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GEOLOGICAL DEVELOPMENT OF THE EXPLOITS AND NOTRE DAME SUBZONES IN THE NEW BAY AREA (PARTS OF NTS 2E/6 AND 2E/11), MAP AREA, NOTRE DAME BAY, NEWFOUNDLAND

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ABSTRACT

In the New Bay area, lower and middle Paleozoic rocks of the Exploits and Notre Dame subzones are disposed about an intra-Dunnage Zone oroclinal flexure in the north-central Newfoundland Appalachians. Strata of Ordovician and Silurian age accumulated in tectonically active basins, whose depocentres were possibly controlled by a migrating crustal bulge or syndepositional arch.

Progressive regional (post-Llandovery) deformation was focussed on basin-margin fault zones. Prior to late-stage transcurrent faulting, deformation proceeded in individual structural domains, regionally oriented either northwest or northeast. Periclinal anticlinoria or synclinoria, bounded by convergent or divergent, conjugate thrusts, evolved into basins and domes outlined by folded faults.

Syndepositional faults, postulated to occur where thrusts show variable amounts of up-dip contractional displacement, may be important features controlling the distribution of felsic pyroclastic domes and related base-metal mineralization. Reactivated synvolcanic or synsedimentary faults are the preferred location of syntectonic multiple intrusions. Screens of gabbro–diorite are variably altered and mineralized, particularly in the Exploits Subzone.

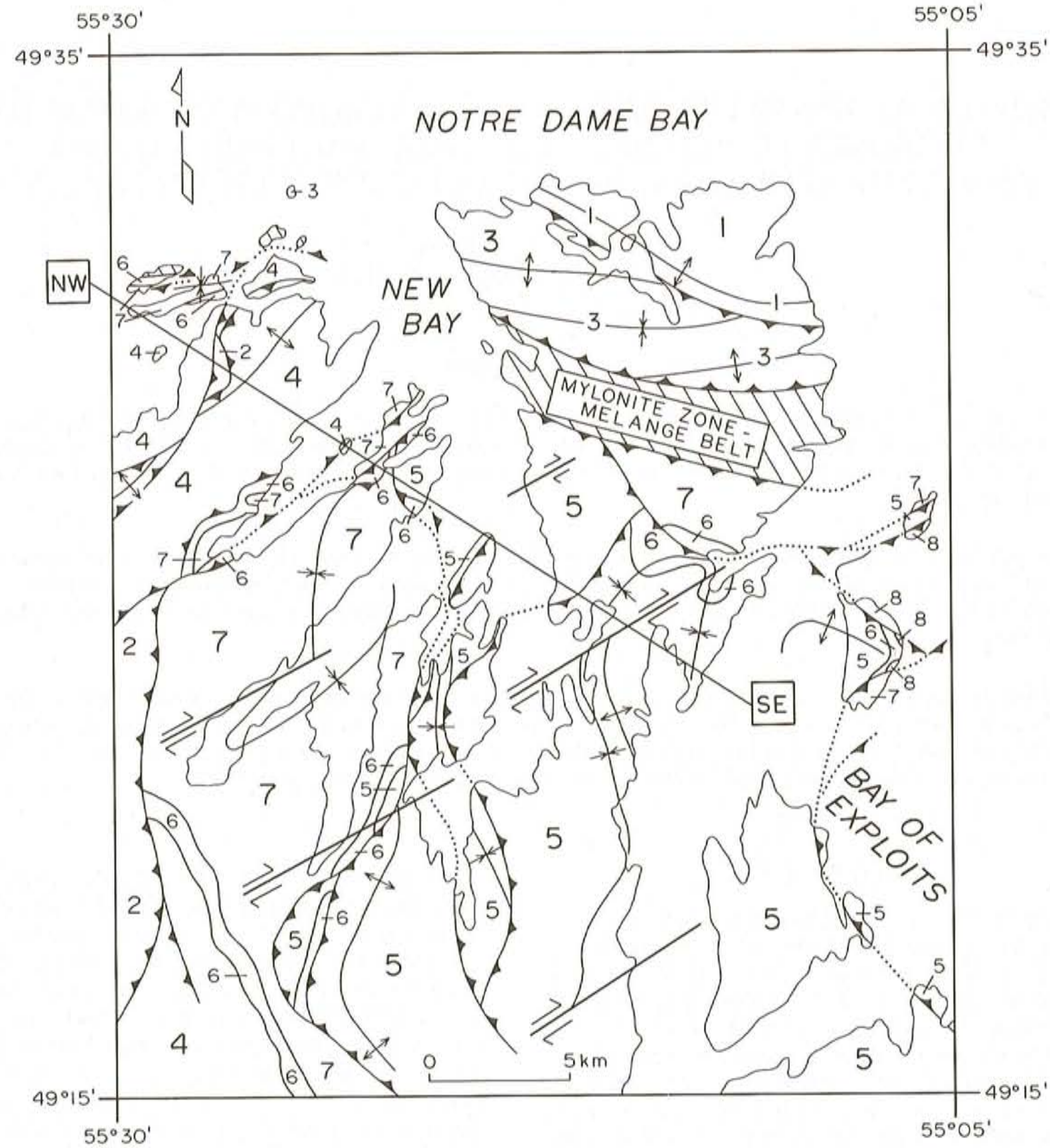
INTRODUCTION

The New Bay area in north-central Newfoundland is underlain, for the most part, by Paleozoic strata belonging to the Exploits and Notre Dame subzones of the Appalachian Dunnage Zone (Williams, *et al.*, 1988; Swinden *et al.*, 1988). The Red Indian Line, which is probably the southeastern limit of sub-Dunnage Zone Grenvillian basement at mid-crustal depths (Keen *et al.*, 1986; Marillier *et al.*, 1989), is manifested within the map area as a 2- to 3-km-wide mylonite zone that contains discontinuous belts of scaly-foliated melange. Throughout the New Bay area, the Red Indian Line separates fossil-bearing, Ordovician and Silurian volcano-sedimentary rocks of the Exploits Subzone to the south, from unfossiliferous and locally undated, volcano-sedimentary and hypabyssal rocks of the Notre Dame Subzone to the north (Figure 1). Progressively deformed constituents of the Red Indian Line structural zone include mylonitic units from both subzones and fault planes of regionally developed thrusts such as the Lukes Arm (Horne and Helwig, 1969; Blewett,1989), Sops Head (Nelson, 1981; Bostock, 1988), New Bay (Helwig, 1967; Dean, 1977) and Northwest Arm faults (Helwig, 1967).

AGE, DISTRIBUTION AND REGIONAL RELATIONSHIPS

The distribution of lithostratigraphic units in the New Bay area is shown at 1:250,000 scale in Figure 1. Within this region, Units 1 to 4 are fault-bounded at exposed contacts, are apparently unfossiliferous and do not contain rocks for which absolute isotopic ages are available. They are assigned an Ordovician or earlier age based on previous regional correlations with units in other areas (Dean, 1977, 1978; Swinden *et al.*, 1988). Unit 1 has been correlated with the Late Cambrian Moretons Harbour Group. Unit 2, which includes the presumed Ordovician South Lake ophiolite, has been termed the South Lake Igneous Complex. Unit 3 comprises the main tract of the Cottrells Cove Group, originally postulated as Silurian in age (Dean and Strong, 1977), but more recently correlated with the Early Ordovician (Dunning *et al.*, 1987) Buchans and Roberts Arm groups. Unit 4 represents a small part of the Wild Bight Group, the uppermost portion of which probably correlates with the stratigraphically highest (Early Ordovician) parts of Unit 5.

Each of Units 5 through 8 contains one or more stratigraphic intervals that yield shelly or graptolitic faunas (Dean, 1977; Williams, *in press;* W.D. Boyce, personal communication, 1990). These fossils indicate a shallow and/or deep-marine origin for their siliciclastic and calcareous host rocks, and a probable Llanvirn–Llandovery stratigraphic range for Units 5 through 8. Volumetrically, turbiditic shale, sandstone and conglomerate interstratified with pillowed, brecciated or scoraceous, mafic lava predominate most of the Llanvirn–Llandovery units. Although primary subunits and resedimented megaclasts of iron formation and chert, reefal-, shelly- and conodont-bearing limestone, sulphide-rich



SILURIAN AND ORDOVICIAN

Ashgill - Llandovery

8	Botwood Group

Ashgill

7	Point Leamington Greywacke (includes Goldson Conglomerate)

Caradoc

6	Lawrence Harbour Shale

Llanvirn - Llandeilo

5	Exploits Group

ORDOVICIAN OR EARLIER

4	Wild Bight Group
3	Cottrells Cove Group
2	South Lake Igneous Complex
1	Moretons Harbour Group

Figure 1. *Regional geology of the New Bay area. Simplified from Open File (Nfld) Map 90-124. Formations and subunits discussed in the text are undivided in Figure 1 (1:250,000 scale) but are separated on Map 90-124 (1:50,000 scale).*

mudstone, and felsic agglomerate or tuff are subordinate, they alone permit field-based lithostratigraphic subdivision of Units 5 to 8.

The order of superposition of Units 5 to 7, discernible from locally preserved lithostratigraphic contacts, corroborates their biostratigraphic age assignments. Most or all of Unit 5 corresponds to the Exploits Group of recent workers (e.g., Kean *et al.*, 1981). A sparse fauna collected from the upper part of the group in the New Bay area may indicate a Llanvirn–Llandeilo age (S.H. Williams, personal communication, 1990). Rocks included in Unit 5 in the extreme northwest and southeast of its outcrop area (Figure 1) may be more appropriately assigned to the Ordovician and earlier Wild Bight Group and the Cambro-Ordovician Dunnage Melange, respectively (e.g., Williams, 1962).

The most diagnostic and laterally persistant unit in the New Bay area is Unit 6, the Lawrence Harbour Shale, which is observed to conformably overlie Unit 5. Although the focus of considerable structural disruption, it probably originally formed as an anomalously thin unit ranging in age from earliest to latest Caradoc (Williams, *in press*). The Lawrence Harbour Shale has been correlated across the Atlantic Ocean with the strongly condensed Moffat Shale (Helwig, 1967), a major decollement horizon in the Southern Uplands of Scotland.

Conformably overlying Unit 6 in the New Bay area is the Point Leamington Greywacke, bearing Ashgillian graptolites (Williams, *in press*), and the succeeding Goldson Conglomerate, containing Ashgillian limestone clasts (F.L.C. O'Brien, personal communication, 1990). Facies of the Goldson Conglomerate are complexly interstratified with facies of the Point Leamington Greywacke; both comprise Unit 7 in Figure 1. Unit 8 is confined to the western part of the Bay of Exploits, has unknown stratigraphic relations with other units of overlapping or older age, and is tentatively assigned to the Ashgill–Llandovery portion of the Botwood Group (cf. Williams, 1962, 1972; Figure 1).

Throughout the New Bay area, Units 6 to 8 are confined to regional fault-bounded basins. Such basins are generally coincident with early formed, large-scale, structural depressions and many of the bordering faults simply define outcrop boundaries. However, in some localities, Units 6 and 7 display primary stratigraphic relationships at or near the margins of these structural basins. Furthermore, systematic variations in the stratigraphic thickness and relative proportion of component units occur along the margins of the basins as they narrow toward structural culminations. Therefore, as a generalization, basin-margin faults bound sedimentological depocentres as well as structural basins.

LITHOLOGY AND STRATIGRAPHY

MORETONS HARBOUR GROUP (UNIT 1)

In the New Bay area, the Moretons Harbour Group consists of two conformable formations, the older Sweeny Island Formation and the younger Western Head Formation (Dean, 1977). The Sweeny Island Formation is made up of coarse-grained, porphyritic, mafic lava flows as well as localized zones of sheeted dykes separating narrow screens of lava. In ascending order, the Western Head Formation is composed of a lower subunit of mafic agglomerate and pillow breccia, an intermediate subunit of spectacular mafic pillow lava, and an upper subunit of grey chert and siliceous argillite (O'Brien, 1990). The younger formation appears not to contain the abundant swarms of sheeted diabase characteristic of the older formation; however, the Western Head Formation is host to a variety of multiple, mafic to intermediate, minor intrusions.

Neither the stratigraphic base nor the stratigraphic top of the Moretons Harbour Group is exposed in the New Bay area. Its stratigraphic relations to younger units are unknown, unless the Western Head Formation is partly or wholly the equivalent of the Fortune Harbour Formation of the Cottrells Cove Group. If this equivalency is true, then a small amount of thrust displacement has occurred on the Chanceport Fault of Dean and Strong (1977). Although the lower and upper subunits of the Western Head Formation are restricted to a small area in the extreme southwest of the Unit 1 outcrop, they probably indicate that the intermediate subunit of pillow lava has a highly variable thickness.

SOUTH LAKE IGNEOUS COMPLEX (UNIT 2)

The oldest part of the South Lake Igneous Complex is composed of layered gabbros and pyroxenites, which are commonly amphibolitized or chloritized and intruded by diabase dykes. Younger elements of the complex include trondhjemite and granodiorite (Lorenz and Fountain, 1982). Although most of the external boundaries of the complex are faults that are regionally focussed in the Lawrence Harbour Shale and upper Wild Bight Group (O'Brien, 1990; Figure 1), Dean (1977) reports intrusive contacts between granodiorite and Wild Bight country rocks in several localities. The only stratigraphic constraint on the South Lake Igneous Complex and the Wild Bight Group in the New Bay area is the observation of probable detrital clasts of both units in Ashgillian (Unit 7) strata.

COTTRELLS COVE GROUP (UNIT 3)

The main tract of the Cottrells Cove Group corresponds with the distribution of Unit 3, although recognizable tectonic slivers of this group occur, with or without associated melange belts, in the major mylonite zone to the south. The Cottrells Cove Group contains two formations, the older Fortune Harbour Formation and the younger Moores Cove Formation. In ascending order, the Fortune Harbour Formation is made up of a lower subunit of mafic agglomerate and pillow breccia, an intermediate subunit of spectacular pillow lava, and an upper subunit of felsic tuff and agglomerate interbedded with grey and red chert and siliceous argillite (O'Brien, 1990). The Moores Cove Formation is composed of distinctly weathered, ferruginous and calcareous, feldspathic and lithic wacke interbedded with variable amounts of grey argillite. Taken regionally and as a whole, the formation is thick-bedded at its stratigraphic base and becomes thin-bedded toward the top of the exposed succession.

Neither the stratigraphic base nor the stratigraphic top of the Cottrells Cove Group is exposed. As originally defined, the Moores Cove Formation represented the lowest formation of the north-facing, Silurian Cottrells Cove Group (Dean, 1977) and was held to have been originally stratigraphically continuous (Kean *et al.*, 1981) with Upper Ordovician wacke and olistostromal melange (Unit 7). In tectonic terms, this basal formation of volcanogenic flysch was purported to separate an overlying, post-Ashgillian, island-arc volcanic sequence from an underlying, pre-Caradocian, island-arc volcanic sequence floored by ophiolitic basement (Dean, 1978).

Re-assigning the Moores Cove Formation to a position stratigraphically above the Fortune Harbour Formation (O'Brien, 1990) has important paleogeographic implications for the evolutionary development of the Cottrells Cove Group. Although most commonly faulted, the contact between the Fortune Harbour and Moores Cove formations is observed to be stratigraphically gradational. Primary lateral changes in the rock types are the likely cause of the present distribution of subunits. As a result, mafic volcanic and (variably thin) felsic volcanic rocks occur chiefly in the north of the Cottrells Cove Group, whereas mafic volcanic and (variably thick) sedimentary rocks are present mostly in its southerly outcrop. The intermediate subunit of pillow lava in the Fortune Harbour Formation is widespread in the northwestern part of the area near the northern fault boundary of Unit 3. It is also found as small tectonic inliers in the Moores Cove Formation, especially in the southeastern part of Unit 3 near its southern fault boundary. However, the outcrop pattern of this pillow lava subunit suggests that, in the northwestern exposures of the Fortune Harbour Formation, it is not appreciably thick. Based upon similar arguments, the Moores Cove Formation appears to obtain substantial thicknesses only along the southeastern flank of the Cottrells Cove Group.

WILD BIGHT GROUP (UNIT 4)

In the New Bay area, only a small proportion of the Wild Bight Group is represented by Unit 4 in Figure 1. Dean (1977) correlated most of the rocks included in Unit 4 with the Pennys Brook Formation, a mappable unit that he considered as the uppermost formation of the Wild Bight Group.

Unit 4 is composed of two subunits (O'Brien, 1990); one chiefly of volcanic rocks and the other largely of sedimentary rocks. Mafic agglomerate, pillow breccia and pillow lava form the older subunit. The younger subunit contains distinctively green, siliceous argillite interbedded with tuffaceous sandstone and ferruginous wacke. Grey and red parallel-laminated cherts are also present.

Neither the stratigraphic base nor the stratigraphic top of the Wild Bight Group is exposed in the New Bay area. The outcrop of the mafic volcanic subunit of Unit 4 is restricted to the extreme west of the area and is areally insignificant in comparison to the sedimentary subunit.

EXPLOITS GROUP (UNIT 5)

The New Bay area contains the type area of what recent workers refer to as the Exploits Group (Dean, 1977). Unit 5 generally corresponds with the Exploits Group as compiled by Kean *et al.* (1981) and, as such, it is the most widely distributed unit in the region (Figure 1). Although Helwig (1967) employed the term Exploits Group to include Units 5 to 7, he nevertheless, originally separated most of Unit 5 into four conformable units of formational rank. In ascending order, these regionally mappable yet locally discontinuous units are the Tea Arm Volcanics, the Saunders Cove Formation, the New Bay Formation and the Lawrence Head Volcanics.

The Tea Arm Volcanics consists of a lower subunit of spectacular pillow lava associated with abundant mafic dykes and sills, an intermediate subunit of felsic tuff and agglomerate, and an upper subunit of mafic agglomerate, pillow breccia and pillow lava along with minor interbeds of feldspathic wacke and laminated argillite (O'Brien, 1990). The Saunders Cove Formation sharply overlies the Tea Arm Volcanics and contains red chert, interbedded red and green, siliceous argillite, feldspathic wacke and minor conglomerate. Gradationally overlying the Saunders Cove Formation is the older of two, stratigraphically gradational subunits of the New Bay Formation (O'Brien, 1990). It is generally composed of interbedded, grey shale and grey sandstone, although conglomeratic wacke is also common in the lower part of the subunit. The younger subunit of the New Bay Formation is made up of feldspathic wacke and graded, boulder to cobble conglomerate at its base and contains increasing amounts of grey argillite near its top. In some but not all locations, the spectacular pillow lava and pillow breccia of the Lawrence Head Volcanics sharply overlie the New Bay Formation.

In the New Bay area, the stratigraphic base of the Exploits Group is not exposed; however, its stratigraphic top is observable in the eastern part of the region beneath the Lawrence Harbour Shale (Figure 1). Some of the sedimentary rocks in the Wild Bight Group (Unit 4) are identical to fossil-bearing strata in the uppermost Exploits Group and, in terms of lithofacies, are similar to parts of the Saunders Cove and New Bay formations. Therefore, the Exploits and Wild Bight groups may be partially equivalent and conceivably be Exploits Subzone correlatives. However, considering the overall stratigraphy and lithology of the Exploits Group, the strongest case for its correlation could be made with the Cottrells Cove Group in the Notre Dame Subzone immediately north of the Red Indian Line structural zone. Clearly, correlation of rock units in the Dunnage Zone cannot be based on stratigraphy and lithology alone (e.g., Heyl, 1936) and must await the integration of petrochemical, paleontological, geochronological and paleomagnetic data.

Throughout the New Bay area, a thin subunit of graptolite-bearing, ferruginous chert and feldspathic wacke lies conformably beneath the Lawrence Harbour Shale. It displays complex facies relations with mappable units of Llanvirn–Llandeilo limestone in the Bay of Exploits region. This regionally extensive subunit rests, in different localities, conformably above the lower and upper Tea Arm Volcanics, the upper New Bay Formation and the top of the Lawrence Harbour Volcanics. It appears to pass laterally into the Saunders Cove Formation and, possibly, the intermediate subunit of felsic volcanic rocks in the Tea Arm Volcanics. The maximum, total-combined, stratigraphic thickness of Exploits Group formations occurs in the east of the New Bay area, where at least 3.5 km of strata underlies the distinctive subunit of ferruginous chert and feldspathic wacke. Toward the west, the Exploits Group appears to thin dramatically beneath its uppermost graptolitic subunit. The lack of a surface of erosional unconformity beneath this subunit suggests that the volcano-sedimentary constituents of the Exploits Group basin were already exposed in variably thick, rock belts by Llanvirn–Llandeillo time, long before the initiation of regional deformation.

LAWRENCE HARBOUR SHALE (UNIT 6)

The New Bay area contains the type area and reference section of the Lawrence Harbour Shale (Williams, *in press*). All Unit 6 occurrences in the New Bay area (Figure 1) have been previously correlated with the black shale and cherty black shale sequences at Lawrence Harbour (Helwig, 1967; Dean, 1977).

The Lawrence Harbour Shale contains several distinctive subunits that are present over a large region but are difficult to map individually. In ascending order, they are bioturbated grey chert associated with black argillite laminae, black pyritiferous siltstone having black shale partings, and black carbonaceous shale (O'Brien, 1990). Although the lowest subunit is apparently unfossiliferous and occurs stratigraphically below the first continuous bed of graptolite-bearing (Caradocian) black shale, it is conformable with overlying strata. Most workers consider the laminated grey chert subunit as a part of the Lawrence Harbour Formation and, therefore, it is included in Unit 6 in Figure 1.

In the New Bay area, the stratigraphic top of the Lawrence Harbour Shale is positioned at its gradational contact with the Ashgillian Point Leamington Greywacke (Williams, *in press*). The stratigraphic base of the Lawrence Harbour Shale is placed at its gradational contact with the Llanvirn–Llandeilo subunit of ferruginous chert and feldspathic wacke that occurs at the top of the Exploits Group and possibly the uppermost Wild Bight Group. Despite having conformable lower and upper contacts, it is practical to exclude the Lawrence Harbour Shale and succeeding units from the Exploits Group. This is because biostratigraphically equivalent units of Caradocian black shale comprise an integral part of several groups that are widely dispersed throughout the Exploits Subzone (S.H. Williams, personal communication, 1990).

POINT LEAMINGTON GREYWACKE AND GOLDSON CONGLOMERATE (UNIT 7)

In Figure 1, the Point Leamington Greywacke and the Goldson Conglomerate are grouped together as interstratified units of Ashgillian age (Unit 7). Within the New Bay area, they crop out in two distinct structural basins; one centred around New Bay and the other located in the Bay of Exploits. Whereas the Point Leamington Greywacke is the major constituent of both basins, the Goldson Conglomerate appears to be more extensive in the New Bay basin.

In both the New Bay and Bay of Exploits areas, the Point Leamington Greywacke consists of two subunits (O'Brien, 1990), present in variable proportions in various parts of the basins. The most widespread and volumetrically significant subunit consists of interbedded grey shale and light grey, quartzofeldspathic wacke. It occurs stratigraphically below and, in some parts of the basins, also stratigraphically above the other subunit, which is much more distinctive and faunally diagnostic. Dark-grey carbonaceous shale, light-grey quartzofeldspathic wacke, and olistostromal melange having a black shale matrix comprise the second subunit.

Although there appears to be several, stratigraphically distinct bodies of Goldson Conglomerate, especially in the New Bay basin, each wedge-shape body contains interbedded grey pebbly wacke and graded, boulder to cobble, grey conglomerate (O'Brien, 1990). Mixed extrabasinal and intrabasinal detritus is present in thick polymictic conglomerate horizons. Variably sized, conspicuous clasts of coralline limestone have yielded Ashgillian conodonts (F.L.C. O'Brien, personal communication, 1990) that provide older age limits for the Goldson Conglomerate. In places, grey shale successions separating small tongues of Goldson Conglomerate contain graptolites and illustrate features indicative of turbiditic sedimentation.

Regionally, the Goldson Conglomerate conformably overlies the Point Leamington Greywacke–despite them being complexly interstatified in local parts of the basins. The stratigraphic top of the Goldson Conglomerate is, however, not exposed in the New Bay area. Williams (1962, 1972) placed the Goldson Conglomerate as the basal formation of the Botwood Group, and interpreted this group of Upper Ordovician and Silurian strata as being conformable with Units 5, 6 and 7. Kean *et al.* (1981) removed the Goldson Conglomerate from the Botwood Group but still considered the marine conglomeratic unit to lie stratigraphically beneath the Botwood Group.

BOTWOOD GROUP (UNIT 8)

In the New Bay area, Unit 8 represents a very small tract of Ashgill–Llandovery (W.D. Boyce and S.H. Williams, personal communications, 1990) volcano-sedimentary rocks, which are readily distinquishable from the nearby outcrop of the Ashgillian Point Leamington Greywacke. Accordingly, they are tentatively assigned to the Botwood Group. Several distinctive subunits are exposed on islands in the Bay of Exploits (Figure 1), however, their order of superposition has yet to be determined. Unit 8 includes: a subunit of limy shale, coticule-bearing argillite, calcareous sandstone, siliceous wacke and clastic limestone; a subunit of mafic lava, mafic sills and mafic breccia interbedded with feldspathic wacke and laminated calcareous argillite; and a subunit of polylithic conglomerate and olistostromal melange containing blocks of coralline limestone, green chert and mafic volcanic rocks (O'Brien, 1990).

Neither the stratigraphic base nor the stratigraphic top of Unit 8 is exposed in the New Bay area. The main tract of the Botwood Group, which is largely composed of undated alluvial and deltaic strata in the Lawrenceton and Wigwam formations, occurs much farther southeastward (Williams, 1962). Although shallow-marine Silurian strata (W.D. Boyce, personal communication, 1990) occur near the estuary of the Bay of Exploits and are included in the Botwood Group, they have unknown relations with the deep marine strata of Unit 8 or the terrestrial strata of the Lawrenceton and Wigwam formations. Regional overstep may have occurred during Botwood Group deposition (Williams, 1972) from a depocentre sited near the western part of the Bay of Exploits toward a starved arch located east of the bay.

STRUCTURE

The New Bay area lies within a regional oroclinal flexure in north-central Newfoundland defined, in part, by northeast- and northwest-trending segments of the Red Indian Line structural zone. Major structural features, which outline this oroflex, include a first-order mylonite zone and melange belt, and second-order folds and thrust faults that are themselves regionally extensive (Figure 1). Third-order transcurrent faults trend consistently northeastward across the oroflex.

FOLDS AND FAULTS

Regional bulk-strain patterns were established early during the development of first-generation folds and faults. Areas affected by small total-strain are typified by periclinal anticlinoria and synclinoria about which stratigraphic successions are continuously disposed. Major periclinal folds are located in regionally developed, structural domains characterized by either dominantly northwest- or dominantly northeast-trending, first-generation structures (Figure 1). For the most part, anticlinoria and synclinoria are generally open and gently plunging. Less commonly, areas of negligibly strained strata are also encountered in the hinge zones of steeply plunging, major folds. In such localities, first-generation minor folds, whose axes trend both northeast and northwest, mutually overprint each other.

Most of the major fault zones in the New Bay area formed as high-angle thrusts, which placed older rocks over younger rocks in most, although not all, locations (Figure 2). Approaching these thrusts, first-generation folds (1) become tighter as they concomitantly increase their pitch on axial surfaces, (2) develop a stronger sense of asymmetry (vergence) and (3) become overturned toward the general direction of hanging-wall transport. Although rocks in the hanging walls and footwalls behaved ductilely and show an increase in strain toward thrusts, the sharply defined fault planes are the sites of narrow zones of cataclasis.

In many locations, observable thrust planes dip subvertically. Where fault planes are mesoscopically folded in individual exposures, the steep dip of thrusts is most readily explained by the effect of subsequent deformation (e.g., Dean and Strong, 1977). However, regionally, dips of thrust faults and associated platey zones vary in accord with systematic differences in axial-surface inclinations of the major folds in the low-strain regions. As thrust-zone dips change from steep to gentle along strike, regional overfolds begin to predominate over regional upright folds, although the fold plunge generally remains shallow. Such changes are likely to be primary, as secondary structures are rare in the negligibly strained, simply folded regions. In Figure 1, barbs are drawn on what is deemed the upthrown sides of thrust faults based on regional variations in the vergence and plunge of first-generation folds.

In the New Bay area, first-generation folds and thrusts do not display a regionally dominant direction of axial-surface inclination or fault polarity, respectively. This is particularly evident around the periphery of regions of small bulk strain. Synfolding thrusts on the limbs of anticlinal periclines or domes generally dip inward, converging downward in the direction of the axial traces of regional anticlinoria (Figure 2). Similarly, synfolding thrusts on the limbs of synclinal periclines or basins generally dip outward, diverging downward in a direction away from the axial traces of regional synclinoria. This is consistent with the observation of relatively narrow tracts of inverted strata on periclinal flanks, adjacent to curviplanar thrusts and smaller scale, overturned folds. In the westernmost part of the Exploits Subzone, it appears that thrust-bounded lithostratigraphic assemblages were not transported in a preferred tectonic direction, either toward or away from the Salinic–Acadian hinterland located farther east. This feature, in addition to the lack of any evidence favouring sequential thrusting and back thrusting, supports the interpretation that first-generation structures are mutually interfering and belong to a conjugate system of folds and thrusts.

Whereas subsequent semi-brittle deformation is widespread and witnessed by dextral transcurrent faults and related megakinks of regional periclines and thrusts (Figure 1), ductile deformation postdating first-generation structures is focussed along basin-margin fault zones. In the New Bay area, northeast- and northwest-trending folds of thrust faults are present on various scales; most of those depicted on Figure 2 are shown in oblique section rather than in fold profile. As a regional generalization, where such folds are open to close and gently to moderately, doubly plunging, they commonly display sinistral vergence. However, where thrust planes and imbricate thrust sheets are tightly to isoclinally folded about variably, but generally steeply plunging secondary structures, they illustrate dextral vergence.

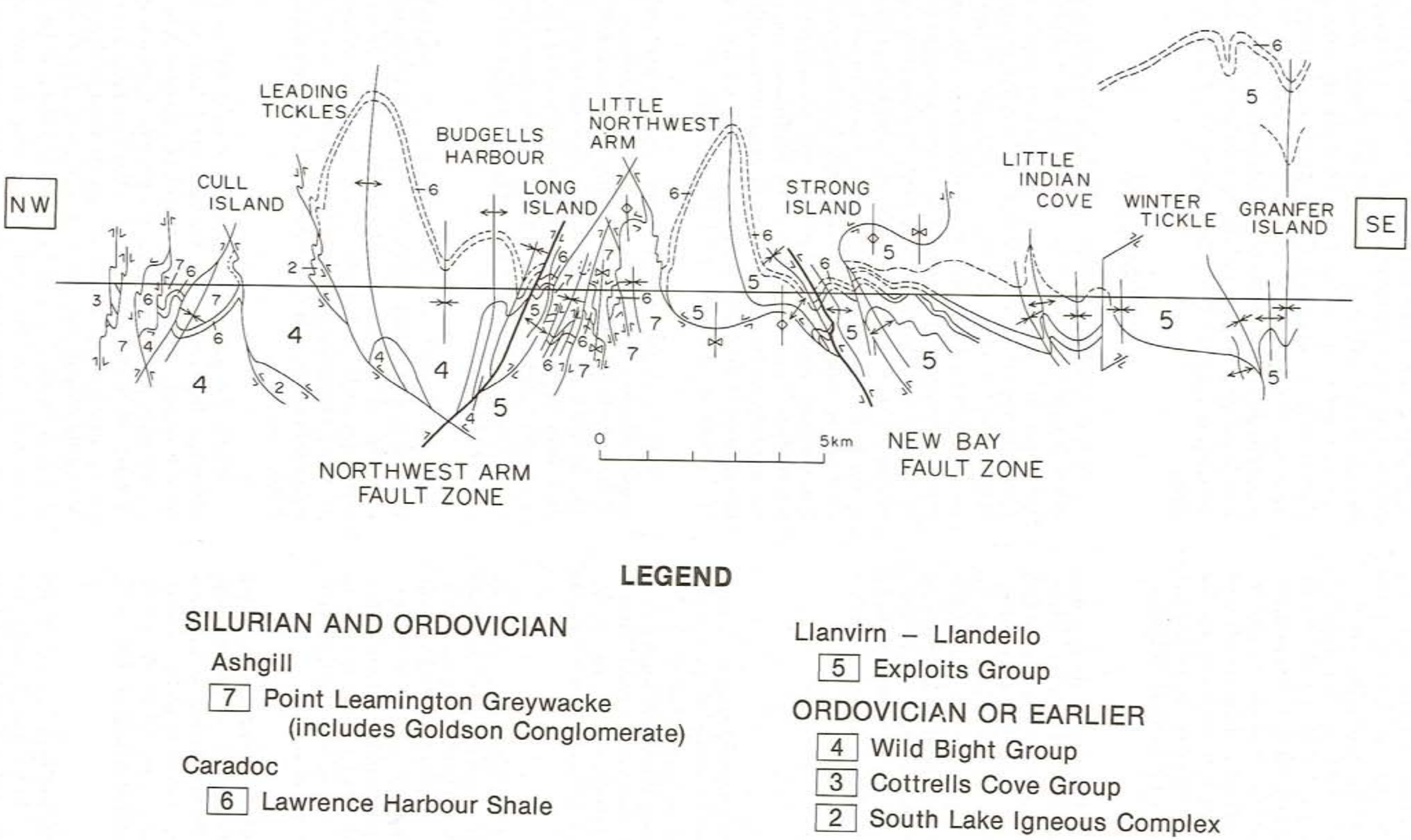


Figure 2. *Representative geological cross-section of the New Bay area. Form lines are coincident with the boundaries of formations and subunits comprising some of the major groups and units. Folds and faults are indicated by symbols. Second-generation folds distinguished from first-generation folds by open arrow heads. Line of section indicated on Figure 1.*

Second-generation folds commonly display an opposing sense-of-vergence (shear sense) than first-generation folds. Consequently, near one boundary of a thrust sheet, dextral folds overprint sinistral folds whereas, near its other boundary, sinistral folds overprint dextral folds. A complimentary observation is that second-generation structures typically face either downward or sideways on both margins of thrust sheets. It appears that, with progressive deformation, the surfaces of thrusts replaced the surfaces of beds as the principal planes of anisotropy. As a result, first-generation synclinoria bounded by conjugate divergent thrusts evolve into second-generation antiformal domes outlined by the early formed faults (Figure 2).

In areas of large total strain, folded thrust sheets outline vertically elongated, dome-and-basin shapes or 'doubly hooked- to eye-shaped' outcrop patterns. Because it is a fault plane rather than a stratigraphic boundary which is folded, such shapes and patterns are unlikely to have been produced by the interference of first- and second-generation folds. Alternatively, if they are sheath folds of thrusts, then the extension direction is presumably subvertical. This would imply that the secondary structures form in response to ductile dip-slip movements and localized shearing in the basin-margin fault zones.

FOLIATIONS

A widespread slaty cleavage defining regional cleavage arcs formed concomitantly with first-generation structures. This foliation developed in a very complex fashion independently from both associated folds and thrusts (e.g., Blewett and Pickering, 1988; Lafrance *et al.*, 1989). Variably spaced, crenulation cleavage is associated with the second-generation, curvilinear folds as well as the later megakinks and transcurrent faults.

Approaching the boundaries of thrust sheets well south or north of the Red Indian Line, a variably pervasive slaty cleavage intensifies and lies parallel to bedding and thrusts in platey zones, which are up to 50 m thick. Highly attenuated, sedimentary and volcanic rocks in these platey zones are reddened in places, presumably as a result of iron oxidization. Laterally discontinuous layers of mylonite and cataclasite, from a centimetre to a decimetre in thickness, occur concordantly within the platey zones.

Most of the bifurcating thrusts in the Exploits and Notre Dame subzones coalesce in the tightly braided mylonite zone marking the Red Indian Line (Figure 1). Over its 2 to 3 km width, the majority of rocks are platey or mylonitic. However, imbricated with these rocks, are relatively small, discontinuous sheets of scaly foliated melange (Cowan, 1985; Moore *et al.*, 1986).

Characteristic features of these melange belts are: (1) that the constituent, unstratified, block-in-matrix rocks are progressively deformed and restricted to the Red Indian Line structural zone, (2) that many of the inclusions or blocks can be identified in unbroken formations or nondisrupted sequences in the Cottrells Cove and Exploits groups, (3) that rocks of known Ashgill and Llandovery age, although present as clasts in olistostromes of demonstrable sedimentary origin, are not observed to pass gradationally into scaly foliated, chaotic melange, (4) that the dark scaly clays in the matrix were produced by brittle or cataclastic deformation, which either predated or accompanied regional ductile deformation, and (5) that melange units are deformed by thrusts, folds and crenulation cleavages that affect Ashgill and Llandovery strata.

MAGMATISM

Most if not all of the plutonic rocks in the New Bay area can be regarded as minor intrusions that range as widely in age as they do in areal extent. Since very few are regionally mappable, they are not shown in Figures 1 or 2. The greatest compositional variety and largest abundance of minor intrusions occur in Early Ordovician or older rocks. Although mafic dykes and sills of synvolcanic and/or syndiagenetic origin occur in the Exploits, Wild Bight, Cottrells Cove and Moretons Harbour groups, they are not numerous and do not appear to have any regional pattern of distribution. In contrast, most plutonic and associated hypabyssal rocks in the New Bay area were emplaced during or after episodes of regional deformation. Suites of undated, minor intrusions are most commonly located within regional anticlinoria or near major thrust faults, both of which are situated along the margins of structural or sedimentological basins (Figure 2).

In the New Bay area, the only dated plutonic and hypabyssal rocks are Mesozoic in age and comprise a part of the Budgells Harbour Gabbro (Strong and Harris, 1974). The undated Long Island Granodiorite, which crops out near the eastern margin of the map area, appears to truncate most of the structures in the Red Indian Line structural zone and is interpreted to thermally metamorphose strata that are as young as Llandovery in age.

Earlier plutonic and hypabyssal rocks include multiple sheets of gabbro, diorite and diabase as well as composite intrusions of quartz–feldpsar porphyry and diabase. Commonly folded and locally foliated, they occur in both the Notre Dame and Exploits subzones and are the most widespread minor intrusions in the New Bay area (O'Brien, 1990).

Where the gabbro–diorite sheets exceed 100 m in thickness, they commonly produce spotted hornfels in adjacent country rocks. In some localities, these hornfelses contain biotite porphyroblasts that overprint the regional slaty cleavage. In the dyke swarm of the New Bay Fault Zone, gabbro–diorite sheets posttectonically intrude older suites of variably mylonitized, mafic intrusions hosted by highly deformed, Caradocian slate. In one of the imbricate thrust sheets of the New Bay Fault Zone, mafic sills yielding geopetal evidence from graded cumulate bands were overfolded and inverted prior to being re-injected by diabase.

The strongest evidence for syntectonic intrusion of this regional swarm of gabbro–diorite sheets comes from their dynamic relationships to mesoscopic and map-scale, folds and faults. In some areas, first-generation folds defined by bedding or regional stratigraphy are also outlined by gabbro–diorite sills. In other localities, gabbro–diorite dykes crosscut strata-defined or older sill-defined, tectonic folds. However, these same dykes are also observed to outline variably plunging, first-generation folds, which are overprinted or transected by regional slaty cleavage. Such intrusion-defined folds commonly have a larger wavelength and amplitude than those defined by bedding. Emplaced parallel, perpendicular and tangential to foliations, fold-axial surfaces or thrust faults, these minor intrusions display characteristic T- and Y-shaped abuttments as well as mutually crosscutting margins.

Notable features of the gabbro–diorite sheets are the thickness variations they display and the positions they occupy in regional scale structures (O'Brien, 1990). Relatively thick, large and solitary intrusions are located in the crestal regions of gently plunging, W- and M-shaped, chevron folds typified by small bulk strains. Relatively thin, small and discontinuous intrusions occur on the limbs of steeply plunging, isoclinal folds or the hanging walls of high-angle thrust faults, both characterized by large bulk strains. Apparently, this distribution is not caused by variations in the degree of tectonic attenuation of the minor intrusions. Rather, regional bulk-strain patterns were already largely in existance prior to magma emplacement and were important parameters in establishing the selective modes of dilatation discussed above. Such processes were also operative, at a later date, when a dyke suite of intermediate composition, developed in equal proportions in early and Late Ordovician basins, was intruded parallel to and preferentially along east-northeast-trending transcurrent faults.

In summary, syntectonic intrusive suites were preferentially emplaced into major ductile fault zones near dilatant structures such as thrust-bounded anticlines or transcurrent faults. In places, they may have utilized the same conduits as the synvolcanic dykes that feed the dominantly volcanic parts of the pre-Caradocian successions.

MINERALIZATION

Disseminated and vein-hosted chalcopyrite mineralization occurs locally within variably pyritized and silicified units of mafic volcanic rocks in the Exploits, Wild Bight and Cottrells Cove groups. In many locations, where the alteration process has completely replaced the original mineralogy of the mafic lava, pseudomorphs of negligiably strained pillows are preserved. Relatively thin, discontinuous units of felsic pyroclastic rocks are commonly associated with the mineralized pillow lava units, although the former are generally much less altered. Elsewhere, at unambiguous stratigraphic contacts, these pillow lava units directly underlie the felsic volcanic rocks. Regionally, the alteration zones follow the folded boundary between the mafic and felsic units suggesting that the mineralization is essentially in the form of stratabound stockworks.

In several localities in the New Bay area, gabbro–diorite sheet intrusions host vein arrays with bilateral, pyrite- and iron carbonate-rich, alteration zones. The adjacent hornfelses of the Exploits and Botwood groups are locally altered, especially where ductility contrasts between country rock and minor intrusion are insignificant. In some intrusive bodies, carbonate alteration increases concomitantly with foliation development. Periods of deformation and alteration are bracketed by various phases of these multiple syntectonic intrusions. Fault zones that yield evidence of a protracted history of mafic intrusion followed by leucogranite or quartz feldspar porphyry are particularly good targets for gold exploration, especially in the Exploits Subzone.

DISCUSSION AND CONCLUSIONS

Submarine mafic lavas, with or without contemporaneous felsic volcanic rocks or thin limestones, are present at several stratigraphic intervals in Early Ordovician and Early Silurian rock groups, but are conspicuously absent from marine units of intermediate age. The lack of Late Ordovician deep-sea volcanism, the increasing carbonate content of Ashgillian strata, and the rise of Caradocian sea level throughout the Exploits Subzone presumably signify a major shift in the paleotectonic and/or paleolatitudinal setting of Early Silurian volcanic islands or seamounts relative to those of Early Ordovician or older age (e.g., van der Pluijm and van Staal, 1988; van der Pluijm *et al.*, 1990). At some time after the cessation of Taconian (mid-Caradoc) obduction along the western margin of the Notre Dame Subzone, there seems to have been significant paleogeographic reconstruction of at least some of the Early Ordovician oceanic basins in the Dunnage Zone (e.g., Neuman, 1984; van Staal *et al.*, 1990). Early Silurian volcanism and sedimentation in remnant oceanic basins of the Dunnage Zone was contemporaneous with this shift in tectonic regime, which caused the bulk of orogen-derived sediment to accumulate east, rather than west, of the sutured Taconian magmatic arc (e.g., Nelson and Casey, 1979; Bourque, 1989).

Discrete unconformity-bounded sequences of Ordovician or Silurian strata are absent in the New Bay area. This, together with the lack of evidence of demonstrable, pre-Llandovery, regional deformation of the basin-fills, suggests that tectonic and/or thermal subsidence were not triggered by the partial closure and sequential inversion of Ordovician and Silurian basins. Nevertheless, a critical feature of the New Bay area is that the depocentres of Early Ordovician, Late Ordovician and Early Silurian basins are not regionally coincident. Although the regional cause of the shift of depocentres is unknown, this phenomenon seemingly indicates that subsidence and deposition were episodic and unsteady rather than being continuous and site-specific. It may be that the relative disposition of depocentres was controlled by the variable location of a broad regional syndepositional bulge (e.g., the outer arc of a piggyback basin) and its consequential effect on the lateral migration of Ordovician and Silurian basins.

The Late Ordovician basin near New Bay appears to have been sited on an arch that was starved of Early Ordovician deposits (Figure 2). Early Silurian volcano-sedimentary rocks are interpretated to have originally covered only the eastern extremity of the New Bay area. A deep marine basin of Ashgill–Llandovery age, unlinked to the Late Ordovician basin in New Bay, is thought to have developed along the southeastern flank of a probable Late Ordovician arch located in the western part of the Bay of Exploits.

In several locations in the New Bay area, slump-folded wacke and iron-rich chert of probable Early Ordovician age display complex stratigraphic relationships with submarine volcanic rocks, which locally host cupriferous stockworks and silicic alteration zones. Pre-Caradocian units in the sedimentary-dominated and volcanic-dominated belts intertongue along and across strike in the vicinity of some of the major fault zones. There, such units are seen to be affected by abrupt facies changes, thickness variations and periodic emergence above carbonate compensation depths.

Certain parts of the New Bay area are possibly underlain by a condensed Llanvirn–Llandeillo succession. These areas may have been starved of the sedimentary and volcanic deposits that accumulated by relatively accelerated modes of deposition in adjacent parts of the region. In the lower parts of the Exploits and Cottrells Cove groups, thick sequences of pillow lava are capped by thin discontinuous horizons of felsic tuff and associated chert, which pass laterally into proximal, feldspathic and lithic wacke. The positions of the felsic pyroclastic domes in these volcanic belts relative to the volcanogenic wacke and plutonic boulder conglomerate of the adjoining sedimentary belts may have important implications for the regional setting of base-metal mineralization in the area. The regional horizontal and vertical distribution of members of the Exploits Group, taken together with the variable offset of its subunits relative to that of the overlying Lawrence Harbour Shale, possibly indicates the presence of an Early Ordovician fault scarp within the New Bay Fault Zone (Figure 2).

Cyclical, localized uplift may have occurred near tectonic hinge lines situated along basin margins, themselves isostatically controlled by synsedimentary and synvolcanic faults. Pre-Caradocian fault zones antedate late Taconic uplift (*sensu* Nelson, 1981) but they may herald the Late Ordovician–Early Silurian shift in tectonic regime. As ancestral faults, they may have been reactivated during the formation of Ashgillian debris flows and arc-derived conglomeratic flysch. Subsequently, tectonic structures and magmas of post-Llandovery age appear to have been focussed along these basin-margin faults.

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