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TECTONICS AND FORELAND BASIN DEVELOPMENT AT THE LEADING EDGE OF THE HUMBER ARM ALLOCHTHON, WESTERN NEWFOUNDLAND, CANADIAN APPALACHIANS

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ABSTRACT. The thrust front of the Northern Appalachians involves Ediacaran rift-related structures of the Laurentian margin that were re-worked in Taconic (Ordovician), Salinic (mainly Silurian) and Acadian (mainly Devonian) deformation events. Much of the thrust front is concealed under the Gulf of St. Lawrence, but Port au Port Peninsula, in western Newfoundland provides a cross-section through the Laurentian passive margin, overlying foreland basins, and the Humber Arm Allochthon.

A large area of foreland basin strata is present in areas formerly mapped as Humber Arm Allochthon. Abrupt thickness changes and an abundance of fault-scarp-derived limestone conglomerate indicate that deposition was influenced by block faulting and differential subsidence in a basin undergoing active flexural extension. A coarsening upward trend in the Goose Tickle Group represents a transition from a distal to a proximal sediment source as the Humber Arm Allochthon was emplaced westwards.

Goose Tickle Group separates two packages of allochthonous rocks. The West Bay Thrust Sheet, the lower package, represents the leading edge of the Taconic allochthon. Its timing of emplacement is constrained by Darriwilian 3 graptolites both above and below the thrust sheet. Its present-day configuration results from a combination of processes including thrusting, extension by gravity spreading, gravity gliding, and subsequent erosion of material that was deposited in the Goose Tickle Group. The structurally higher Lourdes Thrust Sheet is an out-of-sequence structure associated with Acadian (Devonian) orogenesis. High-angle faults show a protracted history of movement that includes early Taconic flexural extension, Acadian inversion, and later Carboniferous or Mesozoic strike-slip motion. The leading edge of the Humber Arm Allochthon was influenced by both thin-skinned and thick-skinned tectonics throughout the development of the Appalachian orogen.

Key words: Newfoundland Appalachians, thrust front, faults, mélange, stratigraphy

INTRODUCTION

The thrust front of the northern Appalachian orogen is a composite feature, potentially bearing the structural record of Taconic (Ordovician), Salinic (mainly Silurian) and Acadian to Neo-Acadian (mainly Devonian) events (for example, Williams, 1984; Hibbard and others, 2007). These events have produced both extensional and contractional structures. In some areas early extensional structures, possibly dating back to the Neoproterozoic rift history of the Laurentian margin (Stenzel and others, 1990; Bradley and Kidd, 1991), are reactivated (inverted) as thrust faults (Waldron and others, 1993; Stockmal and others, 2004; White and Waldron, 2019). Disentangling these events is challenging because 1) the stratigraphic record is incomplete, 2) isotopic ages are scarce in the sedimentary rocks of the outermost part of the Appalachians, and 3) much of the thrust front and adjacent foreland basin are concealed under the Gulf of St. Lawrence.

The Newfoundland Appalachians are a classic area for the study of orogen development and ophiolite emplacement (for example Williams and Stevens, 1974; Williams, 1979; van Staal and others, 1998; Dewey and Casey, 2013). The Port au Port Peninsula (fig. 1) is unique in the Newfoundland Appalachians as it exposes the

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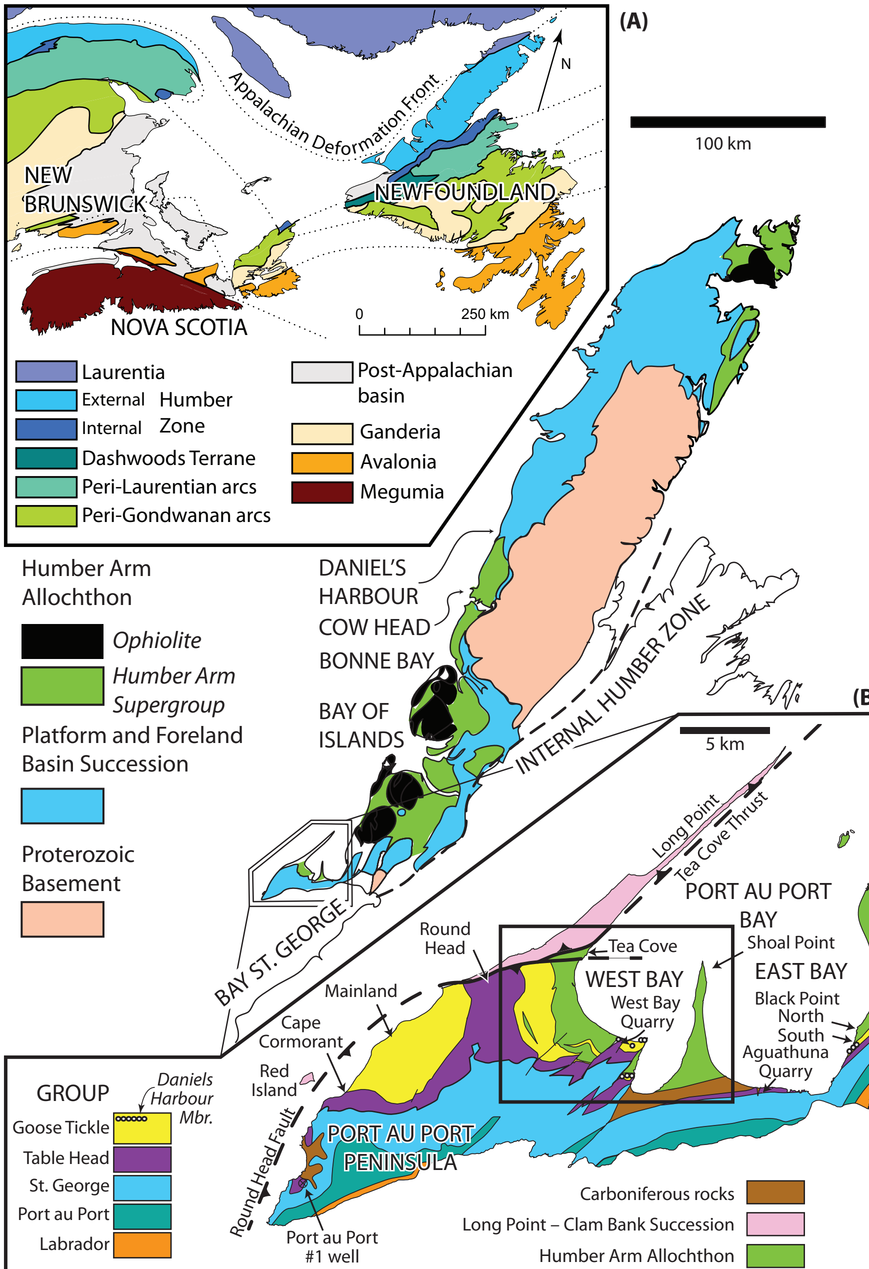

Fig. 1. Map of the Humber Zone in Newfoundland highlighting key localities mentioned in the text. (Inset A) Lithotectonic subdivision map of the northern Appalachians. (Inset B) Map of Port au Port Peninsula with key localities and regionally important faults marked. Box indicates the area shown in more detail in figure 4. Modified from Lacombe and others (2019).

structural front, elsewhere identified offshore in seismic sections (Stockmal and Waldron, 1990; Cooper and others, 2001; White and others, 2020). The Port au Port Peninsula displays little of the metamorphism that affected internal parts of the orogen. The area is also unique in that later deformation has tilted the strata northward, giving a cross-sectional view through the plunging thrust front, exposing a Cambrian to Carboniferous rock record. Geological mapping has been supplemented by subsurface exploration for hydrocarbons in this area (Cooper and others, 2001). Hence, the peninsula provides a unique opportunity to study the emplacement of the allochthon and the development of associated foreland basin (Waldron and others, 1993; Macdonald and others, 2017).

The Taconic Humber Arm Allochthon on the Port au Port Peninsula was previously mapped as largely unsubdivided scaly shale and mélange (Williams and others, 1985; Williams and Cawood, 1989). The western extremity of the allochthon has been variously interpreted as a Late Ordovician angular unconformity (Stevens, 1970; Cawood and others, 1991), a Middle Ordovician raft produced by gravity gliding into foreland basin deposits (Waldron and others, 1993), the tip of a Devonian tectonic wedge (Stockmal and Waldron, 1990; Stockmal and others, 1998), or some combination of these. Mapping by Lacombe (ms, 2017) showed that this area includes foreland basin sedimentary rock, deposited in stratigraphic continuity with the underlying autochthonous carbonate units of the Laurentian passive margin. By subdividing the area previously mapped as mélange, we have been able to separate the effects of Taconic and subsequent deformation events and identify areas where the Taconic thrust front was protected from later tectonic reworking. Lacombe and others (2019) describe the internal structural development of the allochthonous rocks. This paper aims to describe and interpret relationships within the foreland basin units into which the Humber Arm Allochthon was emplaced, and thereby resolve the complex history of extension and shortening at the thrust front.

GEOLOGICAL SETTING

The Humber Zone of western Newfoundland (Williams, 1978) (fig. 1) represents the early Paleozoic margin of Laurentia, and records opening and closure of the Iapetus Ocean. Neoproterozoic rifting of Mesoproterozoic basement led to the deposition of syn- and post-rift clastic strata of the Labrador Group (Williams and Hiscott, 1987), and its offshore equivalent, the Curling Group (Stevens, 1970) (fig. 2). This was followed by the development of a Cambrian-Ordovician carbonate passive margin represented by the Port au Port and St. George groups (Chow, ms, 1985; Chow and James, 1987; Knight and James, 1987). Offshore and downslope, deeper water conditions were recorded by the Cow Head Group, here defined, following Lacombe and others (2019), to include all the deep-water equivalents of the carbonate shelf in the Humber Arm Allochthon. Passive-margin development was brought to an end by Taconic orogenesis in the Early to Middle Ordovician when eastward subduction culminated in an arc-continent collision (van Staal and others, 1998; Waldron and van Staal, 2001). Early stages of collision are recorded by turbiditic "flysch" (Stevens, 1970) that overlies the Cow Head Group, here assigned to the Western Brook Pond Group (Johnson, 1941; Lacombe and others, 2019). This collision ultimately led to ophiolite obduction (Cawood and Suhr, 1992; Dewey and Casey, 2013) and the emplacement, in the Humber Arm Allochthon, of deformed deep-water rocks above their shallow-water equivalents (fig. 2).

Early to Middle Ordovician loading of the Laurentian margin by the encroaching Taconic allochthons resulted in flexure and westward migration of a peripheral bulge, or forebulge, across the former shelf (Jacobi, 1981; Knight and others, 1989). This was followed by a rapid series of events during the Darriwilian, beginning with the activation of Taconic extensional, normal faults such as the Round Head Fault (fig. 1)

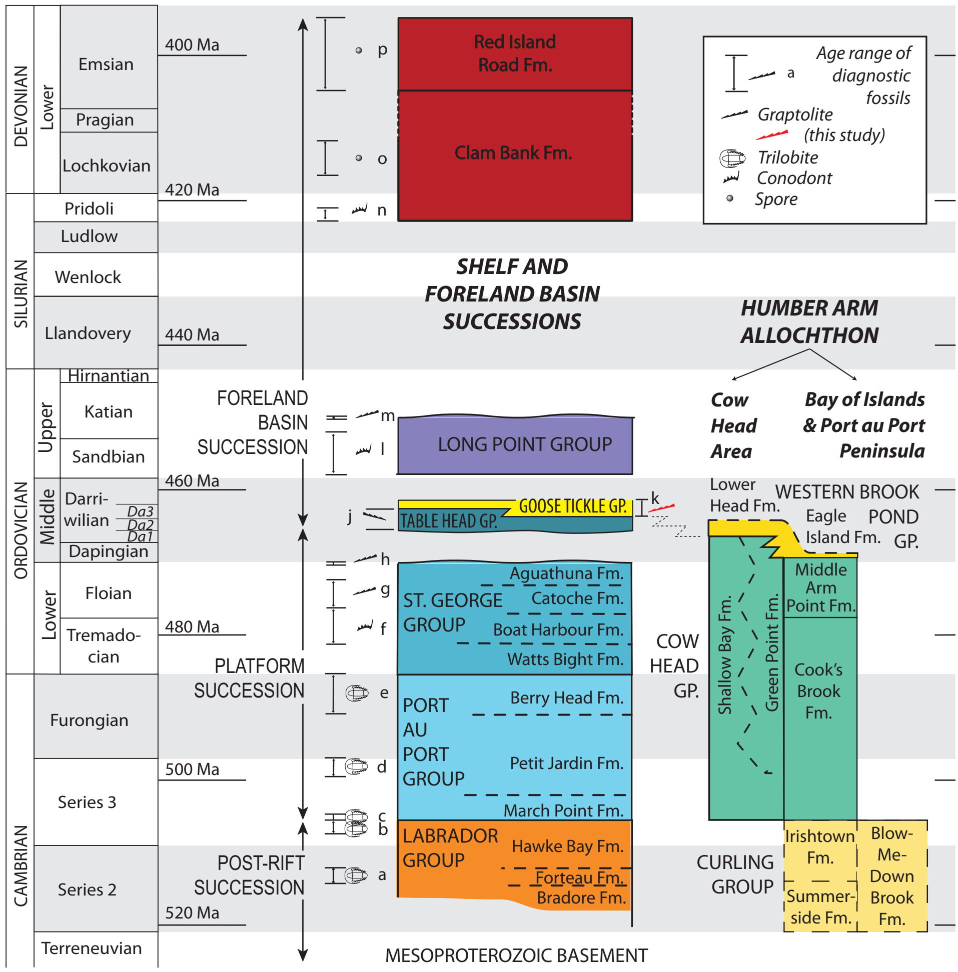

Fig. 2. Stratigraphy of western Newfoundland. Lithostratigraphic units after Lacombe and others (2019). Compilation of biostratigraphic ages based on Lacombe (ms, 2017): (A) trilobites: middle *Bonnia–Olenellus* Biozone (Knight and others, 2017); (B) trilobites: *Glossopleura* and *Albertella* Biozones (Knight and Boyce, 1991); (C) trilobites: *Olenoides longispinus*, *Ehmaniella cloudensis* (Knight and Boyce, 1987); (D) trilobites: *Cedaria Zone*, *Crepicephalus* Biozone (Knight and Boyce, 1991); (E) trilobites: *Saukiella junia*, *Saukiella serotina*, *Mississquoia*, *Symphisurina Brevispicita* (Knight and Boyce, 1991); (F) Conodonts: *Macerodus dianae* and *Cordylodus andgulatus* (Zhang and Barnes, 2004); (G) graptolites: *Tetragraptus akzharensis*, *Tetragraptus approximatus*, *Pendeograptus fruticosis* and *Didymograptus bifidus*; (H) graptolites: *Isograptus victoriae lunatus* (Zhang and Barnes, 2004); (I) base within the *Undulograptus dentatis* graptolite Biozone (Maletz and others, 2011); (J) graptolites: *Holmograptus lentus* Biozone, *Nicholsonograptus fasciculatus*, *Pterograptus elegans* Biozone; (K) graptolites: *Nicholsonograptus fasciculatus*, ?*Pterograptus elegans* (this study) (L) conodonts: *Amorphognathus tvaerensis* (Batten Hender and Dix, 2008; Bergstrom and others, 1974); (M) graptolite: *Geniculograptus pygmaeus* (Quinn and others, 1999) (N) *Ozarkodina eosteinhornensis* Biozone (Burden and others, 2002); (O) *Emphanisporites micromatus* – *Streelispora newportensis* Assemblage Zone (Burden and others, 2002); (P) spores: *Emphanisporites annulatus* – *Camarozonotiletes sextantii* Biozone (Quinn and others, 2004) correlated with (Streel and others, 1987).

(Stenzel, ms, 1992; Waldron and others, 1993). Flexure and extension resulted in increasing accommodation and deposition of the carbonate-dominated Table Head Group (fig. 2). Accommodation space was eventually filled with incoming clastic detritus shed from the advancing allochthon forming the Goose Tickle Group (fig. 2)

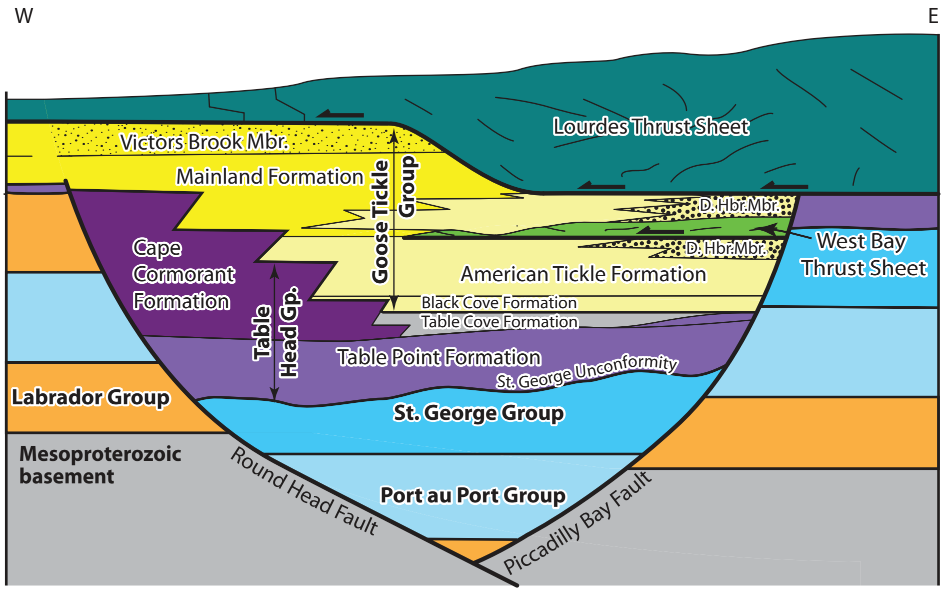

Fig. 3. Summary of Middle Ordovician stratigraphic relationships. Schematic of stratigraphic relationships between foreland basin units including the structural position of allochthonous thrust sheets on Port au port Peninsula. Abbreviations: Mbr. = Member, D. Hbr. Mbr. = Daniels Harbour Member.

(Botsford, ms, 1987; Stenzel, ms, 1992; Quinn, 1995). The Humber Arm Allochthon was emplaced westward such that it partially overlies its foreland basin (Stevens, 1970; Williams, 1985; Quinn, ms, 1992b; Quinn, 1995).

Upper Ordovician to Lower Devonian foreland basin fill is represented by the Long Point Group and overlying Clam Bank and Red Island Road formations (fig. 2). The succession dips northwest from Port au Port Peninsula into an offshore monoclinal structure (Stockmal and Waldron, 1990). It sits above an east-vergent detachment surface, known as the Tea Cove Thrust, at which a tectonic wedge of Humber Arm Allochthon was inserted beneath the Long Point Group (Waldron and Stockmal, 1991), reworking and burying the Taconic structural front (Stockmal and Waldron, 1990; Waldron and others, 1998). The youngest strata folded in the hanging wall of the Tea Cove Thrust constrain the age of final emplacement of this tectonic wedge to Emsian (Devonian) or younger, associated with the Acadian orogenic event (Stockmal and Waldron, 1990; Waldron and Stockmal, 1991; Stockmal and others, 2004). The area has been affected by later, Carboniferous motion, inferred by Waldron and others (2015) to involve a strong component of dextral strike slip, and presumably by Mesozoic deformation associated with Atlantic opening, though there is no stratigraphic record of this history in western Newfoundland.

STRATIGRAPHIC RELATIONSHIPS ON PORT AU PORT PENINSULA

The autochthonous section on Port au Port Peninsula records the early Cambrian to Early Devonian history of the Laurentian margin (fig. 2). Facies relationships within the Middle Ordovician units are summarized in figure 3. Stratigraphic relationships within the Humber Arm Allochthon are described elsewhere (Lacombe and others, 2019).

Autochthonous Carbonate Units: Table Head Group

Table Point Formation.—The Middle Ordovician Table Point Formation, the lower part of the Table Head Group (fig. 2), is dominated by massive burrow-mottled dolomitic limestone with locally abundant fossils (Klappa and others, 1980). It unconformably overlies the St. George Group at the St. George unconformity, interpreted to record the passage of the Taconic forebulge (Jacobi, 1981; Knight and others, 1989), where Stenzel (ms, 1992) suggests between 20 and 50 m of erosion. In contrast to the underlying shelf succession, which shows "layer cake" stratigraphy across western Newfoundland (for example, Waldron and van Staal, 2001), the Table Point Formation varies abruptly in thickness, ranging from $<$50 m to $>$250 m.

Table Cove Formation.—The conformably overlying Table Cove Formation (Klappa and others, 1980; Stenzel and others, 1990) comprises dominantly gray, laminated, concretionary limestone, appearing slabby in outcrop, interbedded with gray characteristically graptolite-rich calcareous shale. A bioturbated crinoidal limestone bed described at the base of the unit by Klappa and others (1980) is difficult to distinguish from the underlying Table Point Formation. For practical mapping purposes we map the contact at the base of the first planar laminated limestone bed, ~2 m higher than Klappa and others (1980).

The Table Cove Formation is discontinuous and varies in thickness (fig. 4). Notably, west of the East Quarry Fault (fig. 4), the Table Cove Formation is ~50 m thick whereas east of this fault it is $>$100 m thick. Farther east, towards the Piccadilly Head Fault, the thickness decreases to ~10 m. In eastern Port au Port Peninsula and along portions of Victors Brook (fig. 4) the Table Cove Formation is absent; the Goose Tickle Group overlies the Table Point Formation directly. Northwest of Victors Brook, the formation likely interfingers with the Cape Cormorant Formation (figs. 4 and 5).

Cape Cormorant Formation.—The Cape Cormorant Formation (fig. 3) occurs only in the western part of the peninsula (Stenzel and others, 1990; Stenzel, ms, 1992). It dominantly comprises poorly-sorted, clast-supported, polymict carbonate conglomerate, interbedded with calcarenite and shale; basal portions of the formation contain bedded intervals similar to the Table Cove Formation (Stenzel and others, 1990). Clasts are lithologically identical to the Port au Port and St. George groups (fig. 2) and yield middle Cambrian through Middle Ordovician fossils (Stenzel and others, 1990) indicating that clasts were derived from these units, exposed in a substantial scarp formed by the Round Head fault (figs. 4 and 5), northwest of the Cape Cormorant Formation. Within the map area, the Cape Cormorant Formation forms a prominent ridge at Round Head (fig. 4). To the southeast, it thins and interdigitates with the Table Cove and possibly the lowest Goose Tickle Group (figs. 3 and 4).

Autochthonous Foreland Basin Units: Goose Tickle Group

Black Cove Formation.—The overlying Goose Tickle Group comprises the Black Cove, American Tickle, and Mainland formations (figs. 2 and 3). The Black Cove Formation, first described by Klappa and others (1980) as part of the Table Head Group, was reassigned to the Goose Tickle Group by Stenzel and others (1990). It lies stratigraphically above the Table Cove Formation, and locally the Table Point Formation (Stenzel and others, 1990). The Black Cove Formation comprises laminated dark gray shale and minor green siltstone, best exposed at Piccadilly Brook and West Bay Quarry (figs. 1 and 4). Stenzel and others (1990) describe the transitional upper contact with the overlying American Tickle Formation.

The Black Cove Formation is 0 to 22 m thick; sparse occurrence in inland outcrops suggests either that it is discontinuous, or that it is unexposed because of its fine-grained recessive nature. For mapping purposes, we include the unit with the overlying American Tickle Formation (figs. 3 and 4). The Black Cove Formation is absent in

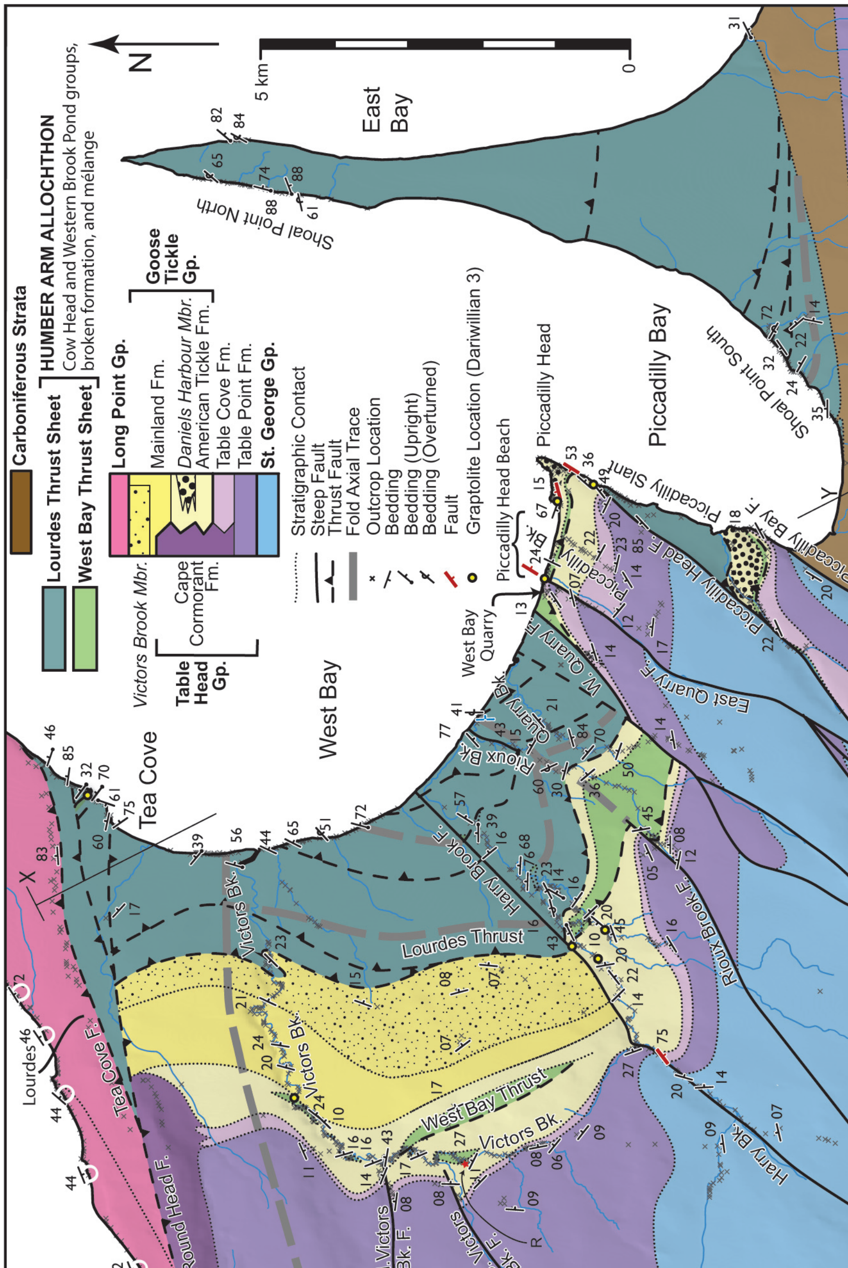

Fig. 4. Geologic map of a portion of Port au Port Peninsula, modified from Lacombe and others (2019). Abbreviations: WBT = West Bay Thrust, LT = Lourdes Thrust, Brk - Brook, Flt. = Fault, Mbr. = Member, Fm. = Formation, Gp. = Group; R = Locality 'R' mentioned in text.

western Port au Port Peninsula, where the Mainland Formation overlies the Table Head Group directly.

Maletz and Egenhoff (2011) recovered *Nicholsonograptus fasciculatus* Biozone graptolites from the Black Cove Formation, approximately correlative (Maletz and

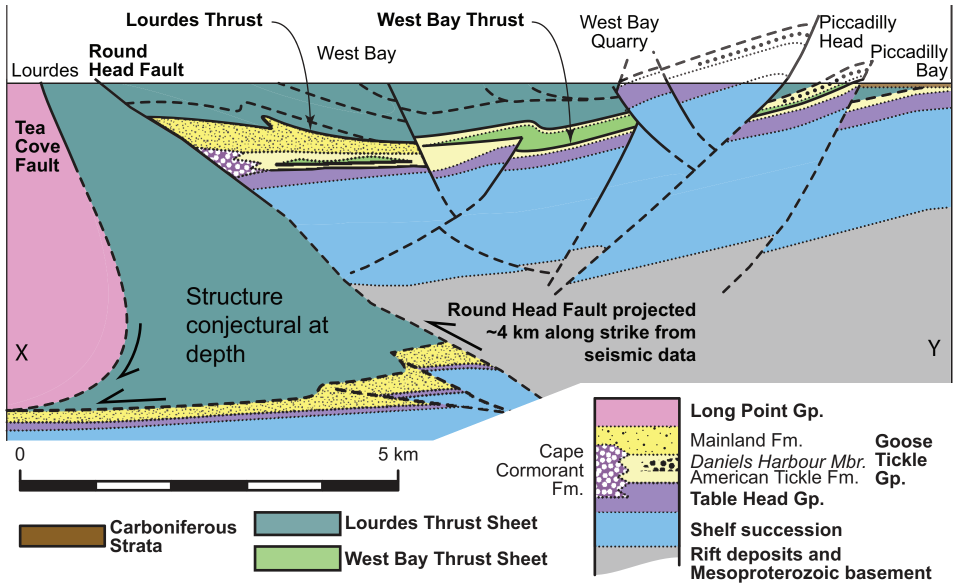

Fig. 5. Schematic cross-section through Port au Port Peninsula. Location of line X-Y shown in figure 4. Not precisely to scale.

Egenhoff, 2011; Loydell, 2012) with the Darriwilian 3 substage of Cooper and others (2012).

American Tickle Formation

Facies.—The American Tickle Formation is characterized by green, gray, and black siltstone and shale with interbedded fine- to medium-grained sandstone; sandstone is generally <30 percent of typical outcrops (fig. 6A) (Quinn, 1995). Intervals of limestone conglomerate are common. Sandstone beds show sedimentary structures consistent with rapid, high energy, deposition via turbidity currents (Quinn, ms, 1992b). The American Tickle Formation overlies Black Cove Formation at Victors Brook and to the east; it is absent farther west near Mainland (fig. 1), where Mainland Formation occurs in an equivalent position (fig. 4).

We recognize three facies of platform-derived limestone conglomerate in the American Tickle Formation (fig. 6):

1. Clast-supported conglomerate of pebble to cobble-sized carbonate lithoclasts in massive beds. Clasts are dominantly gray-weathering lime mudstone to wackestone, but include less common yellow-weathering laminated dolostone, skeletal grainstone and laminated slabby limestone (fig. 6C). Clasts are generally angular but stylolitic boundaries obscure original clast shapes. This unit only occurs east of the West Quarry Fault (fig. 4); it is best exposed at Piccadilly Head, and in road cuts at Piccadilly Slant (fig. 4). This conglomerate type was assigned to the Daniel's Harbour Member by Stenzel and others (1990) (fig. 3).
2. Conglomerate with a green and black mudstone matrix supporting dominantly gray to pink-weathering, nodular limestone clasts. Clasts average pebble-size but range up to boulders (figs. 6F and 6G). This facies is common along Victors

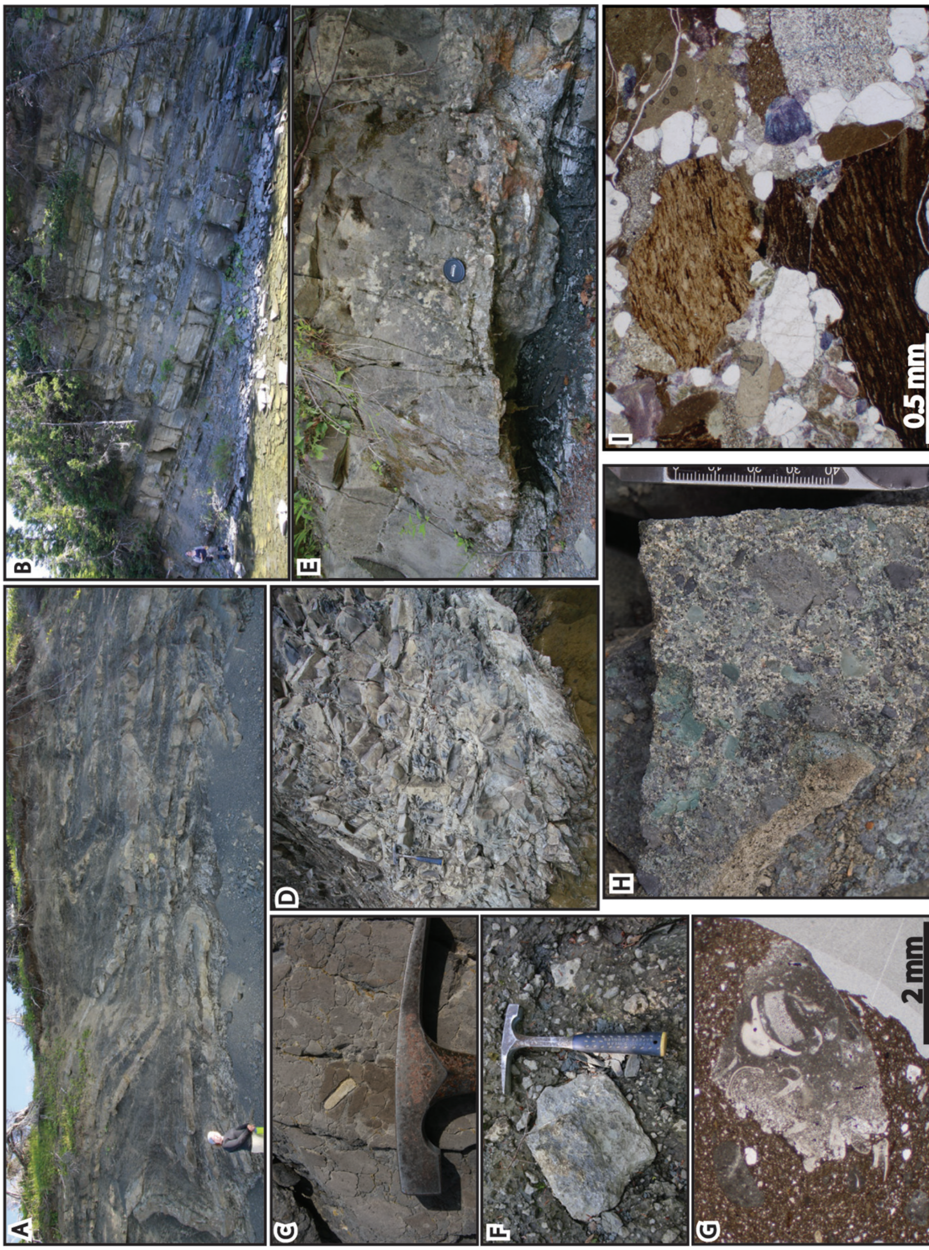

Fig. 6. Facies within the American Tickle and Mainland formations. (A) American Tickle Formation, sandstone and shale facies, at Piccadilly Head Beach. (B) Mainland Formation, sandstone facies, in Victors Brook. (C) American Tickle Formation, Daniel's Harbour Member, at Piccadilly Head. (D) American Tickle Formation, clast supported conglomerate, sandstone matrix and Table Cove Formation clasts, in Harry Brook. (E) Mainland Formation sandstone facies coarsening up to pebble conglomerate near the base with load structures. (F) American Tickle Formation, Harry Brook facies, in Rioux Brook. (G) Photomicrograph of Harry Brook facies, fossiliferous limestone clast in mud. (H) Mainland Formation, Victors Brook Member, on the resource road. (I) Photomicrograph of the Victors Brook Member. Locations identified in figure 4.

Brook and Harry Brook; smaller sections were also observed in Rioux Brook and Quarry Brook (fig. 4). This unit was termed "Type 1 conglomerate" by Waldron and others (1993) and "the second type of Daniel's Harbour conglomerate" by Stenzel and others (1990). This unit is here termed the Harry Brook facies of the American Tickle Formation.

3. Limestone conglomerate, matrix-supported, or rarely clast-supported, with a matrix of medium to coarse sandstone and gray siltstone. Clasts are cobble-sized slabby limestone, or pebble-sized, nodular, burrow-mottled limestone (fig. 6D). This unit is best exposed in cliff sections along Harry Brook (fig. 4).

Larger rafts of Table Head Group are also present within the American Tickle Formation; one such, composed of Table Cove Formation concretionary limestone and shale, is exposed in Victors Brook (fig. 4 Locality R). This raft, ~50 cm thick and ~2 m wide, overlies Harry Brook facies limestone conglomerate and is overlain and partially surrounded by sandstone and shale.

Distribution.—In central Port au Port Peninsula, two packages of American Tickle Formation are separated by rocks of the Humber Arm Allochthon (fig. 4). The lower package stratigraphically overlies the Table Head Group (figs. 2 and 4). This package is continuous from Victors Brook to Piccadilly Slant (fig. 4). Traced west (figs. 3 and 4), it likely interdigitates with the Cape Cormorant and Mainland formations (figs. 3 and 4).

A second package of rocks assigned to the American Tickle Formation overlies a portion of the Humber Arm Allochthon in central Port au Port Peninsula (fig. 4); this package thickens from Harry Brook eastward towards Rioux Brook (fig. 4). The lower contact, where it overlies the Humber Arm Allochthon, is only observed in Victors Brook (fig. 4). Here, Waldron and others (1993) interpreted the contact (fig. 7A) as sedimentary, above discontinuous outcrops of the allochthon interpreted as rafts within the Goose Tickle Group. Our new mapping suggests that these discontinuous outcrops of allochthonous material were originally continuous with a thicker package sitting below the Goose Tickle Group to the east in Harry Brook, Rioux Brook and Quarry Brook (fig. 4). Our discovery of additional outcrops of Humber Arm Supergroup occupying the same structural position along strike leads us to reinterpret the outcrops in Victors Brook as remnants of a single continuous sheet of Humber Arm Allochthon, the West Bay Thrust Sheet (WBTS), and suggests that their contact with the overlying portion of the Goose Tickle Group is unconformable. This observation is consistent with the occurrence of pebble to boulder-sized clasts of deformed material derived from the Humber Arm Allochthon in the overlying strata (Waldron and others, 1993).

Limestone conglomerate units, including portions of the Daniels Harbour Member and Harry Brook facies, occur as discontinuous lenses irregularly distributed within the upper package of American Tickle Formation. The most prominent exposures of the Daniels Harbour Member conglomerate are found at the point of Piccadilly Head and to the south along Piccadilly Slant (fig. 4), here considered to be part of this upper package. These packages of Daniels Harbour conglomerate are thickest in the hanging walls of the Piccadilly Head and Piccadilly Bay faults (figs. 4 and 5). The American Tickle Formation also occurs east of the map area, at Black Point, where it underlies rocks of the Humber Arm Allochthon (fig. 1) and overlies the Table Head Group.

Biostratigraphy.—Graptolites were recovered from shale and sandstone of the American Tickle Formation at a number of locations including Black Point, Piccadilly Slant, Piccadilly Head Beach, and along both Harry Brook and Victors Brook (figs. 1 and 4). These graptolites are identified as *Archiclimacograptus caelatus, Archiclimacograptus ridellensis, Archiclimacograptus angulatus, Haddingograptus oliveri, Hustedeograptus* sp.,

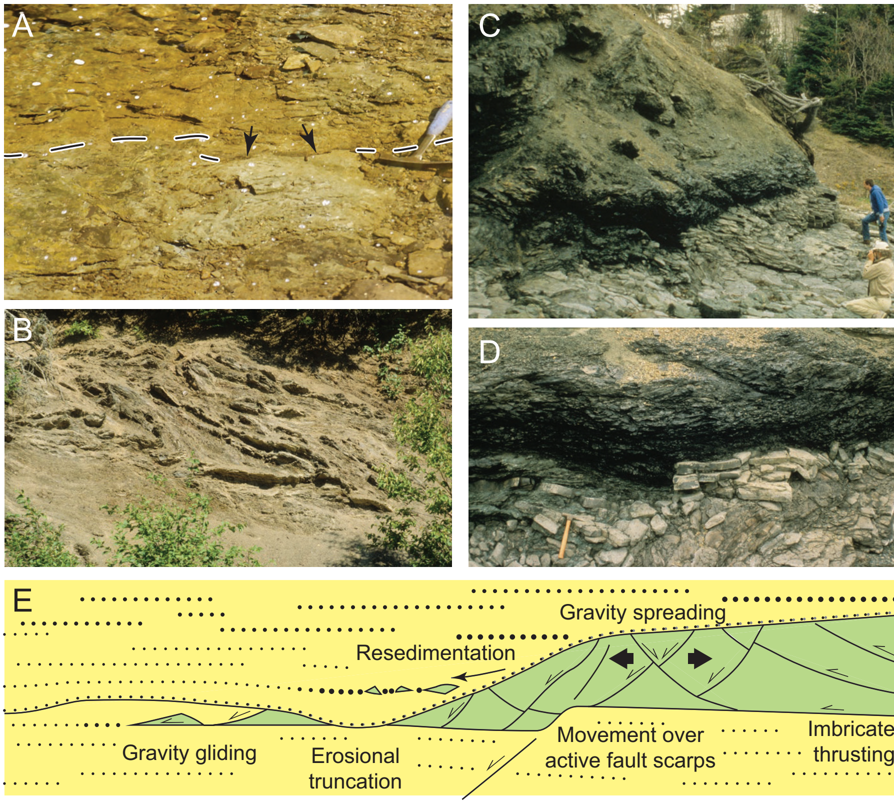

Fig. 7. Outcrop relationships of the West Bay Thrust Sheet (WBTS). (A) Top surface of WBTS exposed under water in bed of Victors Brook; dashed line and arrows indicate contact of Goose Tickle Group on scaly shale of Humber Arm Allochthon. (B) Internal structure of WBTS exposed in Victors Brook; scaly fabric and lithological layering have been tightly folded. (C and D) Base of the WBTS exposed on shoreline north of West Bay Quarry. (E) Cartoon showing potential fragmentation processes at the leading edge of the WBTS.

Paraglossograptus holmi, Glossograptus tentaculatus, Pterograptus elegans?, Nicholsonograptus fasciculatus and *Acrograptus?* sp. (fig. 8). This graptolite assemblage implies a Middle Ordovician, Darriwilian 3 age for the American Tickle Formation both above and below the WBTS.

Mainland Formation

Facies.—The sandy Mainland Formation of Schillereff and Williams (Quinn, ms, 1992b; Schillereff and Williams, 1979) is confined to the area west of the Harry Brook Fault (fig. 4), where it stratigraphically overlies Cape Cormorant Formation (Quinn, ms, 1992b) (fig. 1). However, it extends farther east than the Cape Cormorant Formation, overlying portions of the American Tickle Formation in the Victors Brook area (fig. 3). No stratigraphic upper contact is seen (Quinn, ms 1992b).

The Mainland and American Tickle formations are most easily distinguished on the basis of sandstone/shale ratio and the contained conglomeratic facies. Typical outcrops of Mainland Formation are dominantly sandstone whereas the American Tickle Formation is characteristically mainly mudstone and shale (Quinn, 1992a; Quinn, 1995). Conglomerate in the Mainland Formation is dominated by shale clasts, whereas limestone conglomerate predominates in the American Tickle Formation.

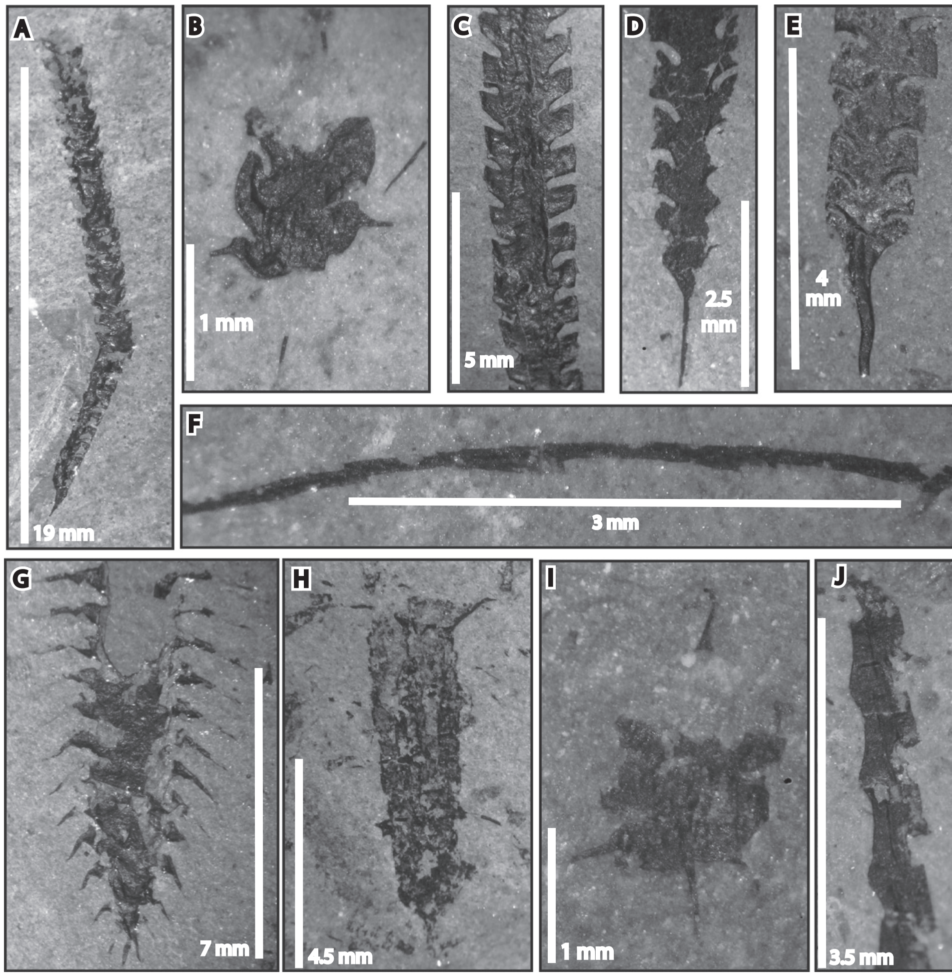

Fig. 8. Fossils collected from the American Tickle Formation. (A-B) *Archiclimacograptus caelatus* at Piccadilly Head (C-E) *Archiclimacograptus caelatus* inland Harry Brook (F) *Acrograptus* sp. inland Harry Brook (G) *Paraglossograptus holmi* inland Harry Brook (H) *Glossograptus tentaculatus* at Piccadilly Head (I) *Archiclimacograptus ridellensis* inland Victors Brook (J) *Nicholsonograptus fasciculatus* at Piccadilly Head. Collection localities marked in figure 4.

Two facies of Mainland Formation are here identified. The first is dominated by graded, thinly to thickly bedded (scale of Ingram, 1954), fine to medium sandstone with abundant parallel laminae and less common ripple marks. This facies dominates the coastal exposures described by Quinn (ms, 1992b). Mudstone and shale interbeds make up less than 20 percent of typical outcrops (figs. 6B and 6E), although in some outcrops the proportion reaches 50 percent. Sandstone beds are friable and split easily, owing to a large proportion of matrix and abundant shale lithoclasts concentrated along lamination surfaces. Some beds grade downward into pebble conglomerate at the base (fig. 6E). Basal surfaces commonly also show flutes, grooves and load structures. Paleocurrent data (Stenzel, ms, 1992; Quinn, 1995) show that sediments travelled axially (SSW present-day direction) into the basin via turbidity currents.

A second facies, here termed the Victors Brook facies, comprises medium sandstone to "shale-chip conglomerate" dominated by clasts of shale and siliceous mudstone (figs. 6H and 6I). Beds are graded and commonly amalgamated or locally interbedded with shale. This facies is only observed between Victors Brook and the Harry Brook Fault (fig. 4). It was described by Waldron and others (1993) as "type 2 conglomerate". This facies is similar to the Howe Harbour Member described by Quinn (ms, 1992b) farther north (fig. 1). Map relationships in Victors Brook suggest that a thick section of Victors Brook facies at the top of the Mainland Formation (fig. 3) underlies a region of Humber Arm Allochthon (figs. 4 and 5); this section is referred to as the Victors Brook Member. A discontinuous lower section of the Victors Brook facies occurs as isolated patches within the American Tickle Formation near Humber Arm Allochthon (WBTS) in Victors Brook (Waldron and others, 1993).

Distribution.—Quinn (1995) suggested that allochthon-derived sediment was channelized, via the 'Serpentine Lake Discontinuity' of Cawood and Botsford (1991), as a means to explain the spatial restriction of the Mainland Formation. Our mapping shows that the formation is presently confined between the Round Head and Harry Brook Faults. It interfingers with and overlies the American Tickle Formation in Victors Brook, and overlies the Cape Cormorant Formation farther west (figs. 1, 3, and 4). The lower, sandstone-dominated unit of the Mainland Formation thins southeastward to terminate at the Harry Brook Fault; the Victors Brook Member, on the other hand, thickens southeastward, but terminates at the same fault (fig. 4).

Biostratigraphy.—Graptolites from this unit are reported by Quinn (ms, 1992b) and references therein, indicating Darriwilian 3 age. Earlier suggestions that the unit extends to the early Sandbian remain unsubstantiated as original fossils could not be located (Quinn, ms, 1992b; Quinn, 1995). The Mainland Formation is therefore roughly equivalent in age to the American Tickle Formation (Quinn, ms, 1992b; Quinn, 1995) though relationships in Victors Brook (fig. 4), where the Mainland Formation overlies American Tickle Formation, suggest that the top may be slightly younger.

STRUCTURE

Map-scale Structure: Low-angle Faults and Allochthonous Units

Distribution of units.—The Humber Arm Allochthon, previously mapped as a single contiguous map unit (Williams and Cawood, 1989; Waldron and others, 1993; Knight and others, 2008), occurs in central Port au Port Peninsula as two packages of allochthonous rock separated by an intermediate band of Goose Tickle Group (figs. 2 and 4). Steep faults, which offset the underlying platform succession, cut up section and offset these two allochthonous packages together with intermediate Goose Tickle Group strata (fig. 5).

The lower allochthonous package, here named the West Bay Thrust Sheet (WBTS), is both underlain and overlain by portions of the Goose Tickle Group (figs. 2 and 3). The name West Bay Thrust was previously applied by Waldron and others (2012) to describe its basal contact, well exposed on the coast immediately north of West Bay Quarry (figs. 4, 7C, and 7D). The upper, sedimentary contact was described in Victors Brook by Waldron and others (1993) and is shown in figure 7A. The upper allochthonous package, sitting above intermediate Goose Tickle Group strata, is here named the Lourdes Thrust Sheet (LTS), bounded at the base by the Lourdes Thrust. Our mapping suggests that this thrust can be traced westward to the tip of the tectonic wedge near Lourdes (fig. 4) which is itself cut by the pre-Mississippian Round Head Thrust (Stockmal and others, 2004) (fig. 5), indicating that final emplacement was Acadian.

West Bay Thrust Sheet.—Discontinuous shale and chert surrounded by Goose Tickle Group in Victors Brook (fig. 7B) were previously considered sedimentary rafts of Humber Arm Allochthon by Waldron and others (1993); however, much thicker sections of Humber Arm Allocthon at equivalent positions in Harry Brook, Rioux Brook (figs. 3 and 4) suggest that this unit was more continuous than previously recognized; it is here interpreted as an originally continuous thrust sheet that thickens eastward (fig. 4) and has been extended by gravity-driven processes; Lacombe and others (2019) show that gravity spreading and gravity gliding may be effectively indistinguishable at the toe of an allochthon advancing under conditions of high internal fluid pressure. Erosion of the top surface may have contributed to the thinning of this sheet. Farther east, between the West and East Quarry faults, a package of allochthonous scaly shale and chert overlies the Table Cove Formation directly (figs. 2, 4, and 7D); this section is also probably part of the WBTS, although this cannot be unequivocally demonstrated because the overlying units on this structurally high block lie beneath Port au Port Bay. Farther east, near the mouth of Piccadilly Brook, shale with scaly fabric (Lacombe and others, 2019) and chert are again exposed between outcrops of American Tickle Formation sandstone, shale and limestone conglomerate; the scaly shale and chert are interpreted as a thin remnant of the WBTS (fig. 4). Between the Piccadilly Head and Piccadilly Bay faults, a thin WBTS is found below an E-W ridge of Daniels Harbour conglomerate. East of the Piccadilly Bay Fault, the WBTS has not been identified (fig. 4).

The WBTS is composed of mixed shale, siliceous mudstone, chert, limestone and less common sandstone or pebble conglomerate, all showing variable levels of disruption. Rare mafic igneous blocks are found in highly disrupted sections. Its internal structure is described by Lacombe and others (2019) who classify the disrupted rocks as broken formation and mélange, and show that abundant brittle extensional structures, including veins containing both calcite and pyrobitumen, are related to emplacement under conditions of high fluid pressure during hydrocarbon generation.

Goose Tickle Group above the West Bay Thrust Sheet.—A thick package of Goose Tickle Group, including both American Tickle and Mainland formations, overlies the WBTS (figs. 4 and 5), where its depositional contact (fig. 7A) with deformed rocks of the Humber Arm Allochthon was described by Waldron and others (1993). To the east, in Harry Brook, Rioux Brook and Quarry Brook, thicker portions of the WBTS are overlain by eastward-thickening sandstone, shale and conglomerate (Harry Brook facies) of the American Tickle Formation (figs. 3 and 4). Between the East Quarry Fault and Piccadilly Bay Fault, exposures of this intermediate package are dominated by folded sandstone and shale and by Daniels Harbour conglomerate. Farther south, along Piccadilly Slant, an E-W ridge of Daniels Harbour conglomerate also belongs to this intermediate package (fig. 4). In eastern Port au Port Peninsula the base of the allochthon is obscured by sparse outcrop and unconformable Carboniferous strata; there is no evidence of Goose Tickle Group in this area (fig. 4). Farther east in the coastal section between Black Cove and Fox Island River (fig. 1), there is no indication of Goose Tickle Group overlying the Humber Arm Allochthon, so the WBTS and LTS are not separable.

Lourdes Thrust Sheet.—The LTS overlies Goose Tickle Group in Victors Brook, Harry Brook, Rioux Brook and Quarry Brook (figs. 2 and 4). In each brook, outcrops of the Humber Arm Allochthon occur northeast of the Lourdes Thrust and extend to the coast of Port au Port Bay (fig. 4). At Piccadilly Slant, north of the prominent E-W trending ridge of Daniels Harbour conglomerate (fig. 4), the LTS is represented by disrupted sections of limestone, shale, siliceous mudstone and rare mafic igneous, ophiolite-derived blocks, classified variously as broken formation and mélange by

Lacombe and others (2019). Farther east, at Shoal Point, the WBTS and LTS cannot be distinguished as no Goose Tickle Group is exposed; we tentatively assign the allochthonous rocks in this area to the LTS (fig. 4).

Map-scale Structure: High-angle Faults

Several large platform-cutting faults were observed or inferred from offsets in stratigraphic boundaries (figs. 4 and 5). The largest of these, the Round Head Fault (Stenzel, ms, 1992; Waldron and others, 1993), has previously been shown to have a protracted history beginning with Neoproterozoic to Cambrian rifting and continuing through Taconic and Acadian orogenic events into at least the Devonian (Waldron and Stockmal, 1991; Waldron and others, 1993; Stockmal and others, 2004). The Round Head Fault strikes east-west within the map area (figs. 4 and 5), but curves, farther west, to strike NE-SW. Where seismically imaged, the Round Head Fault clearly dips SE (Waldron and others, 1998; Cooper and others, 2001) and shows a reverse throw of ~4500 m. A fault subparallel to the Round Head fault, but with much smaller, SE-down throw was identified by Stockmal and others (2004) as the Victors Brook Fault. We identify two strands in the region of figure 4 as the North and South Victors Brook faults. Their combined stratigraphic throw is about 80 m. Stockmal and others (2004) interpreted the Victors Brook Fault as a NW-dipping, inverted graben-bounding fault antithetic to the Round Head Thrust and suggested in their map that the Mainland Formation of the Goose Tickle Group was restricted to the graben to the north. However, seismic profiles show SE dip, suggesting that the Victors Brook faults are, instead, minor synthetic splays from the Round Head Thrust that did not undergo significant later inversion.

The other high-angle platform-cutting faults identified within the map area are, from west to east: the Harry Brook, Rioux Brook, West Quarry, East Quarry, Piccadilly Head, and Piccadilly Bay faults (figs. 4 and 5). Of these faults, the Harry Brook, East Quarry and Piccadilly Head faults can be directly observed and measured in outcrop (fig. 4); the others are inferred from topographic lineaments coincident with abrupt along-strike juxtaposition of stratigraphic units. Changes in the thicknesses of units within the Table Head and Goose Tickle groups occur across several of these faults, allowing inferences about the timing of fault movement. We use the distribution of limestone conglomerate units to show that: (1) the Middle Ordovician units were deposited syntectonically with Taconic extension, and (2) that high-angle faults were active both before and after emplacement of the WBTS.

The *Harry Brook Fault* dips steeply SE and juxtaposes St. George Group in the footwall with Table Point Formation in the hanging wall (figs. 2, 4, and 5). It separates thinned Table Head Group and American Tickle Formation to the northwest from thicker packages to the southeast (fig. 4). These map relationships suggest that the Harry Brook Fault was active as a normal fault during deposition of these units, when sediment preferentially accumulated on the subsiding, hanging wall block.

The *Rioux Brook Fault* is inferred from abrupt transitions from low-lying, poorly exposed allochthon into prominent cliffs of Table Point Formation along regional strike. We speculate that it dips NW; it transitions upward into a fold within overlying foreland basin and allochthonous rocks (fig. 4). There are no clear mappable thickness changes across the fault and therefore it probably did not undergo significant Taconic movement (fig. 4); most of the inferred offset is interpreted as Acadian.

The *West Quarry Fault* is likewise interpreted from abrupt scarps in the topography, separating recessive Humber Arm Allochthon and Goose Tickle Group from resistant Table Head Group. Westward thickening of the WBTS and overlying American Tickle Formation suggests that the West Quarry Fault dipped northwest during and after emplacement of the WBTS (figs. 4 and 5). However, based on our cross-sections, it is likely that more than one fault is present. Our preferred solution to the map geometries shows the observed offset as the result of a west-dipping normal fault and an east-dipping reverse fault, possibly conjugate to the Rioux Brook Fault.

The *East Quarry Fault* is well exposed in quarries inland from West Bay. It dips southeast and juxtaposes American Tickle Formation in the hanging wall with Humber Arm Supergroup in the footwall. This fault preserves thickened Table Head Group and Goose Tickle Group in its hanging wall (fig. 5) suggesting that it was also active as a normal fault during Taconic extension.

The *Piccadilly Head Fault*, exposed along Piccadilly Slant (fig. 4), dips NW and juxtaposes Daniels Harbour Member in the hanging wall with shale containing blocks of Daniels Harbour Member, and showing a scaly fabric, in the footwall (fig. 9A). In the footwall, a relatively thin Table Point Formation suggests that this block was upthrown prior to emplacement of the WBTS (figs. 4 and 5). Thick packages of Daniels Harbour conglomerate in the hanging wall overlie the WBTS (figs. 4 and 5) indicating that the fault continued active extension after the emplacement of the thrust sheet, allowing clasts of limestone eroded from the footwall to be deposited above the WBTS.

The *Piccadilly Bay Fault* is not observed in outcrop but is marked by prominent NE-SW topographic lineaments (fig. 4). It shows >3 km dextral separation of mapped boundaries and is interpreted as a NW-dipping feature in offshore seismic profiles (Stockmal and others, 2004). These relationships are consistent with both reverse and dextral slip. Relatively thick American Tickle Formation, including Daniels Harbour conglomerate, below the WBTS in its hanging wall suggests normal movement during the Middle Ordovician, prior to emplacement of the West Bay Thrust.

Outcrop-scale Structures

Piccadilly Head Beach.—Sandstone and shale of the American Tickle Formation are exposed in a well-known coastal section, directly east of the East Quarry Fault (figs. 4 and 10). Although this section has been interpreted as part of the Humber Arm Allochthon (Macdonald and others, 2017), our recovery of Darriwilian 3 graptolites shows that it is younger than any part of the Western Brook Pond Group in the Humber Arm Allochthon (fig. 2). This section lies above the WBTS, exposed just inland in Piccadilly Brook (fig. 4), and therefore likely sits in the footwall of the Lourdes Thrust (fig. 4). Within the exposed American Tickle Formation, thrust faults cut up section to the west (fig. 10A). Between these thrust faults are west-facing, overturned, rounded folds with tight interlimb angles that are gently inclined to the west and plunge gently north (fig. 10). Within the nearly horizontal, upright limbs, conjugate faults show consistent orientations, dipping gently WNW and steeply ESE. Faults in the hinge regions and overturned limbs of these faults are contractional, because they shorten and duplicate bedding surfaces, although they technically show normal (hanging-wall-down) offsets of bedding (fig. 10).

The overall style and vergence of folds in this section are consistent with top-to-the-west transport. We interpret the contractional faults to have initially formed as normal faults during Taconic extension. The faults were inverted during subsequent shortening, resulting in duplicated strata, and rotated by folding into their present configuration. The west-vergent thrusts and overturned folds formed during this later shortening, probably during emplacement of the overriding LTS.

Piccadilly Slant.—It the northern part of Piccadilly Slant, near Piccadilly Head (fig. 4), Daniels Harbour conglomerate is exposed in the hanging wall of the NW-dipping Piccadilly Head Fault (fig. 4), where it is juxtaposed with Humber Arm Supergroup shale showing scaly fabric and containing isolated blocks of limestone and siliceous mudstone (figs. 9A and 9B). The Daniels Harbour conglomerate slices and the scaly foliation of the shale dip steeply to near-vertical (fig. 9). Overlapping sheets of slickenfibres on the most prominent fault surface indicates dominantly sinistral strike slip, with a minor extensional dip-slip component (figs 9B, 9C, and 9D); however, this

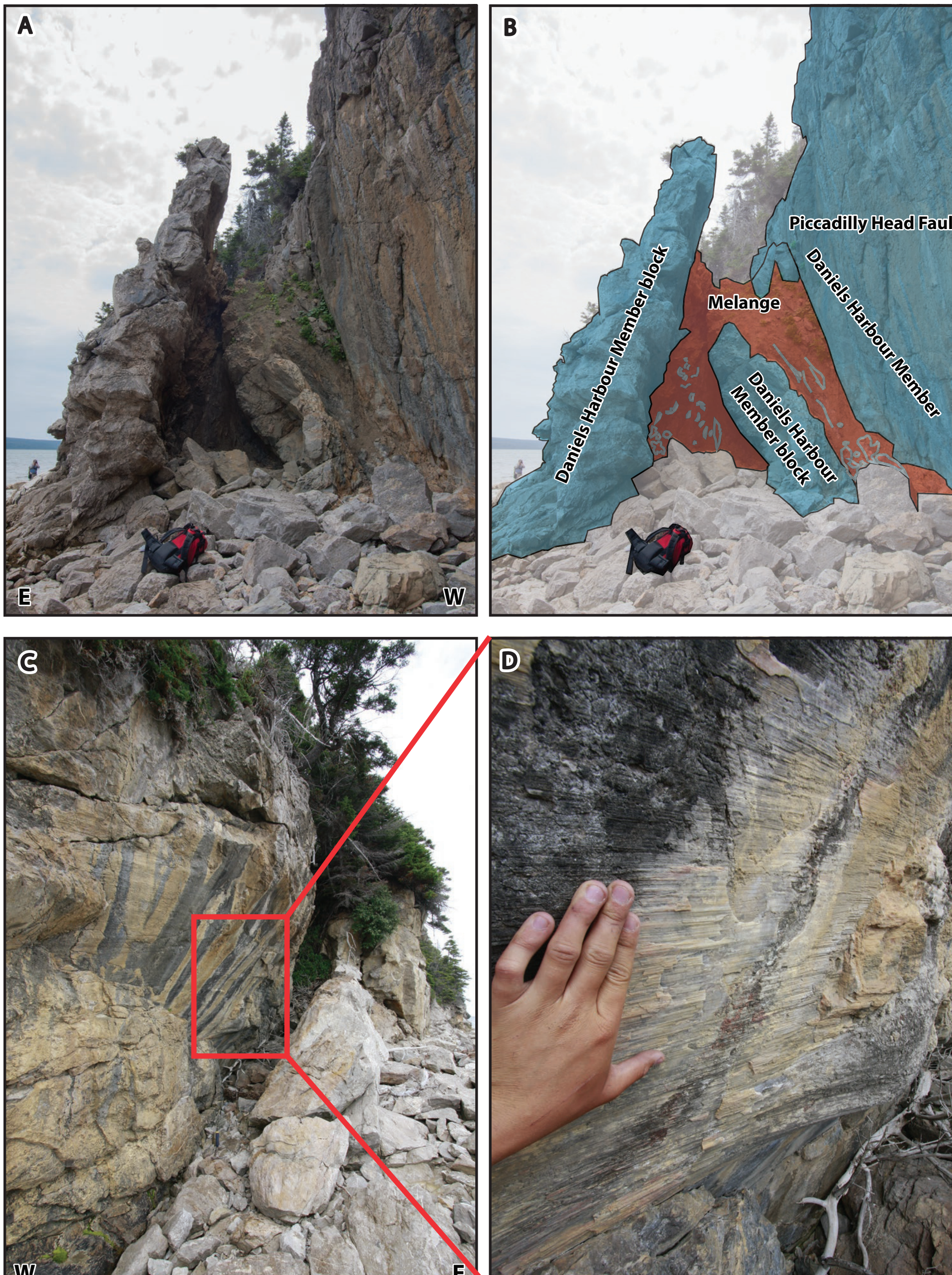

Fig. 9. Structural relationships along the Piccadilly Head Fault at Piccadilly Slant. (A) Fault surface at Piccadilly Head with annotated sketch (B) showing Daniels Harbour Member in the hanging wall and mélange in the footwall (mélange contains a large near-vertical slice of Daniels Harbour Member). (C) West-dipping Piccadilly Head fault (204/53) with (D) prominent SW-plunging slickenfibers (220-17) with overlapping sheets indicating sinistral and normal slip.

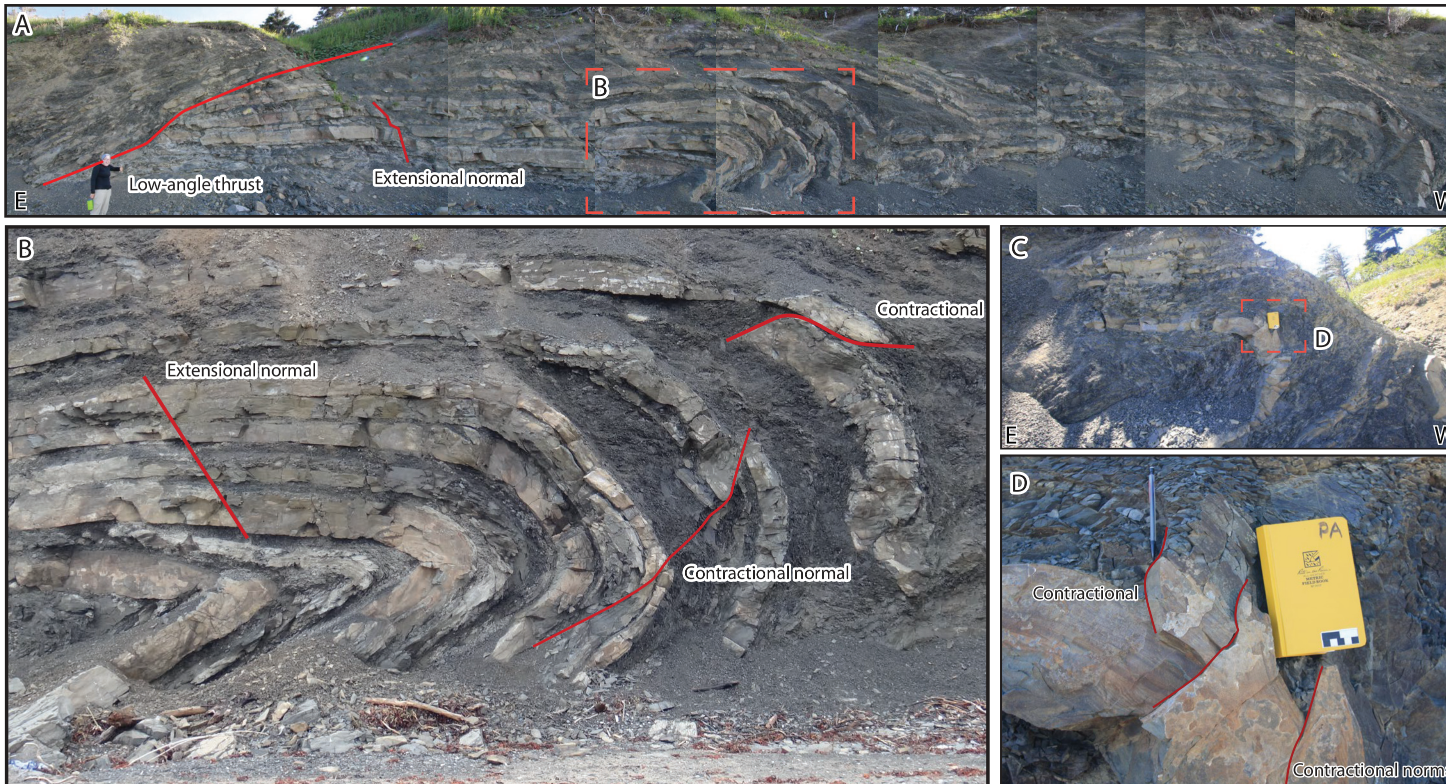

Fig. 10. Structural relationships at Piccadilly Head Beach. (A) Photo-mosaic showing overturned folded strata with interpreted low-angle thrust fault and extensional fault. (B) Overturned fold containing extensional, contractional, and contractional normal faults. (C) Overturned fold showing location of photograph (D) within the hinge of the fold. (D) Contractional normal faults in the hinge of the overturned fold.

sense of slip cannot explain the observed map separation, which requires earlier dextral and/or reverse motion.

We interpret that the Daniels Harbour conglomerate was deposited during Taconic extension; this conglomerate unit is thicker in the hanging wall suggesting that the fault was originally active as a normal fault. The steep to vertical orientations of the Daniels Harbour conglomerate and scaly shale fabric in the footwall suggest that the fault was later reactivated as a reverse fault, folding the overlying strata during propagation, and accounting for the present distribution of map units. However, reactivation of the Piccadilly Head Fault as a thrust fault is inconsistent with the slickenlines that suggest extension and sinistral slip. It is therefore likely that the Piccadilly Head Fault, first active as a normal fault in the Taconic, was reactivated as a thrust during Acadian deformation, and then reactivated a second time as a strike-slip fault during late Paleozoic or Mesozoic transtension (Waldron and others, 2015).

DISCUSSION: HISTORY OF THE THRUST FRONT

Middle Ordovician Carbonate Foredeep: Table Head Group

Following passage of the Taconic forebulge across the shelf (Jacobi, 1981; Knight and others, 1989), recorded by the St. George unconformity, the overlying Table Head and Goose Tickle groups record a rapid series of events during Darriwilian 2 and 3 time, as the Humber Arm Allochthon encroached on the foreland basin. The Table Point Formation (figs. 3 and 11) records rapid accommodation in the Taconic foredeep after passage of the forebulge. Its shallow-marine facies indicates that carbonate production kept pace with subsidence, maintaining the foreland basin in a filled condition, despite an initial lack of orogen-derived detritus. The variable thickness therefore indicates variable subsidence rates, probably under the influence of extensional block faults. Extensional structures are unusual in foreland basin settings; these may have resulted from flexural extension of the Laurentian plate and/or slab-pull forces during arc-continent collision (Jacobi, 1981; Bradley and Kidd, 1991; Knight and others, 1991; Stenzel, ms, 1992).

The overlying Table Cove Formation records a transition to an underfilled foreland basin in which carbonate production no longer kept pace with subsidence (Stenzel, ms, 1992). Lateral thickness changes and the discontinuous nature of the formation suggest differential subsidence under the influence of extensional faults. Limestone turbidite beds were probably shed from horsts within the basin.

The Cape Cormorant Formation, confined to the northwest portion of the map area (fig. 4), is interpreted to have formed by localized erosion of a submarine scarp along the Round Head Fault (Stenzel and others, 1990; Waldron and others, 1993). The range in ages of carbonate clasts within this formation suggest that there was >1 km of normal-sense throw on this fault during the Darriwilian (Stenzel and others, 1990), which contributed to subsidence in the faulted basin to the east. The footwall of the Round Head Fault, preserved in the deep subsurface, was penetrated by Port au Port #1 well, where it displays only a thin (15 m) Table Point Formation (Cooper and others, 2001) directly overlain by Goose Tickle Group, consistent with deposition on an upthrown block. Devonian inversion resulted in the present-day, reverse fault geometry (Stockmal and Waldron, 1990; Waldron and others, 1993; Stockmal and others, 2004).

Clastic Foredeep: Goose Tickle Group

The base of the Goose Tickle Group marks the end of carbonate deposition in the foreland basin, recording subsidence of the last remaining platform areas below the photic zone of high carbonate productivity. The lowest, Black Cove Formation, represents low-energy, deep-water conditions before the first sandy turbidites arrived.

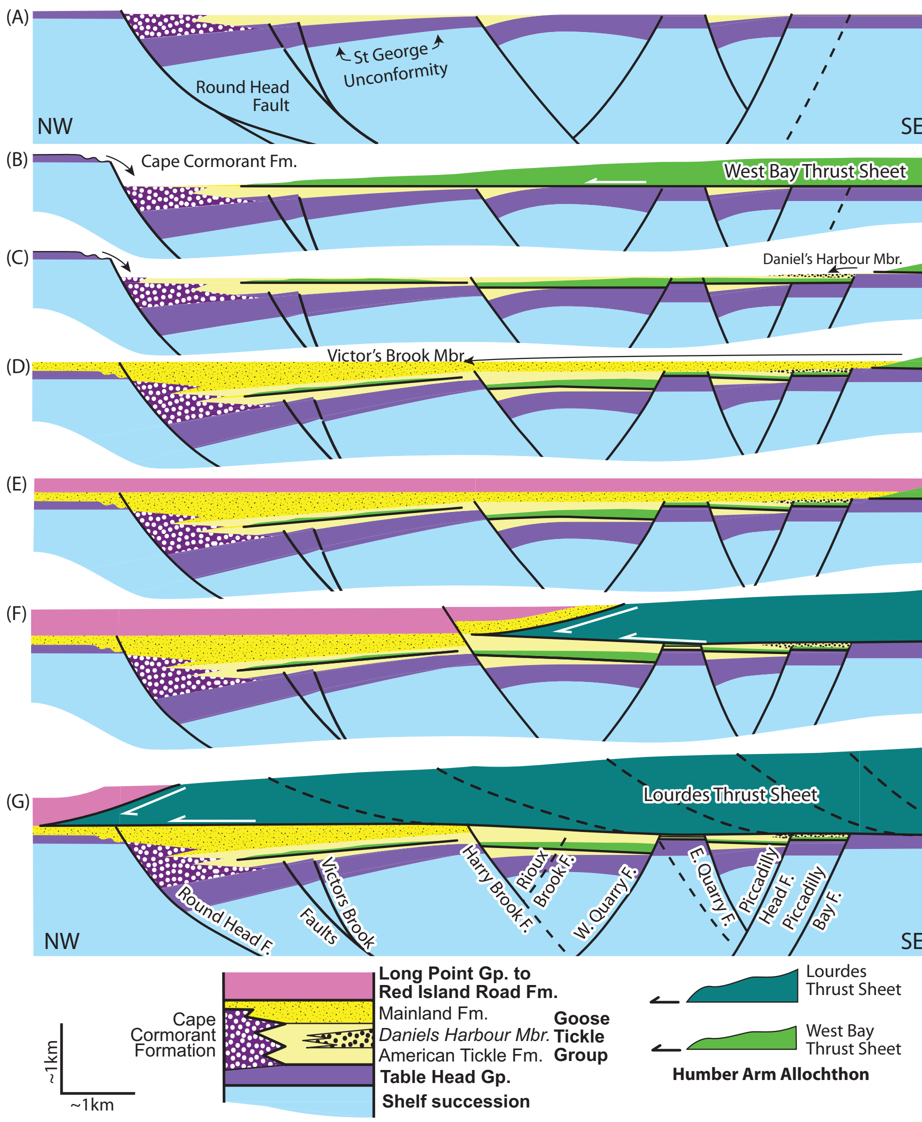

Fig. 11. Schematic cross-sections showing the evolution of structural elements at the Appalachian thrust front. (A) Early Darriwilian foreland basin dissected by normal faults. (B) Darriwilian 3 emplacement of the West Bay Thrust Sheet across Port au Port Peninsula. (C) Erosion and continued movement along high-angle fault leads to burial of the eroded remnants of the West Bay Thrust Sheet beneath limestone conglomerate of the American Tickle Formation. (D) Deposition of Mainland Formation, at first confined by Round Head Fault but eventually spilling to the NW. (E) Deposition of Long Point Group. (F) Inversion of Harry Brook Fault followed by emplacement of Lourdes Thrust Sheet. (G) Devonian emplacement of the Lourdes Thrust Sheet to its present position, forming a tectonic wedge within foreland basin strata. Note that Lourdes Thrust cuts up-section where it intersects inverted Harry Brook Fault.

Overlying units are dominated by clastic turbidites shed westward from the Humber Arm Allochthon (Quinn, ms, 1992b). The American Tickle Formation undergoes abrupt changes in thickness at high-angle, platform-cutting normal faults, most notable at the Harry Brook and East Quarry faults (figs. 4 and 11), where they are associated with platform-derived conglomerate, implying that these faults were still active, influencing basin geometry during deposition. Interdigitation of the American Tickle Formation with distal portions of the Cape Cormorant Formation (figs. 3 and 4) indicates that movement on the Round Head Fault also continued.

Carbonate conglomerate units punctuate the American Tickle Formation. Conglomerate facies range from angular, clast-dominated varieties suggesting deposition via granular flow to rounded, matrix-dominated varieties that suggest transport via debris flows. Most carbonate clasts show textural and lithological similarities to the underlying Table Head Group, interpreted as the main source. A minor proportion of laminated dolostone clasts suggest that some source areas exposed uppermost St. George Group (figs. 2 and 3). A previous interpretation by Stenzel (ms, 1992) and Quinn (1995) suggests that the limestone conglomerates were generated as a result of thrust fault movement which exposed the carbonate platform in the up-thrown hanging walls and led to erosion and deposition of conglomerate onto the footwalls. This hypothesis seems unlikely as limestone conglomerate only occurs in the hanging walls of high-angle faults (figs. 1 and 4). Their distribution is better explained by an extensional setting in which clasts from horsts were redeposited into adjacent grabens. We see no evidence for shortening of the underlying platform succession during Taconic deformation.

Although the occurrence of extensional faults in a zone of convergence is at first unexpected, extensional faults in down-going plates have been widely documented in modern oceanic subduction zones (Nakanishi, 2011; Nakamura and others, 2013; Chester and Moore, 2018), in continent-arc collisions (McConachie and others, 2000; Harris, 2011), and elsewhere in the Appalachian Taconic foreland basin (Bradley and Kidd, 1991). They are commonly interpreted as products of flexural extension due to bending of the down-going plate, although slab-pull (Forsyth and Uyeda, 1975) may be an additional factor.

Emplacement of the West Bay Thrust Sheet

The West Bay Thrust Sheet occurs within the Goose Tickle Group. Within the thrust sheet, pervasive brittle fractures, some of which contain hydrocarbons (Waldron and others, 1993; Lacombe, ms, 2017; Lacombe and others, 2019), suggest that it was emplaced as an internally extending sheet, where extensional fracture development was facilitated by high fluid pressure during petroleum generation.

Portions of the Goose Tickle Group are also found above the WBTS (figs. 4 and 5). Three scenarios can be envisaged to explain the mapped relationship. In the first scenario, the allochthon was emplaced as a tectonic wedge into the Goose Tickle Group. In a second scenario, the upper portion of the Goose Tickle Group was deposited on the Humber Arm Allochthon, in the wedge-top depozone, prior to westward emplacement of both into their present positions. The third scenario is that the upper portion of the Goose Tickle Group was deposited unconformably on the WBTS after its Taconic emplacement. We favor this third scenario, for the following reasons:

1) The upper contact of the WBTS, where it is exposed in the bed of Victors Brook (fig. 7A) is a depositional contact of Goose Tickle Group sandstone (passing up into conglomerate), in contrast to the highly sheared lower contact (figs. 7C and 7D) (Waldron and others, 1993).
2) Smaller rafts and isolated boulders of Humber Arm Supergroup, and adjacent shale-chip conglomerate (figs. 6H and 6I) occur within the Goose Tickle Group in the Victors Brook area (Waldron and others, 1993). This extreme compositional immaturity suggests that the allochthon was close to its present position when these rocks were deposited (scenarios 2 and 3).
3) A thick package of Daniels Harbour conglomerate occurs above the WBTS in

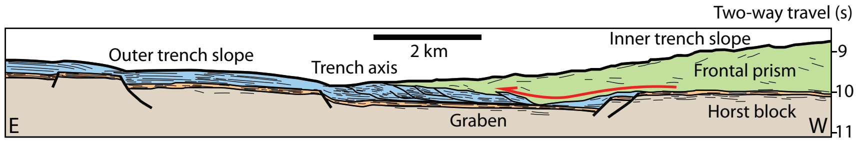

Fig. 12. Possible modern analogue for emplacement of the West Bay Thrust Sheet over a faulted autochthon, based on a modern cross-section through the Japan Trench (Nakamura and others, 2013), redrawn in orientation comparable with the Humber Arm Allochthon in the Middle Ordovician.

the hanging wall of the W-dipping Piccadilly Bay Fault (figs. 5 and 11), interpreted as derived from the footwall. If this occurred before insertion of a tectonic wedge (scenario 1), that wedge would have to have been inserted through Table Head Group in the footwall block. There is no evidence to support this unlikely tectonic path for the WBTS. In the second scenario, the conglomerate would have been transported into its present position from the west; the relationship with the Piccadilly Bay Fault would therefore be coincidental. In the third scenario, the WBTS would have been subjected to a period of erosion before being drownthrown in the hanging wall of the Piccadilly Bay Fault where it was covered by Daniels Harbour conglomerate (figs. 11A and 11B), a much more likely scenario.

The evidence supports scenario three. We therefore bracket the timing of emplacement of the WBTS as Darriwilian 3, from graptolite assemblages in American Tickle Formation both above and below the WBTS (fig. 4).

These observations suggest that the Humber Arm Allochthon was initially emplaced during a protracted period of platform extension and block faulting, and that Goose Tickle Group foreland basin sediment continued to be deposited in a wedge-top setting after arrival of the allochthon. Observations within the allochthon suggest that the latest stages in its emplacement involved gravity spreading (Schultz-Ela, 2001) during collapse of the thrust-wedge taper, that probably alternated with thrust stacking. Lacombe and others (2019) further note that at the leading edge of such an allochthon, extensional structures formed by gravity spreading may be intergradational with extensional landslides. In this context, observations and interpretations of the Japan Trench by Nakamura and others (2013) are particularly relevant, as they image the toe of an allochthonous accretionary prism that has been emplaced over an actively faulting lower plate (fig. 12). As the accretionary prism passes across a normal fault scarp that dips toward the foreland (analogous to the Piccadilly Bay and Piccadilly Head faults), its basal surface tilts toward the foreland, consistent with motion by gravity gliding (Schultz-Ela, 2001), not thrusting, into the foredeep. In such a scenario, the slope of the basal décollement favours extension within the allochthon even in the absence of weakening by high fluid pressure.

In conclusion, the thin and discontinuous character of the WBTS resulted from thrusting, modified by extension during emplacement, gravity gliding at the thrust front, and subsequent erosion (fig. 7E).

Wedge-top Sedimentation: Goose Tickle Group Above the West Bay Thrust Sheet

The WBTS is overlain by sandstone and shale of the American Tickle Formation, including lenses of Daniels Harbour Member and Harry Brook facies conglomerate; these conglomerate units resulted from continued block faulting after the WBTS was emplaced, exposing Table Head Group strata.

Later phases of clastic foreland basin fill are recorded by the Mainland Formation (figs. 3, 4, and 11). The Mainland Formation is only found between the Harry Brook and Round Head faults. Its distribution suggests that the turbidity currents that deposited the formation were confined to the hanging wall of the curved Round Head Fault by a substantial fault scarp that guided the distribution of orogen-derived sand into western Port au Port Peninsula; this model would account for the southwestward paleocurrent data collected by Stenzel (ms, 1992) and Quinn (1995). Unlike the hypothetical Serpentine Lake Discontinuity suggested as a structural control by Quinn (1995), the Round Head Fault is well constrained both structurally and temporally by outcrop and seismic sections (Waldron and Stockmal, 1991; Waldron and others, 1993; Stockmal and others, 2004). Ponding of sediment against the Round Head Fault can better account for the localized distribution of the Mainland Formation within the map area. A similar scenario is suggested for fault-controlled sedimentation in the Taconic foredeep of the Mowhawk Valley by Jacobi and Mitchell (2002).

Shale-chip conglomerate of the Victors Brook facies displays very low compositional maturity suggesting deposition close to a source of lithified shale fragments at the leading edge of the Humber Arm Allochthon. The association of this facies with allochthonous rocks in Victors Brook is interpreted to represent interfingering of the Mainland Formation and American Tickle formations (fig. 3) as suggested by Quinn (ms 1992b, 1995). However, the Mainland Formation largely overlies the American Tickle Formation at map scale (figs. 3 and 4).

Therefore, the Goose Tickle Group represents an overall coarsening upward sequence beginning with the fine-grained Black Cove Formation and continuing upwards sequentially into: mud-dominated turbidites of the American Tickle Formation; sandstone-dominated turbidites of the Mainland Formation; and finally, shale-chip conglomerates of the Victors Brook Member (fig. 3). This overall sequence probably records a transition from a distal to proximal sediment source as the Humber Arm Allochthon was emplaced. The absence of limestone conglomerates from the Mainland Formation shows that horsts of exposed Table Head Group were eventually buried by orogen-derived clastic sediment or by Humber Arm Allochthon.

Post-Taconic Deformation and Emplacement of the Lourdes Thrust Sheet

The Lourdes Thrust is interpreted as an out-of-sequence thrust which overrode the WBTS and overlying Goose Tickle Group rocks; it is also interpreted as the basal detachment for the Acadian tectonic wedge farther west. Preservation of the earlier WBTS was facilitated by high-angle, extensional faults that form a broad graben between the Piccadilly Bay Fault and the Round Head Fault, in which the WBTS was dropped down and buried beneath the Goose Tickle Group (fig. 11B). The LTS overrode these strata (fig. 11C) reworking previous extensional faults, while also deforming the strata in west-vergent low-angle thrusts and overturned folds.

East of the Piccadilly Bay Fault, the Lourdes and West Bay thrust sheets cannot be separated. We interpret that in this area the two thrusts are coincident; any wedge-top Goose Tickle Group rocks that were present above the WBTS have been reworked into the LTS or transported into the tip of the tectonic wedge offshore to the northwest (figs. 11F and 11G),

Northwest of Harry Brook, the footwall of the Lourdes Thrust contains rocks assigned to both the American Tickle and the overlying Mainland formations. However, no Mainland Formation was observed southeast of the Harry Brook Fault (fig. 4). We suggest that the Harry Brook Fault was inverted prior to the arrival of the LTS. As a result, the Lourdes Thrust appears to climb up-section across the Harry Brook Fault (figs. 2, 3, 11F, and 11G).

Continued westward emplacement of the LTS propagated the tectonic wedge to its current position where it was subsequently crosscut by the inverted Round Head Fault (Waldron and Stockmal, 1991; Waldron and others, 1993; Stockmal and others,

2004) (fig. 5). The base of the LTS is similarly crosscut and deformed at Piccadilly Slant (fig. 4). Field relationships at this location suggest two phases of deformation after the LTS had been emplaced. An earlier event inverted the Piccadilly Head Fault, explaining the large dextral separation apparent from map relationships. Prominent slickenlines on the fault surface (fig. 9) that indicate sinistral transtension resulted from a later phase of deformation. Post-Emsian deformation also occurred at the Rioux Brook, West Quarry and Piccadilly Bay faults as all these faults deform the Lourdes Thrust. It is not possible to discern separate phases of inversion and strike-slip movement on these faults as slickenlines are unavailable.

CONCLUSIONS

Port au Port Peninsula displays a structurally complex, three-dimensional geometry resulting from a protracted history of deformation, in which low-angle and high-angle faults were concurrently active from Middle Ordovician to at least Early Devonian. Deposition of foreland basin units was affected by block faulting during initial foredeep subsidence, controlling stratigraphic thicknesses in the Table Head Group. Within the Goose Tickle Group, the American Tickle Formation was deposited while active carbonate horsts were still exposed, shedding local conglomerates into the basin. The overlying and interfingering Mainland Formation (fig. 4) formed when these horsts had been submerged by allochthon-derived sediment. The Mainland Formation was confined along the extensional Round Head Fault during much of its deposition.

The Humber Arm Allochthon, previously interpreted as a single thrust sheet, occurs in two structural packages, the WBTS and the LTS. The WBTS preserves the initial leading edge of the Taconic Humber Arm Allochthon. Graptolites constrain its emplacement within the Darriwilian 3 substage. Limestone conglomerate in the Goose Tickle Group above the WBTS indicates that block faulting continued after emplacement. The LTS was emplaced during the Acadian orogeny as an out-of-sequence tectonic wedge above the Goose Tickle Group and the older WBTS. Relationships at the Harry Brook Fault suggest that inversion started prior to the emplacement of the LTS, which reached its present position in the Early to Middle Devonian. Continued inversion produced the present-day geometry in which the Round Head Fault displays over 4 km of reverse separation.

These results show that deposition of foreland basin sediments and the subsequent geometry of thrust sheets at the Appalachian thrust front were inextricably linked to movement on high-angle faults, as deformation of the underlying platform evolved from Taconic extension to Acadian contraction. Inherited thick-skinned faults may be as important as thin-skinned thrust faults in controlling the development of foreland basins and thrust fronts.

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