Current Research (2002) Newfoundland Department of Mines and Energy
Geological Survey, Report 02-1, pages 35-45

STRATIGRAPHY AND STRUCTURE OF SEDIMENTARY ROCKS IN THE HUMBER ARM ALLOCHTHON, SOUTHWESTERN BAY OF ISLANDS, NEWFOUNDLAND

T. Calon, C. Buchanan, E. Burden, G. Feltham and J. Young
Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Newfoundland, A1B 3X5

ABSTRACT

Sedimentary mélange units in diverse settings at the front of the Humber Arm Allochthon are subdivided into four informal stratigraphic assemblages defined by distinctive lithological associations and palynomorph biostratigraphy. The Riley's Brook, Bear Cove and Blow Me Down Brook assemblages are tentatively correlated with Early Cambrian to Early–Middle Ordovician formations of the Humber Arm Supergroup as defined in the trailing part of the allochthon. The Late Cambrian–Early Ordovician Little Port Assemblage is a separate tectonostratigraphic element associated with the volcanic arc suite of the Little Port complex. Thin successions of the assemblages lie interleaved in easterly (hinterland-) dipping thrust systems. Structures within the imbricate stacks indicate two phases of regional deformation, both involving the development of westerly directed fold–thrust structures. The distribution of units in the stacks is mainly controlled by second-generation out-of-sequence thrusts, which re-imbricate pre-existing duplexes of the assemblages and locally breach the sole thrust of the Little Port complex in the upper thrust slice.

INTRODUCTION

The Humber Arm Allochthon is situated in the western, external portion of the Humber Zone in the Newfoundland Appalachians (Figure 1). It represents remnants of the early Paleozoic Iapetus Ocean and flanking Laurentian margin (Williams, 1975, 1995). Lower and intermediate slices of the westerly transported thrust stack are composed of late Precambrian to Early–Middle Ordovician sedimentary rocks of the Humber Arm Supergroup. Upper thrust slices contain oceanic crust and mantle of the Bay of Islands Ophiolite Complex (Church and Stevens, 1971) and the volcanic arc suite of the Little Port complex (Williams, 1973; Malpas, 1979). Mélange with sedimentary and igneous blocks set in shale or serpentinite matrix separate the main tectonostratigraphic elements (Williams and Cawood, 1989). The allochthon was initially assembled and emplaced on the Laurentian platform during the Taconic Orogeny in response to ophiolite obduction (e.g., Dewey and Bird, 1971). It was later re-activated during contraction and extensional collapse of the Acadian orogenic wedge (Cawood, 1993).

Thick sedimentary successions of the Humber Arm Supergroup are exposed in the eastern basal portion of the allochthon, and are divided into the Curling and Northern Head groups (Waldron and Palmer, 2000). Siliciclastic rocks of the Curling Group include the Blow Me Down Brook, Summerside and Irishtown formations but range in age from late Precambrian to Middle Cambrian. The Middle Cambrian to Early–Middle Ordovician Northern Head group includes the limestone- and shale-dominated Cook's Brook and Middle Arm Point formations, and the sandstone- and shale-dominated Llanvirn Eagle Island formation, which represents syn-orogenic deposition.

Sedimentary successions in the western portion of the allochthon lie in thrust slices at an intermediate structural position within the thrust stack (Williams, 1975), and are interleaved with slices of volcanic suites including the Fox Island group (Figure 2; Williams and Cawood, 1989). The Blow Me Down Brook formation directly underlies the ophiolite complex in broken successions, whereas diverse carbonate and siliciclastic successions underlie the Little Port complex at the front of the allochthon (Williams, 1973; Williams and Cawood, 1989). The latter successions have been treated as mélange in view of their highly dismembered and internally strongly deformed architecture (e.g., Williams, 1971). Williams (1973) tentatively correlated the rocks in the mélange with the Cooks Brook formation,

Note: Stratigraphic nomenclature used in this article is used in the sense of Waldron and Palmer (2000).

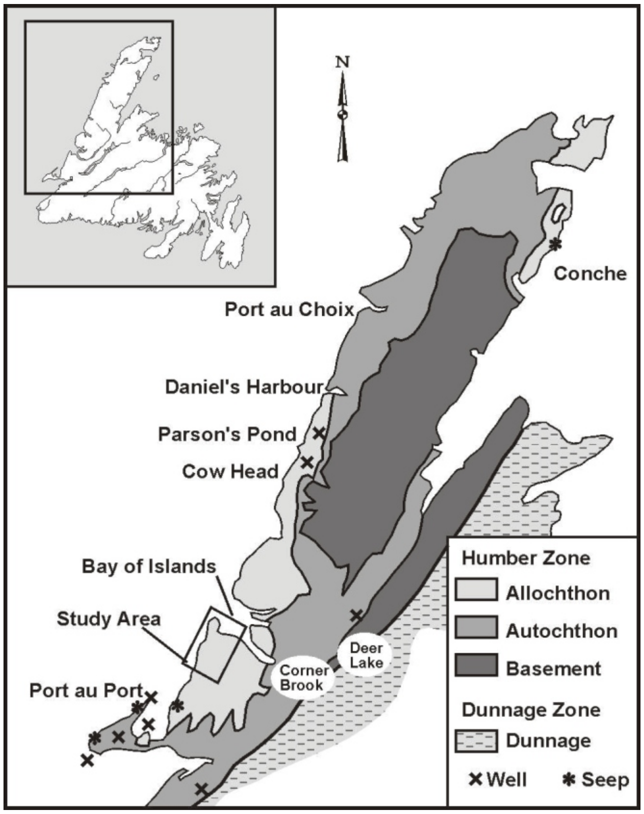

Figure 1. *Tectonic division of the Humber Zone in Newfoundland, and location of study area in the Humber Arm Allochthon.*

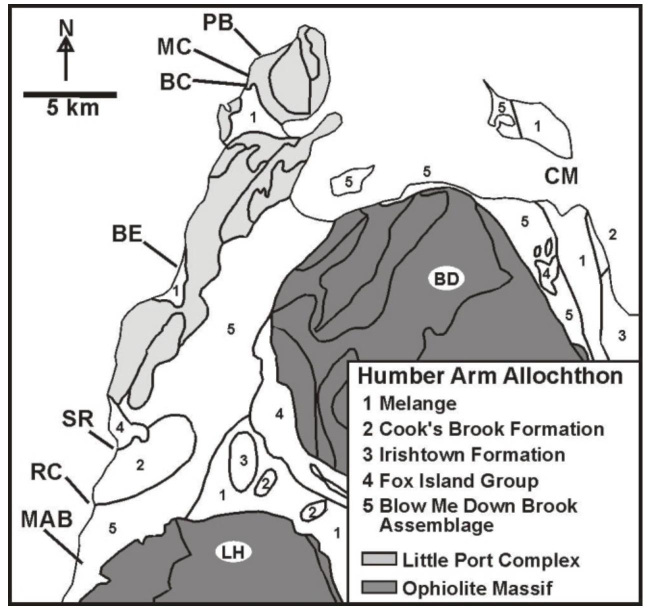

Figure 2. *Location map for outcrop areas identified in this paper: BC – Bottle Cove, BD – Blow Me Down massif, BE – Bear Cove, CM – Companion mélange, LH – Lewis Hills massif, MAB – Molly Ann Brook, MC – Miranda Cove, PB – Parker Beach, RC – Rope Cove, SR – Serpentine River. Geology compiled from Williams (1973) and Williams and Cawood (1989).*

although many sections include successions dominated by sandstone. Williams and Cawood (1989) included blocks of Blow Me Down Brook formation and volcanic rocks in shale-dominated mélange of inferred Middle Ordovician age beneath the upper thrust slices. Extensive belts of strata around the mouth of Serpentine River and Rope Cove Brook were assigned to the Cooks Brook and Blow Me Down Brook formations (Godfrey, 1982; Williams and Cawood, 1989).

Burden *et al.* (2001) identified four lithological assemblages in sedimentary rocks previously treated as mélange at Bear Cove and in the Little Port–Lark Harbour–York Harbour area. The Blow Me Down Brook, Little Port, Bear Cove and Riley's Brook assemblages are recognized as mappable units, and correlated between occurrences in diverse structural settings on the basis of lithofacies and palynological data. Lindholm and Casey (1990) identified the trace fossil *Oldhamia* in several localities of the Blow Me Down Brook assemblage along the southern shore of the Bay of Islands, placing this unit in the late Precambrian to Early Cambrian. Palynology indicates that the Little Port assemblage is Late Cambrian, the Bear Cove assemblage is mainly Tremadoc, and the Riley's Brook assemblage is Arenig (Burden *et al.*, 2001). Thus, the new lithological subdivision, combined with detailed structural analysis, resulted in significant refinement of the mélange architecture during the first phase of mapping in the northwestern portion of the area.

RESULTS

This field season focussed on detailed shoreline mapping from Molly Ann Brook in the southwest to the Companion mélange at Frenchman's Cove in the northeast (Figure 2). The coastline exposures reveal the nature and extent of the lithological assemblages and their structural styles in this portion of the allochthon, whereas limited outcrop inland restricts trace mapping of the boundaries between the main tectonostratigraphic elements.

The new results demonstrate the regional distribution of the sedimentary assemblages originally proposed by Burden *et al.* (2001) for the northwestern portion of the map area, and greatly expand the lithological associations of these units. Structures along the frontal portion of the allochthon indicate two phases of regional deformation, both involving the development of westerly directed fold–thrust structures. Structural patterns of units surrounding the ophiolite are more complicated, including north-directed fold–thrust

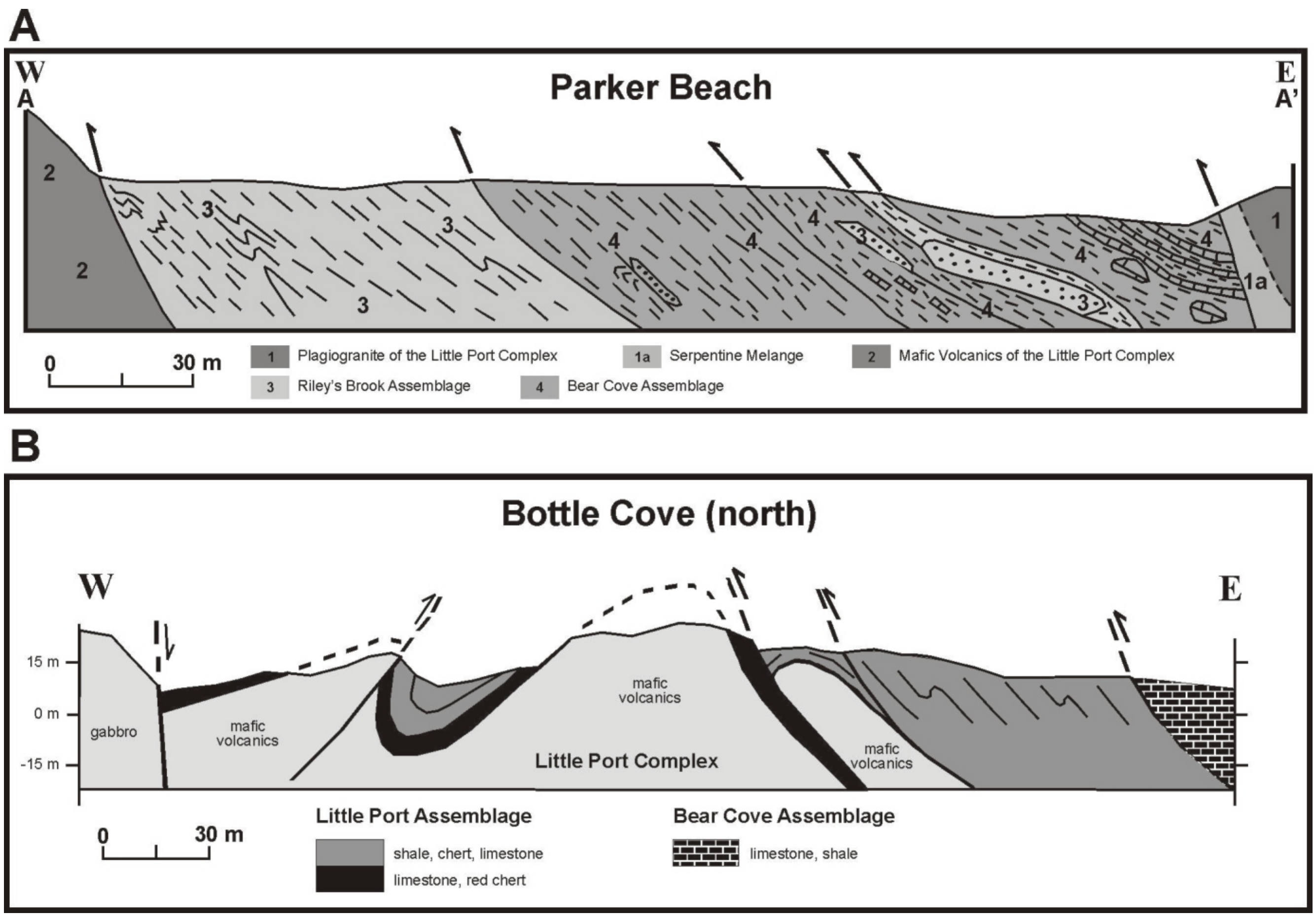

Figure 3. *Schematic geological sections of sedimentary rocks exposed at Parker Beach (A), and at Bottle Cove (B).*

structures in the Blow Me Down Brook assemblage to the north of the massif and polyphase west- and east-directed fold–thrust structures in the Companion mélange to the east of the massif.

Two locations within the map area highlight results of the 2001 mapping season: the corridor from Parker Beach to Bottle Cove in the northwest and the coastal area between Molly Ann Brook and Rope Cove (Figure 2). Other work in the project includes a detailed analysis of the sedimentary thrust stack beneath the Little Port complex at Bear Cove (Feltham, 2001), and the coastal section of the Blow Me Down Brook assemblage and Companion mélange along the southern shore of the Bay of Islands (C. Buchanan, personal communication, 2002).

PARKER BEACH–MIRANDA COVE–BOTTLE COVE

Parker Beach is a narrow, 250-m-long exposure of limestone, shale and sandstone situated within the Little Port complex at Trumpet Cove (Figure 2). This occurrence was first mapped by Comeau (1972) and Williams (1973) as mélange in a structural window underlying the Little Port complex. Due to its limited size, the outcrop does not appear on the compilation map of Williams and Cawood (1989). The sedimentary units lie in an imbricate stack of thin, moderately southeast-dipping thrust sheets (Figure 3a). Strongly cleaved black and red shale assigned to the Riley's Brook assemblage lie in the lower thrust sheets. Imbricate slices of interbedded black shale and ribbon limestone assigned to the Bear Cove assemblage occupy the central portion of the stack. In the top of this section, two small horses (Boyer and Elliott, 1982) of green sandstone of the Riley's Brook assemblage are interleaved with the Bear Cove assemblage (Figure 3a and Plate 1). The uppermost imbricate of the Bear Cove assemblage contains thick oolitic limestone beds within a ribbon limestone–black shale unit. The limestone has hydrocarbon staining and a petroliferous odour comes from freshly broken surfaces.

The base of the imbricate stack is marked by an east-dipping fault contact with mafic volcanic rocks of the Little Port complex in the footwall (Figure 3a). Grooves on this

Plate 1. *Thin thrust sheets of sandstone of Riley's Brook assemblage imbricated with black shales and ribbon limestone of Bear Cove assemblage in eastern part of section at Parker Beach. View to southeast; see also Figure 3A.*

floor thrust confirm dip slip movement. West-verging folds having gently south-plunging fold axes are present in the shales of the lower imbricates. The folds affect a pre-existing bedding-parallel cleavage indicating that they are second-generation (F_2) structures. The roof thrust of the stack is formed by a narrow, steeply southeast-dipping zone of sheared serpentinite and blocks of gabbro. It separates the sedimentary rocks from an overlying plagiogranite unit of the Little Port complex (Figure 3a). The sandstone horses of Riley's Brook assemblage in the upper part of the thrust stack are bounded by southeast-dipping shear zones showing strongly developed cleavage and fault mirrors and slickenlines indicating a reverse sense of shear. The geometry at the base of the imbricate stack clearly shows that the sedimentary thrust slices were emplaced on top of the Little Port complex exposed to the west. Hence, the stack is not necessarily a duplex that is partially exposed in an eyelid window (Boyer and Elliott, 1982), as portrayed by Comeau (1972) and Williams (1973). Rather, the development of the stack is related to a second period of fold–thrust development during which an original sole thrust at the base of the Little Port complex was breached by out-of-sequence thrusts rising from the underlying sedimentary thrust stack. This re-imbrication event can also explain the presence of the isolated sandstone horses within the upper part of the imbricate stack.

Miranda Cove is situated 700 m north of Bottle Cove (Figure 2), and hosts a small exposure of sedimentary rocks adjacent to volcanic rocks of the Little Port complex. The southeast-dipping succession overlies the igneous rocks, but the contact is covered by a narrow zone of scree. A lower black shale unit having dismembered green volcanogenic sandstone beds overlies, with gradational contact, a conglomerate having a shale–sandstone matrix and abundant, poorly sorted mafic volcanic clasts. Shear fabrics in cleaved shales indicate reverse sense movement to the south. An upper unit of black shale contains lenses of volcanic conglomerate and green sandstone, as well as limestone clasts, which lie in a stratified manner at several levels in the succession. The rounded clasts range in size from 10 to 200 cm, and consist of fine-grained brown-weathering limestone and grey limestone conglomerate that is highly recrystallized and veined. The succession is assigned to the Little Port assemblage based on its lithology and setting. The nature and abundance of the volcanic detritus shows that the succession was deposited in proximity to volcanic edifices of the Little Port complex. The distribution and nature of the limestone clasts suggest intermittent olistostromal deposition sourced from carbonate build-ups associated with the volcanic edifices.

Along the north shore of Bottle Cove (Figure 2, 3b), a 15-m-thick sedimentary succession of the Little Port assemblage non-conformably overlies volcanic basement of the Little Port complex consisting of pillowed basalt and pillow breccia with red chert fragments. Laminated limestone, locally interbedded with limestone conglomerate, fills hollows on the top of the basement and is succeeded by red chert and variously coloured siliceous shale. The volcanic rocks and their sedimentary cover are folded in a series of southerly plunging folds that are varied in style and broken by thrusts with moderate dips to the west and east (Figure 3b). Shales in the core of the synform in the western part of the section show bedding-parallel cleavage that is folded in parasitic structures. The small-scale folds have a crenulation cleavage developed parallel to their axial surfaces. Hence, the large fold train and associated thrusts are interpreted as second-generation structures.

In the eastern part of the section at Bottle Cove, a 50-m-thick unit of strongly cleaved siliceous shale along with dismembered sandstone beds is tentatively assigned to the Little Port assemblage (Figure 3b). This panel dips to the east and contains westerly verging mesoscopic folds affecting the cleavage. It is sheared over a folded footwall of volcanic basement with a thin veneer of shale. It is overlain by a poorly exposed, easterly dipping succession of Bear Cove assemblage containing thin crosslaminated and convolute laminated limestone beds and black shale. Red, grey and black shales of the Riley's Brook assemblage occur in small inland exposures to the east of the cross section, and show bedding with gentle easterly dip.

Similar to Parker Beach, the geometry of the structures at Bottle Cove shows that in this part of the allochthon the Little Port complex does not lie as a klippe above the sedimentary thrust sheets as portrayed by previous workers (Comeau, 1972; Williams, 1973; Williams and Cawood, 1989). Instead, strata of several assemblages are emplaced over the western portion of the igneous complex. It is concluded that an important west-verging out-of-sequence thrust extends from Parker Beach to Bottle Cove and farther south. This structure developed during a second phase of regional deformation and breached the sole thrust of the Little Port complex that formed during earlier assembly of the allochthon. The re-imbricated sedimentary successions directly overlie igneous basement at Parker Beach, whereas an indigenous sedimentary cover of the igneous complex is preserved beneath the floor thrust of the sedimentary imbricate stack at Bottle Cove.

The Little Port assemblage at Miranda Beach is considered to lie stratigraphically on volcanic basement in the footwall of the regional out-of-sequence thrust. This succession is correlated with the volcanic boulder conglomerate–sandstone–shale association of the assemblage found at Little Port and the limestone–chert–shale association found at Bottle Cove (*see also* Burden *et al.*, 2001; Cawood *et al.*, 1988; Strowbridge, 2001). The regional distribution and varied lithofacies associations of the Little Port assemblage indicate that highly diverse depositional settings developed locally during the evolution of the arc complex. Processes associated with the formation of the assemblage include mass wastage of fine to coarse igneous detritus, carbonate build-up and collapse around volcanic centres, and hemipelagic deposition of chert and shale. A radiometric date of 505 Ma for plagiogranite of the Little Port complex near Lark Harbour provides a general age bracket for the assemblage (Jenner *et al.*, 1991).

MOLLY ANN BROOK–ROPE COVE AREA

Two northeast-trending belts of sedimentary rocks were delineated by Godfrey (1982) and Williams and Cawood (1989) between the Lewis Hills ophiolite massif and the Little Port complex (Figure 2). The western belt contains interbedded grey to black shale and limestone, and was assigned to the Cooks Brook formation. A shale locality near the mouth of Serpentine River has yielded graptolites of Tremadoc age, and limestone at the shore, approximately 700 m south of the river, yielded a trilobite fauna of Late Cambrian–Early Ordovician age (Kindle and Whittington, 1965). North of Serpentine River, the belt is structurally overlain by a suite of mafic volcanic rocks, associated with large blocks of limestone (Schuchert and Dunbar, 1934). This unit has been assigned to the Fox Island group by Williams and Cawood (1989). The eastern belt structurally underlies the Lewis Hills ophiolite and contains grey to green sandstone and variously coloured shale. The siliciclastic succession was correlated with the Blow Me Down Brook formation (Williams and Cawood, 1989). No macrofossil localities were reported from this unit in previous mapping.

Detailed mapping of the coastal section and limited inland exposures in the area between Molly Ann Brook and Rope Cove has resulted in significant changes in the assignment and distribution of sedimentary units (Figure 4a). Five northeast-trending belts of successions assigned to the Blow Me Down Brook, Bear Cove and Riley's Brook assemblages form part of an overall moderately southeast-dipping composite thrust system. At the north shore of Rope Cove, thin thrust slices of pillowed basalt intruded by porphyritic mafic dykes occur interleaved with successions of the Bear Cove assemblage (Figure 4a, b). The igneous rocks were not described by Godfrey (1982). They are tentatively correlated with the Fox Island group as defined by Williams and Cawood (1989), based primarily on their position within the sedimentary thrust stack.

The Bear Cove assemblage constitutes the western, lowermost belt within the thrust stack. It is spectacularly exposed along the shore between Rope Cove and Serpentine River, but has no outcrop on the glacial terrace of the coastal region. It contains highly telescoped, and internally folded successions of black and grey shale interlayered with white-, grey- and brown-weathering limestone. Shale/limestone ratios are extremely variable, and limestones have thin to medium bed thicknesses. These beds show parallel- and crosslamination, as well as convolute lamination, and are interpreted as turbidite deposits. Thick-bedded successions with limestone conglomerates, as encountered on the White Rocks at Bear Cove (Burden *et al.*, 2001), are not found in the map area. Successions containing possible slump fold systems were recognized by Young (2002) at Rope Cove. The fossil locality near Serpentine River was revisited and new samples containing dendritic graptolites suggest a Late Cambrian to Tremadoc age for the assemblage in keeping with the results of Kindle and Whittington (1965). Preliminary palynological data of shale samples collected in the vicinity of Rope Cove confirm a Tremadoc age for the successions in this part of the thrust stack.

The belt of the Bear Cove assemblage in the vicinity of Rope Cove is divided into two southeasterly dipping imbricate stacks (Figure 4b, c). At Rope Cove Point, the uppermost imbricates of the western stack are overlain by a small hinterland-dipping duplex structure (Boyer and Elliott,

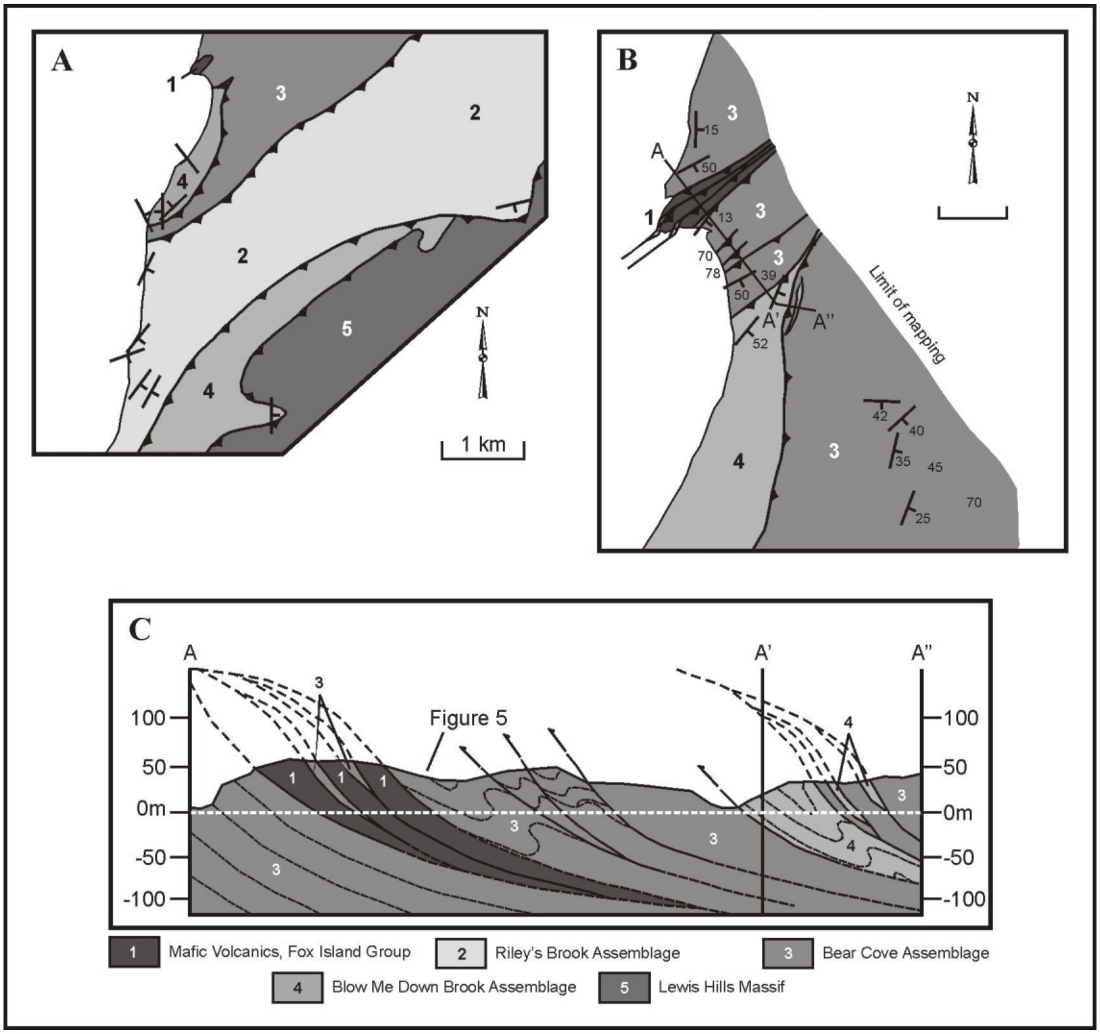

Figure 4. *A) Geological map of Rope Cove – Molly Ann Brook area, showing the distribution of lithological assemblages in this area; B) Detailed geology of Rope Cove; C) Cross-section A – A' – A'' of the imbricate stack at Rope Cove.*

1982) containing rocks of the Fox Island group (Young, 2002). The duplex extends into the sea, and can only be traced in outcrop for 200 m inland. Three thin horses of mainly volcanic rocks are separated by 1- to 5-m-thick, highly sheared zones of shale and thin dismembered limestone beds, which appear similar to successions of Bear Cove assemblage in the surrounding imbricates (Figure 4c).

The imbricates of the Bear Cove assemblage at Rope Cove show complicated fold–thrust geometries (Figure 5, Plate 2). Overprinting patterns provide evidence for polyphase deformation involving at least two phases of fold–thrust development (Young, 2002). The F_1 folds are tight to isoclinal, commonly rootless and intrafolial, and are associated with an axial planar cleavage that is strongly developed in the shales. The folds have reclined orientation patterns, and are generally asymmetric with northerly vergence and facing. The F_2 folds predominate in the imbricates, and are strongly asymmetric with northwesterly vergence (Figure 5; Young, 2002). The folds are close to tight, polyharmonic structures having abundant parasitic folds in the hinge domains. They have moderate to steep southeast-dipping axial surfaces, but an axial planar crenulation cleavage is only locally developed in the shales. Fold axes plunge gently to northeast and southwest. The folds have angular hinges and short, steeply dipping forelimb domains. Facing is generally upward suggesting that the folds mainly overprint the normal limbs of pre-existing F_1 folds. Downward-facing F_2 folds have only been found in a few instances (Young, 2002). The southeast-dipping thrust surfaces bounding the sedimentary imbricates clearly truncate the F_2 fold structures, generally along the overturned limbs. Stylewise, the folds are not typically thrust ramp-related folds (Jamison, 1987), but rather appear to be part of a regional northwest-verging fold system that was breached by contemporaneous thrusts.

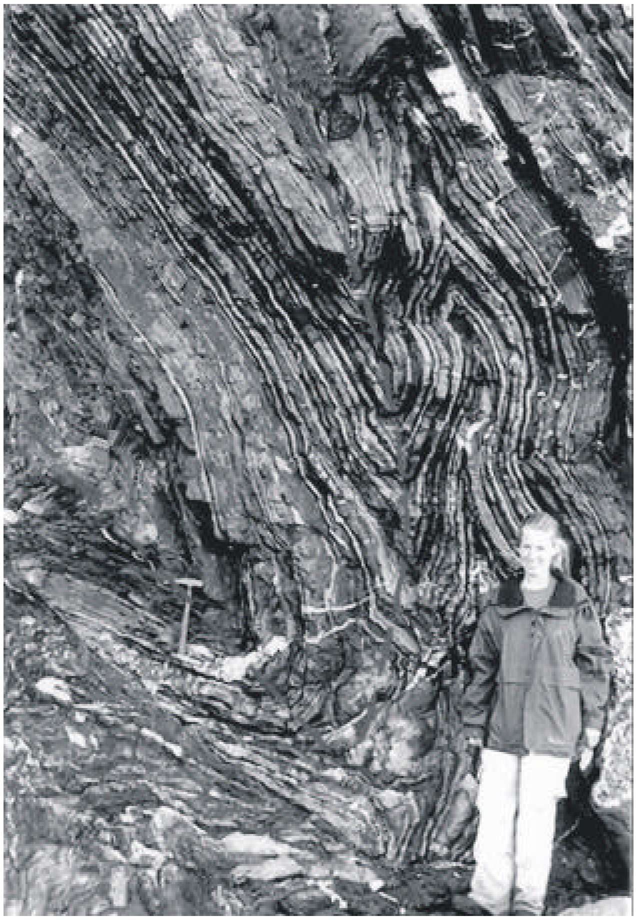

Plate 2. *Hook structure of isoclinal F_1 fold refolded in asymmetric overturned F_2 fold in Bear Cove assemblage at Rope Cove. Outcrop located at the northwestern end of the section in Figure 5.*

The development of the imbricate stack of the Bear Cove assemblage, including the emplacement of the Fox Island group duplex, is interpreted to have occurred during the second phase of regional deformation. The Fox Island group generally occurs in thrust slices lying immediately beneath the base of the upper igneous complexes (Williams, 1975; Williams and Cawood, 1989). The emplacement of this unit within sedimentary thrust slices at a more intermediate position in the allochthon indicates a complicated polyphase thrust scenario involving second-generation out-of-sequence thrusts, which breached earlier formed duplex structures. The F_1 related thrusts, which are folded and truncated by F_2 structures, have been recognized in only a few localities (Figure 5). Restoration of the regional F_1 fold–thrust architecture is difficult to accomplish in view of the penetrative overprinting by F_2 folds and thrusts.

The central stack of thrust sheets of the Bear Cove assemblage at Rope Cove is structurally overlain by a succession of thick-bedded green sandstone and subordinate black and grey shale (Figure 4; Young, 2002). A new fossil locality in shale near the mouth of Rope Cove Brook has yielded the trace fossil *Oldhamia* (Lindholm and Casey, 1989), indicating that this succession can be confidently assigned to the Early Cambrian Blow Me Down Brook assemblage. The rocks lie in an approximately 100 m thick panel of moderately southeast-dipping strata. The internal geometry of the panel is poorly resolved due to lack of exposure inland, but discontinuous outcrop along the lower course of Rope Cove Brook suggests the presence of northwest-verging broken folds. The panel appears to taper toward the northeast, and extends over 2 km southward along the shore of Rope Cove, where the strata lie in a gently north-plunging syncline (Figure 4a, b).

The Blow Me Down Brook assemblage is structurally overlain by the eastern imbricate stack of the Bear Cove assemblage (Figure 4). The thrust contact is well exposed in Rope Cove Brook, where it forms a 30-m-thick, steeply east–southeast-dipping zone of interleaved slices of shale with ribbon limestone assigned to the Bear Cove assemblage and thick sandstone beds of the Blow Me Down Brook assemblage, which lie parallel to the bounding thrusts (Figure 4c; Young, 2002). Truncation of northwest-verging F_2 folds in the shale–limestone slices indicates that the contact zone was formed during a second phase of re-imbrication of the two assemblages. In terms of both stratigraphic and structural relationships, this boundary is highly anomalous, in that it places younger (Tremadoc) rocks over much older (Early Cambrian) rocks and involves the omission of successions covering a large stratigraphic interval. The structural setting of the zone is analogous to that of the Fox Island group duplex in the lower part of the regional thrust system (Figure 4c).

The eastern imbricate stack of the Bear Cove assemblage is poorly exposed in a narrow belt on the southern shoreline of Rope Cove, but has continuous exposure in tributaries of Rope Cove Brook (Figure 4a, b). The unit was incorrectly mapped as the Blow Me Down Brook formation by Godfrey (1982). It contains a grey and green shale–ribbon limestone succession interspersed with intervals of brown medium-bedded crosslaminated limestone. The rocks show complicated refolded fold patterns, and fold panels are commonly enveloped by narrow zones of highly sheared shale. A large zone of downward-facing, east-plunging F_2 folds is delineated in the southeastern part of the map area (Young, 2002). It demonstrates the presence of a macroscopic F1 fold with a large overturned limb domain.

A wide belt of southeasterly dipping successions containing sandstone and shale in various proportions is found in the southwest part of the map area (Figure 4a). A unit of

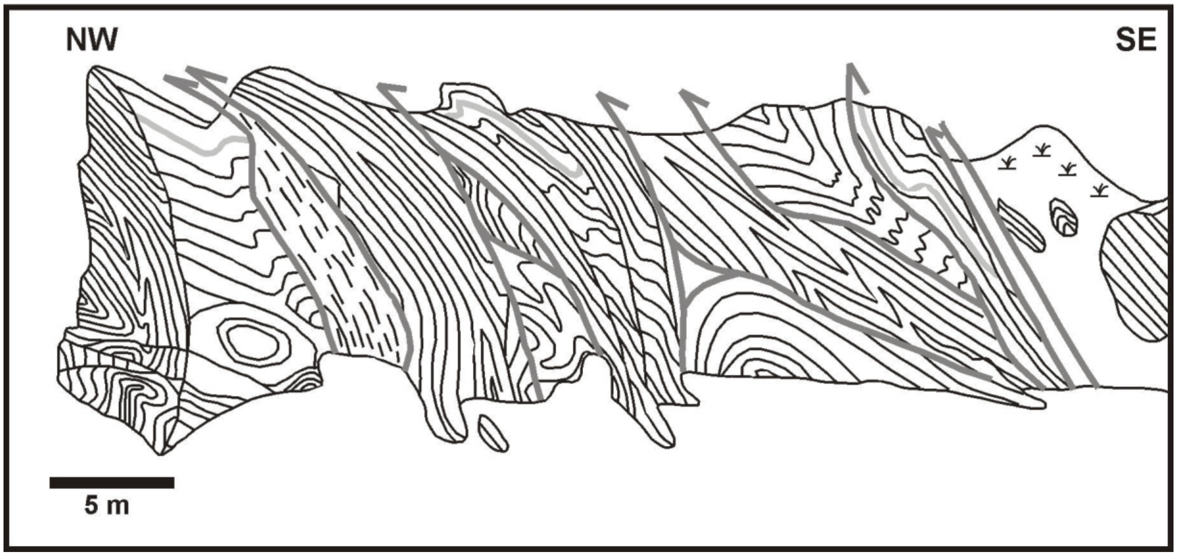

Figure 5. *Detailed sketch of imbricated panels of the Bear Cove assemblage at Rope Cove, directly east of the Fox Island group duplex. Thin thrust sheets contain refolded fold patterns. The structure is dominated by northwest-verging F_2 folds truncated by southeast-dipping thrusts.*

thin- to medium-bedded quartzose and arkosic sandstone interlayered with rusty-weathering black shale along the coastline and the lower course of Molly Ann Brook is assigned to the Riley's Brook assemblage (Plate 3). Acritarch assemblages retrieved from the shale have yielded *Baltisphaeridium longispinosum* (Eisenack, 1958) confirming an Arenig or younger age for the rocks in this belt (Burden *et al.,* 2001). A thick succession of red and black shale exposed in the middle course of the brook overlies the sandstone-dominated succession along an east-dipping fault. The age of this unit remains uncertain as samples have not yielded a diagnostic acritarch assemblage. A succession of black shale and thinly bedded green gritty sandstone structurally overlies the latter unit in the upper course of the brook. The succession lies in a homoclinal, gently southeasterly dipping panel and underlies the gently southeast-dipping base of the Lewis Hills ophiolite thrust sheet. Black shale near the contact with the ophiolite contains a new occurrence of the trace fossil *Oldhamia*, and demonstrates that at least the upper portion of the siliciclastic successions exposed in the brook are part of the Early Cambrian Blow Me Down Brook assemblage (Lindholm and Casey, 1989; Burden *et al.,* 2001).

The delineation of the Arenig Riley's Brook assemblage adds a new stratigraphic element to the thrust stack in this part of the map area. The precise location of the contact of this unit with the overlying Early Cambrian Blow Me Down Brook assemblage remains uncertain, but the contact is clearly a fundamental structural boundary involving a large stratigraphic hiatus. The position of the Blow Me Down

Plate 3. *Riley's Brook assemblage along the lower course of Molly Ann Brook.*

Brook assemblage directly beneath the Lewis Hills massif is analogous to that of the unit beneath the Blow Me Down massif farther to the north (Figure 2). However, the repetition of the assemblage in two thrust slices within the regional structure is a new feature of the thrust stack. Combined with the omission of large stratigraphic sections along the bounding thrusts, it implies that westerly directed out-of-sequence thrusting must have played a role in shaping the architecture of this part of the allochthon.

SUMMARY

Mapping in the frontal exposures of the Humber Arm Allochthon in the area south of the Bay of Islands confirms the validity of the informal stratigraphic subdivision of sedimentary mélange in four assemblages proposed by Burden *et al*. (2001). The Blow Me Down Brook, Little Port, Bear Cove and Riley's Brook assemblages are mappable units characterized by distinctive lithological successions. The inventory of measured sections and facies associations is greatly expanded, but compilation of successions from various occurrences into a regional stratigraphic column for each of the assemblages remains a problem due to the highly imbricated state of the units. Previous and new paleontological results show that successions of the assemblages mapped in localities with diverse settings within this part of the allochthon share similar, restricted age ranges.

The Late Cambrian–Early Ordovician Little Port assemblage is of special interest because of its stratigraphic association with volcanic rocks of the Little Port complex. The nature of the assemblage indicates the presence of highly diverse depositional settings during the evolution of the arc complex, notably including the development of carbonate build-ups. In palinspastic restorations of the tectonostratigraphic elements of the allochthon, the assemblage must be treated separately from successions that were deposited on the evolving distal continental margin of Laurentia. It should, therefore, not be included with the stratigraphic units that constitute the Humber Arm Supergroup. The association of limestone with mafic volcanic rocks of the Little Port complex raises questions about the stratigraphic assignment of similar suites in the southwestern part of the map area. Mafic volcanic rocks and large carbonate build-ups lie in a thrust slice underneath the Little Port complex north of Serpentine River, and were assigned to the Fox Island group (Williams and Cawood, 1989). This unit may be correlable with the Little Port assemblage, representing a detached segment of the arc complex stuck to the sole of the upper igneous thrust slices.

Williams and Cawood (1989) assigned all siliciclastic successions in the map area, including those incorporated in mélange, to the Blow Me Down Brook formation. The restricted late Precambrian–Early Cambrian age of the unit was shown by Lindholm and Casey (1990) based on occurrences of the trace fossil *Oldhamia* in the Bay of Islands (*see also* Burden *et al.,* 2001). Two new occurrences were found in separate belts of the Blow Me Down Brook assemblage at Rope Cove and Molly Ann Brook. The Riley's Brook assemblage also comprises siliciclastic successions with widespread occurrence along the front of the allochthon. Palynology results clearly indicate that this unit is Arenig or younger in age (*see also* Burden *et al.,* 2001). Recognition of the Riley's Brook assemblage adds a new stratigraphic element to the sedimentary units in the intermediate thrust slices at the front of the allochthon. The Riley's Brook assemblage may be a correlative unit of the syn-orogenic (flysch) deposits of Llanvirn age represented by the Eagle Island formation of the Humber Arm Supergroup in the eastern Bay of Islands. Field experience tells that distinction of the Riley's Brook and Blow Me Down Brook assemblages may be difficult without biostratigraphic control in the case of dismembered shale successions with minor sandstone.

The shale–limestone successions of the Bear Cove assemblage have widespread distribution in the frontal portion of the allochthon. Lithological associations are varied, but generally the successions are dominated by shale with thin- to medium-bedded limestone showing turbidite features. Limestone conglomerates are rare, except at the White Rocks in Bear Cove (Burden *et al.*, 2001; Feltham, 2001). Successions with dolomite are rare in the western part of the map area, but form a significant component in the imbricate stack of the Companion mélange. Lithofacies indicate deposition in a distal slope environment. Rare macrofossil occurrences indicate a Late Cambrian–Tremadoc age for the assemblage (Kindle and Whittington, 1965; Williams, 1973), and palynology indicates a similar age range for many localities in the map area. On the basis of lithology, facies and age, the Bear Cove assemblage may be correlative with the upper divisions of the Cooks Brook formation (Botsford, 1988; Boyce *et al.*, 1992). Successions with dolomite may correlate with the Middle Arm Point formation, but this awaits further palynology. The Bear Cove and Riley's Brook assemblages commonly occur together in highly imbricated thrust stacks, but an unambiguous stratigraphic transition between the two units has not been found to date.

Structural patterns along the front of the allochthon indicate two phases of regional deformation, both involving the development of westerly directed fold–thrust systems. The partitioning of stratigraphic units into thin successions of limited age range within the imbricate stacks is attributed to a first phase of duplex formation. This thrust event was associated with the formation of tight to isoclinal, commonly rootless, mesoscopic folds with penetratively developed axial planar cleavage. Dismemberment of beds is common, and is a consequence of transposition. The macroscopic geometry of F_1 systems is difficult to reconstruct because of fine-scale imbrication in the duplexes and intense overprinting by younger structures. Most small F_1 folds face and verge in westerly directions, suggesting tectonic transport to the west. Large folds with extensive overturned limb domains are rare.

Asymmetric westerly verging, close to tight F_2 folds form the dominant structures in the imbricate stacks, and are superposed on F_1 folds and the cleavage. F_2 folds are rarely associated with an axial planar crenulation cleavage. These folds are commonly truncated by thrusts that define the moderately east-dipping architecture of the stacks. Easterly verging F_2 folds and back-thrusts are rare, and only one large downward-facing fold panel has been mapped to date. In the northwestern part of the map, the sole thrust of the Little Port complex is breached by a moderately east–southeast-dipping regional F_2 thrust, which places a sedimentary imbricate stack over the igneous rocks in the western outcrop belt of the complex. Previously published maps showing the sedimentary rocks as lying in structural windows beneath the Little Port complex in this area are no longer valid (Williams, 1973; Williams and Cawood, 1989). In Bear Cove, on the other hand, Feltham (2001) has shown that the sedimentary imbricate stack lies in an hinterland-dipping antiformal stack partially exposed in an eyelid window (Boyer and Elliott, 1982) beneath the folded sole thrust of the Little Port complex. At Rope Cove, the emplacement of the Fox Island group within the sedimentary thrust system, and the interleaving of imbricate stacks of the Bear Cove and Blow Me Down Brook assemblages are attributed by Young (2002) to a second phase of out-of-sequence thrusting. A similar scenario must apply to the structural intercalation of the Riley's Brook and Blow Me Down Brook assemblages at Molly Ann Brook.

ACKNOWLEDGMENTS

This project is funded through an interprovincial NATMAP research agreement with the Geological Survey of Canada, the Geological Survey of Newfoundland and Labrador, and Memorial University of Newfoundland. We appreciate the logistical help and hospitality of Jerry and Rose Sheppard, Mark Childs and Marlaine and Junior Childs.

REFERENCES

Botsford, J.
1988: Stratigraphy and sedimentology of Cambro-Ordovician deep water sediments, Bay of Islands, western Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 473 pages.

Boyce, W.D., Botsford, J.W. and Ash, J.S.
1992: Preliminary trilobite biostratigraphy of the Cooks Brook Formation (Northern Head Group), Humber Arm Allochthon, Bay of Islands, western Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 92-1, pages 55-68.

Boyer, S.E. and Elliot, D.
1982: Thrust Systems. American Association of Petroleum Geologists Bulletin, Volume 66, Number 9, pages 1196 to 1230.

Burden, E., Calon, T., Normore, L. and Strowbridge, S.
2001: Stratigraphy and structure of sedimentary rocks in the Humber Arm allochthon, southwestern Bay of Islands, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 2001-1, pages 15-22.

Cawood, P.A., Barnes, C.R., Botsford, J.W., James, N.P., Knight, I., O'Brien, S.J., O'Neill, P.P., Parsons, M.G., Stenzel, S.R., Stevens, R.K., Williams, H. and Williams, S.H.
1988: A cross-section of the Iapetus Ocean and its continental margins: Field Excursion Guidebook. Vth International Symposium on the Ordovician System (ICS/IUGS IGCP Project 216), St John's Newfoundland, 144 pages.

Cawood, P.
1993: Acadian orogeny in west Newfoundland: Definition, character, and significance. *In* The Acadian Orogeny: Recent Studies in New England, Maritime Canada, and the Autochthonous Foreland. *Edited by* D.C. Roy and J.W. Skehan. Geological Society of America Special Paper 275, pages 399-410.

Comeau, R.L.
1972: Transported Slices of the Coastal Complex, Bay of Islands – Western Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 105 pages.

Church, W.R. and Stevens, R.K.
1971: Early Paleozoic ophiolite complexes of the Newfoundland Appalachians as mantle-oceanic crust sequences. Journal of Geophysical Research, Volume 76, pages 1460-1466.

Dewey, J.F. and Bird, J.M.
1971: Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland. Journal of Geophysical Research, Volume 76, pages 3179-3206.

Eisenack, A.
1958: Microfossilien aus dem Ordovizium des Baltikums. I, Markositschicht, Dictyonema-Schiefer, Glaukonitsand, Glaukonitkalk. Senckenbergiana Lethaea, Volume 39, pages 389-405.

Feltham, G.R.
2001: Stratigraphy and structure of mélange in the Humber Arm Allochthon at Bear Cove, western New-

foundland. Unpublished B.Sc. (Hon) thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 72 pages.

Godfrey, S.
1982: Rock groups, structural slices and deformation in the Humber Arm Allochthon at Serpentine Lake, western Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 182 pages.

Jamison, W.R.
1987: Geometric analysis of fold development in overthrust terranes. Journal of Structural Geology, Volume 9, Number 20, pages 207-219.

Jenner, G.A., Dunning, G.R., Malpas, J., Brown, M. and Brace, T.
1991: Bay of Islands and Little Port complexes, revisited: age, geochemical and isotopic evidence confirm suprasubduction-zone origin. Canadian Journal of Earth Sciences, Volume 28, pages 1635-1652.

Kindle, C.H. and Whittington, H.B.
1965: New Cambrian and Ordovician fossil localities in western Newfoundland. Geological Society of America Bulletin, Volume 76, pages 683-688.

Lindholm, R.M. and Casey, J.F.
1989: Regional significance of the Blow Me Down Brook formation, western Newfoundland: new fossil evidence for an Early Cambrian age. Geological Society of America Bulletin, Volume 101, pages 1-13.

1990: The distribution and possible biostratigraphic significance of the ichnogenus Oldhamia in the shales of the Blow Me Down Brook Formation, western Newfoundland. Canadian Journal of Earth Sciences, Volume 27, pages 1270-1287.

Malpas, J.G.
1979: Two contrasting trondhjemite associations from transported ophiolites in western Newfoundland. *In* Trondhjemites, Dacites and Related Rocks. *Edited by* F. Barker. Elsevier, New York, pages 465-487.

Palmer, S.E., Burden, E. and Waldron, J.W.F.
2001: Stratigraphy of the Curling Group (Cambrian), Humber Arm Allochthon, Bay of Islands. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 2001-1, pages 105-112.

Schuchert, C. and Dunbar, C.O.
1934: Stratigraphy of western Newfoundland. Geological Society of America, Memoir 1, 123 pages.

Strowbridge, S.L.
2001: Stratigraphy and structure of sedimentary rocks of the Humber Arm Supergroup, Little Port–Lark Harbour area, Bay of Islands. Unpublished B.Sc. (Hon) thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 90 pages.

Waldron, J.W.F. and Palmer, S.E.
2000: Lithostratigraphy and structure of the Humber Arm Allochthon in the type area, Bay of Islands, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 2000-1, pages 279-290.

Williams, H.
1971: Mafic ultramafic complexes in western Newfoundland Appalachians and the evidence for their transportation: A review and interim report. Geological Association of Canada, Proceedings, Volume 24, pages 9-25.

1973: Bay of Islands map area, Newfoundland. Geological Survey of Canada, Paper 72-34, with Map 1355A.

1975: Structural succession, nomenclature, and interpretation of transported rocks in western Newfoundland. Canadian Journal of Earth Sciences, Volume 12, pages 1874-1894.

1995: Temporal and spatial subdivisions of the rocks of the Canadian Appalachian region. *In* Geology of the Appalachian-Caledonian Orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada, Geology of Canada, No. 6, pages 21-44.

Williams, H. and Cawood, P.A.
1989: Geology, Humber Arm Allochthon, Newfoundland. Geological Survey of Canada, Map 1678A.

Young, J.
2002: Stratigraphy and structure of the Humber Arm Allochthon at Rope Cove, western, Newfoundland. Unpublished B.Sc.(Hon) thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 80 pages.