Lawrence Head Volcanics and Dunnage Melange, Newfoundland Appalachians: Ordovician ridge subduction or back arc rift?

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Abstract
We review the geological setting and report new geochemical trace element data from the Ordovician Lawrence Head Volcanics (LHV), the underlying gabbro sills of the Exploits Group, and mafic blocks and dikes in the Dunnage Melange. In combination with existing published analyses and ages of these rocks, the volcanics 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 +/- 2Ma). The LHV and their enclosing strata show regional evidence for: 1) decline of volume and grain size of arc-derived volcaniclastics over the uppermost turbidite sediments below the LHV; 2) change to shallow marine conditions locally by the end of LHV volcanism, followed immediately by significant subsidence and 3) no evidence of coarse-grained clastic input, nor of normal faulting, during or immediately after LHV volcanism. Ridge-trench interaction (ridge subduction) at a NW- or SE-dipping subduction system is consistent with all of these features, but a rift (back-arc) origin over a SE-dipping subduction zone can only accommodate the compositions, and is inconsistent with the geological evidence. The Dunnage Melange (DM) has been interpreted either as olistostromal in a developing backarc rift basin, or as a subduction accretionary prism. Peraluminous intrusions in the Melange (Coaker Porphyry - CP) are more readily explained by ridge subduction, and a previously reported zircon age (469+/-4) is reasonably consistent with the age of the LHV and gabbro sills. Blocks of volcanics and gabbro in the DM are lithologically similar to the LHV and related gabbro sills, but some blocks, mainly from the eastern half of the DM, do not resemble them geochemically. 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 (olistostromal versus accretionary), for the origin of the western DM.

Geological setting
Lawrence Head Volcanics, gabbro sills

The Lawrence Head Volcanics are basalts dominated by massive flows in the lower part, and by pillowed basalts in the upper part of the ~ 900 meters thick type section (Figs. 2, 3). They are the uppermost Ordovician volcanic event in the Bay of Exploits section (up. Darriwilian - Fig. 4); volcaniclastic arc-derived turbidites of the New Bay Fm. extend below to the Tea Arm Fm. arc-type volcanics of early Tremadocian age. The Lawrence Head (LHV) are mostly overlain by cherts and argillites of the Shoal Arm Fm., distinctively identifiable, with a basal red/green unit, a middle grey mottled unit, and upper black graptolitic shale unit (Sandbian) throughout the Badger Bay-Bay of Exploits coastal region. To the NE, the LHV and its equivalents on New World Island are locally overlain by shallow marine limestones, which are under the black shale unit (Fig. 4).
Gabbro sills are extensive and abundant in the volcaniclastic section below the LHV (Figs. 2, 3); some doleritic massive layers in the lower LHV may be equivalent, but none occur above the LHV. We think (see Geochemistry section, and the age constraints below) that the gabbros and the LHV are from the same magmatic event.
Prior to the LHV, paleocurrents and slumps in the New Bay Fm. show a SE- to E-paleoslope; there is a corresponding coarse to fine facies gradient in the equivalent volcaniclastics from Wild Bight Group in the NW through New Bay Fm to the Dunnage Melange.

Significant age constraints
1. The U/Pb zircon age of the Coaker Porphyry 469 +/- 4 Ma (Zagorevski et al. 2012)
2. U/Pb baddeleyite age of gabbro sill from New Bay Formation 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 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 limestones 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 (Bergstrom et al, 1974; Arnott et al, 1985) [upper Darriwilian; about 460 Ma.]
6. Fossil age in cherts 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.]

These ages are consistent and suggest: a) the Lawrence Head Volcanics erupted about between 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 Ma. older.

* 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 are shown in [square brackets] and are our estimates; in making these we also used the Ordovician Chronostratigraphic Chart of Bergstrom et al, (2008).

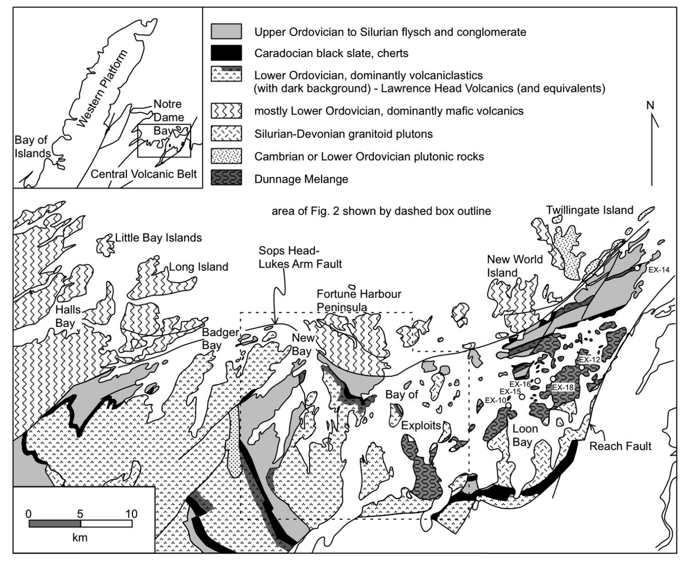


Fig. 1. Outline geological map of the Notre Dame Bay region of Newfoundland. Lawrence Head Volcanics and equivalents shown only for sections dominantly volcanic flows; possible equivalents mostly fragmental are found elsewhere in the Lower Ordovician Exploits Group in the same stratigraphic position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

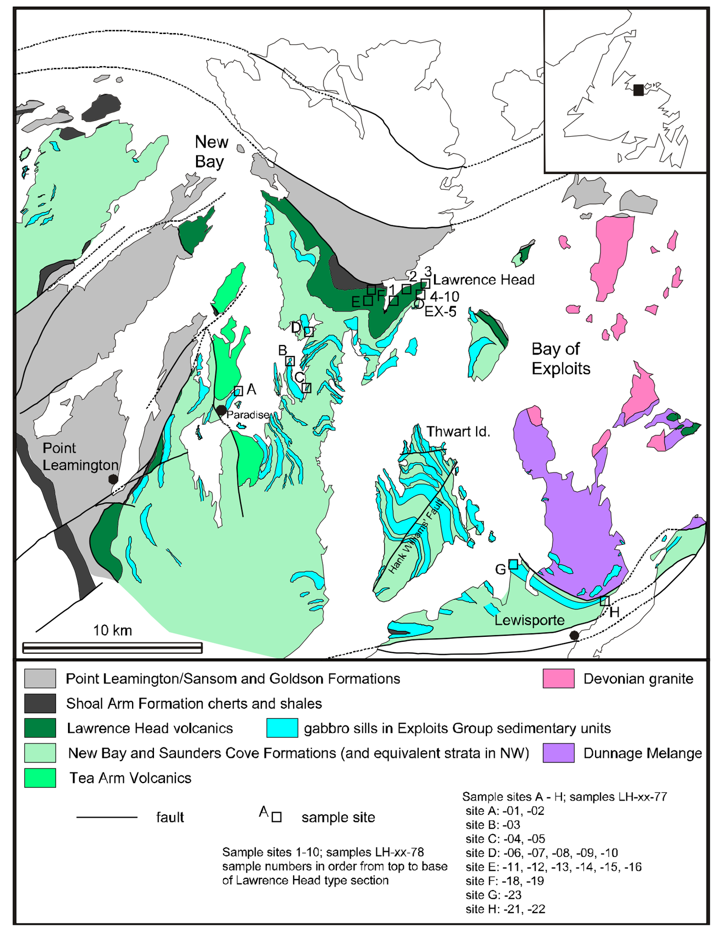


Fig. 2. Geological location map of the Exploits subzone in the New Bay – Bay of Exploits area. Sample sites for this study shown, with sample numbers for each site listed below. Lawrence Head Volcanics and equivalents shown only for sections dominantly volcanic flows; possible equivalents mostly fragmental are found elsewhere in the Lower Ordovician Exploits Group in the same stratigraphic position just below the mid-Ordovician cherts and black shales (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.

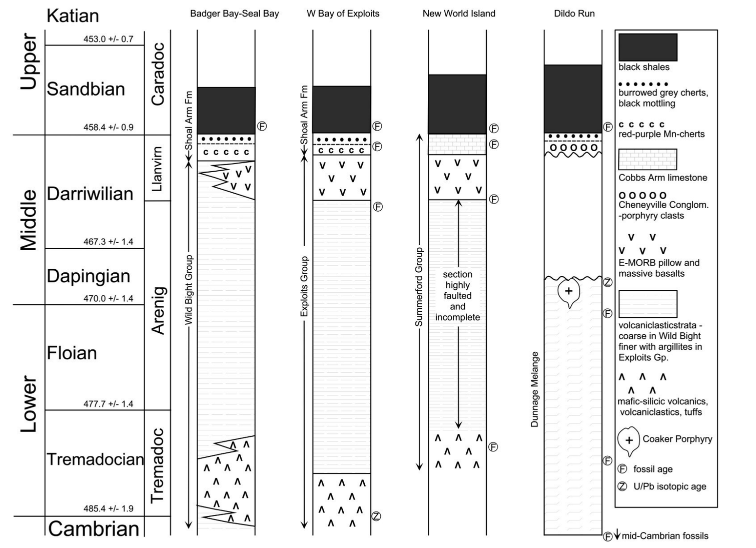


Fig 4. Stratigraphic columns for the Exploits sub-zone Ordovician of Badger Bay-Seal Bay, western Bay of Exploits, New World Island, and Dildo Run areas. Chronostratigraphic calibrations sourced from International Commission on Stratigraphy Chronostratigraphic Chart v2013/1, and Ordovician Chronostratigraphic Chart of Bergstrom et al. (2008). Based on compilation and field data of Nelson (1979), and including data from Helwig (1967; 1969), Horne, (1968; 1969), Horne and Helwig (1969); Kay and Eldredge (1967); Bergstrom at al. 1974), Neuman (1976), Kay (1976); Hibbard and Williams, (1979); modified and supplemented from data in O'Brien et al. (1997); Williams, (1995), Williams, S.H. et al. (1995); Zagorevski et al. (2012). Some boundaries, in particular the to ps of the two main volcanic intervals, may be hiatuses, but age data to show this is not available. Cambrian and Arenig fossils in the Dunnage Mélange are in blocks.

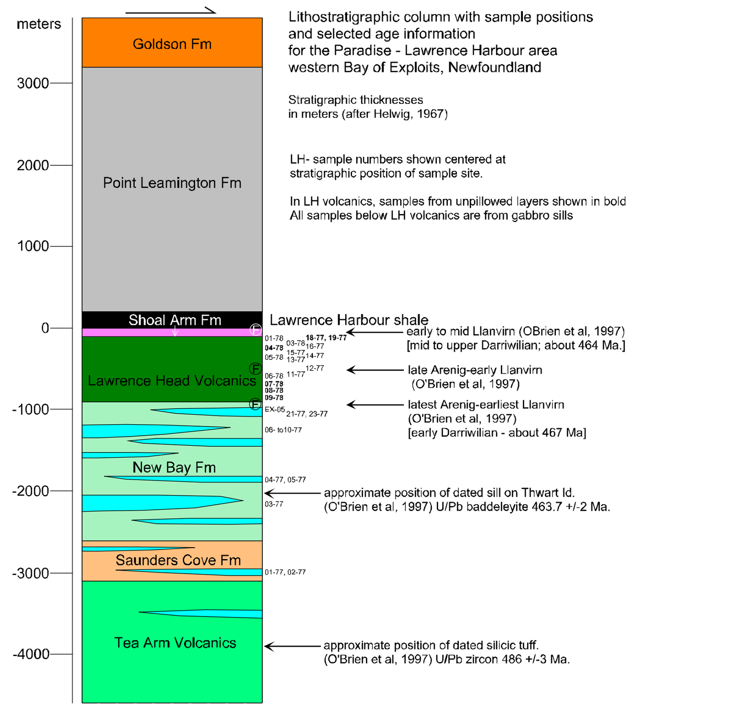


Fig. 3. Lithostratigraphic column for the Exploits Group and adjacent units of the western Bay of Exploits – New Bay area, showing sample positions and numbers, and key age information for the Lawrence Head Volcanics and the gabbro sills. Stratigraphic informati on after Helwig (1967); age information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

Samples we analysed of Lawrence Head Volcanics all come from locations in or near the type section. Samples we analysed of the gabbro sills are mostly from the well-exposed and stratigraphically well-constrained coastal sections to the SW (Fig 2).

Why attempted spreading ridge subduction (ridge-trench interaction) is the solution
These items, first highlighted by Kidd et al. (1977), require explanation:
Lawrence Head Volcanics and gabbro sills below are one magmatic event, EMORB-OIB/WPB, emplaced during 467-463Ma (and possibly a briefer inteval within this).
An early Ordovician volcanic arc, seen indirectly in fining/thinning volcaniclastic sediments of the New Bay Fm (and Wild Bight Gp equivalents), declines in intensity and shuts off just before/at the point where Lawrence Head magmatism occurs.
No volcanism occurs in this area after the Lawrence Head event; sedimentation after the LH event shows evidence of subsidence eventually into deep graptolitic shale conditions, locally starting from shallow-marine carbonates. The latter imply significant uplift associated with the LH event, because New Bay Fm. sediments below the LHV are all turbidites/debris flows
Hypotheses:
Back-arc basin rifting might explain the geochemistry of LHV and sills, but complete lack of arc-derived volcaniclastics in and above LHV is not consistent with this hypothesis.
Random non-plate-margin hot-spot passage across a subducting margin might explain the LHV geochemistry, but not the premonitory decline and termination of subduction-generated magmatism.
Spreading ridge-subduction zone interaction can explain the magmatic event, with EMORB/OIB ridge segment, and the temporally-associated arc shutoff, with either plate margin conversion to transform motion (e.g California Neogene), or to inactive margin with departure of ridge, now slower spreading, outboard.
And.....there's more....in the Dunnage Melange, over to the right.

Geochemistry - Lawrence Head Volcanics and gabbro sills

All rocks analyzed for this study plot in the basalt and alkali basalt fields of the Zr/Ti vs. Nb/Y diagram of Winchester and Floyd (1977).
On chondrite- normalized diagrams (Fig. 6), samples show negative slopes due to strong enrichment in LREE, slightly more enriched than average E-MORB, but significantly less than average ocean island basalts (OIB) .
On the MORB-normalized diagram (Fig. 7), a similar pattern of LREE enrichment occurs, with an absent to very slight Ta-Nb negative anomaly in our samples. The Lawrence Head Volcanics of O'Brien et al. (1997) are similar, but their NB gabbro analyses from Thwart Island show a Ta-Nb negative anomaly
.
On a variety of trace element tectonic discrimination diagrams (Figs. 10-15), our Lawrence Head basalts and NB gabbro sill samples plot in fields consistent with an enriched mantle source, indicative of E-MORB tectonic setting (Figs. 10-11). On diagrams that do not have explicit E- MORB or similar fields, samples generally plot intermediate between N-MORB and within-plate tholeiites (Figs. 12-14). Some of the LH analyses of O'Brien et al. (1997) from sites distant from the type section plot in more alkaline fields (Figs. 12, 13).
The composition of upper continental crust (UC) is shown (from McClennan 2001); 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 on these diagrams no points fall in or near the volcanic arc fields. We concur with the suggestion of O'Brien et al. (1997) that their gabbro samples with Ta-Nb negative anomalies most probably result from local contamination by crustal material.
In discrimination diagrams, LREEs typically form 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 Th/Ta-Yb/Ta diagram, Fig. 11). Arc tholeiites and calc-alkaline rocks associated with arc activity typically plot tangential to these "mantle" arrays. The Lawrence Head Volcanics, in some cases, show a very slight tendency in this direction as evidenced by a slight increase in the ratio of Th/Yb (Fig. 11), Ta-depletion/Th-enrichment (Fig. 10), and a slight depletion of Nb; 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).
In general we conclude that there is no persuasive evidence that the Lawrence Head Volcanics and the gabbro sills below them were products related directly to a volcanic arc, and we also conclude that the LHV and the gabbro sills are not distinguishable geochemically, allowing for minor variations in crustal contamination.

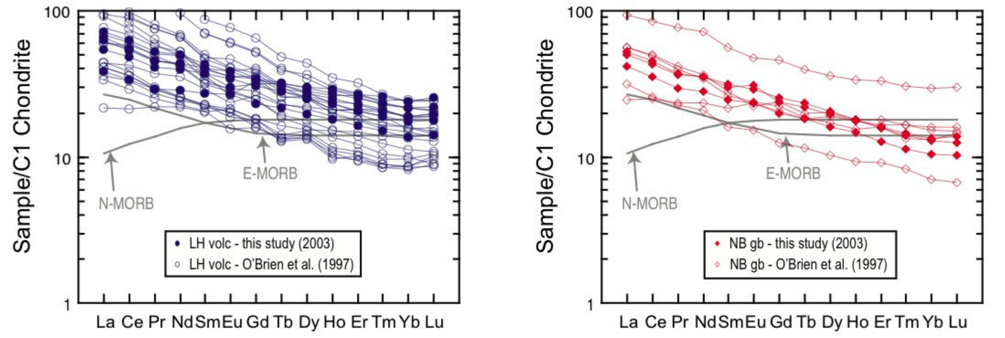


Fig. 6. C1-chondrite normalized diagrams of rare earth elements (REE)

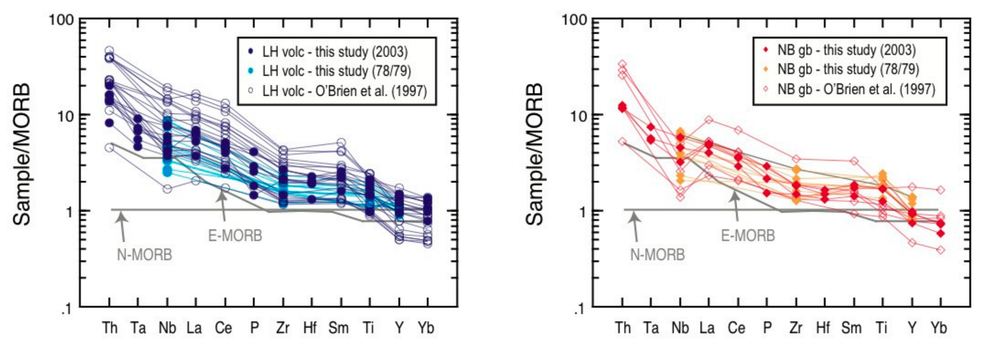


Fig. 7. MORB-normalized diagrams of selected trace elements

In geochemical diagrams
LH volc - Lawrence Head Volcanics
NB gb - gabbro sills from New Bay Fm.
DUN - blocks in Dunnage Melange

Pillow lavas of the upper Lawrence Head Volcanics in the type section on the south side of Lawrence Harbour. These exposures are worth a visit!

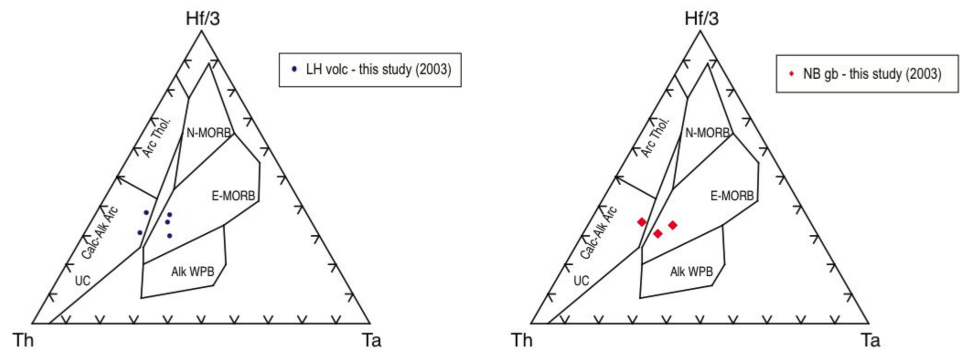


Fig. 10. Th-Hf-Ta diagram of Wood (1980)

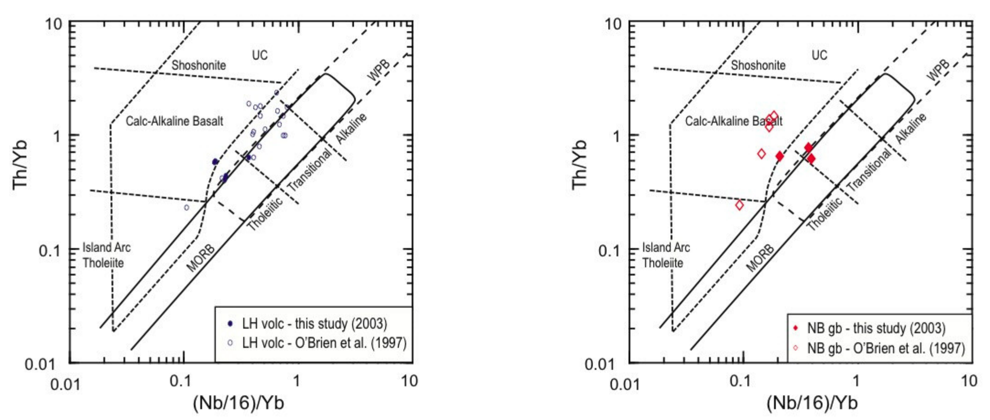


Fig. 11. Modified Th/Yb-Ta/Yb diagram of Pearce (1982) using Nb/16 for Ta

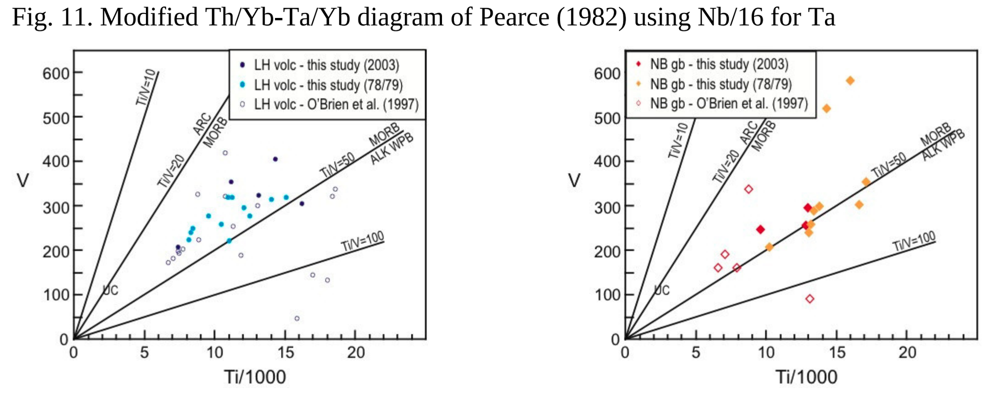


Fig. 12. Ti-V diagram of Shervais (1982)

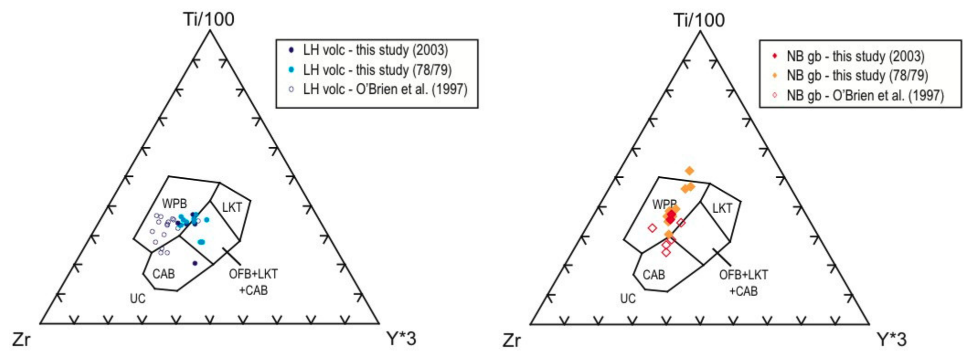


Fig. 13.Ti-Zr-Y diagram of Pearce and Cann (1973)

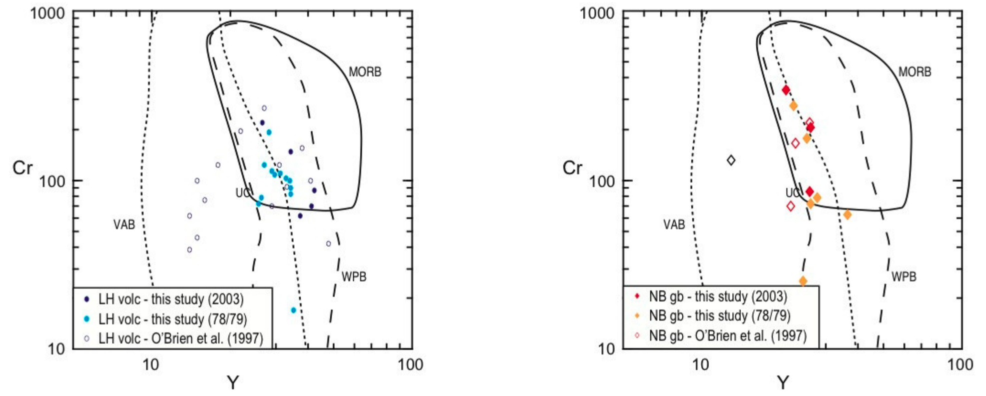


Fig. 14.Cr-Y diagram of Pearce (1982)

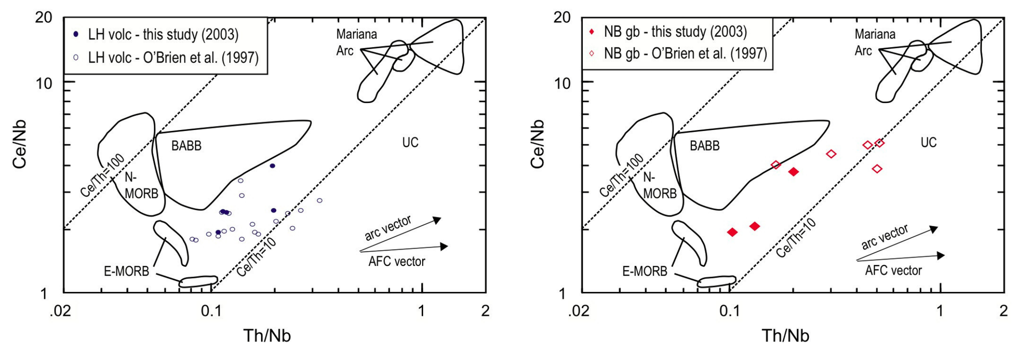


Fig. 15. Ce/Nb vs. Th/Nb diagram of Saunders et al. (1988)

Funding from the National Science Foundation made possible the fieldwork and sampling in 1977 and 1978, and older analyses of those samples. Funding for the more recent geochemical analyses, from the University at Albany Foundation, originating from donations by the alumni of the Geological Sciences at the University, is gratefully acknowledged. Paper dedicated to the memory of K. Douglas Nelson, who participated in the initial field work and research, and Hank Williams, for his inspirational investigations of the geology of Newfoundland, and in this area in particular (Botwood map, 1962).

The Dunnage Melange - subduction-related, or more than one origin?

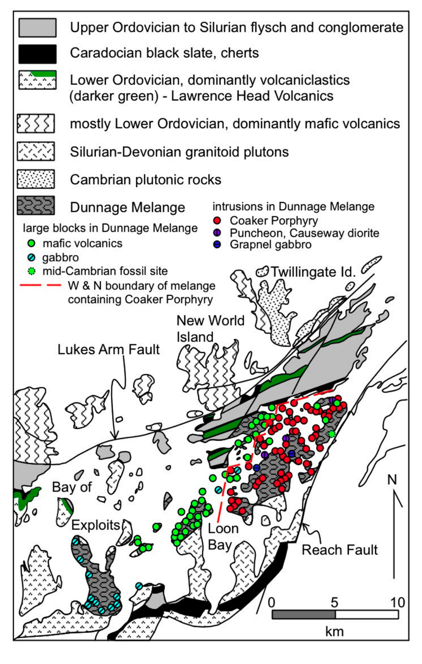
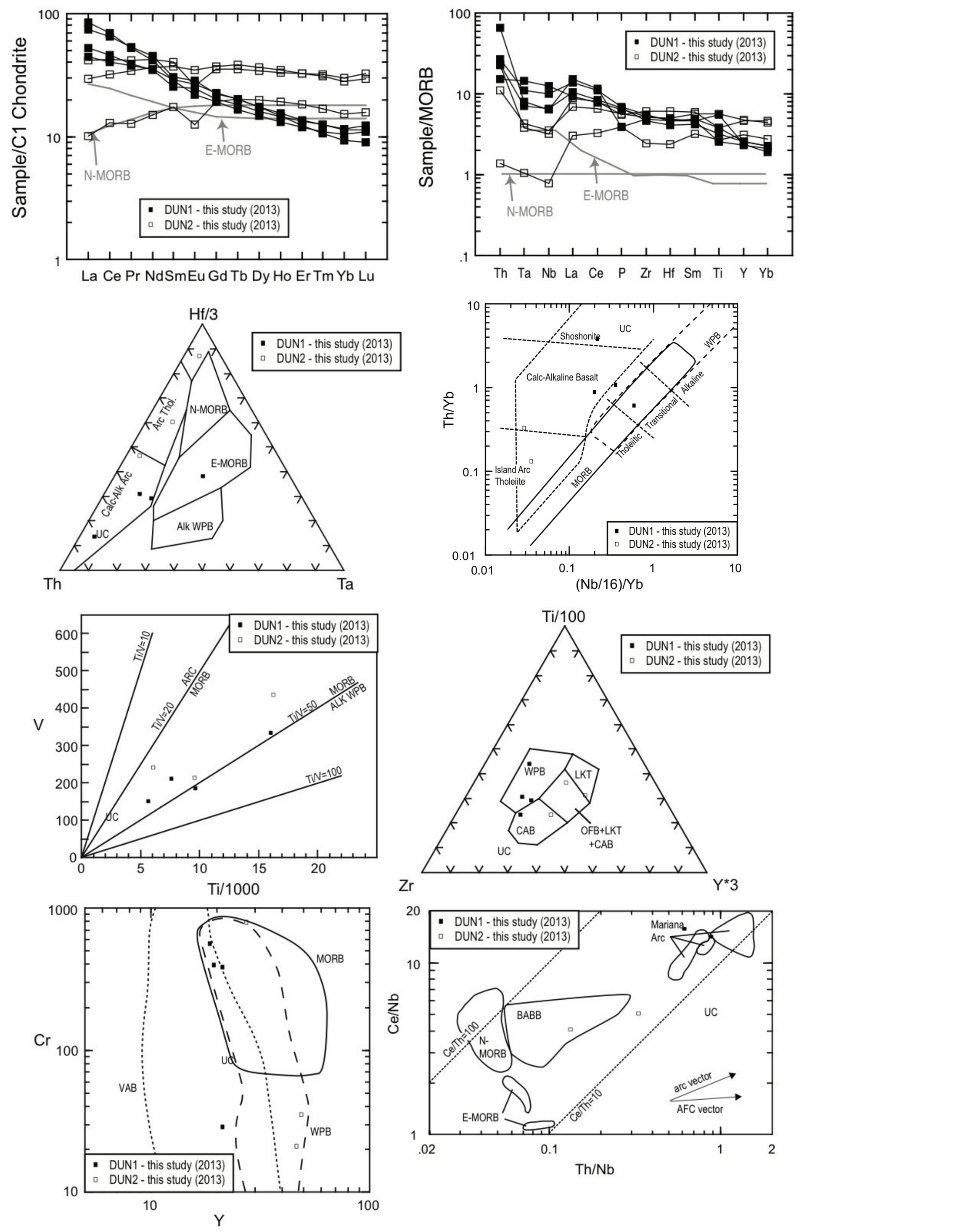


Fig. 17. Outline geological map of the eastern Bay of Exploits – New World Island area showing the distribution of large mafic volcanic and gabbro blocks, and of small igneous intrusions of known or presumed pre-Silurian age, in the Dunnage Mélange. Western/northern boundary of area of the Mélange containing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

Intrusions in the eastern Dunnage Melange
The DUN1 subset includes two samples of phlogopite gabbro dikes (Grapnel Gabbro) which cut the melange fabric in the eastern part of the Dunnage, and which resemble geochemically the Lawrence Head Volcanics. The eastern Dunnage also localizes (Fig 17 above) the more abundant dikes and stocks of the peraluminous dacitic Coaker Porphyry (CP), indicated by Lorenz (1985) to be derived from melting at ~45km depth of pelitic sediments like those forming the bulk of the Dunnage, and intruded into the melange before deformation of the melange ended. Zagorevski et al. (2012) report a U/Pb zircon age from the CP of 469 +/- 4 Ma.
Some of these CP intrusions were exposed to erosion not long afterward, as porphyry cobbles are abundant in the Cheneyville conglomerate, which overlies the northeastern Dunnage Melange, and is under the Sandbian black shales (Fig 4).

Dunnage mafic block and dike geochemistry
Of the seven samples we analyzed of mafic rocks in the Dunnage (pillow lavas, gabbros; sample locations on Fig. 1), there are apparently at least two chemically distinct types, see diagrams below. The DUN1 subset is chemically similar to the Lawrence Head Formation and indicates that these may be Lawrence Head-type magmas entrained in and/or intruding the deforming mélange and that these units were proximally located to one another during magmatism. These data are consistent with that reported 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 sampled other types of magmatic rocks not now exposed adjacent, as suggested by Williams (1994).



Two separate parts to the Dunnage Melange, of different ages and origins?
Field relations, distribution and ages of Lawrence Head Volcanics, related gabbros, and the Coaker Porphyry suggest to us that there are two parts to the main outcrop of the Dunnage Melange, and that these formed at different times, and perhaps by different mechanisms. Maps show (Fig 17 above) the Coaker Porphyry restricted to the eastern part, which constrains most melange deformation in that part to be older than ~469Ma. Most of the large mafic volcanic and gabbro blocks, compositionally resembling the Lawrence Head Volcanics and related gabbro sills (the latter dated ~464Ma nearby), occur in the western part of the Melange, implying that formation of the western Melange was younger by several Ma than the eastern part.

Ridge-trench interaction and the Dunnage Melange
Melting of pelitic sediments to produce the small Coaker Porphyry intrusions into melange at a shallow crustal level demands unusual conditions; Zagorevski et al(2012) show that a spreading ridge subduction event fits the evidence. Rapid return of the silicic melt to near surface conditions is one additional constraint which we think also fits a subduction zone-accretionary melange prism model, as buoyant rise of a crustal package has been inferred to occur in young subduction systems along the upper side of the subduction channel. Melts transported rapidly this way to near the toe of the accretionary prism would have short vertical distances to intrude diapirically into the shallow level melange above. In our interpretation the eastern Dunnage Melange would be a subduction-generated melange, terminated by a ridge subduction event starting ~469Ma.

Ridge-trench interaction and the apparent age discrepancy of the Coaker Porphyry and the Lawrence Head volcanics and related gabbros
The reported age for the Coaker Porphyry 469 +/-4 (Zagorevski et al. 2012) is discrepant with 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. At a slower subduction rate (say 30-50 km/Ma), the projected ridge crest might traverse from the trench under the full width of the former forearc basin (a distance in present day examples about 100-200 km) in 2 to 7 Ma. The ~5 Ma interval between the Coaker Porphyry and Lawrence Head Volcanics and gabbro sill magmatism is consistent with this estimate.

Conclusions
The Lawrence Head Volcanics and the gabbro sills below are the same magmatic event; they represent EMORB magmatism from slab-window opening during a spreading-ridge trench interaction event. The volcanic arc, fueled by subduction at this trench before the event, shut off and did not resume activity in this area afterwards. This implies conversion of the local plate boundary to a strike-slip margin, or a null margin (spreading ridge departing outboard, slowly, afterwards).
The Coaker Porphyry in the eastern Dunnage Melange was also generated by the ridge subduction event, early in the process, shortly after the ridge reached this trench segment.
The Dunnage Melange consists of two parts of different age and origin; the eastern part generated by subduction at a trench up to ~469Ma; the western part formed after Lawrence Head magmatism ~464Ma. We suggest fault scarp mass wasting from a strike-slip fault pull-apart normal fault or strike-slip restraining bend thrust scarp is a possible origin (similar to the origin proposed for the Dunnage overall by Hibbard and Williams (1979).