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HOW DEEPLY BURIED ARE PROSPECTIVE ARC VOLCANIC ROCKS IN THE WESTERN WILD BIGHT GROUP?

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ABSTRACT

The regional triangular-shaped outcrop pattern of the Ordovician Wild Bight Group is interpreted to reflect the lateral ejection of intra-arc sedimentary rocks in the central part of the unit, and their structural translation toward the northeast. As arc volcanic and intra-arc sedimentary rocks were thrust to the southwest (and back thrust to the northeast) during an earlier episode of Silurian orogen-parallel convergence, lateral ejection along northeast-trending structures served to locally reverse the dominant tectonic movement direction of the Wild Bight Group.

The Wild Bight Group probably contains two domal structural culminations separated by a sheared structural depression. Although formed during regional deformation as a consequence of interference, it is postulated that the western and eastern domes are both sited on syndepositional horsts, and that arc volcanic rocks, like those exposed in the eastern culmination, may be situated in subsurface in the southwestern Wild Bight Group.

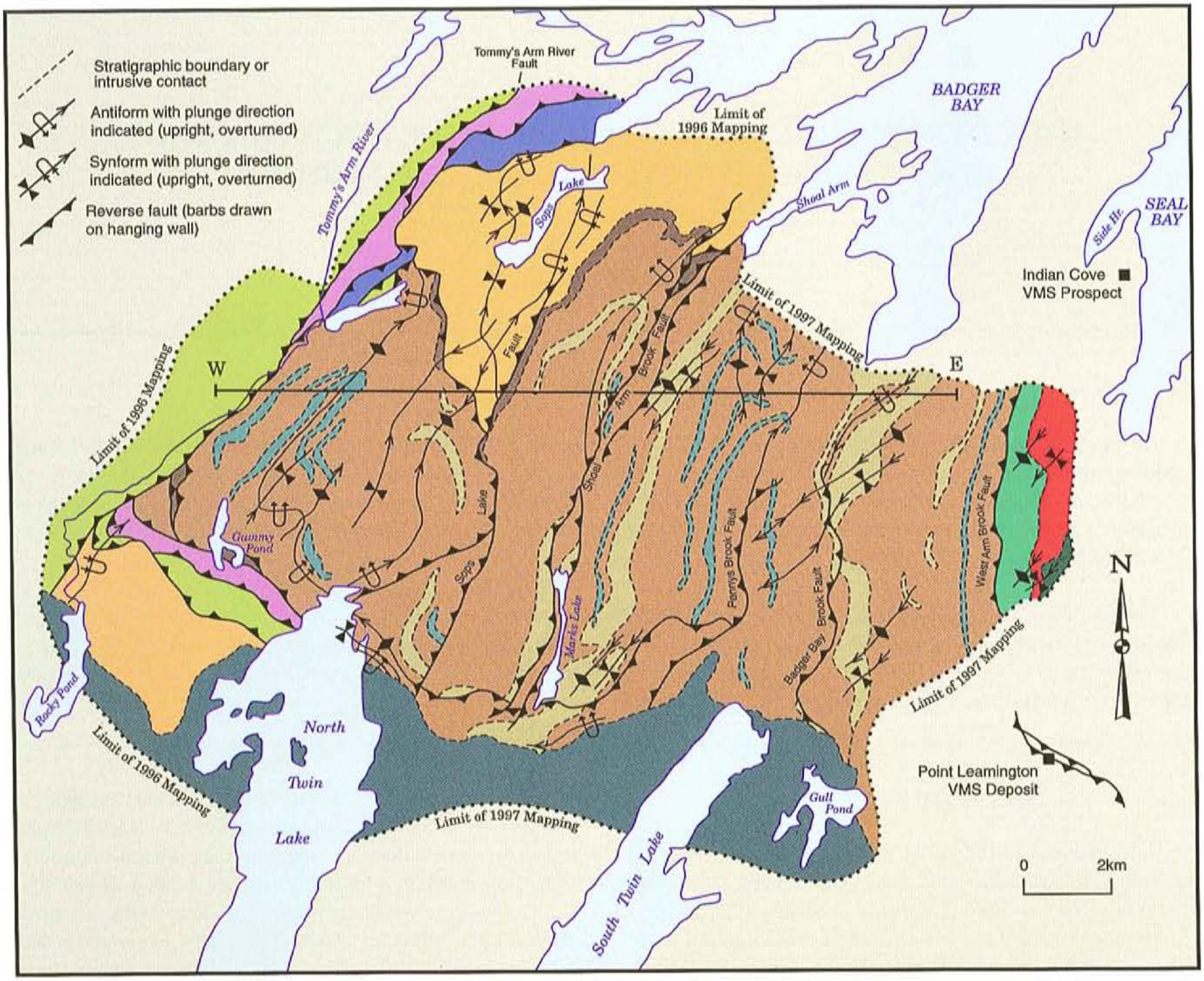
INTRODUCTION

Volcaniclastic turbidites of presumed late Arenig–late Llandeilo age, intruded by epidotized and pyritized laccoliths of Gummy Brook gabbro (O'Brien and MacDonald, 1996), occur throughout most of the western half of the outcrop area of the Wild Bight Group (Figure 1). To the west of Seal Bay, this purported arc-rift to back-arc sequence (Swinden, 1987) contains stratabound alteration zones that are spatially associated with variably thick lenticles of pillow lava, volcanic breccia and olistostrome. Interstratified sedimentary rocks are nodular and ubiquitously silicified, are replaced in various places by Fe–Mn minerals, and are hornfelsed and locally iron-oxidized. They have potential for exhalative, stockwork and skarn mineralization. However, these strata are considered to overlie the Early Ordovician island-arc volcanic rocks associated with the known volcanogenic massive sulphide (VMS) deposits in the Wild Bight Group (Swinden *et al.*, 1989).

The regional distribution of intra-arc turbidites and island-arc volcanic rocks in the northwesternmost Exploits Subzone can be most easily explained in one of two ways. First, Middle Ordovician strata in the Wild Bight Group comprise a westward-thickening wedge sourced from a volcanic arc upland, situated in the east near the Wild Bight Group–Exploits Group boundary. In this scenario, turbidites accumulated above an extended arc substrate that became deeper toward the Red Indian Line. Second, through a combination of Ordovician paleobathymetry and Silurian structure, the extended arc substrate rose toward a western 'high' from beneath a turbidite- and chert-filled depocentre (Figure 1). This Middle Ordovician depocentre, situated between Badger Bay and South Twin Lake, separated rocks now found within the Red Indian Line structural zone from the Lower Ordovician arc volcanic rocks of the eastern Wild Bight Group. The western margin of this eastern 'high' was probably located near the Point Leamington VMS deposit and the Indian Cove VMS prospect (Figure 1).

WHY THE QUERY?

In the early 1990s, E. John Clarke established several fundamental facts concerning the Red Indian Line mélange and adjacent unbroken formations of the Sops Head Complex in the Tommy's Arm River area (Clarke, 1992). First, parts of the Sops Head Complex contain blocks of Shoal Arm Formation sediments that preserve Caradoc graptolites typical of those elsewhere in the Exploits Subzone. Furthermore, stratified conglomerate lenticles faulted directly against the Sops Head Complex contain Ashgill conodonts like those in the Badger Group of the Exploits Subzone. Second, while some pre-Caradoc blocks of MORB-like volcanic rocks may have been derived from the Roberts Arm Group of the Notre Dame Subzone (Nelson, 1981; Bostock, 1988), other blocks of pillowed basalt and felsic tuff are petrochemically similar



POST - ORDOVICIAN INTRUSIVE ROCKS

TWIN LAKES DIORITE COMPLEX

- Posttectonic diorite and granodiorite plutons

ORDOVICIAN OR SILURIAN INTRUSIVE ROCKS

Gummy Brook gabbro

- Pretectonic gabbro - diorite sills and diabase dykes

STRATIFIED ROCKS: NOTRE DAME SUBZONE

Early or Middle Ordovician

ROBERTS ARM GROUP

Crescent Lake Formation

- Unseparated lenticles of basalt, chert, and sandy to conglomerate turbidite

RED INDIAN LINE STRUCTURAL ZONE

Middle Ordovician or Younger

SOPS HEAD COMPLEX

- Block-in-matrix mélange and less-deformed black siltstone
- Unbroken formations of wacke, mudstone, rhyolite, basalt, and limestone

STRATIFIED ROCKS: EXPLOITS SUBZONE

Late Ordovician

BADGER GROUP

Gull Island Formation

- Sandstone turbidites and subordinate siltstone and conglomerate

Middle and Late Ordovician

Shoal Arm Formation

- Multicoloured chert, manganiferous coticules and black shale

Middle Ordovician and Older

WILD BIGHT GROUP

Pennys Brook Formation

- Concretionary sandstone turbidites and siliceous banded argillites
- Lenticles of pillow basalt, basalt breccia and olistostrome

Side Harbour Formation

- Iron-oxidized pillow basalt

Seal Bay Brook Formation

- Felsic pyroclastic rocks
- Pillow basalt and diabase dykes

Figure 1. *Regional geological map of the western Wild Bight Group and adjacent rocks, Notre Dame Bay. Major structures are illustrated, although their relative ages are not distinguished by map symbols. Compiled from O'Brien and MacDonald (1996) and O'Brien (1997).*

to arc volcanic rocks found in the eastern part of the Wild Bight Group. These data pose a tectonic paradox because the closest-exposed Wild Bight Group source of the arc volcanic blocks lies about 25 km southeast of the Sops Head mélange, whereas the fossil-bearing blocks suggest a local derivation.

REGIONAL STRUCTURE OF THE WESTERN WILD BIGHT GROUP

The most significant structural feature of this part of the Exploits Subzone is the extensive system of folded thrust and reverse faults (Figure 1). Although best displayed by the rocks of the Wild Bight Group, this structural pattern is also present in the stratigraphically overlying Shoal Arm Formation and Badger Group (O'Brien and MacDonald, 1996). The deformation sequence associated with the imposition of regional slaty cleavage in central Notre Dame Bay (O'Brien, 1993) is applicable throughout the region surveyed.

Generally, northwest-trending D1 ductile structures are overprinted by northeast-trending D2 ductile structures. Most L1 extension lineations are dip-slip or moderate oblique-slip, and they develop in spatial association with the regionally folded, gently inclined D1 faults. Locally, deformed L1 lineations are observed on S1 foliation surfaces that were microfolded during regional D2 deformation (e.g., the Sops Head mélange on the western shore of North Twin Lake; Figure 1). In contrast, ductile D2 faults are coeval with the regional folds of the earlier formed faults, and they display a significant strike-slip component of offset (e.g., the Tommy's Arm River fault). F2 fold axes vary in plunge from subvertical to subhorizontal on the S2 crenulation cleavage, which is locally developed near the northeast-trending, moderately-inclined D2 fault surfaces.

The western Wild Bight Group and adjacent rocks have been previously interpreted (Figure 4a of O'Brien and MacDonald, 1997) as illustrating a bivergent D1 thrust system. In this conjugate system, the northeast-dipping synthetic faults generally formed first and were regionally responsible for placing older strata above younger strata. The subordinate, southwest-dipping antithetic faults commonly formed later, and 'older-over-younger' and 'younger-over-older' displacements are both observed. This may explain why Wild Bight strata overthrust younger constituents of the Exploits Subzone on the northern *and* southern margins of the group, and why the regional boundary fault dips inward rather than outward around most of the margin of the regional dome cored by the Wild Bight Group. Evidence is lacking to suggest that the northern boundary fault is an original southwest-directed thrust fault, which was overfolded to dip southwestward and, as a consequence, now displays a hanging wall-down sense of normal fault offset. The southwest-directed Silurian thrusting along this part of the composite Gondwanan margin was probably coeval with sinistral transpression along northeast-trending D1 strike-slip thrusts. As such, it is analogous to the partitioned collisional deformation documented in the Scandian of Norway (Northrup and Burchfiel, 1996), where displacements on the composite Baltic margin relate to both orogen-parallel and orogen-normal convergence vectors.

In the western Wild Bight Group, some of the regional D2 structures were probably more effective than the antithetic D1 structures in producing northeast-directed, orogen-parallel transport, although this D2 outcome was evidently restricted to certain areas. Significantly, S-shaped F2 major folds are most typical in the east of the Marks Lake–Badger Bay Brook area (O'Brien, 1997; Figure 1), where they are outlined by D1 reverse faults and F1 overturned folds. In contrast, Z-shaped F2 major folds of such D1 structures are most commonly encountered in the west of this region and also in the Tommy's Arm River–Shoal Arm Brook map area (O'Brien and MacDonald, 1996). This is consistent with the presence of a variably but generally southwest-plunging D2 synformal structure within the central part of the Wild Bight Group.

Thoughout the western Wild Bight Group, it is common for the axes of the largest F2 folds to be replaced by regional D2 fault zones. For example, in the westernmost part of the area surveyed, the D2 Tommy's Arm River fault displaces the northwestern limb and hinge zone of an F2 antiform cored by the Wild Bight Group and flanked by the Shoal Arm Formation and the Badger Group (Figure 1). Similarly, the D2 Sops Lake fault displaces the hinge zone of a regional synform in the Wild Bight Group between Marks Lake and North Twin Lake. In both cases, regional F1 folds are also displaced. The axes of regional F2 synforms are also truncated along the traces of the Shoal Arm Brook fault northeast of Marks Lake, the Penny's Brook fault southwest of Badger Bay, and the Badger Bay Brook fault northeast of South Twin Lake (Figure 1). Within the ductile fault zones that replace these regional folds, it is common to observe imbricate thrust sheets in which the stratigraphic facing direction changes across adjacent fault-bounded panels in the tectonic stack (e.g., northern Marks Lake).

In regions of low-strain D2 deformation, variations in the amount and direction of F2 plunge reflect the presence of overprinted structures related to regional D1 deformation. Such variations can be seen between the Penny's Brook and Badger Bay Brook faults, where the eastern limb of a regional M-shaped anticline is refolded by S-shaped folds (Figure 1). Prior to F2 refolding, some of the eastward-younging strata on the eastern limb were inverted, whereas other parts of the sedimentary succession remained right-way-up. As a result, superimposed open folds plunge southwestward in the upside-down rocks and steeply northeastward elsewhere. This effect is also observed along the axial trace of the anticline in the hanging wall of the Sops Lake fault, in particular where this F2 fold passes from the Wild Bight Group in the hanging wall of a D1 thrust to the Badger Group in the immediate footwall (Figure 1).

Several types of folds were produced during inhomogeneous D2 deformation and each reflects the varying influence of pre-existing structures. Northeast-trending, gently plunging, upright, open F2 folds typically form in areas of low D1 strain, and invariably face upward along D2 minor structures. Locally, F2 periclinal folds plunge very gently in opposing directions along the trace of a single F2 axial surface. Approaching a D2 fault zone, northeastward- and southwestward-closing antiforms and synforms develop in pairs, and display a dextral or sinistral sense of fold asymmetry (Figure 1). Typically, these close-to-tight F2 major folds form on the limbs of regional F2 folds and, although changing from being upright to inclined along the axial trace, they have the same plunge direction as the larger structures. Such fold structures are locally seen to face downward (e.g., the antiformal synclines south of Sops Lake or the synformal anticlines west of North Twin Lake).

Adjacent to some D2 faults, 'doubly-hooked' coaxial folds have two northwest-trending limbs that are parasitically folded but also have in common a relatively straight, northeast-trending fold limb. Closing to the northeast and southwest with opposing senses of F2 vergence, these fold structures have two hinge zones that plunge moderately to steeply in the same or in opposite directions. Typical examples of such structures are the folded trace of the D1 boundary thrust at the western margin of the Badger Group or the folds of the D1 reverse fault at the eastern margin of the Roberts Arm Group and the Red Indian Line mélange (Figure 1). Where both hinge zones plunge in the same direction, one margin of the regional fold structure is upward-facing; whereas, the opposing margin faces structurally downward. To illustrate the point, northeast of the Exploits Subzone rocks, the Sops Head Complex occurs in a northeast-plunging antiformal anticline; whereas, southwest of the same tract of Exploits Subzone rocks, the Sops Head Complex flanks a northeast-plunging synformal anticline. Although some of these structures possess certain geometrical characteristics of sheath folds, the regional D2 strain is very low, and D2 material lines are not folded in northeast–southwest sections of F2 folds.

OUTCROP PATTERN OF THE INTRA-ARC BASIN

Regional mapping of the volcanic lenticles in the middle and upper parts of the Pennys Brook Formation shows that these strata discontinuously encircle the formation's volcaniclastic turbidites in much the same manner as the Llandeilo–Caradoc Shoal Arm Formation encircles the western part of the older Wild Bight Group (Figure 1). An equally important observation is that the youngest and thickest volcanic lenticle (the Badger Bay Volcanics of Swinden, 1987) demarcates a faulted regional synclinorium in the central part of the Wild Bight Group, and that these rocks are probably coextensive with Wild Bight strata in the southern part of the New Bay Pond sequence (Swinden, 1988; Swinden and Jenner, 1992; Kusky, 1996). The oldest Pennys Brook strata on the eastern limb of the regional synclinorium are truncated by the West Arm Brook fault, which places them structurally above the Side Harbour Formation and underlying arc-related rocks of the Seal Bay Brook Formation (Figure 1).

The regional distribution of Middle Ordovician sedimentary and volcanic rocks in the western Wild Bight Group and their varying structural relations with the Shoal Arm Formation and the Badger Group support the notion of a western structural 'dome' and a central structural 'basin'. These tectonic features are schematically illustrated in a regional cross section of the Exploits Subzone rocks between the Tommy's Arm River and West Arm Brook faults (Figure 2). The western 'dome' in the Wild Bight Group is essentially a pop-up structure produced by several ages of bivergent thrusts, and this is probably why F2 folding of D1 thrusts is most commonly seen in the hanging wall of a listric D2 reverse fault. The dominant D2 tectonic movements were along the northwest-dipping D2 faults, although southeast-dipping D2 structures do occur in the east (Figure 2). Regardless of D1 or D2 age, these bivergent faults are responsible for imbricating, detaching and excising the Caradoc–Ashgill succession and, where they root in the underlying substrate, they truncate synclines on the flanks of the pop-up structure in the Wild Bight Group.

It is distinctly possible that the central 'basin' occurs in an eroded triangle zone (Figure 2) similar to that described at the eastern margin of the Wild Bight Group (Williams and O'Brien, 1994). There, the Caradoc–Ashgill succession is also locally omitted as a result of bivergent thrusting, although, in the latter case, this occurs at the mutual boundary of the Exploits and Wild Bight groups. An important structural corollary of having the western 'dome' detached from the central 'basin' is that a western extension of the West Arm Brook thrust may possibly bring the prospective arc volcanic rocks to a shallow depth beneath the "pop-up" block of Pennys Brook turbidites (Figure 2).

A WESTERN STRUCTURAL CULMINATION?

One of the faulted M-shaped anticlines in the western Wild Bight Group lies between the Shoal Arm Brook and Penny's Brook faults. It closes northeastward near Badger Bay but westward between Marks Lake and North Twin Lake (Figure 1). This fold is displaced by a Z-folded reverse fault that merges with a system of thrusts that developed along the

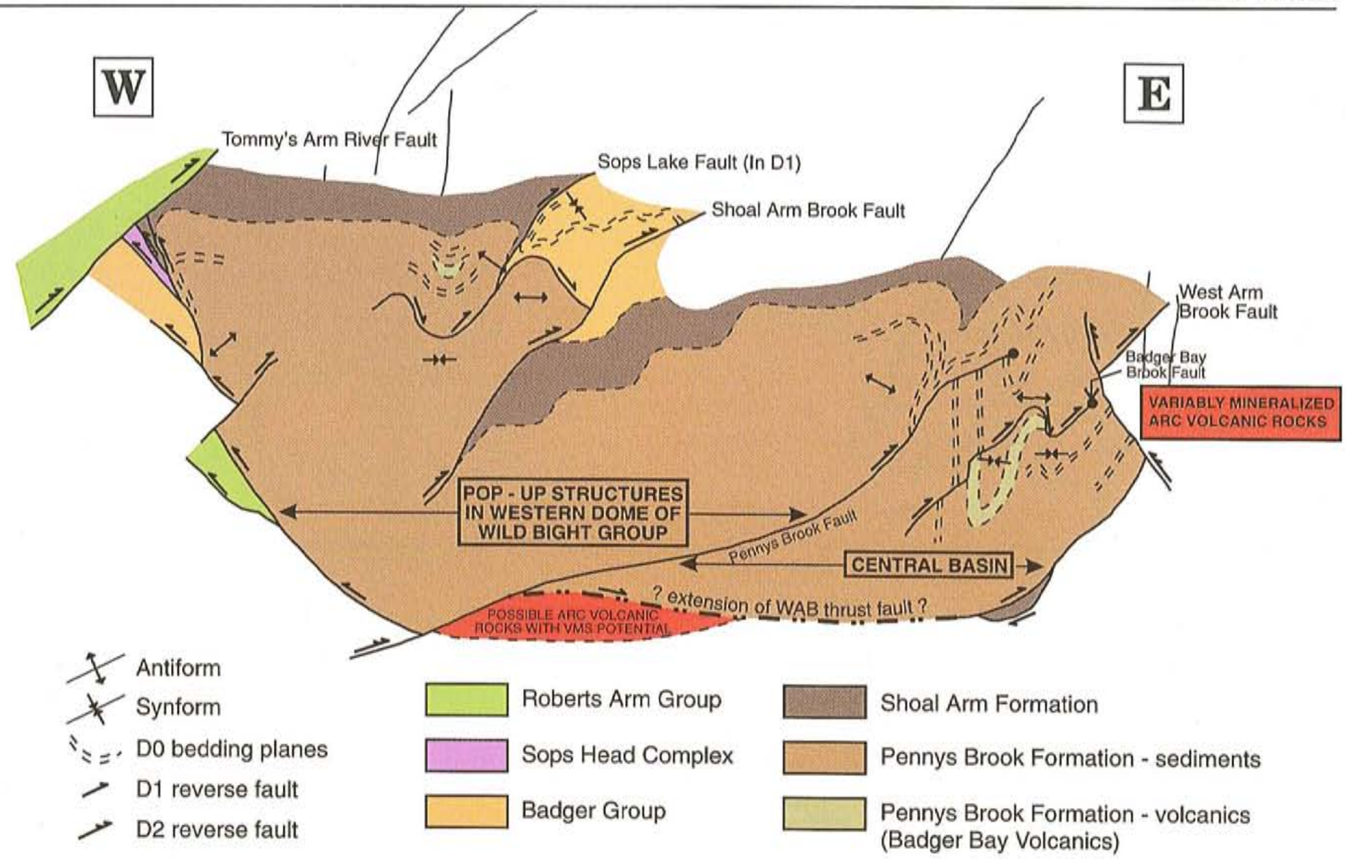


Figure 2. *Cross section of the western Wild Bight Group and adjacent rocks illustrating the generalized regional structure of the area in an oblique view. The 'western dome' is situated between the Tommy's Arm River and Penny's Brook faults, and the 'central basin' is located between the Penny's Brook and West Arm Brook faults. The nature of the culmination and the depression is schematically portrayed. Note that arc volcanic rocks having VMS potential may occur structurally below the 'high' and lie adjacent to a westward extension of the West Arm Brook thrust fault. Section line west-east is shown in Figure 1.*

southwestern margin of the Wild Bight Group. It may have been originally continuous with the overturned F1 anticline between North Twin Lake and Gummy Pond (Figure 1). If so, a domal structural culmination resulting from D1/D2 interference must occur in the western Wild Bight Group between the Penny's Brook and Tommy's Arm River faults. This implies that the anticlines depicted at the margins of the pop-up in Figure 2 are the same curviplanar D1 structure, modified by D2 faults that partially preserve an intervening syncline.

One of the geological oddities of the Wild Bight Group is that many of its oldest known rocks occur near the outer periphery of the map unit. As indicated herein, the youngest strata are thickest and most extensive in the centre of the group and are relatively thin along its external margins adjacent to dated Middle–Late Ordovician strata. This reflects the fact that the Wild Bight Group does not contain one regional anticline whose axis is symmetrically disposed in the central part of the unit's outcrop area.

Two options to explain the regional distribution of the Early and Middle Ordovician rocks in the Wild Bight Group are presented in Figure 3. One interpretation involves D1 diapiric overthrusting of a single, very large, overturned F1 fold nappe, emplacing it preferentially above highly fissile Caradoc shales, and thereby tectonically removing most of the Wild Bight succession on the subrecumbent limb of the anticlinal nappe (Figure 3a). In an alternative explanation, complex F2 refolding of F1 overturned folds (and D2 re-thrusting of bivergent D1 reverse faults) isolated the Wild Bight Group into several, kinematically distinct D2 structural domains (Figure 3b).

INTERPRETATION

The preferred interpretation of the regional structure of the Wild Bight Group is illustrated in Figure 3c. It assumes that, during progressive D2 deformation, the structural culminations and depressions and the fold interference patterns shown in Figure 3b were distorted and displaced by major reverse faults with a significant strike-slip component of offset. As a result, the western, central and eastern parts of the Wild Bight Group were tectonically segmented to form three, discrete, fault-bounded, structural domains (Figure 3c). The domain-bounding faults are the Tommy's Arm River fault, the Penny's Brook fault and the West Arm Brook fault.

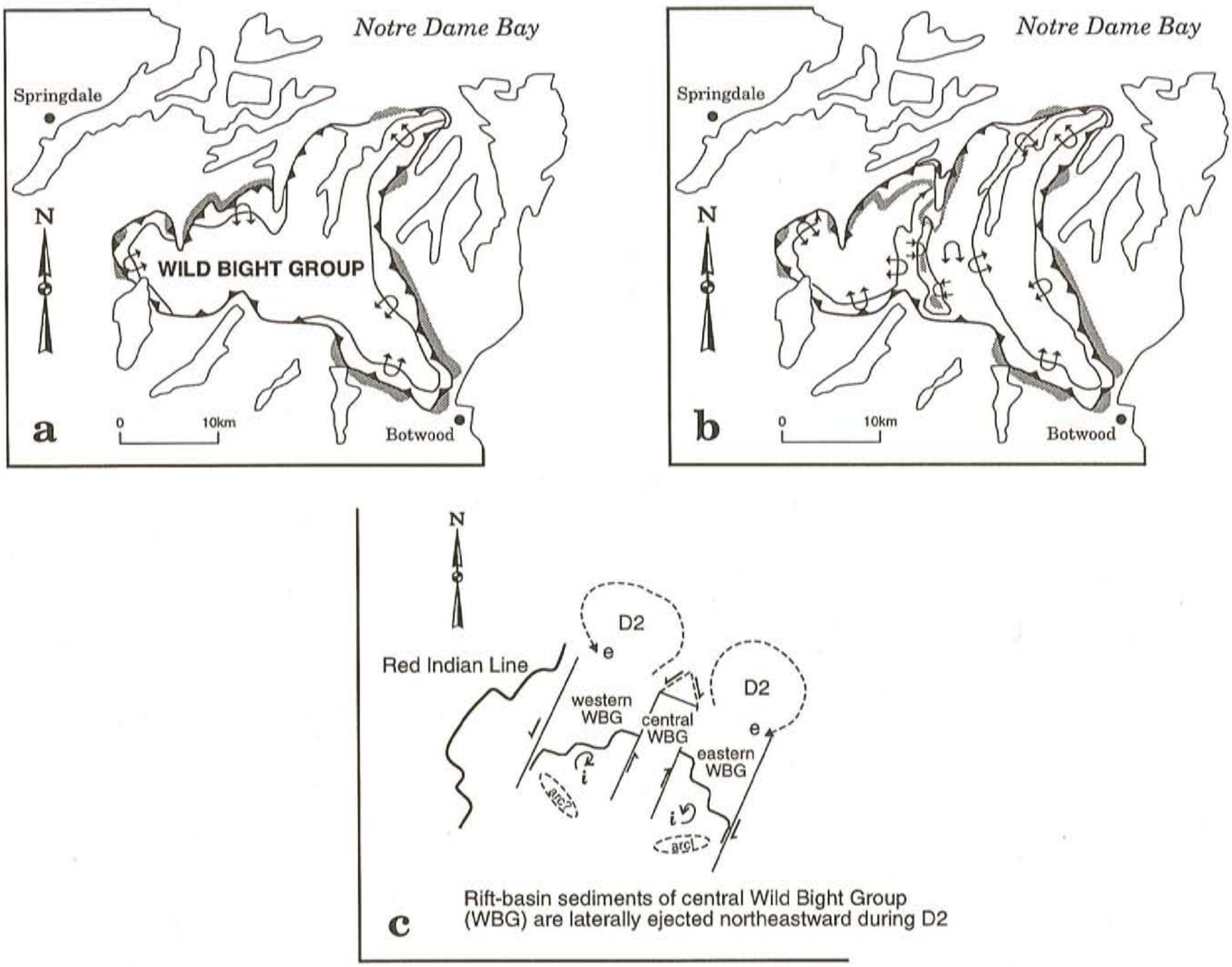


Figure 3. *Alternate interpretations of the regional triangular-shaped outcrop pattern of the Early to Mid Ordovician Wild Bight Group. Discontinuous solid unit represents parts of the Mid to Late Ordovician Shoal Arm and Lawrence Head formations. a) 'mushroom cap' type of D1 structural dome with a refolded rim anticline that overhangs D1 boundary thrusts that root in the 'stalk'. A central depression on the 'cap' is possible. b) 'western' and 'eastern' D2 structural culminations separated by a coeval 'central' structural depression originally cored by the Shoal Arm Formation. c) lateral D2 ejection model to explain the contrasting internal (i) and external (e) rotations of the western and eastern 'highs' due to the strike-slip component of D2 deformation. Note the resultant outcrop pattern of Exploits Subzone rocks adjacent to the Red Indian Line.*

In the eastern Wild Bight Group, where all known arc-related VMS deposits occur, the dominant S-shaped F2 folds indicate an anticlockwise internal rotation within this structural block related to dextral shearing on the D2 faults that externally bound the eastern domain. In the western Wild Bight Group, the dominant Z-shaped F2 folds indicate a clockwise internal rotation and a sinistral external rotation during D2 deformation of the western structural domain (Figure 3c). The relative motions of the structural 'highs' that bordered the central domain were probably responsible for the concomitant shearing and forceful ejection of the central synclinorium in the Wild Bight Group. Thus, the relatively thick and incompetent strata of the central rift basin were translated northeastward by lateral movements on D2 oblique-slip faults (Figure 3c), which amplified the regional southwest plunge of the intra-arc turbidites.

Detailed structural studies of small tracts of Red Indian Line mélange have previously indicated the importance of a dextral strike-slip component of ductile shear on high-angle reverse faults at a relatively late stage in their development (e.g., Lafrance, 1989; Lafrance and Williams, 1992). Governed by transpression, such orogen-parallel displacements are coeval with shortening produced by orogen-normal convergence. Significantly, in the Wild Bight Group, the main northwest–southeast grain induced by regional D1 deformation points to orogen-parallel convergence (and dextral shear) along certain parts of the composite peri-Gondwanan margin.

However, formation of the northeastern apex of its triangular outcrop pattern reflects lateral D2 displacement at a time when the dominant convergence vector was perpendicular to the Appalachian orogen. A D2 lateral ejection model for the Wild Bight Group supports the notion that the colliding Exploits Subzone rocks were displaced northeastward along the margin of the Notre Dame Subzone in D1 time but had reversed their tectonic movement direction by D2 time when the largest parts of most Exploits Subzone units were displaced southwestward (Figure 3c).

SHALLOW BURIAL OF EARLY ORDOVICIAN ROCKS?

Whereas the kinematically distinct subdomains of the Wild Bight Group are interpreted to reflect the role of orogen-parallel displacement in the closure of this particular depocentre, they may also imply that the syndepositional architecture of the Iapetan basin influenced faulting related to orogen-parallel collision. Studies of the adjacent Exploits Group suggest that arc highlands located in the southwest provided detritus to an intra-arc basin located farther northeast; however, beginning in the late Arenig, an arc edifice also emerged to the southeast and paleocurrents were then dominated by a northwestward flow (Helwig, 1967; O'Brien *et al.*, 1997). It is possible that the western 'high' is underlain by Early Ordovician arc-related rocks that originally extended along the entire southwestern margin of the Wild Bight and Exploits groups; northeast-trending arc promontories may have developed in the Mid Ordovician.

In this scenario, the structural culmination present in the western Wild Bight Group may have formed in two stages. Initially, basin inversion of the intra-arc turbidites resulted in the original arc substrate being overplated by southwest-directed D1 thrusts that developed preferentially along the southwest margin of the Wild Bight Group. Subsequently, the syndepositional faults that bounded the hypothetical arc promontories were reactivated, and this resulted in D2 tectonic escape of the intra-arc rift basin.

In one explanation of the pop-up structure in the western dome of the Wild Bight Group (Figure 2), the 1.5- to 2-km-thick succession of Pennys Brook strata measured on the right-way-up limb of the southwesterly overturned anticline is largely excised on the inverted limb of the fold nappe adjacent to the Red Indian Line mélange (O'Brien and MacDonald, 1996, 1997). An alternative explanation, which requires less displacement and comparatively little stratigraphic separation across the sole thrust of the fold nappe, is that this area never received a full 2 km of Pennys Brook sediment due to its Middle Ordovician position on a syndepositional uplift. In either case, it is postulated that prospective Early Ordovician arc volcanic rocks may lie at relatively shallow depth beneath Caradoc black shales in the southwestern part of the Wild Bight Group (Figure 2).

CONCLUSIONS

In the subcrop of the western Wild Bight Group, there is potential for Early Ordovician arc-related volcanic rocks to be present and to be involved with two or more discrete phases of alteration. The older phase of alteration would be related to the Early Ordovician mineralization seen at the Point Leamington deposit and the Indian Cove prospect, while a Middle Ordovician phase might have formed contemporaneously with the alteration system observed in the Side Harbour Formation and the overlying Pennys Brook Formation.

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REFERENCES

Bostock, H.H.
1988: Geology and petrochemistry of the Ordovician volcano-plutonic Robert's Arm Group, Notre Dame Bay, Newfoundland. Geological Survey of Canada, Bulletin 369, 84 pages.

Clarke, E.J.
1992: Tectonostratigraphic development and economic geology of the Sops Head Complex, western Notre Dame Bay, Newfoundland. Unpublished B.Sc. (Honours) thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 102 pages.

Helwig, J.A.
1967: Stratigraphy and structural history of the New Bay area, north-central Newfoundland. Unpublished Ph.D. thesis, Columbia University, New York, 248 pages.

Kusky, T.M.
1996: Tectonic implications of Early Silurian thrust imbrication of the northern Exploits Subzone, central Newfoundland. Journal of Geodynamics, Volume 22, Number 3/4, pages 229-265.

Lafrance, B.
1989: Structural evolution of a transpression zone in north-central Newfoundland. Journal of Structural Geology, Volume 11, Number 6, pages 705-716.

Lafrance, B. and Williams, P.F.
1992: Silurian deformation in eastern Notre Dame Bay, Newfoundland. Canadian Journal of Earth Sciences, Volume 29, pages 1899-1914.

Nelson, K.D.
1981: Mélange development in the Boones Point Complex, north-central Newfoundland. Canadian Journal of Earth Sciences, Volume 18, pages 433-442.

Northrup, C.J. and Burchfiel, B.C.
1996: Orogen-parallel transport and vertical partitioning of strain during oblique collision, Efjorden, north Norway. Journal of Structural Geology, Volume 18, Number 10, pages 1231-1244.

O'Brien, B.H.
1993: A mapper's guide to Notre Dame Bay's folded thrust faults: evolution and regional development. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 93-1, pages 279-291.

1997: Geology of the Marks Lake - Badger Bay Brook area (NTS 2E/5), north-central Newfoundland. Scale 1:50 000. Newfoundland Department of Mines and Energy, Geological Survey, Map 97-09, Open File 002E/05/0992.

O'Brien, B.H. and MacDonald, D.L.
1996: Geology of the Tommy's Arm River - Shoal Arm Brook area (2E/5), north-central Newfoundland. Scale 1:50 000. Newfoundland Department of Mines and Energy, Geological Survey, Map 96-033, Open File 002E/05/0967.

1997: Stratigraphy and structure of the Tommy's Arm River - Shoal Arm Brook area (NTS 2E/5) with reference to the stratabound alteration zones of the upper Wild Bight Group, north-central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 97-1, pages 237-255.

O'Brien, B.H., Swinden, H.S., Dunning, G.R., Williams, S.H. and O'Brien, F.H.C.
1997: A peri-Gondwanan arc–back arc complex in Iapetus: early–mid Ordovician evolution of the Exploits Group, Newfoundland. American Journal of Science, Volume 297, pages 220-272.

Swinden, H.S.
1987: Ordovician volcanism and mineralization in the Wild Bight Group, central Newfoundland: a geological, petrological, geochemical and isotopic study: Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 452 pages.

1988: Re-examination of the Frozen Ocean Group: juxtaposed middle Ordovician and Silurian volcanic sequences in central Newfoundland. *In* Current Research, Part B. Geological Survey of Canada, Paper 88-1B, pages 221-226.

Swinden, H.S., Jenner, G.A., Kean, B.F. and Evans, D.T.W.
1989: Volcanic rock geochemistry as a guide for massive sulphide exploration in central Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 89-1, pages 201-219.

Swinden, H.S. and Jenner, G.A.
1992: Volcanic stratigraphy northwest of New Bay Pond, central Newfoundland, and the strike extent of the Point Leamington massive sulphide horizon. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 92-1, pages 267-279.

Williams, S.H. and O'Brien, B.H.
1994: Graptolite biostratigraphy within a fault-imbricated black shale and chert sequence: implications for a triangle zone in the Shoal Arm Formation of the Exploits Subzone. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 94-1, pages 201-209.