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# STRATIGRAPHIC AND PETROGENETIC RELATIONSHIPS BETWEEN ARC AND NON-ARC BASALTS IN WESTERN AND SOUTHERN PARTS OF THE ORDOVICIAN WILD BIGHT GROUP, DUNNAGE ZONE, NEWFOUNDLAND

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## ABSTRACT

*Basalts are more abundant in the western and southern parts of the Ordovician Wild Bight Group than previously thought. They have enriched incompatible element compositions, and are subdivided into two groups; a 'non-arc' type has positive Nb anomalies and high Ti/Y ratios, whereas an 'arc' type has negative Nb anomalies and low Ti/Y ratios. The arc and non-arc basalt groups have overlapping stratigraphic ranges, rather than forming the separate lower arc type and upper non-arc horizons seen in the compositionally similar Middle Ordovician basalts of the eastern Wild Bight Group.*

*The arc and non-arc basalt groups have similar enriched trace-element compositions, apart from in those elements that characterize a subduction influence in the arc basalts. Transitional compositions are present and it is suggested that the basalts are partial melts of a fertile mantle source, variably modified by subduction-derived fluids in an extensional supra-subduction zone setting.*

*Non-arc basalts occur in the lower stratigraphic units of the western Wild Bight Group, where they are in conformable contact with rhyolites that are typically associated with depleted island-arc tholeiite to boninitic arc basalts. This association may have been generated in an early stage of volcanic arc extension, and has implications for the genesis of, and exploration for, volcanogenic massive sulphide mineralization.*

## INTRODUCTION

In the Central Mobile Belt of northeastern Newfoundland, the Appalachian Dunnage Zone comprises two tectonostratigraphic subzones separated by a long-lived structural boundary, the Red Indian Line (Williams *et al.*, 1988). Rocks in the Notre Dame Subzone (western Dunnage Zone) are believed to have formed on the Laurentian side of the Iapetus Ocean; whereas, Arenig and older rocks in the Exploits Subzone (eastern Dunnage Zone) originated in parts of Iapetus that were peripheral to Avalonia and the main Gondwanan continent (Colman-Sadd *et al.*, 1992 and references therein). The Wild Bight Group (WBG) occurs adjacent to the Red Indian Line at the western margin of the Exploits Subzone.

The Ordovician Wild Bight Group outcrops over an area of approximately 750 km$^2$ in west-central Notre Dame Bay (Figure 1). It is a 3- to 4-km-thick, marine volcanic and sedimentary sequence that has been metamorphosed under sub-greenschist and greenschist conditions. The Wild Bight Group is host to the Point Leamington base-metal deposit (Walker and Collins, 1988), which is the largest tonnage massive sulphide deposit known in the Exploits Subzone.

Dean (1977) originally erected five constituent formations of the Wild Bight Group. He defined the exposed top of the group to coincide with the base of Espenshade's (1937) Caradoc and older Shoal Arm Formation. Although the bottom of the Wild Bight Group was not observable, Dean (*op. cit.*) considered the lowest exposed strata to lie within the Omega Point Formation. However, in mapping the western and southern parts of the Wild Bight Group in detail (O'Brien, 1993; Dickson *et al.*, 1994; O'Brien and MacDonald, 1996; O'Brien, 1997; MacLachlan, 1998; MacLachlan and O'Brien, 1998; MacLachlan, 1999; Dickson, 1999; O'Brien, 1999), and carrying out the geochemistry reported on herein, it became necessary to revise the

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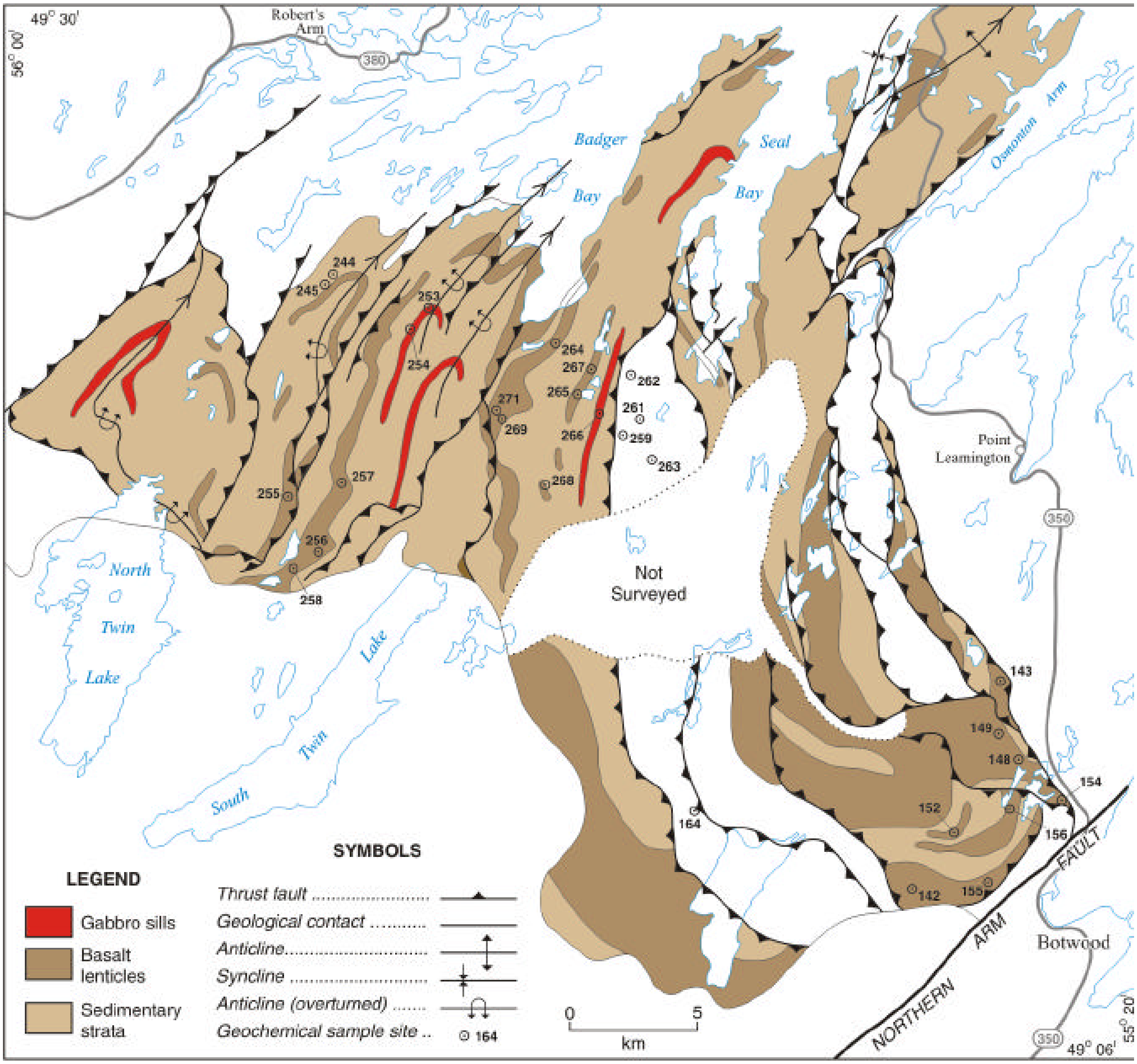


**Figure 1.** *Regional geological map of the Wild Bight Group (WBG) highlighting dark-coloured areas underlain by mafic volcanic lenticles of probable late Early to early Middle Ordovician age* (cf. *MacLachlan and Dunning, 1998b). The lighter coloured areas are dominantly composed of Middle Ordovician sedimentary strata. All of Dean's (1977) original lithostratigraphic constituents of the Wild Bight Group are known to occur in the study area, although the Seal Bay Brook and Side Harbour formations are unshaded. Uncoloured fault-bounded tracts within the shaded part of the Wild Bight outcrop correspond with older parts of the group (and its correlatives) or else they represent other rock units (of late Middle Ordovician and Late Ordovician age). The geology of the western WBG is modified from O'Brien and MacDonald (1996) and O'Brien (1997), the southern WBG from O'Brien (1993), Dickson* et al. *(1994) and Dickson (1999), the eastern WBG from MacLachlan (1999) and MacLachlan and O'Brien (1998), and the northeastern WBG from MacLachlan (1999) and O'Brien (1999). Geochemical sample sites are identified by numbers that are also shown in Tables 1 and 2 and prefixed by 2540.*

stratigraphic order of some of Dean's (1977) formations. In ascending order, for the western and southern WBG only, the revised stratigraphic column is considered to be the Seal Bay Brook Formation, Side Harbour Formation, Omega Point Formation, Sparrow Cove Formation and Pennys Brook Formation (Figure 2).

The uppermost volcanosedimentary formation, which has been deposited within an intra-arc basin in an arc-rift environment (O'Brien, 1998; MacLachlan, 1998), is more extensive than that shown on previous maps of the Wild Bight Group. At approximately 2.5 km thick, the basalts and turbidites of the Pennys Brook Formation represent about 65 percent of the total thickness of the Wild Bight Group. Most basalt lenticles shown in Figure 1 occur in the Pennys Brook Formation, where interrelationships amongst several lenticles have been established. However, the full stratigraphic range of the illustrated basalts is wider, including flows that occur throughout the Sparrow Cove Formation as well as some that reside completely within the Omega Point Formation.

In the eastern Exploits Subzone, Williams and Piasecki (1990) postulated that Middle Ordovician supracrustal rocks had been deposited both on the composite Gondwanan margin and in more outboard oceanic settings. MacLachlan (1998) was the first worker to identify the Middle Ordovician volcanic strata within the Wild Bight Group, and also to recognize some of the Early Ordovician substrate upon which these supracrustal rocks had originally been deposited. She demonstrated that two types of magmatic-arc sequences were present in the Wild Bight Group; *viz*, a late Tremadoc – early Arenig primitive intraoceanic arc and a late Arenig – early Llanvirn immature continental margin arc, developed on composite crust. MacLachlan and Dunning (1998b) suggested a further bipartite subdivision of Middle Ordovician arc-related and non-arc extrusive rocks in the younger WBG sequence, with dated Llanvirn gabbro intrusions being related to the youngest non-arc magmatic event. In Figure 1, the postulated "lower" units of the Early Ordovician Wild Bight Group are amongst the uncoloured tracts, as are the Side Harbour and Seal Bay Brook formations.

Continental collision of the pre-Iapetan basement of the peri-Laurentian and peri-Gondwanan arcs in the Late Silurian affected terrestrial and marine strata throughout the Dunnage Zone (Dunning *et al.*, 1990; Stockmal *et al.*, 1990; Elliot *et al.*, 1991). In the Wild Bight Group, it produced a complex structural rearrangement of the Cambro-Ordovician stratigraphic sequence (Figure 1) and tectonically fragmented the base-metal-bearing and less prospective strata (e.g., Swinden and Jenner, 1992).

## OBJECTIVE

Recent mapping of the western and southern parts of the Ordovician Wild Bight Group has demonstrated the presence of several mappable horizons of basalt in what was previously thought to be a dominantly sedimentary part of this unit (Kean *et al.*, 1981). Pillowed basalts were sampled for geochemical analysis in order to test the regional applicability of the chemostratigraphic scheme for the WBG as presented by MacLachlan and Dunning (1998a,b). The results modify our understanding of WBG chemostratigraphy, with implications for models of the geodynamic evolution of the Wild Bight Group.

## GEOCHEMISTRY

Several samples have high loss-on-ignition (up to 7.5% LOI; Table 1) indicating alteration from magmatic compositions. Therefore, the geochemical discussion is restricted to those elements generally considered immobile during low-grade metamorphism. In this study, basalts are characterized principally using incompatible trace and minor elements, normalized to a ‘primitive mantle' composition on extended rare-earth-element ‘spidergram' plots. This method allows a graphical representation of basalt types and compositional variation; for example, the relative depletion in Nb that is characteristic of subduction zone basalt is apparent regardless of Nb abundance. Normalizing values are from Swinden *et al.* (1990) so that direct comparison with other recent geochemical studies of the Wild Bight Group is facilitated.

All samples, except 2540269 (Table 1), are enriched in incompatible elements, with similar abundances and normalized trace-element profiles except in Nb, Ti and HREE. Samples are subdivided into two groups, ‘non-arc' type and ‘arc' type, based on their primitive mantle-normalized trace-element profiles (Figure 3a): the non-arc group are alkaline to sub-alkaline basalts having positive Nb anomalies, high Ti/Y ratios, and LREE enrichment. Samples plot in within-plate alkaline to tholeiite fields on discrimination diagrams (Figure 4).

The arc group are subalkaline basalts to andesites with negative Nb anomalies, low Ti/Y ratios, Th enrichment, and LREE and HREE enrichment giving concave REE profiles. Generally, samples plot in volcanic-arc-basalt fields (Figure 4).

Sample 2540269 (Table 1) is a depleted basalt that is distinct from the arc and non-arc groups; it is considered further later.

**Table 1.** Major- and trace-element analyses of mafic volcanic and hypabyssal rocks from the western and southern parts of the Ordovician Wild Bight Group

| Sample | 2540142 | 2540143 | 2540148 | 2540149 | 2540152 | 2540154 | 2540155 | 2540156 | 2540164 | 2540244 | 2540245 | 2540253 | 2540254 | 2540255 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO2 | 49.6 | 42.4 | 52.2 | 56.6 | 51.6 | 57.7 | 49.5 | 45.9 | 44.4 | 49.2 | 47.1 | 66.8 | 48.0 | 49.1 |
| TiO2 | 1.27 | 2.35 | 1.16 | 1.01 | 0.92 | 1.11 | 1.84 | 0.95 | 1.77 | 1.66 | 1.52 | 0.83 | 2.38 | 1.43 |
| Al2O3 | 14.2 | 14.0 | 16.6 | 15.7 | 18.1 | 17.7 | 13.1 | 12.6 | 12.7 | 17.1 | 15.5 | 13.8 | 15.2 | 11.0 |
| Fe2O3 | 1.1 | 0.7 | 1.7 | 1.7 | 1.5 | 1.5 | 2.3 | - | 2.1 | 7.7 | 8.7 | 2.5 | 6.0 | 1.4 |
| FeO | 8.4 | 7.8 | 7.4 | 5.7 | 6.5 | 5.9 | 7.5 | - | 9.9 | 1.3 | 3.8 | 2.5 | 5.5 | 8.1 |
| FeOT | 9.4 | 8.4 | 9.0 | 7.2 | 7.9 | 7.2 | 9.6 | - | 11.8 | 8.2 | 11.6 | 4.8 | 10.8 | 9.3 |
| Fe2O3T | 10.4 | 9.4 | 10.0 | 8.1 | 8.8 | 8.0 | 10.7 | - | 13.1 | 9.2 | 12.8 | 5.3 | 12.1 | 10.3 |
| MnO | 0.29 | 0.29 | 0.19 | 0.13 | 0.16 | 0.17 | 0.17 | 0.16 | 0.20 | 0.20 | 0.35 | 0.16 | 0.17 | 0.20 |
| MgO | 6.2 | 4.7 | 4.3 | 3.4 | 4.6 | 3.8 | 6.8 | 10.0 | 12.5 | 6.3 | 6.4 | 1.1 | 5.9 | 8.0 |
| CaO | 13.6 | 10.0 | 6.0 | 5.6 | 11.2 | 2.4 | 14.5 | 11.6 | 9.0 | 7.3 | 7.0 | 3.0 | 9.8 | 11.3 |
| Na2O | 2.5 | 2.9 | 4.4 | 5.2 | 3.5 | 6.2 | 2.1 | 3.5 | 2.0 | 2.3 | 2.4 | 5.2 | 3.5 | 4.0 |
| K2O | 0.49 | 3.33 | 1.45 | 0.46 | 0.49 | 0.46 | 0.28 | 0.18 | 0.55 | 2.38 | 2.08 | 1.86 | 0.37 | 0.49 |
| P2O5 | 0.35 | 0.19 | 0.15 | 0.16 | 0.13 | 0.17 | 0.22 | 0.10 | 0.22 | 0.29 | 0.21 | 0.25 | 0.19 | 0.13 |
| LOI | 1.7 | 9.6 | 4.3 | 4.3 | 1.2 | 3.2 | 1.5 | 5.2 | 4.6 | 3.7 | 4.2 | 1.6 | 3.3 | 4.8 |
| Total | 100.7 | 99.0 | 100.8 | 100.7 | 100.7 | 100.8 | 100.7 | 100.3 | 100.9 | 100.3 | 100.0 | 99.9 | 100.9 | 100.6 |
| Ba | 184 | 539 | 360 | 87 | 100 | 103 | 155 | 34 | 117 | 499 | 564 | 296 | 96 | 94 |
| Rb | 10 | 33 | 24 | 12 | 16 | 14 | 5 | 4 | 14 | - | - | 30 | - | - |
| Sr | 591 | 223 | 208 | 58 | 223 | 134 | 336 | 221 | 156 | 244 | 284 | 183 | 219 | 47 |
| Y | 22 | 20 | 22 | 18 | 19 | 22 | 18 | 14 | 19 | 20 | 30 | 40 | 20 | 15 |
| Zr | 107 | 173 | 72 | 91 | 86 | 99 | 85 | 62 | 100 | 132 | 128 | 201 | 162 | 108 |
| Nb | 7.5 | 23.6 | 4.5 | 6.7 | 5.4 | 7.4 | 15.8 | 4.3 | 11.8 | 7.0 | 10.0 | 15.3 | 16.0 | 10.7 |
| Th | 3.84 | 2.75 | 1.99 | 3.28 | 3.00 | 3.41 | 1.96 | 0.68 | 1.40 | 1.32 | 2.60 | 4.61 | 1.57 | 0.90 |
| Pb | 6.4 | 8.7 | 19.3 | 13.8 | 5.0 | 15.2 | 4.1 | 4.8 | 2.1 | 6.0 | 4.0 | - | - | - |
| Ga | 15 | 20 | 18 | 19 | 18 | 16 | 22 | 15 | 17 | 19 | 28 | 22 | 23 | 14 |
| Zn | 109 | 95 | 109 | 74 | 77 | 94 | 97 | 71 | 100 | 78 | 176 | 76 | 86 | 83 |
| Cu | 23 | 53 | 39 | 34 | 19 | 48 | 103 | 95 | 111 | 30 | 82 | 9 | 32 | 62 |
| Ni | 95 | 29 | 17 | 6 | 21 | 9 | 95 | 240 | 316 | 65 | 238 | 2 | 31 | 178 |
| V | 191 | 246 | 234 | 165 | 222 | 190 | 284 | 206 | 260 | 181 | 187 | 40 | 275 | 188 |
| Cr | 284 | 89 | 52 | 14 | 59 | 19 | 304 | 438 | 403 | 73 | 505 | - | 39 | 264 |
| Hf | 2.74 | 4.23 | 2.28 | 2.79 | 2.47 | 2.91 | 2.63 | 1.80 | 2.80 | 3.04 | 3.22 | 4.54 | 4.10 | 2.64 |
| Sc | 25 | 25 | 28 | 25 | 31 | 27 | 34 | 30 | 33 | 20 | 28 | 18 | 29 | 26 |
| Ta | 0.33 | 1.34 | 0.31 | 0.42 | 0.31 | 0.45 | 0.87 | 0.27 | 0.67 | 0.29 | 0.20 | 0.66 | 0.51 | 0.40 |
| Co | 38 | 23 | 28 | 24 | 27 | 29 | 44 | 59 | 59 | 40 | 52 | 4 | 37 | 52 |
| Li | 16 | 17 | 21 | 18 | 6 | 26 | - | 14 | 25 | 25 | 27 | 4 | 17 | 15 |
| Be | 0.7 | 1.9 | 1.1 | 1.8 | 1.2 | 1.8 | 1 | 0.7 | 0.7 | 0.9 | 3.4 | 1.9 | 0.6 | 0.8 |
| U | 0.84 | 1.10 | 1.11 | 2.14 | 1.35 | 1.93 | 0.85 | 0.61 | 0.54 | - | - | - | - | - |
| La | 27.8 | 16.8 | 8.4 | 12.4 | 8.0 | 11.5 | 14.6 | 5.0 | 11.5 | 11.0 | 19.0 | 24.3 | 10.9 | 7.1 |
| Ce | 60.5 | 41.9 | 20.5 | 28.3 | 21.9 | 29.8 | 32.1 | 12.1 | 26.8 | 26.2 | 34.8 | 51.9 | 25.2 | 16.7 |
| Pr | 7.47 | 5.30 | 2.65 | 3.51 | 2.87 | 3.72 | 4.16 | 1.71 | 3.62 | 3.53 | 4.47 | 6.65 | 3.42 | 2.31 |
| Nd | 30.7 | 23.3 | 12.3 | 14.7 | 12.3 | 16.5 | 18.4 | 8.3 | 16.6 | 15.4 | 20.4 | 28.3 | 15.8 | 10.9 |
| Sm | 5.73 | 5.61 | 3.37 | 3.46 | 3.33 | 3.80 | 4.56 | 2.39 | 4.43 | 3.80 | 4.90 | 6.79 | 4.46 | 3.14 |
| Eu | 1.69 | 2.02 | 1.14 | 1.18 | 0.70 | 1.06 | 1.58 | 0.94 | 1.68 | 1.47 | 1.74 | 2.01 | 1.56 | 0.93 |
| Gd | 4.98 | 5.45 | 3.76 | 3.63 | 3.58 | 4.18 | 4.73 | 2.80 | 4.78 | 4.07 | 5.44 | 7.16 | 4.83 | 3.39 |
| Tb | 0.72 | 0.78 | 0.66 | 0.61 | 0.56 | 0.66 | 0.71 | 0.46 | 0.69 | 0.63 | 0.84 | 1.16 | 0.74 | 0.52 |
| Dy | 4.40 | 4.66 | 4.21 | 3.78 | 3.69 | 4.05 | 4.24 | 2.78 | 4.11 | 4.00 | 5.28 | 7.36 | 4.53 | 3.26 |
| Ho | 0.88 | 0.86 | 0.88 | 0.77 | 0.77 | 0.85 | 0.80 | 0.57 | 0.78 | 0.79 | 1.08 | 1.48 | 0.83 | 0.60 |
| Er | 2.33 | 2.20 | 2.62 | 2.14 | 2.26 | 2.36 | 2.14 | 1.66 | 2.00 | 2.27 | 3.05 | 4.43 | 2.25 | 1.62 |
| Tm | 0.35 | 0.30 | 0.38 | 0.30 | 0.34 | 0.34 | 0.28 | 0.22 | 0.28 | 0.33 | 0.43 | 0.65 | 0.28 | 0.22 |
| Yb | 2.15 | 1.78 | 2.30 | 1.89 | 2.13 | 2.12 | 1.66 | 1.41 | 1.62 | 2.15 | 2.64 | 4.40 | 1.81 | 1.49 |
| Lu | 0.30 | 0.22 | 0.36 | 0.29 | 0.32 | 0.33 | 0.22 | 0.18 | 0.24 | 0.30 | 0.39 | 0.66 | 0.27 | 0.20 |

Table 1. *(Continued)*

| Sample | 2540256 | 2540257 | 2540258 | 2540259 | 2540261 | 2540262 | 2540263 | 2540264 | 2540265 | 2540266 | 2540267 | 2540268 | 2540269 | 2540271 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO2 | 50.0 | 44.0 | 48.4 | 44.4 | 44.5 | 49.1 | 47.0 | 51.6 | 51.6 | 59.2 | 49.9 | 65.5 | 48.7 | 50.8 |
| TiO2 | 2.13 | 2.70 | 1.84 | 1.47 | 1.39 | 1.80 | 1.68 | 1.59 | 0.88 | 1.11 | 0.85 | 0.83 | 1.05 | 1.55 |
| Al2O3 | 13.9 | 14.8 | 12.8 | 13.2 | 13.7 | 14.6 | 14.0 | 15.6 | 16.5 | 14.7 | 19.0 | 14.2 | 13.1 | 14.5 |
| Fe2O3 | 3.2 | 4.5 | 1.6 | 6.5 | 2.8 | 8.4 | 5.9 | 1.6 | 1.4 | 3.4 | 1.3 | 2.4 | 2.0 | 7.6 |
| FeO | 8.3 | 8.0 | 9.1 | 4.3 | 9.2 | 2.6 | 5.5 | 6.3 | 5.6 | 4.9 | 6.4 | 3.1 | 6.9 | 2.9 |
| FeOT | 11.2 | 12.1 | 10.5 | 10.2 | 11.8 | 10.2 | 10.8 | 7.8 | 6.8 | 8.0 | 7.6 | 5.2 | 8.7 | 9.7 |
| Fe2O3T | 12.4 | 13.4 | 11.7 | 11.4 | 13.1 | 11.3 | 12.0 | 8.7 | 7.6 | 8.9 | 8.4 | 5.7 | 9.6 | 10.7 |
| MnO | 0.19 | 0.16 | 0.17 | 0.14 | 0.16 | 0.19 | 0.15 | 0.12 | 0.17 | 0.22 | 0.19 | 0.23 | 0.14 | 0.12 |
| MgO | 6.5 | 6.8 | 10.5 | 5.0 | 10.8 | 5.0 | 8.0 | 5.9 | 3.6 | 2.4 | 4.6 | 1.6 | 11.3 | 6.6 |
| CaO | 9.9 | 11.4 | 9.7 | 11.1 | 9.5 | 8.6 | 9.4 | 9.2 | 9.8 | 5.3 | 7.7 | 5.6 | 8.3 | 6.4 |
| Na2O | 4.5 | 2.6 | 3.0 | 4.6 | 2.2 | 5.0 | 3.6 | 5.4 | 3.9 | 4.2 | 4.8 | 1.3 | 3.1 | 4.7 |
| K2O | 0.21 | 1.46 | 0.49 | 0.86 | 0.68 | 1.81 | 1.11 | 0.09 | 0.20 | 1.32 | 0.31 | 1.89 | 0.14 | 1.30 |
| P2O5 | 0.20 | 0.31 | 0.15 | 0.26 | 0.16 | 0.12 | 0.18 | 0.21 | 0.09 | 0.37 | 0.09 | 0.19 | 0.09 | 0.19 |
| LOI | 1.7 | 3.0 | 0.9 | 7.5 | 4.1 | 3.4 | 3.4 | 2.5 | 5.2 | 2.5 | 4.4 | 2.5 | 4.3 | 3.2 |
| Total | 100.7 | 100.8 | 99.7 | 99.8 | 100.2 | 100.9 | 100.6 | 100.9 | 99.6 | 100.1 | 100.4 | 99.5 | 99.8 | 100.0 |
| Ba | 46 | 354 | 131 | 79 | 99 | 179 | 180 | 42 | 80 | 253 | 88 | 312 | 19 | 186 |
| Rb | - | 17 | - | 9 | - | 15 | 10 | - | - | 14 | 5 | 47 | - | 24 |
| Sr | 110 | 290 | 255 | 173 | 326 | 88 | 323 | 224 | 181 | 370 | 121 | 733 | 364 | 174 |
| Y | 20 | 24 | 19 | 21 | 18 | 20 | 18 | 17 | 19 | 30 | 18 | 38 | 8 | 20 |
| Zr | 145 | 222 | 122 | 120 | 98 | 135 | 116 | 164 | 83 | 141 | 77 | 203 | 47 | 168 |
| Nb | 15.6 | 31.6 | 11.5 | 15.8 | 8.6 | 18.2 | 12.4 | 13.0 | 3.7 | 6.2 | 3.4 | 12.8 | 2.7 | 13.8 |
| Th | 0.84 | 2.56 | 0.94 | 1.83 | 1.21 | 1.88 | 1.07 | 4.05 | 1.94 | 3.14 | 1.82 | 5.00 | 0.39 | 2.71 |
| Pb | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ga | 15 | 24 | 14 | 18 | 18 | 16 | 15 | 21 | 20 | 22 | 18 | 19 | 16 | 20 |
| Zn | 101 | 96 | 89 | 88 | 103 | 85 | 89 | 76 | 60 | 102 | 66 | 113 | 71 | 80 |
| Cu | 53 | 103 | 148 | 30 | 69 | 39 | 107 | 70 | 34 | 17 | 47 | 15 | 61 | 78 |
| Ni | 60 | 157 | 302 | 78 | 477 | 58 | 192 | 96 | 20 | 3 | 24 | 7 | 234 | 105 |
| V | 211 | 235 | 188 | 179 | 191 | 240 | 251 | 197 | 187 | 114 | 186 | 53 | 163 | 194 |
| Cr | 241 | 428 | 509 | 310 | 758 | 171 | 490 | 217 | 72 | 1 | 82 | 16 | 549 | 281 |
| Hf | 3.50 | 4.99 | 3.14 | 3.06 | 2.41 | 3.19 | 2.84 | 3.71 | 2.02 | 3.53 | 2.04 | 4.70 | 1.18 | 4.05 |
| Sc | 31 | 34 | 24 | 28 | 26 | 32 | 34 | 27 | 29 | 22 | 31 | 18 | 25 | 27 |
| Ta | 0.58 | 0.87 | 0.42 | 0.44 | 0.18 | 0.41 | 0.20 | 0.52 | 0.17 | 0.29 | 0.16 | 0.49 | 0.10 | 0.50 |
| Co | 45 | 49 | 66 | 24 | 87 | 38 | 61 | 41 | 30 | 13 | 36 | 7 | 57 | 42 |
| Li | 4 | 23 | 10 | 14 | 15 | 14 | 11 | 9 | 11 | 10 | 11 | 24 | 28 | 18 |
| Be | 0.6 | 1.4 | 0.7 | 0.8 | 0.5 | 0.7 | 0.5 | 1.4 | 1.2 | 1.1 | 1 | 1.5 | 0.7 | 1.2 |
| U | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| La | 8.9 | 19.5 | 8.3 | 14.2 | 7.6 | 14.6 | 9.2 | 16.5 | 8.2 | 17.4 | 7.2 | 24.2 | 2.8 | 13.5 |
| Ce | 22.1 | 44.6 | 19.6 | 32.3 | 18.1 | 31.5 | 21.5 | 36.0 | 18.4 | 39.0 | 17.3 | 54.0 | 7.1 | 29.4 |
| Pr | 3.18 | 5.83 | 2.74 | 4.08 | 2.44 | 4.16 | 2.91 | 4.49 | 2.37 | 5.01 | 2.23 | 6.77 | 1.05 | 3.85 |
| Nd | 15.2 | 25.6 | 12.8 | 18.1 | 11.4 | 17.8 | 13.0 | 19.0 | 10.5 | 22.2 | 9.8 | 29.2 | 5.0 | 16.9 |
| Sm | 4.47 | 6.42 | 3.95 | 4.68 | 3.37 | 4.41 | 3.71 | 4.39 | 2.84 | 5.38 | 2.63 | 6.70 | 1.44 | 4.26 |
| Eu | 1.49 | 2.06 | 1.33 | 1.43 | 1.12 | 1.48 | 1.23 | 1.43 | 0.88 | 1.75 | 0.91 | 1.88 | 0.51 | 1.32 |
| Gd | 4.94 | 6.28 | 4.54 | 4.93 | 3.77 | 4.54 | 4.01 | 4.27 | 3.38 | 5.70 | 3.11 | 6.86 | 1.57 | 4.18 |
| Tb | 0.78 | 0.91 | 0.71 | 0.73 | 0.60 | 0.66 | 0.60 | 0.61 | 0.54 | 0.87 | 0.52 | 1.09 | 0.26 | 0.67 |
| Dy | 4.56 | 5.17 | 4.07 | 4.52 | 3.66 | 3.93 | 3.52 | 3.76 | 3.49 | 5.69 | 3.40 | 7.09 | 1.68 | 4.09 |
| Ho | 0.84 | 0.98 | 0.76 | 0.84 | 0.70 | 0.80 | 0.71 | 0.69 | 0.74 | 1.15 | 0.69 | 1.44 | 0.32 | 0.81 |
| Er | 2.16 | 2.56 | 1.99 | 2.10 | 1.95 | 2.07 | 1.98 | 1.86 | 2.16 | 3.43 | 2.12 | 4.21 | 0.96 | 2.28 |
| Tm | 0.29 | 0.34 | 0.27 | 0.29 | 0.27 | 0.31 | 0.27 | 0.26 | 0.30 | 0.48 | 0.30 | 0.62 | 0.14 | 0.31 |
| Yb | 1.74 | 2.27 | 1.58 | 1.68 | 1.75 | 1.91 | 1.70 | 1.50 | 2.09 | 3.17 | 1.95 | 4.08 | 0.84 | 1.94 |
| Lu | 0.25 | 0.30 | 0.22 | 0.24 | 0.25 | 0.27 | 0.23 | 0.22 | 0.30 | 0.48 | 0.29 | 0.61 | 0.12 | 0.30 |

**Table 2.** Geographic location of analysed basalt and gabbro samples collected from the western and southern Wild Bight Group

| Lab Number | Easting | Northing | NTS Sheet | FieldLog Number |
|---|---|---|---|---|
| 2540142 | 611350 | 5446150 | 2E/3 | 93-0025 |
| 2540143 | 615550 | 5455450 | 2E/3 | 93-0031 |
| 2540148 | 616500 | 5452550 | 2E/3 | 93-0056 |
| 2540149 | 615700 | 5452500 | 2E/3 | 93-0057 |
| 2540152 | 613550 | 5449650 | 2E/3 | 93-0059 |
| 2540154 | 619100 | 5449800 | 2E/3 | 93-0061 |
| 2540155 | 613500 | 5445850 | 2E/3 | 93-0062 |
| 2540156 | 615500 | 5451150 | 2E/3 | 93-0063 |
| 2540164 | 602950 | 5450650 | 2E/4 | 93-0075 |
| 2540244 | 586689 | 5472017 | 2E/5 | 96-0321 |
| 2540245 | 586685 | 5472015 | 2E/5 | 96-0322 |
| 2540253 | 590760 | 5470940 | 2E/5 | 97-0015 |
| 2540254 | 590320 | 5470200 | 2E/5 | 97-0017 |
| 2540255 | 585210 | 5462990 | 2E/5 | 97-0079 |
| 2540256 | 586500 | 5460620 | 2E/5 | 97-0110 |
| 2540257 | 587400 | 5463650 | 2E/5 | 97-0125 |
| 2540258 | 585270 | 5459380 | 2E/5 | 97-0128 |
| 2540259 | 598620 | 5465600 | 2E/5 | 97-0136 |
| 2540261 | 599610 | 5466350 | 2E/5 | 97-0145 |
| 2540262 | 599150 | 5467550 | 2E/5 | 97-0162 |
| 2540263 | 600150 | 5464650 | 2E/5 | 97-0166 |
| 2540264 | 595860 | 5469250 | 2E/5 | 97-0191 |
| 2540265 | 597050 | 5467250 | 2E/5 | 97-0231 |
| 2540266 | 598170 | 5468570 | 2E/5 | 97-0240 |
| 2540267 | 597470 | 5467950 | 2E/5 | 97-0243 |
| 2540268 | 595450 | 5463450 | 2E/5 | 97-0267 |
| 2540269 | 593800 | 5466300 | 2E/5 | 97-0268 |
| 2540271 | 593550 | 5466600 | 2E/5 | 97-0289 |

The arc and non-arc groups of basalts in the Pennys Brook Formation of the western and southern WBG (Figure 3b, c) are compositionally equivalent to the ‘lower succession' calc-alkaline and ‘upper succession' e-tholeiite to alkaline groups, respectively, of the Middle Ordovician part of the eastern WBG of MacLachlan and Dunning (1998b). However, the western and southern WBG basalts, which are interbedded with a relatively thick sequence of volcaniclastic turbidites, do not neatly separate stratigraphically into arc type in the lower part and non-arc type in the upper part. Arc basalts and andesites occur in the stratigraphically lowest exposed lenticles of the Pennys Brook Formation, in the Badger Bay Brook and the New Bay River areas, but arc-type basalts and intrusions also occur high in the formation in both sequences. Non-arc basalts predominate in the middle and upper parts of the Pennys Brook Formation, on both limbs of the major Pennys Brook anticlinorium in the type area (Figure 1), but also occur in the Side Harbour and Seal Bay Brook formations, below the Pennys Brook arc basalts, where they are in stratigraphic contact with rhyolites (Figure 2).

## STRATIGRAPHIC POSITIONS OF ARC AND NON-ARC BASALTS

Below, examples are presented to consider the implications of the stratigraphic overlap of arc and non-arc basalts in the western and southern parts of the Wild Bight Group.

### Arc Basalts of the Upper WBG from the New Bay River Thrust Sheet

Geochemical data were obtained from three, stratigraphically conformable, basalt lenticles within the Pennys Brook Formation lying in a thrust sheet between the New Bay River and Northern Arm (Figures 1 and 2). The lowest sampled lenticle (2540152) contains arc basalt, whereas the next highest lenticle (2540156) contains e-tholeiite non-arc basalt (Figure 3b and c). The uppermost preserved basalt lenticle includes both non-arc (2540155) and arc (2540142) basalts. The arc-basalt sample has a strong subduction zone signature, marked by high LREE and Th content, even though it is stratigraphically separated from the lower arc-

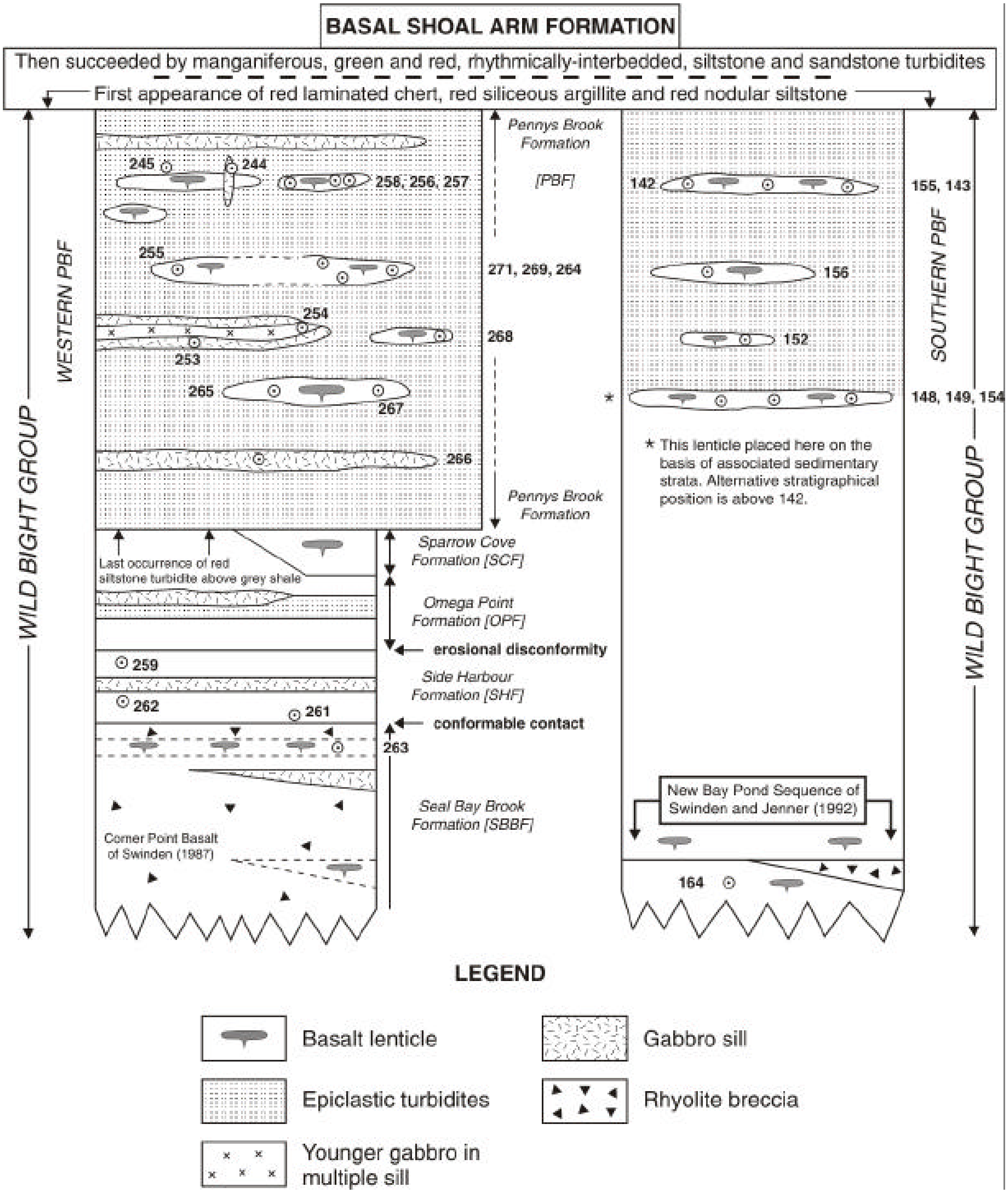


**Figure 2.** *Lithostratigraphic column of the western and southern parts of the Wild Bight Group illustrating the depositional arrangement of basalt lenticles and gabbro sills within a revised succession of Dean's (1977) five constituent formations. The relative spatial position of the 28 analyzed geochemical samples discussed in this paper are also indicated. Column is not drawn to a vertical scale, and only the basal units of the overlying Shoal Arm Formation are depicted.*

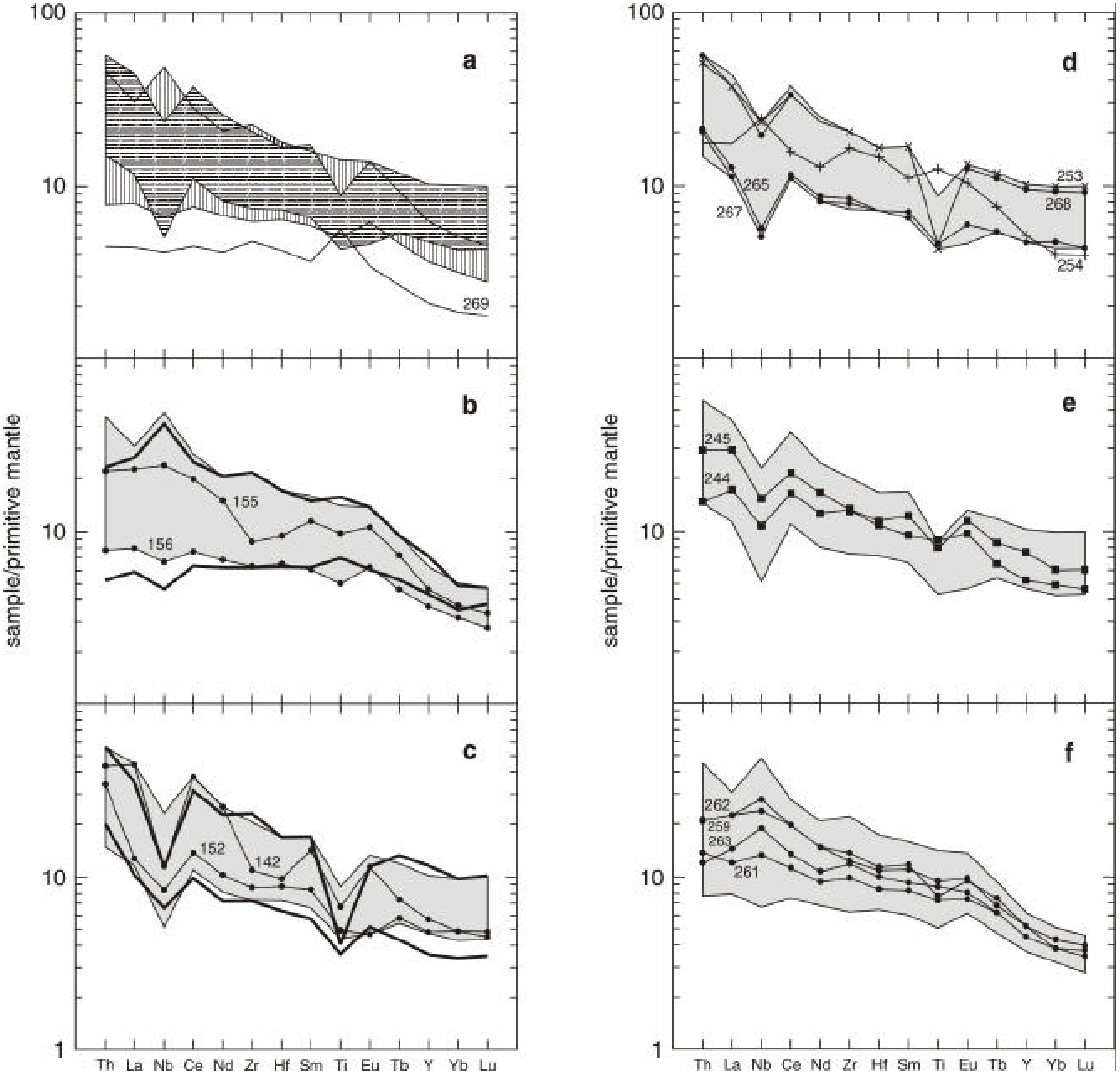


**Figure 3.** *Primitive mantle-normalized trace-element plots for WBG basalts: 3a, fields of 'arc' (horizontal ruling) and 'non-arc' (vertical ruling) groups, and sample 2540269; 3b, limits of "upper succession" e-tholeiite to alkaline group of MacLachlan and Dunning, 1998b (heavy lines) and New Bay River non-arc basalt samples on the non-arc field; 3c, limits of "lower succession" calc-alkaline group of MacLachlan and Dunning, 1998b (heavy lines) and New Bay River arc basalt samples on the arc field; 3d, Gummy Brook Gabbro (crosses) and Badger Bay Brook lenticles samples on the arc field; 3e, upper Pennys Brook olistostrome samples on the arc field; 3f, Side Harbour and Seal Bay Brook basalt samples on the non-arc field.*

basalt lenticle by non-arc basalts. It indicates a return to arc-basalt generation, contemporaneous with continuing non-arc magmatism.

### Folded Sill of Gummy Brook Gabbro in Anticline east of Sops Arm Brook

A single body of Gummy Brook Gabbro, on 1:50 000-scale geological and geophysical maps, contains a highly altered arc diorite (2540253) and a less-altered alkali gabbro (2540254) (Figures 1, 2 and 3d). The arc diorite is compositionally similar to an arc andesite sample (2540268) from the Badger Bay Brook lenticles low in the Pennys Brook Formation. It appears that arc and non-arc magmas have intruded at the same horizon in the Pennys Brook Forma-

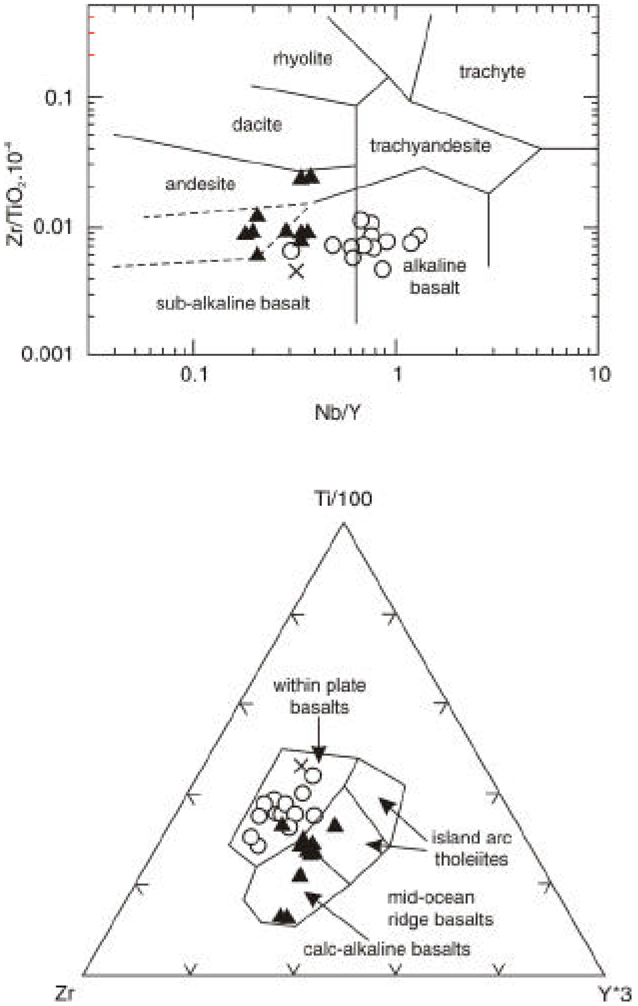


**Figure 4.** *Arc (triangles) and non-arc (circles) samples on immobile trace-element discrimination diagrams (X = sample 2540269).*

tion, above the level where non-arc basalts become predominant, indicating overlap in the periods of generation of arc and non-arc type magmas.

### Olistostrome East of Shoal Arm Brook at the Top of the Highest Lenticle of WBG Basalt

A basalt clast (2540245) from an olistostrome high in the Pennys Brook Formation and a diabase dyke (2540244) cutting the olistostrome (Figure 2) have a weak arc signature in their geochemistry (Figure 3e). Smaller negative Nb anomalies and higher Ti than arc basalts in the Badger Bay Brook lenticles result in these samples variably plotting in arc or non-arc fields on different discrimination diagrams, but they are distinct from compositions in the subjacent non-arc basalt lenticle. This implies not only that arc rocks were resedimented in the Pennys Brook turbidite basin, but that arc magmas were being intruded above all known non-arc extrusive rocks within the Pennys Brook Formation.

### Non-arc Basalts of the Lower WBG in Thrust Sheet between Side Harbour and Seal Bay Brook

Three basalt samples (2540259, 2540261, 2540262) from the Side Harbour Formation and one basalt sample (2540263) from the Seal Bay Brook Formation (Figures 2 and 5a) are part of the non-arc group. Their compositional range from within-plate tholeiite to alkaline basalt overlaps the range of non-arc rocks of the Pennys Brook Formation with no significant differences (Figure 3f). Following the revised stratigraphic and structural interpretation of the "Seal Bay Anticline" (Figure 5b; MacLachlan and O'Brien, 1998), these basalts record an earlier phase of non-arc magmatism.

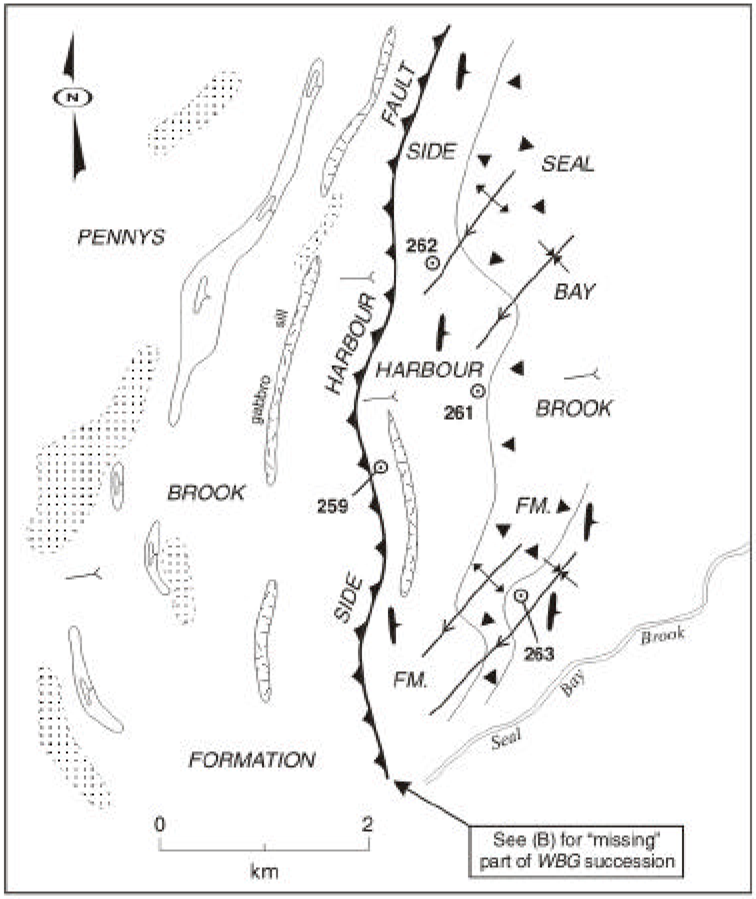
## DISCUSSION

### Some Stratigraphical Implications of Basalt Geochemistry

The above examples document overlapping stratigraphic ranges for arc and non-arc basalts in the western and southern Wild Bight Group, rather than MacLachlan and Dunning's (1998b) distinct "lower succession" calc-alkaline and "upper succession" e-tholeiite to alkaline groups, which were found in the Middle Ordovician part of the eastern Wild Bight Group. Unfortunately, this restricts the use of lithogeochemistry as a mapping tool over the largest stratigraphic interval of the Wild Bight Group, although the arc basalts are distinct from the depleted island-arc tholeiite to boninitic arc basalts of the Early Ordovician arc phase.

Three samples of arc basalt and andesite (2540148, 2540149, 2540154) from the Northern Arm thrust sheet of the Wild Bight Group are similar to the arc basalts of the Pennys Brook Formation. They are separated from non-arc basalt (2540143) by a northwest-trending belt of thrust-duplicated turbidites (Figure 1). Given the evolution of basalts from arc to non-arc to coeval arc and non-arc in the Pennys Brook Formation, it appears that this tectonic panel of basalts could lie at or below the level of the arc basalt and andesite lenticles in the lower Pennys Brook Formation in the New Bay River area (Figure 2), to which it is most geochemically similar. Alternatively, it could preserve part of what would be the thickest upper-arc basalt lenticle of the Pennys Brook Formation, although it is geochemically distinct from the calc-alkaline basalt in the highest preserved lenticle in the New Bay River area.

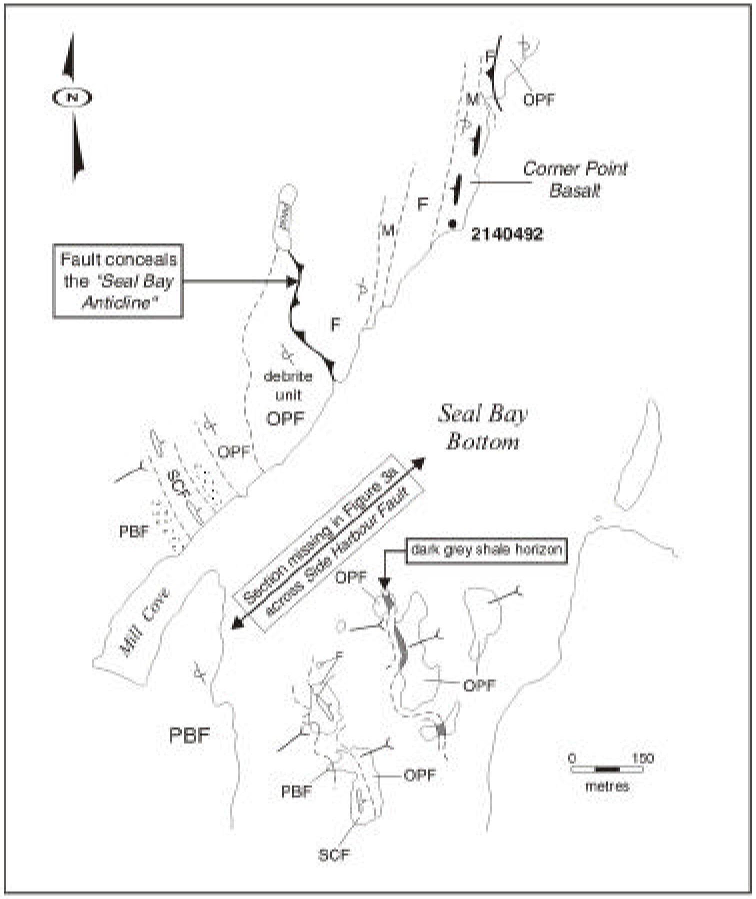
In the area studied, within the WBG stratigraphic column below the Pennys Brook Formation (Figure 2), rhyolites and felsic pyroclastic rocks of the Seal Bay Brook Formation are conformably overlain by non-arc basalts of the Side Harbour Formation and conformably underlain by non-arc basalts of similar composition (Figures 3f and 5a). If



See (B) for "missing" part of *WBG* succession

(A) Seal Bay Brook area

| | |
|---|---|
| ▭ | Pillowed basalt in stratigraphical contact with Pennys Brook epiclastic turbidites |
| ▬ | Pillowed basalt in stratigraphical contact with Seal Bay Brook rhyolite |
| ▒ | Pseudoporphyroblast-bearing alteration zone in turbidites |
| ▲ | Flow-banded rhyolite and rhyolite breccia |
| ⊙ 259 | Geochemical specimen number of basalt |



Fault conceals the *"Seal Bay Anticline"*

(B) Seal Bay Bottom area

| | |
|---|---|
| ▬ | Pillowed basalt in stratigraphical contact with Indian Cove rhyolite (Seal Bay Brook Formation?) |
| ▭ | Pillowed basalt in stratigraphical contact with Pennys Brook epiclastic turbidites |
| ▒ | Pseudoporphyroblast-bearing alteration zone in turbidites |
| • 2140492 | Example of Swinden's (1987) depleted island arc basalt group |

PBF - Pennys Brook Formation

SCF - Sparrow Cove Formation

OPF - Omega Point Formation

F - Felsic pyroclastic unit of Indian Cove sequence

M - Mafic pyroclastic unit of Indian Cove sequence

**Figure 5.** (opposite page) *Geological sketch maps showing the relationships of various pillowed basalt lenticles in the Seal Bay Brook and the Seal Bay Bottom areas. (A) The pillowed basalts in the Seal Bay Brook and Side Harbour formations east of the Side Harbour fault are non-arc lavas; whereas, those in the tectonically adjacent Pennys Brook Formation are arc type (see Figures 1 and 2). (B) The pillowed basalts in the Sparrow Cove Formation (Swinden, 1987; MacLachlan, 1998) southwest of the fault that conceals the "Seal Bay Anticline" are geochemically similar to those in the Pennys Brook Formation near Seal Bay Brook. However, pillowed basalts in the tectonically adjacent Indian Cove panel of the Seal Bay Brook Formation represent more depleted arc type lavas (Swinden, 1987). Note that, on the mainland, Indian Cove felsic pyroclastic rocks overthrust sedimentary rocks of the younger Omega Point Formation but that, on one Seal Bay islet, similar felsic pyroclastic rocks crop out near the Sparrow Cove – Omega Point boundary.*

these felsic volcanic rocks were once contiguous with those in the Indian Cove – Corner Point area (Butler and Stewart, 1993; Figure 1), then the non-arc basalts must stratigraphically underlie the arc basalts of the Badger Bay Brook lenticles of the lower Pennys Brook Formation, and the basalts of the Sparrow Cove Formation (Dean, 1977, Figure 5b), both parts of the 'lower succession' calc-alkaline group of MacLachlan and Dunning (1998b).

It is possible that some or all of the rhyolite units are part of the Omega Point – Sparrow Cove – lower Pennys Brook succession, especially if prominence is given to the close spatial relation of rhyolite breccia and Sparrow Cove arc basalt on one island in Seal Bay (Figure 5b). However, rhyolitic rocks are previously known only from the primitive Tremadoc–Arenig arc sequence of MacLachlan and Dunning (1998a), in which they are high-sodium, high-silica and typically associated with island-arc tholeiite to boninitic arc basalts. These are known to include a non-arc alkaline intrusion dated at 486 ± 4 Ma (Glovers Harbour Gabbro, MacLachlan and Dunning, 1998a) as part of the primitive arc phase.

### Pennys Brook Basalt Petrogenesis

Apart from the relative depletion in Nb and Ti and relative enrichment in Th and L and HREE that characterize the arc basalts of the Pennys Brook Formation, the arc and non-arc basalt groups in this unit have similar enriched trace-element profiles (Figure 3a). The arc basalts apparently were not derived from a residual early-arc-phase depleted mantle source, or mixing of that source with the fertile source of the non-arc basalts. It is suggested that the two types are partial melts of the same mantle source, with modification by ongoing subduction-derived fluids apparent in the arc type; Th, LREE (and other LIL elements) added by fluids, enrichment in HREE and the general dilution in incompatible elements through increased partial melting induced by fluids, and Nb and Ti depletion possibly through phase stability commonly suggested for subduction-related melts (Arculus and Powell, 1986; McCulloch and Gamble, 1991).

Some samples from the non-arc group have relatively depleted Nb or Ti, whereas some of the samples characterized as arc basalts have a relatively weak subduction signature, suggesting a transition between types consistent with a variable subduction-related influence on the same mantle source. However these intermediate types are not stratigraphically confined and do not represent simply a waxing or waning subduction influence on the mantle source. Strong arc signatures are present in the oldest Badger Bay Brook lenticles (lower Pennys Brook Formation) and in the youngest New Bay River lenticle (upper Pennys Brook Formation), with non-arc basalts at intermediate levels and below. Therefore, subduction carried on during deposition of the Pennys Brook arc-rift sequence, with partial melts tapping a fertile mantle source that was variably metasomatised by subduction fluids.

Sample 2540269 is compositionally distinct from all others in this study. Its low incompatible trace-element abundances are generally akin to early WBG-arc basalts from depleted mantle sources (MacLachlan and Dunning, 1998a; Swinden *et al.*, 1990). However, it is unlike these in detail, having relatively enriched LREE and Th and progressively depleted HREE, so that its incompatible trace-element profile looks like a basalt from a fertile mantle source although the actual abundance of these elements is low. In this regard, sample 2540269 is unlike other depleted basalt types such as boninites or adakites. The trace-element profile of sample 2540269 can be approximated by adding a small proportion of typical Pennys Brook non-arc basalt to the early WBG depleted island-arc tholeiite of MacLachlan and Dunning (1998a), although there is no evidence that this represents the actual petrogenesis of the rock.

### Geodynamic Setting

The association of non-arc basalt type with primitive tholeiitic to boninitic arc basalt and trondhjemitic rhyolite in the lower stratigraphic units of the study area has implications for the geodynamic setting and evolution of the Wild Bight Group. Although it is beyond the scope of this paper to address these fully, we suggest that the association could have been generated in the early stage of arc extension. In this scenario, boninitic arc basalt was a high-degree partial melt of a depleted mantle source, generated at the inception of extension. Then, as extension proceeded, fertile asthenospheric mantle was drawn into the zone of melt generation so that later basalts are non-arc e-tholeiite to alkaline basalts. Either basalt type could provide sufficient heat to partially melt older island-arc crust to generate the rhyolites.

In the Wild Bight Group, the association of boninitic arc basalt and high-silica rhyolite is regarded as prospective for volcanogenic massive sulphide (VMS) mineralization (Swinden, 1988). At Indian Cove, a Cu-rich sulphide stockwork is developed in rhyolite breccia (Butler and Stewart, 1993) that is elsewhere associated with non-arc basalt (compare Figures 5a and b). The geodynamic argument above, suggests that non-arc basalt is part of a trinity, with trondhjemitic high-silica rhyolite and boninitic arc basalt, that can host VMS mineralization. It is the extensional, high-heat flow, plate tectonic setting of the trinity that is favourable to focussing and sustaining a hydrothermal mineralizing system, rather than the composition of the magmatism itself.

The arc extension that was initiated in Early Ordovician time in the Wild Bight Group continued during accumulation of the younger parts of the group, although the tectonic regime may have changed (MacLachlan and Dunning, 1998b; van Staal *et al.*, 1998), so that basalts in the Pennys Brook Formation were all extracted from the fertile mantle source, with or without subduction zone signature, to produce the arc and non-arc basalt types.

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