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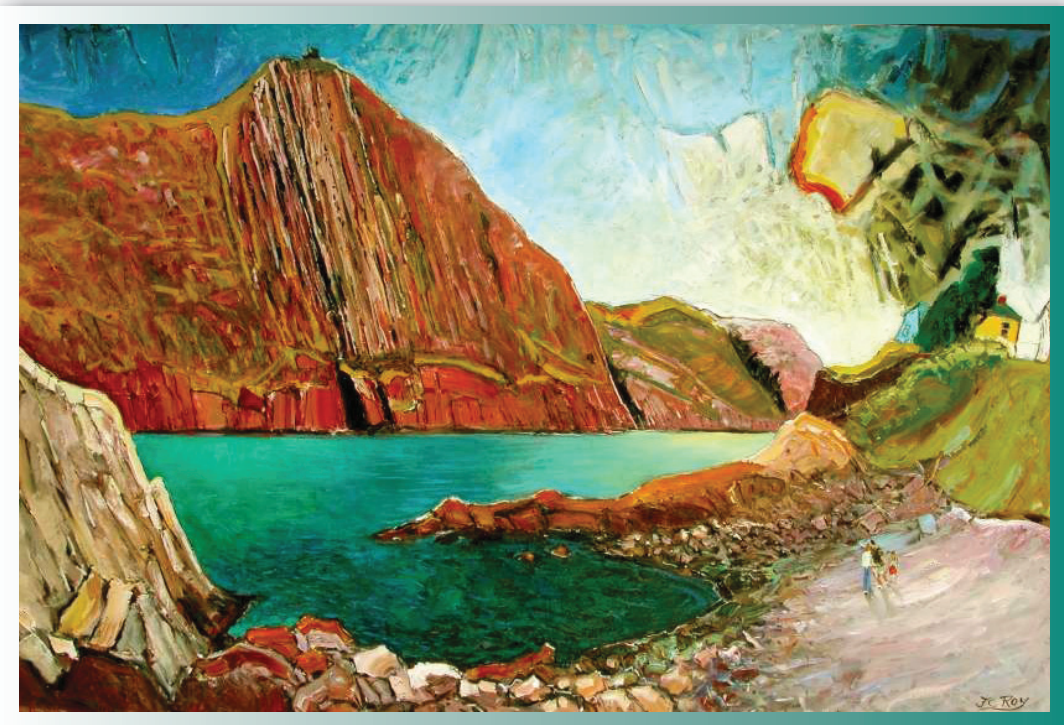

Jean Claude Roy, *Signal Hill from Fort Amherst*, oil on canvas / huile sur toile, 48" x 72", 2006

FIELD TRIP GUIDEBOOK - B2

PERI-GONDWANAN, ARC-BACK ARC COMPLEX AND BADGER RETROARC FORELAND BASIN: DEVELOPMENT OF THE EXPLOITS OROCLINE OF CENTRAL NEWFOUNDLAND

Leader: Brian H. O'Brien

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FIELD TRIP GUIDEBOOK – B2

PERI-GONDWANAN ARC-BACK ARC COMPLEX AND BADGER RETROARC FORELAND BASIN: DEVELOPMENT OF THE EXPLOITS OROCLINE OF CENTRAL NEWFOUNDLAND

FIELD TRIP LEADER

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SAFETY INFORMATION

General Information

The Geological Association of Canada (GAC) recognizes that its field trips may involve hazards to the leaders and participants. It is the policy of the Geological Association of Canada to provide for the safety of participants during field trips, and to take every precaution, reasonable in the circumstances, to ensure that field trips are run with due regard for the safety of leaders and participants. GAC recommends steel-toed safety boots when working around road cuts, cliffs, or other locations where there is a potential hazard from falling objects. GAC will not supply safety boots to participants. Some field trip stops require sturdy hiking boots for safety. Field trip leaders are responsible for identifying any such stops, making participants aware well in advance that such footwear is required for the stop, and ensuring that participants do not go into areas for which their footwear is inadequate for safety. Field trip leaders should notify participants if some stops will require waterproof footwear.

The weather in Newfoundland in May is unpredictable, and participants should be prepared for a wide range of temperatures and conditions. Always take suitable clothing. A rain suit, sweater, and sturdy footwear are essential at almost any time of the year. Gloves and a warm hat could prove invaluable if it is cold and wet, and a sunhat and sunscreen might be just as essential. It is not impossible for all such clothing items to be needed on the same day.

Above all, field trip participants are responsible for acting in a manner that is safe for themselves and their co-participants. This responsibility includes using personal protective equipment (PPE) when necessary (when recommended by the field trip leader or upon personal identification of a hazard requiring PPE use). It also includes informing the field trip leaders of any matters of which they have knowledge that may affect their health and safety or that of co-participants. Field Trip participants should pay close attention to instructions from the trip leaders and GAC representatives at all field trip stops. Specific dangers and precautions will be reiterated at individual localities.

Specific Hazards

Some of the stops on this field trip are in coastal localities. Access to the coastal sections may require short hikes, in some cases over rough, stony or wet terrain. Participants should be in good physical condition and accustomed to exercise. The coastal sections contain saltwater pools, seaweed, mud and other wet areas; in some cases it may be necessary to cross brooks or rivers. There is a strong possibility that participants will get their feet wet, and we recommend waterproof footwear. We also recommend footwear that provides sturdy ankle support, as localities may also involve traversing across beach boulders or uneven rock surfaces. On some of the coastal sections that have boulders or weed-covered sections, participants may find a hiking stick a useful aid in walking safely.

Coastal localities present some specific hazards, and participants MUST behave appropriately for the safety of all. High sea cliffs are extremely dangerous, and falls at such localities would almost certainly be fatal. Participants must stay clear of the cliff edges at all times, stay with the field trip group, and follow instructions from leaders. Coastal sections elsewhere may lie below cliff faces, and participants must be aware of the constant danger from falling debris. Please stay away from any overhanging cliffs or steep faces, and do not hammer any locations immediately beneath the cliffs. In all coastal localities, participants must keep a safe distance from the ocean, and be aware of the magnitude and reach of ocean waves. Participants should be aware that unusually large "freak" waves present a very real hazard in some areas. If you are swept off the rocks into the ocean, your chances of survival are negligible. If possible, stay on dry sections of outcrops that lack any seaweed or algal deposits, and stay well back from the open water. Remember that wave-washed surfaces may be slippery and treacherous, and avoid any area where there is even a slight possibility of falling into the water. If it is necessary to ascend from the shoreline, avoid unconsolidated material, and be aware that other participants may be below you. Take care descending to the shoreline from above.

Other field trip stops are located on or adjacent to roads. At these stops, participants should make sure that they stay off the roads, and pay careful attention to traffic, which may be distracted by the field trip group. Participants should be extremely cautious in crossing roads, and ensure that they are visible to any drivers. Roadcut outcrops present hazards from loose material, and they should be treated with the same caution as coastal cliffs; be extremely careful and avoid hammering beneath any overhanging surfaces.

The hammering of rock outcrops, which is in most cases completely unnecessary, represents a significant "flying debris" hazard to the perpetrator and other participants. For this reason, we ask that outcrops not be assaulted in this way; if you have a genuine reason to collect a sample, inform the leaders, and then make sure that you do so safely and with concern for others. Many locations on trips contain outcrops that have unusual features, and these should be preserved for future visitors. Frankly, our preference is that you leave hammers at home or in the field trip vans.

Subsequent sections of this guidebook contain the stop descriptions and outcrop information for the field trip. In addition to the general precautions and hazards noted above, the introductions for specific localities make note of specific safety concerns such as traffic, water, cliffs or loose ground. Field trip participants must read these cautions carefully and take appropriate precautions for their own safety and the safety of others.

FIELD TRIP OBJECTIVES

The main aim of this field trip to north-central Notre Dame Bay is to investigate the Ordovician evolution of the Iapetan island arc and back arc rocks located within the type area of the Exploits Subzone of the Dunnage Zone. The approach will be to highlight the main depositional and magmatic events recorded in the Early and Middle Ordovician parts of the Exploits Group, the eastern Wild Bight Group and contemporaneous igneous complexes (Figure 1). The field stops are arranged in an effort to track the pretectonic geological history of the Early Ordovician volcanic and plutonic rocks that comprise the oldest peri-Gondwanan ensimatic arc and to demonstrate their tectonostratigraphic linkage to a younger Middle Ordovician arc and a Late Ordovician overstep sequence.

Participants will also have an opportunity to study some of the Middle Ordovician strata outcropping within the Red Indian Line mélange belt at the margin of the peri-Laurentian Notre Dame Subzone and to compare or contrast them with coeval rocks in the peri-Gondwanan extensional arc and back arc sequence. The various stratigraphical and structural relationships that Late Ordovician strata display with the above-mentioned rocks will be examined immediately south of the Red Indian Line near the margins of a mudstone-rich basin in the olistostrome-bearing Badger Group.

In the field trip area, the Notre Dame Bay oroclinal flexure is outlined by greenschist facies stratified rocks that illustrate evidence of inhomogeneous regional ductile deformation. As the oroflex evolved, the early formed tectonites were locally overprinted by secondary transpressional structures as regional metamorphism continued. The presumed Silurian structural history will be addressed, in part, by examining the development of folds, foliations and oblique faults in (a) the southern margin of the Red Indian Line mylonite zone and (b) an arcuate slate belt that controls disposition of the rocks of the Exploits Subzone and its overstep sequence in this part of central Notre Dame Bay.

SUMMARY OF FIELD TRIP STOPS

For all stops on this field trip (Figure 2), the guidebook systematically lists 1) geographic access, 2) large-scale stratigraphical and structural position, 3) pertinent features in the exposure examined, and 4) regional tectonic significance. Cumulative distances (shown in brackets on the road log) are measured along Route 350 and Route 352 and do not include inter-stop distances driven along side roads or traveled on foot to shoreline exposures.

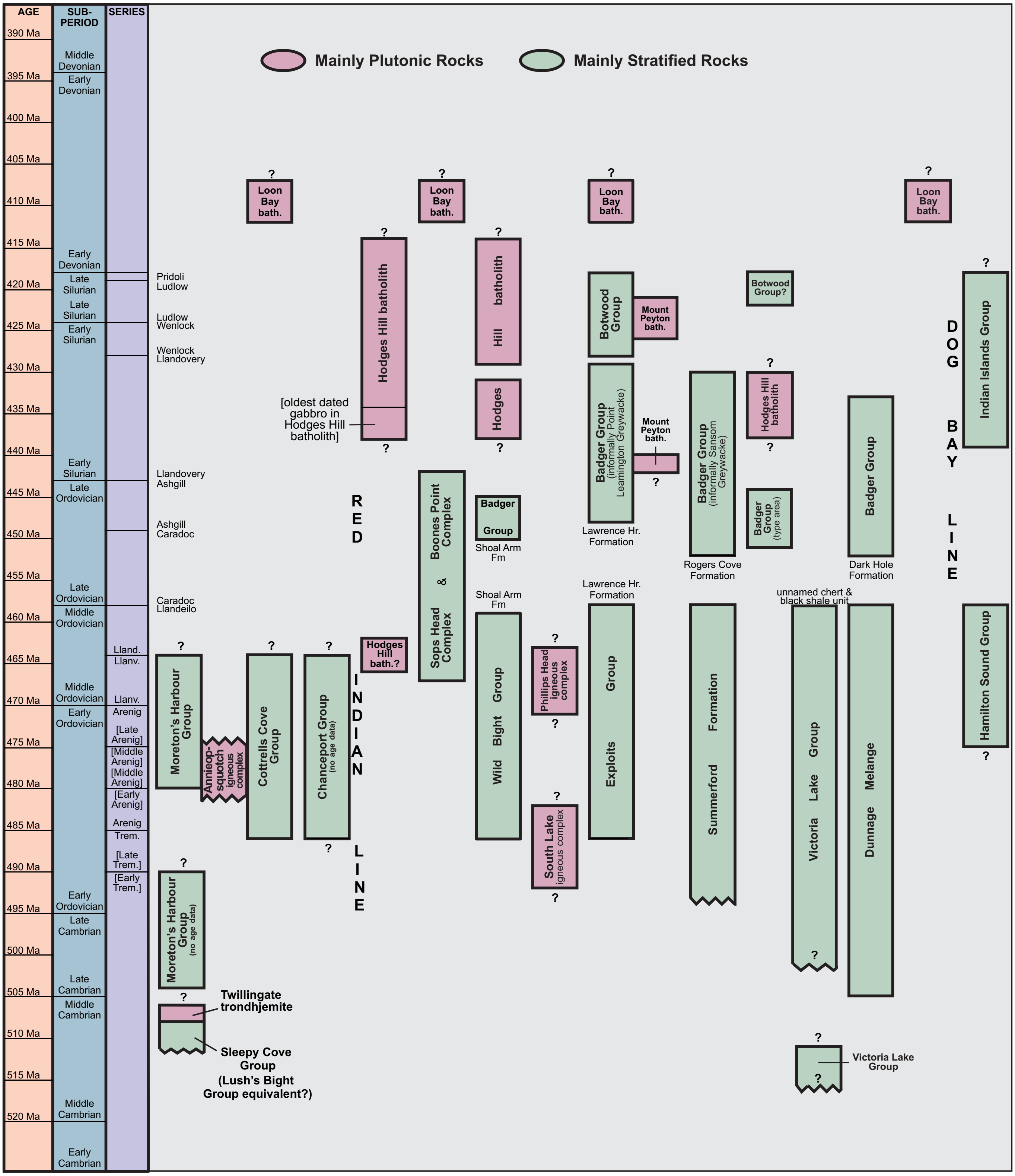


Figure 1. *Generalized Table of Formations highlighting the major stratified rock units and the major plutonic rock units in northeastern Newfoundland between, and adjacent to, the Red Indian Line and the Dog Bay Line. Note that the names and absolute ages of time units are not those currently used by the International Commission on Stratigraphy.*

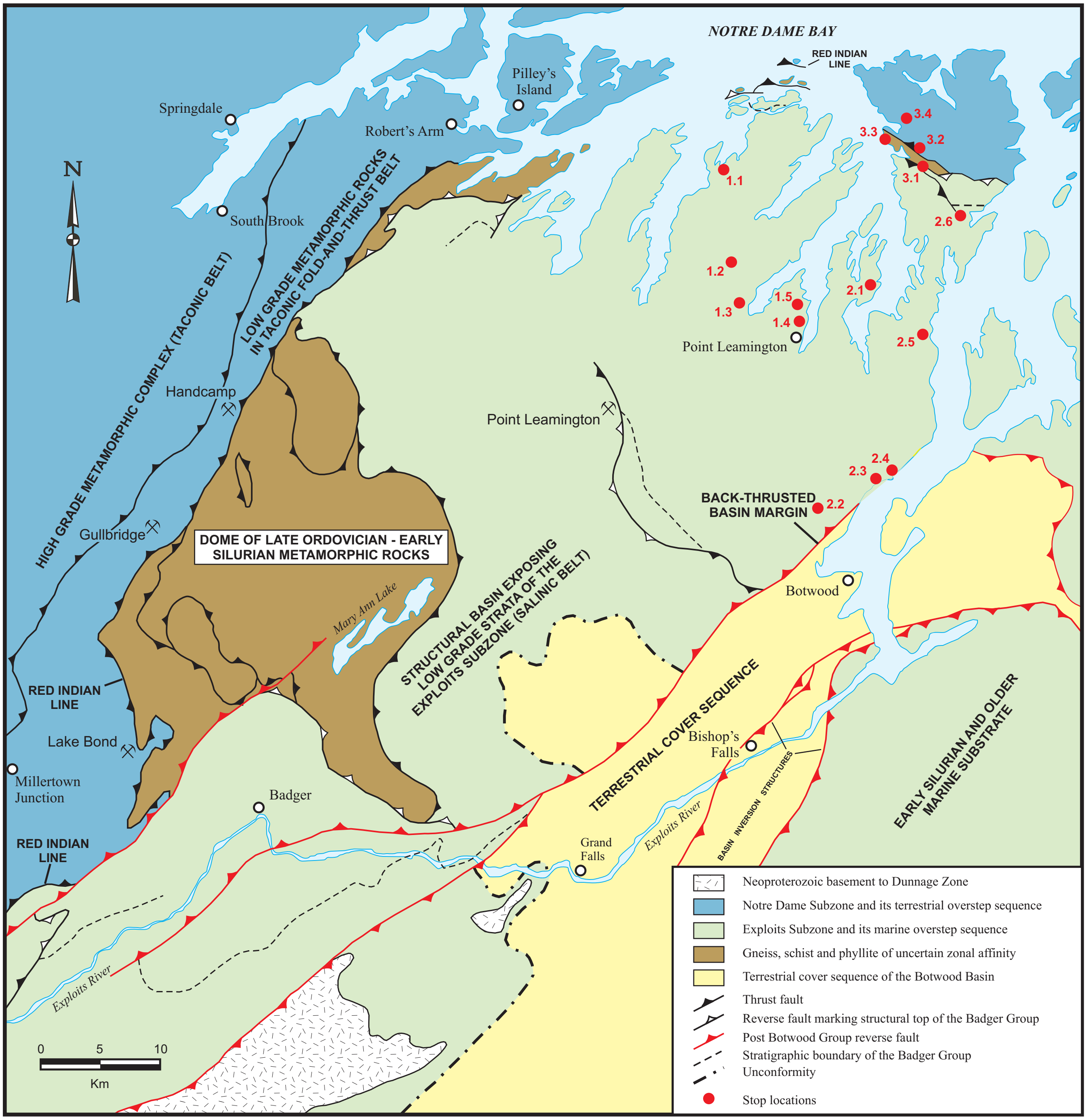


Figure 2. *Simplified tectonic map of the lower Exploits River–central Notre Dame Bay region near the Red Indian Line suture illustrating the main structural elements of the peri-Gondwanan Exploits Subzone and peri-Laurentian Notre Dame Subzone of the Dunnage Zone. Parts of a representative terrestrial cover sequence and a Late Neoproterozoic basement inlier are illustrated within the peri-Gondwanan realm. The regional setting and general location of the field trip stops are also shown.*

On the afternoon of Day 1 of the field trip, Early Ordovician igneous rocks from the Exploits Subzone of the Dunnage Zone and Late Ordovician sedimentary rocks from the Badger Group overstep sequence are to be examined (Stops 1.1 to 1.5). Participants will observe early Tremadocian volcanic rocks of the lower Wild Bight Group, early Tremadocian plutonic rocks (post-ophiolite) of the South Lake Igneous Complex, early Katian (Pusgillian) wacke and conglomerate of the lower Point Leamington Formation, and late Katian (Cautleyan–Rawtheyan) siltstone and debrite of the upper Point Leamington Formation.

On Day 2 of the excursion, the field party has a full day to investigate critical geological relationships within most formations of the Lower–Middle Ordovician Exploits Group (Stops 2.1 and Stops 2.3 to 2.6). Stops are located in the Tremadocian and/or younger rocks of the Tea Arm Formation (remnant oceanic island arc) and Saunders Cove Formation (jasperite-bearing graben), the Dapingian–Darriwilian New Bay Formation (extensional arc rift basin), and the early to late Darriwilian Lawrence Head Formation and the Strong Island Chert (deep marine back arc basin). The anoxic black shale-bearing strata in the transgressive overstep sequence of the Late Ordovician Shoal Arm Formation will also be examined (Stop 2.2).

On a journey to the northern part of the Fortune Harbour peninsula on the morning of Day 3 of the field trip, the focus will be mostly on Middle Ordovician volcanic and sedimentary strata (Stops 3.1 to 3.4), in particular those that locally comprise the southern margin of the Notre Dame Subzone of the Dunnage Zone. Participants will observe rocks in the southern part of the peri-Laurentian Cottrells Cove Group (Red Indian Line imbricate thrust and fold belt) and the Boones Point Complex (Red Indian Line mélange belt).

INTRODUCTION TO THE TECTONICS OF CENTRAL NEWFOUNDLAND AND THE GEOLOGY OF THE FIELD TRIP AREA

Newfoundland's Central Mobile Belt belongs to the Axial Realm of the Appalachian mountain belt in Canada and the United States of America (Hibbard *et al.*, 2006). Although it contains Late Neoproterozoic and Early Cambrian passive continental margin deposits together with minor Grenvillian and peri-Gondwanan basement inliers, the Central Mobile Belt is mainly characterized by Iapetan arc complexes and ophiolite suites of early Paleozoic age (van Staal *et al.*, 1998; O'Brien, 2010). These are succeeded by several discrete, variably tectonized, marine to terrestrial overstep sequences made up of mid Paleozoic synorogenic strata (Williams, 1995; van Staal *et al.*, 2011; Figure 1).

In the Newfoundland Appalachians, Paleozoic rocks considered to have formed in the Iapetus Ocean are mostly Middle Ordovician and older in age. The peri-Gondwanan Iapetan rocks display a Celtic faunal provinciality (*e.g.*, Neuman, 1984) and have been assigned to the Exploits Subzone of the Dunnage Zone (Williams *et al.*, 1988). Farther west, the tectonically adjacent peri-Laurentian Iapetan rocks of the Notre Dame Subzone of the Dunnage Zone display a Scoto-Appalachian or a Toquima-Table Head fauna (*e.g.*, Nowlan and Thurlow, 1984). The 350 km long Red Indian Line is a tectonic boundary marking the suture zone of Dunnage Zone rocks that had paleogeographic origins on opposite sides of the Iapetus Ocean. In north-central Newfoundland, the suture is manifested by a westward-dipping arcuate thrust zone that initially placed the peri-Laurentian rocks structurally above the peri-Gondwanan rocks (Figure 3) and interleaved them with various tracts of olistostromal and tectonic mélange (Figure 4).

Tectonic History of peri-Gondwanan Rocks in the Central Mobile Belt. The peri-Gondwanan ribboned microcontinent that has been argued to comprise the basement to Appalachian Ganderia (van Staal *et al.*, 1996; Hibbard *et al.*, 2006) has an early Paleozoic evolution governed by its paleogeographic position near the southern convergent margin of the Iapetus Ocean (O'Brien *et al.*, 1996; Figure 5). However, it also preserves a Precambrian geological history similar to that seen in easterly adjacent West Avalonian juvenile crust (O'Brien *et al.*, *ibid*) and other convergent margin terranes situated along the Neoproterozoic proto-Gondwanan margin of the Rodinian supercontinent (Nance *et al.*, 2008a). In south-central Newfoundland, the earliest pre-Appalachian phase of orogenesis began with basement orthogneiss formation in the Cryogenean (*ca.* 686 Ma), continued with deposition of a volcanosedimentary cover sequence in the Ediacaran (*ca.* 585-565 Ma) and culminated with emplacement of an arc-related suite of Avalonian stitching plutons (*ca.* 575-560 Ma). Ediacaran remobilization of Cryogenean crystalline basement was coeval with intrusion of the youngest of these plutonic rocks; however, it is the earliest Cambrian tectonism (*ca.* 540-535 Ma) of the linked basement-cover complexes that is characteristic of the pre-Iapetan rocks included in Newfoundland's Ganderia (for summary, *see* Valverde-Vaquero *et al.*, 2006a).

Passive continental margin deposition of a thick quartz-rich turbidite prism is one of the hallmarks of the peri-Gondwanan Gander Zone, a tectonostratigraphic entity located in the southeasternmost part of the Central Mobile Belt (Williams *et al.*, 1988). Accumulation is postulated to have begun after *ca.* 535 Ma in the Early Cambrian and may have persisted in places until the latest Early Ordovician (early Arenigian; *see* Colman-Sadd *et al.*, 1992).

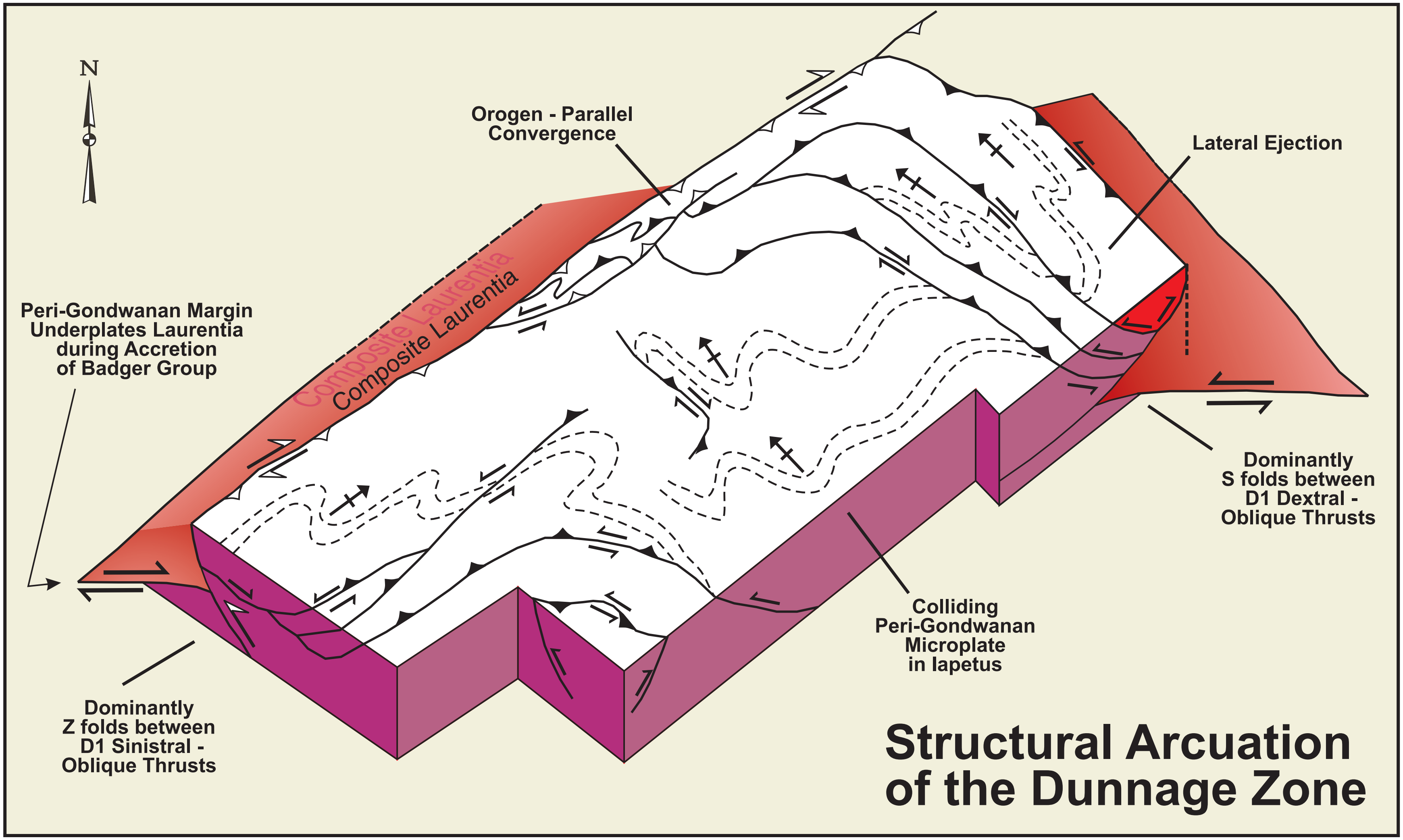


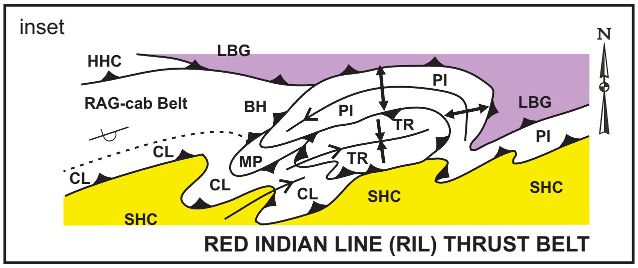
Figure 3. *Model to explain the structural arcuation of the Newfoundland Dunnage Zone in the Mid Paleozoic. During the orogenic accretion and regional metamorphism of the Late Ordovician–Early Silurian Badger Group, composite Laurentia was underplated by a peri-Gondwanan microplate. Subsequent tectonic wedging was antivergent and resulted in the overthrusting of the peri-Gondwanan rocks along with their terrestrial cover. This was facilitated by a switch from sinistral to dextral movement during orogen-parallel convergence.*

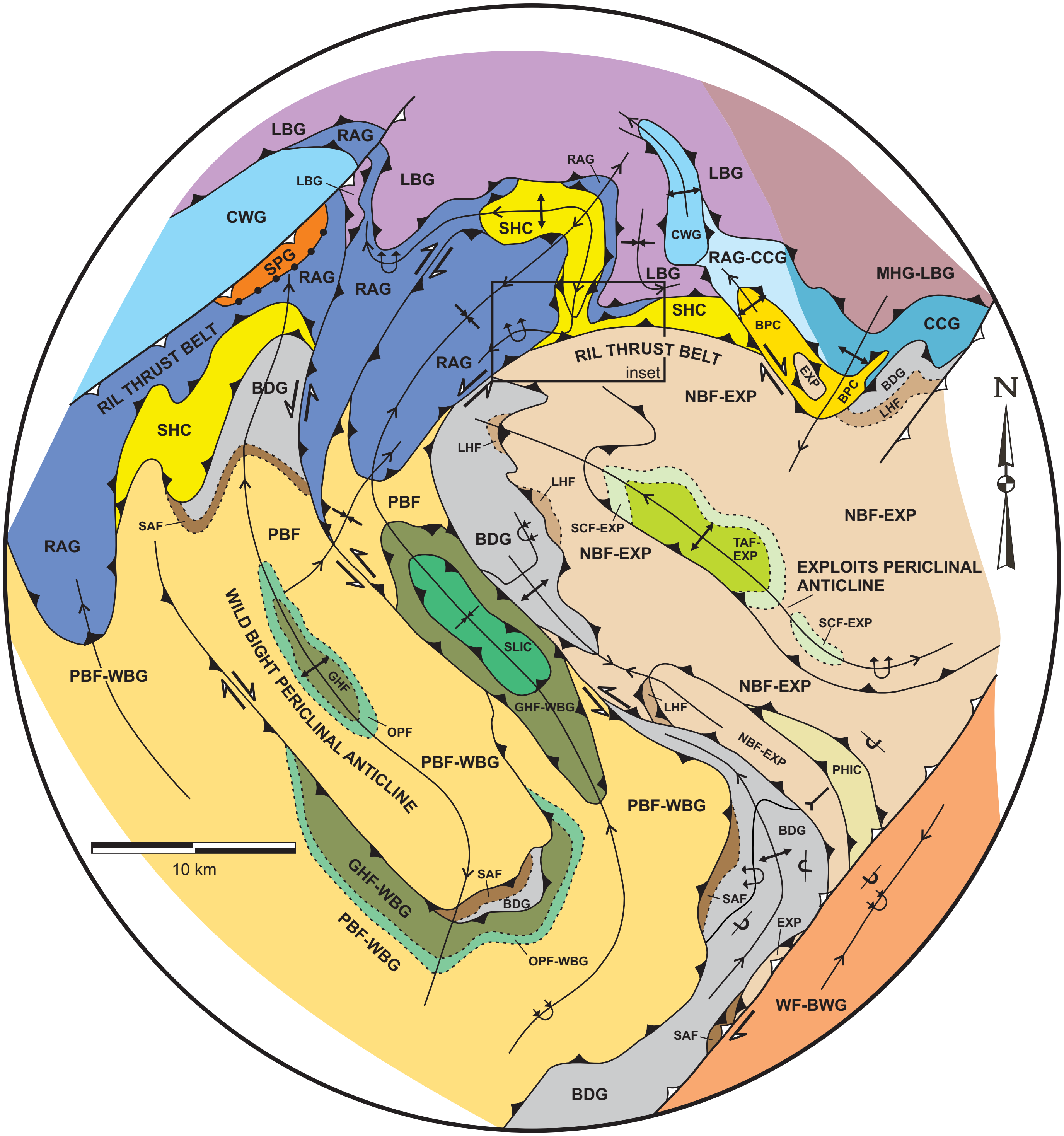
In contrast, the oldest convergent margin subduction-related volcanic strata preserved within the Gondwanan realm of Iapetus are mineralized Middle and Late Cambrian ensialic arc sequences (*ca.* 514-496 Ma; Evans and Kean, 2002; McNicoll *et al.*, 2010). The oldest Cambrian arc rocks (Unit 3t in Figure 5), which have zircons probably inherited from subjacent Ediacaran intrusions (Rogers *et al.*, 2006; McNicoll *et al.*, 2010), are herein interpreted to have accumulated above an uplift of Cryogenean basement (without any substantial thickness of overlying Cambro-Ordovician quartz-rich turbidites) on the open ocean-facing margin of the peri-Gondwanan microcontinent.

The northern portion of the peri-Gondwanan Iapetan realm was dominated by pillowed basalt that had erupted in intraplate seamounts or formed oceanic arcs during Late Cambrian and Early Ordovician times (*e.g.*, Jacobi and Wasowski, 1985; Swinden *et al.*, 1990). Although the depositional substrate of the oldest pillowed basalts in the Exploits, Wild Bight and Summerford groups is not directly observable in an unbroken succession, it is assumed to be a Cambrian coticule-rich pyritic mudstone of abyssal plain origin similar to those observed in the Dunnage Melange (Figure 5 Legend). The ensimatic arcs became dormant however and many of arc sequences were rifted in the late Early Ordovician (*ca.* 475 Ma; Floian; early-mid Arenigian).

In contrast, in the vicinity of the pre-Appalachian basement inliers of south-central Newfoundland (Figure 5), the Cambrian rocks of the peri-Gondwanan Iapetan realm were succeeded by more ensialic volcanic arc rocks as marine volcanism continued throughout the latest Cambrian and earliest Ordovician (for summary, *see* Zagorevski *et al.*, 2010). Consequently, such arc sequences have a significant component of mineralized felsic pyroclastic rocks and subvolcanic quartz-feldspar porphyry relative to the partly coeval intraoceanic arcs located farther north. The younger parts of this southern Exploits Subzone continental arc complex (Furongian–Tremadocian; 491-486 Ma; Zagorevski *et al.*, 2007; Hinchey and McNicoll, 2009), the primitive arc complex in the north of the Exploits Subzone (*ca.* 490-483 Ma; O'Brien *et al.*, 1997; MacLachlan *et al.*, 2001) and the easterly adjacent passive Ganderian margin were all locally drowned and initially buried by dark grey shale in the Early Ordovician (Tremadocian to Floian).

Generation of peri-Gondwanan Ophiolite. The oldest suprasubduction zone ophiolites on the peri-Gondwanan Iapetan margin (*ca.* 499-494 Ma; *e.g.*, Dunning and Krogh, 1985; Jenner and Swinden, 1993) probably formed in proximity to the Ganderian ribboned microcontinent. Related bimodal arc plutons had crosscut the supracrustal rocks of the Edi-


inset
HHC
LBG
RAG-cab Belt
BH
PI
TR
CL
MP
SHC
LBG
RED INDIAN LINE (RIL) THRUST BELT


LBG
RAG
CWG
SPG
RIL THRUST BELT
SHC
BDG
PBF
SAF
PBF-WBG
WILD BIGHT PERICLINAL ANTICLINE
GHF
OPF
GHF-WBG
SLIC
OPF-WBG
RAG-CCG
MHG-LBG
CCG
BPC
EXP
LHF
NBF-EXP
SCF-EXP
TAF-EXP
EXPLOITS PERICLINAL ANTICLINE
PHIC
WF-BWG
10 km
N

Legend for Figure 4

Overstep Sequences

Early to Late Silurian

WF-BWG = Wigwam Formation (Botwood Group)

Early to Middle Silurian

SPG = Springdale Group

Late Ordovician to Early Silurian

BDG = Badger Group

Early Late Ordovician

LHF = Lawrence Head Formation

SAF = Shoal Arm Formation

Peri-Gondwanan Sequences

Middle Ordovician

PBF-WBG = Pennys Brook Formation (Wild Bight Group)

NBF-EXP = New Bay Formation (Exploits Group)

PHIC = Phillips Head Igneous Complex

SHC = Sops Head Complex

BPC = Boones Point Complex

Early Ordovician

SCF-EXP = Saunders Cove Formation (Exploits Group)

TAF-EXP = Tea Arm Formation (Exploits Group)

OPF-WBG = Omega Point Formation (Wild Bight Group)

GHF-WBG = Glovers Harbour Formation (Wild Bight Group)

SLIC = South Lake Igneous Complex

Peri-Laurentian Sequences

Middle Ordovician

CWG = Cutwell Group

Early to Middle Ordovician

RAG = Roberts Arm Group

CCG = Cottrells Cove Group

RAG-CCG = equivalent of RAG or CCG?

Middle Cambrian

LBG = Lushs Bight Group

MHG-LBG = Moretons Harbour Group = partial equivalent of LBG?

INSET:

Peri-Laurentian Sequences

Middle Cambrian

LBG = Lushs Bight Group boninite series

Late Early Ordovician

HHC = Hall Hill Complex ophiolite suite

Early to Middle Ordovician

Robert's Arm Volcanic Belt

Lithotectonic Sequences

BH = Boot Harbour panel

MP = Mud Pond panel

PI = Pilleys Island panel

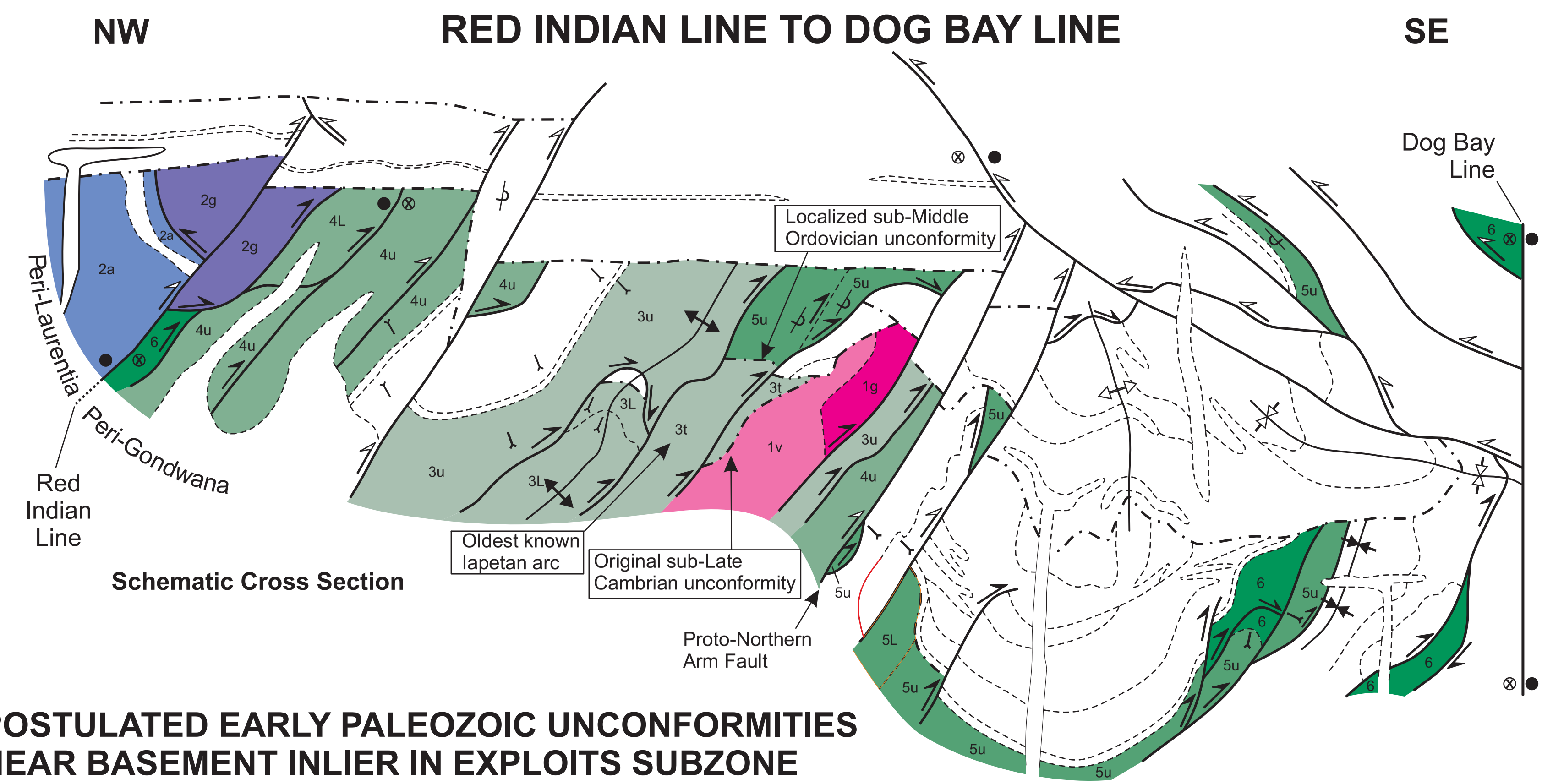
TR = Triton panel

CL = Crescent lake panel

Peri-Gondwanan Sequence

SHC = Sops Head Complex mélange and unbroken formations

Figure 4 (opposite). *Regional disposition and structural setting of selected Ordovician and Silurian rock units in Notre Dame Bay. Note the arcuate periclinal folds of the peri-Gondwanan Exploits and Wild Bight groups and the refolded duplexes of the Red Indian Line thrust belt.*



POSTULATED EARLY PALEOZOIC UNCONFORMITIES NEAR BASEMENT INLIER IN EXPLOITS SUBZONE

PERI-GONDWANAN IAPETAN REALM

6	Dunnage Melange (and correlative mélange tracts)
5u, 5L	Exploits Group (upper and lower formations; parts of Summerford Group included in upper formations)
4u, 4L	Wild Bight Group (upper and lower formations; South Lake ophiolite correlative with lower formation)
3u, 3L, 3t	Victoria Lake Supergroup (upper and lower groups; oldest Tally Pond (3t) arc indicated)

PERI-LAURENTIAN IAPETAN REALM

2a, 2g	Amphibolite gneiss and greenschist near Red Indian Line (derived from the Robert's Arm Volcanic Belt)

PRE-APPALACHIAN BASEMENT INLIER

1v, 1g	Precambrian volcanic rocks and granites near the proto-Northern Arm Fault (including parts of the Sandy Brook Group and the Crippleback Intrusive Suite)

acaran cover sequence in the pre-Appalachian basement complex during this same interval. The formation of the earliest ophiolites may have heralded a latest Cambrian hiatus in volcanic arc construction near the Dunnage–Gander margin. In contrast, the youngest known peri-Gondwanan ophiolite was partly coeval with the *ca.* 490-483 primitive oceanic arc (MacLachlan and Dunning, 1998).

Obduction and Upwelling of peri-Gondwanan Ophiolite. The collision of Dunnage arc complexes and ophiolite suites with the Ganderian continental margin began in the Early Ordovician Penobscot event (*e.g.*, Colman-Sadd *et al.*, 1992). In the southwestern part of the Exploits Subzone, fragments of undated peri-Gondwanan ophiolites were mylonitized along with the latest Cambrian–early Ordovician ensialic arc volcanic sequences (*ca.* 487-483 Ma; Tremadocian). This occurred in a narrow arc collision zone of late Early Ordovician age (Tremadocian–Floian and probably earliest Arenig; *cf.* Tucker *et al.*, 1994) in the region immediately northwest of the largest Neoproterozoic basement inlier in Newfoundland. In the northeastern part of the Exploits Subzone, ophiolitic mélange tracts commonly developed where tectonic slices of ultramafic rocks were subsequently obducted onto the passive continental margin in a thin-skinned collision zone prior to the late Middle Ordovician (pre-late Arenigian or early Darriwilian; *e.g.*, Williams and Piasecki, 1990).

Farther south in the Exploits Subzone, a more protracted phase of Middle Ordovician tectonism resulted in the infrastructure of the peri-Gondwanan Iapetan realm becoming upwelled. There, the suprasubduction zone ophiolites, the structurally underlying quartz-rich turbidite prism and the crystalline basement of the oldest arc volcanic sequences were syntectonically intruded by mesozonal plutonic rocks in the early Middle Ordovician (*ca.* 474-468 Ma; mid to late Arenig; late Floian–Dapingian–earliest Darriwilian) and they continued to be regionally metamorphosed within Abukuma-type migmatite domes until the late Middle Ordovician (*ca.* 465-460 Ma; Llanvirn–Llandeilo; early Darriwilian–Sandbian; *e.g.*, Valverde-Vaquero *et al.*, 2006b). In places, late Penobscottian uplift of the postulated Cambro-Ordovician cover to the ribboned microcontinent persisted throughout Middle Ordovician times and was coeval with back arc development in other parts of the Exploits Subzone.

Figure 5 (opposite). *Schematic cross section of the peri-Gondwanan rocks of the Exploits Subzone (coloured) from the vicinity of the Red Indian Line (northwest) to the Dog Bay Line (southeast). Faulted sub-Late Cambrian and sub-Middle Ordovician unconformities are postulated near the Late Neoproterozoic basement inlier. Section is approximately 100 km long.*

Post-ophiolite Development of peri-Gondwanan Arc-back arc Complexes. In the northern part of the Exploits Subzone, lenticles of calc-alkaline and alkaline basalt are intercalated with variably thick cyclothemic sequences of chert conglomerate, epiclastic wacke and ferruginous argillite (McConnell and O'Brien, 2000). Such strata were interpreted to have accumulated within an extensional volcanic arc lying oceanward of thinned Ganderian continental crust (MacLachlan *et al.*, 2001). They are conformably overlain by mid oceanic ridge tholeiite, ribbon chert and bioclastic limestone that comprise a relatively thin sequence of oceanic back arc rocks, although back arc ophiolites of this age are unknown in the peri-Gondwanan realm of Newfoundland. All of these rocks were intruded by a younger arc-related suite of gabbro laccoliths, beginning in the early Darriwilian (late Llanvirn; O'Brien *et al.*, 1997). Farther east, in the area lying closer to the obducted belt of peri-Gondwanan ophiolites, a thicker unconformity-bounded volcanosedimentary sequence has been interpreted to have been deposited in a Middle Ordovician continental back arc basin situated above the composite Ganderian margin (Valverde-Vaquero *et al.*, 2006b).

The youngest constructional phase of continental margin arc volcanism recorded in the peri-Gondwanan realm of Iapetus produced dominantly felsic pyroclastic and associated sedimentary rocks (Dunning *et al.*, 1987; Evans and Kean, 2002; Rogers and van Staal, 2002; Zagorevski *et al.*, 2007). These accumulated, conformably or disconformably dependent upon location, above an older dormant arc during the late Early Ordovician, the Middle Ordovician and the earliest Late Ordovician. Thus, the youngest known arc magmatism in the Exploits Subzone postdated cessation of the opening of the Exploits oceanic back arc basin. Widely developed throughout the western part of the Exploits Subzone, this arc has been informally referred to as the younger Wild Bight Arc by MacLachlan *et al.* (2001) or the Victoria–Popelogan Arc by Zagorevski *et al.* (2007).

Mass Transport and Olistostrome Formation in the Extensional Arc. Where the remnant arc was uplifted in horst blocks and eroded, volcanic and plutonic detritus sourced from the older edifice was transported into adjacent sedimentary basins developed within the newer active island arc. However, where the remnant arc substrate was buried beneath the flanks of widening and subsiding graben, the basin infill also contained pyroclastic avalanche deposits charged with contemporaneous tephra from calc-alkaline basalt eruptions and muddy debris flows carrying resedimented granite-bearing conglomerate derived from Floian–Dapingian parts of the younger magmatic arc (MacLachlan *et al.*, 2001). Younger epiclastic turbidites were derived from proximal within-plate tholeiites that had erupted in the Dapingian–Darriwilian parts of the extensional arc basin. These were covered by distal ash tuffs of late Darriwilian–Sandbian age and were presumably sourced from the continental margin Victoria Arc.

Dapingian parts of the extensional arc sequence and early Darriwilian parts of the back arc sequence passed laterally into broken formation and a distinctive red or black pebbly mudstone. An associated block-in-matrix diapiric mélange is distinguished by exotic olistoliths of psammitic schist that preserve pre-incorporation amphibolite facies shear zones (*e.g.*, portions of the Dunnage Melange; Williams, 1992). Such rocks are thought to extend discontinuously from the Red Indian Line to the Dunnage–Gander boundary.

Mid Paleozoic Accretion in North-central Newfoundland. Both the peri-Gondwanan and peri-Laurentian magmatic arc complexes generally grew oceanward away from the opposing continental margins of the Iapetus Ocean. At the Red Indian Line arc-arc suture, tectonically encroaching peri-Gondwanan arc-related rocks of late Middle Ordovician and early Late Ordovician age (latest Darriwilian–early Sandbian) were thrust beneath peri-Laurentian rocks of similar age. Subsequently, in the early part of the Late Ordovician (Sandbian–Katian boundary or mid Caradocian), active arc magmatism became focused along old fault lines in the upper and lower thrust plates.

The peri-Gondwanan Exploits back arc basin and underlying Dunnage arc complexes share a complex history of episodic accretion with the easterly adjacent turbidite prism on the Ganderian margin. A protracted history of mid Paleozoic tectonism initially involved multi-pulsed shortening and closure of the Exploits back arc basin during the Silurian Salinic Orogeny. Later, during the Early Devonian Acadian Orogeny, the Avalonian rocks of eastern Newfoundland collided with the Penobscot-sutured and Salinic-reactivated peri-Gondwanan rocks of the Central Mobile Belt (*e.g.*, Holdsworth, 1994). Although there are abundant out-of-sequence structures found in rocks located southeast of the Red Indian Line, it appears that collision zones generally migrated eastward from the northwest to the southeast margin of the peri-Gondwanan Iapetan tract.

During the early part of the Salinic orogenic event, the remnant volcanic arc complex and microcontinental crust appears to been subducted or at least underplated beneath the youngest part of the Exploits–Wild Bight–Victoria arc. This probably occurred in the region that now lies to the west of the fossilized scar of the Penobscot obduction suture. It then rapidly became uplifted and tectonically stabilized (O’Brien, 2011). However, the peri-Gondwanan Iapetan tract was again underplated during the Acadian orogenic event, when it was encroached upon by a more outboard northwest-dipping Benioff Zone responsible for carrying the Avalonian plate westward (*cf.* van Staal *et al.*, 2009).

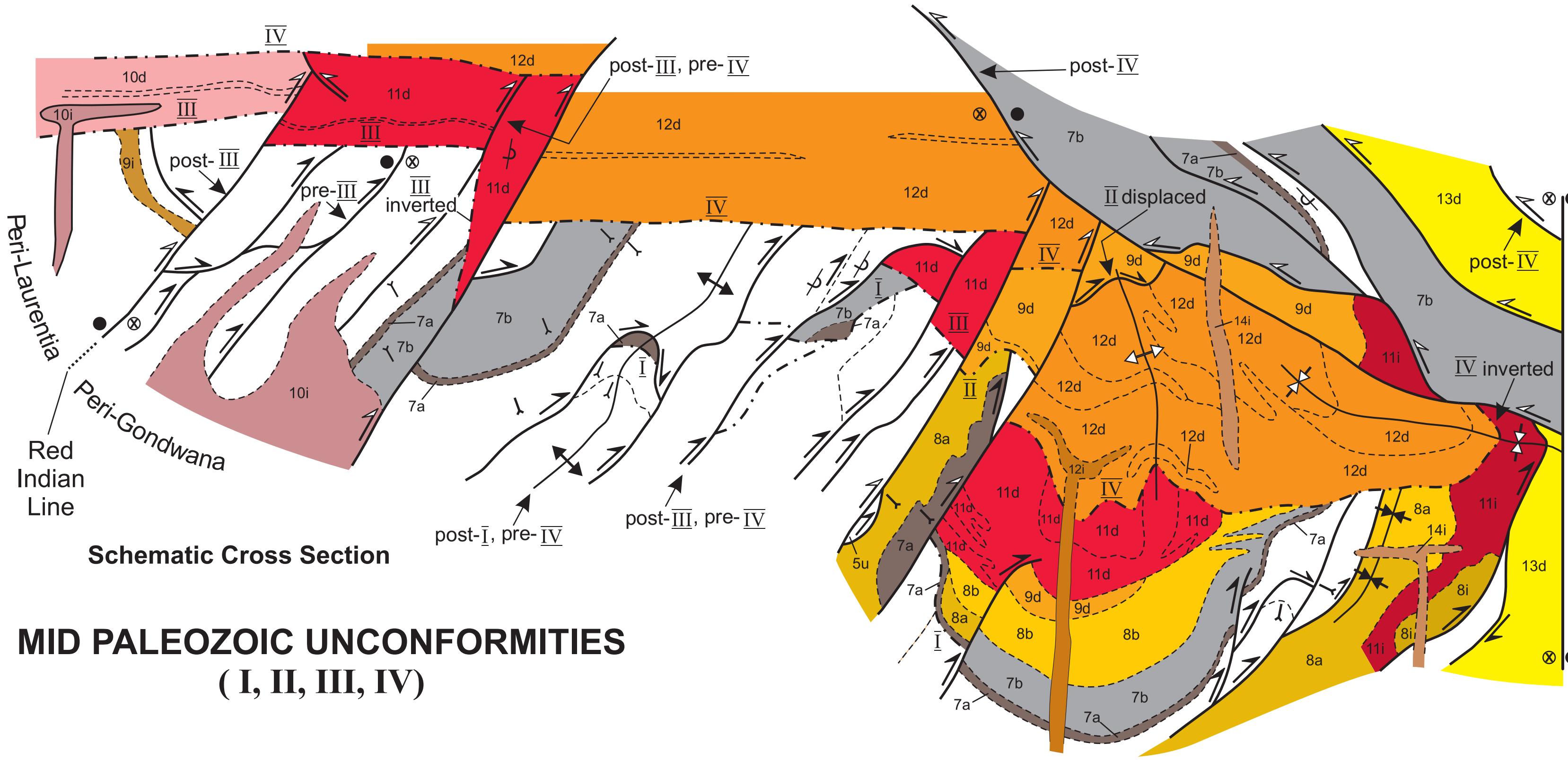
Mid Paleozoic Subbasin Development During Episodic Deformation. Several mid Paleozoic sequences comprise onlap or offlap successions that were originally unconformity-bounded and built directly upon extinct back arc, seamount, mélange and extensional arc complexes of early Paleozoic age (O'Brien, 2003; Figure 6). In the west, Early to Mid Silurian terrestrial volcanic rocks (latest Llandoverian and early Wenlockian) were deposited above Late Ordovician marine strata (Ashgillian) that had been previously deformed and regionally metamorphosed (O'Brien, 2011). By contrast, in localities farther east, gradational shoaling-upward sequences of marine and terrestrial strata of Early Silurian (Llandoverian) age had been deposited conformably above a thick Late Ordovician overstep succession.

However, near certain long-lived structural highs in the overstep basin (*e.g.*, Oversby, 1967), the youngest known marine turbidites (late Early Silurian; Telychian) are interpreted to have onlapped variably tilted sections of Late Ordovician–Early Silurian strata. Such Ashgillian and early Llandoverian (Aeronian and older) turbidites are postulated to have been tectonically disposed within partially inverted depocentres that had originally formed as syndepositional graben (O'Brien, *ibid*). In places, red conglomeratic turbidites of Telychian age transgressed directly onto an eroded substrate made up of typical Middle Ordovician Dunnage Zone strata. Less commonly, Neoproterozoic basement rocks comprise the local substrate of the structural highs (*e.g.*, Rogers *et al.*, 2006; compare Figures 5 and 6).

The Precambrian and early Paleozoic rocks lying beneath the Mid Paleozoic overstep succession are thought to have comprised uplands that were unconformably overlain by different types or ages of cover sequences. These developed at later intervals in the Silurian (*cf.* the Salinic A, B and C unconformities in northern New Brunswick; Wilson and Kamo, 2011, 2012). The older basalt-dominated volcanosedimentary cover sequences initially developed during the onlap of terrestrial strata near the tectonically active margins of Early

Figure 6 (opposite). *Schematic cross section of putative Late Ordovician to Early Devonian cover sequences and allied intrusions in the northwestern part of the Exploits Subzone. Basement rocks represented by the Middle Ordovician and older rocks of the Dunnage Zone and the Late Neoproterozoic igneous complex are uncoloured. Localized Mid Paleozoic unconformities developed at four different times during the accretion of the peri-Gondwanan realm and were episodically deformed during discrete intervals of basin inversion and basement remobilization.*

RED INDIAN LINE TO DOG BAY LINE



Schematic Cross Section

MID PALEOZOIC UNCONFORMITIES
(I, II, III, IV)

SYNOROGENIC COVER SEQUENCES ABOVE IAPETAN SUBSTRATE AND PRE-APPALACHIAN BASEMENT

14i — EARLY DEVONIAN TERRESTRIAL BASIN (406-412 Ma)
Belt unrecognized in north-central NF
(intrusions equivalent in age to deposits in the upper King George 1V Lake, upper Billiards Brook and Cinq Isles formations of southern NF)

13d — LATEST SILURIAN MARINE BASIN (417-429 Ma)
Indian Islands – Northwest Gander River Belt
Deposits

12d | 12i — LATEST SILURIAN TERRESTRIAL BASIN (419-424 Ma)
Botwood – Stoney Lake – Wigwam Belt
Deposits and Intrusions

11d | 11i — MID SILURIAN TERRESTRIAL BASIN (424-429 Ma)
Botwood – Charles Lake – Rogerson Lake Belt
Deposits and Intrusions

10d | 10i — EARLY TO MID SILURIAN TERRESTRIAL BASIN (426-431 Ma)
Springdale – South Brook – Halls Bay Belt
Deposits and Intrusions

9d | 9i — LATEST EARLY SILURIAN MARINE BASIN (431-436 Ma)
Badger – Martin Eddy Point – Goldson Belt
Deposits and Intrusions

8a | 8b | 8i — LATEST ORDOVICIAN AND EARLY SILURIAN MARINE BASIN
8a (445-451Ma); 8b, 8i (436-439 Ma)
Badger – Lewisporte – Upper Black Island Belt
Deposits and Intrusions

7a | 7b — LATEST ORDOVICIAN MARINE BASIN
7a (450-461Ma); 7b (444-450 Ma);
Badger – Point Leamington – Lawrence Harbour Belt
Deposits

Silurian depocentres. The younger felsic pyroclastic-dominated sequences evolved during the offlap of estuarine and fluvial deposits within Late Silurian subbasins. In places, they buried the earlier Silurian interface between basement and cover. Lying directly one on top of the other in certain localities, and postulated to have been originally separated by either a non-sequence or an angular unconformity, such red beds were deformed before and after a sub-Ludlovian hiatus related to the Salinic Orogeny.

Mid Paleozoic Tectonic Processes in the Northern Exploits Subzone. The above-mentioned rocks were characterized by a geological history that involved repeated cycles of short-lived transpression separated by regional transtensive pulses within the fold belt. The oblique extension phases were generally manifested by an initially slow dilatation of the substrate of the sedimentary basins followed by a relatively rapid infilling and locally thick accumulation of volcanic strata in parts of these basins. Cyclic magmatism is also witnessed by the abundant pre-, syn- and post-tectonic phases of plutonism that affected many of the sedimentary basins of north-central Newfoundland. Here, unlike other parts of the Central Mobile Belt, mafic volcanism and plutonism typically predominated over the felsic counterparts.

In the northeastern part of the Exploits Subzone, bimodal mafic–felsic magmatism continued throughout tectonically-driven episodes of 1) cover basin formation by pull-apart or rifting mechanisms, 2) the later partial inversion of these successor basins, and 3) an allied metamorphic rejuvenation of the underlying Iapetan basement. All of these processes recurred during several discrete episodes in the late Ordovician and Silurian, and may possibly be related to changes in Silurian plate tectonics (*cf.* Whalen *et al.*, 2006). In some places, the opening and closure of post-Iapetan depocentres may have been initiated during the early Late Ordovician (Katian).The strongest evidence for repeated accretionary tectonism is seen in the variety of rocks that were formed between the latest Ordovician (Hirnantian) and the latest Silurian (Pridolian).

In the writer's opinion, many mid Paleozoic rocks in north-central Newfoundland originated during the protracted evolution of an extensional accretionary type of orogen (*cf.* Collins, 2002) that ceased to develop prior to a terminal continental collision in the latest Silurian and/or early Devonian (Figure 7). Fossil-bearing overstep sequences of supracrustal rocks, in particular the Badger retroarc foreland basin, are interpreted to have been controlled by a northwest-dipping subduction zone (present coordinates) that had once underplated this entire region (including the dormant Red Indian Line suture). The paleo-Benioff

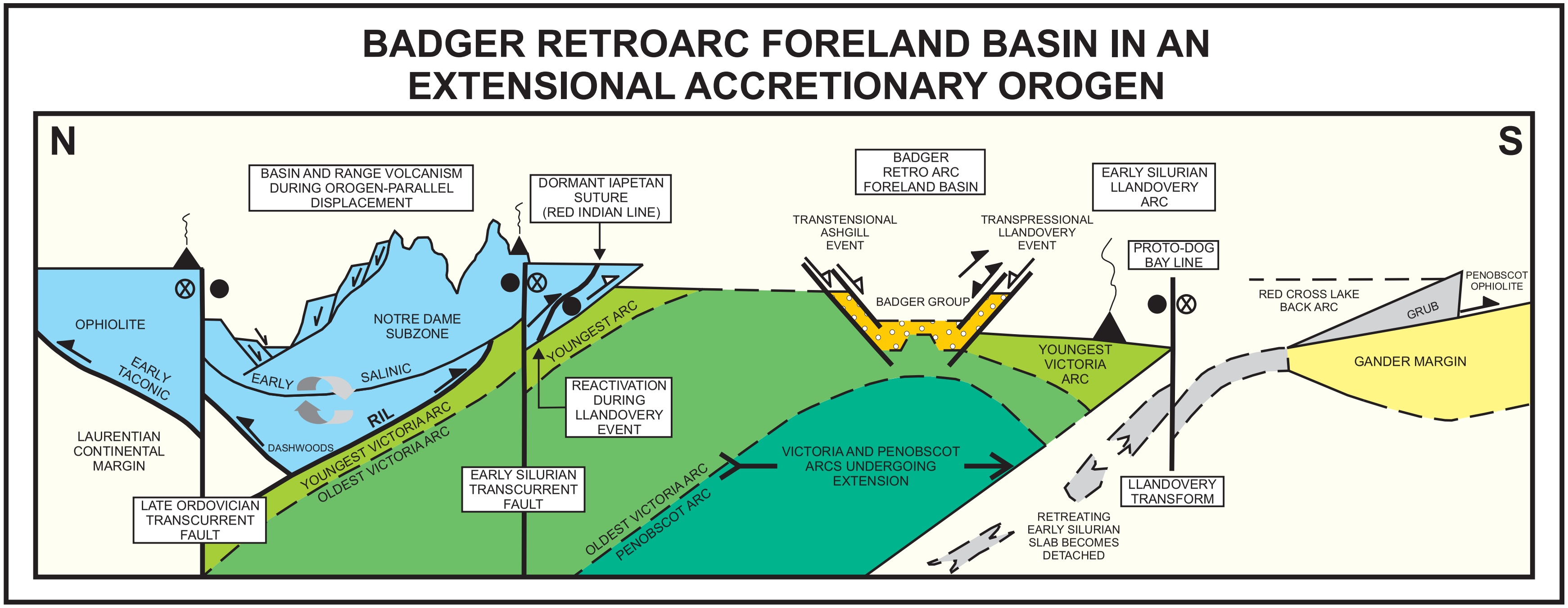


Figure 7. *The tectonic setting of the Badger retro-arc foreland basin above the peri-Gondwanan realm and its geodynamic relationship with the peri-Laurentian basin-and-range volcanic province (located north of the dormant Red Indian Line) is illustrated in this Early Silurian model of an extensional accretionary orogen. In the Llandovery, the main tectonic elements are a southward-retreating (and ultimately detached) oceanic plate, a suprasubduction zone ensialic volcanic arc and transform faults on a sutured continental margin. An analogy might be subduction of the Juan de Fuca oceanic ridge triggering obliquely extensional transcurrent faulting and inboard Tertiary continental Cascadian volcanism that penetrated a Mesozoic thrust stack developed on the back arc side of the Mesozoic continental arc.*

The switch from Ashgillian transtension in marine depocentres above the extended peri-Gondwanan Penobscot and Victoria arc complex to southeastward-directed Llandovery thrusting and transpressional inversion of the Badger Basin was coeval with certain peri-Laurentian pulses of terrestrial volcanism but it predated other ignimbrite eruptions and subvolcanic intrusive episodes in central Newfoundland. Farther north, this process was mirrored by the migration of peri-Laurentian terrestrial volcanism toward the Red Indian Line and by the concomitant reactivation of the Red Indian Line suture as a positive flower structure situated inboard of the Llandovery transform near a contemporaneous synvolcanic transcurrent fault. The cyclic opening, abortion and closure of the submarine to subaerial rift basins and the repeated metamorphism and regional deformation of their Cambro-Ordovician substrate is a hallmark of an extensional accretionary orogen built upon a sequence of older arc-back arc complexes.

Zone appears to have had intermittently retreated southeastward between the Late Ordovician and Early to Middle Silurian (*see* also Murphy *et al.*, 2011). Affiliated suites of metamorphic and plutonic rocks in the underlying Iapetan substrate probably developed by reactivating old tectonic sutures located behind the active front of a Silurian magmatic arc (O'Brien, 2011; Figure 7). This feature likely faced the northern convergent margin of the Rheic Ocean (Nance and Linnemann, 2008b).

REGIONAL GEOLOGY OF ORDOVICIAN ROCKS IN CENTRAL NOTRE DAME BAY: RED INDIAN LINE AND SOUTH

In north-central Newfoundland, most of the coastal region between Badger Bay and the Bay of Exploits is underlain by rocks that make up the type area of the peri-Gondwanan Exploits Subzone of the Dunnage Zone (Figure 8). However, rock groups assigned to the peri-Laurentian Notre Dame Subzone of the Dunnage Zone comprise the northernmost headlands and outermost archipelago of central Notre Dame Bay. On the northern Fortune Harbour peninsula and islands farther east, the peri-Laurentian realm is represented by the Cambrian rocks of the Sleepy Cove and Lushs Bight groups and the Ordovician rocks of the Moretons Harbour and Cottrells Cove groups (Figure 1). In Notre Dame Bay, the Red Indian Line is coincident with the highly arcuate Lukes Arm Fault Zone (Figure 8), which can be traced across the northern part of the Fortune Harbour peninsula in a northwest-trending direction for at least 25 km of its 100 km regional extent.

The Cottrells Cove Group (Figure 1) forms an integral part of the Middle Ordovician and older Buchans–Robert's Arm volcanic belt, one of the major volcanogenic massive sulphide-bearing tracts in the Notre Dame Subzone. In the northern part of the region to be examined, this group is tectonically juxtaposed against a variety of Middle Ordovician rock units that all belong to the peri-Gondwanan realm.

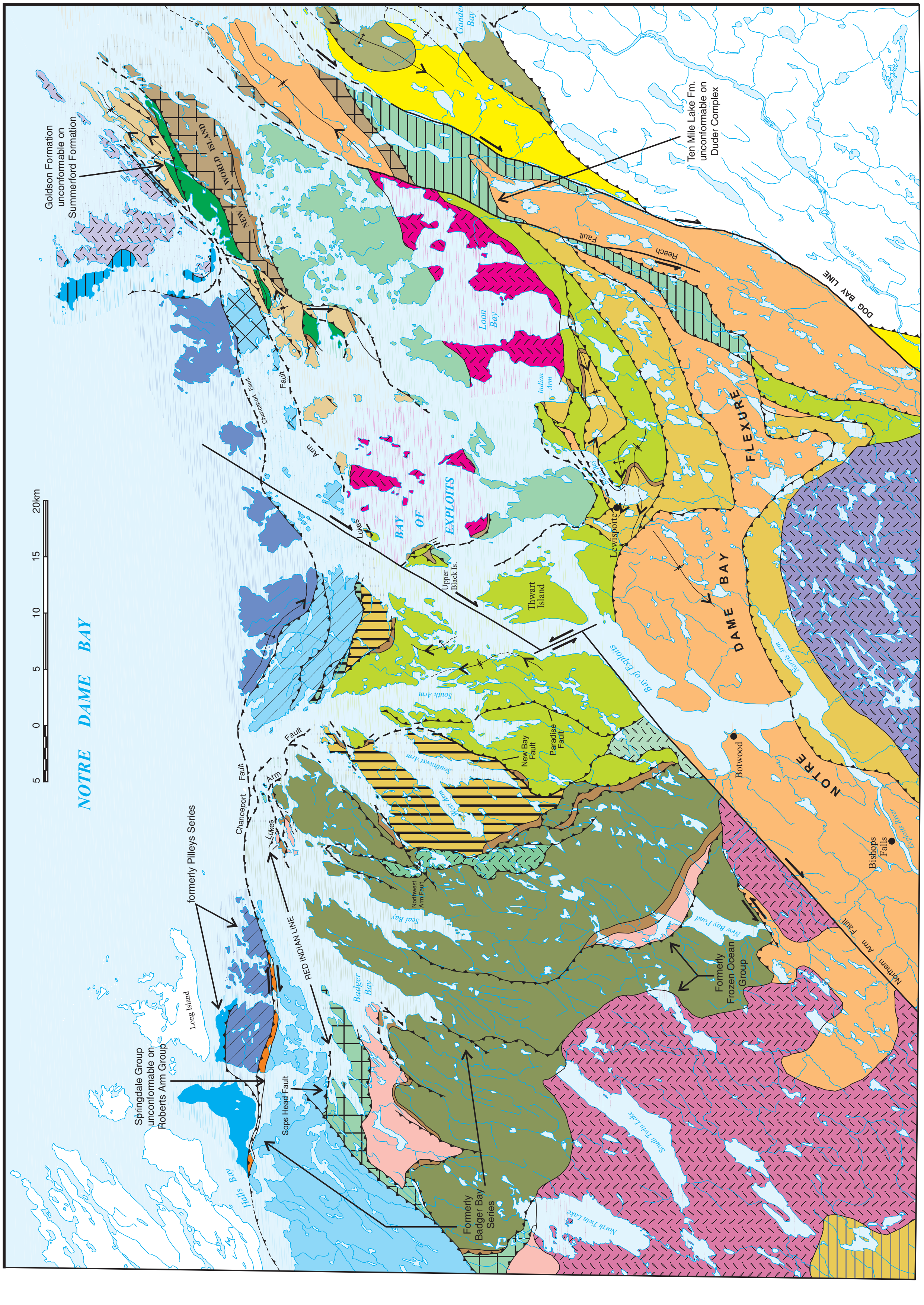
Within the southerly adjacent part of the Exploits Subzone, Early–Middle Ordovician stratified rocks are mainly found in the Exploits Group, which is particularly well exposed around New Bay in the central part of the field trip area. To a lesser extent, age equivalent rocks from the Wild Bight Group are also accessible along the east coast of Seal Bay and near the western shore of the Bay of Exploits. The variably mineralized volcanic and sedimentary strata that comprise the peri-Gondwanan arc-back arc complex are disposed by regional structures such as the Exploits and Wild Bight periclinal anticlines; whereas, the associated arc-root plutonic and older ophiolitic rocks mainly occur in klippen or thrust sheets adjacent to these structural features (Figure 4).

Two discrete basins containing different Late Ordovician successions of the Badger Group are also locally present, one separating the Exploits Group from the Wild Bight Group and the other separating the Exploits Group from the Cottrells Cove Group (Figure 8). The younger turbidite successions, which are devoid of volcanic rocks of any kind and underlain by anoxic black shale, comprise one of the oldest overstep sequences known to have been deposited above a peri-Gondwanan Dunnage Zone substrate.

REGIONAL STRUCTURAL SETTING OF THE FIELD TRIP AREA

In the Notre Dame Bay sector of the Dunnage Zone, the boundary between the Notre Dame and Exploits subzones outlines a Z-shaped oroclinal fold, typical of those seen throughout the Newfoundland Appalachians. On the Fortune Harbour peninsula, the Red Indian Line suture is situated on the middle limb of the Notre Dame Bay oroflex (Figure 9), where it is observed to be weakly crossfolded by mainly northeast-plunging structures. This phenomenon has been interpreted to indicate later shortening of a primary structural arc within the Dunnage Zone (*see* Figures 2 and 3).

In the field trip area, the earliest set of regional folds and thrust faults that formed near the Red Indian Line suture had a northeastward structural inclination (Figure 8). These are found in stratified rocks of Early and Middle Ordovician age within the Notre Dame Subzone and are particularly well developed along the southwestern margin of the Cottrells Cove Group on the Fortune Harbour peninsula. The northeast-dipping structures have been postulated to relate to the dextrally oblique, north-over-south thrusting of a hanging wall sequence of peri-Laurentian rocks above a footwall sequence of peri-Gondwanan rocks. Tectonic subsidence of undeformed Middle Ordovician strata from the Exploits and Wild Bight groups has been interpreted to have occurred when the adjacent Notre Dame Subzone sequence was being upthrusted in the Late Ordovician along the Red Indian Line. The lack of preservation of a marine turbidite succession in the eastern part of the Notre Dame Subzone that is directly correlatable with the Badger Group overstep sequence on the Exploits Subzone has commonly been cited as indirect evidence for Taconian contractional uplift of the peri-Laurentian realm during the Late Ordovician.


NOTRE DAME BAY
0 5 10 15 20km
BAY OF EXPLOITS
NOTRE DAME BAY FLEXURE
DOG BAY LINE
RED INDIAN LINE
NEW WORLD ISLAND
Goldson Formation unconformable on Summerford Formation
Ten Mile Lake Fm. unconformable on Duder Complex
Springdale Group unconformable on Roberts Arm Group
formerly Pilleys Series
Formerly Badger Bay Series
Formerly Frozen Ocean Group
Chanceport Fault
Lukes Arm Fault
Reach Fault
Northern Arm Fault
Sops Head Fault
New Bay Fault
Paradise Fault
Northwest Arm Fault
Lewisporte
Botwood
Bishops Falls
Thwart Island
Upper Black Is.
Long Island
Halls Bay
Badger Bay
Seal Bay
Loon Bay
Indian Arm
South Arm
Southwest Arm
West Arm
Norris Arm
Bay of Exploits
New Bay Pond
North Twin Lake
South Twin Lake
Gander Bay
Gander River
Exploits River

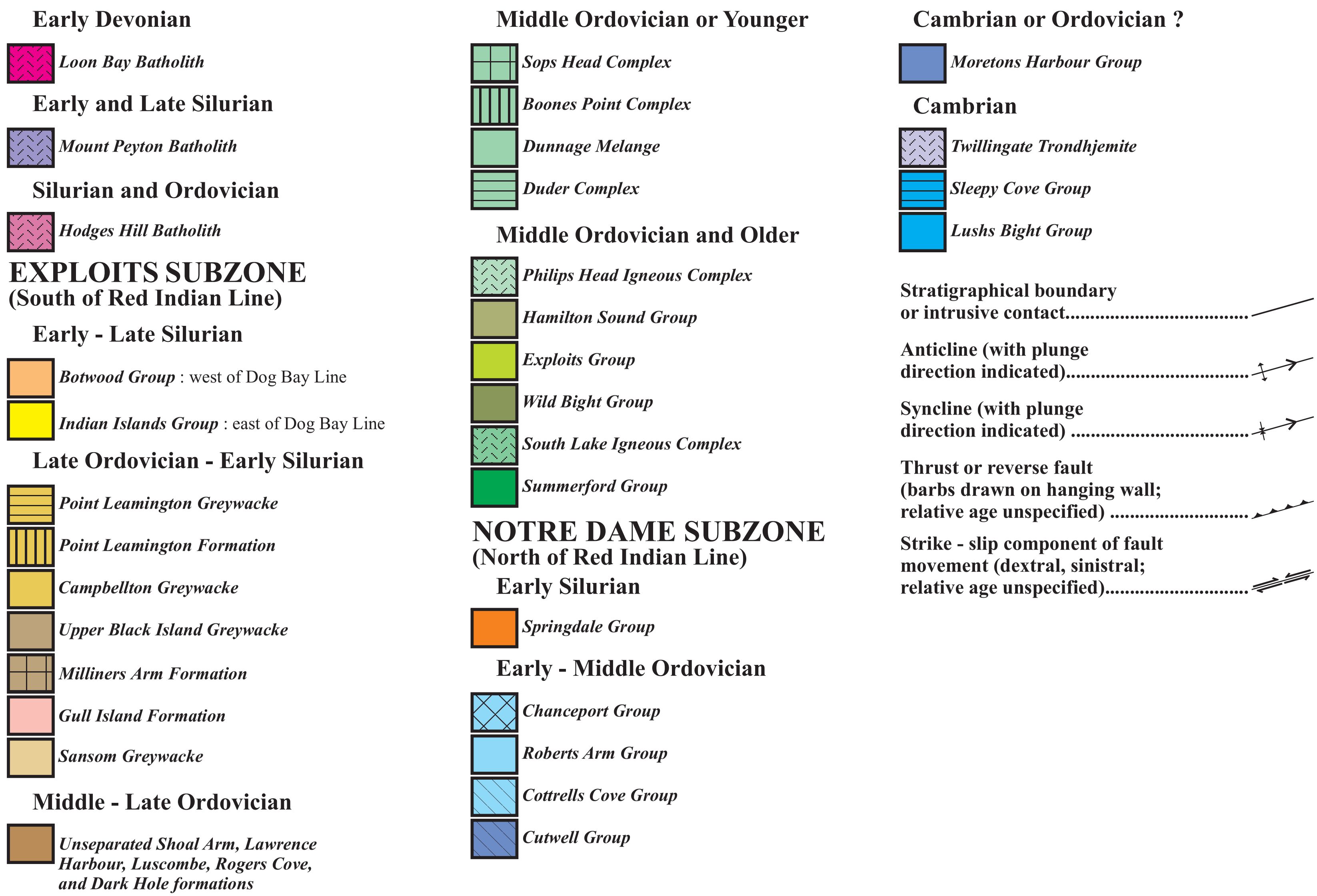


Figure 8. *Simplified regional geological map of the northeastern Dunnage Zone between Halls Bay and Hamilton Sound (part of the NTS 2E district), illustrating the disposition of early and middle Paleozoic rocks in this part of the Central Mobile Belt of northeastern Newfoundland.*

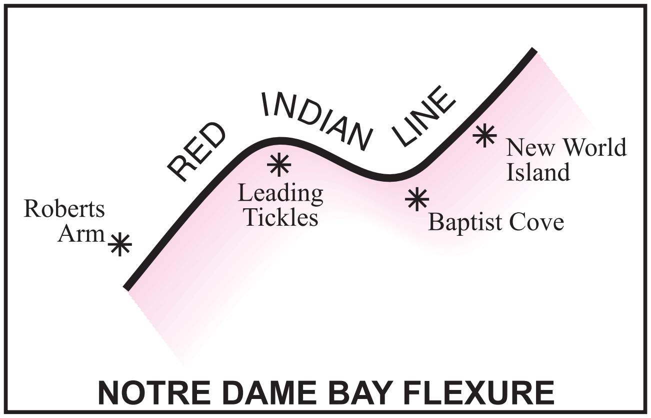


Figure 9. *Tectonic sketch map of the Z-shaped Notre Dame Bay oroclinal flexure depicting the regionally folded Red Indian Line structural zone and the approximate position of three geographic locations in the northwestern part of the Exploits Subzone of the Dunnage Zone (coloured pink). Leading Tickles and Baptist Cove are situated on the Fortune Harbour peninsula.*

A later set of northwest-trending synmetamorphic faults dip southwestward and display sinistral-oblique reverse movement (Figure 3). These back thrusts are locally responsible for inversion of the Late Ordovician succession on the Fortune Harbour peninsula and for placing it and the foliated upside-down strata of the Exploits Group structurally above the previously fault-imbricated rocks of the Cottrells Cove and Moretons Harbour groups. This resulted in the development of a regional structural confrontation zone that was focused on the mélange tracts situated near the Red Indian Line.

SOUTHERN MARGIN OF THE NOTRE DAME SUBZONE ON THE FORTUNE HARBOUR PENINSULA

Thrust-related uplift of Notre Dame Subzone strata, as opposed to a uniform global drop in sea level, has long been purported to have been the trigger for olistostrome formation in the Boones Point and Sops Head complexes of the Red Indian Line mélange belt. The earliest mélange-generating movements along this tectonic suture have been previously considered as having occurred in the Late Ordovician during accumulation of the Badger Group, although regionally developed slaty cleavage may not have formed until the Silurian. The postulated tectonic setting for submarine deposition of this Ordovician–Silurian flysch has varied over time from a piggyback basin governed by active faults near a thrust front (Nelson, 1981) to a strike-slip basin governed by active splays of an ocean-continent transform fault (Arnott *et al.*, 1985) to a foredeep basin proximal to an accretionary complex above an active subduction zone at the ocean-facing edge of composite Laurentia (van Staal *et al.*, 2009).

Boones Point Complex. This Ordovician volcanosedimentary complex is mainly composed of an inhomogeneously deformed, dark grey argillite-hosted, scaly-foliated, block-in-matrix melange that is spatially associated with the Red Indian Line structural zone on the Fortune Harbour peninsula. Historically, most of the blocks were believed to have originated in the peri-Laurentian realm; whereas, most of the matrix was thought to have been originally deposited above the peri-Gondwanan realm. As opposed to the more widespread Sops Head Complex lying farther west or the Exploit Subzone's Dunnage Melange to the east, it contains very little broken formation. Regardless, bedded limestones of late Darriwilian age are present in the Boones Point Complex on islands within New Bay. Peri-Gondwanan carbonates of similar age also occur in the Sops Head Complex and the Dunnage Melange.

The most conspicuous feature of the Boones Point Complex is its variably-sized exotic blocks (**Stop 3.3**), which include extrusive and intrusive mafic and subordinate felsic magmatic rocks, hemipelagic and chemical sedimentary rocks, and sub-littorial limestone and bioclastic carbonate associated with pillow lava. Although the Boones Point melange locally preserves evidence of syndepositional mixing, the complex is generally strongly deformed and variably sheared throughout most of its outcrop area. Most of the hard-rock tectonism of the contained olistostromal deposits is related to regional deformation of probable Early Silurian age.

Moores Cove Formation. On the Fortune Harbour peninsula, the rock unit that is most commonly seen in close spatial association with the Boones Point mélange belt is the younger Moores Cove Formation of the Cottrells Cove Group (**Stop 3.2** and **Stop 3.3**). At its base, this early Darriwilian (earliest Llanvirn) succession is composed of within-plate basalt and bioclastic limestone and passes upward, over several metres, into red, grey and green interbeds of pelagic mudstone and laminated chert. Such strata are succeeded by minor sandstone turbidite and variegated mudstone-rich slump sheets, possibly indicating that the peri-Laurentian lower oceanic slope or abyssal basin plain was, at times, overrun by turbidity currents and mass flows.

Younger parts of the Moores Cove Formation are mainly composed of thicker-bedded and coarser-grained siliciclastic turbidites, illustrate more soft-sediment deformed strata with increasing stratigraphic height, and are interpreted to have formed on deep-sea sedimentary fans that were extensively mottled and burrowed by trace fossils. They are thought to overlie the upper part of the peri-Laurentian back arc sequence illustrated as Dp in Figure 10. These lithofacies of the lower Moores Cove Formation are much older than, though broadly similar to, Late Ordovician beds that were deposited above the rocks of the Exploits Subzone, especially the debrite-bearing turbidite sequence in the Badger Group (**Stop 1.5**).

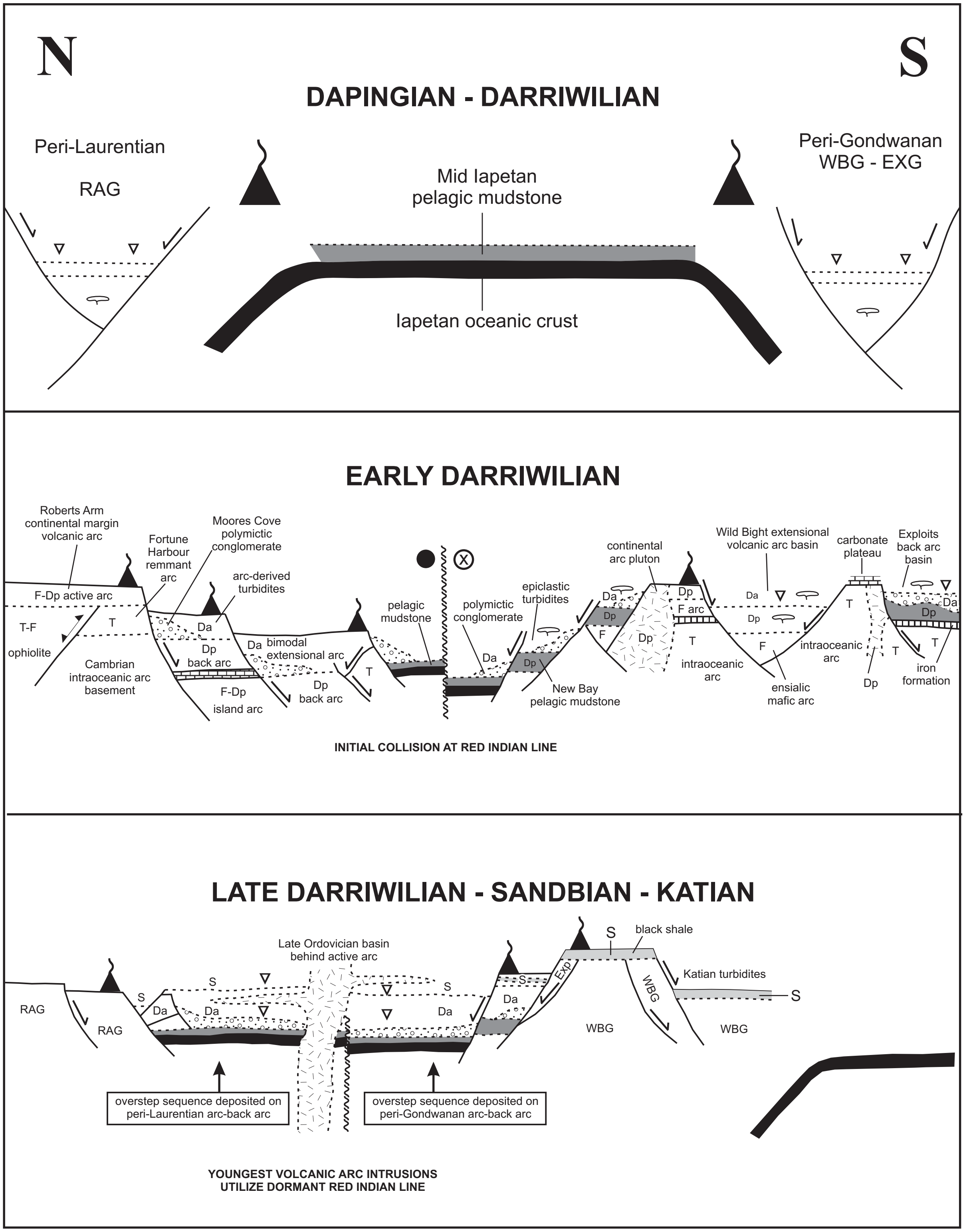


Figure 10. *Diagram illustrating three interpretative cross sections that track the Dapingian (early Middle Ordovician) to Katian (middle Late Ordovician) evolution of rocks near the Red Indian Line in the field trip area. T = Tremadocian, F = Floian, Dp = Dapingian, Da = Darriwilian, S = Sandbian, K = Katian, RAG = Roberts Arm Group, WBG = Wild Bight Group, EXP = Exploits Group.*

A thick division of polymictic boulder conglomerate comprises the uppermost preserved part of the Moores Cove Formation (Figure 10) and is quite distinct from all underlying sedimentary rocks in the Cottrells Cove Group. Although resembling the Early Silurian conglomeratic turbidites of the Goldson Formation of the Badger Group, the Moores Cove conglomerate is Middle Ordovician in age (early to mid Darriwilian).

Fortune Harbour Formation. The oldest volcanosedimentary strata in the Cottrells Cove Group belong to the Early–Middle Ordovician Fortune Harbour Formation, which is exposed in the field trip area on Cuttle Island and Little Grego Island to the immediate north of the Red Indian Line. The Fortune Harbour turbidites are distinct from those in the overlying back arc sequence of the Moores Cove Formation as they have an abundance of proximal pyroclastic and epiclastic detritus sourced from a contemporaneous Early Ordovician volcanic island arc (*see* T in Figure 10). Thus, though basaltic clasts are a common constituent of most sedimentary units in the Cottrells Cove Group, the geochemical signature, age and provenance of the mafic volcanic detritus differs significantly with stratigraphical position.

Sedimentary Basins on the Composite Peri-Laurentian Iapetan Margin. The detrital clasts observed in Moores Cove conglomerate include well-rounded metamorphic, intrusive and carbonate boulders in addition to resedimented rafts of felsic and mafic volcaniclastic strata. This is indicative of the unroofing and erosion of underlying volcanic arc and deeper metamorphic-plutonic terranes, some of which may be located farther west in the Notre Dame Subzone (Figure 10). The Moores Cove conglomerate is herein interpreted as a scree deposit in a peri-Laurentian rifted island arc. However, if this coarsening-upward polymict conglomerate was alternatively interpreted as a Middle Ordovician molasse forming in advance of a Taconian thrust belt, then inversion of the postulated syndepositional graben may have taken place, although this would had to have occurred prior to the mid-Darriwilian development of the peri-Laurentian bimodal extensional arc illustrated in Figure 10. This younger arc, which may correlate with the Red Indian Lake Arc of Zagorevski *et al.* (2006), is tectonically excised from the Red Indian Line structural zone on the Fortune Harbour peninsula.

Black shale and siltstone turbidite, important gliding horizons for volcanic and plutonic megablocks in the Red Indian Line mélange belt, are present in the matrix of the Boones Point Complex. Such deep-sea pyritic strata also comprise a partially broken to unbroken formation of Darriwilian sedimentary rocks within the Sops Head Complex at Julies Harbour in Notre Dame Bay. In contrast, a thick sequence of dark grey siltstone and associated black shale has not been recognized in early Darriwilian and older sedimentary strata of peri-Laurentian origin to the immediate north of the mélange belt, such as the Fortune Harbour, Moores Cove or Crescent Lake turbidite successions. However, the most widespread Darriwilian siltstone turbidite-bearing formations occur in the youngest preserved part of the peri-Laurentian arc sequence in western Notre Dame Bay, where they are found within the structurally lowest levels of the Roberts Arm thrust stack (part of the Red Indian Line structural zone).

THE EXPLOITS SUBZONE AND ITS COVER IN THE NEW BAY – BAY OF EXPLOITS AREA

In central Newfoundland, deep marine sedimentary rocks that range throughout much of the Ordovician, extend into the Early Silurian, display a Celtic fauna in its lower part and contain several horizons of mafic volcanic rocks and block-in-matrix mélange were first recognized in Notre Dame Bay. There, most of this succession was placed in the Ordovician Exploits Group, although as originally defined, it included sedimentary rocks that were later re-assigned to parts of the Wild Bight Group, the Summerford Group, the Dunnage Melange, the Boones Point Complex, the Lawrence Harbour Formation, the Shoal Arm Formation, and the Point Leamington and Sansom formations of the Badger Group (Figures 1 and 8). Nevertheless, the regional tectonostratigraphic element referred to as the Exploits Subzone of the Dunnage Zone (Williams *et al.*, 1988) gleaned its name from the original type area of the aforementioned rock unit. Rocks of the Exploits Group have unknown or unexposed stratigraphical relationships with the deep marine Ordovician sedimentary strata that have been subsequently recognized and mapped within the Victoria Lake Supergroup, the Hamilton Sound Group, the Red Cross Lake Group, the Duder Group, the Davidsville Group, the Baie d'Espoir Group, the Bay du Nord Group and the Harbour Le Cou Group, all of which are constituents of the eastern and southern Exploits Subzone of central Newfoundland (Colman-Sadd and Crisby-Whittle, 2005).

Volcanic and sedimentary rocks of demonstrable Early Ordovician and Middle Ordovician age are present in the redefined Exploits Group (O'Brien *et al.*, 1997). They are disposed in two regional structural basins. In one basin, the internal formations of the group face northeastward whereas, in the other, the same stratigraphical elements face southwestward. **Stops 2.1, 2.5** and **2.6** are in the northeastern basin of the Exploits Group and **Stops 2.2, 2.3** and **2.4** are within or near the southwestern basin. The Early Ordovician massive sulphide-bearing volcanic rocks of the lower Wild Bight Group (MacLachlan *et al.*, 2001) are accessible at **Stop 1.1** in relatively close proximity to an overstep sequence of the Badger Group. At **Stop 2.1**, equivalent rocks and an overlying iron formation and jasperite sequence are observable within the lower Exploits Group. Middle Ordovician volcanic rocks and sub-volcanic intrusions are present throughout the middle and upper parts of the Wild Bight Group; however, rocks typical of the younger Wild Bight arc sequence can be viewed at **Stop 2.3** in close proximity to the Exploits Group.

The Paradise Fault Zone contains a moderately to steeply northeast-dipping reverse fault that separates the two structural basins of the Exploits Group. The northeastern margin of the Exploits Group succession in the northeast-younging basin is a southwest-dipping thrust (a component of the Red Indian Line structural zone). The southwestern margin of the Exploits Group succession in the southwest-younging basin is a northeast-dipping reverse fault (a component of the New Bay Fault Zone). This structure also bounds the Wild Bight Group in some localities.

The framework for lithostratigraphic subdivision of the Exploits Group has been historically based on the recognition that lower and upper units of pillowed basalt are separated, in most places, by an intermediate unit of arc-derived turbidites of deep-sea origin. In contrast, the stratigraphic development of the eastern Wild Bight Group is controlled by the local occurrence of the oldest arc-related volcanic and plutonic rocks along this particular margin of the group, which is otherwise marked by younger hemipelagic deposits, minor arc-derived turbidites and a few lenticles of pillowed basalt. Lying to the immediate west of the Exploits Group, this relatively thin succession is devoid of the deep-sea deposits typical of the middle Exploits Group and contains some of the youngest known strata in the Wild Bight Group.

Lower Lavas, Iron Formation and Tonalite Plutons

The Tea Arm Formation of the lower Exploits Group consists of island arc-related pillow lava with abundant mafic dykes, subordinate high-silica rhyolite and intermediate tuff associated with volcanogenic massive sulphide mineralization, and basaltic andesite flows and andesitic pillow breccia (**Stop 2.1**) separated by thin sedimentary horizons of epiclastic, calcareous or silicified strata. The correlative Glovers Harbour Formation of the lower Wild Bight Group (**Stop 1.1**) contains a quartz-pyrite stockwork in a LREE-depleted arc tholeiite sequence located immediately beneath an overlying unit of high-silica rhyolite and sodic tuff. Quartz tonalite bodies that host sheared mafic dyke swarms in the tectonically adjacent South Lake Igneous Complex (**Stop 1.2**) are thought to be broadly consanguineous with the felsic pyroclastic strata in the Glovers Harbour and Tea Arm formations.

The Saunders Cove Formation (**Stop 2.1**) of the Exploits Group overlies the Tea Arm Formation and, in its lower part, includes a distinctive hematitic chert – red argillite succession intercalated with boninitic andesite and oxide facies iron formation. The equivalent Omega Point Formation of the lower Wild Bight Group is not readily accessible, but polymict conglomerate and LREE-depleted basaltic andesite in the lower Omega Point Formation are locally disconformable on mineralized parts of the Glovers Harbour Formation.

Arc-derived Turbidites, Shaley Flysch and Olistostrome

Conformably overlying the Saunders Cove Formation is the oldest of three, stratigraphically gradational subdivisions of the turbidite-dominated New Bay Formation of the middle Exploits Group. The oldest member is generally sandy, epiclastic and medium- to thick-bedded (**Stop 2.5**), the intermediate member is mostly muddy, siliciclastic and thin-bedded, and the upper member is typically conglomeratic, volcaniclastic and poorly-bedded (**Stop 2.4**). Olistostromes are abundant in the upper member, especially in its lower part. Although the lower and middle subdivisions of the New Bay Formation are probably pre-Darriwilian, they preferentially host a late Darriwilian suite of gabbroic laccoliths that display mature calc-alkaline and enriched tholeiitic compositions.

The calc-alkaline volcanic rocks seen at **Stop 2.3** are probably best correlated with similar LREE-enriched andesite and pillowed basalt lenticles in the middle–upper Wild Bight Group, although they may have been deposited around the same time as the sedimentary rocks within the upper New Bay Formation. In places where the Sandbian–Darriwilian boundary is known to lie within the uppermost Wild Bight Group, the constituent turbidites contain spotted sulphide–silicate assemblages and are underlain by partially silicified beds of coral-bearing limestone conglomerate.

Upper Lavas, Carbonates, Nodular Laminites and Biogenic Chert

The Lawrence Head Formation (**Stop 2.6**) of the upper Exploits Group contains LREE-enriched tholeiitic and alkaline pillow lavas and pillow breccias, which are intruded by sub-volcanic mafic sills. The succeeding Strong Island Chert (**Stop 2.6**) represents a relatively condensed Darriwilian succession dominated by bioturbated radiolarian chert, mottled ferruginous or manganiferous siltstone, and orbicular replacement chert. However, in certain areas, it also contains subordinate beds of felsic ash tuff, basalt-rich volcaniclastic turbidite, black siltstone and coarse polymictic debrite. In localities where the Strong Island Chert was not deposited, the within-plate lavas of the Lawrence Head Formation are capped instead by Middle Ordovician limestone beds that contain Floian (early Arenig), early Darriwilian (early Llanvirn) and late Darriwilian (Llandeilo) bioclasts.

In the Wild Bight Group, Middle Ordovician volcanic rocks that may be chemostratigraphic equivalents of the upper Exploits Group lavas are interstratified with and succeeded by LREE-enriched andesite and diorite sills (McConnell and O'Brien, 2000). Fine-grained nodular laminites similar to those in the Strong Island Chert occur throughout the Early–Middle Ordovician (late Floian to latest Darriwilian) Pennys Brook Formation of the upper Wild Bight Group, where they comprise the upper part of coarse turbidite cyclothems.

Overstepping Sedimentary Rocks of the Badger Belt

Fossil-bearing Late Ordovician sedimentary strata of Sandbian and Katian age (Caradoc and early–middle Ashgill) were originally included in the Lawrence Harbour and Point Leamington formations of the Exploits Group. Similar Sandbian and early Katian strata (Shoal Arm and Gull Island formations) also overlie the Wild Bight Group. They are now excluded as tectonically distinct entities and placed instead at the base of the Middle Paleozoic overstep sequence of the Badger belt (*cf.* Williams, 1995; Figures 3, 6, 7 and 8).

Black graptolitic shales similar to the early Late Ordovician sequence to be examined in the field trip area (**Stop 2.2**) are present in a variety of rock groups throughout the Exploits Subzone. They represent the most stratigraphically condensed and thinnest units on the peri-Gondwanan margin of Iapetus. The widespread, albeit diachronous, deposition of Sandbian pelagic shale marks the drowning of exhumed arc-root and back arc complexes, the cessation of deep marine back arc volcanism, and the most extensive high-stand of Iapetan sea level. The development of sulphidized, manganese carbonate-rich, coticule-bearing beds is related to localized chertification of strata below the black shale succession. Although this occurred at different times in different places, the alteration and mineralization had ceased prior to the earliest Katian (latest Caradoc), when the most widespread transgression of anoxic black shale took place.

The Magmatic Arc–Arc Rift–Extensional Arc–Back Arc Transition in the Exploits Subzone: A Summary for the Field Trip Area. The stratigraphical, sedimentological and geochemical features of the volcanic and sedimentary formations of the Exploits and Wild Bight groups may be explained by several distinct stages of volcanic arc construction and sedimentary basin formation behind the front of an active island arc (Swinden *et al.*, 1990; O'Brien *et al.*, 1997). The temporal and spatial evolution of this peri-Gondwanan arc-back arc complex began with the Early Ordovician formation of a primitive magmatic arc that was rifted to produce the mineralized felsic volcanic centres. These graben were either further infilled by later primitive island arc eruptions or else parts of the rift zones became uplifted to locally expose the Exploits Subzone ophiolites, the arc root plutons and the altered rhyolites. The Early Ordovician arc then became dormant. Subsequently, an Early–Middle Ordovician continental margin arc was built up above the remnant oceanic arc (MacLachlan *et al.*, 2001). The main site of younger arc volcanism and coeval sedimentation migrated westward, as the basins within the younger extensional arc widened and deepened. The Exploits back arc basin formed in the east on the deep abyssal plain, where it was unaffected by the contemporaneous Wild Bight arc eruptions that had taken place farther west. As the back arc basin spread, certain parts of its substrate were uplifted above the Iapetan carbonate compensation depth. The Exploits back arc basin infill and the Wild Bight–Victoria arc sequence later came under the influence of a late Darriwilian–Sandbian magmatic event that was locally focused along the dormant Red Indian Line suture (Figures 7 and 10). In the peri-Gondwanan realm, Sandbian felsic pyroclastic eruptions mainly occurred above the western part of the extensional arc, although hydrothermal alteration affected the underlying strata of the back arc basin at this and earlier times.

In the Exploits Group, volcanism occurred during two temporally distinct events. The older volcanic episode was controlled by the generation of subduction zone-related magmas, while magma melts unaffected by the presence of a subducting slab were produced during the younger volcanic episode. Thus, the island arc and within-plate lavas within the Exploits Group are only rarely in direct contact with one another in contiguous parts of the group. Interstratification of these different petrochemical types of volcanic rocks has not been observed in the Exploits Group, although it is a characteristic feature of the youngest Pennys Brook Formation of the Wild Bight Group.

Ordovician subvolcanic intrusions are related to several major plutonic events that affected the Exploits Group. During an Early Ordovician cycle, arc tholeiite dykes and alkaline gabbro sills were intruded during the initiation and rifting of the primitive Tea Arm arc sequence. Subsequently, diorite sills emplaced into lower New Bay turbidites bear witness to a limited Middle Ordovician phase of younger Wild Bight arc magmatism, as do the lower member's reworked andesitic tuffs. During a late Middle Ordovician cycle, within-plate gabbros intruded earliest Darriwilian tholeiitic basalts in the course of an initial rift-drift phase of Lawrence Head magmatism in the Exploits back arc. In contrast, the late Darriwilian gabbroic laccoliths present within the upper Exploits Group mark a return to active subduction-related plutonism.

Interrelationships Between Peri-Gondwanan Strata of the Exploits Group and the Wild Bight Group. Although broadly correlative, important time-space variations existed between the Exploits Group and the Wild Bight Group, particularly as these mid Iapetan arc complexes drifted northward and approached the composite peri-Laurentian margin of the Dunnage Zone. These variations in geological evolution underscore, firstly, the Middle Ordovician history of uplift and erosion of contemporaneous and extinct volcanic arcs and the northwestward transport and depositional recycling of detrital material from such arc edifices. This occurred within Middle Ordovician sedimentary depocentres situated along the southern flank of the Red Indian Line.

Secondly, a repeated history of Middle and Late Ordovician stratigraphic condensation and non-deposition that has been interpreted as having occurred above uplands within emergent parts of the peri-Gondwanan realm, especially those near the Exploits–Wild Bight boundary. Partially consanguineous with the aforementioned uplift and erosion, these events took place in the Wild Bight extensional arc basin or the Exploits back arc basin or above both of them after Middle Ordovician infilling was complete.

Thirdly, the increasing influence on this region by felsic eruptions and mafic intrusions that are related to a Middle to Late Ordovician magmatic arc, now partially preserved in the westernmost part of the Exploits Subzone (*i.e.*, the upper part of the continental margin Victoria Arc). These distinguishing geological features are summarized below:

1. A variable thickness of felsic pyroclastic strata of Late Ordovician age (Sandbian) that are typically interstratified with shard-rich argillite, manganiferous siltstone, concretionary volcaniclastic turbidite, and shale-rich or basalt-rich debrite. Although a relatively minor component in terms of the total stratigraphic thickness, these waterlain felsic tuffs are present throughout the Wild Bight Group but are absent or very thin in the Exploits Group. As presently dated, the record of Sandbian (early Caradocian) arc

volcanism and chemical sedimentation is apparently longer within the peri-Gondwanan realm than it is in the tectonically adjacent rocks of the peri-Laurentian realm.

2. The variable thickness of a condensed but laterally persistant succession of ribboned radiolarian chert and ferruginous replacement chert that is developed above the Middle Ordovician (early Darriwilian) within-plate pillowed basalts of the Exploits back arc basin. Developed in both groups below overstepping Late Ordovician pyritic black shales, it is generally thicker in the upper Wild Bight Group and thinner in the upper Exploits Group.

3. The highly variable thickness of an olistostrome-bearing Middle Ordovician volcanosedimentary sequence marked by Dapingian–Darriwilian calc-alkaline basalts of extensional arc origin. Characteristic of the middle part of the Wild Bight Group, these volcanic lenticles become widely developed and very thick toward the west, where they are intercalated with alkaline pillowed basalts. They are, however, completely absent in the Exploits Group.

4. The presence of a fining-upward cyclothemic sequence of Middle Ordovician (Dapingian–Darriwilian) turbidites marked by abundant intraclasts of basalt breccia, mottled quick sand, slump-folded argillite and orbicular secondary chert. Intruded by unaltered laccoliths of calc-alkaline and alkaline gabbro, such peri-Gondwanan strata are the most common host rocks to a regional sub-greenschist facies system of stratabound alteration zones. Such well indurated, differentially compacted and hydrothermally altered rocks are widespread in the thick sedimentary basin of the western Wild Bight Group, but they are uncommon in the Exploits Group and eastern Wild Bight Group.

5. The presence of an early Middle Ordovician (earliest Darriwilian and older) sequence of siltstone turbidite and intercalated pyritic mudstone of lower slope apron to abyssal plain origin. Such strata had drowned parts of the peri-Gondwanan island arc sequence and accumulated prior to the development of the Exploits back arc basin. Hallmark of the middle part of the Exploits Group, they are notably thick in the deepest portion of the easternmost depocentre of the New Bay Formation. This lithofacies thins westward in the Exploits Group and is completely absent in the Wild Bight Group.

6. The local development of a disconformity within the lowest exposed part of the western Wild Bight Group that separates a mineralized Early Ordovician part of the remnant

oceanic arc from younger unmineralized strata. This relationship is contrasted with the conformable stratigraphical boundaries reported throughout the Exploits Group. Similar mineralized rocks in the Lower Ordovician Exploits Group are gradationally overlain by Early–Middle Ordovician iron formation and boninite and Middle Ordovician volcaniclastic turbidites associated with the formation of the younger Wild Bight extensional arc.

7. The development of a fining-upward sequence of deep-sea polymictic conglomerate that is regionally extensive in the Exploits Group and locally present in the northern part of the Wild Bight Group. On the basis of paleocurrent and provenance data, some of this detritus was locally sourced from the Middle Ordovician succession that makes up the middle to upper parts of the Wild Bight Group and also from plutonic rocks in the coeval Phillips Head Igneous Complex. Clasts of quartz diorite, ferruginous chert, volcaniclastic wacke, basaltic andesite and calc-alkaline basalt were eroded from a peri-Gondwanan extensional arc that was active during the Darriwilian.

8. In the Pennys Brook and New Bay formations, Darriwilian boulder conglomerates have a proportion of their detrital components derived from the Early Ordovician plutonic rocks of the South Lake Igneous Complex and coeval volcanic sequences observed in the lower Wild Bight Group and the lower Exploits Group. Clasts of high-silica rhyolite, island arc tholeiite, boninitic basalt, ophiolitic gabbro, arc tonalite, island arc carbonate and iron formation were eroded and transported from a source area underlain by the remnant peri-Gondwanan intraoceanic arc, indicating that much deeper stratigraphical levels of these groups were also affected by dissection and erosion.

In summary, immediately south of the Red Indian Line mélange belt, unbroken formations of Middle Ordovician polymictic conglomerate were derived from a catchment area located farther southeast in the peri-Gondwanan realm (Figure 10). Such arc-related rocks are broadly similar in age and sedimentary environment, if not paleogeographic position, to the polymictic conglomerate present in the peri-Laurentian realm immediately north of the Red Indian Line on the Fortune Harbour peninsula. The thixatropic deformation of the mud-matrix conglomerate of the New Bay Formation and sand-matrix conglomerate of the Pennys Brook Formation may have occurred as a precursor to, or as a consequence of, an initial Early Darriwilian collision of the Wild Bight–Victoria extensional arc with relict Iapetan oceanic crust or the adjacent rifted arc complex on the leading edge of composite Laurentia (Figure 10). Later offscaping of blocks of black siltstone, conglomerate, limestone and back arc basalt from both realms of the Iapetus Ocean may have taken place, at least in part, during Late Darriwilian movements in the Red Indian Line mélange belt.

Sedimentary strata sourced from local Middle Ordovician back arc sequences of the Exploits Subzone, together with outsized plutonic clasts derived from the underlying Early Ordovician peri-Gondwanan arc ophiolite, were resedimented as large olistoliths within adjacent early Katian basins of the Badger Group. In contrast, detrital zircon and chromite grains extracted from Badger Group turbidites have been argued to have been mainly sourced in Grenvillian gneiss and peri-Laurentian Cambro-Ordovician rocks, including ophiolite terranes (Nelson and Casey, 1979; Pollock *et al.*, 2007; J. Waldron *et al.*, 2012). As presently exposed, such rocks are located to the northwest of the Buchans–Roberts Arm–Cottrells Cove volcanic belt.

Thus, in the field trip area, the overstep sequence of the lower Badger Group is thought to contain peri-Gondwanan and peri-Laurentian detritus sourced from a major Late Middle Ordovician collisional suture in the Dunnage Zone (Figure 10). Sediment accumulation and olistostrome formation then switched to a dynamic Late Ordovician shale-rich basin situated immediately southeast of the Red Indian Line, as the zone of accretion above the underplated peri-Gondwanan realm migrated southeastward. Although narrow tracts of tectonic mélange were developed in strata as young as late Katian and early Hirnantian in this part of Notre Dame Bay, it was the folded and foliated, Sandbian-aged black shale that was preferentially sheared and dismembered, especially along the trace of the Red Indian Line.

FIELD TRIP STOP DESCRIPTIONS

DAY 1

DIRECTIONS TO STARTING POINT

From Grand Falls, take the Trans-Canada Highway (Route 1) east-bound, exit at the Route 1 ramp leading to Botwood and Bishop Falls, and turn northward under the Trans-Canada Highway. From St. John's, take the first exit to Botwood after crossing the bridge over the Exploits River along the Trans-Canada Highway. Drive northeastward approximately 14 km along Route 350 and take the second (main) access road to the Town of Botwood, passing along Fernwood Drive en route to Airbase Place and the parking lot of the museum and heritage centre near Killick Point. This is the Day 1 luncheon locality and the assembly point for all participants on the B2 field trip.

The facility near the Flying Boat Museum was once a re-fuelling stop for the amphibious Pan-American 'Clippers', which made the earliest trans-Atlantic scheduled passenger flights. Besides its World War II military use, the historic port of Botwood was also the railhead for ocean-bound shipments of base-metal ore concentrate from the Buchans volcanogenic sulphide deposit.

Depart Botwood via *Commonwealth Drive, rejoin Route 350 and drive about 4 km northward to the Town of Northern Arm and the junction with Route 352. The red beds seen in road cuts between Grand Falls and Northern Arm belong to the younger Wigwam Formation of the Silurian Botwood Group. The terrestrial Botwood Group is purported to have accumulated in a pull-apart successor basin, situated above previously accreted tracts of marine Dunnage Zone strata. Much controversy surrounds the depositional paleolatitude of the Wigwam Formation. Various workers have postulated that it formed either on the Taconian-accreted Laurentian margin about 10 S of the equator like other Notre Dame Subzone Silurian redbeds or, alternatively, as high as 30 S of the equator in a Silurian mid-Iapetan realm above peri-Gondwanan elements of the orogen.*

The transcurrent Northern Arm Fault of presumed Devono-Carboniferous age crosses Route 352 approximately 0.9 km northeast of the junction with Route 350. This brittle structure offsets posttectonic plutons of late Silurian and early Devonian age and locally separates the Middle Paleozoic overstep sequences of the Botwood Belt and the Badger Belt, as defined by Hank Williams. For the remainder of the day, participants will travel through deep-marine Ordovician rocks of the Dunnage Zone and one of its oldest overstep sequences.

Field trip participants might avail of the small store, gasoline bar and lavatory located at the T-junction between Route 352 and Route 350 in the Town of Northern Arm. Take Route 350 and drive northwestward for some 44 km to the village of Glover's Harbour.

STOP 1.1: Early Tremadocian Peri-Gondwanan Primitive Oceanic Arc Sequence in a Tectonic Horse (Sericitic Alteration Zones in Metabasite Schist of the Glovers Harbour Formation of the Wild Bight Group)

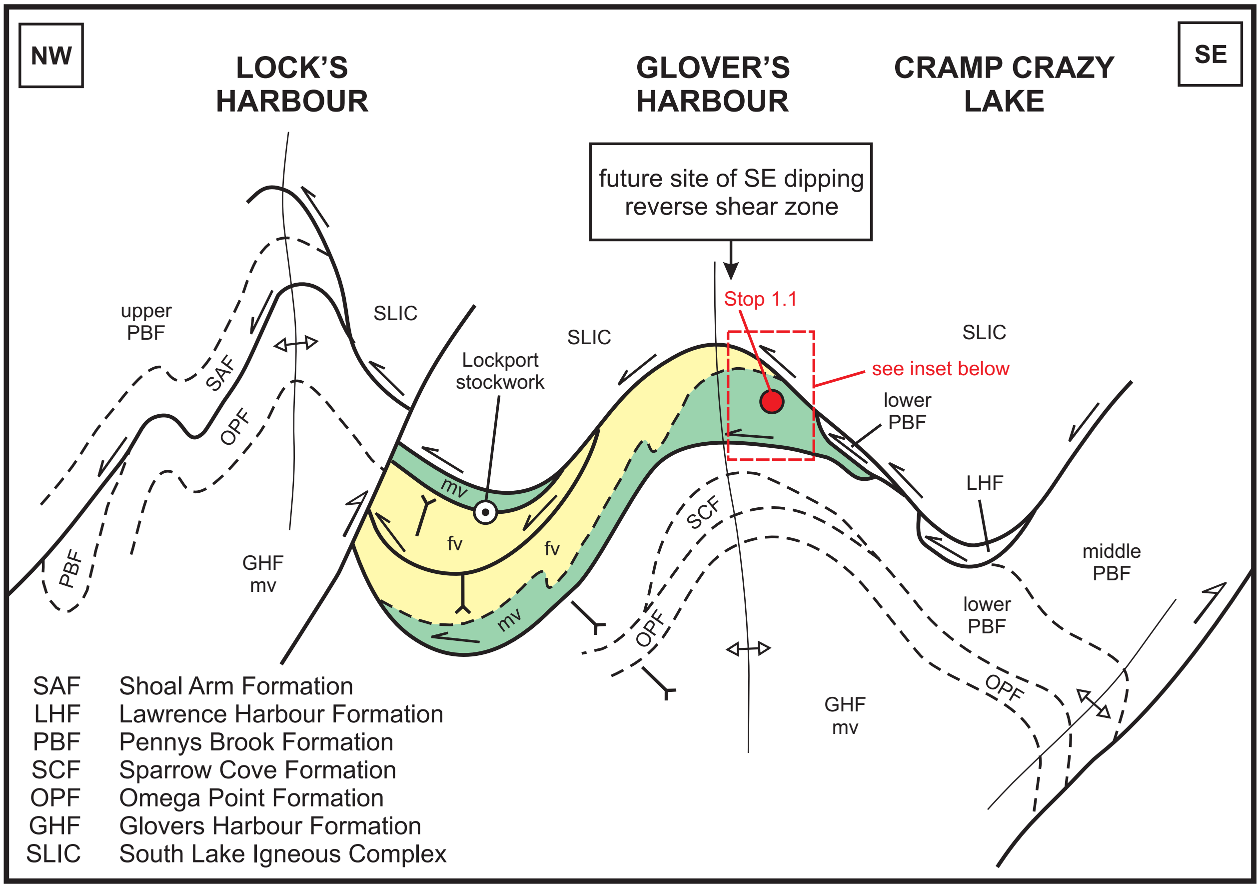
Location: 0.0 km (0.0 km)

At the signpost to Glovers Harbour ("the home of the giant squid") on Route 350, turn westward and proceed through the community for approximately 3 km to the end of the paved road and the parking lot south of the public wharf. Walk to the large rock exposure (E609327 N5478875) near a sharp bend in the road. On the road log for the Day 1 field trip, this point is 0.0 km.

Regional Setting

The pillowed basalts of the Glovers Harbour Formation of the lower Wild Bight Group (Figure 11) are mostly composed of several types of island arc tholeiite, which are variably LREE-depleted, and boninite (MacLachlan and Dunning, 1998a). They are known to be early Tremadocian or older in age on the basis of an intrusive contact with an alkali gabbro sill, exposed at Glovers Harbour Head and isotopically dated at *ca.* 486 Ma by the U–Pb TIMS method (*ibid*, 1998a). These badellyite-bearing intrusions are petrochemically similar to the more widespread Darriwilian sills of alkali gabbro found in the western Wild Bight Group and the Exploits Group, although they are related to fundamentally different episodes of rifting and extension in the peri-Gondwanan arc complex. In the type area of the Glovers Harbour Formation, the high-Si and low-K felsic volcanic rocks are not observed to be intruded by the dated alkali gabbro. However, they are thought to be correlative with the *ca.* 486 Ma felsic pyroclastic strata in the Tea Arm Formation of the lower Exploits Group based on their stratigraphic position and trondhjemitic to tonalitic character.

To the west near Lock's Harbour and Thimble Tickles, felsic and mafic volcanic rocks of the Glovers Harbour Formation are faulted against the ferruginous boulder conglomerate, jasperite and iron formation, red siliceous argillite and grey carbonaceous siltstone, and rare boninitic basalt flows of the overlying Omega Point Formation. A chaotically slumped debrite in the lower part of this formation illustrates hematized volcanic and sedimentary blocks, some of which have been sourced from altered parts of the Glovers Harbour For-



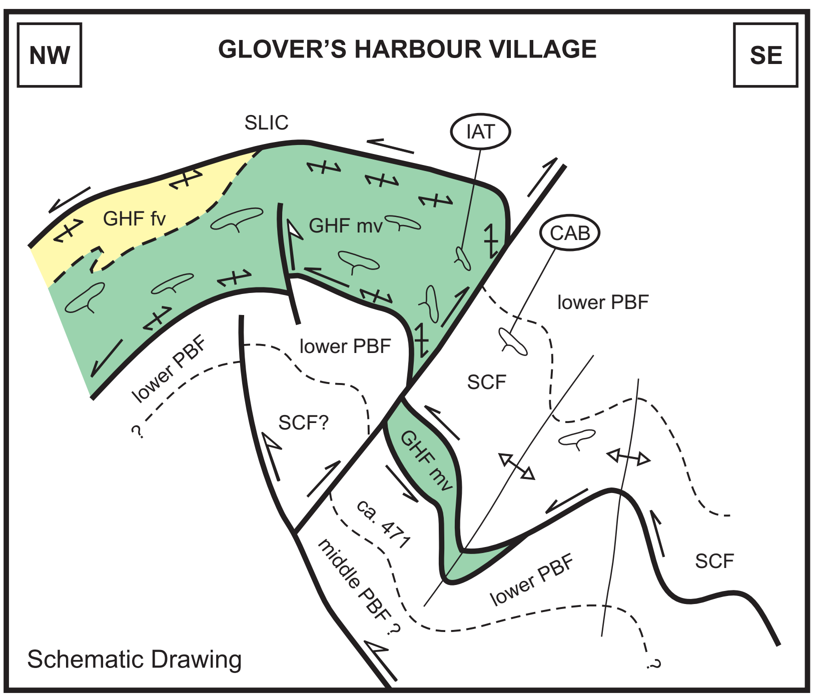


Figure 11. Northwest–southeast cross section of the Early-Middle Ordovician Wild Bight Group in the Seal Bay–Osmonton Arm area, illustrating the role of early formed (reorientated) thrust faults in structurally isolating a tectonic slice of mineralized volcanic rocks. Hosting the Lockport stockwork, the oldest Glovers Harbour Formation of the Wild Bight Group is interpreted to lie beneath a synformal klippe of South Lake Igneous Complex tonalite and Lawrence Harbour Formation black shale. Structural section is approximately 5 km in length. Inset shows detailed structural section along the coastline of Glover's Harbour village near Stop 1.1. IAT = island arc tholeiite, CAB = calc-alkaline basalt.

mation. In Lock's Harbour, thin felsic tuff and intercalated red chert have been absolutely dated using volcanic zircons in shards and a crystallization age of 472 ± 3 Ma was determined (MacLachlan and Dunning, 1998b). According to the writer's interpretation, the dated rocks occur near the top of the Omega Point Formation (O'Brien, 1996). If correct, this indicates that the Omega Point Formation is latest Floian–earliest Darriwillian in age (or possibly older) in the eastern part of the Wild Bight Group.

Along the east coast of Glovers Harbour, the mature calc-alkaline basalts and andesites of the overlying Sparrow Cove Formation of the Wild Bight Group are separated from the primitive oceanic basalts of the Glovers Harbour Formation by a narrow tract of younger volcaniclastic turbidites from the lower Pennys Brook Formation. On Pig Island in Glovers Harbour, felsic tuff beds within this highly deformed chert-wacke sequence of the Pennys Brook Formation have been dated at 471 ± 2 Ma (MacLachlan and Dunning, 1998b). Farther east, along the road leading to Route 350, the same chert and wacke succession is interdigitated with calc-alkaline or alkaline pillow lavas. Approximately 4 km south of the village, the Glovers Harbour Formation is faulted directly against the South Lake Igneous Complex.

In the vicinity of Glovers Harbour, the oldest arc volcanic rocks in this part of the Exploits Subzone occur in a thrust-bounded tectonic panel of mineralized rocks in structural isolation from the rest of the Wild Bight Group (Figure 11). Some of the adjacent younger formations in the group have also been tectonically excised or duplicated by ductile thrust faulting under greenschist facies conditions. The early-formed thrust faults were initially openly folded by northwest-trending periclinal antiforms and synforms. Subsequently, these structural features were displaced by reverse faults and back thrusts that moved toward the northeast.

The thrust-bounded panels of stratified rocks and later back thrusts were cross folded or otherwise overprinted by younger northeast-trending structures (Figure 11). In the area between Glover's Harbour and Leading Tickles, they were deformed into a regional northeast–southwest orientation, a trend that also characterizes the structurally overlying rocks of the Notre Dame Subzone on nearby offshore islands.

The Glovers Harbour Formation and the South Lake Igneous Complex are thought to be structurally underlain by younger parts of the Wild Bight Group. A regional northeast-plunging anticline disposing most of the Early–Middle Ordovician stratigraphical succession in the eastern part of the group also affects the overlying lithotectonic sequence of early

Tremadocian rocks. In places, this fold had part of its hinge zone displaced by a steeply southeast-dipping, dip-lineated, reverse shear zone. This late-formed metamorphic structure separates the low strain sequence near Glovers Harbour into northwestward- and southeastward-younging volcanic sections.

Description

The rocks at Stop 1.1 occur about 200 m across strike from a copper-bearing stockwork located farther west at the Lockport volcanogenic massive sulphide prospect. In the road exposure, there are numerous iron oxide-weathered horizons of pyritic sericite schist within a thicker sequence of vertical to steeply northwest-dipping chlorite schist. Rocks of the Glovers Harbour Formation are not, however, as strongly silicified at this locality as they are at the Lockport prospect.

Near the southwest end of the road exposure, subvertical crenulation cleavage is preserved adjacent to platey zones of chlorite schist marked by granoblastic sulphides. Later shear bands display moderately northwest-dipping C-planes having a thrust sense of offset or differential displacement of the foliation surface. They may be related to the region's northwest-dipping back thrusts (Figure 11) or possibly to late shortening of the regional antiform that is defined by the thrust-parallel foliation in this horse of the Glover's Harbour Formation.

In the vicinity of the public wharf, small zones of banded mylonite bifurcate around low-strain augen that preserve the highly flattened vesicles of primary basalt flows. Traversing farther downward in the Glovers Harbour Formation along the coast section north of the wharf, chlorite schist and less sheared mafic volcanic rocks are observed to be intercalated with intervals of pillowed basalt gradational to pillow breccia. Here, the lava flows are right-side-up and dip southeastward.

Discussion

The Early Ordovician strata and intrusions within the Glovers Harbour Formation are thought to represent a remnant oceanic arc sequence situated in the stratigraphically lowest part of the Wild Bight Group. In contrast, the early Middle Ordovician volcanic and sedimentary strata in the middle and upper parts of the group have been interpreted as the infill of a rift basin located within a continental margin volcanic arc.

The excision or duplication of lithostratigraphic units in the area around Glover's Harbour was mainly due to thrust faulting. Fault imbrication took place in the immediate footwall sequence of an overlying southwest-directed thrust sheet carrying the South Lake Igneous Complex arc ophiolite and the Lawrence Harbour Formation overstep sequence (Figure 11). It seems that the incompetent Late Ordovician black shale was preferentially utilized as a glide horizon within the thrust stack.

Based on regional considerations, the early-formed thrust faults are interpreted to have had northeast-over-southwest movement, although it is possible that they had the opposite tectonic polarity. The favoured explanation would relate the early Glovers Harbour structures to those developed along the Red Indian Line on the Fortune Harbour peninsula; whereas, the latter scenario would have them mimic the early Red Indian Line structures found in the region west of Badger.

In the eastern part of the Wild Bight Group, the succession from the lower Sparrow Cove Formation to the upper Pennys Brook Formation is relatively thin and stratigraphically condensed. However, based on sediment provenance data, it has been considered to have accumulated above a depositional substrate that included the Glovers Harbour Formation.

Sometime after the deposition of the Badger Group, the remnant oceanic arc sequence outcropping in the Glover's Harbour area became structurally detached from the rest of the group. Despite the protracted history of fault displacement, it is postulated that volcanic and plutonic rocks from the Glovers Harbour Formation and the South Lake Igneous Complex were already together in what was the source area for the conglomerates of the northeastern Wild Bight Group by the early Darriwillian.

STOP 1.2: Early Tremadocian Quartz Diorite and Tonalite in the Infrastructure of the Oldest Peri-Gondwanan Magmatic Arc (Syntectonic Intrusion in Ductile Shear Zones Confined to the South Lake Igneous Complex Arc Ophiolite)

Location: 11.7 km (11.7 km)

Leave Glover's Harbour village and return to the junction with Route 350. Turn southward and drive about 5 km to the bottom of Osmonton Arm at Mill Pond, having traveled through the Wild Bight Group up to this point. Continue southward another 2.5 km along the east shore of South Lake, noting the cabin situated on a picturesque point of land. Drive about 200 m farther south and stop near a large exposure situated at E609924 N5471690. Participants should park on the gravel shoulder and safely cross the highway to the east side of Route 350. Please be cautious of traffic!

Regional Setting

The fault-bounded South Lake Igneous Complex is composed of several regionally extensive bodies of gabbro, diorite and tonalite (Figure 12). These intrusions are host to several discrete swarms of sheared mafic dykes. Ultramafic rocks are not present within this constituent of the Exploits Subzone of the Dunnage Zone.

Most of the plutonic and hypabyssal rocks in the South Lake Igneous Complex have been deformed and metamorphosed in certain localities, and some have been affected by multiple dynamothermal events. However, U–Pb zircon dating carried out by MacLachlan and Dunning (1998a) on some of the oldest mafic (*ca.* 489 Ma) and youngest felsic (*ca.* 486 Ma) plutonic rocks in the complex indicate a relatively short-lived period of igneous crystallization. The Early Tremadocian intrusion and coeval tectonism of the South Lake magmatic suite is considerably older than the depositional age of most of the adjacent rock formations and is unrelated to the regional deformation of these stratified rocks (Figure 12).

The oldest exposed part of the igneous complex consists of cumulate-layered or massive gabbro and schistose or flaser-banded metagabbro. Field relationships of *lit-par-lit* leucogabbro veins to variably sheared and foliated metagabbro indicate that intrusion of younger phases of the South Lake ophiolite accompanied deformation and metamorphism of its older phases. In some locations, these amphibolitized gabbros, hornblendite veins and crosscutting mafic dyke swarms were reworked in protomylonite zones prior to the intrusion of hornblende diorite.

The diorites and tonalites assigned to the South Lake Igneous Complex have been purported, on geochemical grounds, to comprise a comagmatic suite of primitive arc-related plutonic rocks (MacLachlan and Dunning, 1998a). The diorites display a characteristic negative Nb anomaly on extended rare earth element plots, but they are not enriched in the light rare earth elements (LREE). As such, they are distinct from the calc-alkaline diorites in the younger mature arc sequence in the Wild Bight Group.

The high-Si, low-K felsic magmas that crystallized to form the South Lake tonalites do not yield any isotopic evidence of interaction with continental crust in their melt region or upon their ascent. Furthermore, the diorite and tonalite intrusions are not related to each other or the older ophiolitic gabbro by fractional crystallization. Instead, both are thought to have originated as partial melts from a variably depleted mantle source (MacLachlan and Dunning, *ibid*).

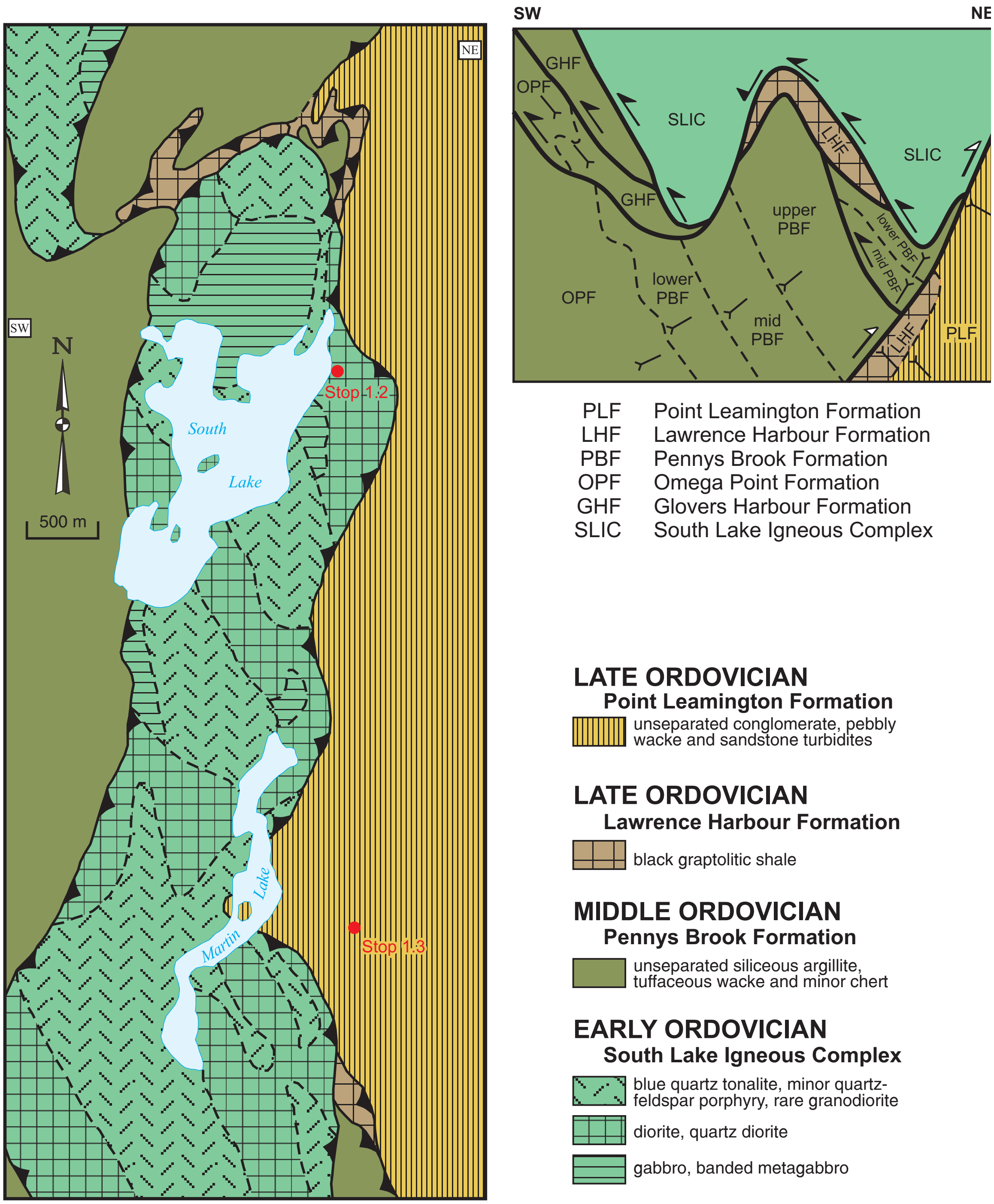


Figure 12. Simplified geological map and cross section of the Early Ordovician South Lake Igneous Complex in the South Lake–Martin Lake area showing the distribution of the constituent plutonic rocks. Also depicted are the complex's external relationships with the Pennys Brook Formation of the Wild Bight Group, the Lawrence Harbour Formation, and the Point Leamington Formation of the Badger Group. Note the displaced footwall syncline in the Wild Bight Group beneath the South Lake klippe. Locations of Stop 1.2 and Stop 1.3 are indicated.

The complex’s coarse grained bodies of quartz porphyritic tonalite were deformed in the magmatic state and the solid state. In places, megacrysts of zoned plagioclase and prismatic quartz show an intratelluric crystal-mush alignment within partially consolidated portions of the tonalite plutons. The unrecrystallized margins of these tonalites illustrate parallel trains of flattened and extended cognate xenoliths crosscut by mafic dykes. Subsequent attenuation, boudinage and partial disaggregation of these diabase dykes overlapped the deformation of the granitic lits back veined from the host tonalite into the synplutonic minor intrusions. Such zones are the preferred site of emplacement for a later suite of composite felsic-mafic dykes.

Tonalites affected by crystal-plastic deformation are observed to be emplaced as a series of anastomosing and tapering sheets that are well foliated but poorly lineated. Schistose bodies display a solid state foliation that is defined by ribboned grains of bluish grey quartz as well as reorientated and neocrystallized amphiboles. Undeformed mafic dykes crosscut the ribboned quartz fabric in metamorphosed tonalite.

The regional partitioning of hornblende diorite and quartz tonalite bodies is strikingly evident in the north of the igneous complex, where mesozonal synmagmatic shear zones in these arc-related plutons wrap around enclaves of ophiolitic metagabbro. Xenoliths of flaser gabbro and hornblende diorite in quartz tonalite indicate that the younger plutons ascended through a tectonically stitched assemblage of older igneous rocks. An internal system of ductile shear zones of intra-ophiolite or arc-root origin were transected obliquely by the Silurian thrust faults that defined the complex's external boundaries.

Description

Bodies of hornblende diorite and quartz–hornblende diorite in the South Lake Igneous Complex vary from fine- to coarse-grained, equigranular to schlieren-textured, and commonly contain mafic pegmatites in diffuse pods or cavities. They are mostly composed of hornblende and cumulate plagioclase, although relict clinopyroxene and late interstitial quartz is present. Like the exposure to be examined, most bodies of quartz-bearing diorite are unfoliated or weakly schistose. In contrast, hornblende diorite bodies on the west side of South Lake are strongly schistose. They contain minor felsic or mafic intrusions that are either foliated along with their host rocks or are autokinematically deformed.

West of the linear outflow of South Lake, a large body of albite-bearing tonalite and quartz-rich granodiorite transitional to microgranite and quartz-feldspar porphyry crosscuts the intrusive contact between hornblende diorite and ophiolitic metagabbro (Figure 12). Near the tombolo on the north shore of the lake opposite Stop 1.2, an unfoliated sericitized sheet of chalcopyrite-bearing tonalite contains xenoliths of mafic mylonite and has been absolutely dated at *ca.* 484 Ma. Narrow dykes related to this intrusion crosscut the quartz–hornblende diorite body exposed along this part of Route 350.

The oldest mafic dyke swarm hosted by metagabbro can be seen in the barren exposures located on the north side of the lake, if lighting conditions are good. Looking southwestward from Stop 1.2 to the tip of the peninsula projecting into South Lake, participants can view a large lake shore exposure located near the southern boundary of the sheared ophiolite (Figure 12). At this site, a crosscutting tonalite intrusion has been absolutely dated at *ca.* 487 Ma.

Discussion

It has been argued that the intrusive rocks in the South Lake Igneous Complex and the extrusive rocks in the lower Wild Bight Group not only formed at the same time in the Early Tremadoc but that they were geochemically and geodynamically related to each other (*e.g.*, MacLachlan and Dunning, 1998a). Each was thought to occupy a different tectonic level of the suprasubduction zone crust that lay above the Early Ordovician mantle wedge.

The South Lake Igneous Complex records the mid-crustal evolution of a peri-Gondwanan magmatic arc emplaced into a relict arc ophiolite of the eastern Dunnage Zone. Several periods of ductile deformation, dynamothermal metamorphism and mesozonal plutonism were focused in precursor and contemporaneous shear zones during the rise of the arc diorite and tonalite magmas. As magmatic state and solid state deformation proceeded within the complex, synplutonic shearing was continuously focused into progressively younger intrusions. Shear zone deformation overlapped, with declining influence, the emplacement of the intrusions that comprise the northern portion of the complex.

Early Tremadocian shear zones are transcurrent structures confined to the South Lake Igneous Complex. They are unrelated to a pre-Penobscottian orogenic event or, for that matter, any other phase of regional ductile deformation that had affected the Wild Bight Group. However, the structures localized in the plutonic infrastructure of the oldest primitive arc may have been governed by the same tectonic forces that controlled the evolution of the Glovers Harbour Formation, in particular the subvolcanic intrusion of alkali gabbro within the suprastructure of the rifting oceanic arc and the felsic volcanism focused within the soda rhyolite-filled grabens.

STOP 1.3: Tonalite-bearing Pebbly Wacke Sourced from Exploits Subzone Rocks near the Southwest Margin of the Point Leamington Basin (Badger Group Channel-fill Deposits above a Scoured Earliest Katian–Latest Sandbian Substrate)

Location: 4.1 km (15.8 km)

Leave Stop 1.2 at South Lake and proceed southward along Route 350 for almost 4 km until the Western Arm of New Bay comes in sight from a ridge overlooking the fjord. Park so as not to impede traffic on the gravel road leading eastward to Cooks Cove and walk downhill along the eastern side of Route 350 about 150 m to a road side exposure located at E610938 N5467940 (see Figures 2 and 12 for location).

Regional Setting

A coarsening-upward Late Ordovician lenticle of massive pebbly wacke and polymictic cobble conglomerate strikes discontinuously for some 20 km along the western margin of the Point Leamington structural–sedimentological basin. In most places, these poorly stratified rocks are underlain and overlain by well-bedded sequences of sandstone turbidite, although they locally interfinger to form lateral splits. The entire sequence from the top of the conglomerate downward to the lowest Point Leamington sandstone varies from about 0.5 to 2 km in thickness around the basin margin. Such strata are thought to be early–mid Katian in age or, alternatively, to lie near the Caradocian–Ashgillian boundary within the revised chronostratigraphic column for the British Ordovician System (Figure 1).

A sporadically fossiliferous sequence of light grey shale and interstratified siltstone comprises a lithological subdivision that is situated at the stratigraphical base of the Point Leamington Formation in certain parts of the basin. The fissile grey shale has a distinctive electromagnetic signal and vertical gradiometer pattern relative to the black pyritic shale of earliest Katian age (Late Caradocian) that conformably underlies it. Grey shale and siltstone is observed to be intercalated with very thin beds of fine-grained sandstone found at the bottom of the early–mid Katian sequence. In most localities in the Point Leamington basin, the overlying sandstone turbidites extend upward to the base of the lowest pebbly wacke.

In other parts of the field trip area, and elsewhere in central Newfoundland, the basal grey shale division of the Badger Group is known to belong to the Pleurograptus linearis graptolite biozone (Williams, 1991; the second oldest graptolite biozone of the Katian; alternatively, the earliest Pusgillian Stage of the Ashgillian succession; *ca.* 453 Ma – *ca.* 450

Ma). In Point Leamington Harbour, the sandstone turbidite sequence lying above the wacke–conglomerate lenticle is capped by graptolite-bearing strata that belong to the *Dicellograptus complanatus* Zone (middle Katian; *ca.* 449-448 Ma; Figure 13).

Description

Unstratified clast-supported sedimentary rocks make up most of the exposure at Stop 1.3. The main representative lithologies are poorly sorted pebbly wacke and featureless granular sandstone. However, in a few places, fine grained feldspathic sandstones form laterally discontinuous beds, at least 5-10 cm thick, before passing upward into massive lithic wacke. Some horizons of pebbly wacke display an erosive base and are locally marked by a basal cobble-bearing lag, possibly indicating deposition by turbidity currents within small channels.

Under the hand lens, a large proportion of the detritus in the wacke is seen to be dominated by internally fractured clasts of individual minerals. Of the coarse grains, the most abundant are prismatic plagioclase and blue quartz crystals. Rarer subangular grains include fresh black amphibole and altered green pyroxene; magnetite and titanite are also locally present.

Well-rounded pebbles of quartz-phyric tonalite are conspicuous in this exposure, although smaller rhombohedral clasts of laminated chert and volcanic rocks are also observable. In thin section, the gritty lithic clasts are also polymict in nature. They include netveined schist, foliated granite, metadiabase, and plagioclase porphyritic diorite. Angular detrital fragments of layered felsic crystal tuff, chloritized quartz-feldspar porphyry and ankeritized vesicular basalt are also seen in very coarse-grained wacke.

Volcanic strata are unknown in the Point Leamington Formation. Sandstone intraclasts are not abundant in the lowest wacke–conglomerate lenticle, although siliciclastic rocks fragments are common higher in the Late Ordovician succession. It is evident that the extraclasts in this lenticle had undergone little mechanical weathering during transportation and that the source area was not significantly affected by chemical weathering prior to erosion.

Discussion

In most places along the western margin of the Point Leamington basin, the lowest wacke–conglomerate lenticle is separated from the Early Ordovician rocks of the South Lake Igneous Complex and the Glovers Harbour Formation of the lower Wild Bight Group

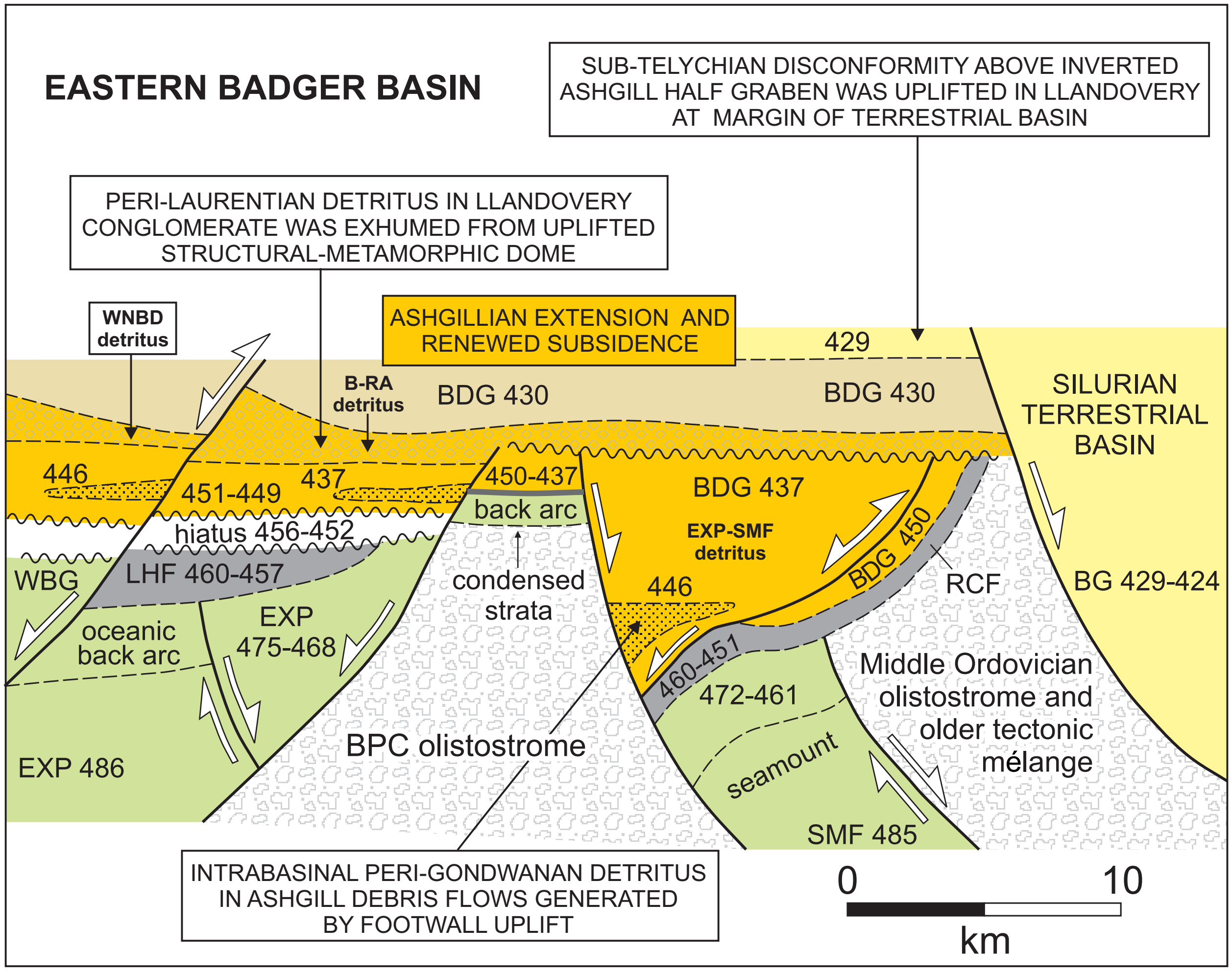


Figure 13. *Figurative cross section showing the restored Silurian geometry of part of the Badger retro-arc foreland basin. In the eastern portion of this basin, peri-Gondwanan source areas were exposed and eroded during the Ashgill by footwall uplift of conjugate normal faults. Mid Ordovician and older arc detritus was deposited during the opening of certain Late Ordovician depocentres. Interpreted to have formed by renewed offset of back arc growth faults, the Ashgillian extensional structures were themselves reactivated during a Telychian shift to syndepositional contraction in the Badger Basin, when the half-grabens of certain depocentres became partially inverted.*

Farther west, Llandovery syndepositional contraction faults controlled polymictic conglomerate development during a 436-430 Ma interval of piggyback basin formation. Hanging wall-up movements in the Telychian shortening basin were coeval with the uplift and emergence of tectonic domes located to the west of the Badger Group. At this time, the oldest arc and ophiolite detritus came from the Taconian Western Notre Dame Bay (WNDB) belt. Exhumation of the Early Silurian metamorphic rocks allowed for the transport of Early Salinic metamorphic detritus sourced from the peri-Laurentian Buchans–Robert's Arm (B-RA) belt and the Red Indian Line (RIL) mélange belt.

by a relatively thin, highly faulted sequence of late Middle Ordovician and early Late Ordovician strata. However, in several localities between South Lake and Martin Lake (Figure 12), early Tremadocian plutonic rocks directly overthrust Katian sedimentary rocks similar to those described above.

Between the exposure examined at Stop 1.3 and West Arm Brook about 1 km to the south, the basal sedimentary contact of the pebbly wacke cuts downward through the oldest sandstone turbidites into the *Pleurograptus linearis* Zone grey shale of the basal Point Leamington Formation (Figure 13). Passing farther south and cutting deeper through a highly condensed sedimentary succession, it lies above *Dicranograptus clingani* Zone black shale belonging to the upper part of the underlying Lawrence Harbour Formation (early Katian). In one locality north of the brook, the pebbly wacke appears to have been deposited above *Climactograptus bicornis* Zone pyritic shale and black siltstone located within the middle part of the Lawrence Harbour Formation. Here, the dissection level of the depositional substrate beneath the Katian pebbly wacke had presumably reached downward as far as the top of the local Sandbian sequence (mid Caradocian).

In several locations along the western margin of the Point Leamington basin, strata in the same black shale sequence are as old as the earliest Sandbian (*Nemagraptus gracilis* Zone, earliest Caradocian). Near Osmonton Arm and Western Arm, the basal black shale sequence is observed to gradationally overlie a Darriwilian–Sandbian mottled turbidite succession that rests above alkaline basalt lenticles within the uppermost parts of the Wild Bight and Exploits groups. This is interpreted to mean that, in mid Katian times, a large submarine canyon was incised into unconsolidated sediment near the basin margin and that syndepositional scouring near the canyon head had unburied the lower part of a Late Ordovician sequence that had originally overstepped the boundary between the Wild Bight Group and the Exploits Group.

A spectacular mud-rich debrite can be seen to underlie the lenticle of tonalite-bearing pebbly wacke along the banks of West Arm Brook. Although this debris flow had accumulated above earliest Katian black shale of the Late Ordovician Lawrence Harbour Formation, it displays large exotic clasts of coral-bearing limestone that have yielded Middle Ordovician fossils (late Arenig to Llandeilo conodonts, F.L.C. O'Brien, 1992, pers. com.). Near South Lake, similar coralline limestone occurs as rounded detrital clasts in a carbonate conglomerate interbedded with early Darriwilian volcaniclastic turbidites in the middle part of the

Pennys Brook Formation of the Wild Bight Group. It appears that the channel filled by the pebbly wacke was localized along a preexisting undersea landslide.

The transgressive *Nemagraptus gracilis* Zone shale found near the base of the Late Ordovician overstep sequence is herein interpreted to have onlapped an edifice composed of South Lake tonalite and ophiolitic gabbro. It may have also been partially built up of mineralized Glovers Harbour volcanic arc rocks. This paleogeographic feature may have already existed in some form during the development of the Wild Bight extensional arc. Nevertheless, renewed uplift and further erosion of this proximal source area of early Tremadocian rocks occurred around the Sandbian–Katian boundary and may have been responsible for providing some of the magmatic extraclasts observed in the lowest pebbly wacke–conglomerate lenticle.

The region near the postulated head of the Katian canyon may have contained polymictic detritus recycled from several formations of the Wild Bight Group. If correct, peri-Gondwanan rocks located immediately south of the Red Indian Line would have comprised a catchment area that was one source of sediment for Early Katian synorogenic strata deposited in the Point Leamington basin. The Katian canyon may have provided a supply path for peri-Gondwanan detritus (Figure 13).

STOP 1.4: Concretionary Shaley Flysch in the Distal part of the Point Leamington Basin (Graptolite-bearing Abyssal Mudstone and Siltstone Turbidite of Uppermost Katian Age in the Point Leamington Formation of the Badger Group)

Location: 8.5 km (24.3 km)

Leave Stop 1.3 near West Arm Brook and proceed eastward along Route 350 for about 6 km until participants reach a T-junction with the main street in the Town of Point Leamington. Turn northward and drive along the paved road that edges the western coastline of Point Leamington Harbour. Pass onto a gravel road, drive a further 150 m, and park outside the gate of the last house overlooking Harvey's Cove. Do not impede access through the gate. If the owners are present, please ask permission to walk along a privately owned trail to coastal exposures located near E6165450 N5467900 (Figure 2).

Regional Setting

Viewed regionally, the turbidites of the Point Leamington Formation are thought to have been deposited in a rhomb-shaped trough. The Katian basin fill within this trough locally subsided above a more laterally extensive substrate of westward-thickening Sandbian strata. The northwestern and southwestern margins of the rhombohedral Point Leamington basin are underlain by the Wild Bight Group; whereas, the Exploits Group underlies its south-eastern and northeastern margins. Siltstone turbidites of mid–late Katian age overlie a highly condensed Middle and early Late Ordovician succession along the northeast margin of the basin. However, near its southwest margin, the same siltstone turbidites lie above a relatively thick succession of early–mid Katian strata. This is consistent with syndepositional evidence for a southerly-dipping regional paleoslope (Pickering, 1987).

The Late Ordovician subdivisions of the Point Leamington Formation are disposed about a major refolded syncline that is cored by the younger Randels Cove Conglomerate (Dec *et al.*, 1993). This coarsening-upward polymict conglomerate varies from about 50 m near the basin margin to 1000 m in thickness near the basin centre and ranges in age from the latest Katian to the earliest Hirnantian (in part, Rawtheyan stage of the Ashgill). It is everywhere characterized by the presence of large rounded boulders of carbonate-cemented volcanic conglomerate and bedded megarafts of reefal limestone.

Deep-sea mudstones and muddy olistostromes are exposed in the central part of the sed-imentological-structural basin beneath this extensive conglomerate deposit. Their age, thick-ness and general nature distinguish the basin fill of the Point Leamington depocentre from the infill of other Late Ordovician subbasins in the field trip area.

Description

Along the coast section, dark grey siltstone and interstratified laminated argillite com-prise very thin and laterally continuous beds. In places, light grey, fine grained sandstones have sharp bases, grade upward into siltstone, and are rich in detrital grains of blue quartz. Folded intrusions of porphyritic diabase are seen to be preferentially hosted by zones of strongly foliated slate.

At Stop 1.4, there are at least two intervals, each about 50-75 m in thickness, dominated by siltstone and argillite that also display numerous carbonaceous shale partings. These very dark grey or black layers commonly host unfragmented graptolites. Mudstone laminae rep-resenting the Bouma E-division are observable at the graded top of pyritic siltstone turbidites.

There are at least two graptolite localities in Harvey's Cove, one of which was docu-mented by Williams (1991). The faunal assemblages at both locations belong to the Dicellograptus anceps Zone (upper Katian; *ca.* 449-445 Ma), although strata at one of the localities may possibly reside in the lower *D. complexus* Subzone of the *D. anceps* Zone (Cautleyan stage of the Ashgill).

Discussion

The dark mudstones and siltstones seen at Stop 1.4 represent a deep water distal facies of the turbidite succession in the Point Leamington basin. They are best developed and thickest in the centre of the depositional basin and are demonstrably younger and more widespread than the grey mudstone facies located near Stop 1.3 at the basin margin. This suggests that this particular depocentre was widening and deepening with time, possibly indicating that sediment accumulation below the Randels Cove Conglomerate took place in a Katian stretching basin (Figure 13).

STOP 1.5: Multiple Mudstone-rich Olistostromes within an Unbroken Formation of Siltstone Turbidite (Intraclasts and Extraclasts within Slump Sheets of Latest Katian Age in the Centre of the Point Leamington Basin)

Location: 3.8 km (28.1 km)

Return through the northern part of the Town of Point Leamington passing along Main Street and turn at a major T-junction onto Leamington Heights Road. Drive westward about 1.5 km and look for a sharp bend in Leamington Heights Road located approximately 75 m from the junction with Route 350 at km 3.8. Leave the paved road at the bend, take a smaller gravel road and drive northwestward about 300 m to a fork. Stay on the road heading northeastward and then northward to Sharrons Cove. Continue to keep right for 2.1 km until a cabin is reached at a location to the immediate east of the culvert over Sharrons Cove Brook. Park in a cleared space along the road and, at a point to the east of the brook, walk a short distance to the low-lying coastal section to be examined. Proceed southeastward to the oldest olistostrome at E616384 N5468541. Participants should consider taking their ruck sacks and using appropriate footwear.

Regional Setting

Graptolites that are biostratigraphically useful have been discovered in several localities in Sharron Cove and also along the coastline of Southwestern Arm to the southeast (down section) and northwest (up section). The faunal assemblage found immediately below the stratigraphically lowest debrite indicates that the strata to be examined in this coastal section lie within the *Paraorthograptus pacificus* Subzone of *Dicellograptus anceps* Zone (uppermost Katian). Sedimentary blocks in the lowest olistostromal deposit are much older than the background siltstone observed between Harvey's Cove and Sharron Cove, but are similar in age to the Late Ordovician graptolite-bearing strata at the margin of the Point Leamington basin.

Environmentally sensitive dendroid (benthic or rooted) graptolites may be present in unbroken beds of deep marine origin between two of the stratigraphically highest debrites near Sharrons Cove Brook in the youngest part of the coastal section at Stop 1.5. Graptolite-bearing strata located farther northwest near Whitehorn Cove occur well above the muddy olistostrome-bearing section in the Point Leamington Formation at Sharron Cove; however, these sandy and conglomeratic turbidites also reside in the *D. anceps* Zone.

Description

Most of the debrite horizons in Sharrons Cove are less than 5 m thick and occur within the darkest grey turbidite intervals. They are mainly composed of small decimetre scale blocks of well-bedded wacke, sandstone and siltstone; however, larger fragments contain soft-sediment deformed siltstone beds outlined by mudstone partings. The bedding planes in the sedimentary blocks are commonly seen to be sharply truncated by matrix shale, although the margins of some blocks display tapered beds injected by sand and enclosed by mudstone. The internal portions of several of these debrites are observed to be clast-supported however, and made up almost entirely of transported blocks.

Some of the smaller debrites in the Sharron Cove section illustrate a stratigraphical base beginning with a fine-grained wacke that preserves features of traction sedimentation. Such wackes pass gradationally upward into sand-matrix rocks displaying block-in-matrix texture or diffusely into mud flows. In contrast, some mélange horizons are seen to have cut downward through underlying size-graded beds that comprise laterally continuous sequences in unbroken parts of the Point Leamington Formation.

In a spectacular debrite located at the southeast end of the Sharrons Cove section, graptolites were recovered from shale partings in two different sedimentary olistoliths, one belonging to the *D. clingani* Zone and the other to the *P. linearis* Zone. The distinctive coherently bedded clasts of bioturbated or mottled chert found in some of these debrites resemble the grey chert located immediately beneath *N. gracilis* Zone black shale in the type area of the Lawrence Harbour Formation and an identical grey chert located within the *N. gracilis* Zone in the type area of the Shoal Arm Formation.

Slump folds of interbedded siltstone and dark shale are commonly observed to become partially dismembered and pass laterally into blocks in muddy debrite. One such debris flow in the middle of the Sharrons Cove section also displays extraclasts of vesicular basalt and turquoise chert. These are typical of lithologies that occur locally in the uppermost parts of the Exploits and eastern Wild Bight groups, where they have been included in the succession assigned to the Exploits back arc basin. Mafic volcanic and hypabyssal rocks preserving a wide variety of primary textures comprise small but conspicuous olistoliths in some of the debris flows, especially those in the upper part of the Sharron Cove section.

Discussion

Most of the intraclasts within the debris flows at Sharron Cove are carbonate-rich concretionary siltstones similar to those found in the fossil-bearing *in situ* turbidites between the debris flows. However, a few of the rip-up clasts of nodular limestone contain conodonts indicative of the *Amorphognathus superbus–Amorphognathus ordovicicus* bizones (late Katian). Graptolite-bearing *D. anceps* Zone olistoliths have not been recognized in the olistostromal section at Stop 1.5, although this relationship has been documented within underlying *D. complanatus* Zone debrites elsewhere in the Point Leamington basin.

Unless the Middle–Late Ordovician substrate of the Point Leamington basin had become available as a source area in syndepositional arches within the basin centre, the extraclasts must have been derived from the basin margin. Therefore, for at least a second time, fluidized flows carried older blocks and other multi-cycled debris from an unstable margin toward the basin depocentre. Some far-traveled slump sheets scoured into and mechanically incorporated siltstone and mudstone that had possibly accumulated on the outer turbidite fan or abyssal plain.

In contrast, higher in the Late Katian succession of the Point Leamington Formation, carbonate extraclasts in *P. pacificus* Subzone lenticles of polymict conglomerate contain macroscopic corals and bryozoans. Thus, prior to the dawn of the Hirnantian, a shallow water reef may have flanked one of the margins of the Point Leamington basin. Bioclasts eroded from this putative reef were recycled along with volcanic arc detritus. At this time, some magmatic and metamorphic extraclasts may have had a peri-Laurentian origin (WNDB and B-RA detritus in Figure 13). They were transported and re-deposited in a much deeper Late Katian marine environment characterized by pyritic siltstones similar to those scoured by debris flows at Sharrons Cove. The destruction of Late Katian reefs could be interpreted as a result of the cooling of marine waters prior to a global glaciation in the early part of the Hirnantian or, if coeval tectonic forces were active and overbearing, it might indicate that the Point Leamington basin had switched from a stretching basin to a shortening basin (Figure 13).

The Late Ordovician zones of olistostrome and broken formation in this part of north-central Notre Dame Bay are orders of magnitude smaller than the Middle Ordovician zones of olistostrome and broken formation. Unlike some of the older block-in-matrix mélange belts, the Late Ordovician counterparts were not derived, in part, from pre-existing tectonosomes. Furthermore, evidence is lacking for interaction of the soft sediment-deformed Katian mudstones with contemporaneous magmatic rocks.

DAY 2

TRAVEL DIRECTIONS TO BEGIN DAY 2 OF THE EXCURSION

Take the Trans-Canada Highway (Route 1) from Grand Falls eastbound about 20 km to Exit 22 (Route 350 North). Then drive northward along the Botwood Highway a further 20 km to the Town of Northern Arm and the junction between Route 350 and Route 352. Continue northwestward toward the Town of Point Leamington by taking Route 350 and driving another 18 km along this paved highway. Stop 2.1 below is the first exposure to be examined on Day 2 of the field trip (Figure 14).

STOP 2.1: The Tea Arm–Saunders Cove Transition from Hematized Boninitic Andesite to Jasperite and Replacement Chert in the Lower Exploits Group (Compacted, Silicified and Slumped Blocks of Cupriferous Pillow Lava in a Size-graded Carbonate-bearing Breccia)

Location: 9.0 km (9.0 km)

Take Route 350 northbound to the signpost marking the southern entrance to the Town of Point Leamington. Turn northward at the T-junction with Pleasantview Road at the 0.0 km location for Day 2 (if one crosses the highway bridge over the New Bay River, you have driven approximately 250 m too far!). Passing initially along the southeast side of Point Leamington Harbour, drive about 9 km to the end of this paved road at Paradise Cove in the village of Pleasantview. Park the vehicles near a large rock exposure on the north side of the road without blocking the entrance way to the shellfish plant. From here, participants will walk about 750 m northward to Mouse Cove and, therefore, they should use appropriate footwear and outerwear.

The owner of the last house in Paradise Cove should be consulted before crossing private property to take the trail to Mouse Cove. Please leave the asphalt-covered driveway about 3 m north of the main road to access this footpath. First walk westward around a vegetable garden before turning northward along a fenced agricultural field. Please realize that there are several intersections with other trails that do not end in Mouse Cove. However, if participants always KEEP RIGHT on the inbound hike, they will remain on the correct footpath. In sight of salt water, less than 100 m from the end of the trail, please verge northwestward through open to partially cleared ground to the shingle beach and then walk to the northwestern side of the cove. The Mouse Cove copper prospect is found within this coastal section at E622205 N5470046 (Figure 14).

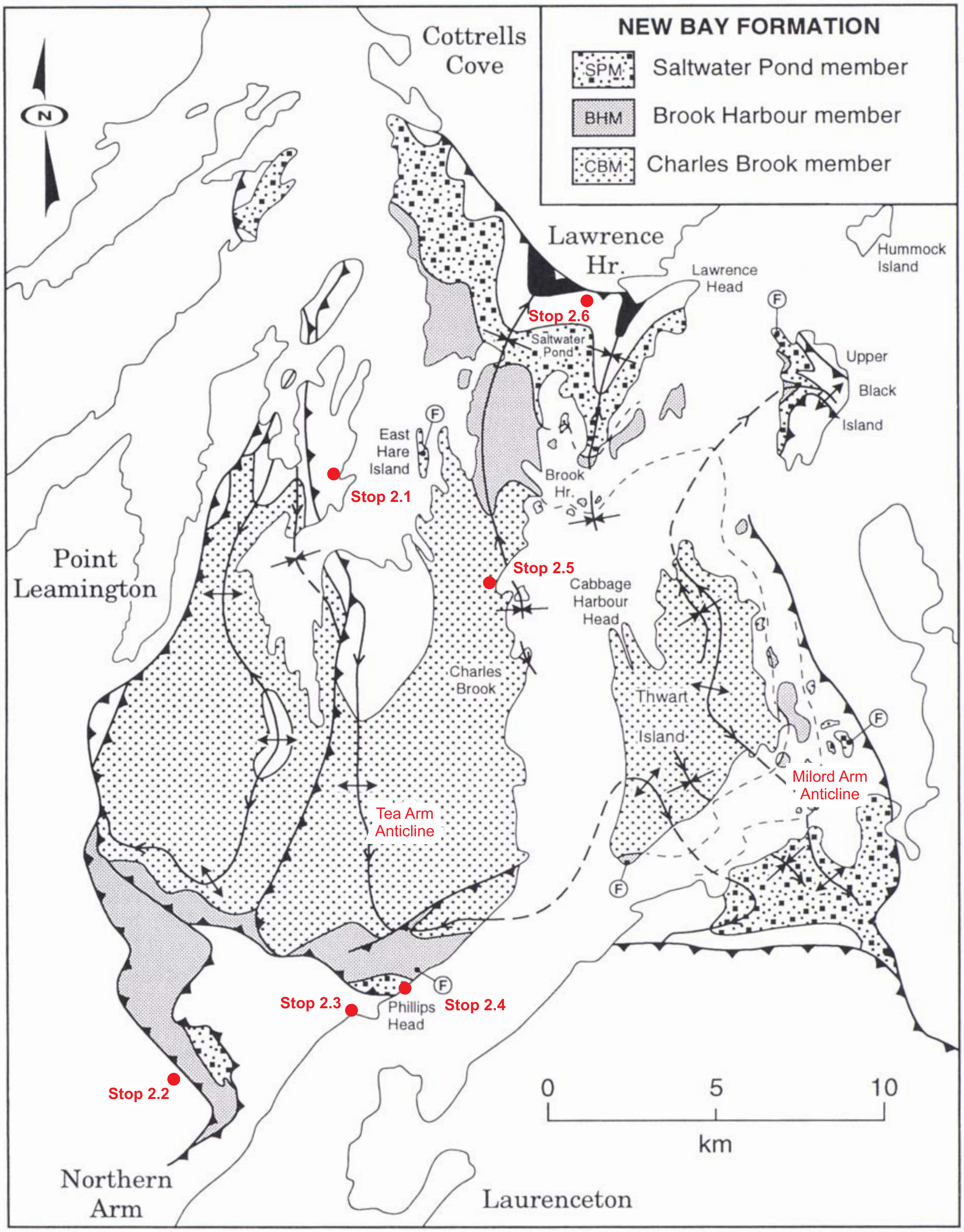


Figure 14. *Regional geological map highlighting the distribution and disposition of the various sedimentary members of the New Bay Formation of the Exploits Group in the New Bay–Bay of Exploits type area. Note the locations of Stop 2.1 through Stop 2.6. F = fossil locality in the New Bay Formation. Legend lists the three members of the formation in ascending order.*

Regional Setting

In the area north of Pleasantview, the Early Ordovician Tea Arm Formation of the Exploits Group is disposed in a regional northwest-trending periclinal anticline bounded by the northeast-dipping Paradise thrust zone (Figure 15). Both structures are overprinted by northeast-trending folds and allied reverse faults. Southeast of Mouse Cove, the stratigraphically overlying Saunders Cove Formation of lower Exploits Group crops out within one of these secondary structural features (a northeast-plunging syncline). Farther west, this rock formation comprises part of the structural footwall sequence that lay beneath the primary overthrust sheet carrying the older Tea Arm rocks (Figure 15).

The marine volcanic rocks of the Tea Arm Formation are generally represented by a lower division of island arc tholeiite and a mafic dyke swarm (Little Arm East Member), a relatively thin intermediate division of felsic pyroclastic rocks (Pushthrough Member) and an upper division of low-K calc-alkalic tholeiite and andesite (Pleasantview Member). They are interpreted to have been erupted in a primitive oceanic island arc (O'Brien *et al.*, 1997). The mineralized Pushthrough high-silica sodic rhyolites have been absolutely dated at *ca.* 486 Ma. Such early Tremadocian strata have been correlated with similar felsic and mafic volcanic rocks in the Glovers Harbour Formation of the Wild Bight Group (Stop 1.1). Rare lenses of crinoidal limestone occur within the carbonate-altered mafic volcanic rocks of the Pleasantview Member, although they are not biostratigraphically useful.

The red marine strata of the Saunders Cove Formation (Figure 16) have been historically correlated with the late Floian or older Omega Point Formation of the Wild Bight Group. The Saunders Cove succession typically includes laterally continuous beds of ribboned chert and jasperite, siltstone turbidite and replacement chert, and ferruginous and carbonaceous argillite. The graphite-rich argillaceous rhythmmites and exhalative laminites in the upper part of the formation comprise a regional marker horizon that, in some places, is scoured by coarse debrites carrying outsized blocks of stockwork-veined basalt.

A stratigraphical transition zone between the chloritic pillowed calc-alkaline basalt and hematitic porphyritic andesite breccia of the uppermost Pleasantview Member of the Tea Arm Formation and the red cherts and jasperites of the lower Saunders Cove Formation is up to 75 m thick (Figure 16). It is composed of several size-graded horizons of mafic pyroclastic strata and sedimentary breccia, both of which are marked by locally transported fragments of altered and mineralized rocks.

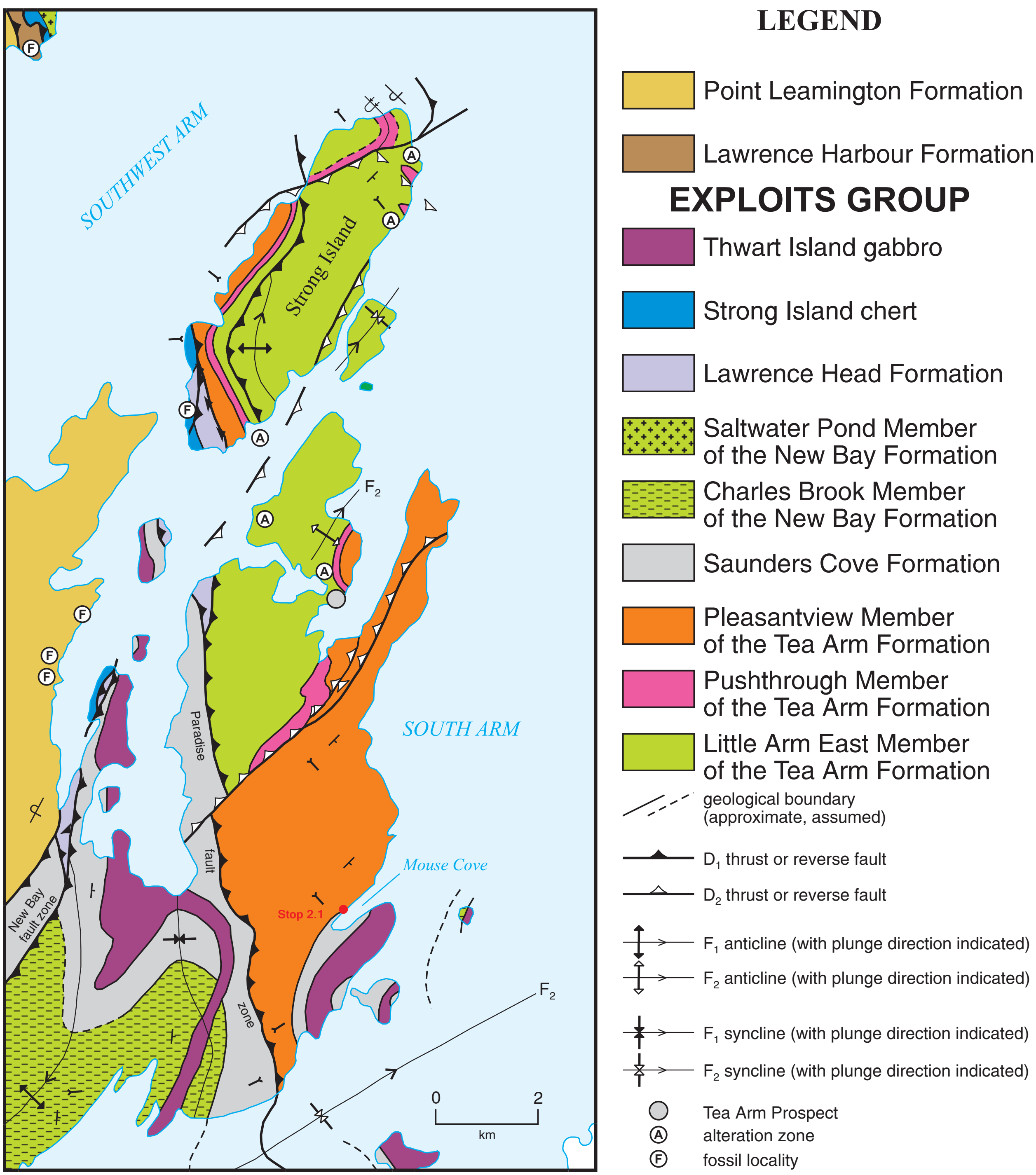


Figure 15. *Geological map of the Early-Middle Ordovician Exploits Group in the vicinity of the Mouse Cove prospect, emphasizing the disposition of the lithostratigraphic members of the oldest Tea Arm Formation and the overlying Saunders Cove Formation. Note the location of Stop 2.1 at the transitional boundary between these marine volcanic and hemipelagic sedimentary formations and its structural position within the regional hanging wall sequence of the northwest-trending Paradise overthrust.*

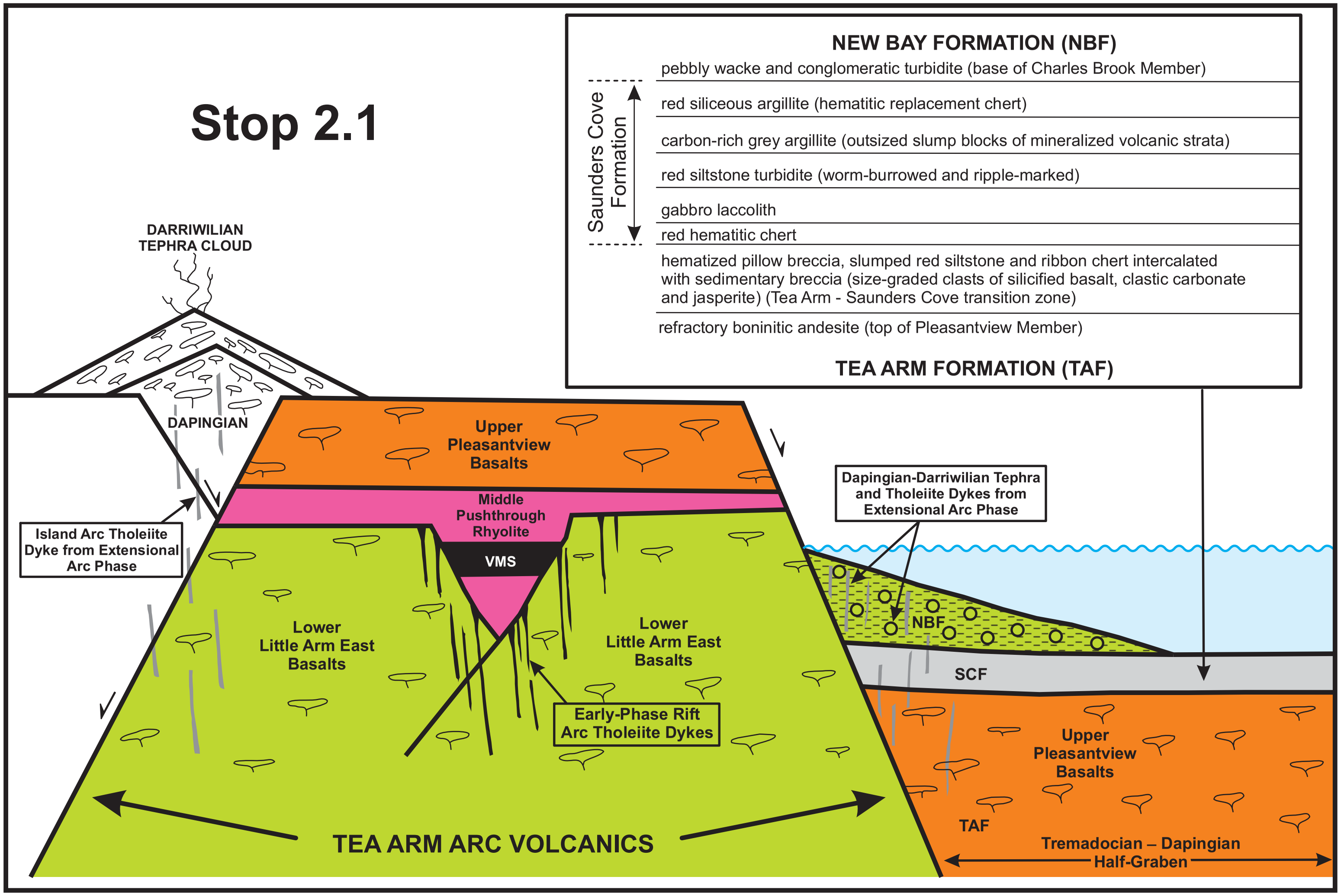


Figure 16. *Cross section illustrating an interpretation of the accumulation of the Tea Arm Formation and a palinspastic reconstruction of its relation to the Saunders Cove Formation and the lower New Bay Formation of the Exploits Group. Inset describes some of the rocks to be observed at Stop 2.1. The Middle Ordovician (Dapingian–Darriwilian) evolution of the primitive arc volcanic rocks is depicted and differentiated from the Early Ordovician (Tremadocian) history, thus invoking a model of episodic rifting, block faulting and extensional arc magmatism in this part of the peri-Gondwanan Iapetan realm. VMS = volcanogenic massive sulphide. Uncoloured horst block in the far left of the diagram may have been composed of Tremadocian volcanic and plutonic rocks from the Glovers Harbour Formation of the Wild Bight Group and the South Lake Igneous Complex, respectively. Darriwilian sea level is represented by the wavy blue line in the right side of the diagram.*

Hematized basalt and clastic carbonate are present as rounded cobbles and boulders in the overlying deep-sea turbidites of the New Bay Formation of the Exploits Group. Such detrital clasts are similar to the rocks observed in the Tea Arm–Saunders Cove transition zone, and one such bioclast in the New Bay Formation has yielded conodonts of early Arenigian (early Floian) age.

Description

The primary textures of the sedimentary and volcanic strata in the Mouse Cove section through the Tea Arm–Saunders Cove transition zone are readily discernible, although the rocks are locally strongly cleaved and deformed by steeply southwest-plunging chevron folds. Most of the Saunders Cove-type red beds seen in this coastal section are thin-bedded lutaceous strata associated with ferruginous chert. Prior to cementation and induration, these background sediments originally comprised a mudstone sequence interbedded with siltstone turbidite.

In places, some of the red lutites illustrate clast-supported pebbles and matrix-supported granules of grey basalt, including chlorite-altered, carbonate-altered and quartz-altered varieties. It is presumed that the matrix of these fine siliciclastic beds was already red when the detrital grains accumulated by traction on the ocean floor. In other areas where the Tea Arm–Saunders Cove transition is well exposed, the red siltstones and hematitic cherts are associated with narrow bands of oxide facies iron formation.

One of the characteristic features of the Tea Arm–Saunders Cove transition is the presence of stratabound redox boundaries in both the vesicular basalt flows and the clastic sedimentary strata. Concentrically zoned amygdules in trachytic and andesitic flows can be observed to be distorted by a flow foliation outlined by plagioclase laths. The growth sequence of replacement minerals is epidote, calcite, chlorite, magnetite and hematite. At the Mouse Cove prospect, intense silicification and sulphidation predated iron oxidation, chertification and gossan formation.

In many places along the coastline, the matrix of the sedimentary breccias is observed to be the most jasper-rich part of the deposit. This suggests that fluids percolated through the sedimentary matrix after accumulation of the suspensed load or during cementation and burial. However, some of the coarse-grained breccias display jasperite clasts derived from the jasperitized tops of individual basalt flows, altered clasts of chalcopyrite-bearing basalt derived from underlying mineralized pillow breccias, and clastic carbonate – lava megaclasts derived from pillow lavas lower in the succession.

In contrast, other blocks of altered volcanic rocks are seen to have been relatively soft upon incorporation. They became further fragmented and injected by the hematitic matrix upon compaction of the well stratified breccias or the lateral flow of the incoherently bedded debrites. In Mouse Cove, differentially compacted pillow lavas are selectively replaced by jasper-bearing chert arrays and then slump folded. The coexistence of fresh and altered fragments within many of the graded breccias indicates that accumulation of the mixed volcanic-sedimentary deposits overlapped the development of several sulphidation and oxidation events affecting the substrate and infill of the transition zone basin.

Discussion

It is postulated that Ordovician swarms of mafic dykes and related synvolcanic graben formed during and after the accumulation of the Tea Arm Formation and the Saunders Cove Formation. This occurred during discrete Early and Middle Ordovician events in the evolution of the lower Exploits Group (Figure 16).

In some places, the felsic volcanic fill of Tremadocian graben became tectonically uplifted and resedimented in Dapingian–Darriwilian turbidites. This is believed to be due to the fact that the zone of rifting shifted with time and, consequently, some of the older down-dropped blocks were re-positioned within newer horsts (Figure 16). Alternatively, in other locations, volcanically active areas were built up above graben that had opened above older horst blocks and dormant volcanic edifices. Such depocentres formed during several phases of extension that were operative within this peri-Gondwanan volcanic island arc (Figure 16).

The uppermost Pleasantview pillowed andesites and the lowermost Saunders Cove jasperites are interpreted to have been deposited in a Tremadocian–Dapingian half-graben (Figure 16). This second-order feature lay beneath a northeastward-thickening depocentre within the larger basin that controlled the accumulation of the middle and upper parts of the Exploits Group (Figure 4). Active faulting during deposition of the red lutites exposed parts of the upper Tea Arm Formation, made it available as a source area of altered volcanic rocks, and possibly aided in the transportation of this detritus in the Saunders Cove debris flows.

In most parts of the northeastern Exploits basin, such Tea Arm rocks are presumed to have remained buried beneath the Saunders Cove Formation. However, some 4 km north of Mouse Cove on Strong Island, the Saunders Cove Formation is observed to be missing at the depositional boundary between the early Darriwilian strata of the upper Exploits Group and the Tremadocian–Floian (?) strata of the Pleasantview Member of the Tea Arm Formation.

The stratified chert beds and clastic carbonate pods in the Mouse Cove section have not yielded any microfossils. Despite the fact that worm burrows are present in ripple marked red siltstone, the cherts and carbonates have not preserved any record of micro-organisms having been present prior to silicification. Thus, although the association of the mafic volcanism with the silica-carbonate alteration is strong, evidence for a hydrothermal versus biogenic origin for sedimentary rocks in the Tea Arm–Saunders Cove transition zone is locally absent.

STOP 2.2: Chert–Mudstone–Turbidite Transition in a Condensed Overstep Sequence of the Graptolite-bearing Upper Ordovician Shoal Arm Formation (Southwest-directed Structures in part of a Triangle Zone below Overthrust Sheets of the Exploits and Wild Bight Groups)

Location: 22.8 km (31.8 km)

Return by foot to Paradise Cove and drive along Pleasantview Road back to Route 350. Continue southward from the junction some 13 km along Route 350 to Stop 2.2 located at E617553 N5451879 near a sharp bend in the highway (Figures 2 and 14). Without impeding traffic, park safely off the highway near the beginning of a small gravel road heading northeastward to the Frontier Fort Camp of the Botwood Boy's and Girl's Club. The exposures to be examined occur on both sides of Route 350. Please be cautious of vehicular traffic when crossing this busy segment of the highway, as the exposures are situated only 500 m northwest of the Department of Transportation and Works depot and about 5 km from the Town of Northern Arm.

Regional Setting

The early Late Ordovician Shoal Arm Formation is representative of the oldest overstep sequence known to stratigraphically overlie the rocks of the Exploits Subzone of the Dunnage Zone. This formation is distinguished by the presence of one of the thickest successions of early Sandbian hemipelagites in north-central Newfoundland.

Most workers consider the Shoal Arm Formation to be composed of 1) a basal subunit of red radiolarian chert, dark-grey manganiferous chert and green celadonite-bearing chert,

2) a conformably overlying intermediate subunit of light grey chert that is distinctively mottled and possibly bioturbated, and 3) a gradationally overlying uppermost subunit dominated by black carbonaceous shale. Several metre-thick sandstone turbidite beds define its upper stratigraphical boundary with the overlying beds of the Badger Group. All three subdivisions are present at Stop 2.2.

In the graptolite-bearing part of this formation, the highest black shale beds belong to the *Dicranograptus clingani* Zone (late Caradocian–Ashgillian boundary or early Katian); whereas, some of the stratigraphically lowest shales occur in the *Climacograptus bicornis* Zone (mid-Caradocian or late Sandbian).West of this locality, the basal subunit of ferruginous and manganiferous chert is known to reside within the *Nemagraptus gracilis* Zone (early Caradocian or early Sandbian).

Regionally, the Shoal Arm Formation is non-contiguous along its strike and, in only a few localities, does this unit preserve its original stratigraphical relations with both older and younger rocks. As a generalization, at least one of the external boundaries of the formation is an early-formed, northwest-trending thrust or reverse fault. These ductile structures are inclined, in different places, to the northeast and to the southwest (Figure 17). Between Northern Arm and New Bay Pond, laterally discontinuous tracts of folded and cleaved strata in the Shoal Arm Formation have had the reverse faults that define their external boundaries deformed by northwest-trending fold axes. These structures were overprinted by northeast-trending cross folds having attendant axial planar slaty cleavage.

Biostratigraphically constrained examples of schuppen structure and thrust faulting are found in the Sandbian to Katian sequence of grey chert and black shale. For example, in some parts of the Shoal Arm Formation, Sandbian strata are known to structurally overlie Katian strata (Figure 17). This older-over-younger relationship has been corroborated by the graptolite faunas present in the hanging wall and footwall sequences of some of the northwest-trending reverse faults. Certain faults within this imbricate system are responsible for local juxtaposition of the Exploits and Wild Bight groups.

The lithostratigraphic elements of the Shoal Arm Formation exposed in the road cuts at Stop 2.2 are typical of those occupying the early Late Ordovician interval in the Badger belt (Williams, 1995). Tectonically, the transition is generally from 1) variably reduced, ferruginous and manganiferous cherts that accumulated in locally starved or restricted marine basins to 2) graptolitic, anoxic, pelagic mudstones which formed during a trans-Iapetus high

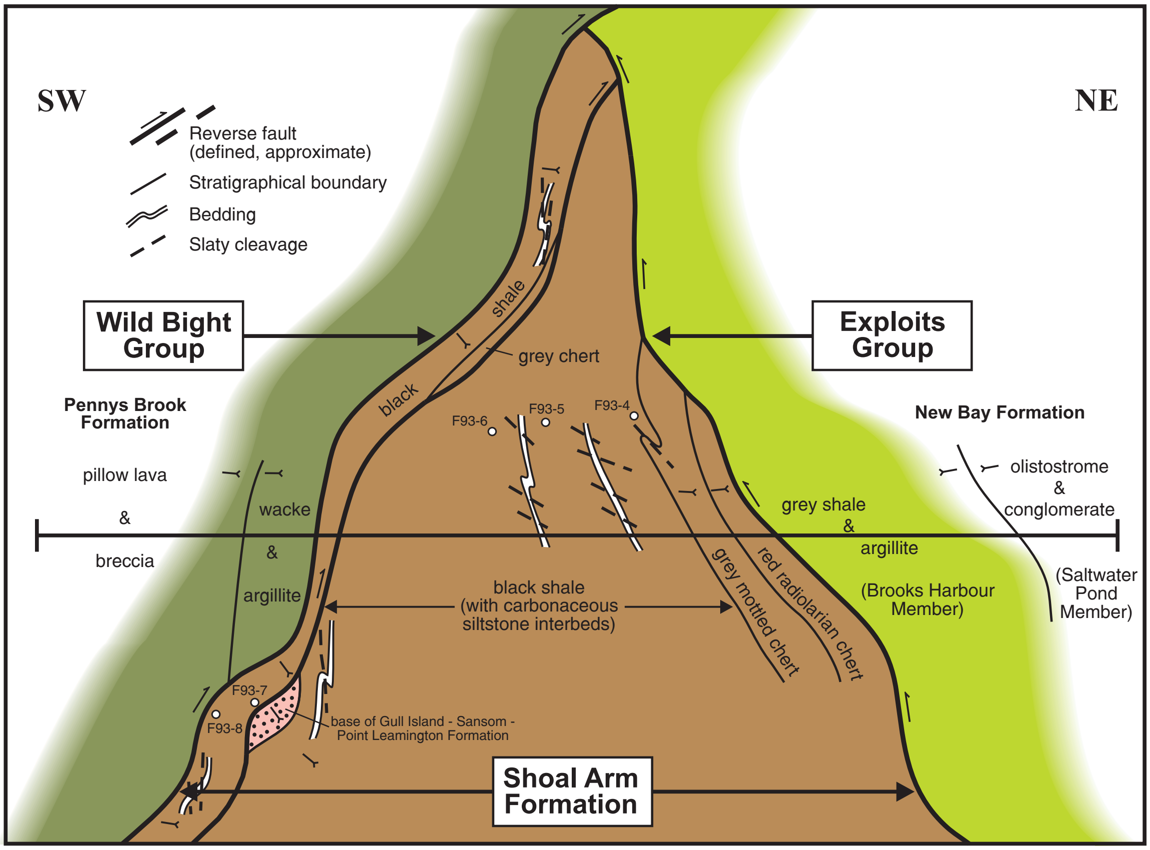


Figure 17. *Cross section, viewed looking northwest, showing the upper part of the structural triangle zone outlined by the Late Ordovician Shoal Arm Formation at Stop 2.2 near Northern Arm. The lithostratigraphic and structural position of the black shale-hosted graptolite localities (F93 series) is illustrated in each thrust sheet. Selected early-formed minor structures are schematically depicted; vertical scale is exaggerated.*

stand of sea level and that are locally enriched in metals to 3) synorogenic sandstone turbidites which have the lowest constituent olistostrome present near the base of the Badger turbidite succession or, locally, as the infill of erosional channels in the underlying black mudstone.

Description

Sandstone turdidites at the top of the Shoal Arm Formation are exposed in road cuttings on the west side of Route 350 opposite the road leading to the Frontier Fort Camp. At least one of the thick sandstone beds is observed to be conformably overlain and underlain by black graptolitic shale. However, approximately 200 m southwest of the highway, these Badger Group turbidites occur in the footwall sequence of a southwest-dipping reverse fault. There, the structural hanging wall sequence is made of older *C. bicornis* Zone black shales similar to those observed at Stop 2.2.

Gently plunging folds display a moderately northeastward-dipping axial surface in the black shale sequence located on the east side of the highway. These inclined folds are associated with a general southwestward direction of tectonic transport in the Shoal Arm Formation. Near the off-road to the camp, an asymmetrical antiform can be seen to have opposing subvertical and gently northeast-dipping fold limbs. Several asymmetrical antiform-synform pairs are also seen in shale exposures on both sides of Route 350. These northwest-trending minor folds are related to reverse faults with a northeast-over-southwest sense of displacement. A regional example of such a fault structure is located to the northeast of this Late Ordovician exposure, where it defines the boundary of an overthrust sheet carrying the Early Ordovician strata of the Exploits Group (Figure 17).

Walking northwards along Route 350 obliquely to the strike of the beds, participants traverse farther down the stratigraphy of the Shoal Arm Formation. Excellent examples of bioturbation are observable in the formation's grey mottled chert division. The underlying red radiolarian cherts of the lower Shoal Arm Formation occur within the northernmost of the highway exposures at Stop 2.2 and also at the end of the road leading to the camp site. Mafic dykes, which trend east-northeasterly across the folded Late Ordovician chert sequence, are thought to relate to some of the mafic dyke swarms present in the post-Devonian granitic phases of the Hodges Hill Intrusive Suite.

Discussion

The Shoal Arm sequence examined at Stop 2.2 is less than 300 m in thickness yet it ranges biostratigraphically through a considerable portion of the early Late Ordovician. Although it is unlikely that every lithological division is internally in correct stratigraphic order, a regional southwest-younging direction is evident for this particular section of the Shoal Arm Formation (Figure 17).

Considered as a whole, this Sandbian–Katian formation is demonstrably composed of a number of non-continuous tectonic sequences. Internal reorganization of the Shoal Arm Formation has been achieved by duplication and amalgamation of its primary constituent members, or through structural excision and fragmentation of parts of the unit.

Northwest of Northern Arm, the Shoal Arm Formation's cross-sectional geometry is interpreted as a structural triangle zone caused by the displacement of northeast-dipping reverse faults by southwest-dipping reverse faults (Figure 17). The depositional base of the Badger Group, which is preserved within this structural feature, is truncated by one of the bivergent reverse faults. Significantly, the graptolite localities within the black shales of the triangle zone are located, structurally, within separate southwest-directed and northeast-directed thrust sheets.

STOP 2.3: Pillow Breccia of Island Arc Tholeiite Composition within the Phillips Head Volcanoplutonic Complex (Thrust-bounded Inlier of the Wild Bight Group Extensional Arc Sequence within the New Bay Formation of the Exploits Group?)

Location: 12.4 km (44.2 km)

Continue southeastward along Route 350 to the junction with Route 352 in the Town of Northern Arm. Turn northeastward at the T-junction and drive approximately 8 km along Route 352 to Phillips Cove in the southern part of the village of Phillips Head. Stop 2.3 is located at the southern end of the shingle beach from which the public wharf and several fishing stages extend (Figures 2 and 14). The maximum available space for parking is found, unfortunately, on the northern shoulder of Route 352. Park safely there, cross the highway and walk to the large coastal exposure located closest to the road side.

Regional Setting

The volcanic breccias and basaltic lavas in the Phillips Cove section are openly folded, weakly strained and illustrate excellent primary textures (Figure 18). The Phillips Head volcanic succession becomes generally younger on proceeding northward around the headland toward a northeast-dipping thrust fault that separates the igneous complex from the structurally overlying New Bay Formation of the Exploits Group. At the west coast of the Bay of Exploits, this early-formed ductile structure is responsible for tectonic excision of the Exploits back arc succession from the hanging wall sequence. Inland, at various localities along the thrust faulted boundaries of the Phillips Head complex, the arc-related volcanic rocks are directly juxtaposed against early Middle Ordovician sedimentary rocks from the middle and upper divisions of the New Bay Formation. Structurally underlying thrusts in the northeast-dipping imbricate stack affect the Late Ordovician sedimentary rocks of the Shoal Arm Formation, as seen near Stop 2.2.

Mafic volcanic rocks in the Phillips Head Igneous Complex occur as enclaves within a pretectonic suite of highly vesicular diorites. However, the diorite intrusions are separated from all other stratified rocks in the region by the northwest-trending system of imbricate thrust faults. The Phillips Head plutonic rocks are extensively hydrated, intensely altered, and show textures indicative of intratelluric devolatilization. The diorite plutons, which are

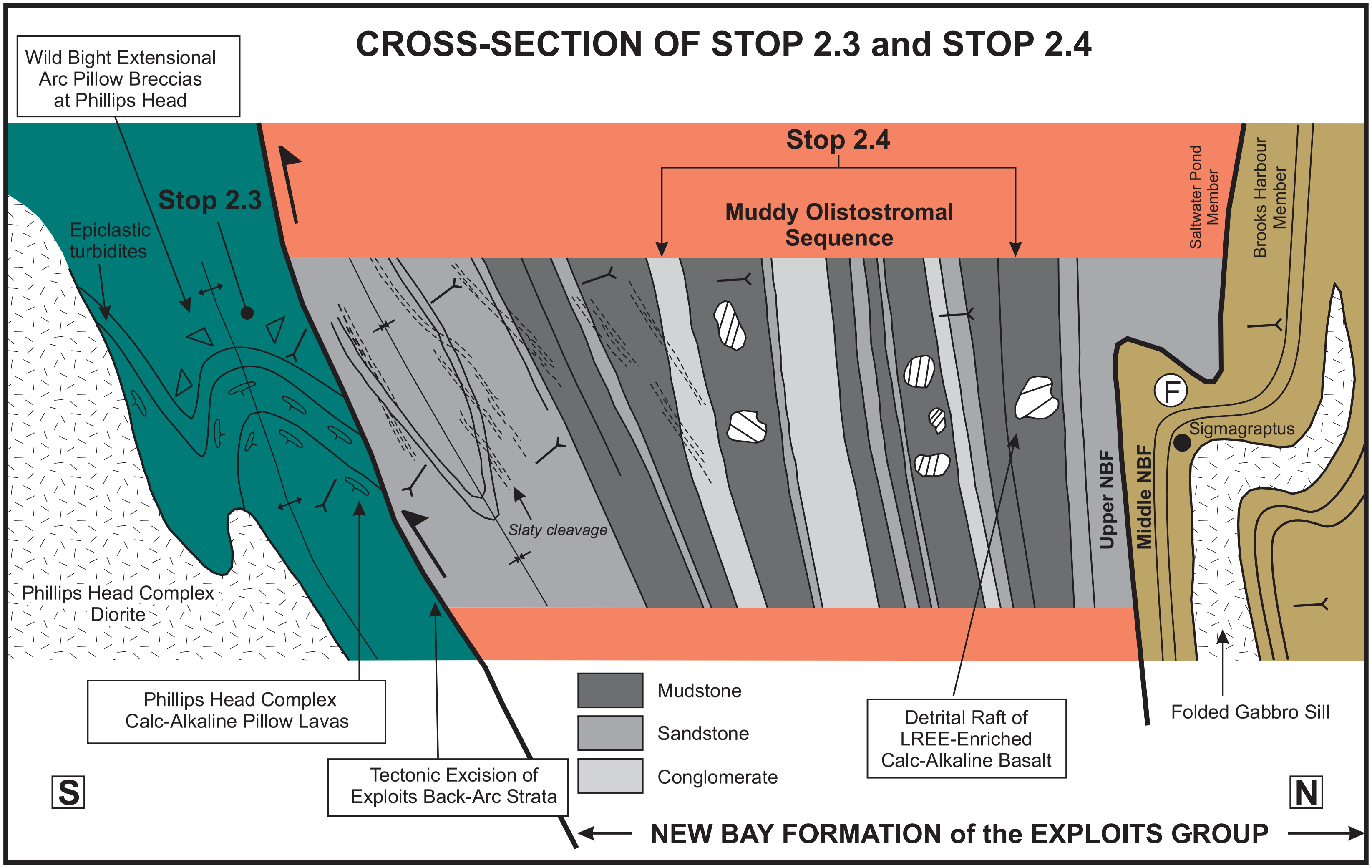


Figure 18. *Schematic cross section drawn along the coast line of the Bay of Exploits near the village of Phillips Head and incorporating the field trip localities at Stop 2.3 and Stop 2.4. Note the mafic volcanic strata of island arc origin in the Phillips Head Igneous Complex (younging northward), the muddy olistostromal sequence in the lower part of the Saltwater Pond member of the New Bay Formation (younging southward), and the local tectonic excision of the Exploits back arc succession. Stratified volcanic olistoliths occur along with exotic clasts of granite and limestone in these Darriwilian debris flows.*

host to suites of texturally similar mafic dykes, are interpreted as subvolcanic intrusions into the andesites, calc-alkaline basalts, and island arc tholeiites of the Phillips Head Igneous Complex.

Description

Rocks examined on the shore at Stop 2.3 are a part of the same sequence which is observable along the coast at the northern end of the shingled beach. On the headland, in addition to volcanic breccias, this sequence contains several discrete horizons of pillow lava separated by variably thick intervals of graded epiclastic turbidite (Figure 18).

Many of the mafic blocks in the volcanic breccia located by the side of the highway have chilled glassy rims. They display a wide variety of volcanic textures and some are evidently parts of larger pillows. A distinctive pyroxene porphyritic texture is seen in a number of the pillow fragments. A similar texture is present in the bedded lavas and it is also seen in a suite of minor intrusions that are regionally developed throughout the igneous complex. Pyroxene porphyritic basalts are uncommon in the volcanic formations of the Exploits Group.

Extended rare earth element plots of pillow lava and pillow breccia at Phillips Head show LREE patterns with pronounced negative Nb, Ti and positive Th anomalies (2540111 in Figure 19). Such rocks have LREE concentrations that are slightly depleted relative to HREE and this is consistent with the mafic volcanic rocks being of island arc tholeiite composition. In certain tectonic discrimination diagrams, the Phillips Head diorite plots within the field of high-K orogenic andesite. In contrast, the Phillips Head diabase plots within the N-MORB field.

Discussion

Volcanic lenticles made up of calc-alkaline basalt, andesite and island arc tholeiite occur within an epiclastic turbidite succession in the Middle Ordovician part of the Wild Bight Group (McConnell and O'Brien, 2000). There, they are also interstratified with mafic volcanic lenticles composed of LREE-enriched mid ocean ridge basalt, within-plate tholeiite, and alkali basalt. The regional intercalation of these types of rocks is characteristic of the Pennys Brook Formation of the Wild Bight Group.

The mafic volcanic rocks seen in the Phillips Cove section are best correlated with the island arc tholeiites in the tectonically adjacent Northern Arm Basalt sequence of the Pennys

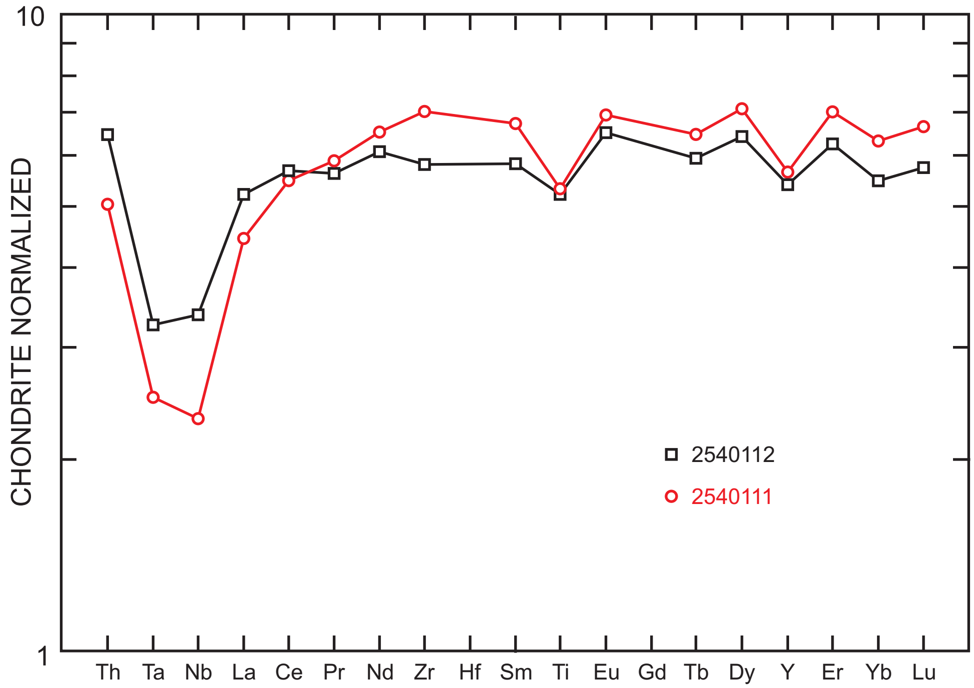


Figure 19. *Chondrite-normalized plots showing extended rare earth element (REE) patterns for pillowed basalts. Sample 2540112 is from a large raft within a Saltwater Pond debrite at Stop 2.4; sample 2540111 was collected at Stop 2.3 in the Phillips Head Igneous Complex. Note the positive Th–negative Nb anomalies and the generally flat light rare earth element (LREE) profile, typical of volcanic rocks that are transitional between island arc tholeiite and calc-alkaline basalt. Although evidently not from the same magma batch, the resedimented rafts of LREE-enriched arc-related basalt seen within the olistostromal deposits of the upper New Bay Formation of the Exploits Group are similar to the pillow lavas and pillow breccias in the Phillips Head Igneous Complex and to those in the Middle Ordovician extensional arc sequence of the Pennys Brook Formation of the Wild Bight Group. Primitive mantle-normalization values, indicated logarithmically on the ordinate, are approximately twice chondrite.*

Brook Formation. If this correlation is correct, the volcanic breccias at Stop 2.3 would represent a part of the Middle Ordovician extensional arc sequence that was erupted above the remnant peri-Gondwanan primitive oceanic arc and possibly the tectonically thinned Ganderian continental margin (MacLachlan *et al.*, 2001). The Phillips Head basalts are not nearly as LREE-depleted as the Tremadocian island arc tholeiites within the Tea Arm Formation of the Exploits Group.

The Phillips Head lavas may have originally comprised part of an Early–Middle Ordovician volcanic uplift that separated the Wild Bight and Exploits depositional basins and that was transgressed by Late Ordovician black shale. As such, the uplifted region could have provided volcanic arc detritus to the New Bay Formation (Figure 16), especially within the southwestern depocentre of the Exploits Group. However, it is also possible that the Phillips Head lavas comprise part of a completely allochthonous thrust sheet and that the petrochemical similarity with the pillow lavas found in the middle to upper parts of the Wild Bight Group is fortuitous.

STOP 2.4: Mudstone-rich Olistostromal Sequence within the Early Middle Ordovician Saltwater Pond Member of the Upper New Bay Formation of the Exploits Group (Detrital Megaraft of Arc-derived Pillow Lavas Associated with Re-Sedimented Beds of Plutonic Boulder Conglomerate)

Location:0.9 km (45.1 km)

Proceed northward through the village of Phillips Head bypassing the sign-posted roads leading to the World War II gun batteries on Phillips Head proper. Participants should take note of a cluster of houses near the shoreline on the southeast side of Route 352 in the northern part of the village. Park vehicles in a large clearing on the opposite side of the highway, cross the road safely, and walk to the most southwestern dwelling in this cluster. After consulting with the owner and asking for permission to access private property, open the fence situated near a culvert underneath Route 352. Take the gated staircase along the side of the house to the coastal section at E623732 N5454033 (Figure 14). The rocks to be examined at Stop 2.4 extend northward for approximately 250 m along the shore front.

Regional Setting

The deep-sea volcaniclastic turbidites of the New Bay Formation are a hallmark of the Exploits Group. They comprise the most regionally extensive division of this rock group (Figures 14 and 20) and, in places, are up to 1.5 km thick. In ascending order, the New Bay Formation is made up of the sandy Charles Brook Member, the muddy Brook Harbour Member and the conglomeratic Saltwater Pond Member.

The Saltwater Pond Member provides an indication of intrabasinal conditions immediately prior to the development of the Exploits Group back arc and its subsequent drowning and burial by starved pelagic shale. It is also considered, by some, to have been originally gradational with the Dunnage Melange and to be one of major sources of the sedimentary blocks present within the broken parts of this unit.

Near Phillips Head proper, the Lawrence Head Formation and the Strong Island Chert have been tectonically removed from the local succession of the upper Exploits Group by offset along a northwest-trending thrust fault. They are present, however, on the opposite shore of the Bay of Exploits near the hill farms (glaciomarine deposits) of Browns Arm, which can be viewed looking northeastward from Stop 2.4. There, the within-plate pillow lavas of the Lawrence Head Formation stratigraphically overlie the Saltwater Pond Member of the middle Exploits Group.

The Saltwater Pond Member of the New Bay Formation is also exposed northeast of Browns Arm on James Island, where detrital limestone clasts have been reported to yield conodonts indicative of an early to middle Arenigian age (Floian to Dapingian). They provide a lower limit for the depositional age of the upper part of the New Bay Formation. Fragments of unidentifiable graptolites and a possible example of *Sigmagraptus* are found in coastal exposures near the middle New Bay–upper New Bay boundary immediately north of this field trip stop (Figure 18).

Description

In that part of the Saltwater Pond Member to be examined at Stop 2.4, strata generally become younger southward from the contact with the underlying Brook Harbour Member (Figure 18). In the northern part of the section, sedimentary strata face stratigraphically southwestward, regardless of whether they are right-side-up or inverted. However, upside-down strata dip toward the northwest in the southern part of the section, as they have been cross folded and cross faulted by northeast-trending structures. Strongly cleaved north-facing beds locally occur adjacent to the southern tectonic boundary of the Saltwater Pond Member (Figure 18).

A mudstone-rich olistostromal succession typical of the lower part of the Saltwater Pond Member is well displayed in this coastal section. The exposures first encountered on the shoreline show the greatest proportion of dark grey mudstone and illustrate many of the textural relationships that mud rocks have with coarser-grained sedimentary rocks. Intraformational mudstone is seen wrapping around exotic clasts, and lozenges of mudstone have a streaked appearance in siltstone and in sandstone. Farther north in the succession, unsorted debrites having a sandy or muddy matrix contain subrounded clasts of mafic volcanic rocks, felsic plutonic rocks and limestone. Such poorly bedded rocks are intercalated with unbroken sequences of well-bedded turbidites, including graded beds of polymictic conglomerate.

Near a small wooded headland at the end of a pocket beach, a large raft of interbedded pillow lava and pillow breccia illustrates a primary depositional boundary with debrite. This contact is well exposed in the intertidal zone on the shoreline. The exposure is located at the northern end of the section to be examined at Stop 2.4.

In an extended rare earth element plot of the pillowed basalt from within the megaraft (2540112), the LREE pattern is seen to be relatively flat (Figure 19), especially in comparison to typical calc-alkaline basalt. However, the pattern also displays pronounced negative Nb, Ti and positive Th anomalies characteristic of most volcanic arc-related basalts. These transported pillow lavas are interpreted to be island arc tholeiites that are slightly less depleted in LREE than geochemically similar volcanic rocks in the Phillips Head Igneous Complex (2540111). Neither of these rocks is as strongly LREE-depleted as the tholeiite suite basalts found in the Tea Arm Formation of the lower Exploits Group.

The outsized blocks observed at Stop 2.4 represent large fragments of volcanic rocks that were already stratified and altered prior to incorporation in the host sedimentary rocks. The rounded boulders of bioclastic limestones and variably foliated plutonic rocks were eroded from an external source area, transported down slope, deposited in unconsolidated beds, and re-sedimented within debris flows.

Discussion

The edifice skirted by the Saltwater Pond depositional slope may have been part of a marine magmatic arc complex made up of Middle and Early Ordovician volcanic and plutonic rocks. This is suggested by 1) the presence of abundant detrital limestone and pillow basalt, 2) the mature island arc geochemical affinity of large transported rafts of basaltic lava, and 3) the similarity of the magmatic clasts in debrites to the Early Ordovician tonalites and arc diorites in adjacent parts of the South Lake Igneous Complex. Any combination of erosion and resedimentation could have taken place at or below the marginal slope of such an edifice. It is postulated that these processes may have led to localized non-deposition of the New Bay Formation near the Paradise Fault Zone and accumulation of relatively thick sequences of New Bay Formation turbidites along the southwest and northeast margins of the Exploits Group.

The thick sequence of olistostromes observed in the section north of Phillips Head may have been triggered by the earliest Darriwilian uplift of an exhumed block of peri-Gondwanan arc crust (Figure 10). Soft-sediment slumping of arc-derived detritus occurred above an unstable blanket of mudstone in the deep-marine environment. It resulted in the reamalgamation of well indurated volcanic and carbonate deposits from a supracrustal region of the arc as well as metamorphic tectonites and arc ophiolites from a deeply eroded part of the complex. Since the debris flows were generally formed from coarse-grained turbidites injected by mud, the olistostromes have been interpreted as probable slope apron deposits situated above the Brook Harbour abyssal plain.

STOP 2.5: Volcaniclastic Turbidites, Pyroclastic Flows and Gabbro Sills of the Charles Brook Member of the Lower New Bay Formation (Northeastern Subbasin of the Lower–Middle Ordovician Exploits Group near the Refolded Slates of the Sunday Island Syncline)

Location: 15.7 km (60.8 km)

Return to the vehicles parked in Phillips Head North and drive approximately 16 km northward along Route 352 to Charles Brook (Figures 2 and 14), once the site of a salmon fishing camp used by Beothuk Indians. South of the outflow of this brook into the Bay of Exploits, a cluster of several houses and wharves are seen to be scattered around a small protected boat harbour. If participants approach a bridge over a licensed salmon river, then you have traveled about 250 m too far!

Sunday Island comes into view where Route 352 runs along the south shore of the boat harbour. Proceed northward to a large road cutting on the east side of the paved road. The exposure to be examined begins near the junction with a small gravel road heading around the north side of the cove. Park safely on the shoulder of the highway near the access road (E626916 N5466535) and do not impede traffic to the cottages. Please be aware of small children and be cautious of oncoming all-terrain vehicles!

Regional Setting

The Charles Brook Member of the lower New Bay Formation is approximately 850 m thick and is mainly composed of epiclastic sandstone turbidites. These pale green to light grey siliciclastic strata display complete Bouma intervals, are commonly cross bedded, and have abundant flutes, tool marks and other bottom structures. In the northeastern structural basin of the Exploits Group, terrigeneous sediment in the Charles Brook Member was generally dispersed to the east and northeast during the construction of the outer part of a submarine fan.

In the lower part of the Charles Brook member, the well-bedded sandstone succession is scoured by massive pebbly wackes having rare conglomerate lags. Such deposits are rich in epiclasts of hematitic basalt and intraclasts of thixatropically deformed sandstone. In the middle to upper part of the Charles Brook Member, conspicuous lapilli stone horizons are rich in tuffaceous fragments, are locally interstratified with dark grey argillite and siltstone turbidite, and are intruded by a regionally folded suite of gabbro sills.

At East Hare Island, along strike of Stop 2.5 (Figure 14), Charles Brook turbidites have yielded transported fossils including unidentified inarticulate brachiopods and fragmentary graptolites. Based on several lines of evidence, this member is demonstrably older than late Middle Ordovician (Darriwilian) and is presumed, at least in part, to be late Early Ordovician (mid Arenigian or late Floian–early Dapingian).

Columnar-jointed gabbro laccoliths of known Ordovician age illustrate margin-parallel pegmatitic schlieren, graded cumulate layering, crescumulate texture and other geopetal features. Some of the thicker sills have an island arc-related geochemical signal and display peperitic margins where they intrude the chert succession in the upper part of the Exploits back arc basin. Other sheeted gabbro complexes are interpreted to be consanguineous with the tholeiitic pillow lavas that overlie the New Bay Formation. Pretectonic diorite sills emplaced into Charles Brook turbidites locally produce a centimetric scale zone of spotted hornfels in well-consolidated sedimentary strata. On Thwart Island, an arc-related gabbro sill hosted by the Charles Brook Member is known to be late Darriwilian in age.

Early-formed slaty cleavage, mesoscopic parasitic folds and small high-angle reverse faults trend northwestward in the New Bay Formation on the northeast limb of the northwest-plunging Sunday Island Syncline (Figure 20). South of Charles Brook near Govers Point (E627900 N5464300), a northwest-trending anticline is clockwise transected by southwest-dipping cleavage and displaced by a southwest-dipping reverse fault having sinistral-oblique movement. These structural features are overprinted by northeast-trending minor structures at the same location.

Description

In the exposure at Stop 2.5, the sandstone turbidites of the Charles Brook Member are locally intercalated with dark grey intervals made up of thin-bedded siltstone turbidite and laminated mudstone. The lutaceous strata are particularly well displayed at the southern end of the exposure. Strata at this locality occur approximately 400 ms above the contact with the underlying marine red beds of the Saunders Cove Formation and below the contact with the overlying mudstone-dominant Brooks Harbour Member of the New Bay Forma-

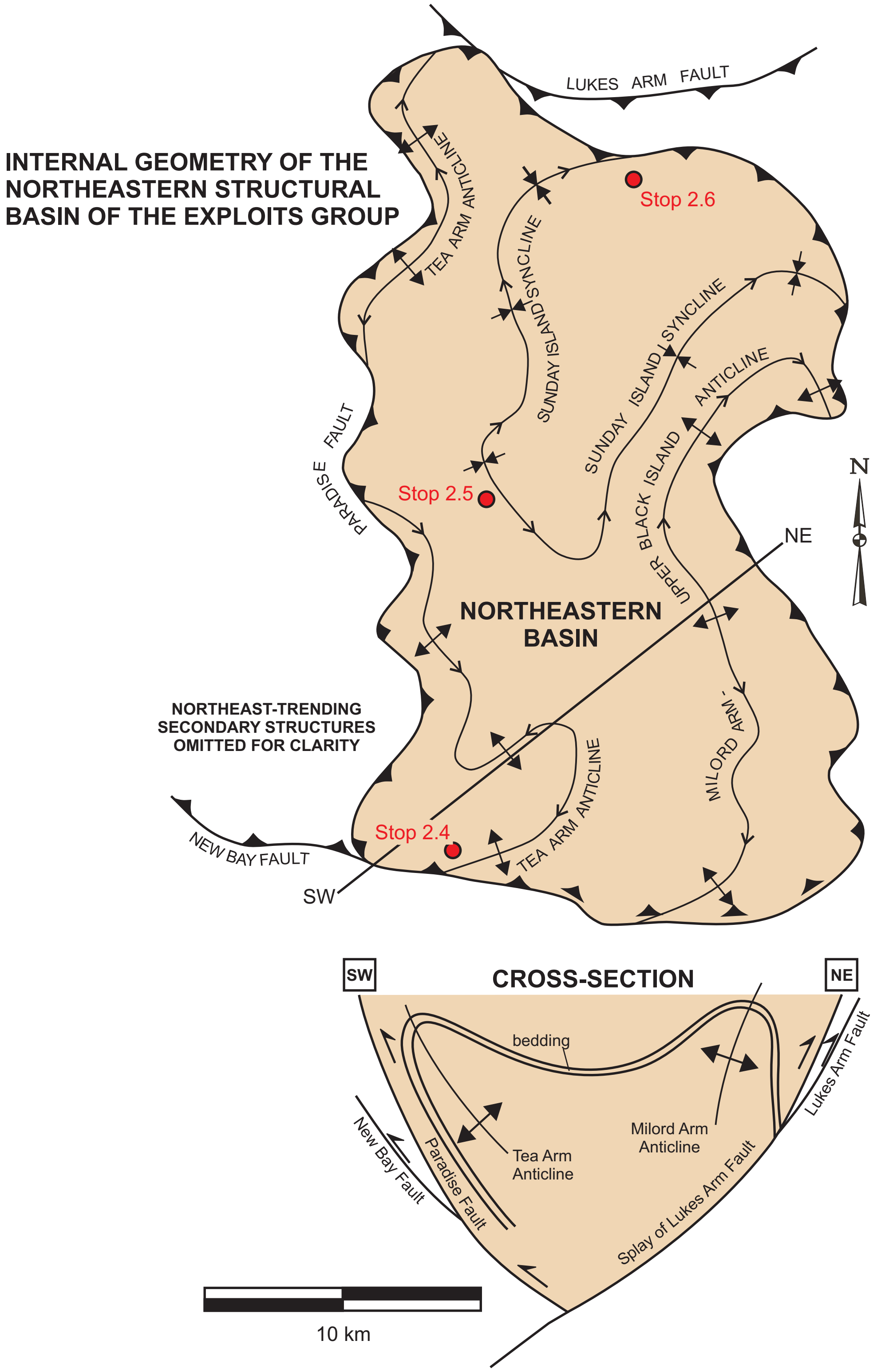


Figure 20. *Simplified regional structural map showing the early-formed synmetamorphic structures that define the external boundary of the northeastern structural basin of the Exploits Group and those that occur within this tectonic feature. See the locations of Stop 2.4, Stop 2.5 and Stop 2.6 and note the northeast-southwest line of section. The cross section illustrates ductile imbricate thrust faults that dip toward the southwest and the northeast and, lying above both of them, an originally northwest-trending, basin-wide, M-shaped conjugate fold.*

tion. Along the highway, this right-way-up section strikes northwestward and dips moderately to the northeast being located, structurally, on the generally less cleaved (southwestern) limb of the Sunday Island Syncline.

The road section near Charles Brook exposes two thick pyroclastic flows separated by dark grey mudstones thought to have been deposited on the Early–Middle Ordovician basin plain. One of these massive flows has a vertically graded top that is 50 cm thick. The beds are cut by at least two porphyritic diorite sills and several diabase dykes; chilled margins are observable near the north end of the exposure.

The conglomeratic portions of the pyroclast-rich turbidites have vesicular basaltic and abundant andesitic clasts set in a fine-grained tuffaceous matrix. In thin section, mafic detritus from the lower pyroclastic bed has abundant well preserved grains of low-Ti clinopyroxene. These dark wispy fragments commonly illustrate an outer concentric reaction rim that is lighter in colour than the volcanic matrix inside. The upper pyroclastic turbidite horizon has a larger proportion of bombs that are composed of coarse-grained felsic tephra, although some indurated blocks of banded chert and porphyritic andesite are present along with the fine-grained mafic tephra. The massive central parts of these pyroclastic deposits contain large rip-up clasts of dark grey laminated argillite.

Discussion

Throughout the sedimentary sequence, volcanogenic clinopyroxene grains are preserved in the tuffaceous turbidites, even where they were reworked in debris flows. Average compositions of the relict clinopyroxenes from the two horizons can be expressed as $Wo_{42,40}$ $En_{36,38}$ $Fs_{22,22}$ (Dec *et al.*, 1993b). The 'orogenic-type' of major element signature suggests derivation of a significant quantity of the andesitic tephra and other volcanic detritus from island arc eruptions.

The enriched LREE patterns of the whole rocks have pronounced negative Nb, Ti and positive Th anomalies and support this conclusion. The active island arc-related volcanism was synchronous with sedimentation of the lower New Bay Formation and may be represented today by the mature calc-alkaline volcanic rocks mapped in the Pennys Brook Formation of the Wild Bight Group.

The Charles Brook lapillistones have been interpreted as marine pyroclastic avalanche deposits (Figure 16) that were ultimately sourced from an active and possibly emergent

Middle Ordovician volcano located farther southwest (present coordinates). At this time, resedimented pyroclastic material was dispersed to the northeast, at least in the northeastern basin of the Exploits Group.

It is possible that the Dapingian–Darriwillian tephra originated from eruptions within the upland volcanic block postulated to have once separated the Wild Bight and Exploits depocentres (*see* Stop 2.3). Some of the epiclastic detritus in the lower part of the Charles Brook Member appears to have come from the same source area that supplied the Tea Arm–Saunders Cove transition zone, probably implying that this edifice was also constructed, in part, by rocks from the Tremadocian remnant arc (Figure 16).

STOP 2.6: Strong Island Radiolarian Chert and Lawrence Head within-plate Basalt of the Uppermost Exploits Group (Late Middle Ordovician Infill of the Exploits Back Arc Basin in the North-central Exploits Subzone)

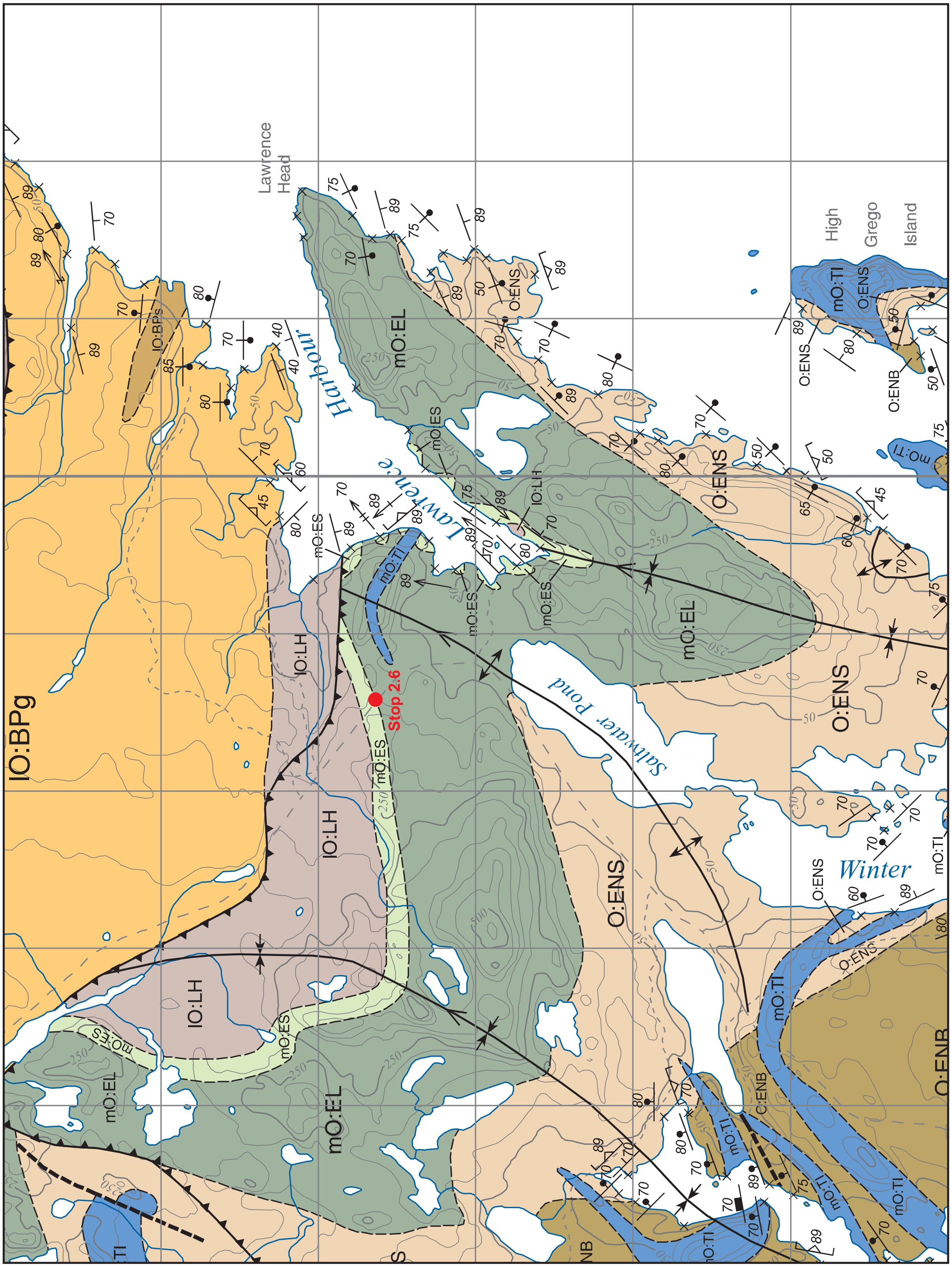
Location: 11.1 km (71.9 km)

Continue northward on Route 352 along the eastern side of the Fortune Harbour peninsula by driving approximately 11 km to the vicinity of a steep ridge overlooking Lawrence Harbour (Figures 2, 14 and 20). First, bypass the mussel farm at Saltwater Pond and the gravel access road leading east to southern Lawrence Harbour and then proceed around a large sharp bend in Route 352 (Figure 21). The field trip stop is found near E629575 N5475650 immediately uphill from the location where the power lines cross the highway. The exposures occur on both sides of the paved highway. Please go to the highest outcrop, park the vehicles on the northeast shoulder, and be careful of traffic when walking downhill and crossing the road to examine these rocks.

If participants observe a black shale quarry on the northeast side of the highway, then they have passed Stop 2.6. Please turn vehicles safely near the entrance to the quarry and drive about 400 m southeastward back to the field trip stop.

Regional Setting

Stratified rocks within the oceanic back arc succession of the Exploits basin are fundamentally represented by three lithofacies. Listed in order of decreasing volume, they are within-plate basalt, hemipelagic chert and bioclastic limestone. The first two lithofacies are assigned to two separate lithostratigraphic units in the upper part of the Exploits Group and both are observable at Stop 2.6 (Figure 21).



lO:BPg
lO:BPs
lO:LH
mO:EL
mO:ES
mO:TI
O:ENS
O:ENB
C:ENB
Stop 2.6
Lawrence Head
Lawrence Harbour
Saltwater Pond
High Grego Island
Winter

Legend

Iapetan Overstep Sequence

Late Ordovician to Early Silurian

BADGER GROUP

Late Ordovician

Point Leamington Formation

lO:BPs — *Late Ordovician.* Thinly stratified, graptolite-bearing argillaceous turbidite; dominantly dark-grey, graded siltstone interbedded with dark-grey to black carbonaceous shale and subordinate light-grey, thin-bedded, quartz-rich sandstone; multiple olistostrome horizons with slump-folded siltstone, shale, chert and limestone blocks set in a black shale matrix

lO:BPg — *Late Ordovician.* Light-grey, thin-bedded sandstone turbidite displaying secondary, soft sediment-deformed carbonate nodules; subordinate, medium-bedded, graded, quartz- and feldspar-rich wacke; minor, grey-laminated siltstone gradational to, or interbedded with, dark-grey shale; rare, thick-bedded to massive, granular sandstone and lithic wacke

Note: North of Lawrence Harbour, laterally continuous beds of sandstone and medium bedded sandy wacke dominate the lowest part of Unit lO:BPg of the Point Leamington Formation. There, this unit is devoid of mappable conglomerate lenticules. It is succeeded by a much thicker stratigraphic interval of thin-bedded, light-grey sandston dark-grey siltstone rhythmites as well as a thin discontinuous lenticule of Unit OS:BPs shaley flysch. In contrast, northwest of Babies Cove in Osmonton Arm, similar fine-grained rhythmites overlie the lowest and thickest conglomerate lenticle in Unit lO:BOpc and contain slump sheets of partially disaggregated, soft-sediment folds as well as indurated rip-up blocks of fossiliferous black argillite, grey bioturbated chert and massive limestone.

Lawrence Harbour Formation

lO:LH — *Late Ordovician.* Unseparated subunits of dark-grey shale interbedded with light-grey laminated argillite; black and dark-grey carbonaceous shale; black siliceous siltstone with pyritic black shale partings; light grey and buff radiolarian chert with bioturbated black shale laminae

Note: Dark-grey to- black, lutaceous sedimentary strata have yielded graptolites (Williams, 1995) in all subdivisions of the Lawrence Harbour Formation.

Exploits Subzone of the Dunnage Zone

Middle Ordovician

Thwart Island gabbro

mO:TI — *Late Middle Ordovician.* Layered or massive, medium- to coarse-grained, hornblende pyroxene gabbro laccoliths; quartz diorite sills and diabase dykes; hornblende-bearing pegmatite; Unit mO:TI intrusions are hosted by the Exploits Group and the Dunnage Melange

Latest Cambrian to Middle Ordovician

EXPLOITS GROUP

Strong Island chert

mO:ES — *Middle Ordovician.* Ribboned radiolarian chert with rare graptolitic mudstone partings; cream laminated, mottled or orbicular chert; light-green, medium-bedded, graded, crystal-lithic wacke interstratified with light-grey, thin-bedded concretionary siltstone, cryptocrystalline argillite and rare nodular limestone; minor, rhythmically bedded intervals of red banded argillite and green siliceous sandstone; minor pillow breccia interbedded with ferruginous turquoise chert, variegated tuffaceous sandstone, chert-rich conglomerate and basalt-rich debrite; rare, very thinly bedded, pumiceous tuff (Dec et al., 1992)

Lawrence Head Formation

mO:EL — *Middle Ordovician.* Basaltic pillow lava with red, green and grey interstitial chert; subordinate, dark-grey pillow breccia and light-green mafic tuff; minor intervals of dark-green and turquoise chert and greyish-green volcaniclastic sandstone; columnar-jointed diorite sills and rare diabase dykes

New Bay Formation

O:ENS — *Late Early Ordovician to Middle Ordovician. Saltwater Pond Member:* Light-grey, nodular, siliceous argillite interbedded with siltstone turbidite; thin-bedded, slump-folded sandstone; grey and red olistostrome containing resedimented cobble conglomerate blocks and detached soft-sediment folds of volcaniclastic wacke set in a chaotically deformed sandstone or mudstone matrix; graded conglomeratic turbidite and pebbly wacke containing distinctive clasts of tonalite, limestone and basalt; minor, red and green chert rhythmically interstratified with banded siliceous argillite; rare, graptolite-bearing mudstone

O:ENB — *Early to Middle Ordovician. Brook Harbour Member:* Dominantly dark-grey, very thinly - bedded siltstone turbidite interstratified with black pyritic slate; thinly laminated shale locally containing fragmentary graptolites; subordinate light-grey, thin-bedded sandstone grading to dark-grey siltstone

Figure 21. *Detailed geological map of the area near Lawrence Harbour on the eastern side of the Fortune Harbour peninsula near Stop 2.6. Note the northeast-plunging synclinorium responsible for the disposition of the Middle Ordovician Lawrence Head Formation and Strong Island Chert. Such strata comprise the upper part of the Exploits Group.*

The youngest marine basalt formation of the Exploits Group crops out as a widespread but sporadically developed unit. Where its primary boundaries are observed, the Lawrence Head Formation is conformable and gradational with deep-marine Darriwilian sedimentary strata that lie above and below it.

In most areas, mafic lava flows and pillow breccia within the upper part of the Lawrence Head Formation are interstratified with, and overlain by, multicoloured intervals of ribboned ferruginous chert. However, thin grey cherts having carbonate nodules predominate where the Lawrence Head Formation is locally missing from the Exploits Group. The variable along-strike distribution of Lawrence Head basalts is caused by non-deposition in certain places but by tectonic removal in other localities.

In areas where ribboned chert and other hemipelagic strata are thin or were never deposited, early Darriwilian limestone lenses are intercalated with pillowed basalt in the uppermost part of the Lawrence Head Formation. Felsic volcanic rocks have not been observed within the Lawrence Head Formation, although centimetre thick beds of felsic ash tuff are locally conspicuous in the underlying Saltwater Pond turbidites of the New Bay Formation. Inorganic replacement chert and silicified turbidites marked by stratiform redox boundaries are found discontinuously beneath the basal tholeiitic basalt flows of the Lawrence Head Formation. This is suggestive of a period of localized fluid flow in the sedimentary basin prior to tholeiite eruption.

Transgressive gabbro sills are observed to intrude lava flows within the Lawrence Head Formation. Many of these hypabyssal rocks pass gradationally into marginal zones of highly vesicular diabase, whose offshoots are observed, in places, to feed lava tubes.

The Strong Island Chert of the upper Exploits Group is a widespread unit without formal rank that varies from 0-400 m in total thickness across the region. Although the type section occurs on the southwest end of Strong Island near the Tea Arm Formation (Figure 15), the unit is also well exposed near Lawrence Harbour (Figure 21). The Strong Island Chert conformably underlies the basal division of grey bioturbated chert in the black shale-dominated Lawrence Harbour Formation. On the basis of the graptolite fauna present in these immediately overlying strata, the uppermost beds of the Strong Island succession are earliest Sandbian in age.

The Strong Island Chert is mostly composed of multicoloured radiolarian chert interbedded with lesser amounts of graded volcaniclastic wacke. Turquoise ribbon cherts contain the clay mineral celadonite and are notably ferruginous. Others are rich in lead, chromium, fluorine and phosphorous. They are interlayered with red hematitic cherts where these hemipelagites are in direct stratigraphic contact with pillowed basalts of the Lawrence Head Formation.

In the lower part of the unit, Strong Island cherts are interstratified with alkali basalt flows and other types of within-plate pillow lavas. Some volcaniclastic wackes and small debris flows are particularly rich in mafic volcanic and chert clasts, although none of these Strong Island lithologies are seen in the relatively thin sedimentary section at Stop 2.6.

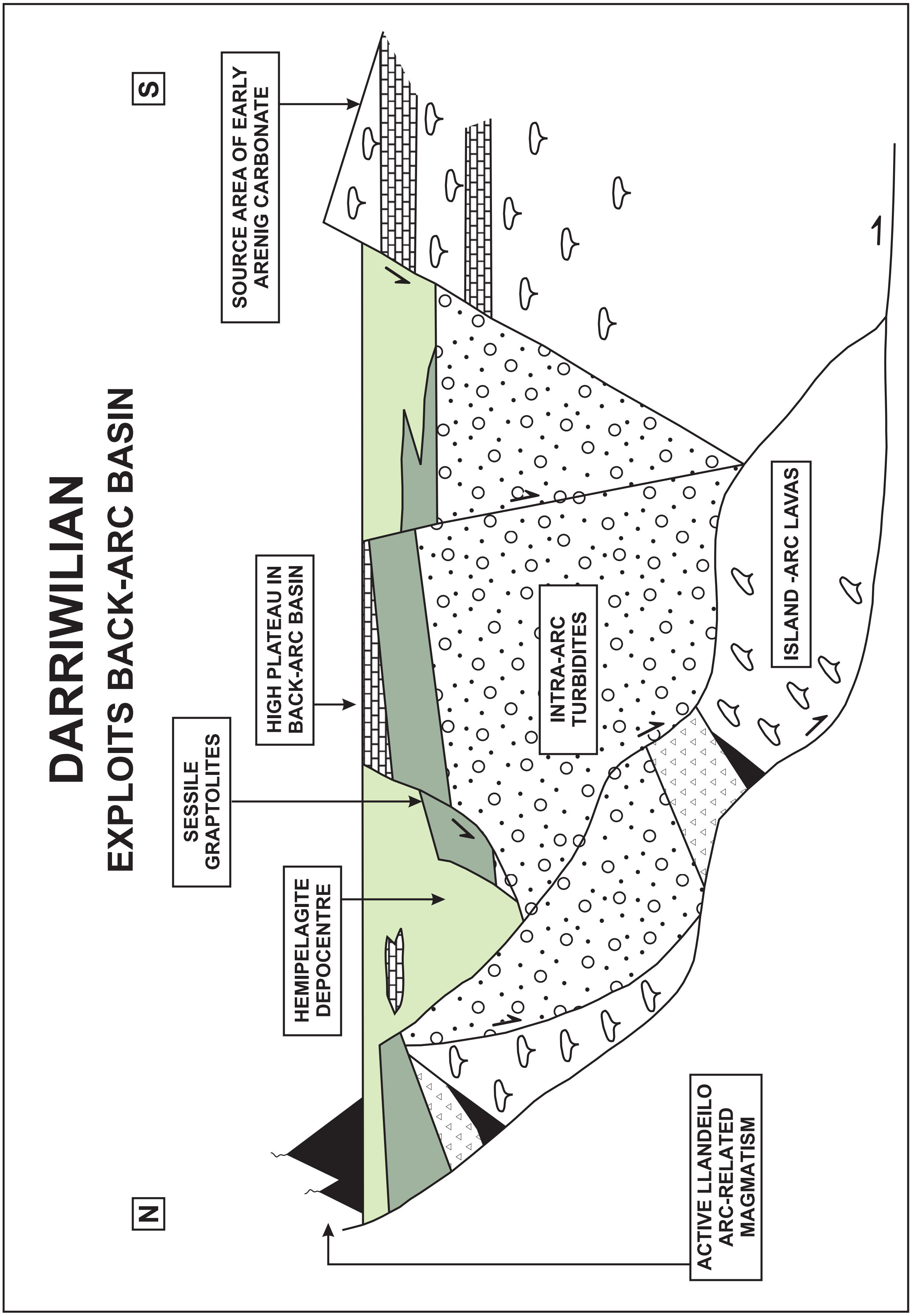
Biostratigraphically, the Strong Island Chert is presumed to range throughout most of the late Middle Ordovician. Graptolite-bearing siltstone intervals in chert directly overlying alkali basalt indicate that part of the map unit is as old as the early Darriwilian (earliest Llanvirn; top *Didymograptus hirundo* Zone or *Didymograptus artus* Zone) or possibly the basal Darriwilian (latest Arenig; *Undulograptus austrodentatus* Zone). Delicate benthic graptolite fragments imply limited post-mortem transport from an original shallow-ocean volcanic environment. In the Exploits Group, it is likely that a variably thick and locally condensed succession of back arc chert accumulated throughout all of the Darriwilian (Figure 22).

Description

At Stop 2.6, a northward-facing succession of Lawrence Head basalts crosscut by several mafic intrusions occurs closest to the bend in Route 352. The best pillow structure and interstitial chert is seen in the southernmost exposures on the east side of the highway. Bore holes were drilled and cores were extracted for paleomagnetic studies where the strike and dip of the lava flows could be reliably determined. Basalts are overlain by about 1 m of red laminated chert at the northernmost exposure of the formation on the west side of the highway.

Farther north across a small exposure gap, beds representative of the Strong Island Chert are well displayed, particularly in road cuttings on the east side of Route 352. Thin turquoise beds of laminated celadonitic chert are interstratified with grey argillite and minor wacke. Locally, the uppermost part of the unit is not exposed. One mafic dyke intruding this succession is probably a late Jurassic lamprophyre; the ages of the other intrusions are unknown and unconstrained.

The Lawrence Head Formation contains several types of subalkaline and alkaline basalt (O’Brien *et al.*, 1997). Pillowed alkali basalts from the upper part of the formation have the


DARRIWILIAN
EXPLOITS BACK-ARC BASIN
N
S
SOURCE AREA OF EARLY ARENIG CARBONATE
HIGH PLATEAU IN BACK-ARC BASIN
SESSILE GRAPTOLITES
HEMIPELAGITE DEPOCENTRE
INTRA-ARC TURBIDITES
ISLAND -ARC LAVAS
ACTIVE LLANDEILO ARC-RELATED MAGMATISM

highest LREE-enrichment and highest concentrations of incompatible elements for any Exploits Group volcanic rock. Other slightly LREE-enriched pillowed basalts from the Lawrence Head Formation are within-plate oceanic tholeiites.

Although the pillow lavas in these road cuts have not been sampled, basalts have been geochemically analysed along strike on both the east and west coasts of the Fortune Harbour peninsula at Lawrence Harbour and Southeast Arm, respectively. These transitional tholeiitic to mildly alkaline rocks display REE-patterns with negative Th anomalies and flat slopes, and are more similar to modern enriched mid oceanic ridge basalts (E-MORB lavas) than to oceanic island basalts (OIB). Normal mid oceanic ridge basalts (N-MORB lavas) have not been recognized in the Lawrence Head Formation.

In the quarry still farther north, black shales of the Lawrence Harbour Formation (Figure 21) belong to the *Nemagraptus gracilis* and *Climacograptus bicornis* graptolite biozones (Sandbian; early to mid Caradocian).

Discussion

Pillowed basalts of the Lawrence Head Formation have geochemical signatures that are quite distinct from any of the older Tea Arm arc-related lavas, a critical feature where both units are tectonically juxtaposed. The Lawrence Head types of 'non-arc' lavas are similar to alkali basalts and LREE-enriched tholeiites and to modern basalts found in spreading marginal basins.

Volcanic rocks in the upper Exploits Group are thought to be, at least in part, the chemostratigraphic correlatives of the back arc volcanic sequence in the upper Wild Bight

Figure 22 (opposite). *Figurative cross section showing an interpretation of the restored Darriwilian geometry of the Exploits back arc basin. The dark green unit and the light green unit correspond to the Lawrence Head Formation and the Strong Island Chert, respectively (*see *Figure 21). The contemporaneous peri-Gondwanan volcanic arc lay farther north in the Exploits Subzone.*

Note that back arc strata locally onlapped volcanic and sedimentary rocks from the lower and middle parts of the Exploits Group, as a consequence of reactivation of listric growth faults that had developed during the arc rift phase of extension. Certain horst blocks emerged above the carbonate compensation depth during late Middle Ordovician widening and localized deepening of the back arc basin. In places, island arc carbonates of Early Ordovician age were exhumed and transported as bioclasts when within-plate tholeiites and alkali basalts were erupted in parts of the Exploits back arc basin.

Group. Therefore, on the basis of published Nd isotopic characteristics (Swinden *et al.*, 1990), volcanic units in this region of the Exploits Subzone are interpreted to contain island arc and back arc successions that developed above uncontaminated simatic crust. This is despite the fact that older ensialic arcs are known to occur in the Exploits Subzone of south-central Newfoundland.

The presence of Early Ordovician and Middle Ordovician conodonts in one single horizon of supra-Lawrence Head limestone has important implications for the back arc history of rocks near the Red Indian Line. The incorporation of older fossils into considerably younger deposits implies that the back arc lavas were affected by syndepositional tectonic activity (Figure 22) or a eustatic drop in sea-level or both.

The recycling of Early Ordovician conodonts with possible peri-Laurentian affinities and their preservation within late Middle Ordovician stratigraphic units of the peri-Gondwanan Exploits Subzone presumably implies intra-Iapetus proximity of both realms by the time the back arc lavas had rose above carbonate compensation depths. This point is possibly supported by the low paleolatitude determinations made on the pillow lavas from the exposure at Stop 2.6 (Todaro *et al.*, 1996). Alternatively, Darriwilian growth faulting in the Exploits back arc may have reactivated extensional arc structures within the underlying Tea Arm remnant arc and provided an exhumed peri-Gondwanan source area for Floian carbonate detritus (Figure 22).

DAY 3

TRAVEL DIRECTIONS TO BEGIN DAY 3 OF THE EXCURSION

Take the Trans-Canada Highway (Route 1) from Grand Falls eastbound about 20 km to Exit 22 (Route 350 North). Then drive northward along the Botwood Highway a further 20 km to the Town of Northern Arm and the junction between Route 350 and Route 352. This is the 0.0 km location for Day 3. Taking Route 352, continue northeastward along the Fortune Harbour peninsula some 46 km toward the village of Cottrell's Cove. Stop 3.1 below is the first exposure to be examined on the morning of Day 3 of the field trip (Figures 2 and 23).

STOP 3.1: Primary Depositional Features and Block-within-Block Hierarchy in the Boones Point Complex (Giant Olistolith of Slump-folded Sandstone Turbidite and Re-amalgamated Granite-bearing Conglomerate set in the Black Shale Matrix of the Mélange)

Location: 40.8 km (40.8 km)

After passing the road side exposures that the field party examined at Stop 2.6 on the afternoon of Day 2, continue approximately 5.5 km farther northwest along Route 352. Participants should notice a conspicuously long and narrow pond that will come into sight on the eastern side of the highway. On the southern slope of the valley containing this pond, a large blasted road cutting occurs at E626545 N5480007 on the west side of Route 352. Please park vehicles on the eastern shoulder and cross the road safely to examine the exposure at Stop 3.1. When viewing, be careful of falling rocks from above and make sure that your footing is secure near the talus scree.

Regional Setting

On the Fortune Harbour peninsula, the block-in-matrix melange unit associated with the Red Indian Line suture has been referred to as the Boones Point Complex (Figure 2). Regionally, it separates the peri-Laurentian Cottrells Cove Group from the peri-Gondwanan Exploits Group. The largest known structural tract, the Southeast Arm panel of the Boones Point Complex, is tectonically overlain by the Late Ordovician Point Leamington Formation and is overthrust from the southwest by Middle Ordovician formations of the Exploits Group (Figure 24).

Negligibly strained sedimentary rocks, such as those seen at Stop 3.1, are well preserved within parts of the Southeast Arm panel. Located in the central part of the bivergent Red Indian Line structural zone, the block-in-matrix mélange occurs approximately 0.5 km south

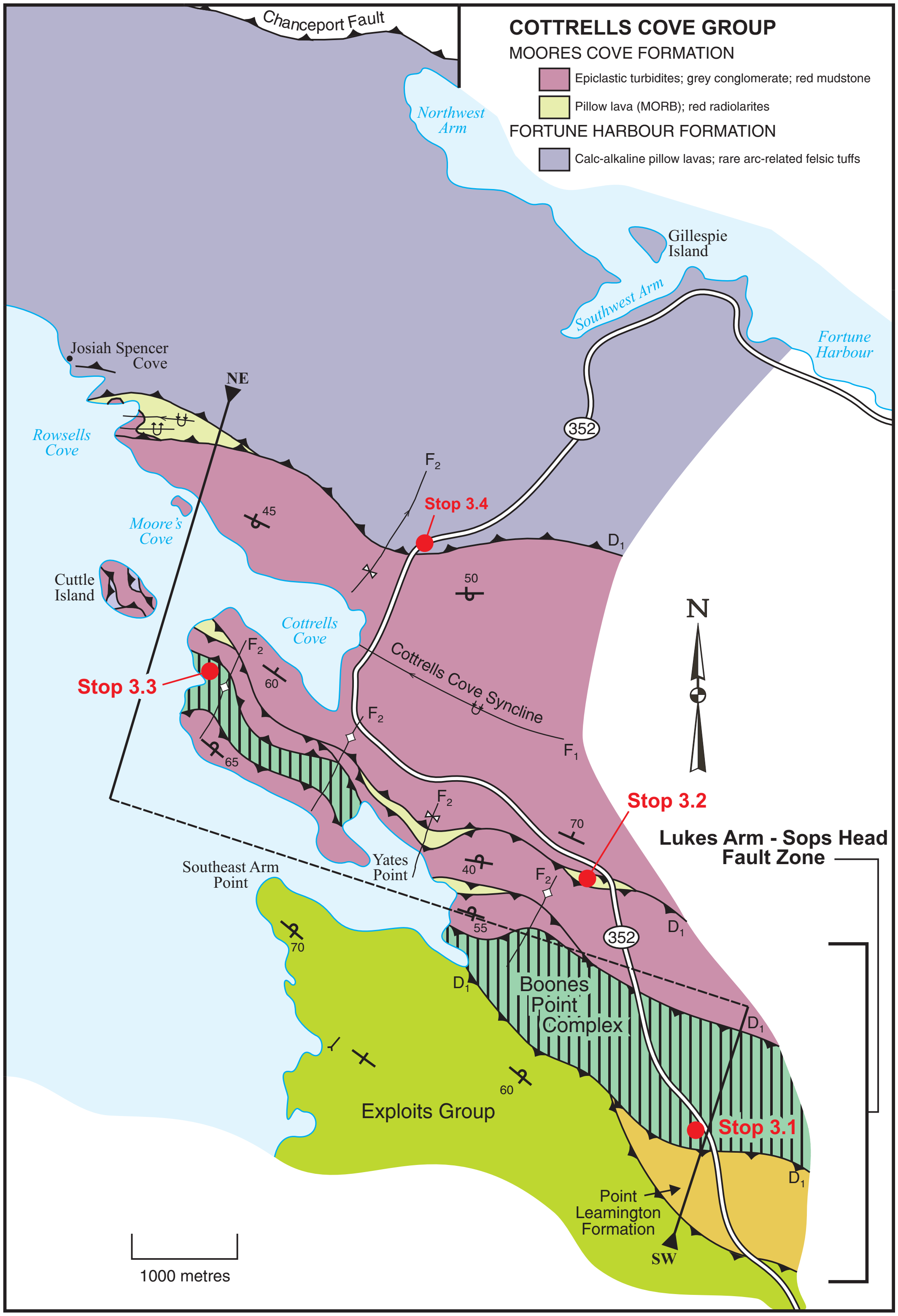


Figure 23. *Detailed lithostratigraphical and structural map of the type area of the peri-Laurentian Cottrells Cove Group adjacent to the Lukes Arm–Sops Head fault zone. Parts of the Exploits Group, the Boones Point Complex and the Point Leamington Formation of the Badger Group are also illustrated. Note the locations of Stop 3.1 through Stop 3.4. The Red Indian Line is locally coincident with the southwest margin of the Southeast Arm panel of the Boones Point Complex. Section line for Figure 24 is indicated.*

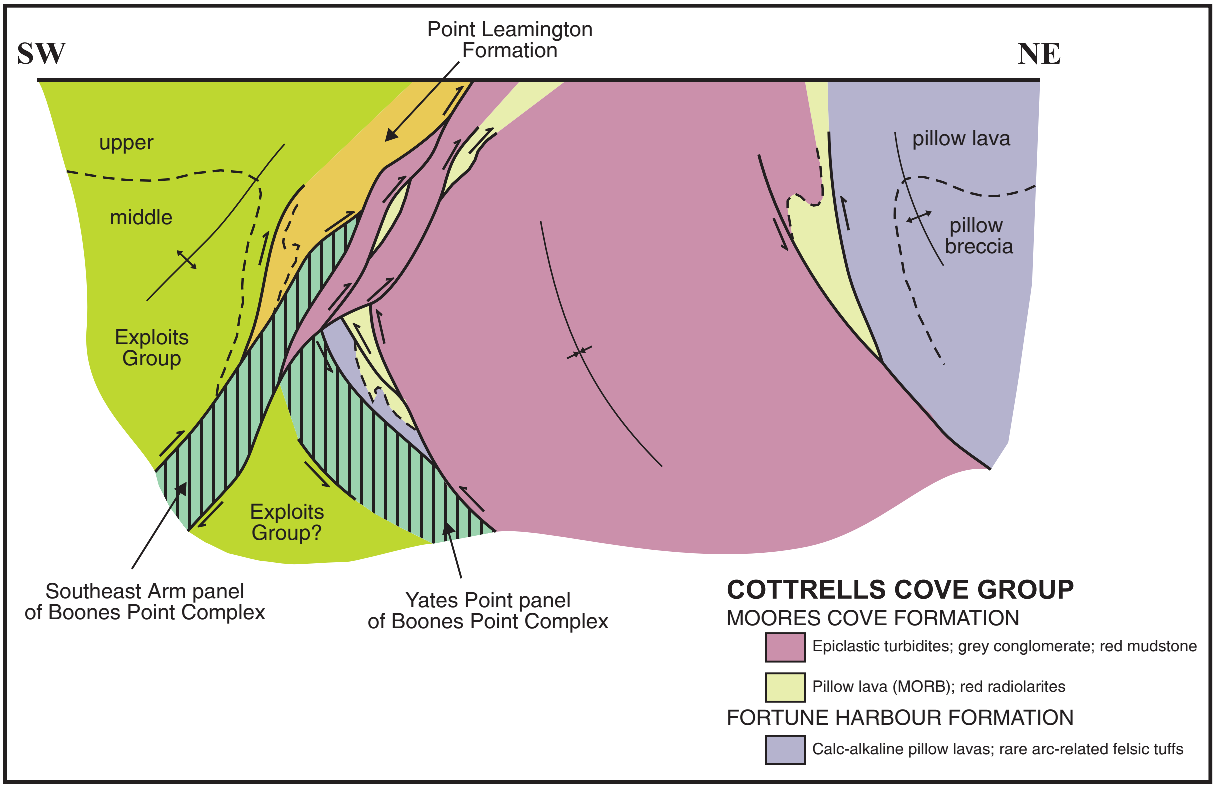


Figure 24. *Regional cross section, viewed looking northwest, highlighting the northwest-trending structural confrontation zone that is centered on the olistostromal mélange tracts of the Boones Point Complex. A southwest-dipping imbricate thrust stack is interpreted to have been emplaced above a northeast-dipping imbricate thrust stack. The boundary between the Notre Dame and Exploits subzones of the Dunnage Zone is coincident with the highest imbricate thrust to affect the Boones Point Complex (Red Indian Line mélange belt) and the Moores Cove Formation of the Cottrells Cove Group.*

of a stratigraphically coherent succession of the Middle Ordovician Moores Cove Formation and about 1 km north of relatively undisturbed Middle Ordovician succession assigned to the Lawrence Head Formation and the Strong Island Chert.

Along the southern margin of this particular tract of the Boones Point Complex, olistostromal melange is tectonically juxtaposed against stratigraphically *in situ* volcanic rocks as old as the early Darriwilian and unbroken sedimentary rocks as young as the Katian. Many of the blocks in the adjacent black shale melange superficially resemble strata that make up the local hanging wall sequence of the Badger Group, the Lawrence Harbour Formation and the Exploits Group.

Description

In the section through the melange in the road cut, an extremely large sedimentary block is sharply bounded on its northern margin by dark-grey shale carrying a strong slaty cleavage. Chaotically-mixed beds of different texture and grain size illustrate features of soft-sediment deformation and are observable within this metric scale olistolith. Such strata include polymictic boulder conglomerate, sandstone turbidite and ferruginous ribbon chert.

At the southern end of the road side exposure, a granular to gritty volcaniclastic wacke marked by black mud chips is observed to be gradational with conglomerate. In the central part of Stop 3.1, similar conglomerate displays conspicuous clasts of felsic plutonic rocks. The well rounded pebbles, cobbles and boulders of coarse grained granite indicate that at least some of the detritus is polycyclic. In the northern end of this outcrop, the pyritic black shale of the matrix is seen to be associated with thin-bedded phacoidal wacke and minor pebbly mudstone.

In some localities, evidence for the primary deposition and interstratification of silty, sandy and conglomeratic turbidites is preserved inside the olistolith. In other places, however, laterally discontinuous conglomerate beds were injected by sandstone dykes and both were subsequently fragmented and distended in quicksand. They are observed to comprise re-amalgamated sedimentary horizons within the megablock.

Discussion

In areas of low bulk regional strain in the Boones Point Complex, syndepositional deformation features and chaotic mass-flow textures are seen within blocks set in a dark shale matrix. Nevertheless, a full appreciation of the olistostromal aspects of this melange is best gained by detailed mapping of well-exposed areas in which a 'block-in-block-within-block' hierarchy is demonstrable.

A large part of the block of sedimentary strata examined at Stop 3.1 may represent a slump-folded debris flow. Polymictic conglomerate may have originally filled channels in turbidite fans adjacent to an edifice partly composed of plutonic rocks. Such conglomerates were then possibly reworked with other material on the fan as sediment was transported farther down slope into the area of deposition.

Historically, the plutonic boulder conglomerates that are preserved within the Boones Point melange tracts have been generally interpreted as originating from the equivalents of the late Llandovery Goldson Formation on New World Island (Badger Group) and, hence, the Early Silurian age assignment for parts of the Boones Point Complex (Figure 8). They have prompted some workers to regard this complex as having formed at the same time and in a similar fashion to the better documented olistostromal melange of late Llandovery age at Joey's Cove on New World Island.

The presence of polymictic conglomerate and pebbly wacke situated below partially broken sequences of Middle Ordovician basalt, limestone, chert and black shale has also been considered as an important factor in explaining the origin of this particular block-in-matrix melange. Many workers have interpreted this arrangement as being the result of syn-depositional thrust imbrication of the Exploits back arc succession and its overstep sequence, possibly below an overriding peri-Laurentian nappe.

Much older candidates for correlation with the Boones Point conglomerate at Stop 3.1 are possibly located in the granite- and limestone-bearing conglomerate units of the upper Moores Cove Formation of the peri-Laurentian Cottrells Cove Group (no stops) and in the upper New Bay Formation of the peri-Gondwanan Exploits Group (Stop 2.4). These protoliths would not necessitate a Late Ordovician–Early Silurian age of olistostrome formation and would be compatible with the generation of Middle Ordovician debris flows in the Boones Point Complex (Figure 10). Hard-rock (post-Katian) tectonism of the block-in matrix mélange would be at least 20 My younger than the deposition of these polymict conglomerate-bearing units.

STOP 3.2: Altered Tectonic Sliver of Notre Dame Subzone Mid-Ocean Ridge Basalt within Folded Turbidites of the Middle Ordovician Moores Cove Formation (Bivergent Faulting and Lithostratigraphic Separation in the Cottrells Cove Group within the Red Indian Line Imbricate Thrust Belt)

Location: 1.2 km (42.0 km)

If participants leave Stop 3.1 and drive a further 2.5 km northward along Route 352, they should arrive at an exposure in a road cut on the west side of the highway located at E626122 N5481106. This is Stop 3.2 (Figure 23). Extending northwestward to E626097 N5481112, the rocks to be examined occur near a large bend in the road about 200 m south of the Pentecostal Assembly cemetery for the community of Cottrell's Cove.

Regional Setting

The intensity of regional deformation increases in the peri-Laurentian rocks of the Notre Dame Subzone on proceeding southward toward the rocks of the Exploits Subzone and its Late Ordovician overstep sequence. This phenomenon is well displayed along the western coast of the Fortune Harbour peninsula, particularly in the section south of Cottrell's Cove and north of the Red Indian Line (Figure 23). Within this region, the Early–Middle Ordovician Cottrells Cove Group is disposed in thrust fault-bounded panels that progressively lose internal stratigraphic integrity as they become smaller in size toward the south.

As the Cottrells Cove Group becomes increasingly structurally fragmented and stratigraphically incoherent, volcanic rock units are seen to be variably mylonitized. Volumetrically, much more of the sedimentary rock units are significantly strained and such strata take on a tectonic platey character. However, primary geopetal features are preserved within repeated imbricate slices of the lower part of the Moores Cove Formation. It appears that, in the area immediately north of the Exploits Group, the Cottrells Cove Group generally becomes younger northeastward, dips regionally southwestward and is mainly upside-down (Figure 24).

Small discontinuous lenses of Moores Cove Formation basalt outline folded imbricate thrust sheets on the southwest limb of the regional Cottrells Cove Syncline. They comprise part of a southwest-directed belt of overturned folds and thrusts that were displaced by later northeast-directed back thrusts. Together, these bivergent reverse faults form a major structural confrontation zone that was centred on the Red Indian Line mélange (Figure 24).

Near Yates Point, thrust slices of altered basalt detached from the Moores Cove Formation originally flanked a northwest-trending antiform cored by the younger Boones Point Complex. This thrust-bounded domal structure was modified by southwest-dipping ductile shear zones related to the regional system of back thrusts seen at Stop 1.1 and Stop 1.2. The F2 cross-folded thrust sheet of Moores Cove basalt located in Yates Cove contains a smaller scale antiform that passes upward and outward into an inverted and partially dismembered sequence of Moores Cove turbidites (Figure 23).

Description

At the southwest end of the exposure at Stop 3.2, the grey-green pillowed basalts of the basal Moores Cove Formation become mylonitized and hematized adjacent to a faulted contact with upside-down, southwest-dipping beds of green wacke and grey argillite. Such thick-bedded sedimentary strata are typical of the middle turbidite division of the Moores Cove Formation. At the north end of the exposure, where the wacke succession is right-side-up and northeast-dipping, it is structurally overlain by red laminated siltstone turbidite and green siliceous argillite typical of the lower sedimentary part of the Moores Cove Formation.

The steeply southwest-dipping reverse fault that bounds the reddened and sheared sequence of mafic volcanic rocks occurs on the limb of a northeasterly-overturned fold. The immediately underlying Moores Cove footwall succession is inverted and shows weak bed-parallel cleavage. On passing northeastward into a right-side-up succession, the beds of the Moores Cove Formation fan through the vertical position and are affected by open, gently plunging S-shaped folds. Viewed from the perspective of the footwall, the hanging wall basalts occupy the position of a sheared or displaced anticline.

Discussion

Several podiform tectonic slices of hematized pillowed basalt occur immediately north of the mélange tracts in the Red Indian Line structural zone. Together with the structural panels of the Moores Cove turbidites, these rocks comprise a ductile imbricate fault zone approximately 1.5 km wide along the west side of the Fortune Harbour peninsula. This northwest-trending zone of bivergent thrust faulting is associated with the lateral ejection of overthickened strata in thrust sheets within the Notre Dame Bay sector of the Notre Dame Subzone (Figure 3). Similar structural facing confrontation zones are, however, seen in the northern part of the Exploits Subzone.

The pillowed basalts from the upper Fortune Harbour–lower Moores Cove transition in the Cottrells Cove Group are characteristically N-MORB lava flows erupted above the early Darriwilian carbonate compensation depth. However, disposed along strike from the lenses of basal Moores Cove basalt near Route 352, are the podiform thrust slices of mafic volcanic rocks on Cuttle Island (Figure 24). There, well preserved pillow lavas are overlain by hematitic and manganiferous chert and thin-bedded felsic tuff; they are devoid of limestone.

This is suggestive of the local presence of the Early Ordovician island arc-related succession of the lower Fortune Harbour Formation, a unit widely developed farther north on the peninsula in the lowest exposed part of the Cottrells Cove Group. The southwest-directed thrust sheets of mafic–felsic volcanic rocks on Cuttle Island are structurally imbricated with the turbidites of the Moores Cove Formation, as are the younger Moores Cove basalts.

On the east side of the Fortune Harbour peninsula and on islands in the Bay of Exploits, the arc-derived turbidites of the middle–upper Fortune Harbour Formation attain a stratigraphical thickness estimated to be in excess of 1000 m (Dec *et al.*, 1997). However, southwest of the Cottrells Cove Syncline, the sedimentary rocks of the Fortune Harbour Formation are locally missing, in particular in the region between the thrust sheets on Cuttle

Island and those carrying Moores Cove basalt in the vicinity of Yates Cove. In the cross section of the Lukes Arm–Sops Head Fault Zone near Cottrell's Cove (Figure 24), this contact is interpreted as a primary stratigraphical boundary that has been folded and displaced by faults.

STOP 3.3: Polydeformed Block-in-Matrix Mélange and Scaly-Foliated Pebbly Mudstone near the Red Indian Line (Strongly Cleaved Turbidites from the Notre Dame Subzone Thrust Southwestward above a Boones Point Mélange Tract Marked by Large Exotic Blocks)

Location: 3.9 km (45.9 km)

Upon entering the southern part of the settlement of Cottrell's Cove on Route 352, and approaching the southern shorefront of the inner harbour, participants should turn westward at a T-junction onto a paved road near a general store. Drive along the southwest coastline of Cottrell's Cove about 1 km and, without impeding traffic, park vehicles near a turning area for school buses. Participants should wear or carry appropriate footwear and outerwear, as they will hike around a coastal headland that is exposed to the sea and the weather.

Embark on foot to the end of the paved road, bypassing the last house (and dog) in the community, to a smaller turning area for cars situated near open farmland. Follow a well-marked gravel track northward to an outbuilding located in sight of the coastline. From here, a small footpath trends northwestward, westward and southwestward for some 200 m through woodland. Participants should then follow a path that heads to the southwest through a linear meadow for some 250 m until they reach a shingle beach in a small protected headland cove. The coastal section to be examined at Stop 3.3 extends from the northern to the southern end of this cove (Figure 23). There are several prominent cliffs that stand out from an otherwise recessive shoreline; these are megablocks in the softer matrix of the Boones Point mélange.

Upon their return to the parked vehicles, participants can take either the left-hand or right-hand branches of the northeast-trending trail because, after forking, they coalesce again before reaching the coast of Cottrell's Cove.

Regional Setting

Each of the discontinuous tracts of block-in-matrix mélange within the Red Indian Line structural zone is externally fault-bounded. On the western coast of the Fortune Harbour peninsula, the mélange tracts of the Boones Point Complex are variably strained and are thrust fault-imbricated with detached and inverted parts of the Cottrells Cove Group. In the southwestern part of the local section across the Red Indian Line, the Boones Point Complex and the Cottrells Cove Group are both overthrust from the south by various formations belonging to the Exploits Group and the Badger Group (Figure 24).

There has been a long history of debate over the depositional age and tectonostratigraphic affiliation of the sedimentary rocks of the Moores Cove Formation of the Cottrells Cove Group and whether they have been everywhere correctly separated from the Late Ordovician turbidites of the Badger Group and the Middle Ordovician turbidites of the Exploits Group. This is an especially important point as unbroken parts of all of these rock units are in direct contact with the Red Indian Line mélange tracts on the Fortune Harbour peninsula, although the Moores Cove Formation has the most intimate association.

Depending on their individual size and structural position in the imbricate thrust fan, the mélange tracts illustrate a considerable internal variation in bulk strain. Some parts of the shaley mélange tracts are negligibly deformed and illustrate primary sedimentological features. Parts of other mélange tracts assigned to the Boones Point Complex display recognizable volcanic and sedimentary rocks that were mylonitized or tectonically straightened during regional deformation. These have subsequently become embrittled, altered and then ruptured, and are observed to pass laterally and gradationally into structurally comminuted rocks marked by block-in-matrix texture.

On the western side of the Fortune Harbour peninsula, the regional traces of the ductile shear zones that bound the thrust sheets of the Boones Point Complex outline secondary map-scale folds (Figure 23). Minor structures related to these folded thrust faults affect the regional slaty cleavage developed within the block-in-matrix mélange. They are commonly developed near the margins of the mélange tracts as crenulation folds and crenulation cleavages, which trend both northeasterly (D2) and northwesterly (D4) dependent upon age.

Tectonic mélanges are observed as olistoliths in the Darriwilian mud matrix of the Dunnage Melange to the immediate east of the Fortune Harbour peninsula. However, younger examples of tectonic mélange are found throughout many parts of the Exploits and Notre Dame subzones of the Dunnage Zone. Progressively deformed mélanges of tectonic origin are present in faulted – but otherwise unbroken – lithostratigraphic units of Ordovician and Silurian age.

Description

At the end of the track on the north side of the cove, buff weathered rocks of the peri-Laurentian Moores Cove Formation carry a gently- to moderately-northeast dipping cleavage lying sub-parallel to bedding. In places, rootless intrastratal folds lie in the plane of the regional northwest-trending slaty cleavage. The contact with the much darker coloured rocks of the Boones Point Complex is not exposed. However, the strike swing of the well developed inclined foliation in the adjacent part of the mélange is compatible with the Moores Cove Formation structurally overlying the Boones Point Complex at this locality. This is shown in the regional cross section of the Yates Point panel of the Boones Point Complex (Figure 24).

Strongly deformed, highly pyritiferous, dark grey argillite and slate represent most of the matrix of the Boones Point Complex mélange. In a few exposures in this cove, lithons in matrix slate have shale laminations preserved at a discernable angle to cleavage. Many of the scaly-foliated clay minerals show evidence of microscopic cataclastic deformation.

In the northern part of the coastal section, macroscopic blocks in the Boones Point mélange vary from a fraction of a centimetre to tens of metres in size. They constitute a variety of exotic and local lithologies which are embedded in, or are totally surrounded by, the mélange matrix. Epidotized basalt, laminated chert, siliceous siltstone, thin-bedded argillite, recrystallized limestone and massive to poorly stratified sandy wacke comprise most of the mélange blocks. Locally, two or more of these lithologies are observed to be interbedded within some of the largest blocks in the mélange.

Along the middle and southern part of the shoreline at Stop 3.3, two outsized megablocks, one of light green basalt and one of dark grey argillite, are well exposed. Most of the large blocks in the coast section illustrate a great assortment of geometric configurations, some of which appear to be partly controlled by lithology or lithodemic association. There are augened, rounded, angular, boudined and lozenge shapes to be seen.

Some mélange blocks have sharply defined external margins and show a variably attenuated internal layering at these margins. Other blocks display comminuted tails and diffuse external boundaries. Some sedimentary megablocks have an extensively shattered internal texture, yet contain bedded ‘jigsaw-fit’ fragments that have been individually affected by only a slight rotation relative to each other. In contrast, incompletely spalled pieces of well jointed volcanic megablocks possess small injections or 'veins' of block-in-matrix melange. Large competency contrasts between matrix and outsized blocks makes it difficult to interpret the variations in the shape of blocks, or to ascertain whether such changes reflect regional structural or syndepositional processes.

Immediately south of the Moores Cove Formation and north of the basalt megablock located in the middle of the cove, northeast-trending minor folds crenulate the matrix cleavage and deform or augen the smaller blocks in the mélange. Such secondary folds display highly curvilinear fold axes. Where they can be continuously followed along their axial traces, fold axes vary from plunging gently northeastward through the vertical into moderately southwestward directions of plunge.

Discussion

Four conjectures that follow have been historically assumed about the Boones Point Complex: 1) the mélange matrix has been considered to have formed over a considerable age range from the Katian (Ashgillian Stage) of the Late Ordovician to the Telychian (Llandoverian Stage) of the Early Silurian, 2) with the exception of late Darriwilian limestone clasts, the mélange blocks are presumed to have been predominantly derived from a northerly uplift of Early and Middle Ordovician peri-Laurentian rocks located within the Notre Dame Subzone of Notre Dame Bay, 3) the depositional substrate of the olistostromal part of the mélange has been perceived as the Sandbian black shale marker that had overstepped the peri-Gondwanan arc-back arc complex of the Exploits Subzone (Stop 1.3 and Stop 2.2) , and 4) the purported accumulation site of the block-in-matrix mélange and the black pebbly mudstone is in the same piggyback shortening basin or transform-parallel pull apart basin that controlled deposition of the tectonically adjacent Late Ordovician olistostrome-bearing turbidite succession (Stop 1.4 and Stop 1.5).

In the coast section at Stop 3.3, mélange blocks consisting of dark grey shale and turbidite sandstone have yet to yield graptolites or conodonts. This stands in marked distinction to the southerly adjacent Sandbian and Katian strata within the Lawrence Harbour Formation and the Point Leamington Formation. To date, the only fossils recovered from the Boones Point mélange are late Middle Ordovician conodonts from limestone blocks situated on Green Island off the northwest coast of the Fortune Harbour peninsula. These have been compared to the late Darriwilian (Llanvirn–Llandeilo) conodont fauna described in the peri-Gondwanan Cobbs Arm Limestone of New World Island. Despite extensive searches over many decades, fossils of Late Ordovician or Early Silurian age have not been found in the blocks or matrix of the Boones Point mélange. This is also the situation for the better known Dunnage Melange.

In the Boones Point mélange, exotic carbonate rocks occur as discrete fragments set in matrix mudstone, as detrital clasts in bedded sedimentary blocks, and as intra-pillow lenses within basalt blocks. The earliest Darriwilian clastic limestones in the Moores Cove Formation may possibly represent a peri-Laurentian source for the calcareous mélange blocks, as might possibly older carbonates residing higher in the Roberts Arm thrust stack. However, limestone horizons in the Cottrells Cove back arc basin are much thinner and less laterally persistant than those within the Exploits back arc basin. It may be that the paleogeographic realms represented by the Notre Dame and Exploits subzones were in close proximity by the Darriwilian when the conodont-bearing limestones were being deposited (*see* Discussion section of Stop 2.6).

Based on major element geochemistry, the blocks of pillow lava in the Boones Point mélange generally belong to the tholeiite suite. The calc-alkaline suite of mafic volcanic rocks is apparently under represented. Outsized blocks of enriched mid-ocean ridge basalt (E-MORB), normal mid-ocean ridge basalt (N-MORB) and island arc tholeiite (IAT) have been recognized on the basis of their rare earth element signatures.

Island arc tholeiite is present in the Roberts Arm Group and the Moretons Harbour Group in the structurally highest parts of the peri-Laurentian thrust stack in central Notre Dame Bay. Ocean island basalt (OIB) occurs in association with E-MORB and minor N-MORB lavas in the lowest exposed part of the Floian Moretons Harbour Group (Swinden, 1996; Cutts *et al.*, 2012). They lie stratigraphically beneath island arc volcanic and intrusive rocks. The limestone-bearing E-MORB tholeiites located at the early Darriwilian base of the Moores Cove Formation are interstratified with less common tholeiites of N-MORB composition (Dec *et al.*, 1997). Both overlie the dominantly calc-alkaline basalts of the Fortune Harbour Formation of the Cottrells Cove Group.

Although the Lawrence Head volcanic fill of the Exploits back arc basin does contain LREE-enriched tholeiites, it is notably devoid of N-MORB lava flows. The local Lawrence Head succession occurring immediately south of the Boones Point Complex is made up of transitional tholeiitic to mildly alkaline basalts. Thus, it is probable that the large E-MORB and N-MORB volcanic blocks in the Boones Point mélange (Figure 25) were derived from the Cottrells Cove Group or the Moretons Harbour Group of the Notre Dame Subzone (Figure 8).

Although some of the volcanic rocks in the Boones Point Complex may have been derived from a local source area in the Notre Dame Subzone farther north on the peninsula, a

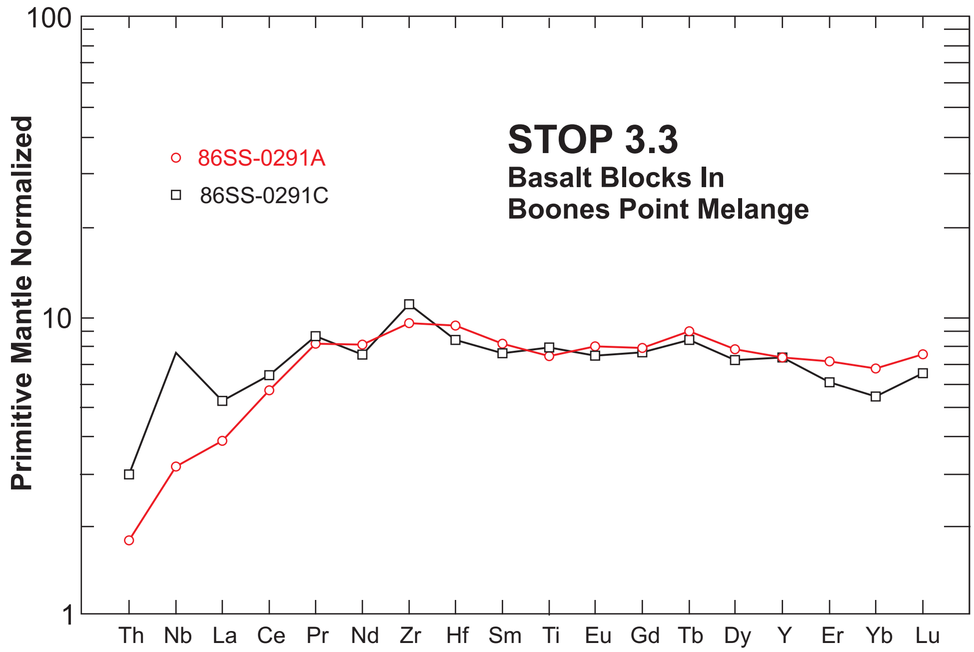


Figure 25. *Primitive mantle-normalized plots showing extended rare earth element (REE) patterns for outsized blocks of pillowed basalt within the block-in-matrix mélange of the Boones Point Complex. Note the negative slope of the light REE pattern, the generally flat heavy REE pattern, and the lack of a negative Nb anomaly relative to Th. Sample 86SS-0291A resembles normal mid-ocean ridge basalt (N-MORB), whereas Sample 86SS-0291C is similar to enriched mid-ocean ridge basalt (E-MORB). In contrast, the tectonically adjacent basalts from the peri-Gondwanan Lawrence Head Formation in Southeast Arm are represented by transitional tholeiitic to mildly alkaline basalts; N-MORB lavas have not been recognized in the Exploits back arc basin.*

similar peri-Laurentian provenance for the more abundant mottled blocks of siliceous siltstone and pyritiferous argillite is much harder to substantiate. Such sedimentary rocks are, however, present in the southernmost unbroken formations of the Sops Head Complex farther west along the Red Indian Line. They have been structurally removed from the Boones Point Complex on the Fortune Harbour peninsula.

It remains unresolved whether or not the sandy wacke blocks and the boulder conglomerate blocks originated from one or more stratigraphical divisions within the peri-Laurentian Moores Cove Formation. Alternatively, they could have been sourced, along with the bioclastic carbonates, in the peri-Gondwanan realm within either the Pennys Brook Formation or the New Bay Formation (Figure 10).

STOP 3.4: Boundary between the Moores Cove and Fortune Harbour Formations on the Southwesterly-overturned Limb of the Cottrells Cove Syncline (Large Displacement or Non-deposition at the Contact between Tremadocian Island Arc Lavas and Darriwilian Abyssal Plain Turbidites?)

Location: 2.9 km (48.8 km)

Return along the southwest coastline of Cottrell's Cove to the T-junction with Route 352 and turn northwards onto the main highway. Drive through the central part of the village, bypass the paved road heading west from Route 352 and signposted to Moore's Cove, and enter the outer parking lot of Cottrell's Cove Academy in the northern part of the community. Please be aware of school children. Turn vehicles around at the school and drive southwestward along Route 352 about 250 m to a large road cut near a sharp bend in the highway. Located at E624523 N5483571, this is Stop 3.4 (Figure 23). Participants should park safely on the northwest shoulder of Route 352. Please be careful of traffic and falling rocks when viewing these exposures.

This is the last scheduled stop of the field excursion. Participants will not be returning to Grand Falls–Windsor. From here, they will be traveling directly to Gander and back to St. John's.

Regional Setting

Calc-alkaline pillowed basalt, basaltic andesite and subordinate island arc tholeiite occur in the lower part of the Fortune Harbour Formation of the Cottrells Cove Group. These volcanic island arc-related rocks are stratigraphically overlain by a regionally extensive blanket of Tremadocian felsic pyroclastic strata. However, these subaerial to submarine volcanic deposits are thickest and most coarse grained in the northwest of the peninsula and become considerably thinner and much finer grained toward the southeast.

Volcaniclastic marine sedimentary rocks up to 1 km thick dominate the middle and upper parts of the Fortune Harbour Formation. The succession begins with thin-bedded wacke intercalated with red chert, ferruginous siltstone and grey manganiferous mudstone, passes upward into medium-bedded lithic and feldspathic wacke derived from pillowed basalt and felsic tuff, and ends with massive volcaniclastic conglomerate and unsorted debrite. Basalt having a known island arc-related geochemical signature is present as variably reworked clasts in strata throughout the succession (Dec *et al.*, 1997). This type of sedimentary provenance distinguishes the Fortune Harbour turbidites from the younger Moores Cove turbidites.

In the Moores Cove Formation, the lower siliciclastic sedimentary division is made up of very thin, laterally continuous beds of red and green siltstone turbidite and laminated maroon mudstone. Such strata are conformably underlain by basaltic pillow lava of enriched mid oceanic ridge affinity intercalated with early Darriwilian bioclastic limestone. A few isolated basalt flows are interstratified with thin-bedded siltstone–sandstone rhythmmites in the basal section.

In certain places in the Cottrells Cove Group, the calc-alkaline Early Ordovician arc-related volcanic rocks and the tholeiitic Middle Ordovician back arc volcanic rocks are directly juxtaposed with each other. Although situated near the regional boundary between the Fortune Harbour and Moores Cove formations, thick successions of arc-derived Fortune Harbour turbidites are conspicuously missing from these lithotectonic sequences. An example of this phenomenon occurs in the area between Rowsell's Cove and Stop 3.4 on Route 352 (Figure 23).

Description

At the northeastern end of the road cut, flows of amygdaloidal calc-alkaline basalt display rip-up clasts of red laminated chert. Farther south, they are also succeeded by thin-bedded intervals of jasper and hematitic chert. Closer to the southwest end of the exposure, the moderately northwest-dipping basalt is observed to structurally overlie a southeasterly-overturned sequence of red laminated chert, grey cryptocrystalline chert, buff siliceous tuff and possibly felsic crystal tuff. The buff siliceous tuff is observed to be extensively netveined and sericitized in the gently northeast-plunging hinge zone of a shallowly inclined to sub-recumbent fold. These folded strata are typical of the lower Fortune Harbour Formation.

At the base of the road cut, lying below the above-mentioned rocks, participants should be able to access a 1-2 m thick interval of altered and sheared sedimentary strata. These beds of sandy wacke and dark grey argillite have been assigned to the Moores Cove Formation.

The regional southwest-directed thrust fault that displaces the overturned limb of the Cottrells Cove Syncline trends northeastward across Route 352 as it passes through Stop 3.4. Although the basal tholeiitic basalts are missing at the field trip stop, they are thought to be present along strike in Rowsell's Cove (Figure 23). The first exposures encountered to the south of Stop 3.4 near the access road to Moore's Cove belong to the upper part of the lowest turbidite division of the Moores Cove Formation. The thick bedded feldspathic wacke and sandstone turbidite-dominated middle member of the Moores Cove Formation crops out in the main harbour of Cottrells Cove.

Discussion

The juxtaposition of basalts of volcanic island arc and back arc affinity adjacent to the younger sedimentary strata of the Moores Cove Formation can be interpreted in several ways. It may indicate that Middle Ordovician pillow lavas generated in an uplifted region of a peri-Laurentian back arc basin disconformably overlay pillow lavas from an older remnant arc. After rifting ceased, the back arc basin became flooded with the coarse detritus seen in the polymictic conglomerate of the uppermost division of the Moores Cove Formation.

Alternatively, the direct juxtaposition of arc-related and back arc basalts may be everywhere a structural phenomenon. A thick succession of Fortune Harbour ribbon chert and volcaniclastic wacke may have been tectonically excised from the underlying calc-alkaline basalts. It is even possible that the Fortune Harbour arc-related rocks are regionally allochthonous relative to the Moores Cove basin fill and that they were generated in a more distal part of the peri-Laurentian margin.

ACKNOWLEDGMENTS

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PRE-MEETING TRIPS

FT-A1 **Accreted Terranes of the Appalachian Orogen in Newfoundland: In the Footsteps of Hank Williams**
Cees van Staal and Alexandre Zagorevski

FT-A2 **The Dawn of the Paleozoic on the Burin Peninsula**
Paul Myrow and Guy Narbonne

FT-A4 **Mistaken Point: A Potential World Heritage Site for the Ediacaran Biota**
Richard Thomas

FT-A5 **Neoproterozoic Epithermal Gold Mineralization of the Northeastern Avalon Peninsula, Newfoundland**
Sean J. O'Brien, Gregory W. Sparkes, Greg Dunning, Benoît Dubé and Barry Sparkes

FT-A9 **Cores from the Ben Nevis and Jeanne d'Arc Reservois: A Study in Contrasts**
Duncan McIlroy, Iain Sinclair, Jordan Stead and Alison Turpin

POST-MEETING TRIPS

FT-B1 **When Life Got Big: Ediacaran Glaciation, Oxidation, and the Mistaken Point Biota of Newfoundland**
Guy M. Narbonne, Marc Laflamme, Richard Thomas, Catherine Ward and Alex G. Liu

FT-B2 **Peri-Gondwanan Arc-Back Arc Complex and Badger Retroarc Foreland Basin: Development of the Exploits Orocline of Central Newfoundland**
Brian O'Brien

FT-B3 **Stratigraphy, Tectonics and Petroleum Potential of the Deformed Laurentian Margin and Foreland Basins in western Newfoundland**
John W.F. Waldron, Larry Hicks and Shawna E. White

FT-B4 **Volcanic Massive Sulphide Deposits of the Appalachian Central Mobile Belt**
Steve Piercey and John Hinchey

FT-B5 **Meguma Terrane Revisited: Stratigraphy, Metamorphism, Paleontology and Provenance**
Chris E. White and Sandra M. Barr

FT-B6 **The Grenville Province of Southeastern Labrador and Adjacent Quebec**
Charles F. Gower

FT-B7 **Geotourism and the Coastal Geologic Heritage of the Bonavista Peninsula: Current Challenges and Future Opportunities**
Amanda McCallum and Sean O'Brien