the Lawrence Head Volcanics, emplaced at the time of, or very shortly following cessation of arc activity (Kidd et al. 1977), has an E-MORB chemical signature (Wasowski and Jacobi 1984; O'Brien et al. 1997; Zagorevski et al. 2007) and has been suggested as a possible product of spreading ridge subduction (or ridge–trench interaction) by Kidd et al. (1977), van Staal et al. (1998) and Zagorevski et al. (2007, 2012). This magmatic event is approximately coeval with ophiolite emplacement and the related Taconic orogenic event on the Laurentian continental margin.

We present geochemical trace element data from a new sample suite of the Lawrence Head Volcanics (LHV) and the gabbro sills of the Exploits Group, intentionally restricted in geographic and geological extent, and of some potentially related rocks from the Dunnage Mélange; we compare these data to existing analyses of igneous rocks of the Exploits Group and Dunnage Mélange. The geologic setting of Lawrence Head volcanism has significant implications for the arc–basin geometry and subduction history of the Middle Ordovician of north-central Newfoundland and other equivalent regions of the northern Appalachians. This paper also evaluates the conflicting tectonic models proposed for these rocks (e.g. Kidd et al. 1977; Hibbard and Williams 1979; O'Brien et al. 1997; Zagorevski et al. 2010).

GEOLOGIC SETTING

The Exploits Group is part of the Dunnage Zone, a regionally extensive group of oceanic and arc-related rocks within the Northern Appalachians (e.g. Dewey and Bird 1971; Kay 1972, 1976; Williams 1979; Lorenz 1985; Coleman-Sadd et al. 1992; O'Brien et al. 1997; MacLachlan et al. 2001; Zagorevski et al. 2007, 2010), widely regarded to have formed within the Iapetus Ocean (e.g. Williams 1979; Dewey et al. 1983). The Dunnage Zone is broadly divided by the Red Indian Line, a regionally extensive fault boundary separating western peri-Laurentian rocks of the Notre Dame Subzone from easterly peri-Gondwanan rocks of the Exploits Subzone (Williams et al. 1995); as such the Red Indian Line is the fault-modified relict of the major suture formed during closure of the Iapetus Ocean. The Exploits Group, part of the Exploits Subzone, forms a continuous sequence of volcanic, intrusive, and sedimentary rocks that occurs southeast of the Red Indian Line (Sops Head–Lukes Arm Fault in this area), extending to the Dunnage Mélange to the southeast in the Bay of Exploits–New Bay region of Notre Dame Bay in north-central Newfoundland (Williams 1995; Fig. 1).

The Exploits Group in the New Bay–Bay of Exploits area (Helwig 1967, 1969; Horne and Helwig 1969; O'Brien et al. 1997; Figs. 2, 3, 4) consists largely of volcaniclastic and volcanic rocks with slate and chert, prominently folded and mostly in lowest greenschist (Nelson 1979) or prehnite-pumpellyite facies (Franks 1974). At its base, the Tea Arm Formation (originally Tea Arm Volcanics; Helwig 1969) consists of a series up to about 1500 m thick of dominantly mafic volcanic rocks, commonly in pillowed flows, with rare hyaloclastite, and with rhyolitic flows and pyroclastic rocks and minor interflow limestone beds near its top (O'Brien et al. 1997). Trace element geochemistry of these volcanic rocks indicates an arc origin (O'Brien et al. 1997), including boninitic compositions (Wasowski 1985), and the volcanic rocks of the Tea Arm Formation are interpreted to be related to the Cambrian to early Ordovician Penobscot arc that may have formed as an intra-oceanic arc (Dunning et al. 1991;

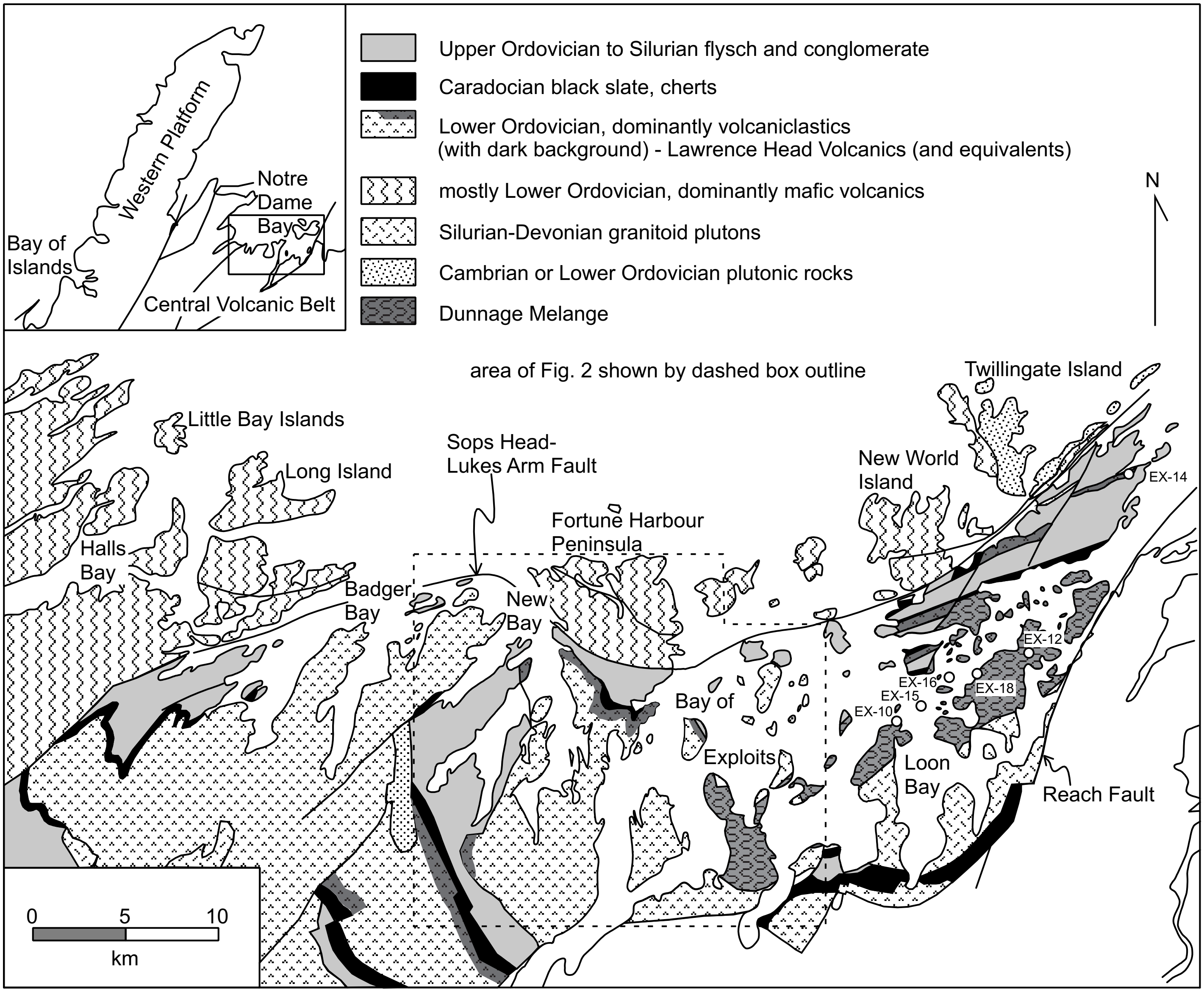

Figure 1. Outline geological map of the Notre Dame Bay region of Newfoundland. Lawrence Head Volcanics and equivalent volcanic rocks are shown only for sections that are dominantly volcanic flows; possible mostly fragmental equivalents are found elsewhere in the Lower Ordovician Exploits Group in the same stratigraphic position just below the mid-Ordovician cherts and black shale (Shoal Arm Fm.). Sample locations and numbers of this study are shown only for those sites outside the area of Figure 2 (dashed outline).

O'Brien et al. 1997), or on the western margin of Ganderia (Zagorevski et al. 2007, 2010). They are correlated with other basal arc-related magmatic rocks of the Wild Bight, Pats Pond, Tulks, Long Lake, and Tally Pond groups (Zagorevski et al. 2007, 2010). Age data from the Tea Arm Formation and other related rocks in the Exploits Subzone range widely (see references in Zagorevski et al. 2010, p. 369) but in the area of focus of this paper O'Brien et al. (1997) obtained a well-constrained concordant U–Pb (zircon) age of 486 ± 3 Ma from a tuff in the upper part of the Tea Arm Formation. The volcanic section is conformably overlain by marine, volcanic-derived arenites and mudrocks of the Saunders Cove Formation, largely turbidites, about 400 m thick. The top of the Tea Arm Formation is conformably interbedded, and in part laterally equivalent with the Saunders Cove Formation; hematitic red argillite layers in that unit were probably derived from sub-aerial weathering of (lateral equivalents to) volcanic rocks of the upper Tea Arm Formation (Horne and Helwig 1969).

Conformably overlying the Saunders Cove Formation (top of the lower Exploits Group section) is the New Bay Formation (Helwig 1969; Horne and Helwig 1969), a sedimentary sequence at least 1700 m thick, dominantly consisting of coarse (in places pebbly) to fine-grained volcaniclastic turbidites and pelites (Horne and Helwig 1969; Helwig 1969; Hughes and O'Brien 1994; O'Brien et al. 1997). Near the top of the New Bay

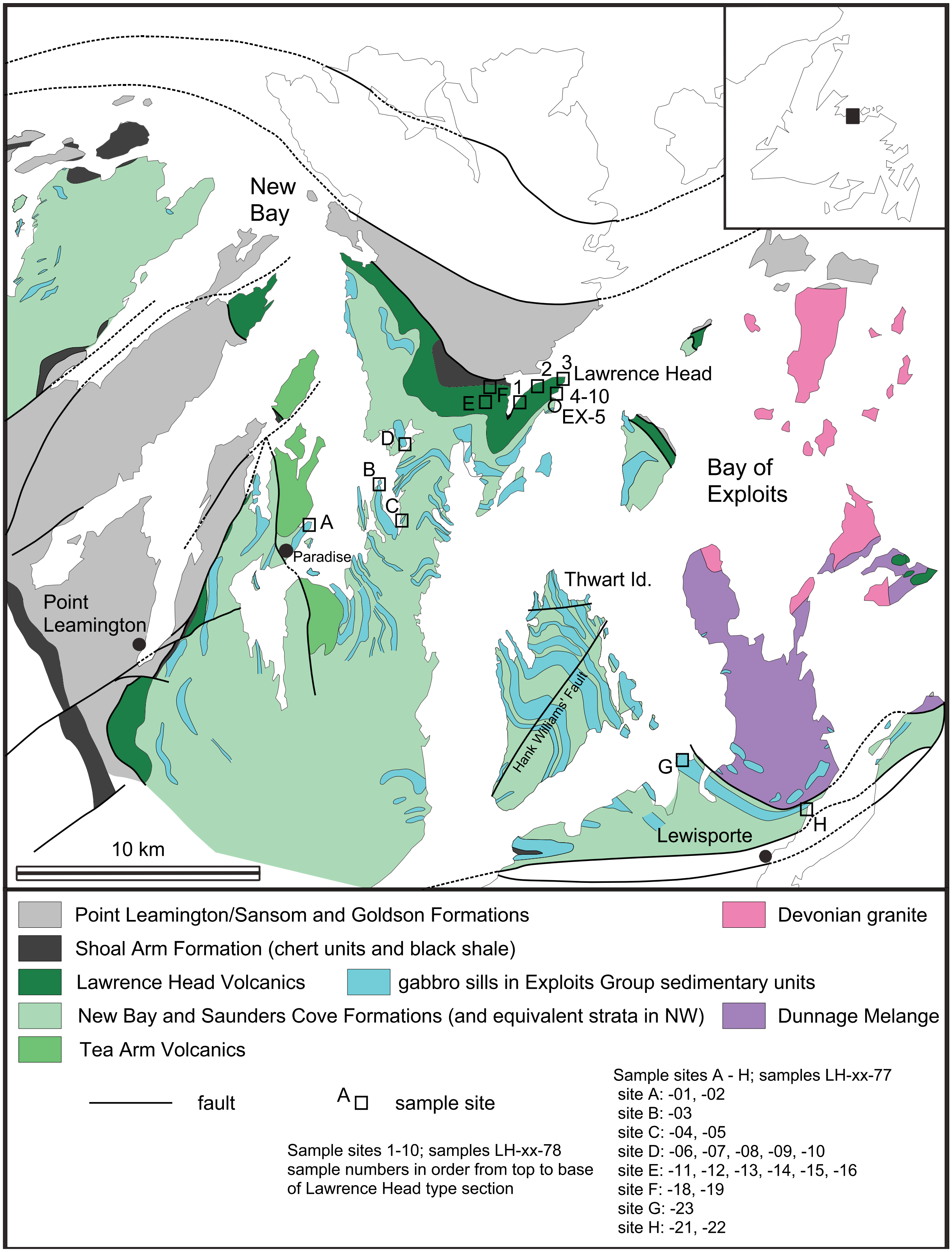

Figure 2. Geological location map of the Exploits subzone in the New Bay–Bay of Exploits area. Sample sites for this study are shown, with sample numbers for each site listed below. Lawrence Head Volcanics and equivalents are shown only for sections that are dominantly volcanic flows; possible mostly fragmental equivalents are found elsewhere in the Lower Ordovician Exploits Group in the same stratigraphic position just below the mid-Ordovician cherts and black shale (Shoal Arm Fm.). Gabbro sills occur throughout the New Bay and Saunders Cove Formations up to the base of the Lawrence Head Volcanics, forming about 25% of the section thickness in this area. Map compiled from those of Williams (1964), Helwig (1967), Nelson (1979), Hibbard and Williams (1979), Livaccari (1980), O'Brien (2006), and field observations.

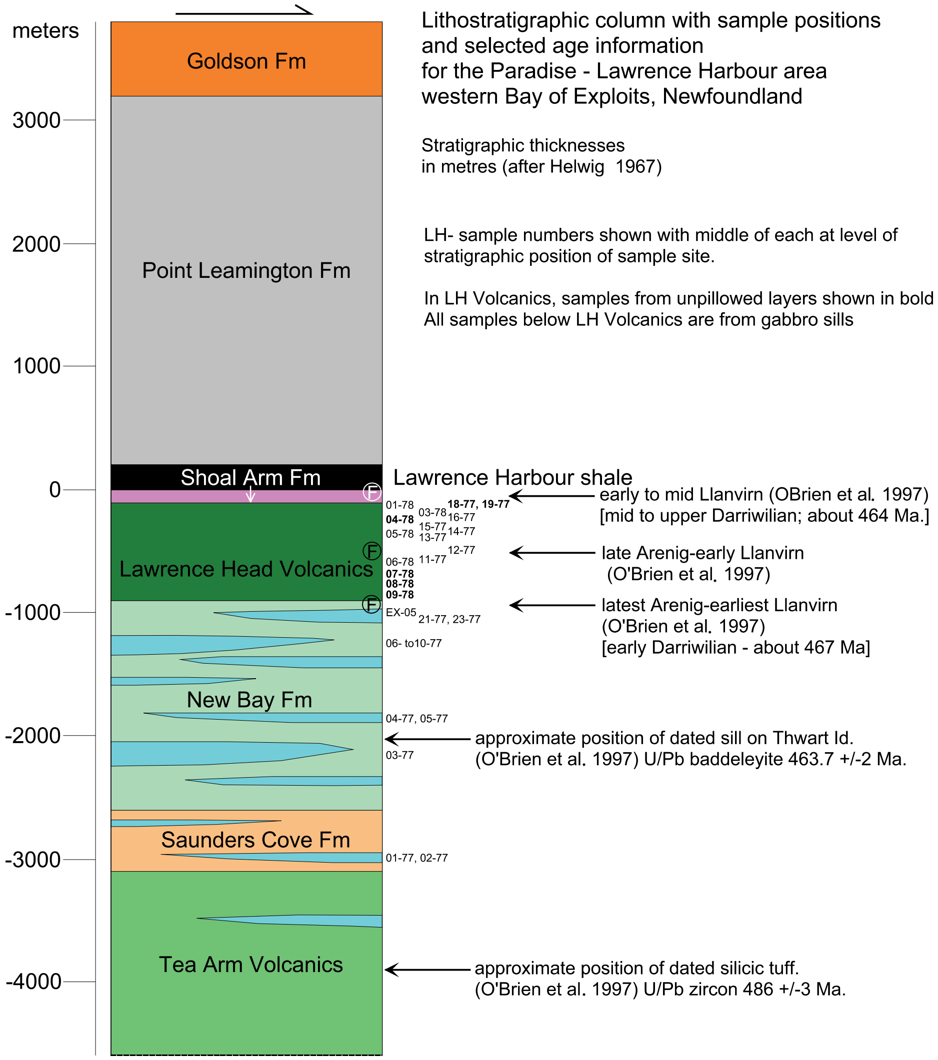

Figure 3. Lithostratigraphic column for the Exploits Group and adjacent units of the western Bay of Exploits–New Bay area, showing sample positions and numbers, and key age information for the Lawrence Head Volcanics and the gabbro sills. Stratigraphic information after Helwig (1967); age information from O'Brien et al. (1997).

Formation, directly below volcanic rocks of the overlying Lawrence Head Formation, latest Arenig to earliest Llanvirn[1] graptolites are present (O'Brien et al. 1997).

Facies relationships in the New Bay Formation, and its lateral equivalent to the northwest, a substantial part of the Wild Bight Group, are such that coarser grained volcaniclastic and pelite-poor sequences occur to the northwest, whereas finer grained, pelite-rich facies occur to the southeast (Nelson 1979). This trend continues to the southeast in the Dunnage Mélange, in which the volumetrically dominant argillaceous matrix and blocks strongly resemble the lithologies of the New Bay Formation, to which it is correlated (Hibbard and Williams 1979; O'Brien et al. 1997). This facies arrangement suggests a volcanic sediment source to the northwest (present day coordinates). Helwig (1967) reported local sole marks in turbidite sections of the New Bay Formation that indicate a northeast to east transport direction, presumably parallel with the bathymetric long axis of the basin.

The New Bay Formation is overlain by the Lawrence Head Volcanics, a sequence up to about 900 m thick in the type section of mafic volcanic rocks (Helwig 1969; Horne and Helwig 1969), erupted during a magmatic event that is the main focus of this paper. In the type section at Lawrence Head, these rocks are dominated by massive flows and possibly shallow-level sills that are metres to tens of metres thick in its lower part, and by pillowed basalt in its upper part. Late Arenig to early Llanvirn graptolites occur in interflow sedimentary rocks in the upper part of the volcanic section in a locality on Strong Island (O'Brien et al. 1997), about 10 km west of the type section, and early to mid-Llanvirn conodonts were found in limestone (Hummock Island Limestone) directly on the topmost pillow lava of the Lawrence Head Formation about 5 km ENE of the type section (O'Brien et al. 1997). Given these fossil occurrences at the top of the New Bay Formation and within and near the top of the Lawrence Head Formation, eruption of volcanic rocks likely occurred during the interval 467–463 Ma (see discussion of ages, below).

Geochemical studies (Wasowski and Jacobi 1984; O'Brien et al. 1997) have shown the Lawrence Head Volcanics to be enriched in light rare earth elements (LREE) and O'Brien et al. (1997) interpreted them to be within-plate tholeiites erupted in a back-arc basin. In this paper we more fully address the geochemical properties of the volcanic rocks and the likely tectonic environment in which they erupted, as well as their relationship with gabbroic sills in the New Bay Formation, and presumed equivalent volcanic and gabbroic blocks in the Dunnage Mélange.

The New Bay and underlying Saunders Cove Formations both contain abundant gabbroic intrusions (Helwig 1967; Franks 1974), mostly sills, some of substantial size and lateral extent, and forming perhaps 25–30% of the total thickness of the Saunders Cove–New Bay section in the Paradise–Lawrence Head area below the Lawrence Head Volcanics type sec-

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[1] stage names for fossil assemblage age picks are given as reported in the original reference; equivalence to the new Ordovician stages is made later in this paper in the section discussing age constraints.

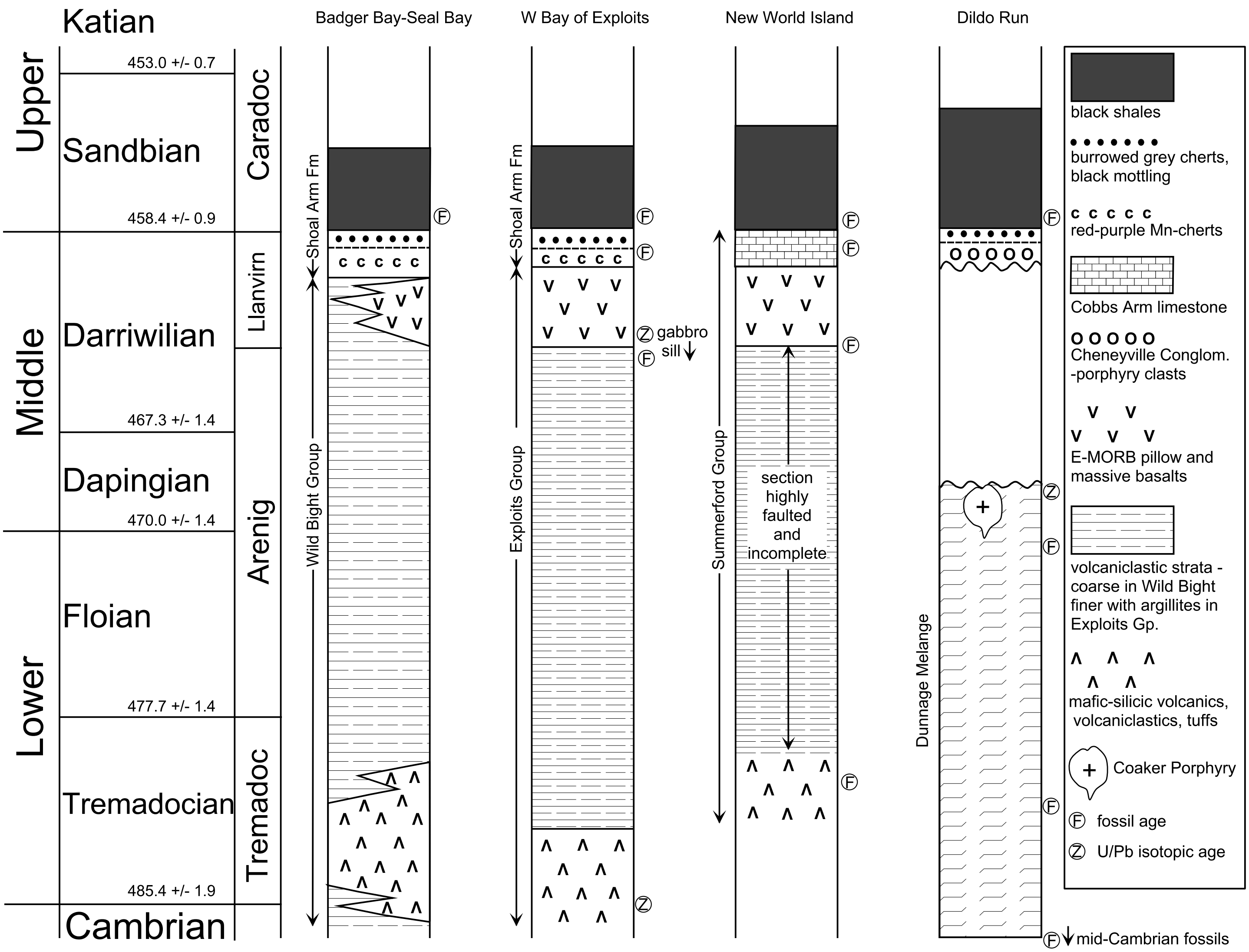

Figure 4. Stratigraphic columns for the Exploits sub-zone Ordovician sections of Badger Bay–Seal Bay, western Bay of Exploits, New World Island, and Dildo Run areas. Chronostratigraphic calibrations sourced from the International Commission on Stratigraphy Chronostratigraphic Chart v2013/1 (ICS 2013), and the Ordovician Chronostratigraphic Chart of Bergström et al. (2009). Based on compilation and field data of Nelson (1979), and including data from Helwig (1967, 1969), Horne (1968, 1969), Kay and Eldredge (1968), Horne and Helwig (1969), Bergström at al. (1974), Neuman (1976), Kay (1976), and Hibbard and Williams (1979); modified and supplemented by data from Williams (1995), S.H. Williams et al. (1995), O'Brien et al. (1997), and Zagorevski et al. (2012). Some boundaries, in particular the tops of the two main volcanic intervals, may be hiatuses, but age data to show this are not available. Cambrian and Arenig fossils in the Dunnage Mélange are in blocks.

tion (see map Fig. 2). These gabbroic rocks are referred to as the Thwart Island Gabbro by O'Brien et al. (1997). The gabbroic rocks are present in the sedimentary section up to the base of the Lawrence Head Volcanics and, according to O'Brien (2012), some gabbroic intrusions lead to diabase sections within the basal Lawrence Head, and those in some cases are feeders to lava tubes. Franks (1974) first suggested the gabbro sills are the intrusive equivalent to the overlying Lawrence Head Volcanics; followed by Kidd et al. (1977) in linking this magmatism to a ridge subduction event. However, a U–Pb date [baddeleyite] of 463.7 ± 2 Ma obtained by O'Brien et al. (1997) from a gabbro sill on Thwart Island, and some differences in trace element geochemistry, led O'Brien et al. (1997) and Zagorevski et al. (2010) to suggest that the gabbroic intrusions are unrelated to the Lawrence Head Formation volcanic rocks, which they also inferred to be slightly older than the gabbro sills.

In the area of New World Island, thrust sheets of the Exploits terrane detached within an early Ordovician volcanic section (Summerford Group; Horne 1968, 1969; Kay 1976; van der Pluijm 1986) contain lavas equivalent to the Lawrence Head (Jacobi and Wasowski 1985). In many places structural complexities and incomplete outcrop confuse definitive correlation, but in some areas where the section is stratigraphically better preserved (as at Cobbs Arm) the lavas immediately underlying the middle Ordovician black shale and local limestone can be identified as likely Lawrence Head correlatives.

The Lawrence Head Volcanics are conformably overlain by a thin unit of red and green chert and argillite, then by a mottled grey chert unit (the lower two of three members of the Shoal Arm Formation; termed Strong Island Chert by O'Brien et al. 1997) that are succeeded (Helwig 1967, 1969) by the black, graptoliferous shale of the Lawrence Harbour Shale; these chert and shale units are collectively referred to as the Shoal Arm Formation (Espenshade 1937; Helwig 1969; Nelson 1979; Brüchert et al. 1994; O'Brien et al. 1997), and recognizably extend throughout the Exploits terrane. The Strong Island chert contains a graptolite fauna identified as of late Arenig or early Llanvirn age, and no higher than mid-Llanvirn, by O'Brien et al. (1997). Geochemical trace element characteristics of the red and grey chert units of the Shoal Arm Formation show the detrital clay component in the red chert was derived (probably by weathering, given the accompanying hematite) from Lawrence Head-type volcanic rocks, and this input declined on passage up into the overlying grey chert (Brüchert et al. 1994).

The black shale of the Lawrence Harbour Formation and equivalent units throughout the Exploits terrane (Fig. 4) mark the initiation of a foreland basin on the previously volcanic arc or arc-adjacent strata below (Brüchert et al. 1994; Zagorevski et al. 2008). More than 3500 m of turbidite and debris flow deposits accumulated above it in the New Bay area, a coarsening-upward flysch sequence assigned to the late Ordovician–early Silurian Point Leamington and Goldson Formations by Helwig (1967); the Badger Group (H. Williams et al. 1995). A very similar sequence of the same age range and sedimentary facies is well documented from New World Island (Horne 1968; Horne and Helwig 1969; Kay 1976; McKerrow and Cocks 1978; Arnott 1983; Arnott et al. 1985). This marine foreland basin, probably a site of rapid flexural subsidence, was initiated by the deep water graptolitic black shale, then progressively filled with clastic material dominantly derived from erosion of plutonic rocks of magmatic arc origin (Helwig 1969) and from the northwest (Helwig and Sarpi 1969). The lower turbidites also contain a significant component of ophiolite-derived chromite (Nelson and Casey 1979). Paleocurrent evidence shows basin axis-parallel flow mostly to northeasterly through southerly directions (Helwig 1967, 1969; Nelson 1979; Arnott 1983); slump structures indicate a southeasterly downslope direction in the New Bay area (Pickering 1987). Evidence of a component of contemporary southeast-directed thrust tectonics is found on the northwest margin of the Exploits terrane in the Sops Arm–Boones Point Mélange (Nelson 1979, 1981) where the mélange matrix and many blocks are derived from Point Leamington turbidites, with some blocks derived from the adjacent older Roberts Arm–Chanceport terrane volcanic rocks in the thrust hanging wall. The plutonic-dominated clastic content, the paleoslope indicators, and the direct evidence of late Ordovician–early Silurian overthrusting from the northwest, show that the uplifting eroding source terrane for this foreland basin was to the northwest. We think substantial later repositioning or removal by strike-slip displacements must have occurred as no eroded plutonic-dominated source terrane of suitable dimensions, adequate to supply the coarse thick conglomerates containing very sparse proportions of volcanic clasts, is now found adjacent to the Exploits terrane in Notre Dame Bay.

The Dunnage Mélange is a regionally extensive, chaotic and disrupted shale matrix unit that contains dismembered blocks of mafic volcanic rocks, sedimentary materials (mostly greywackes), and (mostly gabbroic) intrusive rocks (Horne and Helwig 1969; Kay 1972, 1976; Hibbard and Williams 1979; Williams 1994). The main body of mélange borders the east and northeast part of the main belt of the Exploits Group (Fig. 1) and correlative units on New World Island border the mélange to the north. Kay and Eldredge (1968), and Kay (1976) reported Middle Cambrian trilobites from a limestone bed interstratified with volcanic rocks making up one of the blocks in the Dunnage, and Hibbard and Williams (1979) reported conodonts as young as Arenig from a small limestone block (Fig. 4).

The lithologic similarity of the blocks in the mélange to the New Bay and Lawrence Head units of the Exploits Group led to the conclusion that the Dunnage Mélange is a disrupted version of the New Bay and Lawrence Head formations to which it is adjacent (Williams and Hibbard 1976; Hibbard and Williams 1979; Lorenz 1985; Wasowski and Jacobi 1985; Williams 1994). Those authors suggested that the zone of mélange containing large and abundant mafic volcanic blocks extending northeastward from Sivier Island through the Comfort Cove Peninsula is derived from the Lawrence Head Volcanics (see figure 2 of Hibbard and Williams 1979), and that the main body of gabbroic blocks occurring in the southwest part of the mélange, is derived from the large volume of sills (Thwart Island Gabbro of O'Brien et al. 1997) in the adjacent New Bay Formation (Hibbard and Williams 1979). However, Williams (1994) reported a greater variation in lithology and their proportion of blocks within the mélange than in surrounding units, possibly suggesting a more complicated relationship.

Deformation in the mélange likely occurred during or shortly after deposition due to abundant evidence in it of soft sediment slumping and olistostromal deposits, but the mélange also displays features characteristic of tectonic disruption (Kay 1972; Hibbard and Williams 1979; Lorenz 1985; Williams 1994; Zagorevski et al. 2012). The (by comparison) undisrupted nature of overlying sedimentary units (Dark Hole Formation shale and succeeding Sansom or Milliners Arm Formation flysch turbidites) are good evidence that the mélange had ceased to form by the time of the deposition of the earliest part of this section, defined by faunas from the Dark Hole Formation shale which are later Caradocian [later Sandbian, about 455 Ma] (Bergström et al. 1974; Arnott et al. 1985). If the underlying unfossiliferous Cheneyville conglomerate is equivalent to the older part of the Lawrence Harbour Formation shale, the age of this, *N. gracilis* zone, formerly early Caradocian, now early Sandbian, about 458

Ma, would provide a slightly older upper limit (Fig. 4). Blocks of gabbro show locally intrusive remnant contacts against argillite, and are disrupted in the mélange perhaps suggesting syn-deformation intrusion. The Coaker Porphyry largely cross-cuts the mélange, but shows local evidence of intrusion into soft sediment muds and folding of dykes in the mélange matrix (Kay 1976; Lorenz 1984); a U–Pb zircon date of 469 ± 4 Ma (Zagorevski et al. 2012) places an upper bound on the soft sediment deformation and/or significant tectonic disruption of the Dunnage Mélange.

The Dark Hole Formation shale that structurally overlies the Dunnage Mélange in the vicinity of New World Island (Hibbard and Williams 1979; Lorenz 1985) is correlated with the Lawrence Harbour Formation shale in the New Bay area. The contact between the Dunnage Mélange and Dark Hole Formation (locally with a basal conglomerate at Cheneyville; Kay 1972, 1976; Hibbard and Williams 1979) has been interpreted to be structurally conformable by some authors (Horne 1969; Williams and Hibbard 1976; Hibbard and Williams 1979) but faulted by others (Kay 1972; Lorenz 1985). Lorenz (1985) noted that intrusions of Coaker Porphyry, abundant in the adjacent Dunnage Mélange (Kay 1976), are not present in the Dark Hole Formation shale. However, clasts of quartz-feldspar porphyry are abundant in the Cheneyville conglomerate, stratigraphically just underneath the Dark Hole Formation, and these have been suggested to be eroded from Coaker Porphyry, or porphyry closely resembling it (Kay 1976); such a relationship is consistent with the U–Pb age quoted above and the Caradocian (Sandbian) age of the graptolite fauna in the Dark Hole Formation (Bergström et al. 1974). Also, we emphasize that intrusions of gabbro, and volcanic rocks, are entirely absent from the Dark Hole and Lawrence Harbour shales and the whole thick conformable section of later Ordovician and early Silurian clastic stratigraphic units above the Lawrence Head/Dunnage Mélange.

Tectonic interpretations proposed for the origin of the Dunnage Mélange include either a very large scale olistostromal event into, or by closure/proto-subduction of, a back-arc basin (Hibbard and Williams 1979; Lorenz 1985; Williams 1994; O'Brien et al. 1997; Zagorevski et al. 2010), or from subduction accretion in the inner trench wall and slope of a primary oceanic subduction zone (e.g. Dewey and Bird 1971; Kay 1972, 1976). The geochemistry of xenoliths in the Coaker Porphyry suggests (Zagorevski et al. 2012) that the Dunnage Mélange was involved with a spreading ridge–trench interaction (ridge subduction) and the local deformation of the Coaker Porphyry by the mélange fabric supports this idea.

PETROGRAPHY AND SELECTION OF SAMPLES

All rocks for which analyses are reported in this paper have been examined in thin section and all of the mafic and gabbroic rocks of the units sampled have undergone alteration by low grade metamorphism, either of prehnite-pumpellyite (Franks 1974) or lowest greenschist facies. In the Lawrence Head Volcanics, some outcrops show relict evidence of alteration and mineralization probably by submarine hydrothermal systems. Samples taken for analysis in this study were selected to avoid, by as large a distance as possible, faults, veins, strongly fractured or cataclastic areas, discolouration suggestive of pervasive hydrothermal alteration, altered pillow rinds, and anything more than minor phenocryst content, or amygdales. In addition, samples analyzed from gabbro sills were selected for the most part from the diabase chilled margin(s), apart from three selected within one sill because they show compositional variations due to igneous layering.

Alteration of the primary igneous minerals in the basalt and gabbro samples is variable from slight to extensive and varies in degree from sample to sample for any given mineral species. No primary olivine survives, although serpentine or chlorite pseudomorphs of a few percent of the total rock volume are commonly observed in gabbro samples. Pyroxene, where preserved, is augite or titanaugite, and is commonly zoned to Ti-rich rims. Much pyroxene in many samples has been replaced by actinolitic amphibole. Plagioclase has less commonly preserved its original composition than clinopyroxene, although optical compositional determinations of up to about An_{70} were found in the core of feldspar grains in two gabbro samples. More commonly the plagioclase in gabbro is altered to albite; clear discontinuous rims of albite composition may be primary igneous material. Most plagioclase contains abundant dusty sericite alteration in all but these albite rims. Opaque mineral grains are common, most easily recognized as primary in gabbro samples, where common narrow cryptocrystalline sphene alteration rims reflect the ilmenite composition. In gabbro, some samples contain minor quantities of anhedral quartz that are localized at junctions of other igneous mineral grains and that may represent residual crystallization from the melt. Gabbro dykes (Grapnel Gabbro) sampled from the Dunnage Mélange contain abundant primary phlogopite; this is not seen in the New Bay gabbro sills, nor in the gabbro blocks we sampled from the Dunnage Mélange.

Basalt samples have more extensive metamorphic alteration than gabbro samples; plagioclase is wholly altered to albite, clinopyroxene is much less common, and olivine pseudomorphs are harder to distinguish from altered glassy or fine-grained groundmass. However, despite the extensive alteration of the primary igneous mineralogy of these rocks, the igneous textures are still readily visible, as in both gabbro and basalt samples the alteration mineralogy does not in most places coarsely overgrow the original mineral grain boundaries so as to obscure them. The samples from gabbro blocks in the Dunnage Mélange are unavoidably affected by closely spaced fracturing and narrow zones of cataclastic strain associated with those fractures.

Whole Rock Trace Element Geochemistry

We report a total of 37 new analyses of mafic whole rock samples from the Lawrence Head Volcanics, gabbro and diabase sills from the New Bay Formation, and blocks from the Dunnage Mélange (Table 1; see Figs. 1–3 for sample locations). These include an anorthositic sample (NB-07-77) and a trondhjemitic dyke (NB-02-77), both from gabbro sills within the New Bay Formation, that are not used in the geochemical discrimination diagrams presented below. Samples were analyzed for trace element and rare earth element concentrations using a combination of x-ray fluorescence (XRF), inductively coupled plasma–mass spectrometry (ICP–MS), isotope dilution mass spectrometry (IDMS), and electron microprobe methods (Table 1). Additionally, we have compiled analyses of 19 samples from the Lawrence Head Volcanics, four gabbro samples from the New Bay Formation, and a dyke thought to be a feeder to Lawrence Head flows, for comparison, from O'Brien et al. (1997). Gabbro sills in the New Bay Formation were called the Thwart Island Gabbro by O'Brien et al. (1997) and in the following section we use that term when referring to their samples only, although they are equivalent to gabbro sills we sampled in the New Bay Formation. Detailed laboratory procedures for all samples are described in Appendix 1. Twenty-nine of the samples were collected in 1977 and 1978, and come mainly from the gabbro intrusions in the New Bay Formation and volcanic layers from the type section of the Lawrence Head Formation in the Exploits Group. A further eight samples collected in 2008 (EX-series) include six basalt, diabase, and gabbro samples (including two of the Grapnel Gabbro) collected from blocks, or dykes, within the Dunnage Mélange (Figs. 1–3), one pillow lava at Cobbs Arm from the Summerford Group, and one diabase from a sill in the New Bay Formation near Lawrence Head.

Polished glass beads from whole rock samples from the 1977 and 1978 collections (LH-77 and LH-78 series in Table 1) were analyzed in 1982 for major element concentrations and trace elements (Rb, Sr, Y, Zr, Nb, V, Cr, Co, and Ni) using the ARL electron probe at Harvard University. Eight of the samples were re-analyzed in 2003 by the GeoAnalytical Lab at Washington State University to assess the precision and accuracy of the earlier analyses. Figure A.1 shows the percent difference between the 1982 and 2003 analyses for eight samples and 10 trace elements and TiO_2 ((old–new)/new x 100). For most elements, the difference is less than 25% except for Rb, Nb, and Cu, where some outliers occur. Rb and Cu are not used in our discussion, but Nb is used in several diagrams in this section. However, due to the very low absolute concentrations of Nb, this is likely of little practical significance (e.g. 4.8 vs. 9.0 ppm for sample LH-05-77 is a – 47% difference, but in the context of the Nb-based figures used below, the point moves very little, and does not change any conclusions derived from these diagrams). Percent differences in TiO_2 concentrations, from the older set of analyses to the more recent, range from 3.4 to 7.3%; this also does not significantly affect conclusions drawn. Samples that were re-analyzed in 2003 replace the earlier analyses in Table 1 and are marked with an asterisk. The eight samples (EX series in Table 1) from the 2008 field season were analyzed using XRF and ICP–MS methods at Washington State University in 2013.

As described above, magmatic rocks from this area have been exposed to approximately lower greenschist-facies regional metamorphism and, in at least some places, especially in the volcanic portions, to hydrothermal alteration. Because this raises the potential for major element mobility, our geochemical analysis focuses on the behaviour of immobile trace and rare earth elements to make inferences about mantle source, tectonic setting, and correlations.

All rocks analyzed for this study plot in the basalt and alkali basalt fields of the Zr/Ti vs. Nb/Y diagram (Fig. 5) of Winchester and Floyd (1977). The more alkalic samples (alkali basalt) are exclusively of the Lawrence Head Formation of O'Brien et al. (1997), although some samples of their suite are basalt. They have silica contents that range from 42.84–57.71% (with one outlier [EX-10] with 36.48% SiO_2) and alkali element (Na + K) concentrations of 2.23–6.79%.

Normalized Diagrams

Our samples are differentiated between volcanic and hypabyssal rocks of the Lawrence Head Volcanics, gabbro from sills in the New Bay and Saunders Cove Formations, and volcanic rocks and gabbro samples from the Dunnage Mélange, and are plotted on chondrite-normalized diagrams (Fig. 6). Samples show negative slopes due to strong enrichment in light rare earth elements (LREE), slightly more enriched than average E-MORB, but significantly less than average ocean island basalts (OIB), indicative of an enriched mantle source. For comparison, samples of Lawrence Head Formation volcanic rocks and gabbro from the New Bay Formation (including a dyke thought to be a feeder to a flow in the Lawrence Head Volcanics) published by O'Brien et al. (1997) are plotted in Figure 6. O'Brien et al. (1997) divided their Lawrence Head suite into five groups based on increasing enrichment in LREE from E-MORB to alkaline compositions but these groups are not differentiated in the diagrams used in this paper for the sake of brevity. While there is a greater spread in the Lawrence Head data from O'Brien et al. (1997) towards more alkaline compositions, they show a similar pattern to ours, which most closely resembles their subset of samples that comes mainly from the Lawrence Head type section (as do ours) suggesting the greater variability they found in the volcanics may be related to geographical differences. The gabbro data of O'Brien et al. (1997) show less variability than the volcanic rocks, and are similar to ours from the New Bay gabbro sills.

On the MORB-normalized diagram (Fig. 7), a similar pattern of LREE enrichment occurs, with an absent to very slight Ta–Nb negative anomaly. They have relatively high Zr/Y and Ti/Y ratios, consistent with the overall pattern of LREE enrichment. The Lawrence Head Formation samples of O'Brien et al. (1997; Fig. 7) show a similar pattern, although as on the chondrite-normalized diagram they display greater variability. However, while the Thwart Island Gabbro analyses of their paper also show an overall negative slope, a Ta–Nb negative anomaly is present in those samples.

The Dunnage area samples have been divided into two groups based on geochemical differences displayed in the geochemical diagrams below. The first group (EX-10, EX-12,

Table 1. Geochemical data of samples obtained for this study

Sample #	NB 01-77[*]	NB 02-77[#]	NB 03-77[*]	NB 04-77	NB 05-77[*]	NB 06-77	NB 07-77[#]	NB 08-77	NB 09-77	NB 10-77	LH 11-77	LH 12-77
rock type	diabase	trondhj.	diabase	diabase	diabase	gabbro	anorth.	gabbro	gabbro	gabbro	pbasalt	pbasalt
LOI (%)	2.61	1.00	2.65	2.98	2.59	2.87	1.45	2.52	2.63	2.71	2.62	2.86
Major elements												
XRF (wt%)												
SiO_2	48.69	76.39	48.75	53.32	53.76	51.69	65.42	47.19	44.96	49.91	50.35	50.70
Al_2O_3	15.28	15.08	14.98	16.52	16.91	15.72	18.09	13.03	11.65	13.99	14.06	14.47
TiO_2	1.60	0.23	2.16	2.17	2.13	2.31	0.91	2.38	3.13	2.84	1.83	1.87
FeO[†]	10.67	1.33	11.85	9.76	9.49	12.00	7.04	14.39	16.59	13.42	11.39	10.90
MnO	0.21	0.05	0.20	0.16	0.18	0.22	0.13	0.25	0.28	0.23	0.28	0.27
CaO	11.65	3.02	11.00	7.70	5.90	7.97	2.56	11.14	12.25	8.25	10.02	9.64
MgO	9.50	0.27	6.93	4.91	5.09	4.13	1.01	7.70	7.79	4.54	7.29	7.32
K_2O	0.13	0.00	0.74	0.43	0.52	0.61	0.00	0.93	0.22	0.70	0.19	0.20
Na_2O	2.10	5.45	3.14	4.94	5.70	5.11	6.39	2.53	2.63	4.83	4.14	4.15
P_2O_5	0.18		0.25		0.34							
Trace elements												
XRF (ppm)												
Ni	183		56	31.9	32			57.9	70.5	28.7	52.9	53.3
Cr	343		205	78.3	85			21.3	25.2	6.8	107	114
V	246		297	240	256			519	692	355	319	319
Zr	109		139	140	134			96	95.9	161	119	115
Ga	20		20		22							
Cu	95		86	38.3	40			126	88.3	110	100	101
Zn	72		94	77.5	99			87.4	77.2	59.5	91.2	87.5
ICP-MS (ppm)												
La	9.91		11.87		12.53							
Ce	21.6		26.46		27.5							
Pr	2.82		3.48		3.52							
Nd	13.04		16.51		16.61							
Sm	3.77		4.84		4.56							
Eu	1.36		1.67		1.8							
Gd	4.1		5.18		4.88							
Tb	0.68		0.87		0.82							
Dy	4.05		5.24		4.93							
Ho	0.83		1.02		1							
Er	2.1		2.59		2.64							
Tm	0.29		0.36		0.37							
Yb	1.78		2.2		2.26							
Lu	0.26		0.32		0.35							
Ba	133		137		335							
Th	1.38		1.39		1.49							
Nb	10.56		13.66		7.45							
Y	21.07		26.25		26							
Hf	2.7		3.4		3.09							
Ta	0.75		0.98		0.71							
U	0.63		0.58		0.59							
Pb	3.41		1.49		3.19							
Rb	1.8		20.9		7.5							
Cs	0.94		0.7		0.29							
Sr	223		328		516							
Sc	36.4		41.5		31.2							
W	48.95		67.97		94.34							

Table 1. *(con't)*

Sample #	LH 13-77	LH 14-77	LH 15-77	LH 16-77	LH 18-77	LH 19-77	LH 21-77*	NB 22-77	NB 23-77	LH 01-78*	LH 03-78*	LH 04-78
rock type	pbasalt	pbasalt	pbasalt	pbasalt	mbasalt	mbasalt	diabase	gabbro	gabbro	pbasalt	pbasalt	mbasalt
LOI (%)	2.79	3.51	2.73	2.76	3.21	3.95	1.64	1.75	2.09	2.19	2.40	3.53
Major elements												
XRF (wt%):												
SiO_2	48.67	47.74	55.96	49.86	46.30	47.71	50.59	50.03	49.86	57.71	46.79	48.84
Al_2O_3	15.21	16.74	15.09	16.35	16.88	15.93	16.56	16.13	12.59	16.31	16.05	15.67
TiO_2	2.09	1.41	1.36	1.39	1.59	2.34	2.70	2.76	2.66	1.23	2.19	1.84
$FeO^{\dagger}$	11.31	11.77	8.93	10.86	12.71	12.92	11.61	11.36	16.15	8.11	12.64	11.01
MnO	0.44	0.27	0.21	0.25	0.28	0.61	0.24	0.20	0.27	0.16	0.24	0.20
CaO	11.80	9.86	8.85	10.57	10.52	8.63	5.34	8.97	9.24	6.39	12.18	9.14
MgO	6.20	8.15	5.70	7.29	8.14	8.10	5.68	5.50	4.94	5.06	6.56	8.59
K_2O	0.38	0.19	0.14	0.10	0.03	0.16	2.50	0.57	0.64	0.10	0.60	0.76
Na_2O	2.75	2.73	3.18	2.62	2.51	2.80	4.29	3.63	2.88	4.76	2.46	3.36
P_2O_5							0.48			0.17	0.30	
Trace elements												
XRF (ppm):												
Ni	63.6	101	93.3	94.6	141	91.3	44	49.6	41.4	71	59	133
Cr	110	89.8	103	98.7	192	82.4	62	62.4	1.7	87	147	123
V	277	250	224	241	277	314	306	303	583	208	323	221
Zr	155	118	114	114	88.4	133	198	196	100	157	155	137
Ga							21			18	20	
Cu	102	64.5	58.9	69	86	62.6	4	15.6	64.4	57	127	92.1
Zn	87.3	95.5	85.1	92.8	90.6	87.5	104	97.2	108	87	90	83.9
ICP-MS (ppm):												
La							17.28			13.08	15.86	
Ce							38.88			29.84	34.41	
Pr							5.1			3.99	4.36	
Nd							23.67			18.88	20.33	
Sm							6.69			5.79	5.82	
Eu							2.28			1.76	2.01	
Gd							7.06			6.59	6.34	
Tb							1.17			1.2	1.06	
Dy							7.05			7.79	6.49	
Ho							1.44			1.66	1.32	
Er							3.78			4.5	3.44	
Tm							0.53			0.67	0.49	
Yb							3.26			4.14	3.01	
Lu							0.5			0.66	0.46	
Ba							391			123	188	
Th							1.92			2.4	1.92	
Nb							9.86			12.17	17.92	
Y							37.13			42.1	34.21	
Hf							4.63			4.24	3.92	
Ta							0.73			0.88	1.2	
U							0.68			0.9	0.58	
Pb							4.07			1.78	1.42	
Rb							77.7			0.8	7.2	
Cs							11.13			0.22	0.92	
Sr							311			211	272	
Sc							34.8			38.7	47.6	
W							91.52			54.12	63.90	

Table 1. *(con't)*

Sample #	LH 05-78	LH 06-78	LH 07-78	LH 08-78*	LH 09-78*	EX 05b	EX 10	EXD 12	EXS 14	EX 15a	EX 16	EX 18a	EXD 18b
rock type	pbasalt	pbasalt	mbasalt	mbasalt	mbasalt	diabase	pbasalt	gabbro	pbasalt	diabase	gabbro	pbasalt	gabbro
LOI (%)	3.07	3.49	3.41	3.20	3.10	2.25	10.45	3.00	2.68	4.48	1.85	8.45	4.36
Major elements													
XRF (wt%):													
SiO_2	51.52	49.41	49.89	49.65	49.07	49.92	41.27	55.70	54.53	51.91	53.57	46.91	50.00
Al_2O_3	16.73	13.76	15.74	14.63	14.91	14.21	17.72	15.99	17.66	12.94	17.59	18.21	16.74
TiO_2	1.75	2.52	2.02	2.39	1.86	1.931	2.683	0.952	1.282	2.716	1.608	1.027	1.618
$FeO^{\dagger}$	8.93	13.88	11.29	13.62	11.36	13.25	16.67	7.25	9.16	13.27	10.64	11.77	9.35
MnO	0.19	0.27	0.23	0.37	0.22	0.208	0.428	0.191	0.171	0.287	0.276	0.405	0.161
CaO	9.97	8.17	8.64	8.41	12.68	9.32	9.99	5.55	8.22	8.22	4.63	9.18	8.00
MgO	5.68	7.48	6.72	6.05	6.68	6.94	5.55	8.97	4.57	5.73	4.74	6.42	10.26
K_2O	0.55	0.60	0.71	0.05	0.38	0.33	2.87	2.52	0.34	0.18	0.19	0.53	1.12
Na_2O	3.95	3.52	4.20	4.48	2.64	3.67	2.54	2.72	3.74	4.50	6.51	5.39	2.43
P_2O_5				0.34	0.21	0.217	0.297	0.156	0.325	0.253	0.245	0.153	0.335
Trace elements													
XRF (ppm):													
Ni	59.8	31.3	54.7	41	55	45	191	192	26	23	16	351	200
Cr	79	16.9	72.1	70	219	44	399	558	29	35	21	790	386
V	258	320	295	406	354	318	336	152	213	437	215	242	186
Zr	120	172	133	158	108	120	146	130	123	139	176	53	157
Ga				26	19	17	21	19	20	18	17	13	17
Cu	110	102	122	150	131	156	41	43	16	60	38	54	48
Zn	81	117	90.5	121	96	78	117	86	83	94	106	116	78
ICP-MS (ppm)													
La				15.21	9.2	11.15	10.51	20.17	12.36	7.00	9.95	2.40	17.68
Ce				33.25	20.9	24.93	24.86	42.33	27.93	19.56	25.73	7.95	39.51
Pr				4.35	2.8	3.50	3.60	5.02	3.70	3.24	3.99	1.20	5.06
Nd				20.76	13.55	16.08	16.58	19.54	16.17	16.97	19.72	6.98	21.03
Sm				6.31	4.19	4.59	4.44	4.35	3.89	5.71	6.15	2.68	4.65
Eu				2.1	1.57	1.58	1.54	1.26	1.42	2.03	1.51	0.72	1.66
Gd				7.1	4.78	5.20	4.67	3.95	4.14	7.67	7.26	3.94	4.60
Tb				1.21	0.82	0.88	0.76	0.62	0.68	1.43	1.33	0.75	0.75
Dy				7.65	5.05	5.48	4.45	3.72	4.08	9.26	8.73	5.00	4.40
Ho				1.57	1.04	1.10	0.83	0.74	0.82	1.97	1.87	1.09	0.88
Er				4.19	2.76	2.90	2.02	1.97	2.21	5.42	5.40	3.03	2.24
Tm				0.6	0.39	0.41	0.27	0.28	0.32	0.79	0.81	0.43	0.32
Yb				3.75	2.36	2.48	1.57	1.76	1.97	4.77	5.10	2.58	1.93
Lu				0.57	0.36	0.39	0.23	0.28	0.31	0.75	0.82	0.40	0.29
Ba				54	133	109	515	605	757	431	182	241	265
Th				1.64	0.98	1.20	0.96	6.76	1.73	0.63	1.68	0.04	2.10
Nb				13.95	8.63	9.27	14.59	6.03	6.22	2.68	2.36	0.36	10.88
Y				41.13	26.62	26.69	19.34	18.58	21.18	48.66	46.29	27.39	21.18
Hf				4.02	2.71	2.99	3.60	3.40	2.88	3.79	4.86	1.41	3.45
Ta				0.95	0.62	0.62	0.99	0.46	0.39	0.20	0.17	0.03	0.71
U				0.54	0.34	0.46	0.17	3.48	0.62	0.18	0.47	0.13	0.69
Pb				1.7	1.21	1.25	0.54	8.99	2.08	2.12	1.07	3.00	2.51
Rb				0.7	5.2	6.9	22.1	100.0	6.6	2.5	4.8	11.8	33.0
Cs				0.53	1.04	1.32	2.55	6.39	1.54	0.53	1.64	8.31	5.63
Sr				257	307	323	259	264	586	146	165	367	409
Sc				50.3	52.4	45.0	35.1	23.8	25.3	45.4	31.6	40.2	26.0
W				55.35	62.04								

Notes: 'LH' samples are Lawrence Head Volcanics (pbasalt – pillow lava; mbasalt – massive lava/diabase, "NB" samples are from gabbro sills in the New Bay or Saunders Cove Fms. (diabase from sill chilled margins),
"EX" samples are basalt, diabase, and gabbro blocks (except EX-05b, a NB sill), and "EXD" Grapnel gabbro dykes, in the Dunnage Mélange. "EXS" sample is pillow lava of Summerford Gp. at Cobbs Arm XRF – X-ray fluorescence; ICP-MS – Inductively coupled plasma–mass spectrometry; LOI – loss on ignition
[*] Samples are 2003 analyses; $FeO^{\dagger}$ is total iron.
[#] Silica-rich samples NB-02-77 and NB-07-77 were not used in the tectonic discrimination diagrams.

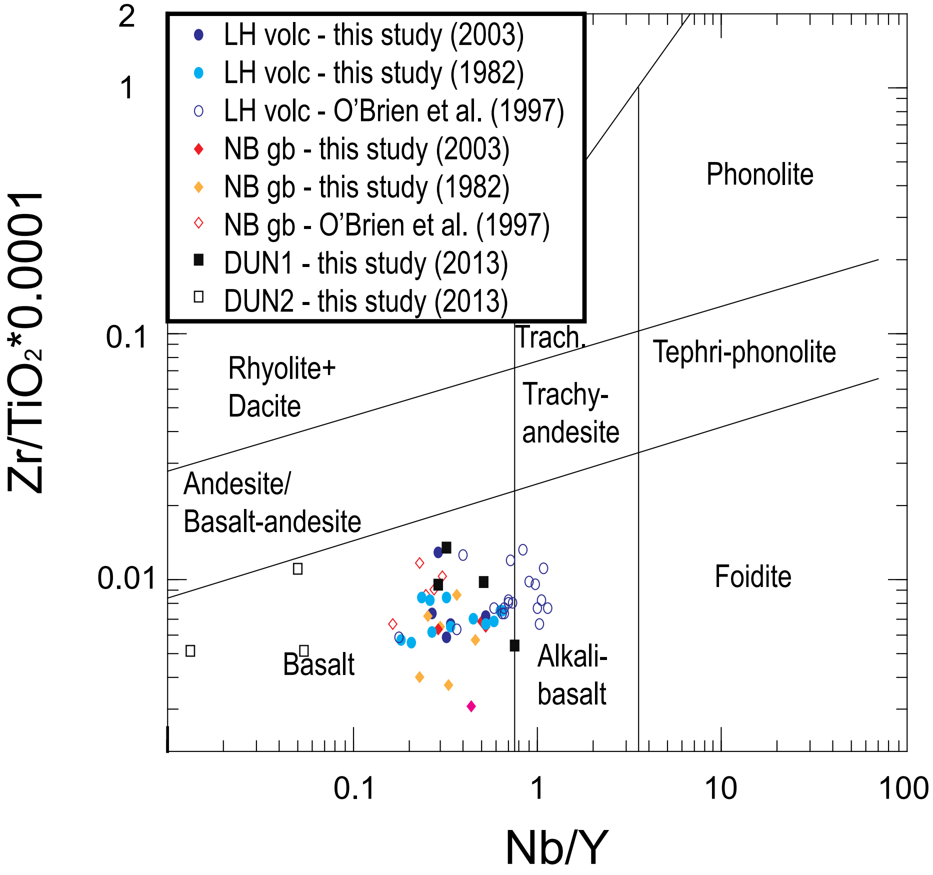

Figure 5. Rock classification diagram of Winchester and Floyd (1977). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN = blocks from the Dunnage Mélange. Year listed for this study (1982, 2003, and/or 2013) refers to the analysis date of each suite of samples.

EX-14, and EX-18b, filled boxes in the diagrams), hereafter referred to as DUN1, display rather uniform compositions similar to the Lawrence Head Volcanics, especially those of O'Brien et al. (1997), and on the MORB-normalized diagram display Ta–Nb negative anomalies and somewhat higher enrichment of the heavy rare earth elements (HREE); they include a pillow lava from a block at Comfort Cove Head, the two Grapnel Gabbro dyke samples (EX-12 and EX18b), and the Summerford Group pillow lava (EX-14). The second group, all blocks from the Dunnage (EX-15a, EX-16 – both gabbro, and EX18a – pillow lava, open boxes), referred to as DUN2, show more variation and have flat REE patterns more typical of N-MORB, although two of them show some enrichment of REE. The samples in this second group are not typical of the other magmatic rocks in this study.

Discrimination Diagrams

Samples were plotted on a variety of trace element tectonic discrimination diagrams (Figs. 8–15) that minimize the secondary effects of weathering and metamorphism that can alter original chemical concentrations. We note that Ta was not analyzed by O'Brien et al. (1997), so Nb/16 (Wood et al. 1979; Pearce 2014) is substituted for Ta in Figure 11. On some tectonic discrimination diagrams, our Lawrence Head basalt and New Bay gabbro sill samples plot in fields consistent with an enriched mantle source, and formed in a tectonic setting indicative of E-MORB (Figs. 8–11). On diagrams that do not have explicit E-MORB or similar fields, samples generally plot intermediate between N-MORB and within-plate tholeiite (Figs. 12–14). On some diagrams, (Figs. 8–11, and 15), samples show some displacement towards volcanic arc fields. In all of these diagrams, there is no consistent differentiation between Lawrence Head and New Bay gabbro sill samples.

The Lawrence Head samples of O'Brien et al. (1997) are also plotted on Figs. 8–15. In general, samples plot in positions similar to our suite, but show one consistent difference: the variation in enrichment of LREE seen on the chondrite-normalization diagram (Fig. 6) is evident here, with samples displaced towards more alkaline fields (Figs. 8, 9, 12, and 13). The subset of samples from the Lawrence Head type section consistently plots near our samples. With the exception of a few samples on the Cr–Y diagram (Fig. 14), none of these samples show any significant volcanic arc character.

The Thwart Island Gabbro samples of O'Brien et al. (1997), in contrast, do show some difference with our gabbro sill samples from the New Bay Formation. Consistent with the pattern seen in the MORB-normalized diagram (Fig. 7), a volcanic arc tectonic setting is indicated on those diagrams that differentiate it (Figs. 8, 9, 11, 13, and 14), with the exception of the Ce/Nb–Th/Nb and V–Ti diagrams (Figs. 15 and 12, respectively). On the Ti–V diagram, O'Brien et al.'s (1997) samples have lower overall absolute abundances of Ti and V, compared to our samples.

In each diagram, the composition of upper continental crust (from McLennan 2001) is plotted. On several diagrams (Fig. 10, 11, 13, and 14), the crustal contamination and arc vectors are sub-parallel and some samples plot in volcanic arc fields on those diagrams. However, on the V–Ti and Ce/Nb–Th/Nb diagrams (Figs. 12 and 15), these vectors are not parallel and samples plot along trends tending toward crustal contamination, rather than arc, and no points fall in or near the volcanic arc fields.

In the Dunnage, the chemical composition of the DUN1 suite most closely resembles the gabbro sills of the New Bay Formation, but is also similar to the Lawrence Head Volcanics, as shown on some of the discrimination diagrams (Figs. 9, 10, 11, 12, and 13). However, on the Y–La–Nb diagram (Fig. 8) samples are scattered across both 'orogenic' and 'anorogenic' fields with rather high alkaline compositions. On the Cr–Y

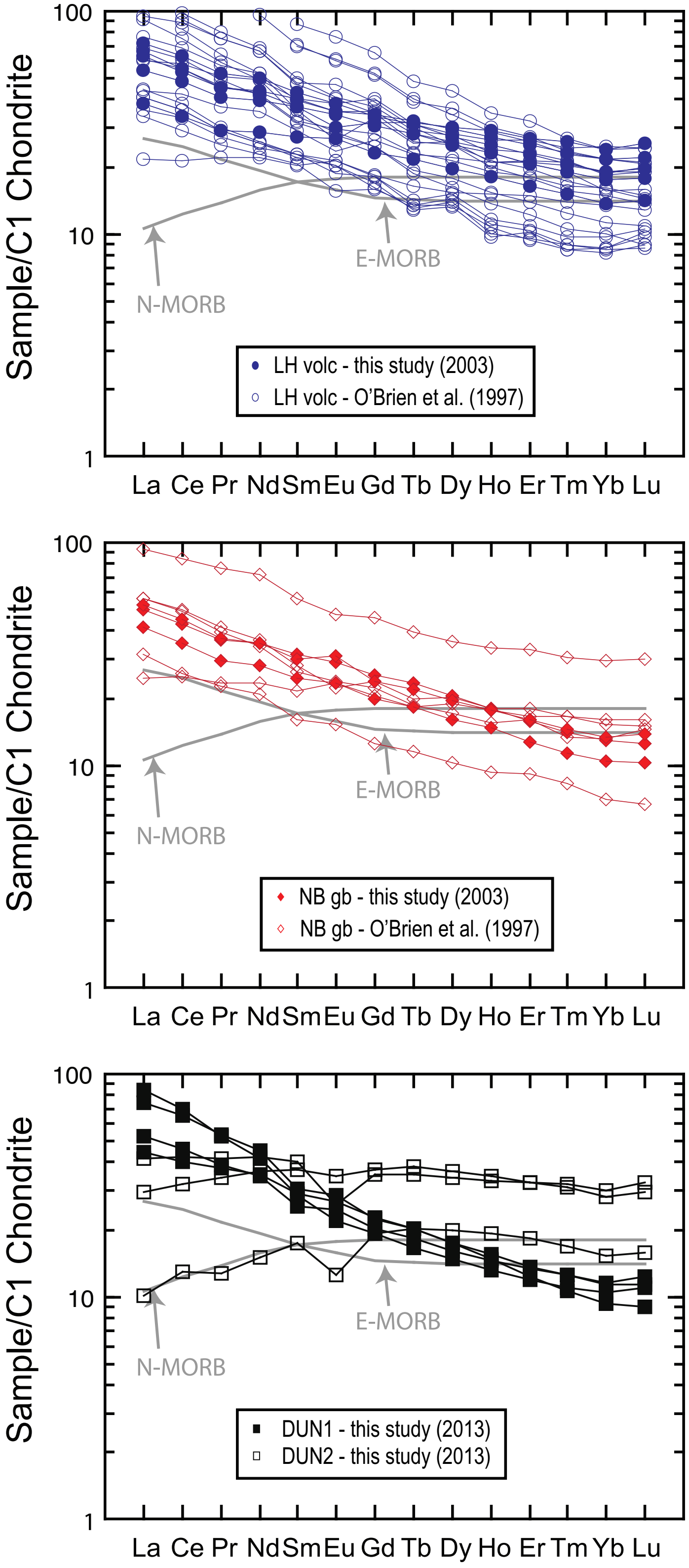

Figure 6. C1-chondrite normalized diagrams of rare earth elements (REE). Normalization values from Sun and McDonough (1989). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (2003, and/or 2013) refers to the analysis date of each suite of samples.

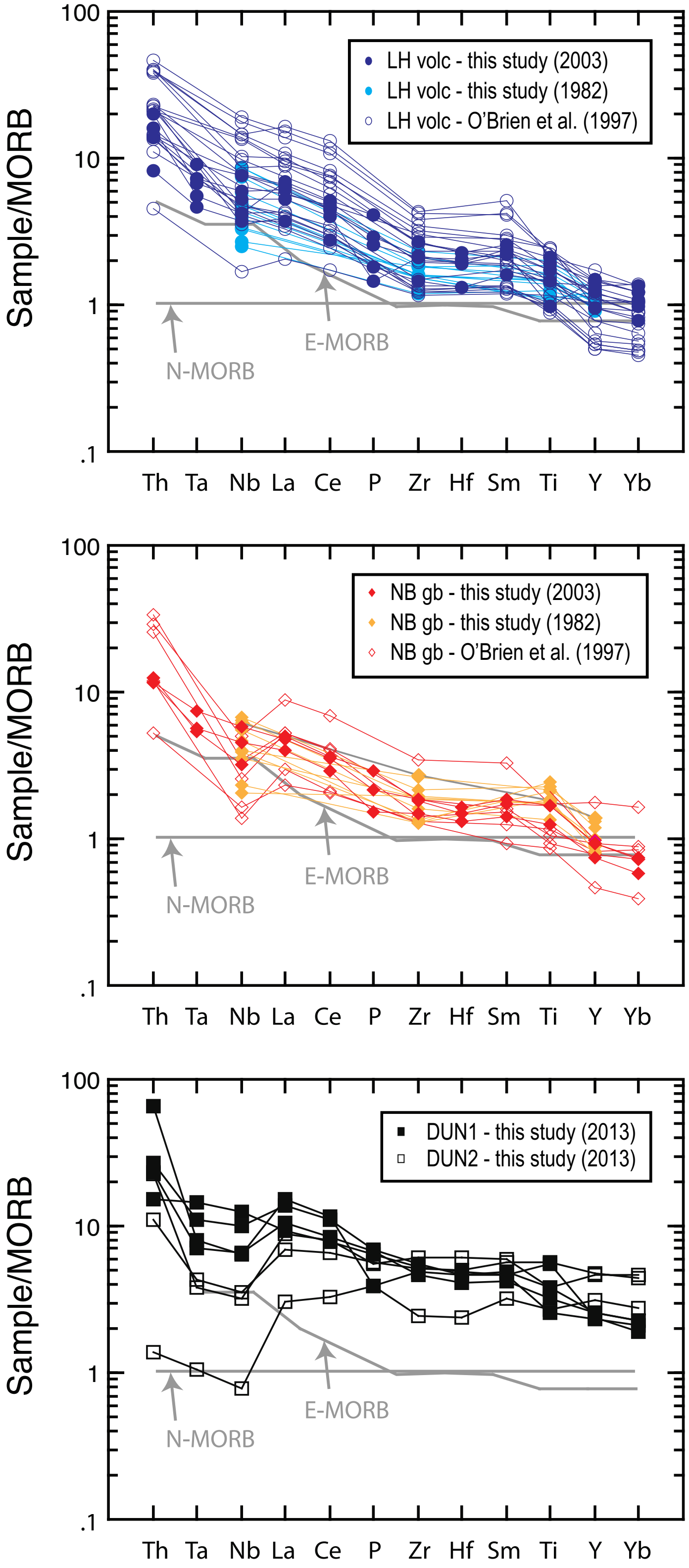

Figure 7. MORB-normalized diagrams of selected trace elements. Normalization values from Sun and McDonough (1989). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (1982, 2003, and/or 2013) refers to the analysis date of each suite of samples.

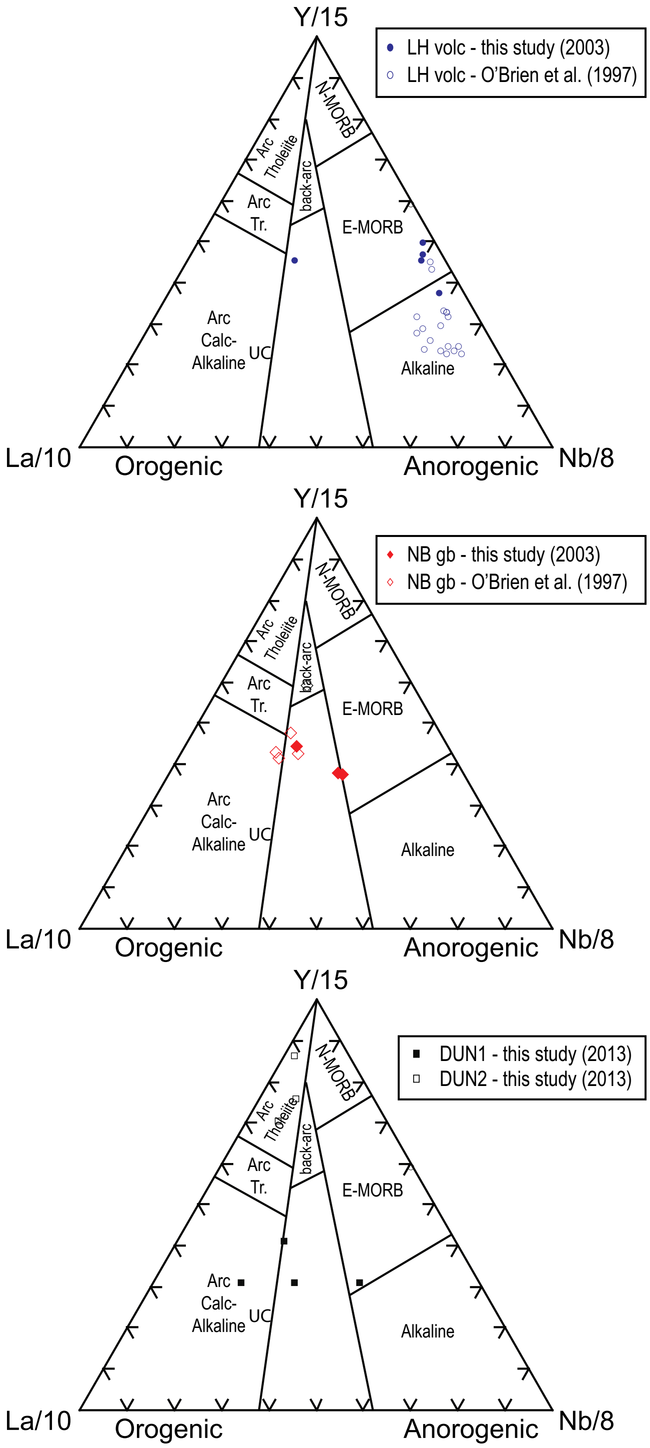

Figure 8. Y/15–La/10–Nb/8 diagram of Cabanis and Lecolle (1989). N-MORB = normal, mid-ocean ridge basalt. E-MORB = enriched mid-ocean ridge basalt. Arc Tr. = transitional field (overlap) between tholeiitic and calc-alkaline basalt. Subduction-related basalt analyses follow the orogenic trend, while non-arc mantle arrays follow the anorogenic trend. UC = average upper continental crust composition from McLennan (2001). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (2003, and/or 2013) refers to the analysis date of each suite of samples.

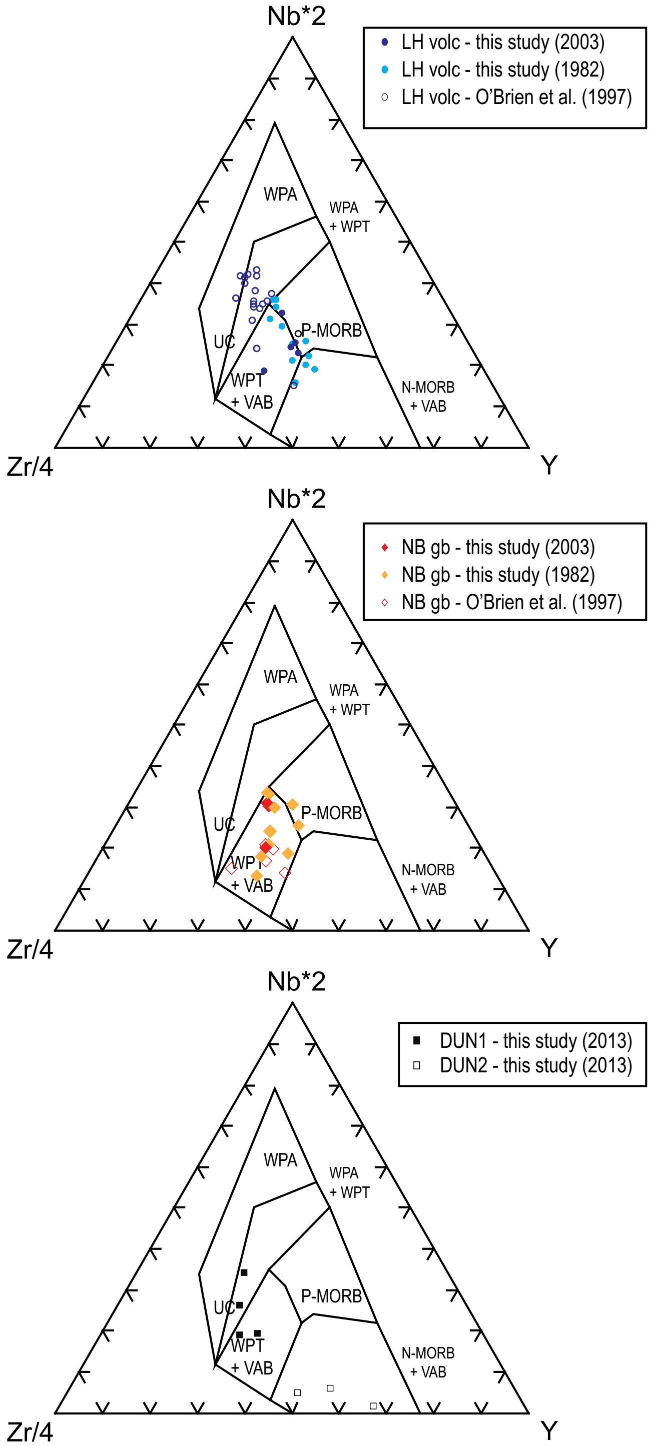

Figure 9. Nb–Zr–Y diagram of Meschede (1986). WPA = within-plate alkaline basalt, WPT = within-plate tholeiite, P-MORB = plume-influenced mid-ocean ridge basalt, N-MORB = normal, mid-ocean ridge basalt, VAB = volcanic arc basalt. UC = average upper continental crust composition from McLennan (2001). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (1982, 2003, and/or 2013) refers to the analysis date of each suite of samples.

diagram (Fig. 14) there is significant variation in Cr, and on the Ce/Nb–Ta/Nb diagram (Fig. 15) samples have compositions that more closely match those from the Mariana arc than any other samples. The DUN2 samples typically plot in N-MORB and volcanic arc fields, although none plot in the arc field of the Ti–V or Cr–Y diagrams (Figs. 12 and 14, respectively). Overall, these do not have any clear analogues in the Lawrence Head or New Bay suites.

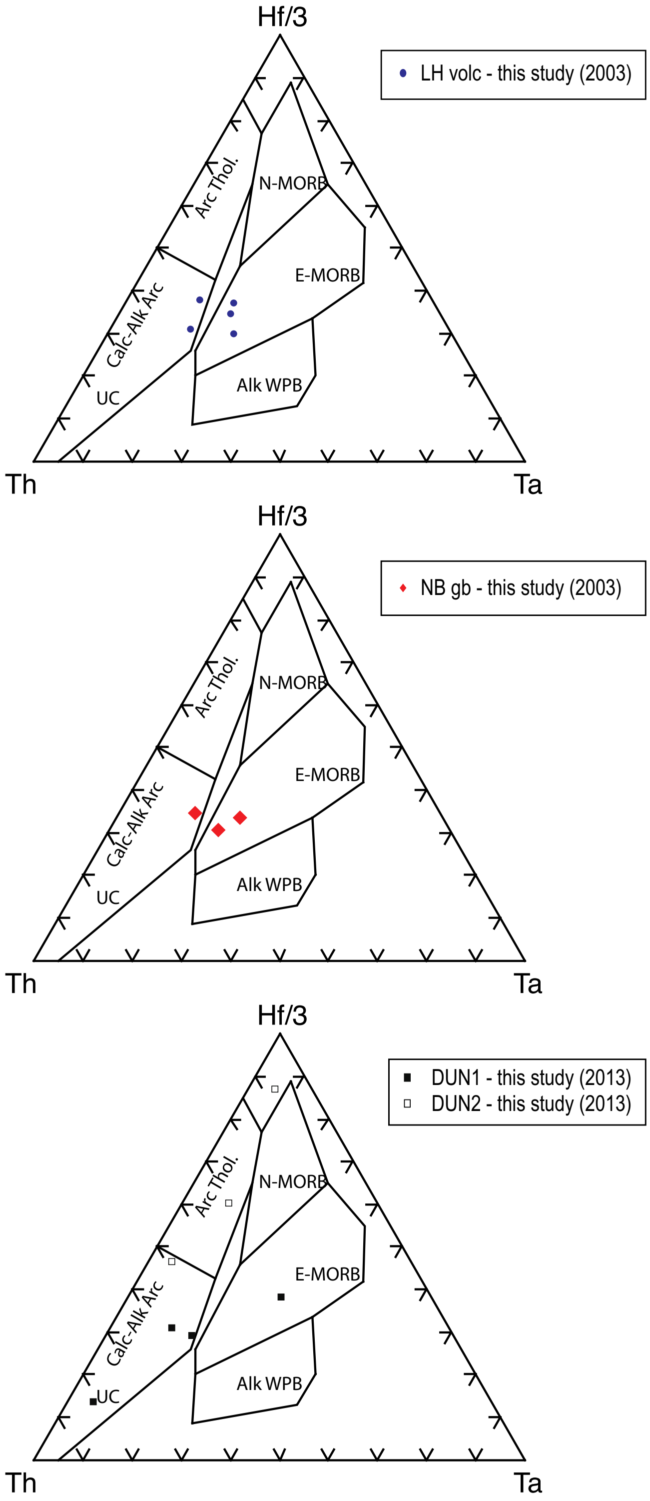

Figure 10. Th–Hf–Ta diagram of Wood (1980). Calc-Alk Arc = calc-alkaline volcanic arc basalt, Arc Thol.= volcanic arc tholeiite, N-MORB = normal, depleted mid-ocean ridge basalt, E-MORB/WPT = enriched mid-ocean ridge basalt and within-plate tholeiite, Alk WPB = alkaline within-plate basalt. The two arc subfields are collectively referred to as the 'destructive margin and differentiates' field, separated by the dashed line. UC = average upper continental crust composition from McLennan (2001). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (2003, and/or 2013) refers to the analysis date of each suite of samples.

Pyroxene Mineral Chemistry

The major element composition of primary preserved pyroxenes, even in weathered or metamorphosed basalt and gabbro has been shown to be related to composition of the magma from which they crystallize, and gives information about the tectonic environment in which they form, and are not significantly affected by partial melting and fractional crystallization processes (Nisbet and Pearce 1977; Leterrier et al. 1982; Beccaluva et al. 1989). Clinopyroxene mineral compositions from gabbros in the New Bay Formation and basalts from the Lawrence Head Formation were determined by electron microprobe. The major element compositions from a representative range of the original analyses are given in Table 2. These clinopyroxene analyses have relatively high TiO_2 that ranges from 0.88–2.13% and Na_2O, typical of pyroxenes that crystallize in MORB (both normal and enriched) and more alkaline oceanic islands, consistent with the whole rock concentrations. Pyroxene compositions plotted on the TiO_2–SiO_2/100–Na_2O diagram of Beccaluva et al. (1989; Fig. 16) lie in or near the overlap fields for N-MORB, E-MORB, Iceland basalts, and oceanic islands.

DISCUSSION

Previous Tectonic Interpretations

Kidd et al. (1977) first suggested that the Lawrence Head Volcanics are the product of a medial Ordovician ridge subduction event, above a northwest-dipping subduction zone. This model elaborates on that proposed by Kay (1976) and requires that the Lawrence Head Volcanics and associated mag-

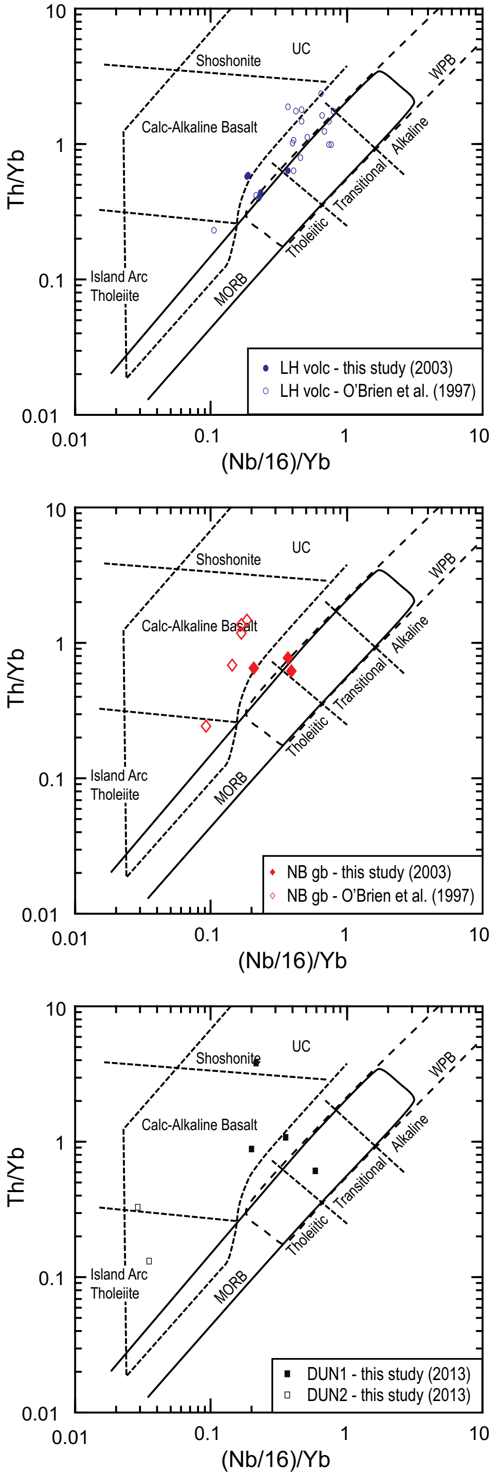

Figure 11. Modified Th/Yb–Ta/Yb diagram of Pearce (1982) using Nb/16 for Ta. MORB = mid-ocean ridge basalt, WPB = within-plate basalt. UC = average upper continental crust composition from McLennan (2001). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (2003, and/or 2013) refers to the analysis date of each suite of samples.

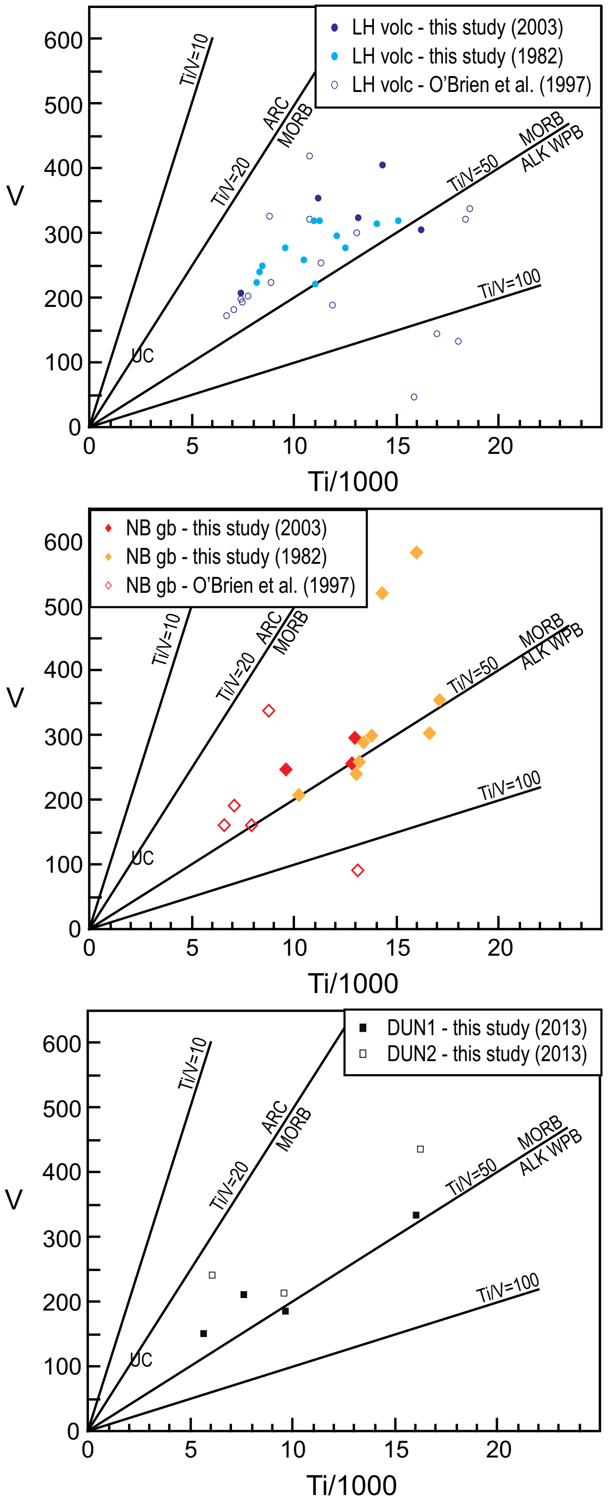

Figure 12. Ti–V diagram of Shervais (1982). ARC = volcanic arc basalt, MORB = mid-ocean ridge basalt, ALK WPB = alkaline within-plate basalt. UC = average upper continental crust composition from McLennan (2001). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (1982, 2003, and/or 2013) refers to the analysis date of each suite of samples.

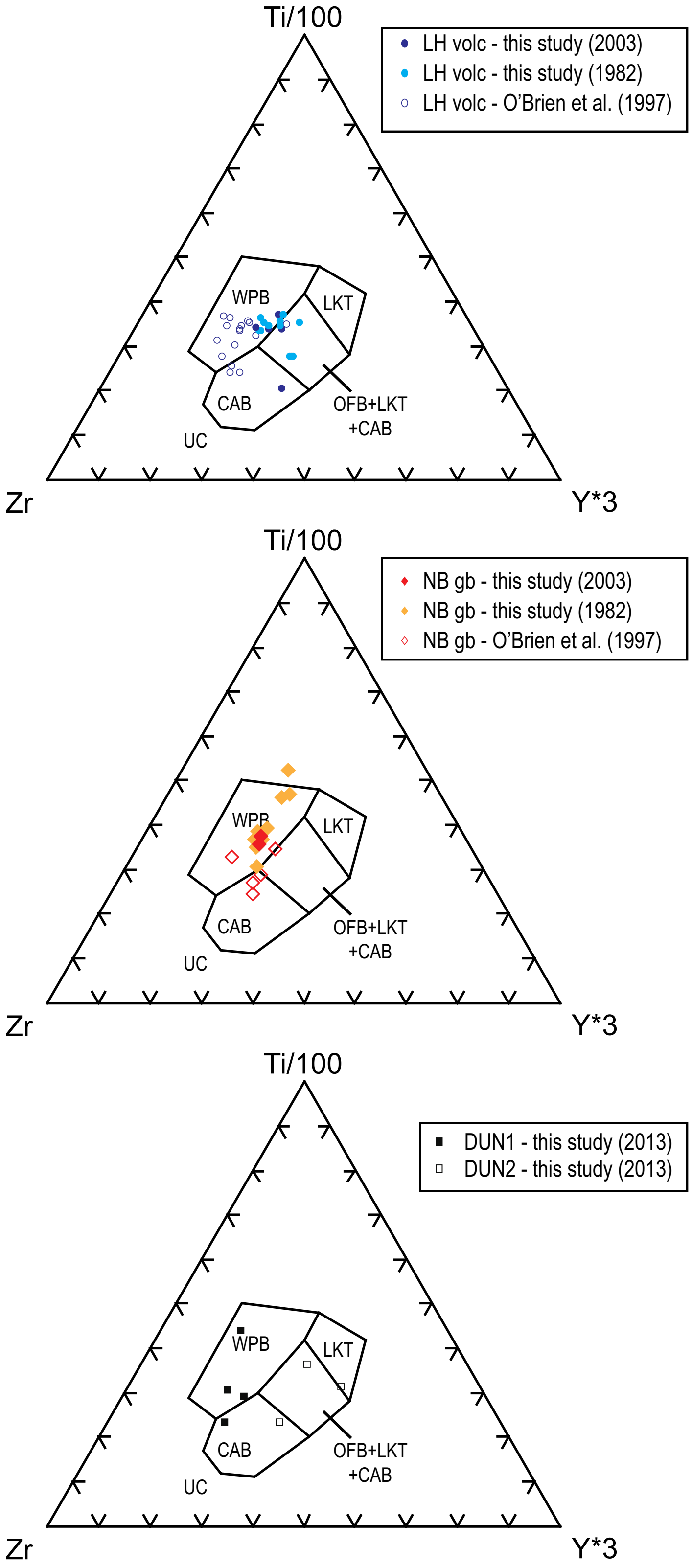

Figure 13. Ti–Zr–Y diagram of Pearce and Cann (1973). WPB = within plate basalt (oceanic and continental), OFB = ocean floor basalt, LKT = low-K tholeiite, CAB = calc-alkaline basalt. UC = average upper continental crust composition from McLennan (2001). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (1982, 2003, and/or 2013) refers to the analysis date of each suite of samples.

matic rocks were emplaced in the arc–trench gap, with an Exploits arc farther to the northwest and an accretionary prism (Dunnage Mélange) directly to the southeast. Subsequent studies have by contrast proposed a west-facing subduction model in which the Lawrence Head Volcanics were erupted in the initial opening stage of a back-arc basin, in part based on their within-plate geochemical characteristics and evidence for extensional deformation in the Dunnage Mélange (Williams 1994; O'Brien et al. 1997). Zagorevski et al. (2007, 2010) proposed Cambrian to earliest Ordovician arc activity (Penobscot Arc), then an interval (~486–473 Ma) in which arc magmatism ceased and the Penobscot Orogeny occurred by collision of this arc with Ganderia, followed by a return to arc activity (Victoria Arc) in the later early to middle Ordovician (473 Ma and younger). The early Victoria Arc was initially accompanied by rifting of the (now inactive) Penobscot arc material, and back-arc basin development (Exploits back-arc). Late Arenig/early Llanvirn fossils occur just below and in the Lawrence Head Volcanics (O'Brien et al. 1997); Zagorevski et al. (2007) suggested these volcanic rocks were associated with the development of an Exploits Subzone back-arc basin. The 463.7 ± 2 Ma baddeleyite age obtained by O'Brien et al. (1997) for the Thwart Island Gabbro led them to suggest that gabbro sills of the New Bay Formation are younger than, and unrelated to, the volcanics of the Lawrence Head, and to associate them instead with the Victoria arc of central Newfoundland.

Summary and Review of Geochemistry

The trace element geochemistry of the Lawrence Head Volcanics is best described as E-MORB-type, rather than as within-plate tholeiite or in some part arc-related, as for back-arc basins. Its LREE-enriched character is illustrated on the chondrite- and MORB-normalized diagrams and some tectonic discrimination diagrams. However, for the most part it is not as alkaline as strict within-plate tholeiite, although it does plot in that field on discrimination diagrams that do not discriminate between E-MORB and within-plate tholeiite. Typically, in dis-

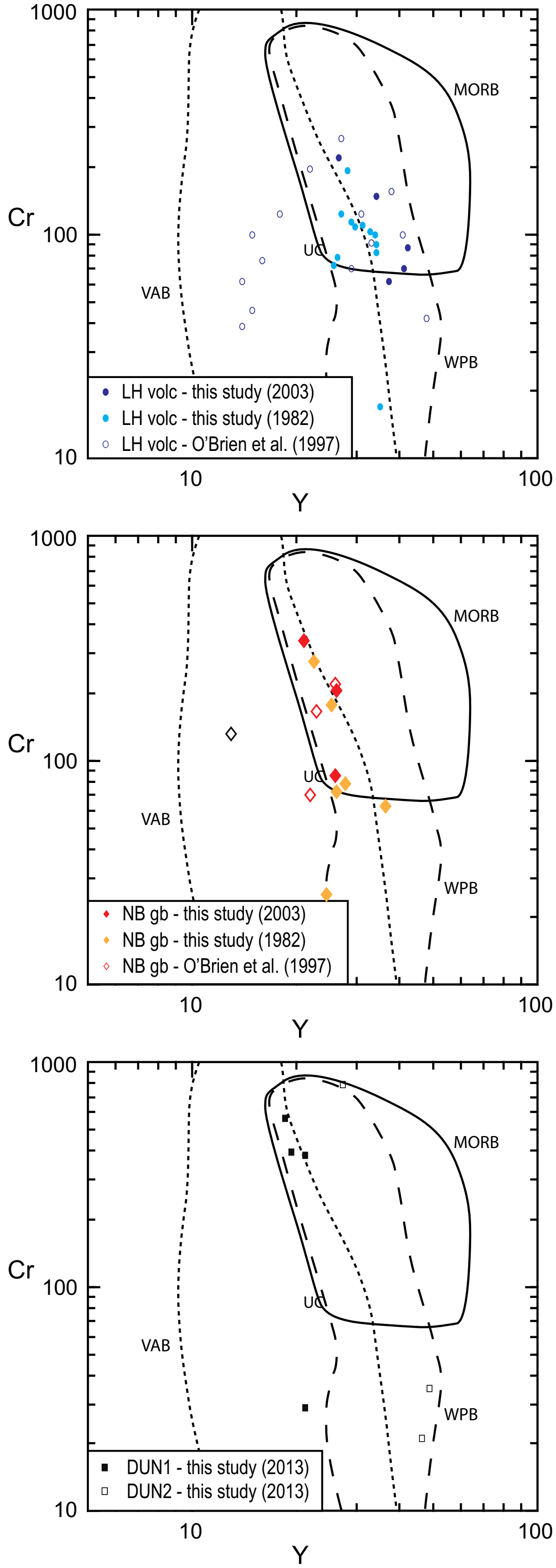

Figure 14. Cr–Y diagram of Pearce (1982). VAB = volcanic arc basalt, MORB = mid-ocean ridge basalt, WPB = within-plate basalt. UC = average upper continental crust composition from McLennan (2001). LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (1982, 2003, and/or 2013) refers to the analysis date of each suite of samples.

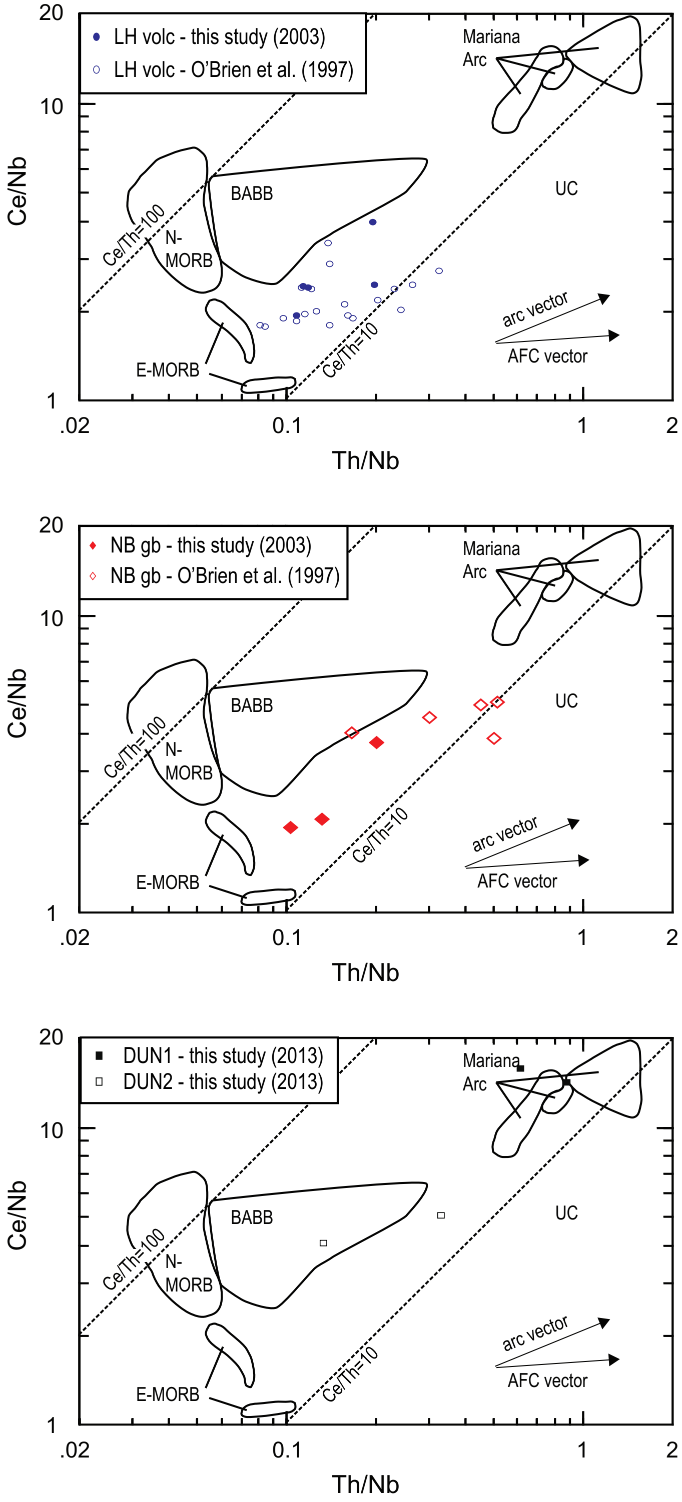

Figure 15. Ce/Nb vs. Th/Nb diagram of Saunders et al. (1988). N-MORB = depleted mid-ocean ridge basalt field, E-MORB = enriched mid-ocean ridge basalt field, BABB = back-arc basin basalt field. UC = average upper continental crust composition from McLennan (2001). AFC = assimilation and fractional crystallization, LH Volc = Lawrence Head Volcanics, NB gb = gabbro sills from the New Bay Formation, DUN1 and DUN2 = blocks from the Dunnage Mélange. Year listed for this study (2003, and/or 2013) refers to the analysis date of each suite of samples.

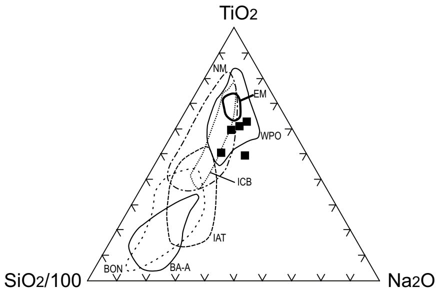

Figure 16. TiO_2–SiO_2/100–Na_2O tectonic discrimination diagram of Beccaluva et al. (1989) using pyroxene compositions. Black boxes are analyzed pyroxene compositions. NM = normal mid-ocean ridge basalt, EM = enriched mid-ocean ridge basalt, WPO = within-plate oceanic islands, ICB = Iceland basalt, IAT = island arc tholeiite, BA-A = quartz tholeiite, basalt-andesite, and andesite, BON = boninite.

Table 2. Selected pyroxene electron microprobe analyses

Sample #:	01-77	06-77	08-77	13-77	16-77
SiO_2	48.78	50.71	50.26	47.20	48.01
TiO_2	1.39	.88	1.15	2.13	1.69
Al_2O_3	5.06	1.89	2.86	5.44	4.42
FeO*	8.24	10.89	9.32	9.85	11.68
MnO	0.20	0.25	0.22	0.29	0.30
MgO	14.47	13.91	14.31	12.97	13.29
CaO	21.27	21.34	21.19	21.44	20.15
Na_2O	0.45	0.36	0.68	0.79	0.60
total	99.86	100.23	99.99	100.11	100.14
Wo	47.6	44.7	46.5	50.2	45.7
En	45.0	40.6	43.6	42.2	41.8
Fs	7.4	14.7	9.9	7.6	12.5

crimination diagrams, the enrichment of LREEs forms a continuum of enrichment between magmas derived from normal depleted mantle (N-MORB) and highly enriched alkaline sources (e.g. mantle array of Pearce's (1982) Th/Ta–Yb/Ta diagram, (Fig. 11), or the spectrum of 'anorogenic' magmas of the Y–La–Nb diagram of Cabanis and Lecolle (1989; Fig. 8). Therefore, the Lawrence Head Volcanics tend to plot in within-plate fields on those diagrams that do not have an intermediate E-MORB field. Arc tholeiites and calc-alkaline rocks associated with arc activity typically plot tangentially to these 'mantle' arrays due to the processes (Th-enrichment) involved in their formation in the mantle wedge. The Lawrence Head Volcanics, in some cases, show a very slight tendency in this direction as evidenced by slight depletion of Nb in Figures 8 and 9, a slight increase in the ratio of Th/Yb in Figure 11, and Ta-depletion/Th-enrichment in Figure 10; however, this could be the result of crustal contamination or a process seen near ridge–trench triple junctions (e.g. South Chile) where arc fluids may have migrated through the slab window (Klein and Karsten 1995), which would result in similar compositions on these diagrams.

Gabbro sills of the New Bay Formation show a greater variation in trace element chemistry and range from Lawrence Head-like compositions towards more alkaline types. Further, some of the Thwart Island Gabbro samples of O'Brien et al. (1997) show greater arc character with distinct Ta–Nb negative anomalies (Fig. 7). The gabbro sample set we obtained was by choice mostly obtained from the section extending from the Lawrence Head type section down to the Tea Arm volcanic rocks; because these could be well located in the stratigraphic section, are well exposed in coastal outcrop and the contacts can be seen, and are likely not to have differed greatly in the metamorphic conditions experienced by the volcanic rocks of the Lawrence Head section. We note that none of our suite contain significant Ta–Nb negative anomalies, and emphasize that they are indistinguishable from the samples of the Lawrence Head type section in the less mobile trace element, and rare earth element geochemistry. While it is of course possible (not all sills were sampled) that one or more with a Ta–Nb negative anomaly was missed, we think that such rocks must be uncommon, or absent, in the section sampled. We concur with the suggestion of O'Brien et al. (1997) that their gabbro samples with Ta–Nb negative anomalies most probably result from contamination by crustal material; we suggest however that this feature of some sills is not convincing evidence for making the whole package of gabbro sills in the pre-Lawrence Head section a separate magmatic event from Lawrence Head volcanism. We point out that an origin of the Coaker Porphyry by basalt magmas causing melting of pelitic sediment derived from the subduction accretionary prism suggests such contamination would be likely, in places, if both Coaker and Lawrence Head magmatism were related events (see below). The source, in part, of the peraluminous Coaker Porphyry was interpreted by Lorenz (1985) and Zagorevski et al. (2012) (following the suggestion of Kidd et al. 1977) as crustal material, probably sedimentary rocks initially forming a lower part of the Dunnage Mélange prior to underthrusting to depths around 45 km where Lorenz (1985) inferred that melting occurred.

Of the seven samples of blocks in the Dunnage analyzed, there are apparently at least two chemically distinct types of blocks (DUN1 and DUN2), but they may be three since two of the DUN2 samples tend to plot in arc fields, while one is more N-MORB-like. The low sample size of this suite does not allow for a confident interpretation of the environment of formation, but does suggest potential correlations. The DUN1 subset is chemically similar to the Lawrence Head Formation and indicates that these blocks may be Lawrence Head-type magmas entrained in the deforming mélange and that these units were proximally located to one another during magmatism. These data are consistent with those for 13 blocks from the Dunnage Mélange in the Boyd's Cove and Dildo Run areas, reported by Jacobi and Wasowski (1985). The DUN2 subset however, is chemically distinct and suggests that the Dunnage

Mélange may have sampled other types of magmatic rocks not exposed elsewhere, as suggested by Williams (1994).

Based on trace element geochemistry, the most likely environment of formation of the Lawrence Head Volcanics involves an interaction between an actively spreading mid-ocean ridge, erupting E-MORB compositions, and a trench (attempted or actual ridge subduction). This conclusion is consistent with that reached by Zagorevski et al. (2012) based on xenolith chemistry of the Coaker Porphyry. Proximity to an arc is indicated by uniformly volcaniclastic material accumulating in the New Bay Formation up to a level slightly below the Lawrence Head Volcanics.

Age Constraints

Critical age information for the Lawrence Head and Coaker Porphyry magmatic events include:

1. The U–Pb zircon age of the Coaker Porphyry of 469 ± 4 Ma (Zagorevski et al. 2012, which we prefer over the 'preliminary' report of 467 ± 5 Ma by Elliott et al. 1991);
2. U–Pb baddeleyite age of gabbro sill from New Bay Formation of 463.7 ± 2 Ma (O'Brien et al. 1997);
3. Fossil age from just below Lawrence Head type section in uppermost New Bay Formation, latest Arenig–earliest Llanvirn (O'Brien et al. 1997) [early Darriwilian – about 467 Ma];*
4. Fossil age from within the Lawrence Head Formation – late Arenig or early Llanvirn (O'Brien et al. 1997) [same as 3. above; less well-constrained];
5. Fossil ages of basal limestone beds at Hummock Island immediately above Lawrence Head – early to mid Llanvirn (O'Brien et al. 1997), [mid to upper Darriwilian; about 464 Ma] and Cobbs Arm limestone immediately above Lawrence Head equivalent at Cobbs Arm – Llandeilo (Bergström et al. 1974; Arnott et al. 1985) [upper Darriwilian; about 460 Ma];
6. Fossil age in chert of middle Shoal Arm Formation (Strong Island chert) – not higher than mid-Llanvirn (O'Brien et al. 1997), [mid-Darriwilian, probably not younger than about 462 Ma].

* translations to those divisions and ages given on the current version of the Ordovician time scale of the International Commission on Stratigraphy Chronostratigraphic Chart v2013/1 (ICS 2013) are shown in [square brackets] and are our estimates; in making these we also used the Ordovician Chronostratigraphic Chart of Bergström et al. (2009).

These ages are consistent and suggest: a) the Lawrence Head Volcanics are likely to have erupted between about 467 and 463 Ma; b) the gabbro sill age is indistinguishable from this interval; c) the Coaker Porphyry age could be taken as coinciding (overlap of error ranges) with the Lawrence Head event, but is more probably a few million years older (see discussion below).

Geological Constraints on the Magmatic Events

A ridge subduction event is consistent with the apparent decline and cessation of arc activity, shown by decrease in volcaniclastic grain size and bed thicknesses in the uppermost New Bay Formation (and in its equivalent in the Wild Bight Group to the west), that would occur as the down-going slab shallowed as the ridge approached the trench in this vicinity. By contrast, in a back-arc basin rifting event, arc magmatism would continue (e.g. Tonga – Lau Basin) and strata showing evidence for this ought to be seen in the developing basin, at least in the early stages of the event. Another aspect of the Lawrence Head Volcanics that we think is inconsistent with the rifting model is the absence of evidence of coarse, rift-flank derived talus in or above the volcanic rocks (contrast, for instance, the Baie Verte lineament ophiolite at Mings Bight; Kidd et al. 1978), and that over a wide area abrupt large thickness changes, characteristic of accumulations of volcanic rocks in normal fault-bounded structures, are not known. Uplift of the fore-arc platform during ridge subduction can account for the temporary and very local evidence of shallow water at the end of the igneous event (limestone above volcanic rocks at Hummock Island, and at Cobbs Arm; and porphyry clasts in the Cheneyville conglomerate (whether or not the present contact with the Dunnage there is faulted) before the rapid and substantial subsidence indicated by the overlying black shale units of the Lawrence Harbour and Dark Hole Formations and the thick succeeding late Ordovician–early Silurian flysch section (see Fig. 4). A back-arc basin rifting event would by contrast be expected to result in subsidence through the contemporary lithospheric stretching of the basinal area where the rifting volcanism is localized. When subsidence did occur, shown by the Shoal Arm Formation overlying the Lawrence Head, from shallower sub-wave base oxygenated red chert of the basal unit, to the black graptolitic chert and shale of the upper unit (Brüchert et al. 1994), this occurred after all magmatism in this area, and these sedimentary rocks neither show any effects of contemporaneous normal faulting in outcrop or in the regional scale mapped continuity of the unit, nor do they contain any quantity of coarse clastic materials. Similarly, at the northern margin of the Dunnage Mélange, shallow water conglomeratic and arenaceous sediments of the Cheneyville unit (with Coaker Porphyry clasts in the conglomerate layers) pass directly up into grey burrowed chert and then black chert and shale age-equivalent to those in the Shoal Arm Formation, and this section gives the same evidence of post-magmatic subsidence in a topographically subdued setting.

It is significant that gabbro sills do not penetrate higher in the section than the base of the Lawrence Head Formation type section, that the only known or potential sills within the volcanic rocks of the type section are diabase, and that no magmatic layers are found in the thick clastic sedimentary stratigraphic section above that unit[2]. If the gabbro sills are slightly younger than the Lawrence Head Volcanics and instead related to renewed arc activity (later Victoria arc; Zagorevski et al. 2012), then it is not immediately clear why gabbro sills should not be found throughout the Lawrence Head Formation, or even above the Lawrence Head in the Shoal Arm Formation chert units. On the other hand, if they are from the same magmatic event, these relationships are what would be expected.

Interpretation of the Magmatic Events

The overall conclusion of van Staal et al. (1998) was that the Exploits terrane/subzone and the Red Indian/Notre Dame Arc started colliding and that the former was partly underthrust in the later Ordovician. Before this happened, we think the evidence is clear that subduction created the Exploits group arc-related rocks of the Notre Dame Bay region, the earlier volcanic rocks as arc-volcanic construct(s) and the overlying volcaniclastic sedimentary rocks as deposits in a fore-arc basin. In the Darriwilian, the trench of this subduction system was approached by and interacted with an active spreading ridge system, resulting in a decline and shutoff of arc volcanism in this area as the last very young oceanic lithosphere entered the subduction channel (Delong and Fox 1977). Upon arrival, subduction of the ridge crest, and separation of the oceanic plates under the former fore-arc basin (a 'slab window') introduced E-MORB magmas into the fore-arc and accretionary prism that erupted as lavas now comprising the Lawrence Head Volcanics and also intruded the underlying Exploits group sedimentary section with a large volume of gabbro sills of the same composition. Early during this magmatic event, some of this magma caused melting at significant depth in the subduction channel of pelitic sedimentary rocks like those forming the matrix of the Dunnage Mélange (Lorenz 1985). The dacitic magma intruded to high levels, into the eastern half of the Dunnage Mélange, interpreted to be a sample of this accretionary prism; the abundant but small stocks and dykes of the Coaker Porphyry are the visible product (Fig. 17), and their field relationships show that the eastern part of the Dunnage was already disrupted mélange when they were intruded (Lorenz 1985; Williams 1994). To return this small-volume magma to near-surface emplacement position (recall the porphyry clasts in the overlying Cheneyville conglomerate) we think requires, for heat-loss considerations, the rapid buoyant rise of a structural package containing the melts along the upper margin of the subduction channel back to a near-trench position under the accretionary prism. This process (Thomson et al. 1999) would allow entrainment of xenoliths of types reported by Zagorevski et al. (2012) from partially subducted slices of fore-arc lithosphere, without requiring diapiric rise of Coaker magmas alone through tens of kilometres of the fore-arc lithosphere and crustal section.

The reported high-precision isotopic ages for the two different magmatic products are 469 ± 4 for the Coaker Porphyry (Zagorevski et al. 2010), and 463.7 ± 2 for a gabbro sill in the New Bay Formation (O'Brien et al. 1997). We point out that the slightly younger age for the inboard (slab window) mafic magmatism is expected for a ridge subduction event, and that coincident ages are not predicted for magmatism at and inboard from the same point along a trench system involved in such an event, except for the special case of a ridge crest entering a trench exactly at right angles. At a slower subduction rate (say 30–50 km/m.y.), the projected ridge crest might traverse from the trench under the full width of the former fore-arc basin (a distance in present day examples about 100–200 km) in 2 to 7 m.y.. The ~5 m.y. interval between the Coaker Porphyry and mafic magmatism of the Lawrence Head Volcanics and gabbro sills is consistent with this order of magnitude estimation.

Comparison of Newfoundland with Known Ridge Subduction Systems

Aspects of well-studied recent and modern examples of ridge subduction in the North Pacific (Alaska) and South Chile (Chile triple junction) margins are compared with those of the Bay of Exploits area (Table 3) and many, but not all aspects of the Alaskan event are seen in South Chile and Newfoundland. One particular difficulty is that in the case of Newfoundland, subsequent orogenic events have perhaps removed some significant components (e.g. emplaced ophiolite; arc platform) of the ridge subduction system, whereas in the more recent examples there is a good geographic and temporal record. Significant hydrothermal activity, high-temperature–low-pressure metamorphism and ductile deformation seen in the South Chile example may have resulted from on-going subduction of multiple ridge segments causing high heat flow in that system (Lagabrielle et al. 2000). This scenario is dependent on the geographic configuration of the ridge segments and relative velocities and directions of the plate boundaries; various configurations can conceivably result in a spectrum of thermal intensities in the fore-arc. While there is no metamorphic evidence of intense thermal activity in the fore-arc (New Bay Formation and Dunnage Mélange), the clear Coaker–Dunnage and Thwart Island gabbro–New Bay Formation intrusive relationships indicate that some such activity must have occurred, and Franks (1974) attributed the prehnite-pumpellyite metamorphism in the New Bay strata to the gabbro sill emplacement.

In other items, the rock record in Newfoundland only preserves indirect evidence of ridge subduction. Evidence for uplift of the fore-arc as the ridge enters the trench is seen in Alaska and Chile in the form of significant vertical and horizontal block motions, and brittle and ductile faulting in the fore-arc (Bradley et al. 2003; Lagabrielle et al. 2000), and in the case of Alaska, a change from trench-parallel flow directions in trench sediments

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[2] In the section on the Fortune Harbour Road, the uppermost two ~5 m thick massive flows (or perhaps diabase sills) of the Lawrence Head Formation have dark green bedded chert below them. Both these igneous layers (samples 18-77, 19-77) have geochemical properties not distinguishable from the rest of the samples from the Lawrence Head type section, and are included by us in that stratigraphic unit.

Table 3. Comparison with known ridge subduction systems

Alaska (Bradley et al. 2003; Sisson et al. 2003)	South Chile margin (Forsythe et al. 1986; Le Moigne et al. 1996; Guivel et al. 1999; Lagabrielle et al. 2000)	Newfoundland (this study)
Melting of accretionary prism sedimentary rocks	Isotopic ratios of Main Volcanic (MVU) and Chile Margin (CMU) units allow assimilation processes	Coaker Porphyry
Magmatic intrusion of the accretionary prism/fore-arc basin	Taitao Peninsula intrusions	Thwart Island Gabbro, Coaker Porphyry
Near-trench volcanism	MVU and CMU volcanism	Lawrence Head Volcanics (LH)
Mixed MORB-VAB geochemistry of mafic rocks	EMORB, MORB and VAB character of MVU and CMU	EMORB and VAB geochemistry of LH, Thwart Island Gabbro, and Coaker Porphyry
Hydrothermal activity	Sulphide veins in MVU	Minor sulphides in LH
Ophiolite emplacement	Taitao Ophiolite	Not seen
Variable trench sedimentation flow directions: trench-parallel followed by highly variable	No data recorded	?Trench-parallel in the New Bay Fm; other directions not recorded
Low pressure–high temperature metamorphism and ductile strain	Zeolite to greenschist-facies metamorphism in MVU lacks associated fabric development	Variable low-grade metamorphism, lack of fabric development
Brittle deformation	Dominantly ductile; numerous ductile strike-slip and normal shear zones	Not widespread; fault scarps suggested by olistostromal sections of Dunnage
Fore-arc uplift	Significant vertical and horizontal block motions	Conglomerate with porphyry clasts over Dunnage; local limestone at top of Lawrence Head Volcanics
Suppression of arc activity	Patagonian volcanic gap	Temporal decrease in grain size and bev thickness of volcaniclastic sedimentation in New Bay Formation prior to LH magmatism; none after LH

to variable flow directions (Bradley et al. 2003). In Newfoundland, uplift is indicated by the Cheneyville conglomerate containing porphyry cobbles unconformably overlying the Dunnage Mélange, local shallow marine limestone overlying the Lawrence Head Volcanics (and equivalent upper Summerford Group volcanic rocks); the regionally extensive red argillite and chert elsewhere found above the Lawrence Head may perhaps indicate sub-aerial erosion of the arc platform. Cessation of arc magmatism is shown by the extended time, based on the fossil occurrences (~6 m.y.), of chert and argillite deposition lacking volcanic input, above the Lawrence Head Volcanics.

The Assembly of the Dunnage Mélange

Mafic volcanic and gabbroic blocks in the western half of the Dunnage Mélange have been proposed on their geological properties to be derived from the Lawrence Head Volcanics and the underlying gabbro sills in the New Bay Formation (Hibbard and Williams 1979). Geochemical properties of these blocks previously reported (Wasowski and Jacobi 1985) and supplemented and summarized in this paper are consistent with this proposal, although our reconnaissance results suggest that blocks from other sources are also present. The fact that most of the large volcanic blocks in the western Dunnage contain pillow lavas suggests that they were derived from the upper section of the Lawrence Head Volcanics because, in the nearby type section, the lower half is mostly not pillowed. As such the disruption of the layered source of these large blocks and the formation of this part of the Dunnage Mélange must be younger than the eruption or intrusion of those blocks incorporated, i.e. probably about or younger than 464 Ma. It also requires that at least this part of the

Dunnage Mélange was located proximally to the Exploits Group after, and perhaps during mafic magmatism.

However, the eastern part of the Dunnage Mélange is intruded by Coaker Porphyry, with a U–Pb age of 469 ± 4 Ma (Zagorevski et al. 2007). Taking the outer ends of the 2σ uncertainty range of both this age and the 463.7 ± 2 Ma gabbro sill U–Pb age of O'Brien et al. (1997) allows the possibility that they coincide at about 465–466 Ma, but this interpretation leaves unanswered why the western part of the mélange lacks Coaker Porphyry intrusions. It is of interest to explore the consequences for the formation of the Dunnage Mélange that result if they are separate igneous events 5 Ma apart. It requires the proposal that the Dunnage Mélange consists of two parts (Fig. 17) with quite different origins; an eastern part formed as subduction-generated mélange before 469 Ma, when it was intruded by Coaker Porphyry, and a western part, containing most of the large mafic volcanic and all the large gabbroic blocks, not intruded by Coaker Porphyry, and formed into mélange at or after 464 Ma. The eastern part would be an accretionary prism product associated with subduction up to the time of local spreading ridge contact with the trench (we intend this to include the suggestion of Zagorevski et al. (2012) of a location at the forearc basin–accretionary prism boundary). The western part would be one or perhaps more large slope failure debris flow product(s) generated after local spreading ridge–trench interaction, probably from a major active fault scarp (similar to the mechanical origin of all the mélange proposed by Hibbard and Williams (1979), although from a thrust or strike-slip, rather than a normal fault system). This presumes that the two parts were juxtaposed at the time of the younger mélange-forming event, or later, but that they are not products of places originally far-separated along the former subduction boundary. The boundary between the two parts (Fig. 17) appears to have small regional strike-parallel offsets of right-lateral sense, a well-known property of Devonian age faults in this area (Kusky et al. 1987), one of which is exposed (Kay 1976, map locality 7).

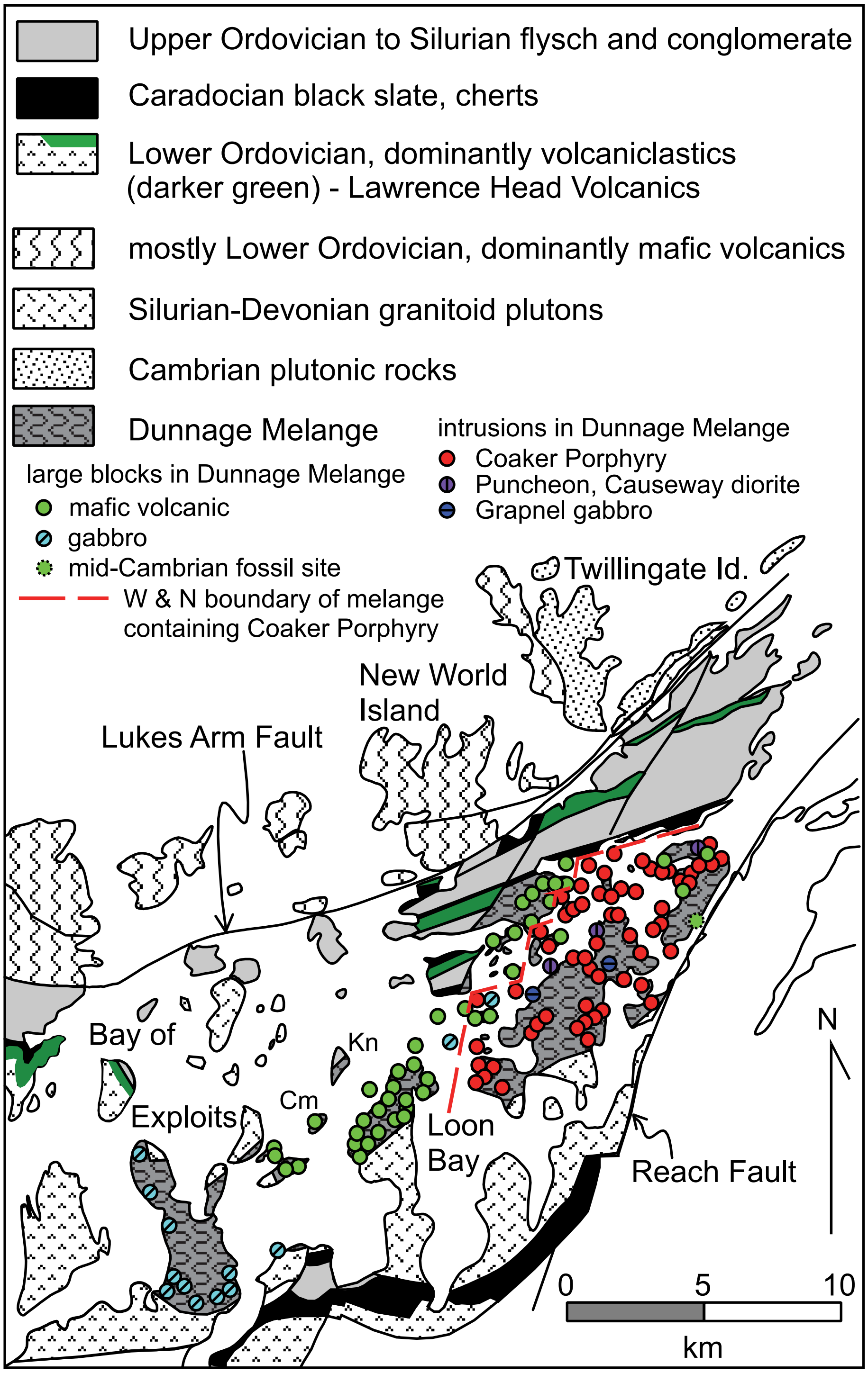

Figure 17. Outline geological map of the eastern Bay of Exploits–New World Island area showing the distribution of large mafic volcanic and gabbroic blocks, and of small igneous intrusions of known or presumed pre-Silurian age, in the Dunnage Mélange. Western/northern boundary of area of the Mélange containing the peraluminous silicic Coaker Porphyry shown by red dashed line. See text for discussion. Blocks and intrusions in the Dunnage Mélange after Kay (1976), Dean (1977a, b) and Hibbard and Williams (1979). Cm - Camel Island; Kn - Knight Island.

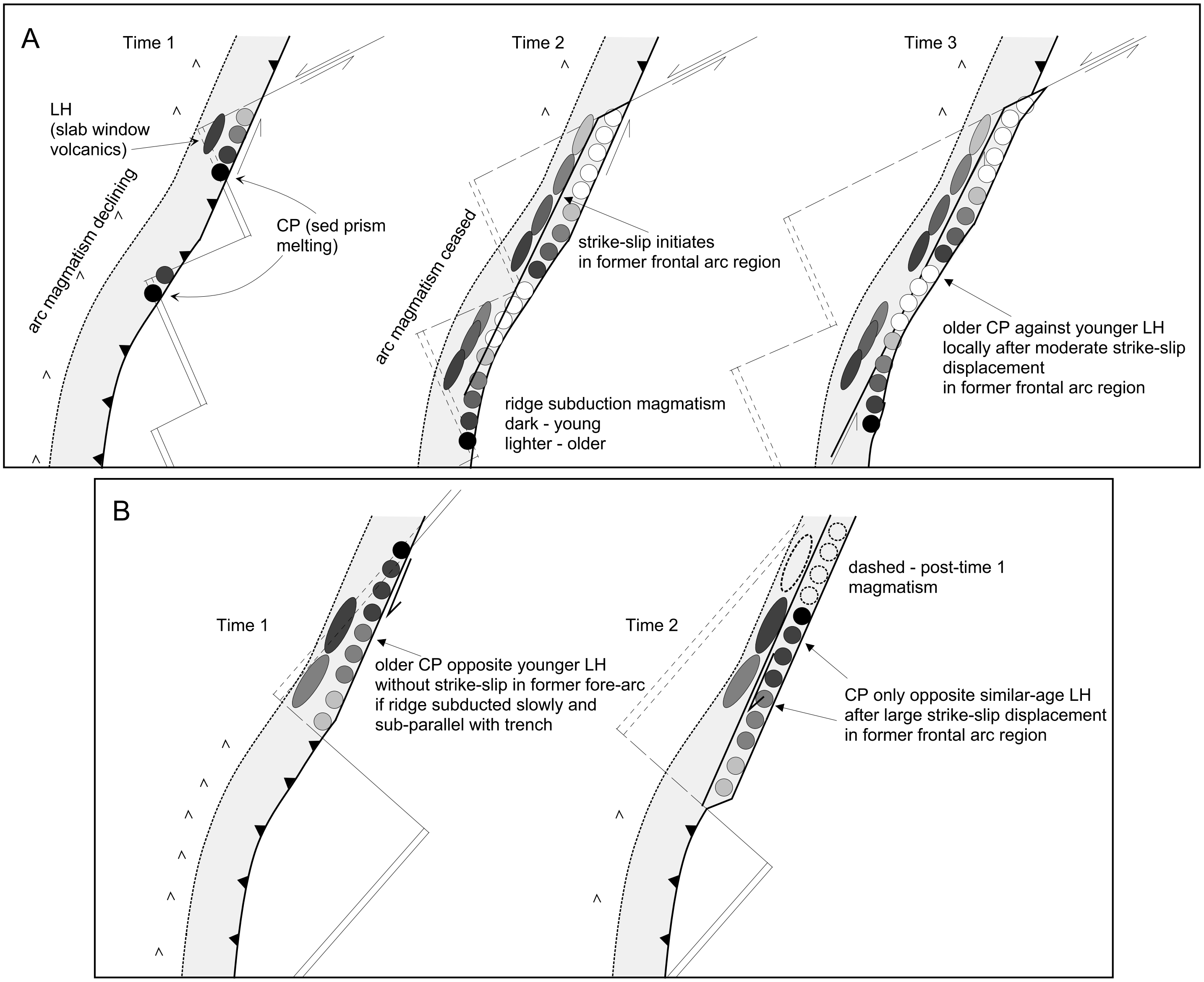

Figure 18. Sketch map diagrams illustrating possible spatial and age relationships of ridge subduction-related magmatism in near-trench locations (mainly Coaker Porphyry – CP – in Dunnage Mélange from melting of aluminous sedimentary rocks) and in former fore-arc basin locations (mainly E-MORB Lawrence Head Volcanics and related gabbro sills – LH – from slab window magmatism). See text for discussion.

Removing these offsets restores an approximately NNE-trending contact about which it would be interesting to know more, if any part of it is exposed above sea level. The orientation crossing regional strike perhaps implies that it was not formed by a major strike-slip fault consequent on a ridge–trench interaction (Fig. 18), and that the two parts of the mélange were not brought from places formerly widely separated.

Two adjacent islands in the central Bay of Exploits (Camel and Knight Islands; Fig. 17) contain strata that might suggest a younger age for formation of the western part of the Dunnage Mélange; aspects of the geology of these localities were discussed by Hibbard and Williams (1979). Our interpretation of the ages implied by lithological correlation of strata exposed on Camel Island suggests involvement in the Dunnage Mélange of manganiferous red and higher grey and black chert equivalent to all the Shoal Arm Formation and of the basal quartzose greywackes of the Point Leamington/Sansom Formation. On Knight Island, probable Sansom Formation-equivalent greywackes appear to contribute to the adjacent mélange (Hibbard and Williams 1979). If these observations apply to the whole of the western part of the Dunnage, then that mélange-forming event would be after the Caradocian (Sandbian) black shale was deposited, probably later Sandbian, and not older than about 456 Ma. However, it is known that olistostrome events occurred in the northern part of the Exploits subzone from the later Ordovician up into the Llandovery (McKerrow and Cocks 1978; Nelson 1981). It seems possible as an alternative that the disrupted materials on Camel and Knight Islands, located near or at the northwestern margin of the western Dunnage Mélange, were generated separately from, and formed at a later time than the bulk of the western Dunnage, which is not elsewhere reported to contain materials of such a young inferred age. In this context, we reject the hypothesis of McConnell et al. (2002) that the Dunnage Mélange is laterally equivalent to the Boones Point–Sops Head Mélange, because it is clear, as reported by Nelson (1979, 1981), that a significant part of the matrix and many of the blocks in the Boones Point–Sops Head are quartz-rich arenite and associated argillite identical to those in the late Ordovician–early Silurian Point Leamington and Gull Island Formations. The Boones Point–Sops Head mélange must be of that age or younger, even though it contains blocks, or olistostromic remnants, containing older Ordovician fossils also reported by Nelson (1981). The Dunnage Mélange, by contrast, does not contain late Ordovician material (with the possible exception of Knight and Camel Islands) and the stratigraphic relations of the eastern mélange show it to predate the Caradocian (Sandbian) black shale that overlies it.

The eastern Dunnage Mélange contains a single occurrence of early mid-Cambrian trilobites in a 60 cm limestone layer interbedded with pillow lavas forming a block a few tens of metres across on Dunnage Island in the southeasternmost exposures of the mélange. The fauna are significant in that they contain trilobite species of both North American and Avalonian affinities (Kay and Eldredge 1968), or likely Gondwanan proximity (Dean 1985). It seems to us most likely that this was introduced into the Dunnage Mélange by subduction-accretion from a seamount on incoming oceanic crust; mafic volcanic rocks in a unit approximately matching in age determined isotopically (Dunning et al. 1991) form the Lake Ambrose volcanic belt of the Exploits subzone. Mafic volcanic blocks in the two areas of the Dunnage Mélange have compositions mostly of E-MORB-type (Wasowski and Jacobi 1985), and apart from three of our samples, no compositional difference has otherwise yet been found between blocks from the eastern and western parts. Volcanic blocks scraped from the ocean floor entering a subduction zone preferentially sample topographic highs, often seamounts tending to have E-MORB compositions. We think that the compositional similarity of mafic volcanic blocks in the eastern and western parts of the Dunnage Mélange should not be taken by itself as evidence that they are all derived from the Lawrence Head event.

Tectonic Consequences of Ridge Subduction

A spreading ridge–trench interaction event can result in continued subduction at a reduced subduction rate where the spreading ridge crest–overriding plate resolved vector is convergent, or in elimination of the subduction zone with the spreading ridge crest departing slowly outboard if the pre-event subduction rate falls between the half and full spreading rates (for the resolved vectors). An oblique strike-slip component of movement must result at the former subduction margin in all cases where convergence continues across this boundary (unless the ridge crest happens to be locally at right angles to the trench), but conversion to a pure strike-slip plate margin will occur only if plate motion rates and directions match this special case (Dickinson and Snyder 1979).

For the Newfoundland Ordovician example, the volcanic and sedimentary stratigraphic record in the Bay of Exploits area suggests that the subduction-generated volcanic arc (that was active before the event) waned and shut off, and did not in this area resume any activity afterwards. Younger (~462–454 Ma) evidence of arc magmatism in an area inland to the southwest (van Staal et al. 1998; Zagorevski et al. 2010) could be a place where the ridge–trench interaction occurred later than farther northeast, for reasons of ridge and/or trench geometry, but is more probably evidence of renewed arc activity and subduction. This renewed arc activity had to be distant from the Bay of Exploits–Badger Bay area because there is no evidence in those well-exposed coastal sections of volcanism of that age range. Evidence that convergence and thrust loading from the northwest started in the Exploits subzone in the early Caradocian is clear from the marine foreland basin sequence of the black shale coarsening-upward flysch turbidite sequence extending into the early Silurian, and the olistostromic horizons within this (McKerrow and Cocks 1978; Nelson 1979; Arnott et al. 1985). This convergence is however not accompanied by volcanism; the sedimentary rocks instead show vigorous erosion of an older arc, the clasts being dominantly from exhumation of its plutonic foundation (Helwig and Sarpi 1969), and they do not contain any known volcanic or ash layers. It appears possible that there may be a significant gap in time between the ridge–trench interaction event and the convergent tectonics in the later Ordovician–early Silurian; fossil evidence (O'Brien et al. 1997) for the age of chert just above the Lawrence Head Volcanics is equivalent to about 464 Ma (see Fig. 3) but the lowest black shale of the foreland basin is equivalent to about 458 Ma; in this up to 6 m.y. long interval no strong evidence of convergent tectonics is apparent.

For this reason, in the ridge–trench interaction event we propose, we think it probable that the former subduction boundary either became a strike-slip boundary, perhaps with a small component of convergence, or became inactive (a null boundary), with the spreading ridge departing outboard. The latter possibility would provide a site for renewed subduction to initiate near the former subduction margin (Casey and Dewey 1984). That the eastern Dunnage Mélange fabric is cut by a NE-trending Grapnel Gabbro dyke (site EX-18 – Fig. 17) is perhaps evidence for the short-lived extension that null margin conversion would have induced.

If the event caused conversion to a strike-slip-dominated plate boundary, and subsequent strike-slip faulting migrated into the former fore-arc (like the present San Andreas Fault system), significant displacement of a near-trench area with respect to areas further inboard might result, and cause discrepancies of ages of adjacent magmatic bodies across the fault. Figure 18B shows that for a single ridge segment entering the trench, this can only result in near-trench magmatic products being placed adjacent to similar age or *older* inboard objects. In order to displace near-trench objects so that, and only locally, older ones end up adjacent to *younger* inboard magmatic bodies, the products of two adjacent spreading ridge segments are required (Fig. 18A). We suggest that, even if conversion to a strike-slip boundary did occur, it is more likely, since it should be the general case, that the apparent age difference of the Coaker Porphyry and Lawrence Head magmatism resulted from the progressive migration inboard of magmatism during a typical ridge-subduction event, rather than resulting from a local anomaly introduced by subsequent margin-parallel faulting.

Oblique strike-slip or thrust displacement of parts of the former fore-arc region might in itself allow development of large topographic escarpments, potentially prone to large scale collapse and production of major olistostrome deposits. Alternatively, development of local pull-apart basins, or oblique thrust segments along a strike-slip fault system produces similar large submarine topographic escarpments (the southern California offshore is a current example), or a combination of these can be envisaged. We suggest collapse from a large fault-generated escarpment, which originated after the spreading ridge arrival at the local trench, could be the origin of the western, Coaker Porphyry-free Dunnage.

Regional Implications

In attempting to reconcile the evidence we think is characteristic of ridge subduction at ca. 469–464 Ma in the Exploits Group and Dunnage Mélange, with the extensive discoveries of the past couple of decades about central Newfoundland geology, there is one consideration particularly pertinent. This is the arrangement of the early Ordovician lithotectonic belts in the Wild Bight/Seal Bay, western Bay of Exploits, New World Island (Toogood and Cobbs Arm belts), and Dunnage Mélange outcrop areas. Early interpretations, based on the existing positions of the belts, and apparent volcaniclastic facies gradient and regional paleoslope, placed the Wild Bight belt originally farthest northwest/west, and the Dunnage belt farthest east/southeast (e.g. Horne and Helwig 1969; Dewey and Bird 1971; Kay 1976; Nelson 1979), and located the Lawrence Head Volcanics in a fore-arc position, with subduction up to the time of the LHV event directed to the northwest under the Dunnage Mélange. From the synthesis of van Staal et al. (1998), and progressing through the revised interpretations and syntheses of van Staal et al. (2009), Zagorevski et al. (2010, 2012), the Dunnage Mélange has been placed on the northwestern side of the Victoria Arc, with the Exploits and Wild Bight Groups to the southeast within that arc, and subduction directed to the southeast under the Dunnage Mélange. This arrangement, with the Dunnage Mélange originally farthest northwest, requires a high-angle truncation of the Wild Bight and Exploits Groups and Dunnage Mélange at the Red Indian Line starting in the vicinity of Crooked Lake on the Trans-Canada Highway, and continuing northeast through the Bay of Exploits area, and also requires a clockwise rotation of about 90 degrees in the local trend of these lithotectonic belts, more pronounced in degree and amplitude than the regional bend in the Red Indian Line. In these syntheses, the Lawrence Head Volcanics and the underlying New Bay Formation volcaniclastic turbidites of the Exploits Group have been identified either as back-arc or intra-arc basin extension (Zagorevski et al. 2008), or ridge–subduction slab window magmas emplaced over the previous fore-arc basin (Zagorevski et al. 2012). For this arrangement, the implications are that the spreading ridge causing the events attributed here to ridge subduction was located in the ocean between the Victoria Arc and the modified margin of Laurentia (Fig. 19A), and that any interruption to subduction at the margin was brief (~5 m.y.), because arc-type volcanic rocks of 462–454 Ma age range occur on the western fringe of the Victoria Arc in central Newfoundland (Zagorevski et al. 2007), and apparently also as volcaniclastic rocks in the uppermost Wild Bight Group which contains a felsic tuff dated 457.5 ± 2.7 Ma immediately below the contact with the Shoal Arm Formation (Zagorevski et al. 2008).

However, there are stratigraphic data that appear to be in conflict with the uppermost Wild Bight Group tuff age. First, there is the age of the fossil assemblage of O'Brien et al. (1997) from the upper part of the Strong Island section of the Shoal Arm chert, which is given as probably late Arenig or early Llanvirn and not younger than the *P. tentaculatus* zone (which is mid-Llanvirn). This translates to a numerical age of not younger than about 460 Ma, and more probably in the range 465–462 Ma (Figs. 3, 4), at a lithostratigraphic level well above the base of the Shoal Arm chert and the dated Wild Bight Group tuff physically located just below that basal contact. This discrepancy might be explained by proposing that the chert deposits were a strongly diachronous facies, younger to the NW, but there is a second reason to think that there is a problem, from the age of the basal black shale. In Lawrence Harbour this is low in the *N. gracilis* zone (Helwig 1967), early Caradocian/Sandbian, about 458 Ma. In the section in Badger Bay (Brüchert et al. 1994) 260 m of the Shoal Arm red and grey chert units lie between the top of the Wild Bight Group volcaniclastic rocks containing the dated tuff layer and the base of the equivalent black shale on Gull Island (which also have an early Caradocian graptolite age – Nelson 1979). We think it is most unlikely that these chert units were deposited so rapidly as to allow the age of the tuff below them to be indistinguishable from the age of the black shale overlying them. Clearly there is a need to resolve this issue, presuming the current calibration of the base of the Sandbian/Caradocian is not in error, by dating of more tuff beds at these and other localities. In this paper, for these reasons, we do not use this uppermost Wild Bight Group age.

We are also not convinced that the synthesis of van Staal et al. (2009, as modified by Zagorevski et al. 2012) is the only possible regional arrangement of mid-Ordovician tectonic elements in the Bay of Exploits area. In particular we point to the lack of stratigraphic and lithologic evidence of renewed volcanism in the sedimentary rocks (Shoal Arm chert) above the

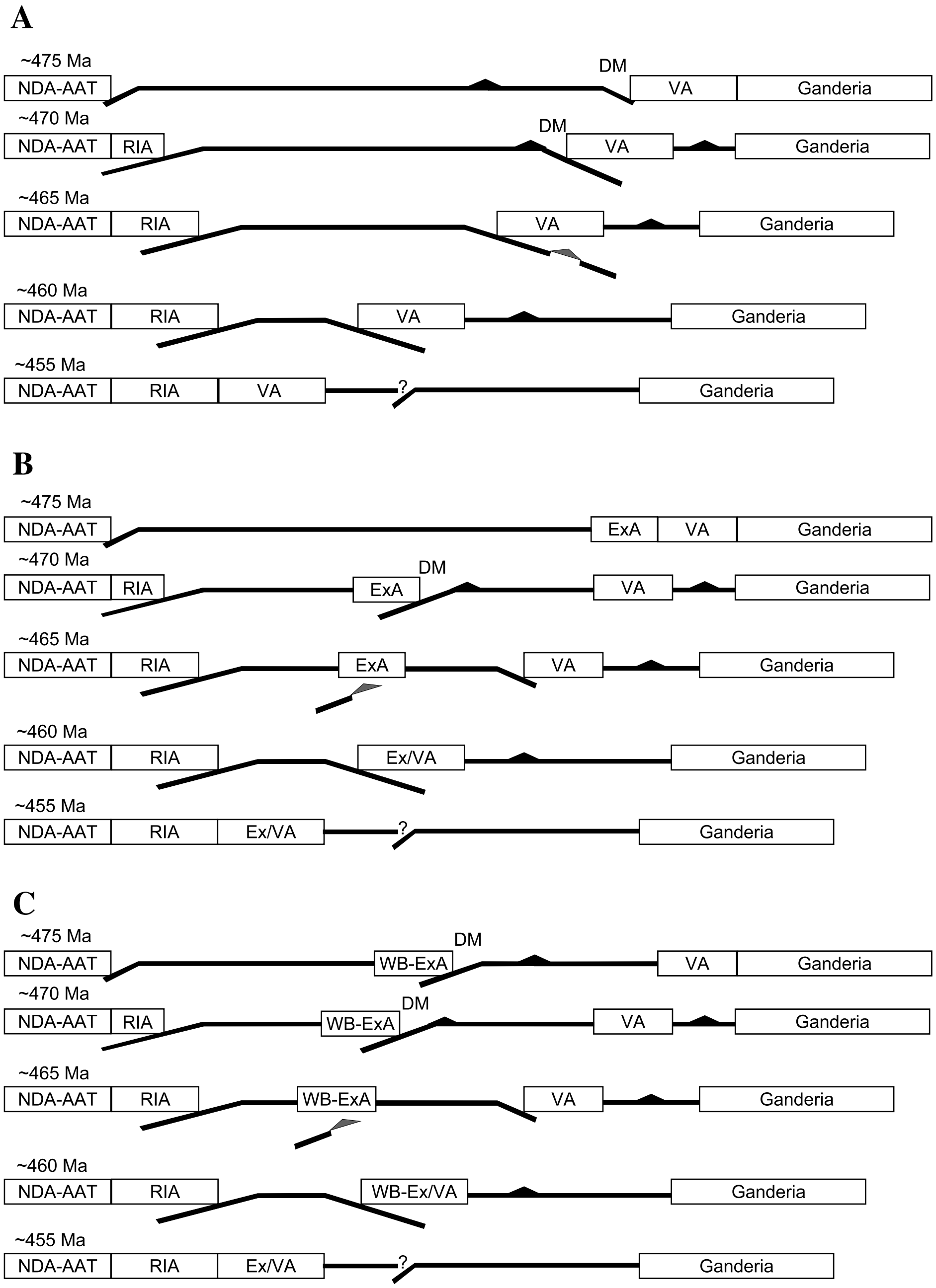

Figure 19. Cartoon sections illustrating possible locations and plate boundary arrangements of arc and microcontinental objects between the Laurentian margin and Ganderia, for time intervals from 475 to 455 Ma. Three different hypotheses are illustrated for the ridge subduction event, discussed in the text. NDA-AAT – Notre Dame Arc–Annieopsquotch Accretionary Terrane; RIA – Red Indian Arc; VA – Victoria Arc; ExA – Exploits Arc; Ex/VA – Exploits and Victoria Arc amalgamated, perhaps along strike rather than in the single section shown; WB-ExA – Wild Bight–Exploits Arc originating separately from VA. Black triangular symbol – active spreading ridge crest; DM – shown over site of actively forming Dunnage subduction mélange; grey triangular symbol – subducted 'ridge crest'/opening slab window; thick black lines – oceanic lithosphere, inclined where active subduction is starting or continuing. Hypothesis A is that proposed by van Staal et al. (2009) and Zagorevski et al. (2010).

Lawrence Head Volcanics, and moreover that there is geochemical evidence in the Shoal Arm chert units (Brüchert et al. 1994) of a decline upward to low values of detrital input from volcanic sources. The implication is that the 462–454 Ma arc volcanic rocks discussed by Zagorevski et al. (2010) were distant from the Lawrence Head Volcanics section around Lawrence Harbour, presuming that there is not an undetected and significant hiatus in that section at the top of the LHV. We also prefer to keep the connection or correlation between the Summerford Group and the Exploits Group originally proposed by Kay and his students (Horne and Helwig 1969; Kay 1976), and more recently incorporated by Zagorevski et al. (2012), unlike the separation of the Summerford Group into a supposed seamount accreted to the outboard side of the Dunnage (van Staal et al. 1998).

If the Dunnage Mélange was formed instead at a SE-facing arc margin, one place could have been on the eastern side of the Victoria Arc (Fig. 19B). van Staal et al. (1998, 2009) interpreted this margin as the back-arc side, and thought that opening of the Tetagouche ocean, splitting the older (now inactive) Penobscot Arc into two parts, starting ~475 Ma, requires this margin not to have become the site of subduction until late Ordovician–early Silurian time, and that subduction ended in the later Silurian by collision of the Exploits subzone with the Ganderia margin (van Staal et al. 1998, 2009), the suture represented now (Williams et al. 1993; S.H. Williams et al. 1995) by the Dog Bay Line. If, however, the Tetagouche spreading event split the Penobscot arc into more than one ribbon remnant arc, and/or formed more than one actively spreading oceanic ridge crest, it seems to us possible that subduction could have developed in the early Ordovician after this rifting, on a southeastern margin, and interacted not long after with the spreading ridge located to its southeast. In this type of scenario, we point out that the Harpoon Hill Gabbro in the eastern Victoria Arc (465.4 ± 0.7 Ma; Zagorevski et al. 2010) has the right position, age and geochemistry to be an equivalent of the Lawrence Head Volcanics as slab window magmatism.

A related alternative possibility might be to localize the Wild Bight–Exploits–Dunnage segment of a ribbon remnant arc with the main part of the Victoria Arc linked to it through an extending transform boundary, similar to the present-day Philippine Arc system, where the subduction changes polarity along the arc platform, for some time interval, before the final arrival and collision of these objects (van Staal et al. 2009; Zagorevski et al. 2010) with the Red Indian Arc at ca. 455 Ma.

We accept that it is very unlikely that the upper Wild Bight/Exploits/Dunnage assemblage could have formed a fore-arc basin–accretionary complex when attached to and affected by ridge subduction at the Laurentian active margin (as originally implied by Kidd et al. 1977, and stated by Brüchert et al. 1994). However, we think that there is no definitive piece of internal evidence in this assemblage that rules out the possibility that the older parts of the Wild Bight and Exploits Groups were either removed from the active Laurentian margin, initially by back-arc basin opening, before development of the earliest part of the Red Indian Arc (about 473 Ma, Zagorevski et al. 2006), or left behind separate from the part of the Penobscot Arc which collided with Ganderia, and from that time located in between the Laurentian margin and the Victoria Arc (Fig. 19C). The paleolatitudes reported by Van der Voo et al. (1991) of the Roberts Arm and Exploits Group for the early–mid Ordovician are not inconsistent with this possibility.

In all interpretations, a difficulty may be located in the influence of ridge subduction on arc magmatism, in that (as first pointed out by Delong and Fox 1977), the arc magmatism tends to be suppressed for an interval both before and after ridge–trench conjunction, the length of time depending on both the spreading and subduction rates. Thus a hiatus in arc magmatism may not require absence of subduction, and the inevitable lack of information on plate motion rates makes interpretation of ancient volcanic arc terranes inherently uncertain. This problem becomes worse if there are later tectonic excisions, and the possibility of subsequent rearrangement/removal of some parts of the Newfoundland eastern Exploits subzone by Silurian to Devonian strike-slip faulting should not be underestimated (a point first emphasized by Kay 1976).

CONCLUSIONS

We think that tectonic models involving a back-arc basin opening or rifting origin of the Lawrence Head Formation magmas are not consistent with some of the associated stratigraphic evidence, particularly of uplift and subsidence timing, even though the geochemical characteristics of the magmas can be fitted to this setting, based on at least one modern example, in the Lau Basin of the Tonga Arc (e.g. Jenner et al. 1987). For the several reasons given above, we strongly prefer the tectonic model where Dunnage Mélange at least in the older part represents an assemblage formed in the inner trench slope region of a significant oceanic subduction zone, and the magmas of the Lawrence Head event including gabbro sills and Coaker Porphyry, were caused by a main ocean spreading ridge approaching and interacting with the trench and its accretionary prism and fore-arc basin system. The spreading ridge segment entering this region had E-MORB or hot spot character, as known to occur intermittently along present-day spreading ridges (Schilling 1975; Sun et al. 1979; le Roex et al. 1987), and which is reflected in the chemistry of the Lawrence Head magmas emplaced above the ridge subduction slab window.

Evidence for ridge subduction in the early–middle Ordovician has also been suggested (Schoonmaker and Kidd 2006) for the terrane exposed in the Chesuncook Dome of north-central Maine, where a mélange unit is extensively and syn-kinematically intruded by gabbro (Bean Brook Gabbro) and adjacent pillow lavas (Dry Way Volcanics) are the volcanic equivalents. Here, the magmatism is N-MORB type, and the (admittedly not well constrained) ~473 Ma age is slightly older than the Lawrence Head event. Being located in a similar zonal cross-strike position in the orogen, it is possible that this may have originated from the same spreading ridge–subduction zone interaction as for the Lawrence Head event, as a diachronous event that depended on particular features and orientations of the spreading ridge and trench geometries. The example of the well-constrained evidence for early Tertiary ridge subduction at the Alaska Trench (Bradley et al. 2003) is instructive for comparison to these northern Appalachian relicts of the variable geological effects caused by ridge subduction including both the scale and the relative timing of such an event along a subduction system.

ACKNOWLEDGEMENTS

We thank Peter Lyman for analytical work; the H_2O and some of the XRF results on the older sample suite. Funding from the National Science Foundation for fieldwork and sampling in 1977 and 1978, and older analyses of those samples, is belatedly acknowledged. Funding for the more recent geochemical analyses, from the University at Albany Foundation, originating from donations by alumni of the Geological Sciences, is gratefully acknowledged. This paper is dedicated to the memory of K. Douglas Nelson, who participated in the original field work and research. We thank Cees van Staal and two anonymous reviewers for their thoughtful comments, which led to significant improvement of this paper.

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Received October 2013
Accepted as revised July 2014
First published on the web September 2014

APPENDIX 1

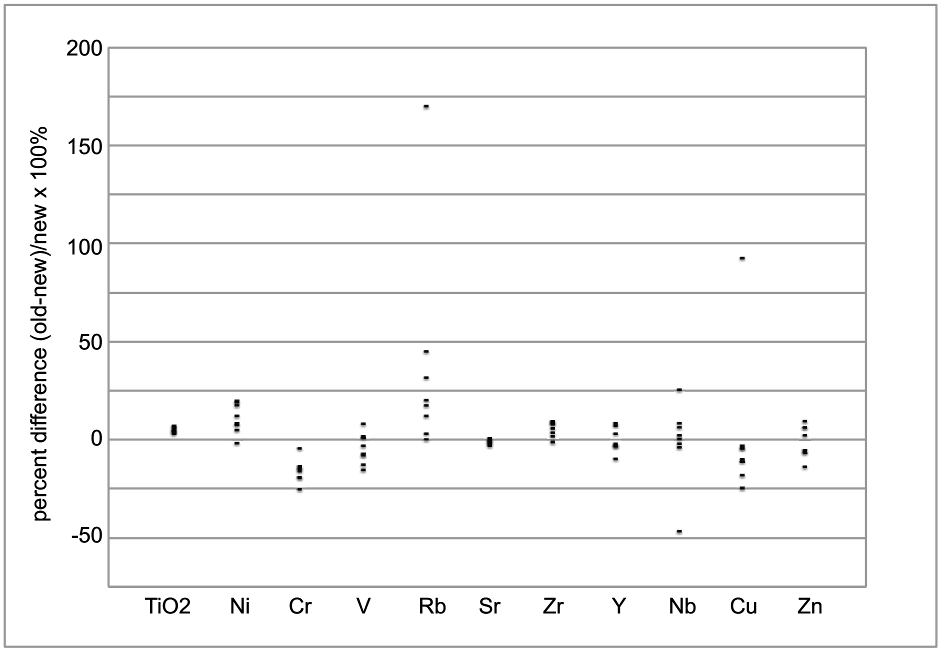

Figure A.1. Comparison of values from old and new XRF analyses of eight samples. Each point represents the percent difference between a single pair of old and new analyses for a given element: (old–new)/old * 100%.

Previously unpublished geochemical analyses of samples from the Lawrence Head Volcanics and gabbro sills in the New Bay Formation were originally made in 1982 (from samples collected in 1977 and 1978) and eight of these samples were re-analyzed in 2003. An additional seven samples from blocks and sills within the Dunnage Mélange were analyzed in 2013. A sill from the New Bay Formation (EX-05b), not previously analyzed, was also analyzed in 2013. Table 1 does not include compositions obtained from the 1982 analyses that were repeated in 2003.

The 1982 analyses were made by preparing glass beads by fusion of whole-rock powders in a Mo-strip furnace under three atmospheres of argon. The resulting beads were fused a second time to ensure homogeneity, and then polished and analyzed on an ARL electron microprobe (Harvard University). The analyses, usually an average of four to five points, are given in Table 1. Because the fusion process drives off the volatiles, the major element analyses in Table 1 are effectively water-free compositions. As one measure of the degree of alteration of the samples, we have also made H_2O+ analyses by a modification of Shapiro and Brannock's (1956) technique (DeLong and Lyman, 1982) and they are given as LOI in Table 1.

Trace element analyses made during 1982 of Rb, Sr, Y, Zr, Nb, V, Cr, Co, and Ni were made by x-ray fluorescence spectroscopy (XRF) at Woods Hole Oceanographic Institution using instrumental conditions and standardization as described by Schroeder et al. (1980), and these results are also presented in Table 1. Additional analyses for rare earth elements (REE) in four samples were obtained by isotope dilution on a 12-inch radius, 90 sector mass spectrometer of NBS design (SUNY at Stony Brook). Sample powder (300 mg) was fused with specially cleaned lithium metaborate in graphite crucibles, then dissolved in nitric acid containing the REE spike. The analytical uncertainty for the REE analyzed is less than two percent of the amount present.

Eight samples from the 1977/78 suite were re-analyzed in 2003 by XRF and inductively coupled plasma–mass spectrometry (ICP–MS) methods. Reported major element and Zr values in Table 1 are XRF results. All other reported elements are from ICP–MS. Figure A.1 was constructed to examine the percent difference between the 1982 and 2003 analyses and is discussed in the text. Samples were chosen to minimize alteration and veins. Rock chips were hand-picked to avoid weathered surfaces, veins and interior inclusions; powders were ground and analyzed (XRF and ICP–MS) at Washington State University's GeoAnalytical Laboratory (WSU). This suite included the Palisades Sill standard PAL-889. We compared the XRF analyses of PAL-899 at WSU with an XRF analysis from the University of Massachusetts (UMass) with the following percent variations (% variation=100*[WSU – UMass]/UMass; batch 2 in parentheses): TiO_2: 0.5% (0.5%), Cr: 0.6% (0.8%), V: 2.6% (3.0%), Zr: 6.5% (6.5%). Similarly, the two ICP–MS analyses of PAL-889 were compared to an INAA analysis from Cornell University, with the following percent variations: La: 0.5% (5.0%), Ce: 8.3% (9.8%), Nd: 6.8% (7.3%), Sm: 2.5% (1.5%), Eu: 10.5% (5.6%), Tb: 3.5% (0.2%), Yb: 6.3% (5.7%), Lu: 3.2% (1.4%), Ba: 4.8% (5.7%), Th: 0.4% (3.2%), Hf: 0.1% (1.2%), Ta: 3.7% (6.0%), U: 8.9% (10.2%), Cs: 10.4% (11.8%), Sr: 3.7% (7.9%).

A further eight samples (one New Bay Sill, EX-05b, and seven samples from gabbro and basalt blocks in the Dunnage Mélange) collected during 2008 were also analyzed at the GeoAnalytical Lab in 2013, using similar methods.

Figure A.1 shows the percent difference between the 1982 and 2003 analyses for eight samples and 10 trace elements and TiO_2 ((old–new)/new x 100).