Current Research (2000) Newfoundland Department of Mines and Energy
Geological Survey, Report 2000-1, pages 279-290

LITHOSTRATIGRAPHY AND STRUCTURE OF THE HUMBER ARM ALLOCHTHON IN THE TYPE AREA, BAY OF ISLANDS, NEWFOUNDLAND

J.W.F. Waldron and S.E. Palmer
Saint Mary's University, Halifax, Nova Scotia, B3H 3C3

ABSTRACT

The type area of the Humber Arm Allochthon contains continental margin sedimentary units of the Humber Arm Supergroup. Clastic units of the Blow Me Down Brook, Summerside, and Irishtown formations are assigned to the Curling Group. Overlying shale and carbonate sediments of the Cooks Brook and Middle Arm Point formations comprise the Northern Head group. At the top of the succession, the Eagle Island formation records the early stages of Appalachian tectonism.

Early (D1) structures in the allochthon include a pervasive, generally bed-parallel foliation or fissility, and abundant boudinage structures generated by brittle fracturing. F1 folds display a variety of relationships with the S1 foliation. In more highly deformed units, bedding cannot be traced through outcrops, and the S1 foliation has a scaly, anastomosing character. Disruption of bedding is measured by a disruption index, on a scale of 1 to 5. Melange is characterized by the mixing of rocks from different formations, in addition to intense disruption of stratification.

D1 structures are overprinted by S2 cleavage that crenulates the S1 cleavage in the west, but which becomes generally penetrative in the east. Upright F2 folds are widespread. The S3 and S4 crenulation cleavages are only locally developed. Map scale F3 folding is responsible for distortion of F2 hinges producing domes and basins in the outcrop pattern.

INTRODUCTION

The geology of the Bay of Islands in western Newfoundland figured prominently in the development of actualistic, plate-tectonic interpretations of orogenesis, and has been a classic area of Appalachian geology since the pioneering work of R.K. Stevens (e.g., Stevens, 1965, 1970), H. Williams (e.g., Williams, 1971) and J.F. Dewey and coworkers (e.g., Dewey, 1974). Igneous and metamorphic rocks of the Bay of Islands ophiolite were amongst the first to be identified as fragments of ancient oceanic crust (Dewey and Bird, 1971). Sedimentary rocks in the Humber Arm Allochthon represent a combination of passive continental margin and foredeep environments (e.g., Williams and Stevens, 1974), preserving a record of rifting, continental margin subsidence, and continent-arc collision.

Despite this attention, much of the Humber Arm Allochthon in the type area has not been mapped in detail, at 1:50 000 scale. The Bay of Islands was mapped by Williams (1973) at 1:125 000 scale. To the northeast, a large area of the Humber Arm Allochthon was mapped at 1:50 000 scale by L. Quinn (Quinn and Williams, 1983; Nyman *et al.*, 1984; Williams *et al.*, 1984). Additional mapping by Williams (1985) at 1:125 000 scale covers the region south of the Bay of Islands.

The stratigraphy of the Humber Arm Allochthon in the Bay of Islands area has been unevenly studied. An informal stratigraphic subdivision into formations was established by Stevens (1965, 1970) and Bruckner (1966). This subdivision has been followed by all subsequent authors, but only Botsford (1988) and Boyce *et al.* (1992) defined type-sections, and only for units in the upper part of the succession. Type sections for the lower, clastic units currently assigned to the Curling Group are proposed here, and the definitions of Botsford (1988) and Boyce *et al.*, (1992) for upper parts of the succession are followed, including allocating these units informally to the Northern Head group, a name proposed informally by Botsford (1988).

Structurally, the sedimentary portion of the Humber Arm Allochthon presents challenges to the mapping geologist. In large parts of the allochthon, stratigraphic successions are disrupted at a variety of scales into blocks of competent rock types surrounded by a matrix of sheared shale. In addition, rocks characteristic of several different formations are found mixed at outcrop scale. These two phenomena (fragmentation and mixing) combine to produce rock units termed ‘melange'. However, previous authors have differed in the extent to which they have recognized discrete faults or applied the term ‘melange' to the various types of deformed material in the allochthon (Williams and Cawood, 1986; Waldron *et al.*, 1988; Cawood and van Gool, 1998).

Following the discovery of oil in Port au Port Peninsula (Newfoundland Hunt Oil Company, 1996), interest has focussed on the sedimentary units of the Humber Arm Allochthon as potential source rocks for petroleum. Lithoprobe seismic profiles (Quinlan *et al.*, 1992) show reflectors beneath the Allochthon that may represent inverted basins in structurally underlying platform rocks (Waldron *et al.*, 1998), encouraging interest in possible deeply buried petroleum reservoirs.

Accordingly, it is appropriate that the sedimentary units of the Humber Arm Allochthon in its type area be mapped as part of the current NATMAP program to investigate a series of transects across the ancient Laurentian continental margin. Mapping was carried out over approximately 2 months in the summer of 1999, including the classic sections along the shores of the Humber Arm and Woods Island (Figures 1 and 2). Access to most outcrops was obtained by traversing on foot, by vehicle on logging roads, and by dory for coastal and island outcrops. Data were recorded on 1:12 500 colour air photographs for later transfer into a Fieldlog database.

HUMBER ARM SUPERGROUP: STRATIGRAPHIC UNITS

All the sedimentary rocks of the Humber Arm Allochthon in the Bay of Islands area are assigned to the Humber Arm Supergroup (Williams, 1975) and were included by Stevens (1965, 1970) in the Curling Group. The group as defined by Stevens (1965, 1970) included a Cambrian siliciclastic lower succession of the Summerside and Irishtown formations, and an Ordovician siliciclastic upper succession termed the Blow-me-down Brook formation[1]. Botsford (1988; *see* also Boyce *et al.*, 1992) suggested that the middle carbonate-rich part of the group should be separated from the lower siliciclastic part and placed in a new group, the Northern Head group; parts of the upper siliciclastic succession, including those parts of Stevens' Blow-me-down Brook formation that overlie the Middle Arm Point formation, were named the Eagle Island formation. Remaining units, previously assigned to the upper siliciclastic succession, including the rocks in the type area at Blow Me Down Brook, were shown to be distinct from the Ordovician 'flysch' (Quinn, 1988), and were assigned a Cambrian age after the discovery of the trace fossil *Oldhamia* (Lindholm and Casey, 1988, 1989). This informal reorganization of the lithostratigraphy of the Bay of Islands area therefore redefined the Curling Group to include only the lower siliciclastic succession of the Summerside and Irishtown formations, together with the Blow-Me-Down Brook formation.

Although the divisions of the Humber Arm Supergroup have never been formally defined, the lithostratigraphy adopted here stays close to the existing informal subdivisions, avoids new terminology, and attempts to place precise stratigraphic boundaries at positions in the stratigraphy that allow lateral correlation and future mapping of poorly exposed inland areas of the allochthon. In particular, the still informal stratigraphic subdivisions of the Northern Head group, and the Eagle Island formation, of Botsford (1988) are firmly adopted here.

CURLING GROUP

Summerside Formation

The Summerside formation consists of maroon and grey-green slates that are interbedded with very fine to coarse-grained, quartz-rich arkosic sandstones. The sandstones are typically grey-green on fresh surfaces but some weather to a distinctive yellowish white. In most areas of continuous exposure, slates predominate, with sporadic ‘packets' of thin- to thick-bedded sandstones. Inland areas are generally intermittently exposed, and isolated sandstone outcrops mostly predominate. Very thin and thin sandstone beds (1 to 10 cm) typically show graded bedding; thicker sandstone beds are generally more massive. Other sedimentary structures in the sandstones include abundant parallel laminations, ripple crosslaminations, dewatering sheet-structures, and uncommon examples of larger scale tabular and trough crossbeds. Crossbedded units tend to be more quartz-rich and better sorted than the overlying and underlying beds. In the slates, inconspicuous parallel laminations and uncommon crosslaminations are the only sedimentary structures. A distinctive interval of grey-green slate at the top of the formation (designated the Summerside–Irishtown transition by Stevens, 1965, 1970) is characterized by abundant small burrows up to 5 mm wide and 10 cm long, which are distinguished by slightly paler or darker colour than the surrounding matrix.

The base of the Summerside formation is unknown. Accordingly, a type section at an area of good exposure that includes the top of the formation is suggested on the north shore of Humber Arm near Summerside (Figure 1). The Summerside formation rests structurally above deformed

[1] (Blow-me-down Brook is hypenated when used in the sense of Stevens (1965, 1970; Bruckner, 1966); elsewhere, usage follows that suggested by the Gazetteer of Canada)

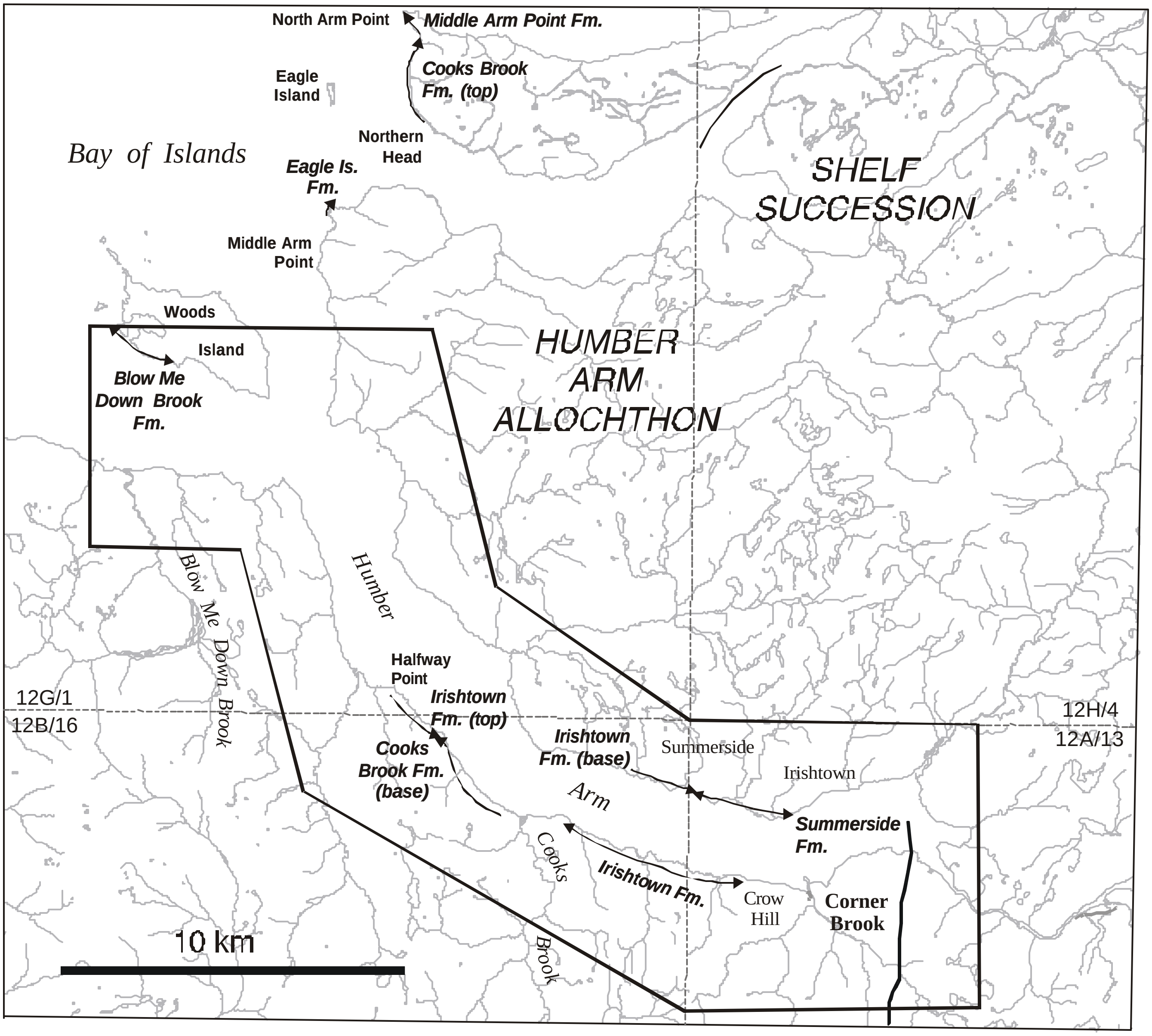

Figure 1. *Map of the southeast Bay of Islands area showing NTS sheet boundaries and place names (upper case) and the proposed locations of type sections (lower case) for formations of the Curling Group (this study) and the Northern Head group and Eagle Island formation (after Botsford, 1988). Bold outline shows area of Figure 2.*

Irishtown formation in the hanging wall of a west-dipping tectonic contact (Crow Hill thrust) exposed on Highway 440 at approximate coordinates East 429540 North 5425010 (UTM coordinates: NAD 27 datum). To the west of the contact, the suggested type section comprises somewhat discontinuous roadside and coastal exposures of predominantly red slate and grey, green and yellow sandstone. Several repetitions are present due to folding, but the section youngs predominantly to the west. Slates dominate the uppermost 50 to 100 m of the section, although red slate becomes less common, giving way westward to grey-green and then black, graphitic slate. Satisfactory sections, although deformed and discontinuous, through this interval are present on the highway and on the adjacent shoreline to the south. The top of the formation is the base of the overlying Irishtown formation, placed at the first occurrence of medium sandstone beds (10 to 30 cm thick), at approximate coordinates East 426900 North 5425710.

Stevens (1965, 1970) placed the top of the Summerside–Irishtown transition zone at the boundary between grey-green slate and black graphitic slate. The boundary, as used here, is probably a few metres higher, at the first sandstone, in recognition of the difficulty of mapping a colour change inland in poorly exposed, recessive slates.

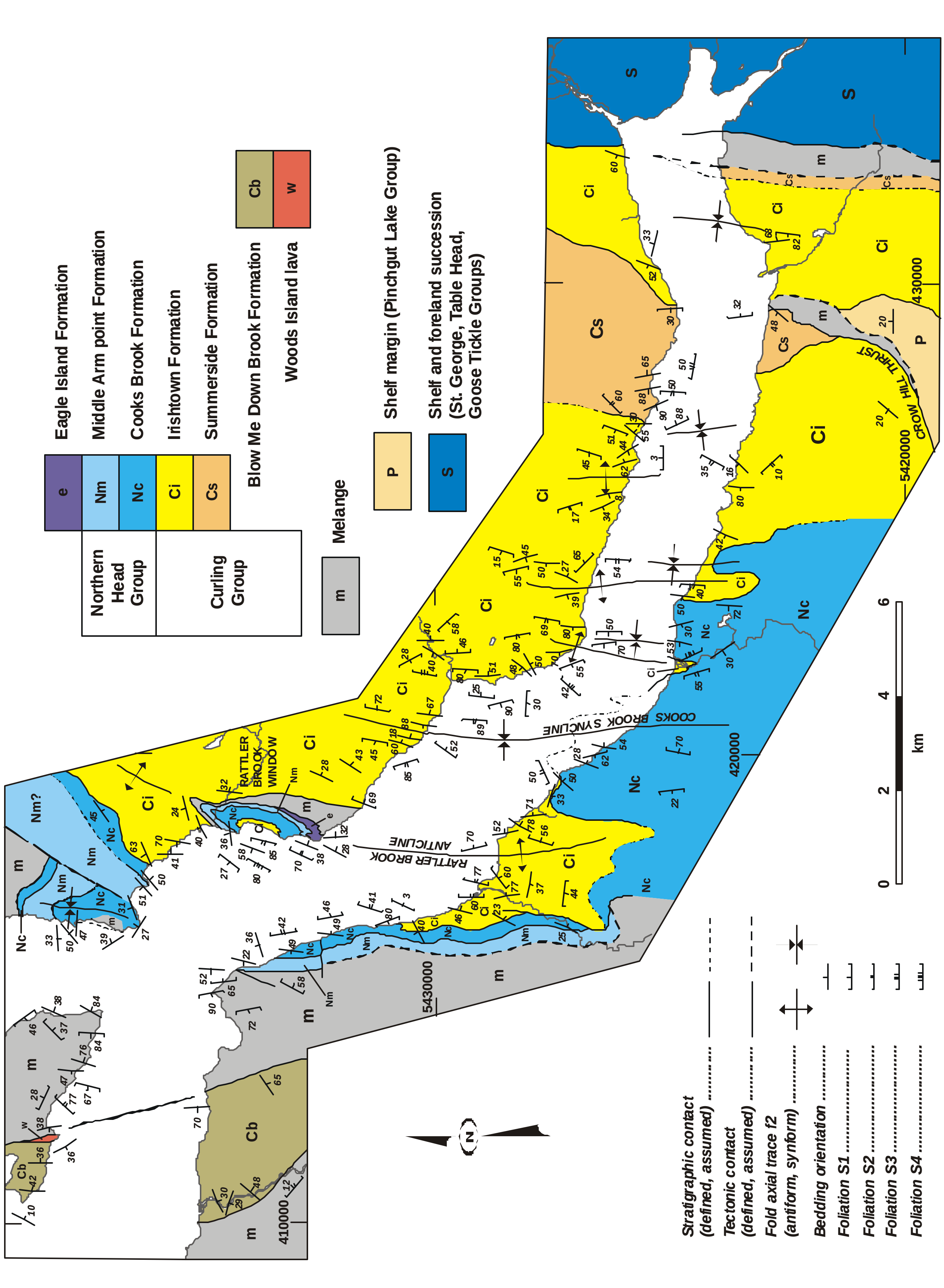

Figure 2. *Preliminary map of a partial transect through the Humber Arm Allochthon in the type area. Note: map boundaries in the Corner Brook area (NTS 12A/13) in part after Cawood and van Gool (1998) and Knight (1996), with modifications by the authors.*

The Summerside formation, despite its red coloration, was probably deposited in a deep-water, turbiditic environment (e.g. Stevens, 1970). The poor sorting, prevalence of graded bedding, and dewatering structures would be consistent with this hypothesis. Better-sorted, crossbedded sandstones are inferred to be products of reworking by bottom currents of longer duration.

No body fossils have been reported in the Summerside formation. The formation must be Early Cambrian or older, based on the Early Cambrian age of the overlying Irishtown formation; the prevalence of trace fossils in the uppermost shale interval suggests that this interval is also Early Cambrian, but lower parts of the formation may extend into the Neoproterozoic.

Irishtown Formation

The Irishtown formation is a unit of dark grey, graphitic, pyrite-bearing slates and sandstones that occupies large parts of the map area north of Humber Arm, and two regions east and west of the Cooks Brook Syncline on the south shore. This formation was originally termed the Meadows formation in the thesis work of Stevens (1965) but renamed Irishtown in subsequent publications (Bruckner, 1966; Stevens, 1970).

The Irishtown formation consists of slate, sandstone, and conglomerate. Dark grey slate is the most abundant rock in well-exposed coastal sections and road-cuts near Humber Arm, but because of its recessive weathering, slate is more poorly represented in typical inland outcrops. The slate locally contains abundant pyrite, and weathers rusty orange. Sandstones are typically quartz-rich and erosion resistant, forming headlands and ridges; they range from dark grey to white. Sandstone beds are typically graded and have partial or complete Bouma sequences; basal surfaces show well preserved flutes, grooves, and load structures. Polymictic conglomerates are found in a number of localities, associated with thick-bedded sandstones. The conglomerates include clasts of plutonic and clastic sedimentary rocks, vein quartz, and rare limestones.

A discontinuously exposed section through the formation occurs along Highway 450 and the adjacent shore, west of Crow Hill. However, in this section the base of the formation is poorly exposed and the top is faulted (Botsford, 1988); hence it may be appropriate to have separate type locations for the contacts. The base of the Irishtown formation is placed at the top of the Summerside formation type section, along the north shore of Humber Arm at UTM coordinates East 429540 North 5425010. Good exposures extend westward from the first decimetre-thick sandstone bed at this point for 1.5 km, both on Highway 440 and on the shoreline 100 to 200 m south of the road. The formation is tightly folded throughout this interval and therefore the total stratigraphic thickness cannot be determined. The top of the Irishtown formation is defined on the south shore of Humber Arm in coastal section and in road-cuts on Highway 450, at Halfway Point. This location corresponds to Botsford's (1988) definition of the base of the overlying Cooks Brook formation. The highest sandstones in the Irishtown formation are very thinly bedded, conspicuously crosslaminated sandstones with common load structures on the bases of beds. These are overlain by an uppermost 50 to 100 m, dominated by black shales or slates, locally with carbonate concretions. The base of the Cooks Brook formation is placed at the base of the lowest overlying continuous bed of calcarenite. On the coastal section, this contact is located immediately west of the tip of Halfway Point (approximate coordinates East 419570 North 5427350). Although the strata dip relatively steeply east, they are tightly folded, and the envelope of bedding dips only gently east. As a result, the contact is exposed several hundred metres farther west in the adjacent road section higher in the cliff at approximate coordinates East 419100 North 4527540.

The age of the Irishtown formation is constrained by fossils in clasts within resedimented conglomerates that are of late Early Cambrian age (Stevens 1965, 1970; James *et al.*, 1988). Lower parts of the formation could extend lower in the Lower Cambrian, but can be no older, because of the abundant trace fossils at the top of the underlying Summerside formation. The Irishtown formation displays abundant evidence for deposition by turbidity currents. The intervening black and locally pyrite-rich slates may have been deposited on a sea-floor lacking abundant oxygen. The formation is inferred to represent the deep-water equivalent of shallow-marine clastics of the Forteau and Hawkes Bay formations in the coeval shelf succession.

Blow Me Down Brook Formation

The Blow Me Down Brook formation is a sandstone-dominated unit widely exposed on the south and northeastern shores of the Bay of Islands, and on Woods Island (Figure 1). The unit was originally described by Stevens (1965) as including a variety of sandstones, some of which contain Early Ordovician graptolites and ophiolite-derived detritus. However, subsequent work (e.g., Quinn, 1988; Lindholm and Casey, 1989) has shown that Stevens' original unit is composite; the Ordovician-, graptolite- and chromite-bearing units are now separated as the Eagle Island formation (*see below*). The main outcrop area of the Blow Me Down Brook formation in the Bay of Islands was explored by Lindholm and Casey (1990) who identified the trace fossil *Oldhamia* at numerous localities, assigning an Early Cambrian age to the unit.

The best and most continuously exposed section is on the south coast of Woods Island. The formation is dominated by thickly bedded, quartz-rich arkosic sandstone that weather buff-yellow, but which are grey-green on fresh surfaces; there are subordinate intervals of grey-brown shale. Intervals of granule conglomerate are also present. Most of the sandstones are massive or show faint parallel laminations, but crosslaminations and crossbedding are locally present. Rare tabular and trough crossbedded units are notably paler, more quartz-rich, and better sorted.

The base of the formation is placed at the exposed west-dipping stratigraphic contact of sandstone on mafic volcanic rocks, on the south coast of Woods Island at approximate UTM E411720 N5438220. The section overlying the lava extends only a few metres to a short covered interval. To the west, the formation mostly dips and youngs gently east, suggesting that the exposure gap conceals a substantial fault, or that the sandstone onlaps against the lava. The total exposed thickness in the section is estimated at 350 m.

Woods Island Lava

Massive and pillowed mafic volcanic rock, volcanic breccia, and minor mafic intrusions exposed on the north and south shores of Woods Island were distinguished by Williams (1973) as the Woods Island member of the Blow Me Down Brook formation. This igneous unit, which is clearly distinct from the thick overlying sedimentary succession of the Blow Me Down Brook formation, is probably better mapped as a separate, informal unit of formation level. It may be correlated with volcanic blocks mapped in the Humber Arm Allochthon to the south that have been distinguished as the Fox Island volcanics by Williams (1985). The lava is stratigraphically overlain by sandstone and shale of the Blow Me Down Brook formation type section.

NORTHERN HEAD GROUP

The Northern Head group was defined in the thesis of Botsford (1988) and in Boyce *et al*. (1992), to include the Cooks Brook and Middle Arm Point formations, formerly included in the Curling Group. The Northern Head group was defined based on distinct lithological changes that separate the Cooks Brook formation from the underlying Irishtown formation, and the Middle Arm Point formation from the overlying Eagle Island formation. The Northern Head group is lithologically comparable to the Cow Head Group in the northern part of the Humber Arm Allochthon, described by James and Stevens (1986). The locations of type sections are indicated approximately by Boyce *et al.* (1992; Figure 2) and more precisely by Botsford (1988).

Cooks Brook Formation

The Cooks Brook formation is a carbonate–shale succession that overlies the Irishtown formation. The most characteristic rock types are 'ribbon' laminated calcarenite beds interbedded with grey shale, and limestone conglomerate. The sedimentology of the Cooks Brook formation has been described by Botsford (1988), who distinguished a number of members within the formation. Following Botsford (*op. cit.*), the base of the Cooks Brook formation is placed at Halfway Point, at the first occurrence of bedded limestone with calcarenite texture above grey and black shale of the uppermost Irishtown formation. The type section extends east of this location, to the axis of the Cooks Brook syncline. The top of the Cooks Brook formation is not exposed in the Cooks Brook syncline. More complete sections through the upper parts of the formation were identified by Botsford (1988) at Northern Head, North Arm Point, and east of Woman Cove. The Cooks Brook formation is about 350 m thick and spans the interval from late Middle Cambrian to Early Ordovician (Botsford, 1988; Boyce *et al.*, 1992).

Middle Arm Point Formation

The Middle Arm Point formation comprises green and minor red, siliceous mudstones and thinly bedded silty dolostones and minor thinly bedded limestone.

Botsford (1988) defined the type section of the Middle Arm Point formation at North Arm Point (Figure 1). He placed the base of the section at the base of a distinctive unit of bedded, crosslaminated, and bioturbated yellow-weathering silty dolostone (Woman Cove member) that overlies limestones of the Cooks Brook formation. The top of the formation is placed at the base of the first bed of sandstone of the overlying Eagle Island sandstone, immediately south of North Arm Point (Figure 1).

The stratigraphic thickness of the Middle Arm Point formation is approximately 100 m. The formation, which is locally graptolitic, spans the Tremadoc and Arenig (Early Ordovician) (Botsford, 1988).

Eagle Island Formation

The Eagle Island sandstone overlies the Middle Arm Point formation. It consists of grey and green lithic sandstones interbedded with grey, green, and locally red shales. Early Ordovician graptolites have been recovered at a number of localities (Botsford, 1988). Stevens (1965) and Bruckner (1966) correlated these sandstones with those exposed at Blow-Me-Down Brook and on Woods Island, referring to both as the Blow-Me-Down Brook formation. However, the discovery of Early Cambrian trace fossils in the type area near Blow Me Down Brook (Lindholm and Casey, 1989, 1990) unequivocally indicates that the formations are distinct. The names Eagle Island sandstone and Eagle Island formation were informally proposed by Botsford (1988).

The type section is defined at Middle Arm Point (Figure 1). The base of the formation is defined at the first bed of sandstone above green and red mudstone, ribbon limestone, and silty, sandy dolostone of the Middle Arm Point formation. The type section was measured at 203 m by Botsford (1988), although this must be regarded as a minimum thickness because the top of the formation is everywhere tectonic.

The Eagle Island formation includes intervals of red and green shale in which colour boundaries cut across bedding and are therefore clearly of diagenetic origin. There are also intervals of classical turbidites with fine bottom structures (flutes, grooves, load structures). Massive intervals of sandstone and granule conglomerate form resistant headlands on shorelines.

The Eagle Island formation is inferred to record an influx of detritus from an advancing 'Taconian' allochthon, which was impinging on the passive continental margin of Laurentia during the Early Ordovician.

STRUCTURE

The greatest challenge in mapping the Humber Arm Allochthon lies in representing the structure satisfactorily. There are clear superimposed structures (refolded folds, crenulation cleavages) at many locations, but because of the generally low metamorphic grade, the predominance of brittle structures, the discontinuity of bedding, and the lack of penetrative fabrics, distinguishing clear overprinting sequences can be difficult.

In mapping the deformed rocks of the Humber Arm Supergroup, four phases of tectonic structures are distinguished, based on clear overprinting criteria. However, the earliest of these, D1, includes a variety of structures, some of which overprint each other, but without any apparent consistency that would enable a subdivision into separate phases of significance beyond single outcrops. Future work might allow the local division of D1 into separate phases D1a, b etc.

D0 (PENECONTEMPORANEOUS SYN-SEDIMENTARY DEFORMATION)

Structures associated with syn-sedimentary or penecontemporaneous deformation are relatively common in the sedimentary units of the Humber Arm Allochthon. Many turbidite sandstone and limestone beds show load structures, convolute lamination or ball-and-pillow structure. A widespread zone of sandstone injection structures is found at the base of the Eagle Island formation (*see also* Botsford, 1988). Elsewhere in the Eagle Island formation, there are folded sandstone beds having strongly thickened hinges, indicating deformation while sand was more ductile than surrounding mud, probably at a very early stage of diagenesis. However, stratigraphic relations require that the Eagle Island formation be tectonically deformed only a few million years after it was deposited: hence it cannot be assumed that soft-sediment structures are necessarily of syn-sedimentary origin. Hence, in some cases it is not possible to unequivocally distinguish ‘early' folds as either F0 (slump folds) or F1 (early tectonic folds).

D1 STRUCTURES

The most characteristic structures of sedimentary rocks in the Humber Arm Allochthon are those that disrupt bedded successions, producing configurations of separated blocks immersed in a matrix of deformed shale, variously termed ‘melange' and ‘broken formation'. Many of these units also contain folds: in some outcrops, tight to isoclinal folds are found within blocks suggesting that folding occurred before fragmentation; elsewhere, the fabric of the sheared ‘matrix' shale that anastomoses around blocks is itself clearly folded, implying that folding occurred after fragmentation. However, despite these apparent overprinting relationships, the complex history of progressive deformation within the fragmental units cannot easily be broken down on a regional basis, into mappable separate generations of structures. Therefore all these structures are designated D1.

In the eastern part of the mapped area, broken formation and melange are clearly overprinted by a later cleavage (S2), axial planar to folds in adjacent coherent units.

Boudinage

The most characteristic and widespread D1 structures are those in competent rocks (generally sandstones and limestones) that extend bedding. Boudinage structures are predominantly brittle; boudins may be bounded either by shear-fractures (producing lozenge or trapezoid-shaped boudins) or by extension-fractures (producing brick-shaped boudins). In many cases, extension has occurred in all directions within bedding, producing ‘chocolate-tablet' structures, suggesting bulk flattening strain. The spaces between boudins are filled with slate that has behaved in a macroscopically ductile manner. However, Waldron *et al.* (1988) show that slate-filled fractures crosscut calcite-filled veins, indicating that the flow of slate postdated early calcite tension gashes; they suggest that on a microscopic scale the behaviour of slate was dominated by brittle, cataclastic flow.

Surfaces of some sandstone bed-blocks show brecciated texture, in which angular sandstone fragments are partially immersed in sandstone matrix; this contrasts with block interiors that are structureless suggesting that these represent beds of sandstone that were only partially lithified at the time of D1 deformation, resulting in a combination of brittle fracture and granular flow comparable to the deformation of compacted, wet sand in a sand-box.

Boudinage structures are much less common in the Summerside formation than in the overlying units; possibly the diagenetic state of the Summerside formation at the time of deformation precluded the development of elevated fluid pressures that affected the rest of the Allochthon (Waldron *et al.,* 1988).

Fabrics

Bed-parallel fissility is extremely well developed in all the mudrocks of the Humber Arm Supergroup except the silicified shales of the Middle Arm Point formation. This fabric is locally axial-planar to F1 folds (below) although elsewhere the early folds deform the bed-parallel fissility. This S1 fabric probably results from the enhancement of an original bed-parallel compactional fissility by the tectonic deformation that extended bedding to produce boudinage structures.

In melange and broken formation, the S1 fabric is anastomosing and scaly. Polished, slickensided surfaces are common, and surround lenticular domains of shale. Fabric orientations within these domains are variable, indicating relative rotation of the domains during deformation. Therefore, this scaly fabric is interpreted as a composite fabric produced by pervasive shearing of already fissile shale.

In the Summerside formation, an early fabric is also present in many sandstones, which is characterized by seams of recessive, quartz-poor material, spaced at 5 mm to 5 cm apart, and is interpreted as a pressure-solution cleavage. At a number of locations that show F1 folds, the orientation of this pressure solution cleavage is consistent with an axial-planar relationship to F1, but not to F2. These relationships suggest that pressure-solution processes dominated the ductility of the Summerside formation, in contrast to the brittle fracturing that affected the remaining units of the allochthon.

Folds

Tight and isoclinal folds at outcrop scale are common in rocks of the Humber Arm Supergroup. All folds that predate the regional S2 cleavage are here characterized as F1, even though overprinting relationships are sometimes discernable within this group. Very commonly, for example, the bed-parallel fissility identified as S1 appears partly folded by F1, although locally the fissility planes can be traced continuously at fold hinges from parallelism with bedding into an axial-planar relationship.

In coherent slices where the way-up is known, F1 folds are overwhelmingly west-facing, although sometimes east-vergent based on fold asymmetry alone. In melanges and broken formation (*see below*), the predominant fold axis orientation (for folds measured in blocks) trends northwest–southeast. This suggested to Waldron (1985) that non-coaxial strain in the melange and broken formation was sufficient to rotate prolate blocks (in which folds are mainly found) toward the transport direction, during emplacement of the allochthon.

Generally, outcrop in the Bay of Islands area is not sufficient for the complete definition of map-scale F1 folds. However, at a number of locations, notably at Crow Hill in Corner Brook and north of Halfway Point on the south shore of Humber Arm (Figure 1), bedding faces downward on S2 cleavage planes over large areas (hundreds of metres across); these areas are inferred to represent the overturned limbs of map- scale F1 folds.

Melange and Broken Formation

The terms ‘melange' and ‘ophiolitic melange' have been variably applied to rocks in the Bay of Islands since the work of Dewey and Bird (1971). However, Waldron (1985) showed that, with the exception of a thin zone at the base of Blow Me Down Mountain, no ophiolitic material was present (either as blocks or matrix) in bulk of the ‘melange' units. The protoliths for these units appear to be entirely the sedimentary rocks of the Humber Arm Supergroup. Waldron *et al*. (1988) described processes of fragmentation involved in the development characteristic melange fabrics, and recognized broad zones in which these fabrics were identifiable, separating structural slices of more coherent stratigraphy.

In the current study, an attempt is made to distinguish, as separately mappable features, between stratal disruption and mixing. The term melange is reserved for material having identifiable protoliths from more than one formation. Other units in which stratification has been completely destroyed, but in which there has not been mixing of units, are referred to as ‘broken formation'. Melange zones presumably reflect sheared zones with greater stratigraphic throw than typical zones of broken formation, although we recognize that a single zone of deformation might change from melange to broken formation as it passes through different parts of the stratigraphy.

Table 1. Definition of disruption index values from 1 to 5

Disruption index	Characteristics
1	Stratification continuous at outcrop scale
2	Beds of competent rock types (sandstone, limestone) cut by extensional faults or pinch-and-swell structures, but not sufficient to separate typical beds into separated fragments
3	Beds cut and separated into fragments by normal faults or other boudinage structures, but fragments of individual beds can be followed for distances of metres across outcrops
4	Beds mainly broken into separate fragments, but local 'strings' of bed-fragments derived from a single bed are recognizable: form surface trace of bedding can be followed distances of metres across outcrops
5	Unit entirely broken into fragments, which cannot be reconstructed into identifiable beds; may or may not be combined with mixing, to produce a melange

In mapping areas of stratal disruption, the level of deformation is recorded by means of a ‘disruption index' given values from 1 to 5 (Table 1) where 1 is undeformed and 5 represents disruption into a configuration of blocks through which original bedding cannot be followed.

D2 STRUCTURES

Fabrics

Penetrative cleavage characterizes the eastern part of the Humber Arm Allochthon in the Bay of Islands area, extending into ‘parautochthonous' rocks of the carbonate platform succession to the east.

In the western part of the map area, S2 cleavage is only sporadically developed, taking the form of a closely (0.1 to 1 mm) spaced crenulation of the S1 fissility of shale. Eastward, this cleavage intensifies and becomes more slaty; east of the axial trace of the Cooks Brook Syncline, the cleavage appears penetrative and slaty in outcrop. In the Summerside formation, S2 is a typical slaty cleavage almost everywhere, yet appears as a clear crenulation cleavage of an earlier S1 in thin, phyllitic laminations that are rich in phyllosilicates.

In zones of D1 broken formation toward the east of the mapped area, S2 surfaces have a much more irregular, ‘crinkled' appearance than typical slaty cleavage, characterized by planes that anastomose on a millimetre scale. The contrast is particularly notable at the base of the Summerside type section, where classical slaty cleavage planes in the Summerside formation pass across a thrust into broken formation derived from the Irishtown formation, in which S2 surfaces are much more irregular. Hence, in zones of broken formation, transposition of the anastomosing scaly S1 fabric into a new orientation was of major importance in the development of S2.

Folds

Open to tight F2 folds are conspicuous in many outcrops along both shores of Humber Arm. The folds vary from upright to moderately inclined, and locally gently inclined to recumbent toward the eastern edge of the allochthon. F2 folds also dominate the map pattern, in particular the major Rattler Brook anticline and Cooks Brook syncline (Figure 2). Waldron (1985) noted that F2 folds plunge predominantly southward in the southern part of the Humber Arm area, but plunge northward farther north at Middle Arm, attributing the plunge culmination to refolding of F2 folds by F3.

D3 AND D4 STRUCTURES

Where S2 is penetrative and slaty, crenulation lineations can commonly be seen on S2 surfaces, at localities in the Corner Brook and Irishtown areas. A steep crenulation cleavage (S3) strikes west-northwest–east-southeast. Locally, S3 is axial planar to upright F3 folds. Map-scale F3 folds having the same orientation interfere with map-scale F2 folds producing the dome-and-basin interference pattern responsible for the Rattler Brook window (Figure 2) and for changes in the plunge of F2 folds.

In the Corner Brook and Irishtown areas, two lineations can be seen, and overprinting relations can locally be discerned. A second steep crenulation cleavage (S4) strikes south-southwest–north-northeast, crenulating both S2 and S3 and distorting the L3 crenulation lineations.

DISCUSSION

The sedimentary successions of the Curling and Northern Head groups record the evolution of the rift and deep-water continental slope and rise of the former Laurentian continent prior to major involvement in Appalachian orogenesis in the Early Ordovician (e.g., Williams and Stevens, 1974; James *et al.*, 1988). The Curling Group is equivalent to the Labrador Group of the shelf succession, representing the rift-phase and early drift-phase of the continental margin. The Northern Head group is equivalent to the carbonate-dominated Port au Port and St. George groups. Within the Curling Group, the Blow Me Down Brook and Summerside formations may be, in part, laterally equivalent. The Eagle Island sandstone records an influx of sediment derived, in part, from allochthons that advanced from the east (Stevens, 1965), although sediment transport paths within the foreland basin were probably complex (Quinn, 1996).

The absolute timing of deformation within the Humber Arm Allochthon is unconstrained. D1 structures and fabrics were assumed by Waldron (1985; Waldron *et al.*, 1988) to record Middle Ordovician emplacement of the Allochthon. However, subsequent work, and particularly the availability of industry seismic profiles offshore (e.g., Stockmal *et al.*, 1998), have shown that the allochthon was thrust some distance west into a tectonic wedge, inserted in foreland basin sediments in post-Pridoli (latest Silurian) time. Furthermore, the relative thicknesses of sedimentary sections in that foreland basin indicate major subsidence, indicative of loading within the orogen, in the Late Ordovician and Late Silurian. Significant Carboniferous deformation occurred in the Deer Lake basin to the west. Thus, the structures here designated D1 to D4 could, in principle, have occurred at almost any stage in this protracted history of orogenesis. Refinement of the timing of deformation will depend on the availability of isotopic techniques for dating the various fabrics seen, and on the stratigraphic distribution of detritus derived from the orogen in foreland basin sediments.

CONCLUSIONS

The sedimentary succession characteristic of the Humber Arm Allochthon in the type area is divided into two groups and six mappable formations. For mapping purposes it is helpful to distinguish structural disruption, measured by an index from 1 to 5, from mixing of protolith rocks which characterizes true melange. There is a clear grouping of structures into four phases, which include D1 structures related to emplacement of complex sedimentary slices, D2 folds and cleavage, and locally developed folds and crenulation cleavages attributed to D3 and D4. Establishing the absolute timing of deformation will depend on future isotopic and/or provenance studies.

ACKNOWLEDGMENTS

This project was supported by the NATMAP Bridges of Atlantic Canada project via a Supply and Services Canada contract with Saint Mary's University. Additional support was provided by NSERC Individual Research Grant A 8508 to J.W.F. Waldron. We acknowledge useful discussions in the field with I. Knight, S. Colman-Sadd, D. Lebel, D. Lavoie and C. van Staal. D. Fox assisted in the field; G. House provided boat transportation and additional logistical support.

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