Stratigraphic and Structural Relationships in the Foreland Basin and Humber Arm Allochthon on Port au Port Peninsula, western Newfoundland

by

Ryan Lacombe

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

Department of Earth and Atmospheric Sciences

University of Alberta

Abstract

Port au Port Peninsula, in western Newfoundland, sits at the western edge of the Appalachian orogen. Middle Ordovician foreland basin strata deposited on the Laurentian margin are primarily derived from, and overridden by, Cambrian to Ordovician deep-water rocks previously mapped as mélange and assigned to the Humber Arm Allochthon. Abrupt thickness changes in the foreland basin are associated with high-angle faults and increased accommodation space in the hanging wall of extensional faults. Foreland basin strata are found between two packages of Humber Arm Allochthon on Port au Port Peninsula; they unconformably overlie the lower, allochthonous, West Bay Thrust Sheet and are overlain in turn by the upper, allochthonous, Lourdes Thrust Sheet. The West Bay Thrust Sheet was emplaced during a period of Taconian extension as an overextended and thinned wedge emplaced rapidly during the Middle Ordovician. Down-dropped along normal faults, the West Bay Thrust Sheet was covered by foreland basin strata; further Acadian (Devonian) deformation duplicated the Humber Arm Allochthon on Port au Port Peninsula to fill a tectonic wedge within the foreland basin. Taconian, extensional faults were reactivated; map offsets and slickenlines suggest two phases of reactivation which are related to Acadian inversion and Carboniferous strike-slip.

The Humber Arm Allochthon comprises the Cooks Brook, Middle Arm Point and Eagle Island formations, and is structurally highly disrupted. Outcrop-scale disruption is assigned a value from 0-V with I-IV constituting broken formation and V constituting mélange. More coherent, folded outcrops of allochthonous rocks show three fold generations; early tight to isoclinal folds are overprinted by two later deformation events which we link to Acadian (Devonian) orogenesis and inversion, and subsequent Carboniferous strike-slip along high-angle faults. Mélange, representing the highest disruption mapped in the area, commonly contains igneous blocks from a variety of sources which we link to olistostromal processes at the early Taconian deformation front. Measured blocks within mélange range from thin-section scale (0.5 mm) to 150 cm. Mélange at outcrop scale shows, on average, 24% blocks to 76% scaly shale. Oriented thin sections collected from mélange show both clockwise and counterclockwise oblique-shear fractures as well as hydrocarbons. Autobrecciation, dewatering structures and sandstone dykes imply high fluid pressures. We suggest that the allochthon underwent coaxial extension within an overall compressional setting as a result of high fluid pressure; due, in part, to the expulsion of hydrocarbons from allochthonous source rocks within the wedge. This resulted in rapid forward movement (and thinning) of the Taconian wedge.

Acknowledgments

I would like to thank my supervisor Dr. John Waldron for the opportunity to work with him. His guidance with this project and seemingly tireless devotion to research provided constant inspiration. I would also like to thank all of my colleagues in the Structural Geology and Tectonics Research Group for their help, support and friendship. A special thanks to Shawna White and Martin Schwangler for their assistance with data collection and for broadening my perspective of Newfoundland through their own research. Thank you to Henry Williams for his expertise with biostratigraphic identification and to Larry Hicks for compiling an informative history of petroleum exploration in western Newfoundland. Thank you to Mark Labbe and Martin Von Dollen for their skillful advice and creation of thin sections for this project. Thank you to Dr. Nick Harris and Omid Ardakani for their assistance with fluorescence microscopy. Funding for this project was supplied by Black Spruce Exploration Corp., the Natural Sciences and Engineering Research Council (NSERC) and the Petroleum Exploration Enhancement Program (PEEP). Finally, I must thank my family and friends for their patience and support through this process.

Table of Contents

List of Figures

Chapter 1: Introduction

Western Newfoundland is a classic area in the tectonics of the Appalachian Orogen (Figure 1.1), preserving remnants of an ancient ocean (Wilson, 1966), termed the Iapetus (Harland and Gayer, 1972) that closed during the Paleozoic era (Figure 1.2).

Port au Port Peninsula is unique in western Newfoundland as it exposes the Appalachian structural front, elsewhere identified offshore in seismic sections by Stockmal & Waldron (1990) and others (Cooper et al. 2001; S. White, University of Alberta, *personal communication*) (Figure 1.3). Because of their proximity to the structural front, rocks on Port au Port Peninsula display little metamorphic or structural overprinting during later orogenic events that affected internal parts of the orogen. Port au Port Peninsula is also unique in that a late phase of deformation has tilted all of the strata to the north, giving a cross-sectional view, at surface, through the platform, foreland basin, and allochthon. The combination of these factors has led to the exposure of a Cambrian to Carboniferous sequence. Because of this, Port au Port Peninsula provides a unique opportunity to study early structures related to emplacement of allochthonous rocks (the Humber Arm Allochthon) and the progressive development of the associated foreland basin during closure of the Iapetus Ocean.

1.1. Appalachian subdivision

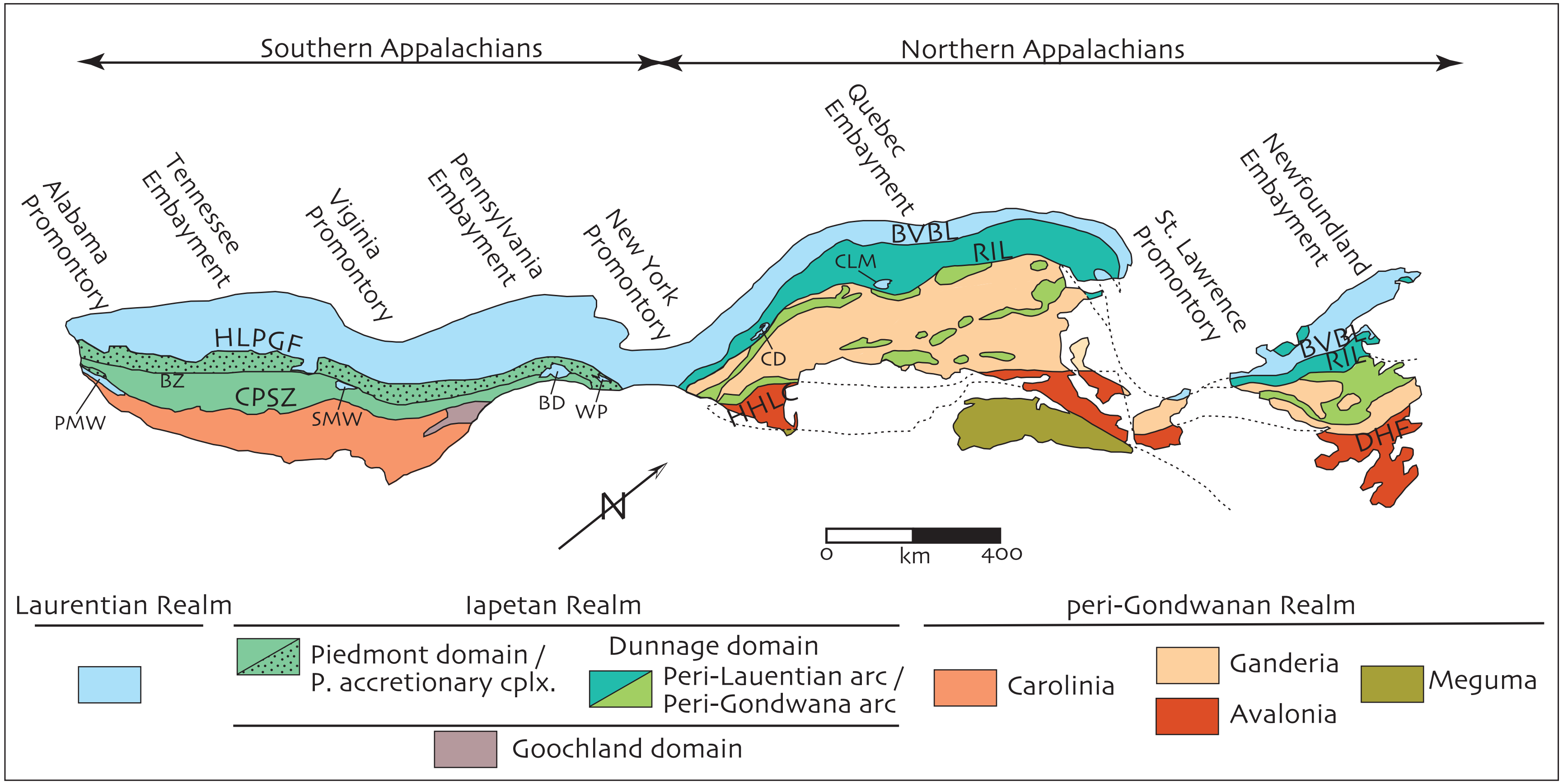
The Appalachian Orogen (Figure 1.1) is subdivided into the Laurentian, Iapetan, and Peri-Gondwanan realms and records the closure of the Iapetus Ocean (Hibbard et al., 2007).

1.1.1. Laurentian Realm

Neoproterozoic to earliest Paleozoic rifting opened the Iapetus Ocean separating Laurentia from Gondwana and Baltica (Figure 1.2). The Laurentian margin comprises rifted Grenvillian basement, a Neoproterozoic rift sequence, an early Cambrian to Middle Ordovician drift sequence and a series of Middle to Late Ordovician synorogenic clastic wedges. A complex rift history,

Figure 1.1: Subdivision of the Appalachian Orogen showing major pre-Silurian lithotectonic divisions.

From Hibbard et al. (2007). Abbreviations: BVBL=Baie Verte - Brompton Line; BD=Baltimore domes; BZ=Brevard zone; CD=Chester dome; CLM=Chain Lakes massif; CPSZ=central Piedmont shear zone; DHF=Dover-Hermitage Bay faults; HHL-C=Honey Hill - Lake Char fault system; HLPGF=Hollins Line - Pleasant Grove fault system; PMW=Pine Mountain window; RIL=Red Indian Line; SMW=Sauratown Mountains window; WP=Westchester prong.



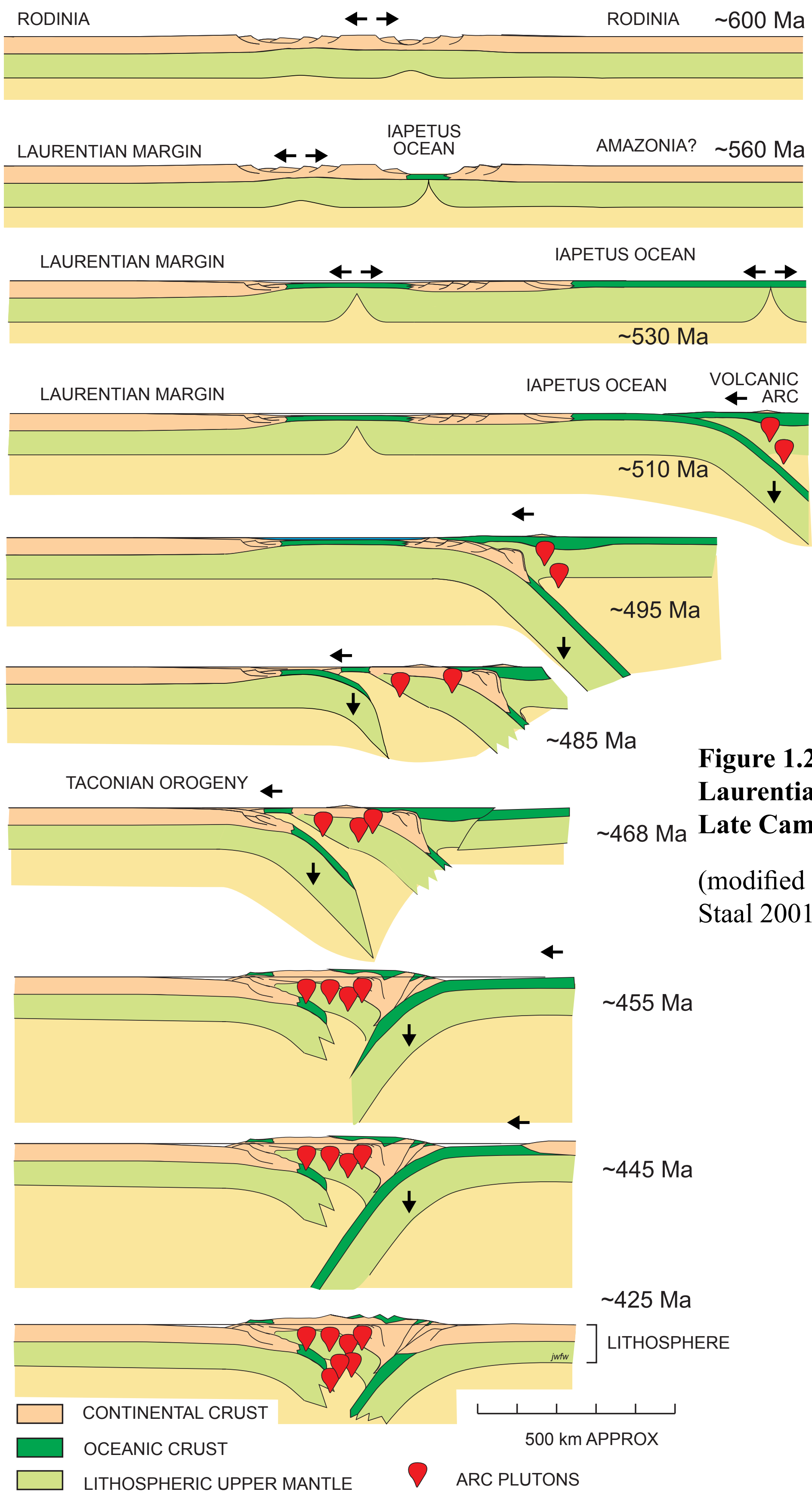
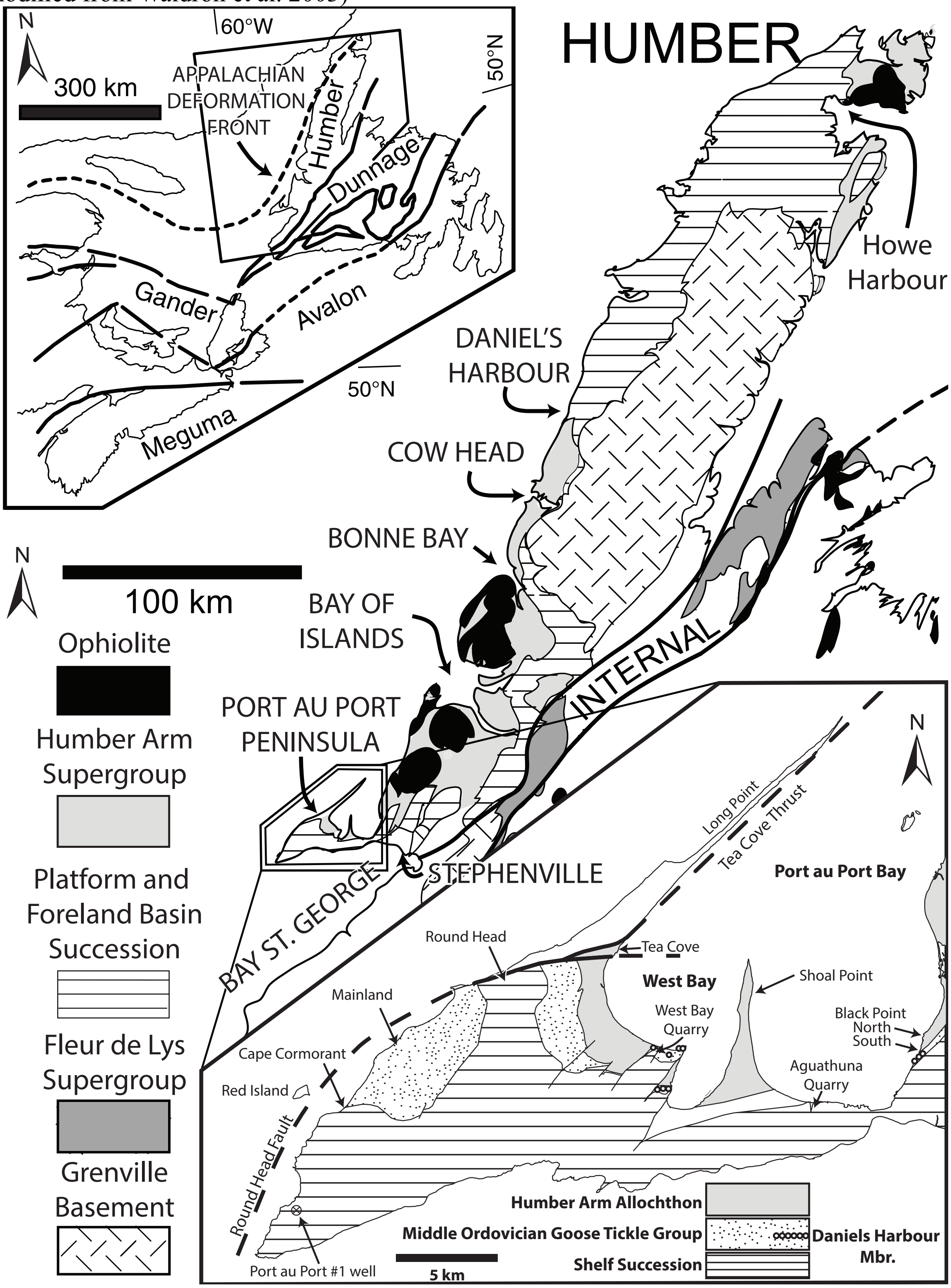


Figure 1.2: Evolution of the Laurentian margin from the Late Cambrian to Late Silurian

(modified from Waldron & van Staal 2001)

Figure 1.3: (a) Lithotectonic subdivision of western Newfoundland and (b) location of the study area on Port au Port Peninsula.

(modified from Waldron et al. 2003)



suggested by Cawood et al. (2001), places the breakup up of Rodinia and formation of the Iapetus Ocean at ~570 Ma; but also recognizes a late Neoproterozoic to earliest Paleozoic phase of rifting which separated a continental block or blocks from the Laurentian margin as a marginal Taconic seaway was opened (Cawood et al., 2001; Waldron and van Staal, 2001; Hibbard et al., 2007) (Figure 1.2). The transition from drift succession to synorogenic foreland basins is marked by foreland bulge unconformities collectively known as the Knox-Beekmantown - St. George unconformity (Hibbard et al., 2007). The Laurentian margin extends eastwards to the Baie Verte-Brompton Line (Figure 1.1) where it is juxtaposed with re-accreted peri-Laurentian microcontinents and magmatic arcs with Laurentian affinity. These fragments of Laurentia extend eastwards to the Red Indian Line where the Laurentian Realm is juxtaposed, in Newfoundland, with peri-Gondwanan components of the orogen (Waldron et al., 2015) (Figure 1.1).

1.2. Appalachian events

Subduction initiated on both sides of the Iapetus Ocean in the early to middle Cambrian is recorded by the oldest volcanic sequences with geochemistry suggesting development in a supra-subduction zone setting (Searle and Stevens, 1984; Jenner et al., 1991). On the Laurentian side of the Iapetus Ocean, eastward subduction initiated outboard of microcontinental blocks such as the Dashwoods block (Waldron and van Staal, 2001); separated from the Laurentian margin by the Taconic seaway (Hibbard et al., 2007) (Figure 1.2).

1.2.1. Taconian

The onset of Taconian orogenesis is marked in Newfoundland by the Taconian peripheral bulge unconformity known as the St. George unconformity; this unconformity marks minor uplift at the transition from passive margin to drowned margin as flexural subsidence increased outboard of the peripheral bulge (Jacobi, 1981; Knight et al., 1991; Hibbard et al., 2007). Overlying Middle to Late Ordovician, easterly-derived, synorogenic clastic wedges record the progressive approach, by rollback of an east-dipping subduction zone at the Laurentian margin and closure of the Taconic seaway during the Middle Ordovician (Hibbard et al., 2007) (Figure 1.2).

A stack of thrust sheets, the Humber Arm Allochthon, sits above these Middle Ordovician syn-orogenic clastic rocks. The Humber Arm Allochthon contains deep-water slope and rise facies strata at its base which are tectonically overlain by igneous and metamorphic rocks of an intermediate slice; ophiolites comprise the structurally highest slice (Figure 1.3). These ophiolites represent oceanic crust of the Taconic Seaway, obducted onto the Laurentian margin during an arc-continent collision that closed the seaway (Waldron and van Staal, 2001; Hibbard et al., 2007) (Figure 1.2).

1.2.2. Salinian

Following closure of the Taconic Seaway subduction stepped back towards the hinterland and underwent a polarity switch to westward-dipping as the Iapetus Ocean continued to close (Hibbard et al., 2007) (Figure 1.2). The Salinian orogeny is marked in western Newfoundland by an unconformity that spans the Late Ordovician to latest Silurian (Quinn et al., 1999). This orogenic event was associated with a period of increased igneous activity within central parts of Newfoundland; however, the long-lived unconformity in western Newfoundland at this time suggests that this region occupied a structurally high position at this time (Cawood, 1993). This deformation episode is diachronous parallel to the length of the orogen, beginning earlier in the north than in the south, and long-lived; this protracted deformation is considered by Waldron et al. (submitted) to be the result of a number of accretion events as peri-Gondwanan terranes collided with the margin of Laurentia (Figure 1.2).

1.2.3. Acadian

Acadian deformation in western Newfoundland is recorded by a package of latest Silurian to Early Devonian clastics indicative of renewed tectonic subsidence (Waldron et al., 1998). These clastic units are folded in the hanging wall of a tectonic wedge on Port au Port Peninsula (Figure 1.3) indicating that emplacement of allochthonous units continued until the Early Devonian

(Emsian) (Stockmal et al., 2004). On Port au Port Peninsula, this tectonic wedge is truncated by an east-dipping inverted normal fault, the Round Head Thrust; inversion post-dates wedge emplacement (Emsian) but does not crosscut unconformably overlying Carboniferous strata (Waldron and Stockmal, 1991; Stockmal and Waldron, 1993; Waldron et al., 1998). Devonian deformation, including both wedge formation and basin inversion in western Newfoundland, is associated with the regional Acadian orogenic event (Stockmal and Waldron, 1993).

1.2.4. Maritimes Basin

The Late Devonian to Permian Maritimes Basin sits to the south of Port au Port Peninsula and contains volcanic, carbonate, evaporite, and clastic units. This basin was formed during a period of transtension along a releasing bend parallel to the orogen (Hibbard and Waldron, 2009; Waldron et al., 2015). NE-SW faults in western Newfoundland which bound smaller Carboniferous basins are related to this period of transtentional deformation (Stockmal and Waldron, 1990; Waldron et al., 1998; Palmer et al., 2002; Waldron et al., 2015).

1.3. Methods

Field work was carried out over three summers (2013, 2014, and 2015) during which time a portion of Port au Port Peninsula was mapped and data and samples collected. Additional data for this area was compiled from field notebooks supplied by Dr. John Waldron that date back to the late 1980's. Some waypoints were also supplied by Shawna White for the Long Point Group in the NW portion of the map area. All data, new and old, were compiled into ArcGIS.

Detailed measured sections were compiled from less disrupted coastal sections in the Port au Port area at Black Point North, Tea Cove and south of Tea Cove along the coast of West Bay (Figure 1.2). Beds >5 cm thick were measured with a hand-held tape measure; larger intervals were measured as apparent thickness along a 50 m measuring tape and converted to stratigraphic thicknesses using the trigonometric function 'true thickness = apparent thickness x cos (θ)'; the angle (θ) is the angle between the pole to bedding and the line of the 50 m tape. Lithology, coloration, and structural features were documented throughout each section.

Sampling of mélange is difficult due to the brittle and friable nature of the scaly shale matrix. In an attempt to keep samples intact for transport and petrographic analysis, we developed a technique using expanding foam in which a pillar was chipped out of the outcrop, an open-ended box was then placed over the pillar, and expanding foam was sprayed around the pillar. The edges of the box were marked to show the sample orientation. Once the foam had set, the pillar was broken off at the bottom and the bottom of the sample was encased in foam. Once transported, the samples were cut along oriented planes, dried, and set with blue colored epoxy so that oriented thin sections could be cut. Thin sections were cut from four samples in the inferred direction of transport (perpendicular to foliation in the shale and parallel to a lineation indicating slip direction, if present). PA014A was the first sample collected and cut; thin sections cut from this sample retain the normal thickness of 30 µm. Thin sections cut from samples SC026A, SA024A, and PF051B were ground to 10 µm so that more detail could be observed in these fine grained rocks. Although significant voids were opened with our sample collection technique, the samples remained sufficiently coherent for study, using transmitted and reflected light. In addition, samples were examined by N. Harris (University of Alberta) and O. Ardakani (Geological Survey of Canada) using fluorescence microscopy. Structures present in each of the samples are measured as clockwise (CW) rakes down from either the SE or NE strike line of each thin-section.

1.4. Roadmap of thesis

Following this introduction, Chapter 2 discusses the evolution of the Middle Ordovician foreland basin in western Newfoundland resulting from eastward subduction of the Laurentian margin under outboard peri-Laurentian magmatic arcs. Mapping near the base of the Taconian allochthon on Port au Port Peninsula (Figure 1.3), where it overlies synorogenic clastics of the Middle Ordovician Goose Tickle Group reveals a number of facies relationships. These facies are used to reinterpret stratigraphic boundaries, reinterpret the nature of allochthonous rafts described by

Waldron et al. (1993), and determine timing relationships between low-angle emplacement related faults and high-angle platform cutting faults. The timing relationships discussed in Chapter 2 are critical to better understanding Middle Ordovician foreland basin development within the Newfoundland Appalachian orogen.

Chapter 2 of this thesis will be submitted to the Geological Society of America Bulletin under the authorship R. Lacombe, J.W.F. Waldron, and S.H. Williams. R. Lacombe was responsible for the data collection and analysis as well as the manuscript composition. J.W.F. Waldron assisted with data collection and contributed to manuscript edits. S.H. Williams contributed biostratigraphic expertise.

Chapter 3 discusses the Humber Arm Allochthon on Port au Port Peninsula (Figure 1.3) and begins with the assignment of a revised stratigraphy to these rocks which have previously been mapped as mélange (Williams and Cawood, 1989); these units are mapped as the Cooks Brook, Middle Arm Point, and Eagle Island formations and are similar to those mapped in the Bay of Islands area by Botsford (1987) (Figure 1.3). Outcrops containing either a mixture of blocks from multiple formations, or exotic igneous blocks, are mapped as mélange. Disruption of these units is qualitatively assessed at the outcrop scale using a disruption index. Three generations of folds are identified within coherent stratigraphy. Disrupted units are quantitatively assessed using scanlines to measure volumetric block proportions within highly disrupted areas. Thin sections from these oriented samples show both an early maturity kerogen within disrupted blocks and over-mature bitumen as a vein fill. Map patterns within the allochthon, along with these small-scale observations allow us to re-examine the structural history of emplacement of the Humber Arm Allochthon onto Port au Port Peninsula.

Chapter 3 of this thesis will be published in a structural geology journal under the authorship R. Lacombe, J.W.F. Waldron, and S.H. Williams. R. Lacombe was responsible for the data collection and analysis as well as the manuscript composition. J.W.F. Waldron assisted with data collection and contributed to manuscript edits. S.H. Williams contributed biostratigraphic expertise.

Detailed measured sections are included as Appendix A.

1.5. Conclusions

Despite the significance of the Humber Arm Allochthon on Port au Port Peninsula (Figure 1.3) to the understanding of both the structural setting and petroleum systems in western Newfoundland, this area has remained a gap in our understanding of Appalachian orogenesis. This mapping project on Port au Port Peninsula allows us to further constrain the timing and effects of various deformation events in western Newfoundland. Understanding the effects of deformation on the Humber Arm Allochthon, a potential source rock for hydrocarbons, is important for risk assessment of potential hydrocarbon plays in the area.

1.6. References

Botsford, J.W., 1987, Depositional history of Middle Cambrian to Lower Ordovician deep water sediments, Bay of Islands, western Newfoundland: Memorial University of Newfoundland, 543 p.

Cawood, P.A., McCausland, P.J.A., and Dunning, G.R., 2001, Opening Iapetus: Constraints from the Laurentian margin in Newfoundland: Geological Society of America Bulletin, v. 113, p. 443–453.

Cooper, M., Weissenberger, J., Knight, I., Hostad, D., Gillespie, D., Williams, H., Burden, E.T., Porter-Chaudhry, J., Rae, D., and Clark, E., 2001, Basin evolution in western Newfoundland : New insights from hydrocarbon exploration: American Association of Petroleum Geologists Bulletin, v. 85, p. 393–418.

Harland, W.B., and Gayer, R.A., 1972, The Arctic Caledonides and earlier oceans: Geological Magazine, v. 109, p. 289–314.

Hibbard, J., Van Staal, C.R., and Rankin, D.W., 2007, A comparative analysis of pre-Silurian crustal building blocks of the northern and the southern Appalachian orogen: American Journal of Science, v. 307, p. 23–45.

Hibbard, J., and Waldron, J.W.F., 2009, Truncation and translation of Appalachian promontories: Mid-Paleozoic strike-slip tectonics and basin initiation: Geology, v. 37, p. 487–490.

Jacobi, R.D., 1981, Peripheral bulge-a causal mechanism for the Lower/Middle Ordovician unconformity along the western margin of the Northern Appalachians: Earth and Planetary Science Letters, v. 56, p. 245–251.

Jenner, G. a., Dunning, G.R., Malpas, J., Brown, M., and Brace, T., 1991, Bay of Islands and Little Port complexes, revisited: age, geochemical and isotopic evidence confirm supra-subduction-zone origin: Canadian Journal of Earth Sciences, v. 28, p. 1635–1652.

Knight, I., James, N.P., and Lane, T.E., 1991, The St. George Unconformity, northern Appalachians: The relationship of plate convergence at the St. Lawrence Promontory to the Sauk/Tippecanoe: Geological Society of America Bulletin, v. 103, p. 1200–1225.

Palmer, S.E., Waldron, J.W.F., and Skilliter, D.M., 2002, Post-Taconian shortening, inversion and strike slip in the Stephenville area, western Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 39, p. 1393–1410.

Quinn, L., Harper, D.A.T., Williams, S.H., and Clarkson, E.N.K., 1999, Late Ordovician foreland basin fill: Long Point Group of onshore western Newfoundland: Bulletin of Canadian Petroleum Geology, v. 47, p. 63–80.

Searle, M.P., and Stevens, R.K., 1984, Obduction processes in ancient, modern and future ophiolites: Geological Society, London, Special Publications, v. 13, p. 303–319.

Stockmal, G.S., Slingsby, A., and Waldron, J.W.F., 2004, Basement-involved inversion at the Appalachian structural front , western Newfoundland : an interpretation of seismic reflection data with implications for petroleum prospectivity: Bulletin of Canadian Petroleum Geology, v. 52, p. 215–233.

Stockmal, G.S., and Waldron, J.W.F., 1990, Structure of the Appalachian deformation front in western Newfoundland: Implications of multichannel seismic reflection data: Geology, v. 18, p. 765–768.

Stockmal, G.S., and Waldron, J.W.F., 1993, Structural and tectonic evolution of the Humber Zone, western Newfoundland, 1. Implications of balanced cross sections through the Appalachian structural front, Port au Port Peninsula: Tectonics, v. 12, p. 1056–1075.

Waldron, J.W.F., Anderson, S.D., Cawood, P.A., Goodwin, L.B., Hall, J., Jamieson, R. a, Palmer, S.E., Stockmal, G.S., and Williams, P.F., 1998, Evolution of the Appalachian Laurentian margin: Lithoprobe results in western Newfoundland: Canadian Journal of Earth Sciences,

v. 35, p. 1271–1287.

Waldron, J.W.F., Barr, S.M., Park, A.F., White, C.E., and Hibbard, J., 2015, Late Paleozoic strike-slip faults in Maratime Canada and their role in the reconfiguration of the northern Appalachian orogen: Tectonics, v. 34, p. 24.

Waldron, J.W.F., Henry, A.D., Bradley, J.C., and Palmer, S.E., 2003, Development of a folded thrust stack: Humber Arm Allochthon, Bay of Islands, Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 40, p. 237–253.

Waldron, J.W.F., Schofield, D.I., and Murphy, J.B., 2017, Diachronous Paleozoic accretion of Peri-Gondwanan terranes at the Laurentian margin: Geological Society of London Special Publication, v. submitted, p. 42.

Waldron, J.W.F., and van Staal, C.R., 2001, Taconian orogeny and the accretion of the Dashwoods block : A peri-Laurentian microcontinent in the Iapetus Ocean: Geology, v. 29, p. 811–814.

Waldron, J.W.F., and Stockmal, G.S., 1991, Mid-Paleozoic thrusting at the Appalachian deformation front: Port au Port Peninsula, western Newfoundland: Canadian Journal of Earth Sciences, v. 28, p. 1992–2002.

Waldron, J.W.F., Stockmal, G.S., Corney, E., and Stenzel, S.R., 1993, Basin development and inversion at the Appalachian structural front, Port au Port Peninsula, western Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 30, p. 1759–1772.

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

Wilson, J.T., 1966, Did the Atlantic close and then re-open? Nature,.

Chapter 2: Stratigraphic relationships at the Leading Edge of the Humber Arm Allochthon, western Newfoundland: implications for Taconian tectonics

Port au Port Peninsula, in western Newfoundland, is situated near the deformation front of the Appalachian orogen. Here, a cross-sectional view through rocks of the Laurentian passive margin, overlying foreland basin, and allochthonous rocks of the Humber Arm Allochthon is observed. Loading of the Laurentian margin during Taconian (Ordovician) orogenesis and resulting tectonic subsidence accommodated deposition of Middle Ordovician foreland basin units including the Table Head Group and overlying Goose Tickle Group. A large area of foreland basin strata is present in areas formerly mapped as Humber Arm Allochthon ; abrupt thickness changes within these units and an abundance of fault-derived limestone conglomerate indicate that deposition was strongly influenced by block faulting and differential subsidence in a basin undergoing active extension.
A coarsening upward trend within the Goose Tickle Group represents a transition from a distal to a proximal sediment source as the Humber Arm Allochthon was emplaced westwards. Three distinctive carbonate conglomerate facies and one shale-chip conglomerate facies are assigned to the Goose Tickle Group. Goose Tickle Group rocks, including carbonate conglomerate, are found separating two packages of allochthonous rocks. The lower allochthonous package, here named the West Bay Thrust Sheet, sits unconformably below these Goose Tickle Group rocks; its timing of emplacement is constrained by Darriwilian 3 graptolites which both underlie and overlie the West Bay Thrust Sheet. The structurally higher allochthonous package, here named the Lourdes Thrust Sheet, is an out-of-sequence thrust associated with Acadian (Devonian) orogenesis. Seven high-angle faults show a protracted history of movement that includes early Taconian (Ordovician) extension, Acadian (Devonian) inversion and later, Carboniferous, strike-slip motion; these faults crosscut and rework the Humber Arm Allochthon on Port au Port Peninsula.

2.1. Introduction

In the Humber Zone of the western Newfoundland Appalachians (Figure 2.1), early Paleozoic, allochthonous, deep-water rocks of the Taconian Humber Arm Allochthon sit structurally above autochthonous rocks of the Laurentian passive continental margin and foreland basin. Port au Port Peninsula (Figure 2.1) is unique in western Newfoundland as it exposes the Appalachian structural front, elsewhere identified offshore in seismic sections by Stockmal & Waldron (1990) and others (Cooper et al. 2001; S. White, University of Alberta, *personal communication*). Because of their proximity to the structural front, rocks on Port au Port Peninsula display little metamorphic or structural overprinting as a result of later orogenic events that affected internal parts of the orogen. Port au Port Peninsula is also unique in that a late phase of deformation has tilted all of the strata to the north, giving a cross-sectional view, at surface, through the platform, foreland basin, and overlying allochthon. The combination of these factors has led to the exposure of an extensive rock record from Cambrian to Carboniferous. Because of this, Port au Port Peninsula provides a unique opportunity to study early structures related to emplacement of the Humber Arm Allochthon and the progressive development of the associated foreland basin.

As a result of both sparse outcrop and pervasive deformation, the Humber Arm Allochthon on Port au Port Peninsula has been previously mapped as a mélange (Williams, 1985; Williams and Cawood, 1989) and detailed subdivision has not been attempted. This paper aims to better resolve this area of mélange by constraining the extent of the Humber Arm Allochthon and separating out the relatively undisrupted but synchronous foreland basin units. An updated stratigraphic framework for foreland basin strata is provided and their structural relationship with allochthonous rocks is examined on Port au Port Peninsula. Taconian (Ordovician) and Acadian (Devonian) orogenic events have each resulted in movement along high-angle (platform cutting) and low-angle (emplacement-related) faults. Previously there has been very little information on the extent of the earlier Taconian emplacement of the allochthon and it was assumed that Acadian orogenesis renewed movement along the same basal thrust. By subdividing this area of mélange on Port au Port Peninsula, and examining the basal contact of the allochthon we are able to separate the effects of the Taconic and Acadian orogenies in western Newfoundland.

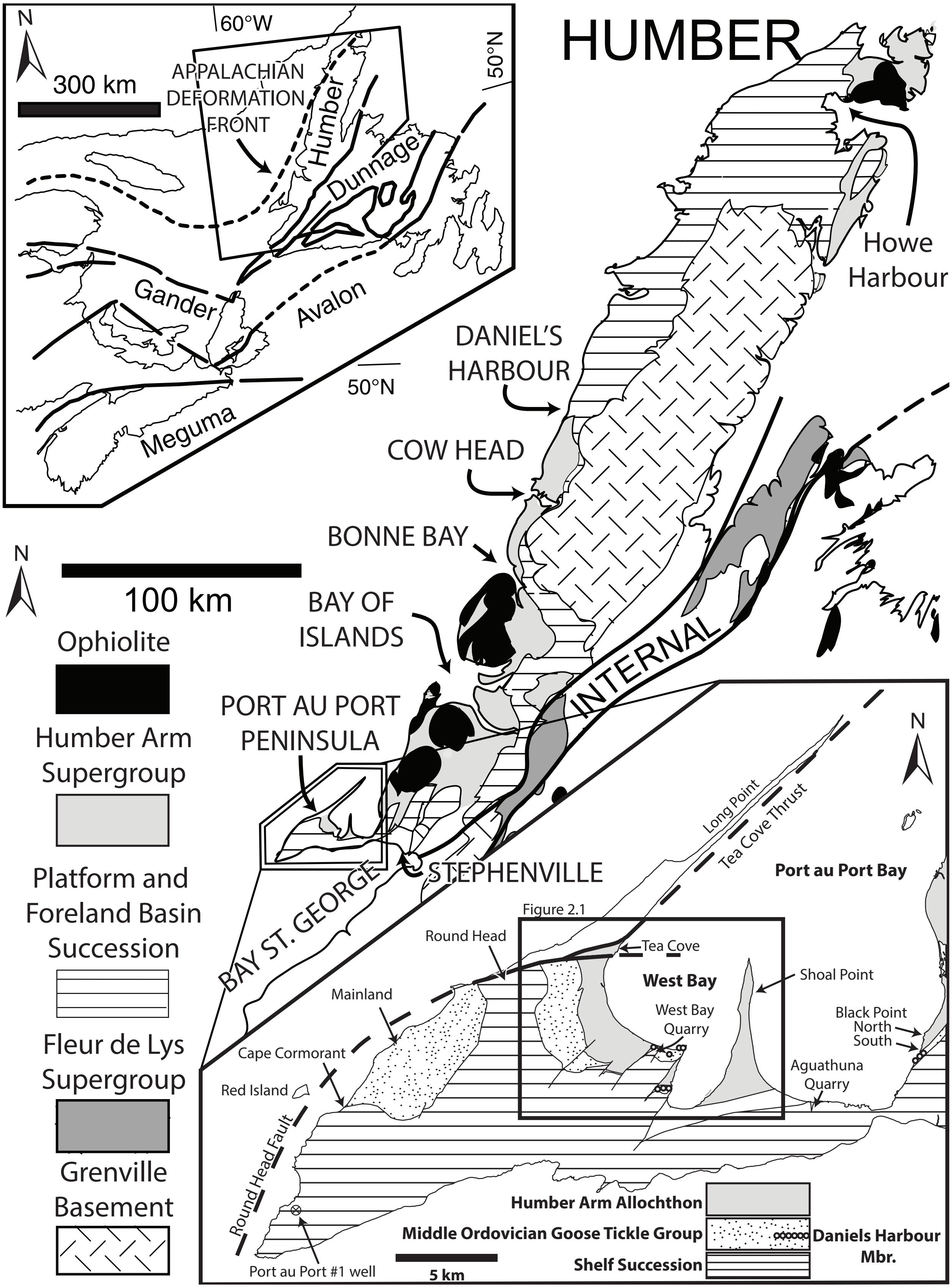
Detailed mapping of Middle Ordovician foreland basin rocks and overlying allochthonous strata has allowed the Taconian and Acadian tectonic events to be separated into discrete phases. The Middle Ordovician Taconian orogenic event includes platform extension, deposition of foreland basin sediments and initial allochthon emplacement (Jacobi, 1981; Stenzel et al., 1990; Bradley and Kidd, 1991; Waldron et al., 1993). In contrast, the Acadian orogenic event was demarcated by further emplacement of the allochthon to its current position offshore, and basin inversion (Waldron and Stockmal, 1991; Waldron et al., 1993). We aim to better constrain timing relationships between movement along high-angle faults and movement along low-angle emplacement related faults using stratigraphic arguments in the Middle Ordovician foreland basin.. These constraints have broad-reaching implications for the timing of allochthon emplacement across western Newfoundland. Stratigraphic arguments made in this paper may be applicable to any study of a developing foreland basin, especially where it is difficult to resolve structural relationships due to later overprinting.

2.2. Geological Setting

The Humber Zone of western Newfoundland (Williams 1978; Figure 2.1) represents the early Paleozoic margin of Laurentia, and records the opening and eventual closure of the Iapetus Ocean. Beginning with rifting of Mesoproterozoic basement rocks in the Neoproterozoic, syn- and post-rift sedimentation led to the formation of the Labrador Group (Williams and Hiscott, 1987), and its offshore equivalent, the Curling Group (Stevens 1970; Waldron & Palmer 2000; Figure 2.2). Rifting was followed by the development of a long-lived Laurentian carbonate passive margin which is represented by the Port au Port and St. George groups (Chow, 1985; Chow and James, 1987; Knight and James, 1987). Offshore and downslope, erosion and re-sedimentation of the carbonate shelf were responsible for deposition of synchronous, deeper water, slope

Figure 2.1: Map of the Humber Zone in Newfoundland highlighting the study area.

(Top left) Lithotectonic subdivision map of the northern Appalachians. (Central) the Humber Zone of western Newfoundland including key localities mentioned in the text. (Bottom right) map of Port au Port Peninsula with key localities and regionally important faults marked. Box indicates the main study area shown in more detail in Figure 2.4. Modified from (Waldron et al., 2003).



N
60°W
300 km
APPALACHIAN
DEFORMATION
FRONT
Humber
Dunnage
50°N
Gander
Avalon
50°N
Meguma
HUMBER
Howe
Harbour
DANIEL'S
HARBOUR
COW HEAD
BONNE BAY
N
100 km
BAY OF
ISLANDS
INTERNAL
Ophiolite
Humber Arm
Supergroup
PORT AU PORT
PENINSULA
STEPHENVILLE
BAY ST. GEORGE
Platform and
Foreland Basin
Succession
Fleur de Lys
Supergroup
Grenville
Basement
N
Long Point
Tea Cove Thrust
Port au Port Bay
Figure 2.1
Round Head
Tea Cove
West Bay
Shoal Point
Mainland
West Bay
Quarry
Black Point
North
South
Cape Cormorant
Aguathuna
Quarry
Red Island
Round Head Fault
Humber Arm Allochthon
Middle Ordovician Goose Tickle Group
Daniels Harbour
Mbr.
Shelf Succession
5 km
Port au Port #1 well

and rise facies now entrained within the Humber Arm Allochthon. Passive-margin development was brought to an end by Taconian orogenesis in the Middle Ordovician when eastward subduction culminated in an arc-continent collision (Van Staal et al., 1998; Waldron and van Staal, 2001). Coupled with ophiolite obduction (Dewey and Casey, 2013), this collision ultimately led to the emplacement of deformed deep-water rocks on top of their shallow-water equivalents (Labrador, Port au Port and St. George groups) (Figure 2.2).

Loading of the Laurentian margin during the Early to Middle Ordovician resulted in flexure and westward migration of a peripheral bulge across the platform culminating in extension, uplift, and erosion (Jacobi, 1981; Knight et al., 1991). This period of uplift and erosion was followed by the activation of Taconian, extensional, normal faults such as the Round Head Fault (Stenzel, 1991; Waldron et al., 1993). Flexure and extension resulted in increasing accommodation and syntectonic deposition of the carbonate-dominated Table Head Group (Figure 2.2). Accommodation space created by loading was filled with incoming clastic detritus shed from the advancing allochthon to form the Goose Tickle Group (Figure 2.2) (Stenzel, 1991; Quinn, 1995). The Humber Arm Allochthon was emplaced westward such that it overlies these clastic foreland-basin rocks (Quinn, 1992a, 1995).

Upper Ordovician to Lower Devonian foreland basin fill is represented on Port au Port Peninsula by the Long Point Group and overlying Clam Bank and Red Island Road formations (Figure 2.2). The succession from Long Point Group to Red Island Road Formation is interpreted to dip northwest from Port au Port Peninsula into an offshore monoclinal structure (Stockmal and Waldron, 1990). The succession sits above an east-vergent detachment surface which overlies the Humber Arm Allochthon. This detachment surface, known as the Tea Cove Thrust, was examined by and places rocks of the Long Point Group (Figure 2.2) above rocks of the Humber Arm Allochthon Waldron & Stockmal (1991). Backthrusting of the foreland basin succession onto the westward migrating frontal wedge of the allochthon reworked and buried the Taconian structural front (Stockmal and Waldron, 1990; Waldron et al., 1998). The youngest strata (the Red

Island Road Formation) (Figure 2.2) folded in the hanging wall of the Tea Cove Thrust constrain the age of latest emplacement of this tectonic wedge to Emsian or younger, associated with the Acadian (Devonian) orogenic event (Stockmal and Waldron, 1990; Waldron and Stockmal, 1991; Stockmal et al., 2004).

2.3. Stratigraphic relationships on Port au Port Peninsula

Port au Port Peninsula contains an autochthonous section of rocks that record the history of the Laurentian margin from the early Cambrian Labrador Group to the Early Devonian Red Island Road Fm. In addition, a diverse assemblage of mainly Ordovician, allochthonous units are represented (Figure 2.2). Of the autochthonous units, only the Table Head and Goose Tickle groups were examined in this study as they are related temporally and structurally to the Middle Ordovician emplacement of the Humber Arm Allochthon. Facies relationships within the Middle Ordovician units are summarized in Figure 2.3.

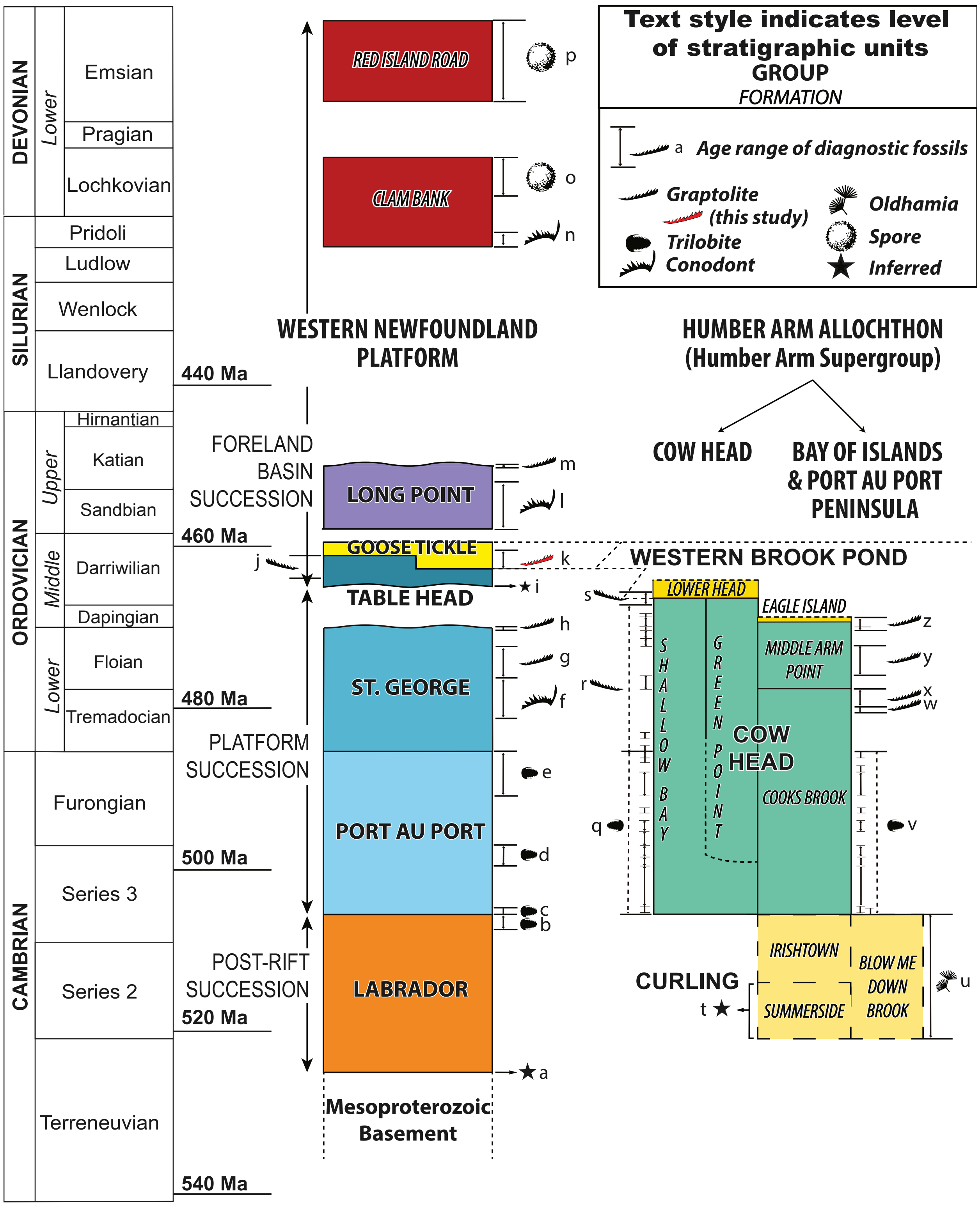
2.3.1. Autochthonous carbonate units: Table Head Group

2.3.1.1. Table Point Formation

The Middle Ordovician Table Point Formation makes up the lower part of the Table Head Group (Figure 2.2); this unit is dominated by massive burrow-mottled limestone to dolomitic limestone but grades to thinly bedded limestone and shale near the top. Our field observations are consistent with those of Klappa et al. (1980) who describe the Table Point Formation as a heavily bioturbated unit that in less bioturbated facies, contains an abundance of fossils and skeletal fragments. This unit marks the transition from a passive carbonate margin to earliest foreland basin and is associated with the onset of Taconic flexure (Stenzel, 1991). The Table Point Formation unconformably overlies the St. George Group at the St. George unconformity, a boundary interpreted to record the passage of the Taconian flexural bulge (Jacobi, 1981; Knight et al., 1991); this contact is visible at Aguathuna Quarry and other localities on Port au Port Peninsula (Figure

Figure 2.2: Stratigraphy of western Newfoundland.

Compilation of biostratigraphic ages: (a) base estimated at 525-520 Ma (Cawood et al., 2001); (b) trilobites: *Glossopleura* Zone and *Albertella* Zone (Knight and Boyce, 1991); (c) trilobites: *Olenoides longispinus*, *Ehmaniella cloudensis* (Knight and Boyce, 1987); (d) trilobites: *Cedaria Zone*, *Crepicephalus* Zone (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 zone (Maletz et al., 2011); (j) graptolites: *Holmograptus lentus* zone, *Nicholsonograptus fasciculatus*, *Pterograptus elegans* zone; (k) graptolites: *Nicholsonograptus fasciculatus*, ?*Pterograptus elegans* (this study) (l) conodonts: *Amorphognathus tvaerensis* (Bergstrom et al., 1974; Batten Hender and Dix, 2008); (m) graptolite: *Geniculograptus pygmaeus* (Quinn et al., 1999) (n) *Ozarkodina eosteinhornensis* zone (Burden et al., 2002); (o) *Emphanisporites micromatus – Streelispora newportensis* assemblage zone (Burden et al., 2002); (p) spores: *Emphanisporites annulatus – Camarozonotiletes sextantii* zone (Quinn et al., 2004) correlated with (Streel et al., 1987); (q) trilobites: *Bathyuriscus-Elrathina* Zone, *Ptychgnostus gibbus*, *Bolaspidella*, *Cedaria*, *Crepicephalus*, *Aphelaspis*, *Dunderbergia*, *Taenicephalus*, *Rasettia magna*, *Missisquoia*, *Symphysurina brevispicata* (James and Stevens, 1986); the basal *Bathyuriscus-Elrathina* Zone is correlated to the boundary between *Glossopleura* and *Ehmaniella* Zone (Peng et al., 2012); (r) graptolites: *Staurograptus dichotomus*, *Anisograptus matanensis*, *Tetragraptus approximatus*, *Didymograptus protobifidus*, *Isograptus primulus*, *Isograptus victoriae lunatus*, *I. v. victoriae*, *I. v. maximus* and others (James and Stevens, 1986); (s) graptolites: base of the Lower Head varies with locality from *I. v. maximus* to *U. austrodentatus* biozone (James and Stevens, 1986; Botsford, 1987); (t) top and bottom estimated by Cawood & Nemchin (2001); (u) *Oldhamia* - (Lindholm and Casey, 1989; Cawood and Nemchin, 2001; Burden et al., 2001) correlated with White et al. (2012); (v) Trilobites: *Ehmaniella* Zone and *Ptychagnostus gibbus* Zone, *Bolaspidella* Zone, *Cedaria*, *Crepicephalus*, *Dunderbergia*, *Taenicephalus*, *Rasettia magna*, *Saukiella junia*, *Saukiella serotina*, *Symphysurina brevispicita* (Boyce et al., 1992) (w) graptolite: *Aorograptus victoriae* (Chapter 3); (x) graptolite: *Araneograptus murrayi* (Botsford, 1987); (y) *Pendeograptus fruticosis* Zone (Chapter 3); (z) graptolite: *I. v. lunatus*, *I. v. victoriae* (Botsford, 1987).



DEVONIAN
Lower
Emsian
Pragian
Lochkovian
SILURIAN
Pridoli
Ludlow
Wenlock
Llandovery
ORDOVICIAN
Upper
Hirnantian
Katian
Sandbian
Middle
Darriwilian
Dapingian
Lower
Floian
Tremadocian
CAMBRIAN
Furongian
Series 3
Series 2
Terreneuvian
440 Ma
460 Ma
480 Ma
500 Ma
520 Ma
540 Ma
RED ISLAND ROAD
CLAM BANK
WESTERN NEWFOUNDLAND PLATFORM
FORELAND BASIN SUCCESSION
LONG POINT
GOOSE TICKLE
TABLE HEAD
ST. GEORGE
PLATFORM SUCCESSION
PORT AU PORT
POST-RIFT SUCCESSION
LABRADOR
Mesoproterozoic Basement
Text style indicates level of stratigraphic units
GROUP
FORMATION
a Age range of diagnostic fossils
Graptolite
(this study)
Trilobite
Conodont
Oldhamia
Spore
Inferred
HUMBER ARM ALLOCHTHON
(Humber Arm Supergroup)
COW HEAD
BAY OF ISLANDS & PORT AU PORT PENINSULA
WESTERN BROOK POND
LOWER HEAD
EAGLE ISLAND
SHALLOW BAY
GREEN POINT
MIDDLE ARM POINT
COW HEAD
COOKS BROOK
CURLING
IRISHTOWN
SUMMERSIDE
BLOW ME DOWN BROOK

Figure 2.3: 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.

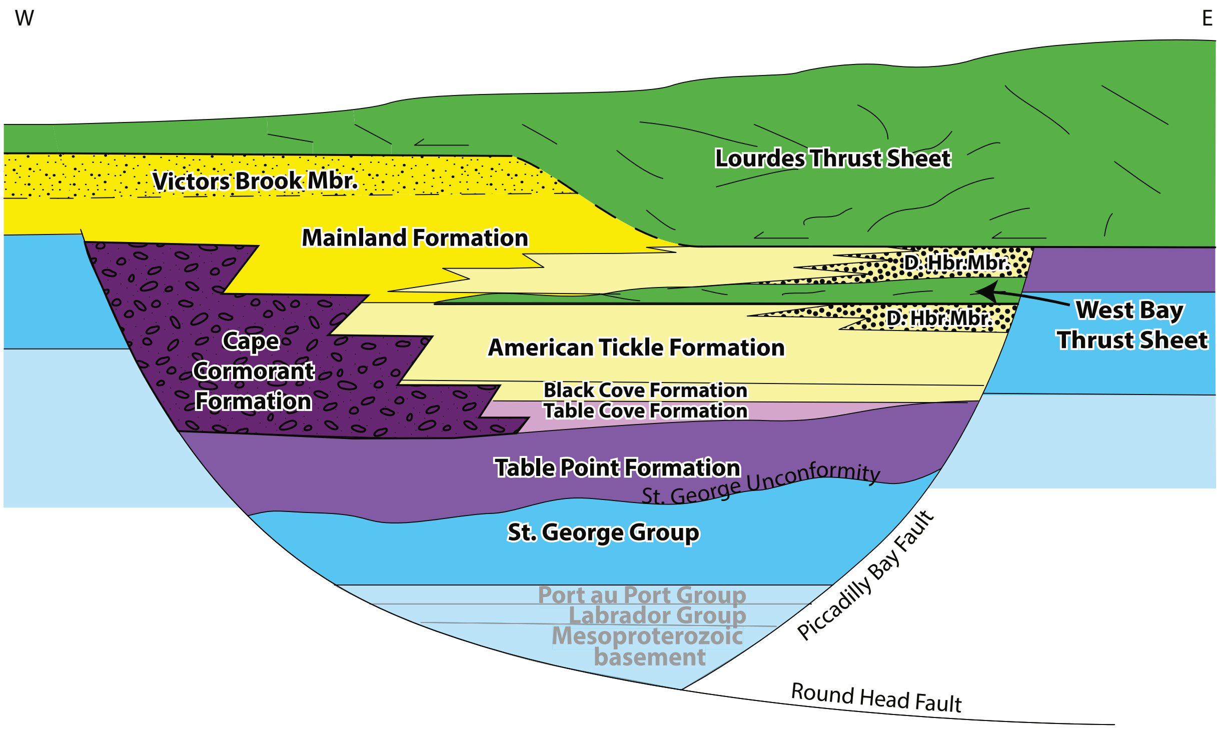
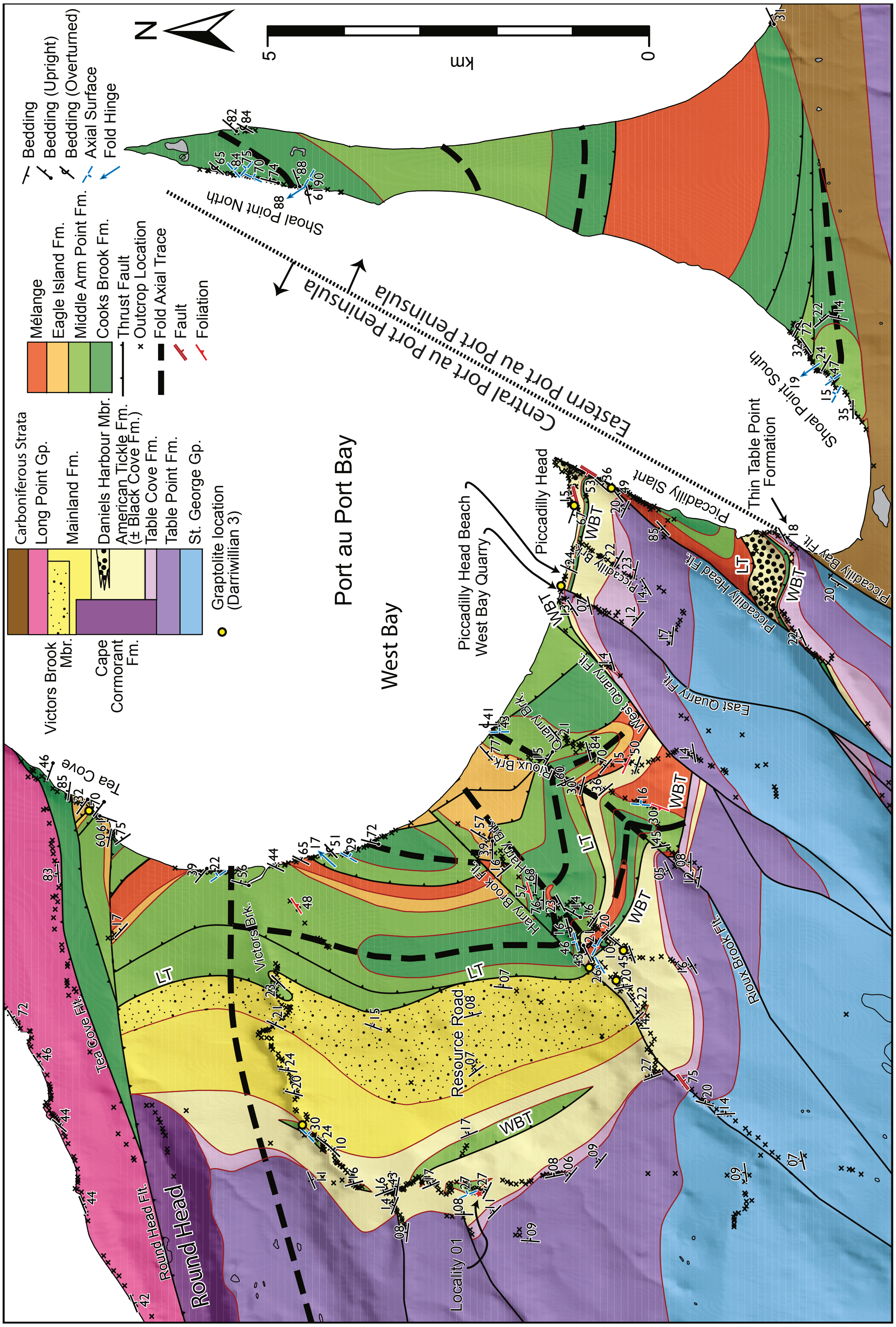


Figure 2.4: Geologic map of a portion of Port au Port Peninsula.

(next page) Abbreviations: WBT=West Bay Thrust, LT= Lourdes Thrust, Brk - Brook, Flt. – Fault, Mbr. – Member, Fm. – Formation, Gp. - Group



Carboniferous Strata
Long Point Gp.
Mainland Fm.
Victors Brook Mbr.
Daniels Harbour Mbr.
American Tickle Fm. (± Black Cove Fm.)
Cape Cormorant Fm.
Table Cove Fm.
Table Point Fm.
St. George Gp.
Graptolite location (Darriwillian 3)
Mélange
Eagle Island Fm.
Middle Arm Point Fm.
Cooks Brook Fm.
Thrust Fault
Outcrop Location
Fold Axial Trace
Fault
Foliation
Bedding
Bedding (Upright)
Bedding (Overturned)
Axial Surface
Fold Hinge
N
5
0
km
Port au Port Bay
West Bay
Central Port au Port Peninsula
Eastern Port au Port Peninsula
Shoal Point North
Shoal Point South
Thin Table Point Formation
Piccadilly Slant
Piccadilly Head
Piccadilly Head Beach
West Bay Quarry
Piccadilly Head Flt.
Piccadilly Bay Flt.
East Quarry Flt.
West Quarry Flt.
Rioux Brook Flt.
Rioux Brk.
Harry Brook Flt.
Victors Brk.
Resource Road
Locality 01
Round Head
Round Head Flt.
Tea Cove
Tea Cove Flt.
LT
WBT

2.1). Stenzel (1991) suggests between 20 and 50 m of erosion at this boundary. Above this contact, the Table Point Formation varies in thickness between 50 m and 250 m in (calculated) stratigraphic thickness.

The Table Point Formation is continuous across Port au Port Peninsula but varies in thickness; this unit is noticeably thinner south of Piccadilly Slant (locality shown in Figure 2.4). In eastern Port au Port Peninsula, the Table Point Formation is unconformably overlain by rocks assigned to the Carboniferous Codroy Group (Figure 2.4).

2.3.1.2. Table Cove Formation

Stratigraphically overlying the Table Point Formation is the Table Cove Formation (Klappa et al., 1980; Stenzel et al., 1990)(Figure 2.3); the contact between the two units can be observed in West Bay Quarry (Figure 2.1). On Port au Port Peninsula it is composed of dominantly grey, laminated, concretionary limestone and impure limestone, commonly appearing slabby in outcrop, interbedded with grey calcareous shale. The shale is characteristically graptolite rich. Klappa et al. (1980) describe the Table Cove Formation as including bioturbated crinoidal limestone at the base. However, this is difficult to distinguish in poor outcrop from the underlying Table Point Formation. For practical mapping purposes we map the base of the formation up to ~2 m higher, at the base of the first planar laminated limestone bed sitting above bioturbated limestones; the difference in position is not significant at map scale.

The Table Cove Formation is discontinuous and varies in thickness across Port au Port Peninsula (Figure 2.4). Most notably, on the western side of the East Quarry Fault (Figure 2.4), near the West Bay Quarry, the Table Cove Formation is ~50 m thick while east of this fault it is just over 100 m thick. Further east towards Piccadilly Head Fault, the thickness is reduced to nearly 10 m. The Table Cove Formation is not observed in eastern Port au Port Peninsula or along portions of Victors Brook where the rocks of the American Tickle Formation overlie the Table Point Formation directly; northwest of Victors Brook, the Table Cove Formation likely interfingers with the Cape Cormorant Formation at Round Head (Figure 2.4).

2.3.1.3. Cape Cormorant Formation

Laterally equivalent to the Table Cove Formation is the Cape Cormorant Formation (Figure 2.3), a unit found only in western Port au Port Peninsula (Stenzel, 1991; Stenzel et al., 1990). This unit dominantly comprises poorly-sorted, clast-supported, polymict carbonate conglomerate which is interbedded with calcarenite and shale; basal portions of the Cape Cormorant Formation contain bedded packstone and wackestone lithologically similar to upper portions of the Table Cove Formation (Stenzel et al., 1990). Clasts within the Cape Cormorant Formation are lithologically identical to underlying platform carbonate units and yield ages of middle Cambrian through Middle Ordovician (Stenzel et al., 1990) indicating derivation from the Port au Port and St. George groups (Figure 2.2). The Cape Cormorant Formation stratigraphically overlies the Table Point Formation. Within the map area, the Cape Cormorant Formation is found only at Round Head where it forms a prominent ridge of limestone conglomerate (Figure 2.4). The Cape Cormorant Formation thins towards the east and fines upwards (Stockmal and Waldron, 1993). Southeast of Round Head, the Cape Cormorant Formation likely interdigitates with both the Table Cove and American Tickle formations (Figure 2.4; Figure 2.3); thus, the Cape Cormorant Formation is highly discontinuous on Port au Port Peninsula.

2.3.1.4. Table Head Group: Interpretation

The massive to burrow-mottled nature of the Table Point Formation indicates deposition in a shallow marine environment. The presence of an unconformable basal surface and the variable thickness of this unit are indicative of deposition within a foreland basin subsiding at variable rates under the influence of extensional block faults; the shallow-marine facies of this unit indicates that carbonate production kept pace with subsidence. Block faulting was a result of Taconian flexural extension which occurred after the peripheral bulge migrated through the area (Jacobi, 1981; Knight et al., 1991; Stenzel, 1991; Bradley and Kidd, 1991).

The Table Cove Formation represents an environment in which carbonate deposition could no longer keep pace with subsidence. Laminated limestone beds likely represent turbidites of platform material shed from horsts developed in the foreland basin at this time. The Table Cove Formation is laterally discontinuous in places and shows large thickness variations (< 5 m to > 100 m) across Port au Port Peninsula. These lateral changes in thickness and the discontinuous nature of the Table Cove Formation suggest that some areas on Port au Port Peninsula were subsiding more rapidly than others under the continuing influence of Taconian normal faults (Stenzel, 1991).

The Cape Cormorant Formation is spatially associated with the Round Head Fault on Port au Port Peninsula (Figure 2.1). It is interpreted to have formed by localized erosion of a submarine scarp which formed through extension along the Round Head Fault (Stockmal and Waldron, 1993). The range in ages for carbonate clasts within this formation suggest that there was upwards of 1 km of normal-sense throw on this fault during the Middle Ordovician (Stenzel et al., 1990). Subsequent inversion resulted in the present-day, reverse fault geometry (Stockmal and Waldron, 1990, 1993).

2.3.2. Autochthonous foreland basin units: Goose Tickle Group

2.3.2.1. Goose Tickle Group: Black Cove Formation

The Goose Tickle Group is composed of the Black Cove, American Tickle, and Mainland formations; this unit sits stratigraphically above the Table Head Group (Figure 2.2; 2.3). The Black Cove Formation was first described by Klappa et al. (1980) as part of the Table Head Group and was subsequently assigned to the Goose Tickle Group by Stenzel et al. (1990). It sits stratigraphically above the highest limestone bed of the Table Cove Formation, and locally above the Table Point Formation (Stenzel et al., 1990). The Black Cove Formation is composed of laminated, non-calcareous, dark grey shale and minor green silt. The Black Cove Formation is most readily observed along Piccadilly Brook and at West Bay Quarry (Figure 2.4; 2.1) and is between 0 m and 22 m thick. Sparse observation of the Black Cove Formation in inland outcrops suggests either that this unit is discontinuous or that because of its fine-grained recessive nature, it is typically unexposed. Stenzel et al. (1990) describe the upper transitional contact between the Black Cove Formation and overlying American Tickle Formation, and define the boundary at a point above which more than 30% of the rock comprises green siltstone laminae.

Distribution: Because it is thin and poorly exposed, we include the Black Cove Formation with the overlying American Tickle Formation in one map unit (Figure 2.4; 2.3). The Black Cove Formation is not seen in western Port au Port Peninsula, near the town of Mainland (Figure 2.1), where the Mainland Formation overlies the Table Head Group directly.

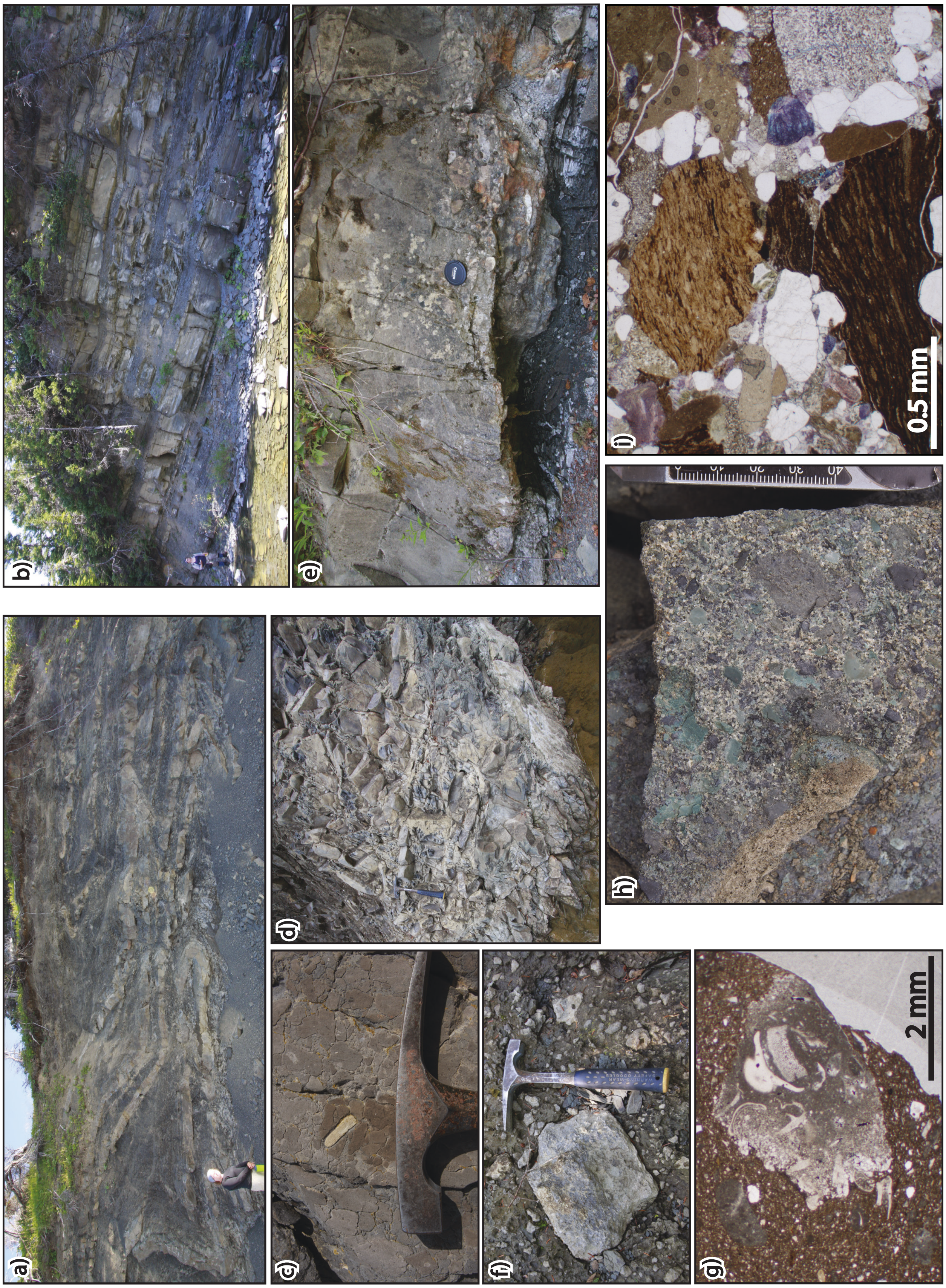
Biostratigraphy: Maletz & Egenhoff (2011) recovered *Nicholsonograptus fasciculatus*, *Achiclimacograptus sp.,* and *Xiphograptus robustus* graptolites from the Black Cove Formation south of Black Point and at West Bay Quarry (Figure 2.1). The *Nicholsonograptus fasciculatus* Biozone roughly correlates with the Darriwilian 3 graptolite zone (Maletz & Egenhoff 2011; Loydell 2012; Cooper et al. 2012).

2.3.2.2. Goose Tickle Group: American Tickle Formation

The American Tickle Formation on Port au Port Peninsula is characterized by green, grey, and black siltstone and shale with lesser amounts of interbedded fine- to medium-grained sandstone; sandstone generally makes up less than 30% of typical outcrops (Figure 2.5a), consistent with observations by Quinn (1995) in sections of American Tickle Formation north of Port au Port Peninsula. Intervals of platform-derived limestone conglomerate are also common. Sandstone beds commonly show grading, parallel lamination and scoured erosional basal surfaces characterized by flute and load casts. An outcrop-scale angular discordance is present in Victors Brook where it separates two sandstone and shale units of the American Tickle Formation (Figure 2.4; near locality 01). Cross-lamination and convolute lamination are less common. The American Tickle Formation and underlying Black Cove Formation overlie carbonates of the Table Head

Figure 2.5: 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 grading 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 2.4.


a)
b)
c)
d)
e)
f)
g)
h)
i)
2 mm
0.5 mm

Group at Victors Brook and to the east across Port au Port Peninsula; these units are not seen southwest of the map area, where the Mainland Formation occurs in an equivalent position above the Table Head Group (Figure 2.4).

The American Tickle Formation on Port au Port Peninsula contains an abundance of platform-derived limestone conglomerate. Three facies are observed (Figure 2.5):

1. Clast-supported carbonate conglomerate composed primarily of pebble to cobble-sized lithoclasts in massive beds. Clasts are dominantly grey-weathering lime mudstone to wackestone, but less common lime mudstone, yellow-weathering laminated dolostone, skeletal grainstone and laminated slabby limestone clasts were also observed (Figure 2.5c). Clasts are generally angular with stylolitic boundaries indicating that significant pressure solution occurred during diagenesis to obscure original grain shapes. This unit is only exposed in areas east of the West Quarry Fault (Figure 2.4); it is best exposed at the point of Piccadilly Head, and in road cuts along Piccadilly Slant (Figure 2.4). This clast-dominated limestone conglomerate is assigned to the Daniel's Harbour Member by Stenzel et al. (1990) (Figure 2.3). Our observations are consistent with those of Stenzel et al. (1990) who noted fossiliferous and peloidal wackestone and packstone clasts in the type section at Daniels Harbour (Figure 2.1).

2. Matrix-supported conglomerate with a matrix of green and black mudstone and silt supporting dominantly grey to pink-weathering, nodular limestone clasts. Clasts average pebble-size but range up to boulders (Figure 2.5f; 2.5g). Laminated and concretionary limestone clasts are less common. This facies is common inland along Victors Brook and Harry Brook; smaller sections were also observed in Rioux Brook and Quarry Brook (Figure 2.4). This unit is the same as the "Type 1 conglomerate" of Waldron et al. (1993) and "the second type of Daniel's Harbour conglomerate" of Stenzel et al. (1990). This unit is here referred to as the Harry Brook facies of the American Tickle Formation.

3. Matrix-supported, or occasionally clast-supported, limestone conglomerate with a matrix composed of medium to coarse-grained sandstone and grey siltstone. Clasts are cobble-sized slabby limestone, or pebble-sized, nodular, burrow mottled limestone oriented randomly within the sandstone matrix (Figure 2.5d). This unit is best exposed in cliff sections stratigraphically above the Table Point Formation along Harry Brook (Figure 2.4).

Rafts composed of Table Head Group lithologies are also present within the American Tickle Formation; one such raft, composed of Table Cove Formation concretionary limestone and shale, is exposed in Victors Brook surrounded by facies of the American Tickle Formation (Figure 2.4 Locality 01). This raft, ~50 cm thick and ~2 m wide, overlies matrix-supported limestone conglomerate of the Harry Brook facies, and is overlain by sandstone and shale.

Distribution: In central Port au Port Peninsula, two packages of American Tickle Formation are separated by rocks mapped as the Humber Arm Allochthon (Figure 2.4). The lower package of American Tickle Formation, which includes Black Cove Formation at its base, stratigraphically overlies the Table Head Group (Figure 2.2; 2.4). This package of American Tickle Formation likely interdigitates with the Cape Cormorant Formation and Mainland Formation in Victors Brook, and to the NW at Round Head. This explains the lack of American Tickle Formation strata in western Port au Port Peninsula (Figure 2.4; 2.3). This package is continuous from Victors Brook to Piccadilly Slant (Figure 2.4).

A second package of rocks, assigned to the American Tickle Formation, is found overlying a portion of the Humber Arm Allochthon everywhere in central Port au Port Peninsula except for a small area north of West Bay Quarry (Figure 2.4); this package of rock thickens from Harry Brook eastward towards Rioux Brook (Figure 2.4). The lower contact of this Goose Tickle Group package, where it overlies the Humber Arm Allochthon, is only observed in Victors Brook (Figure 2.4). Here, Waldron et al. (1993) interpreted discontinuous outcrops of the lower allochthon as rafts within the Goose Tickle Group. We suggest that these discontinuous outcrops of allochthonous material join with a thicker package sitting below the Goose Tickle Group to the east in Harry Brook, Rioux Brook and Quarry Brook and that this contact is unconformable. Limestone conglomerate units, including portions of the Daniels Harbour Member and Harry Brook facies are discontinuous and 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 (Figure 2.4) and are here considered to be part of this upper package of American Tickle Formation. These packages of Daniels Harbour conglomerate are thickest in the hanging walls of the Piccadilly Head and Piccadilly Bay faults (Figure 2.4). The American Tickle Formation is not exposed in eastern Port au Port Peninsula but can be found east of the map area, at Black Point, underlying rocks of the Humber Arm Allochthon (Figure 2.1; Figure 2.4).

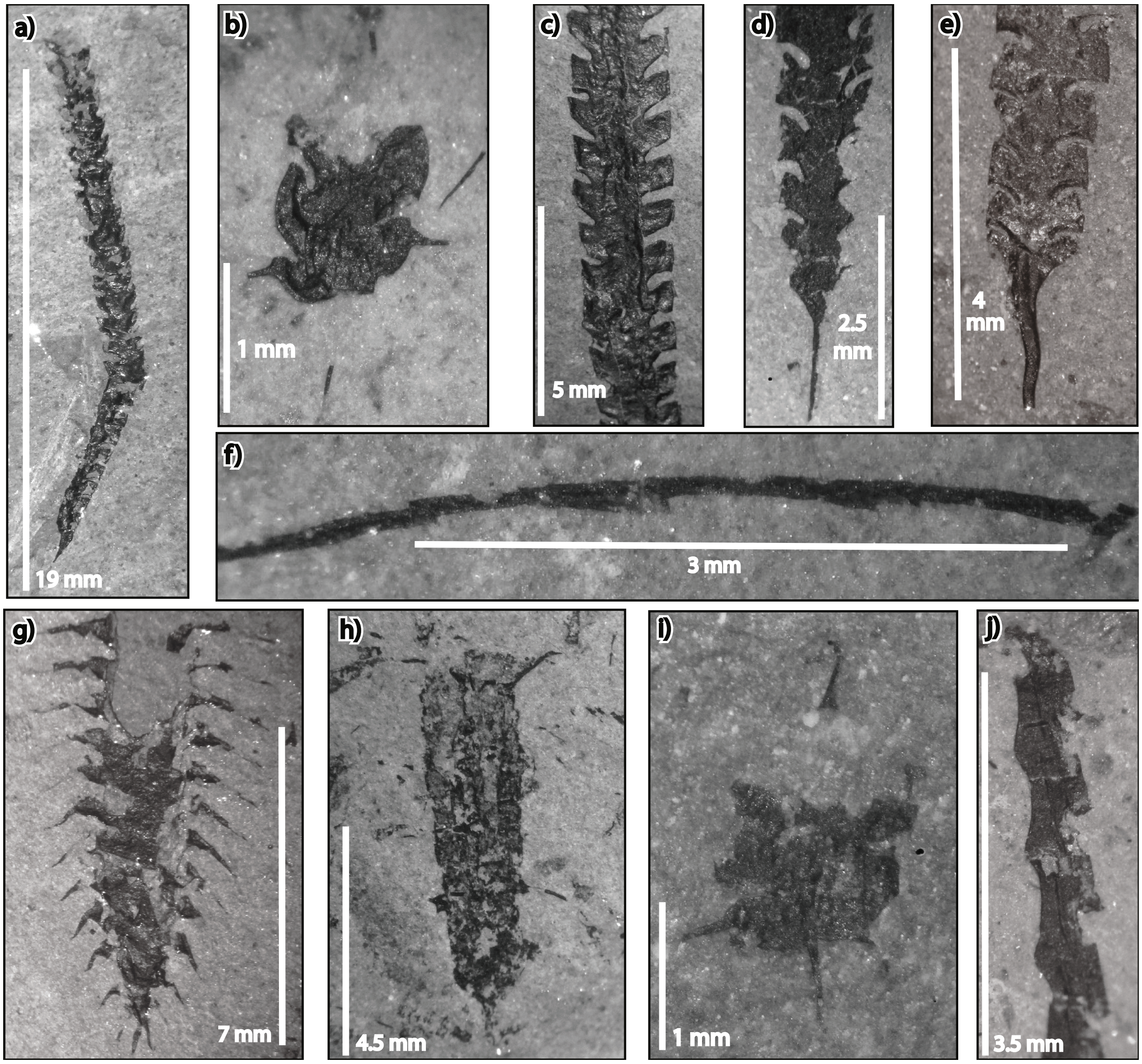
Biostratigraphy: Graptolites were recovered from shale and sandstone of the American Tickle Formation at a number of locations including Black Point, Piccadilly Slant, Piccadilly Head Beach, and along both Harry Brook and Victors Brook (Figure 2.4; 2.1). These graptolites are identified as *Nicholsonograptus fasciculatus, Archiclimacograptus sp., Paraglossograptus holmi, Glossograptus tentaculatus, Haddingograptus oliveri,* ?*Pterograptus elegans,* ?*Janograptus sp.* and ?*Acrograptus sp.* (Figure 2.6). This graptolite assemblage gives a Middle Ordovician, Darriwilian 3 age for the American Tickle Formation at all localities where sufficient material was obtained.

2.3.2.3. Goose Tickle Group: Mainland Formation

The Mainland Formation of Schillereff & Williams (1979) is formally described by Quinn (1992b) in exposures near Mainland on Port au Port Peninsula (Figure 2.1). The Mainland Formation is spatially restricted to Port au Port Peninsula, west of the Harry Brook Fault (Figure 2.4); it stratigraphically overlies the Cape Cormorant Formation at Cape Cormorant and at Round Head (Quinn, 1992a) (Figure 2.1). We interpret the Mainland Formation to stratigraphically

Figure 2.6: 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 2.4.



overlie portions of the American Tickle Formation in the Victors Brook area (Figure 2.3). Quinn (1995) suggested that sediment was channelized, via the hypothetical 'Serpentine Lake Discontinuity' of Cawood & Botsford (1991), westward into Port au Port Peninsula as a means to explain the spatial restriction of the unit. No stratigraphic upper contact has been found for the Mainland Formation (Quinn, 1992a).

Along Victors Brook and a nearby resource road (Figure 2.4), two facies of the Mainland Formation are identified. The first is dominated by graded, thinly to thickly bedded (scale of Ingram 1954), fine to medium sandstone containing abundant parallel lamination and less common ripple marks; mudstone and shale interbeds make up less than 20% of typical outcrops (Figure 2.5b; 2.5e). However, in some outcrops the proportion of mudstone and shale reaches 50%. Sandstone beds are friable and split easily along parting surfaces due to a large proportion of mud matrix and abundant black and green shale concentrated along lamination surfaces. This facies is similar to Mainland Formation lithologies described by Quinn (1992b). Basal bedding surfaces commonly show flutes and grooves; beds occasionally grade into pebble conglomerate near the base where they are associated with load structures (Figure 2.5). Paleocurrent data collected by Stenzel (1991) and Quinn (1995) suggest that sediments travelled south-southwest (present-day direction) via turbidity currents into the basin.

The second conglomeratic facies, here referred to as the Victors Brook facies, is composed of shale and siliceous mudstone clasts ranging from medium-sand up to pebble size (Figure 2.5h; 2.5i). Beds are graded and commonly amalgamated or locally interbedded with shale. This conglomerate is only observed between Victors Brook and the Harry Brook Fault (Figure 2.4). This facies was previously observed in Victors Brook by Waldron & Stockmal (1991) and is the same as the "type 2 conglomerate" of Waldron et al. (1993). This facies may also correlate with the Howe Harbour Member of Quinn (1992b), a unit that directly underlies allochthonous rocks near Howe Harbour far north of the map area, and was there included in the American Tickle Formation (Figure 2.1). Our map relationships in Victors Brook suggest that the Victors Brook facies occurs at the top of the Mainland Formation (Figure 2.3) and underlies a region of Humber Arm Allochthon exposed along the coast (Figure 2.4); this thick section is referred to as the Victors Brook Member. A discontinuous lower section of the Victors Brook facies is also found as isolated patches near allochthonous rafts inland in Victors Brook (Waldron et al., 1993); here, both the Victors Brook facies and allochthonous rafts are situated between rocks of the American Tickle Formation.

Distribution: The Mainland and American Tickle formations are most easily distinguished on the basis of contained conglomeratic facies and on the basis of the sandstone to mudstone ratio. Typical outcrops of Mainland Formation are dominantly composed of sandstone (rarely <50% sandstone) while the American Tickle Formation is characteristically dominated by mudstone and shale (Quinn, 1992b, 1995). The Mainland Formation interfingers with and overlies the American Tickle Formation in Victors Brook; the Mainland Formation overlies the Cape Cormorant Formation at Cape Cormorant and likely northwest of Victors Brook, at Round Head (Figure 2.1; 2.4; 2.3). The Mainland Formation is not found in, or to the east of, Harry Brook (Figure 2.4). The Mainland Formation is divided into two mappable units; a lower sandstone dominated unit and, an upper shale-chip conglomerate unit (the Victors Brook Member) (Figure 2.4). The sandstone-dominated unit thins from Victors Brook southeastward to terminate at the Harry Brook Fault; the Victors Brook Member, on the other hand, thickens southeastward to terminates at the Harry Brook Fault (Figure 2.4).

Biostratigraphy: Graptolites from this unit are reported by Quinn (1992b) and references therein; documented fossils from the Mainland Formation yield a Darriwilian 3 age. Earlier suggestions that the unit extends to the early Sandbian remain unsubstantiated as original fossils could not be located (Quinn, 1992a, 1995). The Mainland Formation is therefore considered equivalent in age to the American Tickle Formation (Quinn, 1992a, 1995) though stratigraphic relationships in Victors Brook (Figure 2.4), where the Mainland Formation overlies American Tickle Formation, suggest that it may be slightly younger.

2.3.2.4. Goose Tickle Group: Interpretation

Abundant planar laminated siltstone and shale, particularly within the Black Cove and American Tickle formations, indicate a low energy, likely deep-water depositional environment. Sandstone interbeds, common within the American Tickle Formation and dominating the Mainland Formation, have sharp, undulatory basal surfaces displaying flute casts, grooves, load features, graded beds, and Bouma sequences. An angular discordance observed within the sandstone and shale facies of the American Tickle Formation near Locality 01 in Figure 2.4 suggests that deposition was at least partially channelized, eroding into underlying strata. These observations are consistent with rapid, high energy, deposition via turbidity currents (Quinn, 1992a). An abundance of mud both within and between sandstone beds suggests a deep water, shale-rich source consistent with lithologies in the overlying Humber Arm Allochthon. The angularity of sandstone grains and high proportion of mudstone and shale within these units suggests low compositional and textural maturity.

Carbonate conglomerate facies within the American Tickle Formation range from angular, clast-dominated varieties to rounded, matrix-dominated varieties suggesting a change from proximal to distal deposition via debris flows. These carbonate conglomerate units are dominated by clasts with clear textural and lithological similarities to the underlying Table Head Group indicating erosion and redeposition of underlying platform units. A previous interpretation by Stenzel (1991) and Quinn (1995) suggests that these limestone conglomerates were shed from the exposed hanging walls of shallow platform-cutting thrust faults onto the footwall block; this hypothesis seems unlikely as limestone conglomerate units are only observed in the hanging walls of high-angle faults on Port au Port Peninsula (Figure 2.1; 2.4). This distribution would be better explained in an extensional setting in which conglomerate units eroded from the footwall block were redeposited on the hanging wall block. A minor proportion of dolomitic clasts within the Daniels Harbour Member would suggest that at least some of these extensional faults exposed portions of the St. George Group as well (Figure 2.2; 2.3). From relationships near Victors Brook we infer that the American Tickle Formation continues northwest of Victors Brook and likely overlies or interdigitates with distal portions of the Cape Cormorant Formation (Figure 2.4; 2.3).

The Victors Brook facies of the Mainland Formation displays a very low maturity suggesting that deposition was proximal to a shale source, probably in the overlying Humber Arm Allochthon. The association of the Victors Brook facies with allochthonous rafts found within the American Tickle Formation is interpreted to represent an interfingering of the Mainland Formation with the American Tickle Formation in Victors Brook (Figure 2.3). This relationships supports a previous hypothesis that the American Tickle Formation and Mainland Formation are partially synchronous (Quinn, 1992a, 1995). However, the Mainland Formation also overlies the American Tickle Formation with inferred stratigraphic contact in Victors Brook (Figure 2.4; 2.3). In this succession, the Goose Tickle Group represents a 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 (Figure 2.3). This overall coarsening upward sequence can be explained as a result of the transition from a distal to proximal sediment source as the advancing Humber Arm Allochthon was emplaced across the peninsula.

2.4. Structure

2.4.1. Low-angle faults and the distribution of allochthonous units

The Humber Arm Allochthon, previously mapped as a single contiguous map unit on Port au Port Peninsula (Williams and Cawood, 1989; Waldron et al., 1993; Knight et al., 2008) is remapped here, in central Port au Port Peninsula, as two packages of allochthonous rocks structurally separated from one another by an intermediate band of Goose Tickle Group strata (Figure 2.2; 2.4); steep faults offset all these units. The lower package of allochthonous strata, here named the West Bay Thrust Sheet, is separated from underlying strata by the West Bay Thrust.

The West Bay Thrust Sheet overlies and underlies portions of the Goose Tickle Group (Figure 2.2; 2.3) and is associated here with the Taconian orogeny. The name West Bay Thrust was previously informally applied by Waldron et al. (2012) to describe the base of a single allochthon on Port au Port Peninsula. It is therefore appropriate for the fault that defines the base of the lower allochthonous thrust sheet identified here. The upper package of allochthonous strata, sitting above the intermediate package of Goose Tickle Group strata, is here named the Lourdes Thrust Sheet, separated from underlying strata by way of the Lourdes Thrust; the Lourdes Thrust Sheet is here associated with the Acadian orogeny.

West Bay Thrust Sheet: A series of discontinuous, allochthonous, shale and chert outcrops surrounded by Goose Tickle Group in Victors Brook were previously considered rafts by Waldron et al. (1993); however, many of these outcrops are here reinterpreted to be part of the more continuous West Bay Thrust Sheet mapped farther east in Harry Brook, Rioux Brook and Quarry Brook (Figure 2.4; 2.2; 2.3). The West Bay Thrust Sheet thickens eastward from Harry Brook into Rioux Brook and Quarry Brook (Figure 2.4). The West Bay Thrust Sheet observed in these three brooks also sits between two packages of Goose Tickle Group rocks assigned to the American Tickle Formation, the underlying package passing continuously down into carbonate rocks of the Table Head Group (Figure 2.2; 2.4).

Between the West Quarry Fault and East Quarry Fault a package of allochthonous scaly shale and chert, not clearly defined as part of either thrust sheet, overlies the Table Cove Formation directly (Figure 2.2; 2.4). Close to the mouth of Piccadilly Brook, a small outcrop of scaly shale and chert sits structurally between outcrops of American Tickle Formation sandstone, shale and limestone conglomerate; this small outcrop is a thinned portion of the West Bay Thrust Sheet (Figure 2.4). Between the Piccadilly Head and Piccadilly Bay faults, a thin West Bay Thrust Sheet is again found to the south of, and structurally below, an E-W trending ridge of Daniels Harbour conglomerate. Here, an isolated outcrop of Humber Arm Supergroup, including igneous material, is found adjacent to the Piccadilly Head Fault. East of the Piccadilly Bay Fault, on

Shoal Point, no West Bay Thrust Sheet has been identified(Figure 2.4).

Goose Tickle Group above the West Bay Thrust Sheet: An intermediate package of Goose Tickle Group rocks, comprising both American Tickle Formation and Mainland Formation facies, overlies the discontinuous West Bay Thrust Sheet in Victors Brook (Figure 2.4). In Harry Brook, Rioux Brook and Quarry Brook, thicker, more continuous portions of the West Bay Thrust Sheet are overlain by sandstone, shale and the Harry Brook facies of the American Tickle Formation (Figure 2.3; 2.4). This intermediate package of rock thickens eastward from Harry Brook to Quarry Brook but is not exposed between the West Quarry and East Quarry faults (Figure 2.4). Between the East Quarry Fault and Piccadilly Bay Fault, exposures of this intermediate package are dominated by sandstone and shale along the beach and by Daniels Harbour conglomerate towards the point of Piccadilly Head. South along Piccadilly Slant, the E-W trending ridge of Daniels Harbour conglomerate also belongs to this intermediate package (Figure 2.2; 2.4). In eastern Port au Port Peninsula, on Shoal Point, the base of the allochthon is obscured by sparse outcrop and unconformable Carboniferous strata; there is no evidence of any Goose Tickle Group strata in this area (Figure 2.4).

Lourdes Thrust Sheet: The Lourdes Thrust Sheet overlies the intermediate Goose Tickle Group strata in Victors Brook, Harry Brook, Rioux Brook and Quarry Brook along the Lourdes Thrust (Figure 2.2; 2.4). In each brook, Cow Head Group, Western Brook Pond Group, and mélange are found to the northeast of the Lourdes Thrust all the way to the coast of Port au Port Bay (Figure 2.4). Along the coast at Piccadilly Slant, north of the prominent E-W trending ridge of Daniels Harbour conglomerate, the Lourdes Thrust Sheet is exposed in a disrupted section of limestone, shale, siliceous mudstone and intermittent blocks of igneous material (Figure 2.4; 2.3). Near the base of Shoal Point, the obscured platform-allochthon contact gives no indication of the West Bay Thrust Sheet or overlying Goose Tickle Group; we tentatively assign this package of allochthonous rocks to the Lourdes Thrust Sheet rather than the West Bay Thrust Sheet (Figure 2.4).

2.4.2. High-angle faults

Seven large platform-cutting faults were either directly observed or inferred from offsets in stratigraphic boundaries (Figure 2.4). The Round Head Fault, which has previously been studied in detail (Stenzel, 1991; Waldron et al., 1993), has been shown to have a protracted history which likely began with early Cambrian rifting and continued through both the Taconic and Acadian orogenic events into the Devonian (Waldron and Stockmal, 1991; Waldron et al., 1993; Stockmal et al., 2004). The Round Head Fault is a curved feature that strikes east-west within the map area (Figure 2.4), but curves around Round Head to the west into a northeast-southwest orientation; in seismic lines the Round Head Fault is a southeast-dipping feature (Waldron et al., 1998).

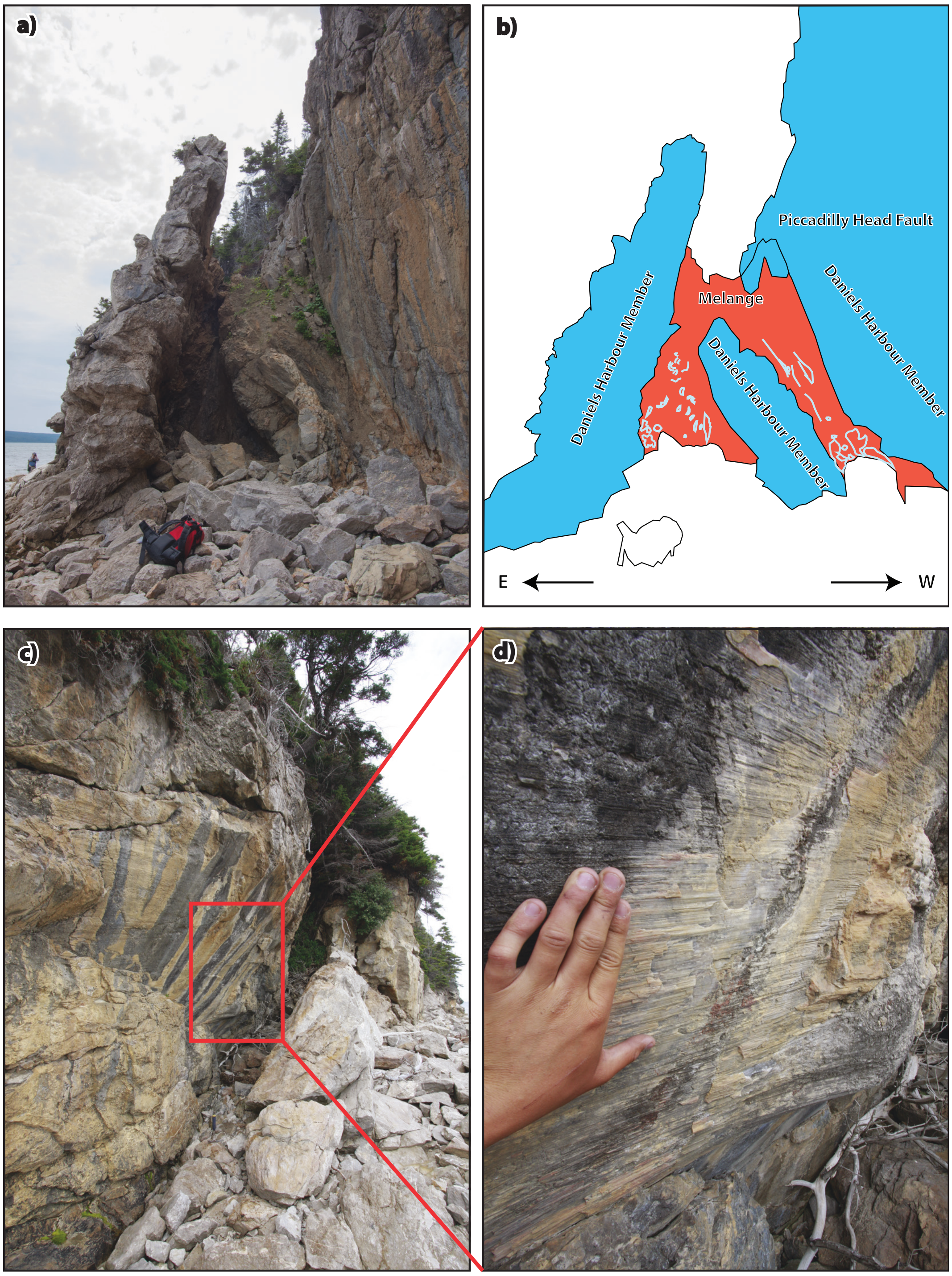
The other six high-angle platform-cutting faults identified within the map area are, from west to east: the Harry Brook, Rioux Brook, West Quarry, East Quarry, Piccadilly Head, and Piccadilly Bay faults (Figure 2.4). Of these six faults, the Harry Brook, East Quarry and Piccadilly Head faults were directly observed and measured in outcrop (Figure 2.4).

The *Harry Brook Fault*, observed in Harry Brook, dips steeply southeast and juxtaposes portions of the St. George Group to the NW with the Table Point Formation to the SE (Figure 2.2; 2.4). The *East Quarry Fault* dips southeast and juxtaposes American Tickle Formation in the hanging wall with allochthonous siliceous mudstone and chert in the footwall. The *Piccadilly Head Fault*, along Piccadilly Slant (Figure 2.4), dips northwest and juxtaposes Daniels Harbour Member in the hanging wall with allochthonous scaly shale containing blocks of the Daniels Harbour Member in the footwall (Figure 2.7a). The most prominent slickenlined surface of the Piccadilly Head Fault indicates a dominantly sinistral strike-slip sense of movement with a minor extensional dip-slip component (Figure 2.7b); however, this sense of slip cannot explain the observed map geometry which requires earlier dextral and/or reverse motion.

The *Rioux Brook Fault* and *West Quarry Fault* were inferred from abrupt transitions from low-lying, poorly exposed outcrops of allochthonous rocks into prominent cliffs of Table Point

Figure 2.7: 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) Piccadilly Head fault (204/53 NW) with (d) prominent slickenlines (220-17 SW) indicating sinistral and normal slip.



Formation along regional strike. The *Piccadilly Bay Fault* is not observed in outcrop but is marked by a prominent NE-SW lineament, similar to the other mapped faults, in both satellite images and digital elevation models (Figure 2.4). The Piccadilly Bay Fault shows significant (>3 km) dextral separation on mapped boundaries and is interpreted in a number of offshore seismic sections (Stockmal et al., 2004).

In addition to mapped offsets, abrupt changes in thickness within the Table Head Group and American Tickle Formation (Figure 2.2; 2.3) also correlate with some of these faults. An example of a thickness change is evident at Harry Brook where theAmerican Tickle Formation is almost twice as thick as its counterpart to the west, in the footwall of the Harry Brook Fault (Figure 2.4). Just as the Cape Cormorant Formation and limestone conglomerate facies within the American Tickle Formation suggest deposition during block faulting; thickened foreland basin stratigraphy in the hangingwall of a fault can indicate early syn-depositional fault movement.

2.4.3. Outcrop-scale structures

Piccadilly Head Beach: Sandstone and shale of the American Tickle Formation are exposed along the beach directly east of the East Quarry Fault (Figure 2.4; 2.8). This section of American Tickle Formation lies above the West Bay Thrust Sheet, found just inland in Piccadilly Brook (Figure 2.4), and therefore likely sits in the footwall of the Lourdes Thrust Sheet (Figure 2.4). Large thrust faults cut up section to the west within this coastal section (Figure 2.8a).Between these thrust faults are west-facing, overturned, rounded folds with tight interlimb angles that are gently inclined to the west and gently north-plunging (Figure 2.8). Within the nearly horizontal, upright limb of these folds, extensional fractures are perpendicular to bedding and show consistent (~190/30 NW and ~030/60 SE) orientations. Contractional normal faults, found only in the hinge and overturned limb of folds, duplicate strata while down-dropping the eastern, hanging wall block along steep east-dipping faults (Figure 2.8).

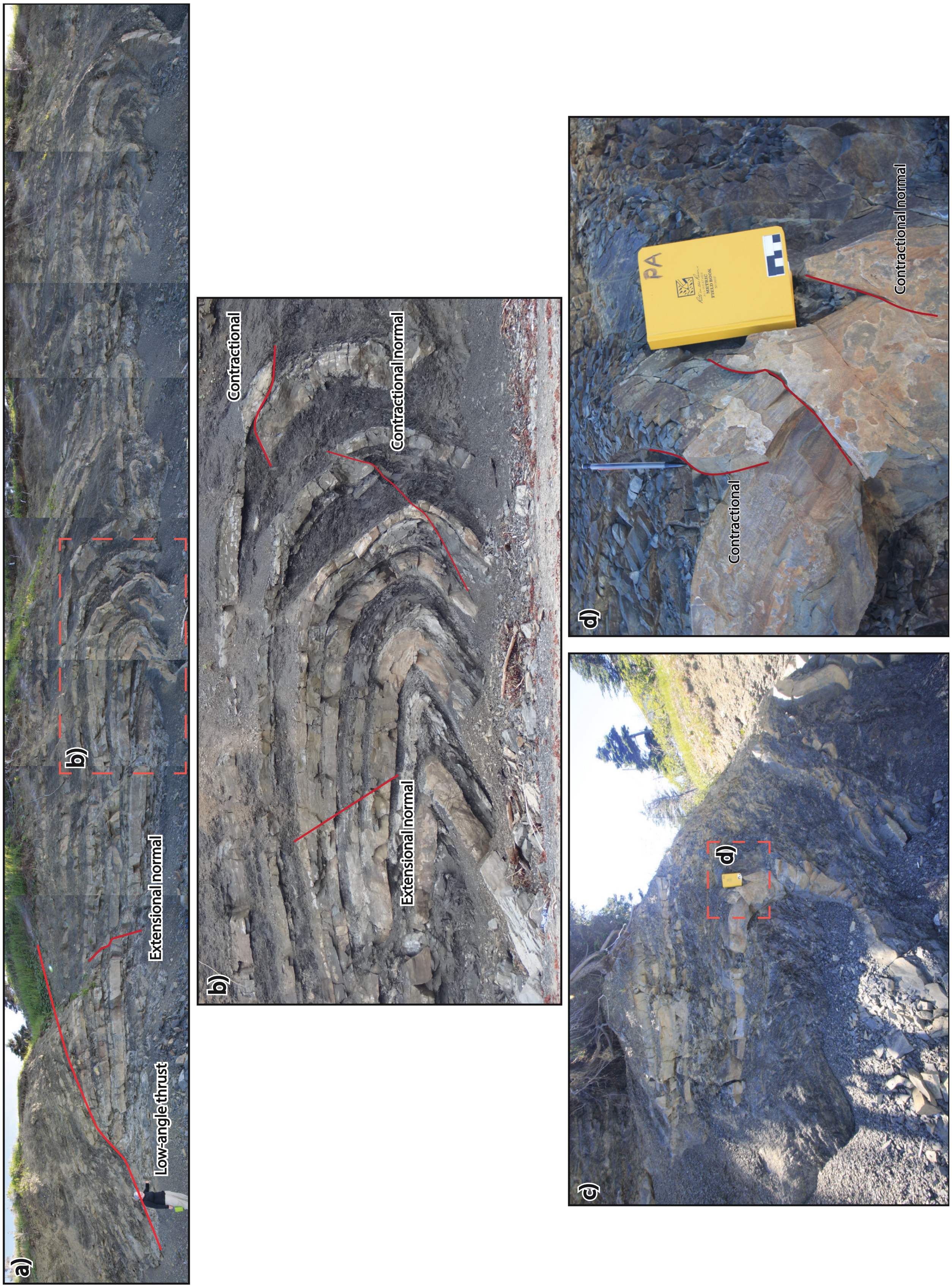
Piccadilly Head Beach interpretation: The American Tickle Formation deposited here, above the West Bay Thrust Sheet, was subjected to Taconian extension. Contractional normal faults are interpreted to have initially formed during extension, parallel to high-angle map-scale faults. West-dipping extensional faults were subsequently inverted to duplicate strata and then rotated with the overturned limb of the fold into their present configuration. Large low-angle, west-vergent, thrusts, contractional normal faults and west-vergent overturned folds are all indicative of a later phase of shortening likely from emplacement of the overriding Lourdes Thrust Sheet.

Piccadilly Slant: Along the northern portion of Piccadilly Slant, near Piccadilly Head (Figure 2.4), Daniels Harbour conglomerate (Figure 2.2) is exposed in the hanging wall of the NW-dipping Piccadilly Head Fault (Figure 2.4). Here, a nearly vertical ridge of Daniels Harbour Member marks the fault surface where it is juxtaposed with scalyshale of the Humber Arm Supergroup containing isolated blocks of limestone and siliceous mudstone (Figure 2.7a; 2.7b). In the footwall of the Piccadilly Head Fault, two large slices of Daniels Harbour conglomerate sit within scaly shale; these slices of Daniels Harbour conglomerate and the foliation of the scaly shale are steeply dipping to near-vertical (Figure 2.7). The Piccadilly Head Fault surface displays slickenlines indicating that the latest fault movement was primarily sinistral and extensional (Figure 2.7c; 2.7d).

Piccadilly Slant interpretation: The Daniels Harbour conglomerate, which sits in both the hanging wall and footwall of the Piccadilly Head Fault, was produced during Taconian extension; this conglomerate unit is thickened in the hanging wall of the Piccadilly Head Fault suggesting that this fault was originally active as a normal fault. The steep to vertical orientation of the Daniels Harbour conglomerate and scaly shale in the footwall of the Piccadilly Head Fault suggest that the fault was later reactivated as a thrust; folding the overlying strata before they were crosscut. Reactivation of the Piccadilly Head Fault as a thrust fault is inconsistent with the slickenlines found on the fault surface which suggest extension. It is therefore likely that the Piccadilly Head Fault, first active as a normal fault in the Taconian, was first reactivated as a thrust fault, and then reactivated again during a later period of transtension.

Figure 2.8: Structural relationships at Piccadilly Head Beach.

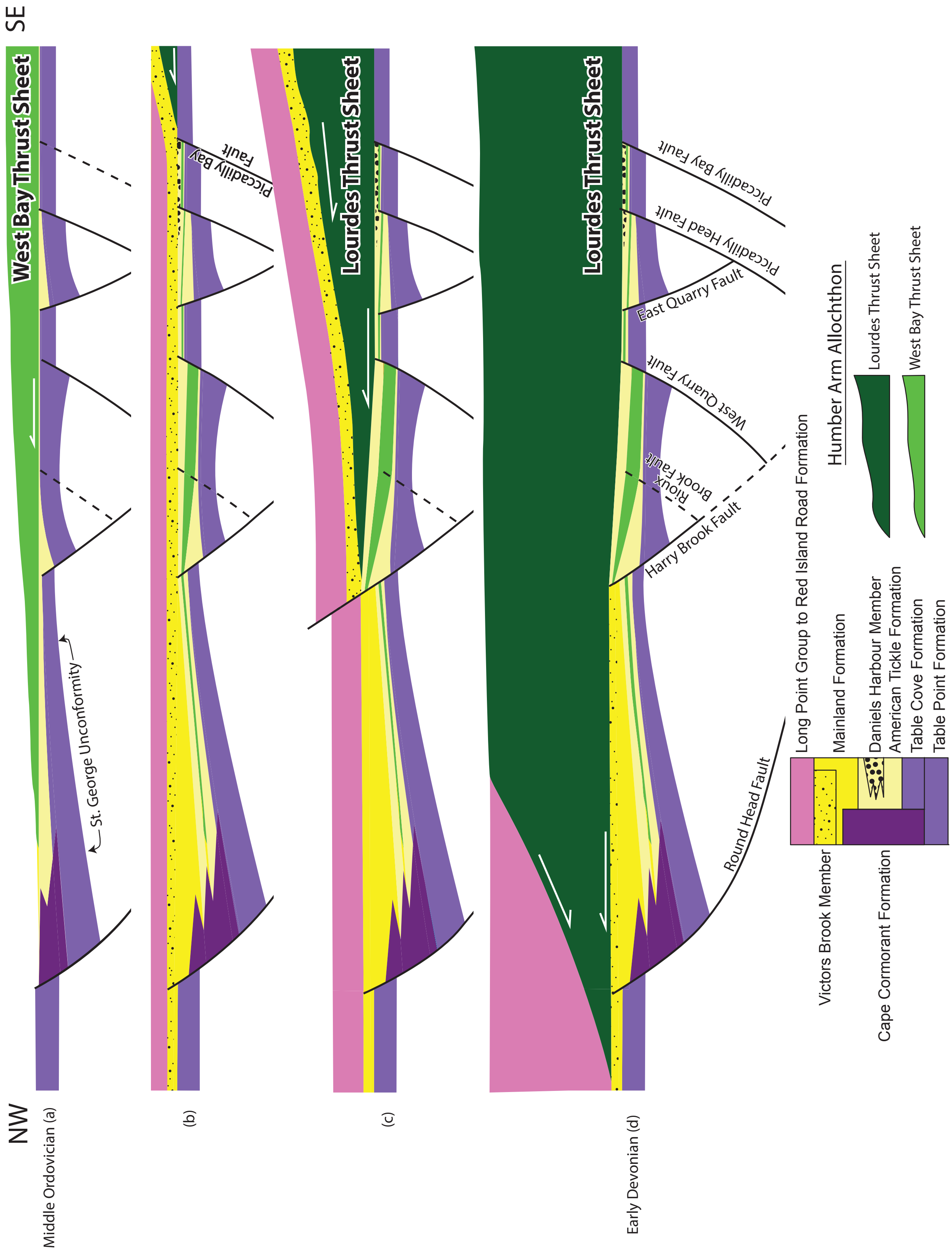
(a) Photo mosaic showing overturned folded strata with interpreted low-angle thrust fault and extensional fault. (b) Overturned fold containing extensional, contractional, and contractional normal faults. (c) Overturned fold showing location of photograph (d) within the hinge of the fold. (d) contractional normal faults in the hinge of the overturned fold.



a)
b)
Low-angle thrust
Extensional normal
b)
Contractional
Contractional normal
Extensional normal
c)
d)
d)
Contractional
Contractional normal
PA

Figure 2.9: Schematic cross-sections showing the evolution of structural elements on Port au Port Peninsula.

(1) Movement along various high-angle faults provide structural control for foreland basin sediment resulting in variable thickness. The West Bay Thrust Sheet is emplaced across Port au Port Peninsula. (2) Continued movement along high-angle fault buries the eroded remnants of the West Bay Thrust Sheet beneath limestone conglomerate of the American Tickle Formation. Early portions of the Mainland Formation are deposited to the NW against the Round Head Fault. (3) The Harry Brook Fault is inverted raising the tip of the Lourdes Thrust Sheet allowing it to cut up section to the NW. (4) The tip of the Lourdes Thrust Sheet is emplaced to its present position offshore of Port au Port Peninsula forming a tectonic wedge within foreland basin strata.


NW
SE
Middle Ordovician (a)
(b)
(c)
Early Devonian (d)
West Bay Thrust Sheet
St. George Unconformity
Piccadilly Bay Fault
Lourdes Thrust Sheet
Lourdes Thrust Sheet
Piccadilly Bay Fault
Piccadilly Head Fault
East Quarry Fault
West Quarry Fault
Rioux Brook Fault
Harry Brook Fault
Round Head Fault
Long Point Group to Red Island Road Formation
Mainland Formation
Victors Brook Member
Daniels Harbour Member
American Tickle Formation
Cape Cormorant Formation
Table Cove Formation
Table Point Formation
Humber Arm Allochthon
Lourdes Thrust Sheet
West Bay Thrust Sheet

2.5. Interpretation

2.5.1. Middle Ordovician: Table Head Group

Early stages of lithospheric flexure and the onset of tectonism in western Newfoundland during the Ordovician are recorded by the St. George unconformity; this unconformity separates the underlying shelf succession from the overlying Table Head Group and represents the passing of the Taconian peripheral bulge across western Newfoundland (Jacobi, 1981). The Table Point Formation directly overlies the St. George unconformity (Figure 2.3; 2.9) and is continuous within the map area indicating that the entirety of Port au Port Peninsula began to subside after the migration of the Taconian peripheral bulge. The overlying Table Cove and Cape Cormorant formations are partially synchronous and laterally equivalent (Figure 2.4). The Cape Cormorant Formation, in the northwest portion of the map area, has previously been interpreted as a fault scarp deposit and is associated with extensional movement on the Round Head Fault (Stenzel et al., 1990; Waldron et al., 1993). The Table Cove Formation thickens and thins across the peninsula; abrupt changes in thickness occur near high-angle faults (Figure 2.4). Increasing shale content within the Table Cove Formation and the occurrence of slabby limestone beds suggest a transition in depositional environment to deeper water and decreased carbonate productivity. Over 1 km of slip, documented on the Round Head Fault by Stenzel et al. (1990) from the variety of clasts within the Cape Cormorant Formation, likely contributed to flexural subsidence and the transition to a deeper water environment. Thickness changes within the Table Point and Table Cove formations likely resulted from differential subsidence during block faulting (Figure 2.9).

2.5.2. Middle Ordovician: Goose Tickle Group

The Goose Tickle Group stratigraphically overlies the Table Head Group and is dominated by turbidites shed from the Humber Arm Allochthon westward over Port au Port Peninsula (Quinn, 1992a). The lowest, Black Cove Formation, dominated by mudstone and shale, represents the first clastic sediment transported into the basin from a distal source. The overlying American Tickle Formation contains the first influx of sandstone indicating a transition to a more proximal sediment source as the allochthon encroached westward towards Port au Port Peninsula. The American Tickle Formation undergoes abrupt changes in thickness at high-angle, platform cutting normal faults, most notable at the Harry Brook Fault and East Quarry Fault (Figure 2.4; 2.9). This suggests that these faults influenced the geometry of the basin during deposition. Limestone conglomerate units, including the Daniels Harbour Member and other carbonate conglomerate, punctuate the American Tickle Formation. Carbonate clasts and rafts with characteristic Table Head Group lithology are mixed into sands and muds of the American Tickle Formation suggesting that carbonate material continued to be exposed and eroded along these high-angle fault scarps, contributing material into the foreland basin.

2.5.3. Middle Ordovician: emplacement of the West Bay Thrust Sheet

Within the American Tickle Formation is a package of Humber Arm Supergroup. This package is composed of disrupted and typically mixed shale, siliceous mudstone, chert, limestone, less common sandstone or pebble conglomerate, and rare igneous blocks. These older, deeper-water rocks of the Humber Arm Allochthon are placed above the American Tickle Formation by the West Bay Thrust and form the West Bay Thrust Sheet. Portions of the Goose Tickle Group are also found above the West Bay Thrust Sheet; we suggest two possible scenarios to explain the structural relationship at this upper contact. In the first scenario, the allochthon was emplaced as a wedge into the Goose Tickle Group, resulting in Goose Tickle Group strata being thrust eastward above of the West Bay Thrust Sheet. This scenario requires that rocks of the American Tickle Formation were deposited prior to allochthon emplacement such that they could be incorporated into the hanging wall of this tectonic wedge. The second scenario, and the one we favour, is that a portion of the American Tickle Formation was deposited unconformably on top of the allochthon and includes carbonate conglomerate resulting from continued erosion of carbonate units in the exposed hanging wall of Taconian extensional faults. This second scenario requires that the American Tickle Formation continued to be deposited during and after Taconian emplacement of the West Bay Thrust Sheet. We favour scenario two, for the following reasons:

1. In Harry Brook and Rioux Brook the West Bay Thrust Sheet is thickened while in Piccadilly Brook and south along Piccadilly Slant it is thinned; in Victors Brook it appears discontinuous (Figure 2.4; 2.9). Changes in thickness and the discontinuous nature of the West Bay Thrust Sheet across Port au Port Peninsula aremore consistent with an unconformable upper contact than a thrust contact.

2. Contained within the American Tickle Formation in Victors Brook are “rafts” of Humber Arm Supergroup (Waldron et al., 1993). Adjacent to these “rafts” are isolated boulders of chert and shale chip conglomerate, lithologies consistent with erosion of the allochthon.

3. The Piccadilly Bay Fault (Figure 2.4) dips NW in seismic profiles (Stockmal et al., 2004). A thick package of Daniels Harbour conglomerate exists in the hanging wall of this fault where it is found structurally above the West Bay Thrust Sheet (Figure 2.9). This package of conglomerate is reasonably interpreted as derived from the Piccadilly Bay Fault as a similar conglomerate unit is not found in the footwall block. We interpret that the West Bay Thrust Sheet was subjected to a period of thinning and erosion before being dropped down in the hanging wall of the Piccadilly Bay Fault where it was subsequently covered by Daniels Harbour conglomerate (Figure 2.9a; 2.9b). This relationship is consistent with the second scenario and is more difficult to explain by thrusting alone as envisaged in the first scenario. In the first scenario, the Daniels Harbour conglomerate would have to be deposited first, prior to its incorporation into the hanging wall of a westward propagating wedge. However, along this NW dipping fault, the earlier formed conglomerate would be in a structurally lower position than the tip of the wedge, unable to then be incorporated above it.

These observations suggest that: (a) a period of tectonic thinning and erosion followed initial allochthon emplacement creating variably thick and sometimes discontinuous portions of the

West Bay Thrust Sheet; and (b) the Humber Arm Allochthon was emplaced during a period of platform extension which allowed the Daniels Harbour Member and other carbonate conglomerate facies to be deposited above the West Bay Thrust Sheet (Figure 2.9). The evidence strongly supports scenario two. We therefore bracket the timing of emplacement of the West Bay Thrust Sheet from graptolite assemblages in American Tickle Formation both above and below the West Bay Thrust Sheet, which yield Middle Ordovician Darriwilian 3 ages (Figure 2.4). Emplacement of the West Bay Thrust Sheet above an actively extending platform was likely facilitated by either gravitational collapse or coaxial extension within the allochthon resulting from either high fluid pressures (Waldron et al., 1988) or from changes in geometry as the allochthon passed from the former continental slope onto the shelf. The West Bay Thrust Sheet at the time of emplacement may have been more than 800 m thick in places, eroded remnants of this thrust sheet are found next to rafts of allochthonous rocks in Victors Brook (Figure 2.4).

2.5.4. Middle Ordovician and later: Goose Tickle Group

The West Bay Thrust Sheet is overlain by sandstone and shale of the American Tickle Formation in some areas and by Daniels Harbour Member and Harry Brook facies conglomerate in others; these conglomerate units indicate that extension continued after emplacement of the West Bay Thrust Sheet, exposing, and allowing erosion of, Table Head Group strata. The Mainland Formation overlies the Cape Cormorant Formation near Cape Cormorant and at Round Head (Figure 2.1) but overlies the American Tickle Formation in Victors Brook and east towards the Harry Brook Fault (Figure 2.4; 2.3; 2.9). The Mainland Formation is only found in western Newfoundland west of the Harry Brook Fault adjacent to the Round Head Fault. Continued extension on the curved Round Head Fault could have facilitated the accumulation of this material in its hanging wall. We suggest that these sand-rich sediments were likely carried along a submarine channel and distributed into western Port au Port Peninsula; this model would account for the southwest paleocurrent data collected by Stenzel (1991) 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 et al., 1993; Stockmal et al., 2004). Ponding of sediment against the Round Head Fault can better account for the localized distribution of the Mainland Formation within the map area. The transition from sandstone and shale to shale-chip conglomerate within the Mainland Formation represents a transition to a more proximal, allochthon-derived, sediment source, likely overcoming the structural control placed on early deposition of the Mainland Formation (Figure 2.9).

2.5.5. Timing of block faulting

The juxtaposition of map units on Port au Port Peninsula has led to the interpretation of six high-angle, platform-cutting faults within the map area: the Harry Brook, Rioux Brook, West Quarry, East Quarry, Piccadilly Head, and Piccadilly Bay faults (Figure 2.4; 2.9). In an attempt to determine the roles of these faults in Taconian extension, we use the distribution of limestone conglomerate units in the foreland basin to show that: (1) the Middle Ordovician units were deposited syntectonically with Taconian extension, and (2) that high-angle faults were active before and after emplacement of the West Bay Thrust Sheet.

The Harry Brook Fault separates a thinned Table Head Group and American Tickle Formation to the northwest from thicker packages to the southeast (Figure 2.3). These map relationships suggests that the Harry Brook Fault was in active extension during deposition of these units, with sediment being accumulated on the southeastern, subsiding, hanging wall block of the fault. The Rioux Brook Fault does not correspond to a noticeable thickness change in Middle Ordovician strata and therefore likely did not undergo extension in the Middle Ordovician (Figure 2.4). The Rioux Brook Fault offsets mapped boundaries along a prominent scarp within the Table Point Formation and is probably a later, possibly Acadian feature. We speculate that this fault dips to the northwest within the platform but transitions to a fold within overlying foreland basin and allochthonous rocks (Figure 2.4). Thickening of the West Bay Thrust Sheet and overlying American Tickle Formation eastward across the peninsula from Harry Brook to Rioux Brook and into Quarry Brook suggests that the West Quarry Fault is a northwest-dipping feature active during and after emplacement of the West Bay Thrust Sheet (Figure 2.4; 2.9). The East Quarry Fault is observed in outcrop as a southeast dipping feature; this fault preserves thickened Table Head Group and Goose Tickle Group in its hanging wall (Figure 2.9) suggesting that it was active during the Taconian orogeny. The Piccadilly Head Fault dips to the northwest in outcrop. Thickened American Tickle Formation below the West Bay Thrust in the hanging wall of the Piccadilly Head Fault suggest that it was active during the Middle Ordovician. The Piccadilly Bay Fault dips to the northwest in seismic profiles (Stockmal et al., 2004) and was in active extension after the emplacement of the West Bay Thrust Sheet as indicated by the thick packages of Daniels Harbour conglomerate in its hanging wall overlying the West Bay Thrust Sheet (Figure 2.9b). A thin package of Table Point Formation in the hanging wall of the Piccadilly Bay Fault could suggest that the hanging wall block was in a structurally high position during the early Middle Ordovician prior to emplacement of the West Bay Thrust Sheet (Figure 2.9a); the Table Point Formation was either slowly deposited, or more likely, was being eroded.

2.5.6. Emplacement of the Lourdes Thrust Sheet and post-Taconian deformation

The Lourdes Thrust is interpreted as an out-of-sequence thrust which overrode the West Bay Thrust Sheet and overlying Goose Tickle Group rocks; the Lourdes thrust is also interpreted to be the basal detachment for the tectonic wedge which sits offshore of Port au Port Peninsula and is therefore likely an Acadian (post-Emsian) feature. Duplication of the allochthon was facilitated by high-angle, extensional faults which remained active after initial low-angle thrusting in the basin to form a broad graben between the Piccadilly Bay Fault and the Round Head Fault; between these faults the earlier West Bay Thrust Sheet was dropped down and buried beneath the American Tickle Formation (Figure 2.9b). The Piccadilly Bay Fault is, therefore, likely responsible for offsetting the base of the allochthon leading to its later duplication. The Lourdes Thrust Sheet overrode American Tickle Formation strata (Figure 2.9c). Along the beach at Piccadilly Head (Figure 2.4), this compressional event reworked previous extensional faults, creating contractional normal faults in the hinges and overturned limbs of west-vergent overturned folds, while also imbricating the strata along west-vergent low-angle faults.

The Goose Tickle Group in the footwall of the Lourdes Thrust in Victors Brook contains rocks assigned to both the American Tickle Formation and the overlying Mainland Formation These units continue southeast from Victors Brook to the Harry Brook Fault; however, no Mainland Formation was observed southeast of the Harry Brook Fault (Figure 2.4). We suggest that the Harry Brook Fault was inverted prior to the arrival of the front of the Lourdes Thrust Sheet. As a result, the Lourdes Thrust appears to climb up section across the Harry Brook Fault into the stratigraphically higher Mainland Formation or to the base of the Long Point Group (Figure 2.9c; 2.9d; 2.2; 2.3). At Tea Cove (Figure 2.4) the allochthon is overlain by the Long Point Group (Waldron and Stockmal, 1991).

Continued westward emplacement of the Lourdes Thrust Sheet propagated the tectonic wedge to its current position offshore of Port au Port Peninsula by the Early to Middle Devonian where it was subsequently crosscut by the inverted Round Head Fault (Waldron and Stockmal, 1991; Waldron et al., 1993; Stockmal et al., 2004) (Figure 2.9d). The base of the Lourdes Thrust Sheet is similarly crosscut and deformed at Piccadilly Slant (Figure 2.4). Field relationships at this location suggest that two phases of deformation affected the area after the Lourdes Thrust Sheet had been emplaced across Port au Port Peninsula. An earlier inversion event folded and tilted strata in both the hanging wall and footwall of the Piccadilly Head Fault and explains the large dextral offset apparent from map relationships. Prominent slickenlines on the fault surface that indicate sinistral transtension are attributed to a later phase of deformation (Figure 2.7). Similar post-Emsian deformation is evident for the Rioux Brook, West Quarry and Piccadilly Bay faults as all of these faults crosscut or deform the base of the Lourdes Thrust Sheet. It is however difficult in most cases to separate the inversion and strike-slip movement where the fault surface is poorly exposed and slickenlines are not available.

2.6. Conclusions

Port au Port Peninsula displays a structurally complex, three-dimensional geometry that has resulted from a protracted and dynamic history of deformation. Facies variation within the Goose Tickle Group has allowed the separation of the American Tickle Formation from the overlying Mainland Formation near Victors Brook (Figure 2.4). Deposition of foreland basin units on Port au Port Peninsula was complicated by block faulting in the platform. Intermittent activation of high-angle faults throughout the Middle Ordovician created a variety of limestone conglomerate units which were shed into the foreland basin and are preserved within the American Tickle Formation.

The Humber Arm Allochthon on Port au Port Peninsula is separated into two structural packages here named the West Bay Thrust Sheet and Lourdes Thrust Sheet which both place older rocks of the Humber Arm Supergroup on top of younger Goose Tickle Group strata. These thrust sheets are separated from one another by a package of Goose Tickle Group rocks. The structurally lower West Bay Thrust Sheet is situated both structurally above and unconformably below portions of the Goose Tickle Group. Graptolites recovered from the overlying Goose Tickle Group rocks indicate that emplacement of the West Bay Thrust Sheet across Port au Port Peninsula occurred in the Middle Ordovician; the West Bay Thrust Sheet is therefore considered to be the preserved leading edge of the Humber Arm Allochthon emplaced during Taconian orogenesis. LFormationimestone conglomerate sitting unconformably above the West Bay Thrust Sheet indicates that extension and exposure of the platform continued, as a result of lithospheric flexure, after the West Bay Thrust was emplaced.

Deposition of foreland basin sediments and the subsequent geometry of the Lourdes Thrust Sheet were inextricably linked to movement on high-angle faults as the basin evolved from an extensional setting to a compressional one. The Mainland Formation was channelized along the extensional Round Head Fault during a period of uplift and erosion of the allochthon; it sits stratigraphically on top of the Cape Cormorant Formation where it interfingers with, and overlies, the American Tickle Formation. The Lourdes Thrust Sheet was emplaced as a tectonic wedge within foreland basin sediments above portions of the Goose Tickle Group which unconformably overlie the older West Bay Thrust Sheet; the younger Lourdes Thrust is therefore an out-of-sequence thrust. Stratigraphic and structural relationships in the foreland basin strata indicate that fault inversion was not strictly a post-Emsian process as previously discussed with respect to the Round Head Thrust; evidence from the Harry Brook Fault suggests that inversion occurred prior to the emplacement of the Lourdes Thrust Sheet across Port au Port Peninsula. The Lourdes Thrust Sheet was emplaced to its present position in the tectonic wedge offshore of Port au Port Peninsula in the Early to Middle Devonian and is therefore Acadian. The constraints on timing of emplacement for these two thrust sheets, Middle Ordovician for the West Bay Thrust Sheet and Devonian for the Lourdes Thrust Sheet and their separation by a period of extensional faulting allow us to distinguish between a Taconian and Acadian emplacement. A number of high-angle faults similar to the Round Head Fault have crosscut or deformed the base of the Lourdes Thrust Sheet indicating that fault reactivation occurred, in some cases twice, throughout this portion of the basin.

2.7. References

Batten Hender, K.L., and Dix, G.R., 2008, Facies development of a Late Ordovician mixed carbonate-siliciclastic ramp proximal to the developing Taconic orogen: Lourdes Formation, Newfoundland, Canada: Facies, v. 54, p. 121–149.

Bergstrom, S.M., Riva, J., and Kay, M., 1974, Significance of conodonts, graptolites, and shelly faunas from the Ordovician of western and north-central Newfoundland: Canadian Journal of Earth Sciences, v. 11, p. 1625–1660.

Botsford, J.W., 1987, Depositional history of Middle Cambrian to Lower Ordovician deep water sediments, Bay of Islands, western Newfoundland: Memorial University of Newfoundland, 543 p.

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

Bradley, D.C., and Kidd, W.S.F., 1991, Flexural extension of the upper continental crust in collisional foredeeps: Geological Society of America Bulletin, v. 103, p. 1416–1438.

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

Burden, E.T., Quinn, L., Nowlan, G.S., and Nill, L.A.B., 2002, Palynology and micropaleontology of the Clam Bank Formation (Lower Devonian) of western Newfoundland, Canada: Palynology, v. 26:1, p. 37–41.

Cawood, P.A., and Botsford, J.W., 1991, Facies and structural contrasts across Bonne Bay cross-strike discontinuity, western Newfoundland: American Journal of Science, v. 291, p. 737–759.

Cawood, P.A., McCausland, P.J.A., and Dunning, G.R., 2001, Opening Iapetus: Constraints from the Laurentian margin in Newfoundland: Geological Society of America Bulletin, v. 113, p. 443–453.

Cawood, P.A., and Nemchin, A.A., 2001, Paleogeographic development of the east Laurentian margin: Constraints from U-Pb dating of detrital zircons in the Newfoundland Appalachians: Geological Society of America Bulletin, v. 113, p. 1234–1246.

Chow, N., 1985, Sedimentology and diagenesis of Middle and Upper Cambrian platform carbonates and siliciclastics, Port au Port Peninsula, western Newfoundland: Memorial University of Newfoundland, 458 p.

Chow, N., and James, N.P., 1987, Cambrian Grand Cycles : A northern Appalachian perspective: Geological Society of America Bulletin, v. 98, p. 418–429.

Cooper, M., Weissenberger, J., Knight, I., Hostad, D., Gillespie, D., Williams, H., Burden, E.T., Porter-Chaudhry, J., Rae, D., and Clark, E., 2001, Basin evolution in western Newfoundland : New insights from hydrocarbon exploration: American Association of Petroleum Geologists Bulletin, v. 85, p. 393–418.

Cooper, R.A., Sadler, P.M., Hammer, O., and Gradstein, F.M., 2012, The Ordovician Period, *in* Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G. eds., The Geologic Time Scale 2012, Elsevier B.V., v. 1–2, p. 489–523.

Dewey, J.F., and Casey, J.F., 2013, The sole of an ophiolite: the Ordovician Bay of Islands Complex, Newfoundland: Journal of the Geological Society, v. 170, p. 715–722.

Ingram, R.L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geological Society of America Bulletin, v. 86, p. 937–938.

Jacobi, R.D., 1981, Peripheral bulge-a causal mechanism for the Lower/Middle Ordovician unconformity along the western margin of the Northern Appalachians: Earth and Planetary Science Letters, v. 56, p. 245–251.

James, N.P., and Stevens, R.K., 1986, Stratigraphic correlation of the Cambro-Ordovician Cow Head Group, western Newfoundland: Geologic Survey of Canada Bulletin, v. 366, p. 143.

Klappa, C.F., Opalinski, P.R., and James, N.P., 1980, Middle Ordovician Table Head Group of western Newfoundland: a revised stratigraphy: Canadian Journal of Earth Sciences, v. 17, p. 1007–1019.

Knight, I., Azmy, K., Boyce, W.D., and Lavoie, D., 2008, Tremadocian carbonate rocks of the lower St. George Group, Port au Port Peninsula, western Newfoundland: lithostratigraphic setting of diagenetic, isotopic and geochemistry studies: Newfoudland and Labrador Department of Natural Resources Geological Survey, v. Report 08-, p. 115–149.

Knight, I., and Boyce, W.D., 1991, Deformed Lower Paleozoic platform carbonates, Goose Arm–Old Man's Pond: Newfoundland Department of Mines and Energy, Geological Survey Branch, v. Report 91-, p. 141–153.

Knight, I., and Boyce, W.D., 1987, Lower to middle Cambrian terrigenous-carbonate rocks of Chimney Arm, Canada Bay: Lithostratigraphy, preliminary biostratigraphy and regional significance: Current Research (1987) Newfoundland Department of Mines and Energy, Mineral Development Division, v. Report 87-, p. 359–365.

Knight, I., and James, N.P., 1987, The stratigraphy of the Lower Ordovician St. George Group, western Newfoundland: the interaction between eustasy and tectonics: Canadian Journal of Earth Sciences, v. 24, p. 1927–1951.

Knight, I., James, N.P., and Lane, T.E., 1991, The St. George Unconformity, northern Appalachians: The relationship of plate convergence at the St. Lawrence Promontory to the

Sauk/Tippecanoe: Geological Society of America Bulletin, v. 103, p. 1200–1225.

Lindholm, R.M., and Casey, J.F., 1989, Regional significance of the Blow Me Down Brook Formation , western Newfoundland : New fossil evidence for an Early Cambrian age: Geological Society of America Bulletin, v. 101, p. 1–13.

Loydell, D.K., 2012, Graptolite biozone correlation charts: Geological Magazine, v. 149, p. 124–132.

Maletz, J., and Egenhoff, S., 2011, Graptolite biostratigraphy and biogeography of the Table Head and Goose Tickle Groups of western Newfoundland, *in* Gutierrez-Marco, J.C., Rabano, I., and Garcia-Bellido, D. eds., Ordovician of the World, Cuadernos del Museo Geominero, 14. Instituto Geológico y Minero de España, Madrid, 3-9.

Maletz, J., Egenhoff, S., Böhme, M., Asch, R., Borowski, K., Höntzsch, S., Kirsch, M., and Werner, M., 2011, A tale of both sides of Iapetus – upper Darriwilian (Ordovician) graptolite faunal dynamics on the edges of two continents: Canadian Journal of Earth Sciences, v. 48, p. 841–859.

Peng, S., Babcock, L.E., and Cooper, R.A., 2012, The Cambrian Period, *in* Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G. eds., The Geologic Time Scale 2012, Elsevier B.V., v. 1–2, p. 437–488.

Quinn, L., 1995, Middle Ordovician foredeep fill in western Newfoundland, *in* Hibbard, J.P., van Staal, C.R., and Cawood, P.A. eds., Current perpecives in the Appalachian-Caledonian orogen: Geological Association of Canada, Special Paper 41, p. 43–64.

Quinn, L., 1992a, Foreland and trench slope basin sandstones of the Goose Tickle Group and Lower Head Formation, western Newfoundland: Memorial University of Newfoundland, 574 p.

Quinn, L., 1992b, Diagenesis of the Goose Tickle Group, western Newfoundland: A Report for

Mobil Oil,.

Quinn, L., Bashforth, a R., Burden, E.T., Gillespie, H., Springer, R.K., and Williams, S.H., 2004, The Red Island Road Formation: Early Devonian terrestrial fill in the Anticosti Foreland Basin, western Newfoundland: Canadian Journal of Earth Sciences, v. 41, p. 587–602.

Quinn, L., Harper, D.A.T., Williams, S.H., and Clarkson, E.N.K., 1999, Late Ordovician foreland basin fill: Long Point Group of onshore western Newfoundland: Bulletin of Canadian Petroleum Geology, v. 47, p. 63–80.

Schillereff, S., and Williams, H., 1979, Geology of the Stephenville map area, Newfoundland, *in* Current Research, Part A, Geological survey of Canada, Paper 79-1A, p. 327–332.

Van Staal, C.R., Dewey, J.F., Niocaill, C.M., and McKerrow, W.S., 1998, The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus: Geological Society, London, Special Publications, v. 143, p. 197–242.

Stenzel, S.R., 1991, Carbonate sedimentation in an evolving Middle Ordovician foreland basin, western Newfoundland: Memorial University of Newfoundland, 612 p.

Stenzel, S.R., Knight, I., and James, N.P., 1990, Carbonate platform to foreland basin: revised stratigraphy of the Table Head Group (Middle Ordovician), western Newfoundland: Canadian Journal of Earth Sciences,.

Stevens, R.K., 1970, Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a Proto-Atlantic Ocean, *in* Lajoie, J. ed., Flysch Sedimentology in North America. Geological Association of Canada, Special Paper 7, p. 165–177.

Stockmal, G.S., Slingsby, A., and Waldron, J.W.F., 2004, Basement-involved inversion at the Appalachian structural front , western Newfoundland : an interpretation of seismic reflection data with implications for petroleum prospectivity: Bulletin of Canadian Petroleum Geology, v. 52, p. 215–233.

Stockmal, G.S., and Waldron, J.W.F., 1990, Structure of the Appalachian deformation front in western Newfoundland: Implications of multichannel seismic reflection data: Geology, v. 18, p. 765–768.

Stockmal, G.S., and Waldron, J.W.F., 1993, Structural and tectonic evolution of the Humber Zone, western Newfoundland, 1. Implications of balanced cross sections through the Appalachian structural front, Port au Port Peninsula: Tectonics, v. 12, p. 1056–1075.

Streel, M., Higgs, K., Loboziak, S., Riegel, W., and Steemans, P., 1987, Spore stratigraphy and correlation with floras in the type marine Devonian of the Ardenne-Rhenish regions: Review of Palaeobotony and Palynology, v. 50, p. 211–229.

Waldron, J.W.F., Anderson, S.D., Cawood, P.A., Goodwin, L.B., Hall, J., Jamieson, R. a, Palmer, S.E., Stockmal, G.S., and Williams, P.F., 1998, Evolution of the Appalachian Laurentian margin: Lithoprobe results in western Newfoundland: Canadian Journal of Earth Sciences, v. 35, p. 1271–1287.

Waldron, J.W.F., Henry, A.D., Bradley, J.C., and Palmer, S.E., 2003, Development of a folded thrust stack: Humber Arm Allochthon, Bay of Islands, Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 40, p. 237–253.

Waldron, J.W.F., Hicks, L., and White, S.E., 2012, Stratigraphy, tectonics and petroleum potential of the deformed Laurentian margin and foreland basins in western Newfoundland: Geological Association of Canada–Mineralogical Association of Canada Joint Annual Meeting, Field Trip Guidebook B3. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Open File NFLD/3172, p. 131.

Waldron, J.W.F., and Palmer, S.E., 2000, Lithostratigraphy and structure of the Humber Arm allochthon in the type area, Bay of Islands, Newfoundland: Newfoundland Department of Mines and Energy, Geological Survey, Report, v. 2000–1, p. 279–290.

Waldron, J.W.F., and van Staal, C.R., 2001, Taconian orogeny and the accretion of the Dashwoods block : A peri-Laurentian microcontinent in the Iapetus Ocean: Geology, v. 29, p. 811–814.

Waldron, J.W.F., and Stockmal, G.S., 1991, Mid-Paleozoic thrusting at the Appalachian deformation front: Port au Port Peninsula, western Newfoundland: Canadian Journal of Earth Sciences, v. 28, p. 1992–2002.

Waldron, J.W.F., Stockmal, G.S., Corney, E., and Stenzel, S.R., 1993, Basin development and inversion at the Appalachian structural front, Port au Port Peninsula, western Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 30, p. 1759–1772.

Waldron, J.W.F., Turner, D., and Stevens, K.M., 1988, Stratal disruption and development of melange , Western Newfoundland : effect of high fluid pressure in an accretionary terrain during ophiolite emplacement: Journal of Structural Geology, v. 10, p. 861–873.

White, C.E., Palacios, T., Jensen, S., and Barr, S.M., 2012, Cambrian-Ordovician acritarchs in the Meguma terrane, Nova Scotia, Canada: Resolution of early Paleozoic stratigraphy and implications for paleogeography: Bulletin of the Geological Society of America, v. 124, p. 1773–1792.

Williams, H., 1978, Tectonic lithofacies map of the Appalachian orogen: Memorial University of Newfoundland,.

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

Williams, H., 1985, Humber Arm Allochthon and nearby groups between Bonne Bay and Portland Creek, western Newfoundland, *in* Geological Survey of Canada Current Research,

p. 399–406.

Williams, H., and Hiscott, R.N., 1987, Definition of the lapetus rift-drift transition in western Newfoundland: Geology, v. 15, p. 1044–1047.

Zhang, S., and Barnes, C.R., 2004, Arenigian (Early Ordovician) sea-level history and the response of conodont communities, western Newfoundland: Canadian Journal of Earth Sciences, v. 41, p. 843–865.

Chapter 3: The Taconian Humber Arm Allochthon on Port au Port Peninsula, western Newfoundland

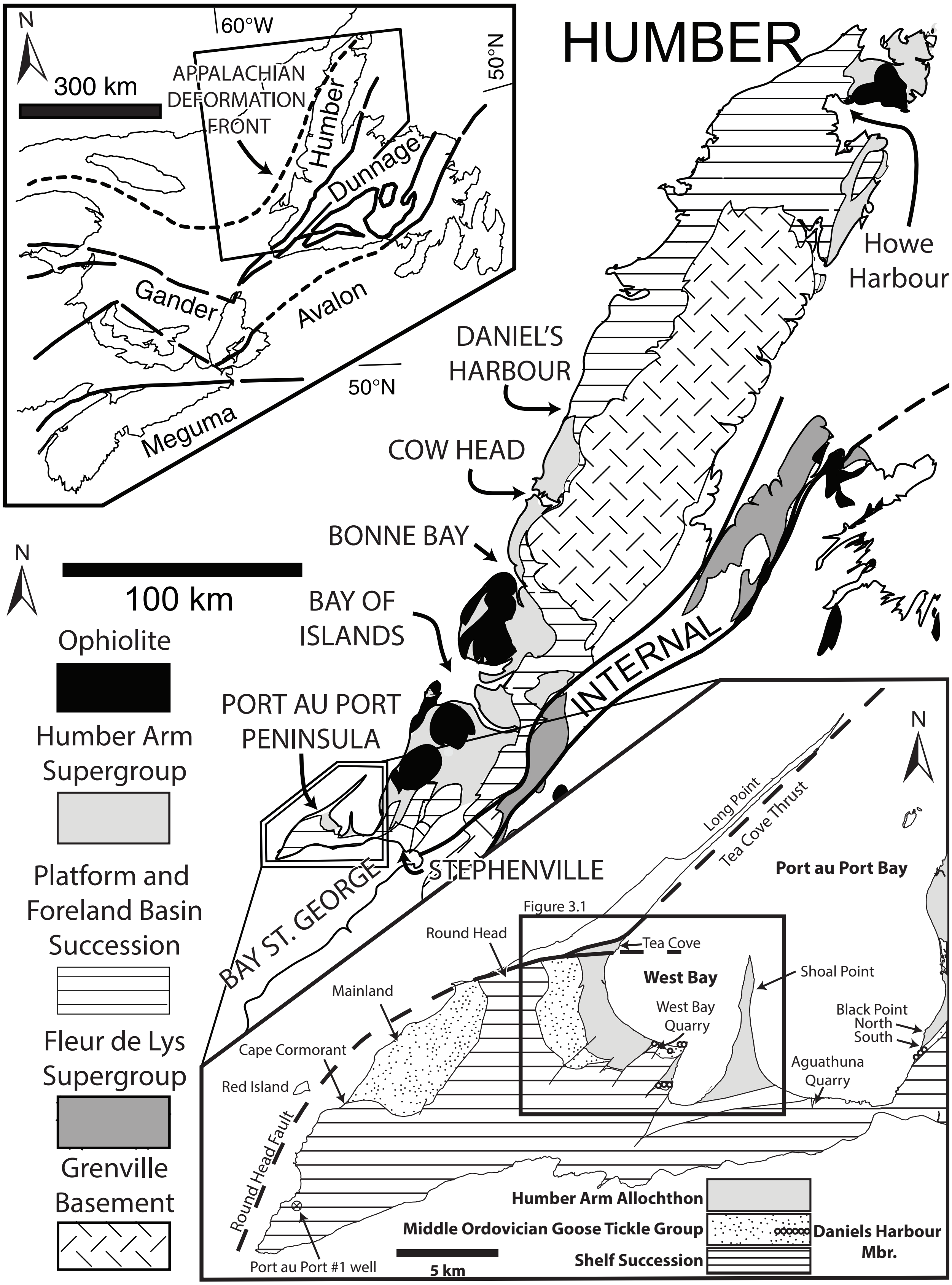
The Humber Arm Allochthon was structurally emplaced onto the Laurentian margin in western Newfoundland during Taconian (Ordovician) and Acadian (Devonian) deformation. On Port au Port Peninsula, allochthonous rocks previously mapped as mélange comprise four map units: the Cooks Brook Formation, Middle Arm Point Formation, Eagle Island Formation, and mélange. At the outcrop scale, a qualitative assessment of disruption separates the first three units into a broken stratigraphy separate from the highly disrupted and mixed mélange unit. Within coherent portions of the broken stratigraphy, three generations of folds are related to Taconian, Acadian and Carboniferous deformation events. In more disrupted parts, volumetric block proportions at outcrop scale show an average of ~24% blocks to 76% shale with a range in block sizes between 0.5 cm to 158 cm. A new sampling technique has allowed for the recovery of oriented mélange samples for thin-section. Multiple orientations of extensional fractures in thin section suggest the Humber Arm Allochthon underwent coaxial extension. Abundant carbonate veins and less common hydrocarbon shows in mélange suggest that high fluid-pressure played a role in the emplacement of the Humber Arm Allochthon. High fluid-pressure is supported by dewatering structures, sandstone dykes and an abundance of autobrecciated carbonate. Map relationships along with outcrop and thin-section scale observations lead to a reinterpreted structural history for western Newfoundland in which an early, thinned, West Bay Thrust Sheet was rapidly emplaced onto the Laurentian margin and subsequently overridden by the out-of-sequence Lourdes Thrust.

3.1. Introduction

Port au Port Peninsula is situated at the westernmost extremity of the region affected by Appalachian deformation in the Humber Zone of western Newfoundland (Figure 3.1). Port au

Figure 3.1: Map of the Humber Zone in Newfoundland highlighting the study area.

(Top left) Lithotectonic subdivision map of the northern Appalachians. (Central) the Humber Zone of western Newfoundland including key localities mentioned in the text. (Bottom right) map of Port au Port Peninsula with key localities and regionally important faults marked. Box indicates the main study area shown in more detail in Figure 3.4. Modified from (Waldron et al., 2003)



N
300 km
60°W
APPALACHIAN
DEFORMATION
FRONT
Humber
Dunnage
50°N
Gander
Avalon
50°N
Meguma
HUMBER
Howe
Harbour
DANIEL'S
HARBOUR
COW HEAD
BONNE BAY
N
100 km
BAY OF
ISLANDS
INTERNAL
Ophiolite
Humber Arm
Supergroup
PORT AU PORT
PENINSULA
STEPHENVILLE
BAY ST. GEORGE
Platform and
Foreland Basin
Succession
Fleur de Lys
Supergroup
Grenville
Basement
N
Long Point
Tea Cove Thrust
Port au Port Bay
Figure 3.1
Round Head
Tea Cove
West Bay
Shoal Point
Mainland
West Bay
Quarry
Black Point
North
South
Cape Cormorant
Aguathuna
Quarry
Red Island
Round Head Fault
Humber Arm Allochthon
Middle Ordovician Goose Tickle Group
Daniels Harbour
Mbr.
Shelf Succession
5 km
Port au Port #1 well

Port Peninsula is a critical location for the current understanding of the Humber Arm Allochthon (Stockmal and Waldron, 1990; Waldron et al., 1993; Stockmal and Waldron, 1993; Waldron et al., 1998; Stockmal et al., 1998, 2004). It displays important structural relationships within a relatively undeformed, unmetamorphosed cross-section through the Appalachian deformation front brought about by a late phase of deformation which has tilted all of the strata to the northwest. The Humber Arm Allochthon on Port au Port Peninsula has previously been mapped as mélange due to the highly disrupted nature of rock units (Williams and Cawood, 1989). However, results presented by Lacombe (Chapter 2) show that the area mapped as mélange includes substantial sections of foreland basin strata. The reduced area now mapped as Humber Arm Allochthon represents one of the last 'unknowns' in this structurally important area.

Taconian (Ordovician) orogenesis signals the onset of Iapetus ocean closure in western Newfoundland; ophiolites found in the Bay of Islands area (Figure 3.1) were obducted onto the Laurentian margin during this period of eastward subduction and arc-continent collision (Hibbard et al., 2007; Dewey and Casey, 2013). These ophiolites form the highest structural slice within a package of allochthonous, deep water rocks collectively known as the Humber Arm Allochthon (Williams, 1975). Within the Humber Zone of western Newfoundland, rocks of the Humber Arm Allochthon overlie autochthonous passive margin carbonates and foreland basin siliciclastics of the ancient Laurentian margin.

Regional study of Taconian events in western Newfoundland is hindered by a proliferation of stratigraphic terms used for closely similar units in different areas. We outline a rationalized stratigraphy for western Newfoundland, consolidating stratigraphic terminology. We describe map patterns within the Humber Arm Allochthon that are indicative of a complex deformation history involving out-of-sequence thrusting of the allochthon, multiple generations of folds, and reactivation of underlying high-angle faults. We then outline a method of disruption mapping that allows the distinction of broken formation from mélange and makes it easier to identify map-scale structures amongst sparse outcrop. The friable nature of most mélange outcrops makes sample collection difficult; therefore, a technique for extracting oriented samples from mélange was developed. We use the resulting data to examine deformation within the allochthon and attempt to piece together a chronology for both fault movement and fold overprinting on Port au Port Peninsula.

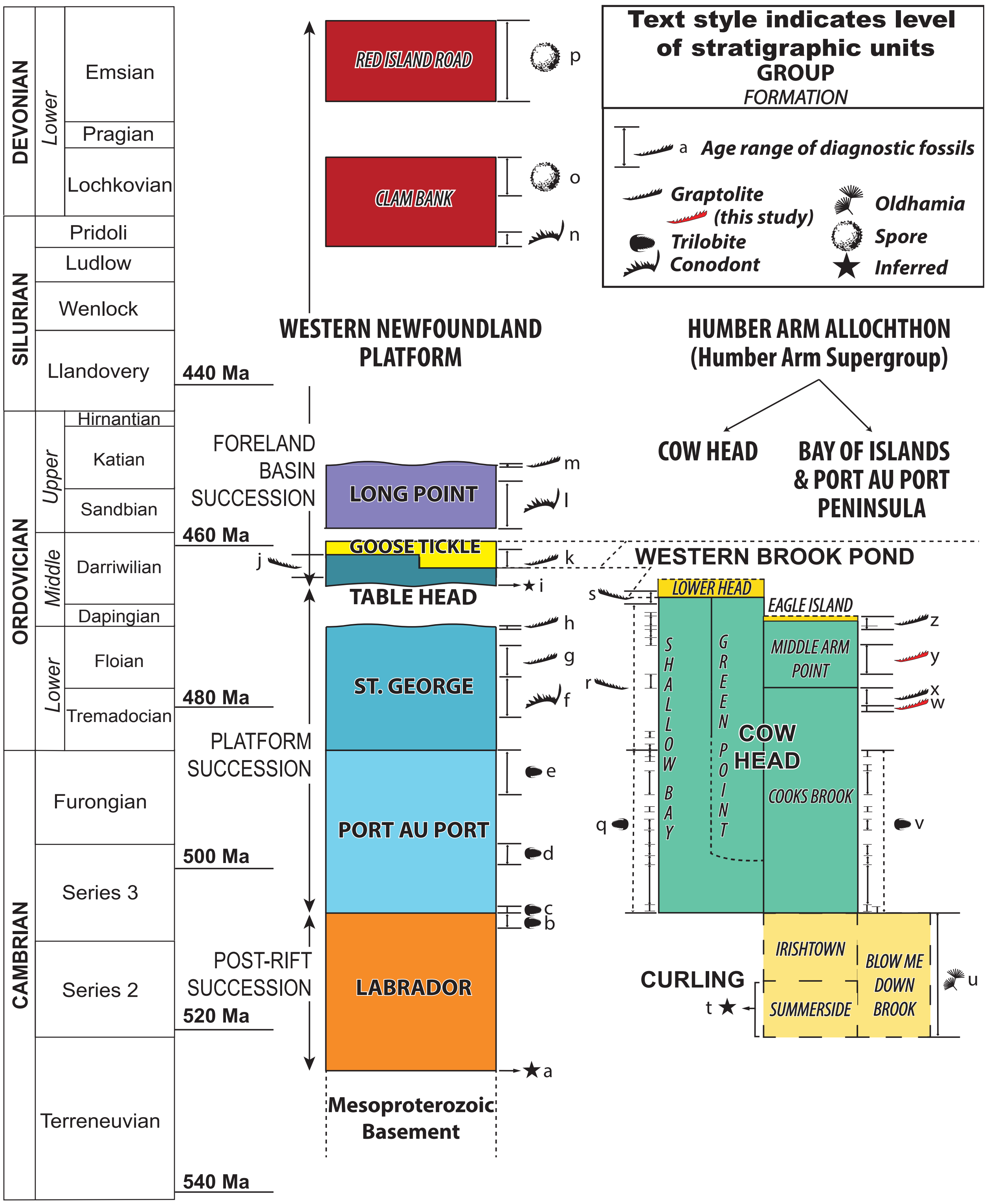
The Humber Arm Allochthon is the likely source rock for petroleum systems in western Newfoundland (Cooper et al., 2001). Oil seeps, documented on Port au Port Peninsula since 1865, were found within areas of allochthonous mélange (Hicks and Owens; Waldron et al., 2012). A number of wells have been drilled since then, many of which were drilled on Shoal Point (Figure 3.1) (Waldron et al., 2012). Although the Humber Arm Allochthon is a likely source rock for hydrocarbons (Schwangler et al., *in preparation*), the feasibility of any potential hydrocarbon play would rely on an understanding of the heterogeneity of both lithology and structure within the allochthon.

3.2. Geological Setting

Rifting of the Laurentian margin during the Neoproterozoic opened the Iapetus Ocean (Williams and Hiscott, 1987; Cawood et al., 2001). In Newfoundland, the Labrador Group (Williams and Hiscott, 1987) and offshore equivalent Curling Group record rift and post-rift deposition (Figure 3.2; Stevens 1970; Waldron & Palmer 2000). Above the Labrador Group, a long-lived Cambrian to Early Ordovician carbonate platform is represented by the Port au Port and St. George groups (Chow, 1985; Chow and James, 1987; Knight and James, 1987). Debris shed from the platform into deeper water was deposited stratigraphically above the Curling Group in an offshore carbonate and shale succession here assigned to the Cow Head Group (Figure 3.2). Eastward subduction, and obduction of suprasubduction ophiolites (Dewey and Casey, 2013), during Taconian (Ordovician) arc-continent collision loaded the Laurentian margin; loading resulted in a westward-migrating peripheral bulge which uplifted portions of the carbonate shelf to produce the Middle Ordovician St. George Unconformity (Jacobi, 1981; Knight et al., 1991). Continued

Figure 3.2: Stratigraphy of western Newfoundland.

Compilation of biostratigraphic ages: (a) base estimated at 525-520 Ma (Cawood et al., 2001); (b) trilobites: Glossopleura Zone and Albertella Zone (Knight and Boyce, 1991); (c) trilobites: *Olenoides longispinus*, *Ehmaniella cloudensis* (Knight and Boyce, 1987)*; (*d) trilobites: *Cedaria Zone, Crepicephalus Zone* (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 zone (Maletz et al., 2011); (j) graptolites: *Holmograptus lentus zone, Nicholsonograptus fasciculatus, Pterograptus elegans zone*; (k) graptolites: *Nicholsonograptus fasciculatus, ?Pterograptus elegans* (Chapter 2); (l) conodonts: *Amorphognathus tvaerensis* (Bergstrom et al., 1974; Batten Hender and Dix, 2008)*; (*m) graptolite: *Geniculograptus pygmaeus* (Quinn et al., 1999) (n*) Ozarkodina eosteinhornensis zone* (Burden et al., 2002)*;* (o) *Emphanisporites micromatus – Streelispora newportensis* Assemblage zone (Burden et al., 2002); (p) spores: *Emphanisporites annulatus – Camarozonotiletes sextantii* zone (Quinn et al., 2004) correlated with (Streel et al., 1987); (q) trilobites: *Bathyuriscus-Elrathina* Zone, *Ptychgnostus gibbus, Bolaspidella, Cedaria, Crepicephalus, Aphelaspis, Dunderbergia, Taenicephalus, Rasettia magna, Missisquoia, Symphysurina brevispicata* (James and Stevens, 1986); the basal *Bathyuriscus-Elrathina* Zone is correlated to the boundary between *Glossopleura* and *Ehmaniella* Zone (Peng et al., 2012); (r) graptolites: *Staurograptus dichotomus*, *Anisograptus matanensis*, *Tetragraptus approximatus*, *Didymograptus protobifidus*, *Isograptus primulus*, *Isograptus victoriae lunatus*, *I. v. victoriae*, *I. v. maximus* and others (James and Stevens, 1986); (s) graptolites: base of the Lower Head varies with locality from *I. v. maximus* to *U. austrodentatus* biozone (James and Stevens, 1986; Botsford, 1987); (t) top and bottom estimated by Cawood & Nemchin (2001); (u) *Oldhamia* - (Lindholm and Casey, 1989; Cawood and Nemchin, 2001; Burden et al., 2001) correlated with White et al. (2012); (v) Trilobites: *Ehmaniella* Zone and *Ptychagnostus gibbus* Zone, *Bolaspidella* Zone, *Cedaria*, *Crepicephalus*, *Dunderbergia*, *Taenicephalus*, *Rasettia magna*, *Saukiella junia*, *Saukiella serotina*, *Symphysurina brevispicita* (Boyce et al., 1992) (w) graptolite: *Aorograptus victoriae*; (x) graptolite: *Araneograptus murrayi* (Botsford, 1987); (y) *Pendeograptus fruticosis* Zone; (z) graptolite: *I. v. lunatus*, *I. v. victoriae* (Botsford, 1987).



DEVONIAN
Lower
Emsian
Pragian
Lochkovian
SILURIAN
Pridoli
Ludlow
Wenlock
Llandovery
ORDOVICIAN
Upper
Hirnantian
Katian
Sandbian
Middle
Darriwilian
Dapingian
Lower
Floian
Tremadocian
CAMBRIAN
Furongian
Series 3
Series 2
Terreneuvian
440 Ma
460 Ma
480 Ma
500 Ma
520 Ma
540 Ma
RED ISLAND ROAD
CLAM BANK
WESTERN NEWFOUNDLAND PLATFORM
FORELAND BASIN SUCCESSION
LONG POINT
GOOSE TICKLE
TABLE HEAD
ST. GEORGE
PLATFORM SUCCESSION
PORT AU PORT
POST-RIFT SUCCESSION
LABRADOR
Mesoproterozoic Basement
Text style indicates level of stratigraphic units
GROUP
FORMATION
Age range of diagnostic fossils
Graptolite
(this study)
Trilobite
Conodont
Oldhamia
Spore
Inferred
HUMBER ARM ALLOCHTHON (Humber Arm Supergroup)
COW HEAD
BAY OF ISLANDS & PORT AU PORT PENINSULA
WESTERN BROOK POND
LOWER HEAD
EAGLE ISLAND
MIDDLE ARM POINT
SHALLOW BAY
GREEN POINT
COW HEAD
COOKS BROOK
CURLING
IRISHTOWN
SUMMERSIDE
BLOW ME DOWN BROOK

lithospheric flexure led to a period of extension across the carbonate platform that during subsidence, eventually drowned the platform, reducing carbonate productivity within the foreland basin; this period is recorded by the Table Head Group (Figure 3.2) (Stenzel 1991; Chapter 2). Turbidites were shed from an advancing allochthon onto the autochthonous platform where they overlie the Table Head Group; these turbidites comprise the Middle Ordovician Goose Tickle Group (Figure 3.2) (Quinn, 1992b, 1992a).

The Humber Arm Allochthon is lithologically and structurally diverse in western Newfoundland. North of Bonne Bay (Figure 3.1), near Cow Head, the allochthon comprises primarily sedimentary rocks deposited on the ancient slope and rise of the Laurentian margin and is overlain by foreland basin clastics; these rocks are now arranged in a series of imbricate thrust slices. In contrast, the Humber Arm Allochthon documented in the Bay of Islands area (Figure 3.1) is made up ofa number a thrust slices with a more diverse range in lithology; the lowest of which, containing slope and rise strata and overlying foreland basin clastics equivalent to those mapped north of Bonne Bay, is characterized by complex folding and stratal disruption (Waldron et al., 1988). Intermediate thrust slices in this area comprise volcanic and plutonic units of the Skinner Cove Formation (Baker, 1978) and Little Port Complex (Williams and Malpas, 1972) while the structurally highest slice comprises the Bay of Islands Ophiolite Complex (Williams, 1995).

On Port au Port Peninsula, only the lowest of these thrust slices is present; higher units are presumed to have been removed, if they were present, through weathering and erosion. Here, Lacombe (*Chapter 2)* has mapped two allochthonous thrust sheets on Port au Port Peninsula separated from one another by autochthonous and neo-autochthonous Middle Ordovician foreland basin strata (Figure 3.3). The structurally lower West Bay Thrust Sheet represents the preserved tip of the Humber Arm Allochthon emplaced across Port au Port Peninsula during Middle Ordovician Taconian orogenesis (Chapter 2). The West Bay Thrust Sheet is thin (between 10 and 20 m in places) and is unconformably overlain by Goose Tickle Group strata. Overlying fault scarp detritus, included in the Goose Tickle Group, indicates that block faulting continued after it was emplaced (Chapter 2). The out-of-sequence Lourdes Thrust Sheet (Chapter 2) tectonically overlies the Goose Tickle Group on Port au Port Peninsula and fills a tectonic wedge within foreland basin strata in offshore seismic profiles (Stockmal and Waldron, 1990; Waldron and Stockmal, 1991). The tectonic wedge is considered to have reached its final position in the Early Devonian or later, as Early Devonian strata are folded above the wedge (Figure 3.3) (Stockmal et al., 2004).

The Round Head Fault (Figure 3.1) crosscuts the tectonic wedge as seen in seismic profiles (Stockmal et al., 2004); the Round Head Fault is a basement-cutting thrust at present day that has inherited its geometry from a normal fault developed during Taconian extension and possibly earlier Iapetan rifting (Waldron et al., 1993). Inversion of the Round Head Fault post-dated final emplacement of the Lourdes Thrust Sheet; the Round Head Fault does not crosscut overlying Carboniferous strata, implying that inversion probably occurred during the Middle to Late Devonian (Waldron and Stockmal, 1991; Waldron et al., 1998). This period of deformation, including both wedge formation and basin inversion, is associated with the regional Acadian orogenic event by Stockmal & Waldron (1993).

High-angle faults bound structural blocks on Port au Port Peninsula and show a protracted history of movement (Figure 3.4). These faults dominantly strike NE-SW and dip steeply either to the NW or SE (Chapter 2). Faults are identified by abrupt changes in thickness of Middle Ordovician stratigraphy indicative of syntectonic deposition along Taconian extensional faults (Chapter 2). At least one fault, the Harry Brook Fault, was active after emplacement of the West Bay Thrust but before the Acadian Lourdes Thrust. Some of these faults, similar to the Round Head and Harry Brook Fault, were later inverted in the Devonian (Lacombe Chapter 2; Waldron & Stockmal 1991; Waldron et al. 1993; Palmer et al. 2002; Stockmal et al. 2004). Additionally, high-angle faults which bound Carboniferous basins on Port au Port Peninsula and nearby in the Bay St. George area commonly show strike-slip movement associated with Late Devonian to Early Carboniferous deformation (Figure 3.1) (Stockmal and Waldron, 1990; Waldron et al.,

Figure 3.3: Schematic cross-section through Port au Port Peninsula in the Early Devonian.

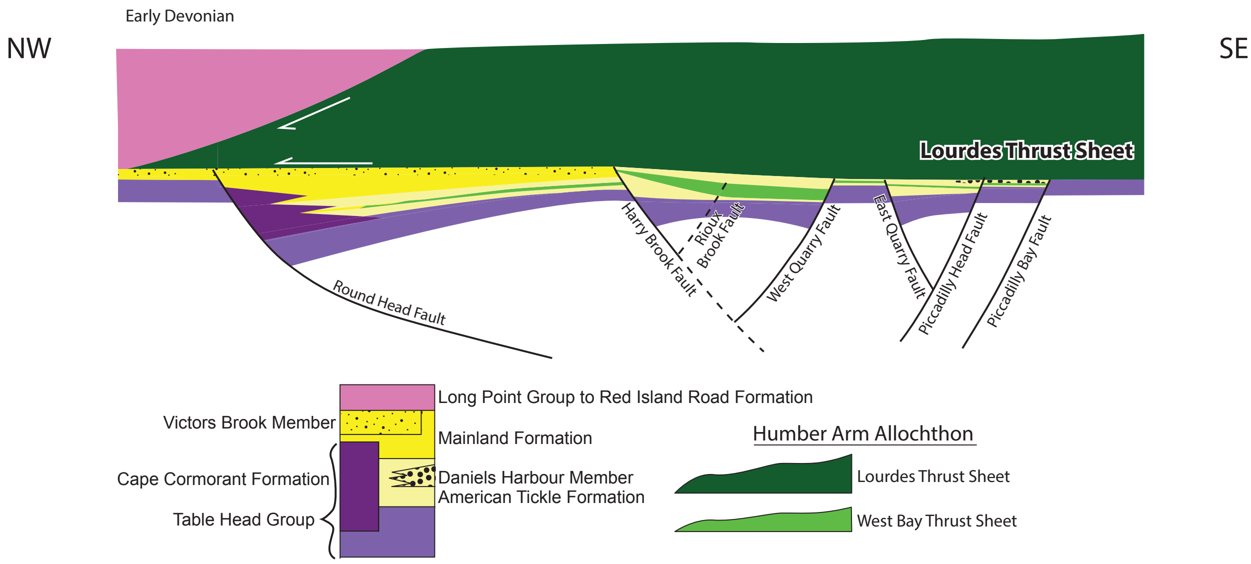
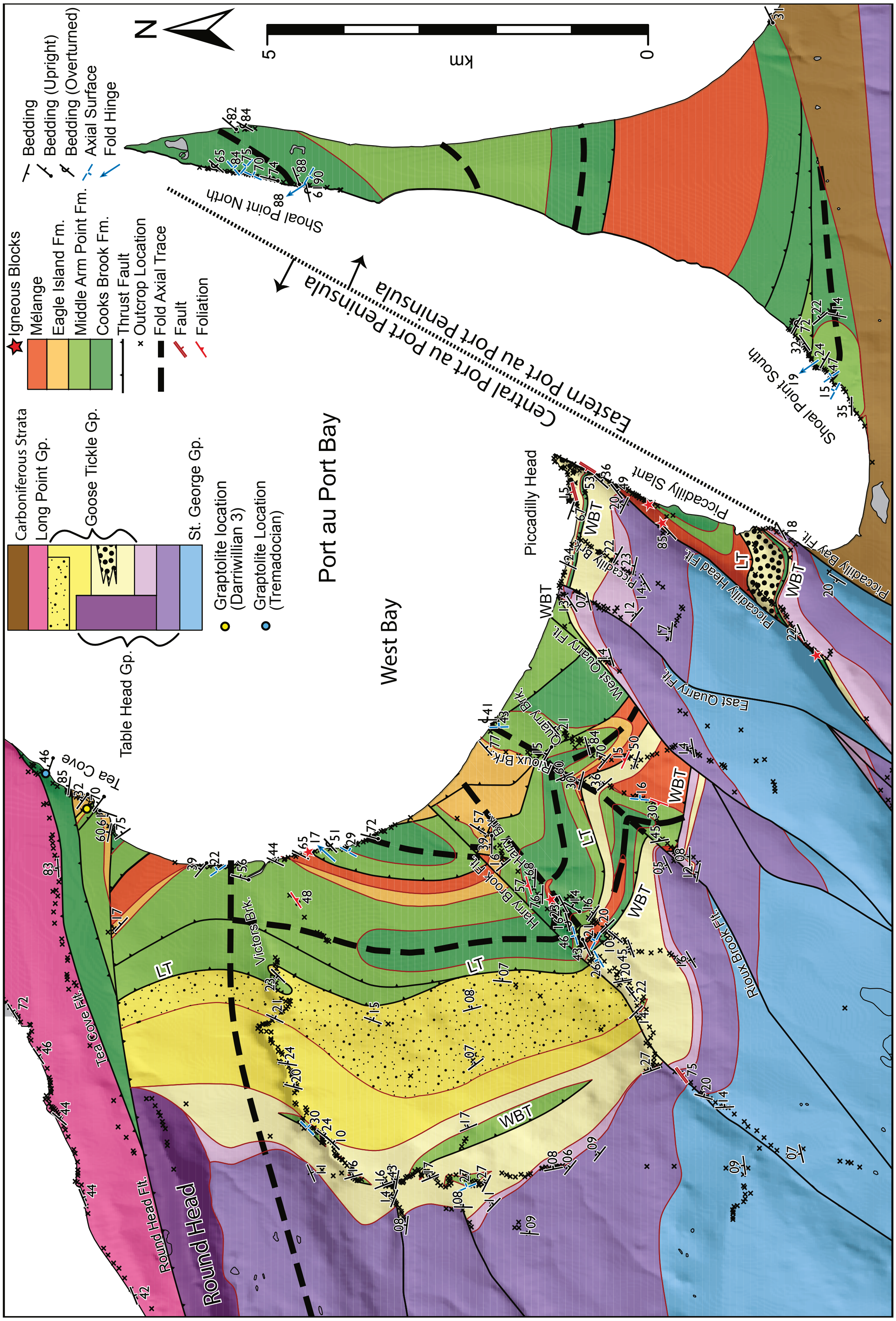


Figure 3.4: Geological map of a portion of Port au Port Peninsula.

(next page) Key localities are shown including graptolite locations and igneous block locations. Abbreviations: WBT=West Bay Thrust, LT= Lourdes Thrust, Brk=Brook, Flt.=Fault, Gp.=Group, Fm.=Formation, Mbr.=Member



Carboniferous Strata
Long Point Gp.
Goose Tickle Gp.
Table Head Gp.
St. George Gp.
Graptolite location (Darriwillian 3)
Graptolite Location (Tremadocian)
Igneous Blocks
Mélange
Eagle Island Fm.
Middle Arm Point Fm.
Cooks Brook Fm.
Thrust Fault
Outcrop Location
Fold Axial Trace
Fault
Foliation
Bedding
Bedding (Upright)
Bedding (Overturned)
Axial Surface
Fold Hinge
N
5
0
km
Port au Port Bay
West Bay
Central Port au Port Peninsula
Eastern Port au Port Peninsula
Shoal Point North
Shoal Point South
Piccadilly Head
Piccadilly Slant
Tea Cove
Round Head

1998; Palmer et al., 2002; Waldron et al., 2015). These later fault movements have crosscut all of the structures on Port au Port Peninsula.

3.3. Stratigraphy

3.3.1. Previous work

Different stratigraphic schemes have been assigned to rocks of the Humber Arm Allochthon north and south of Bonne Bay (Figure 3.1; 3.2); these stratigraphic schemes have been inconsistently applied to the Port au Port Peninsula. To avoid these ambiguities and facilitate regional correlation we here suggest a rationalization and simplification of the lithostratigraphy of the Humber Arm Allochthon. To the north of Bonne Bay, allochthonous rocks are organized in a series of imbricated thrust slices (James and Stevens, 1986); the Cow Head Group and stratigraphically overlying flysch of the Lower Head Formation comprise the Humber Arm Allochthon in this area (Figure 3.1; 3.2) (Schuchert and Dunbar, 1934; Kindle and Whittington, 1958; James and Stevens, 1986). The Cow Head Group is divided into the Shallow Bay and Green Point formations which are, respectively, proximal and distal equivalents of one another (Figure 3.2) (James and Stevens, 1986). South of Bonne Bay, in the Bay of Islands area (Figure 3.1), allochthonous rocks are heavily folded, display disorganized thrust and normal faults, and include both mélanges and prominent ophiolites (Stevens, 1970; Botsford, 1987; Waldron et al., 1988; Cawood and Botsford, 1991; Dewey and Casey, 2013). The Humber Arm Allochthon in the Bay of Islands area contains strata contemporaneous with the Cow Head Group and overlying Lower Head Formation; these strata were assigned to the Northern Head Group and overlying Eagle Island Formation by Botsford (1987) and Williams & Cawood (1989) (Figure 3.2). The Northern Head Group is composed of the Cooks Brook Formation (closely similar to the Green Point Formation) and the overlying finer-grained Middle Arm Point Formation (Botsford, 1987). In contrast to the Cow Head area (Figure 3.1), these carbonate-dominated units are underlain by Cambrian rift- and drift-related siliciclastic rocks of the Curling Group, offshore equivalents to the autochthonous Labrador Group (Figure 3.2). The Curling Group includes the younger Irishtown Formation and the older Summerside Formation (Stevens, 1965); the Blow-Me-Down Brook Formation is a tectonically separate unit that is probably time-equivalent to the Summerside Formation (Lindholm & Casey 1989; Palmer et al. 2001; Figure 3.2).

3.3.2. Revised Stratigraphy

3.3.2.1. Cow Head Group

The area previously mapped as Humber Arm Allochthon on Port au Port Peninsula includes interbedded limestone, shale, chert and rarer limestone conglomerate that are stratigraphically overlain by sandstone and shale flysch. This general stratigraphy is consistent with both the Bay of Islands area and the Cow Head region north of Bonne Bay (Figure 3.1); both stratigraphic schemes have previously been informally applied to outcrops on Port au Port Peninsula (Waldron et al. 2012; Figure 3.2). Our observations confirm the interpretation of Botsford (1987) who suggested that the Green Point Formation (Cow Head Group) and the Northern Head Group are lithologically similar and that the Northern Head Group is likely either a distal or a lateral equivalent of the Cow Head Group (James and Stevens, 1986). However, we consider that a group-level distinction between the two successions is inappropriate. We recommend that the Cooks Brook and Middle Arm Point formations be placed into an expanded Cow Head Group (Figure 3.2) and the Northern Head Group of Botsford (1987) be abandoned.

3.3.2.2. Western Brook Pond Group

Continental slope successions of the Cow Head Group, as defined here, are stratigraphically overlain by clastic “flysch” deposits mapped as the Lower Head Formation north of Bonne Bay (James and Stevens, 1986) and the Eagle Island Formation in the Bay of Islands area (Botsford, 1987). The stratigraphic top of each of these units is either unexposed or tectonically faulted against overriding allochthonous units (James and Stevens, 1986; Botsford, 1987). The Lower

Head and Eagle Island formations are both composed of turbiditic sandstone, conglomerate, siltstone, and shale that are difficult to distinguish in the field. Neither formation has been consistently assigned to any group-level unit previously. The name Western Brook Pond Group, previously proposed by Johnson (1941) to describe similar lithologies, was subsequently abandoned by James & Stevens (1986); we revive this group-level designation for the Lower Head and Eagle Island formations. This group level designation has utility in mapping in poorly exposed areas where a distinction between closely similar units is not easily made, or when discussing allochthonous flysch units within the Humber Arm Allochthon as a whole.

3.3.3. Cow Head Group: Cooks Brook Formation

Lithology and Location: The Cooks Brook Formation on Port au Port Peninsula is dominated by thinly to rarely thickly bedded (bed thickness scale of Ingram 1954) parted limestone to ribbon limestone, dolomitic limestone, and grey shale (Figure 3.5a). This unit is best exposed at Tea Cove just south of the Tea Cove thrust (Figure 3.4) in a series of disrupted slices, and on the northwest coast of Shoal Point in a folded beach section (Figure 3.4). Lithologically, these sections resemble portions of the Cooks Brook Formation mapped further north in the Bay of Islands area by Botsford (1987). Coarse-grained portions of the Cooks Brook Formation are also found further south along the coast at Tea Cove where the Cooks Brook Formation is in tectonic contact with younger strata (Figure 3.4; 3.5b; 3.5c; 3.5d; Appendix A). This section is dominated by coarse sand-sized amalgamated beds of limestone and dolomitic limestone with scattered pebble and cobble-sized clasts commonly concentrated above scoured surfaces as pebble lags.

On weathered surfaces, limestone beds are commonly planar or cross laminated and consist of very fine to fine sand-sized carbonate grains. Fresh surfaces typically appear crystalline with faint or no depositional structures. Less common are concretionary micritic limestone beds, and thick beds of calcarenite to calcirudite with limestone clasts ranging in size from coarse sand to pebbles. Flat-pebble conglomerates occur rarely (Figure 3.5d). Calcite and variable amounts of dolomite averaging silt-size (~0.02 mm) form continuous calcisiltite beds or, within coarser calcarenite and calcirudite units, form the matrix between clasts. Peloids are the most common grain constituents followed by ooids and fragmented body fossils such as trilobites and brachiopods; lithoclasts containing groups of these constituents are found within coarser portions of this unit (Figure 3.5c). Quartz and chert grains comprise anywhere from 1% to 40% of a sample; in abundance, the clastic grains commonly define lamination. Limestone beds in more deformed parts of the allochthon commonly have an auto-brecciated appearance (the 'rubbly surface texture' of Waldron et al. 1988) characterized by an abundance of extensional fractures crosscutting the bedding surfaces (Figure 3.6). These fractures are commonly filled with rubble or brecciated mud material from adjoining beds (Figure 3.6). A thin section through one of these auto-brecciated carbonates reveals that multiple generations of calcite veins were present prior to brecciation (Figure 3.6).

Stratigraphic Contacts: Nowhere in the mapped area is the base of the Cooks Brook Formation exposed. The formation top, however, may be exposed in a cliff section (Figure 3.5e; 3.5f) along the coast of Piccadilly Slant (described under Middle Arm Point Formation below; Figure 3.4).

Biostratigraphy: Graptolites were recovered from this unit at Tea Cove (Figure 3.4). They include *Paratemnograptus isolatus*, *Aorograptus victoriae* and *Rhabdinopora sp.* (Figure 3.5), collectively placing this unit within the A. Victoriae biozone of the lowest Ordovician, Tremadocian stage. Based on this faunal evidence, the unit mapped on Port au Port Peninsula is correlative to at least the upper, Ordovician portions of the Cooks Brook Formation mapped in the Bay of Islands by Botsford (1987) (Figure 3.1). This fossil evidence also correlates the Cooks Brook Formation on Port au Port Peninsula to the lower portion of the autochthonous St. George Group (Figure 3.2). No Cambrian fossils have been found in the Humber Arm Allochthon on Port au Port Peninsula. The Curling Group, underlying the Cooks Brook Formation in the Bay of Islands area, is absent (Figure 3.2; Figure 3.1).

Interpretation: The relatively uniform alternation of shale and thinly bedded (scale of Ingram 1954) detrital limestone suggests that hemipelagic to pelagic sedimentation was punctuated by a

Figure 3.5: Typical lithologies, upper contact and graptolites found in the Cooks Brook Formation.

(a) Ribbon limestone and grey shale and; (b) massive calcarenite at Tea Cove. (c) Photomicrograph of calcarenite. (d) Flat-pebble conglomerate at Tea Cove. e - f) Unannotated and annotated contact of Cooks Brook Formation with overlying Middle Arm Point Formation at Piccadilly Slant. Graptolite species recovered from the Cooks Brook Formation: g-h) *Rhabdinopora sp.* collected at Tea Cove; (i) *Aorograptus victoriae* collected at Tea Cove and; (j-k) *Paratemnograptus isolatus* collected at Tea Cove. All localities can be found in Figure 3.1 or Figure 3.4.

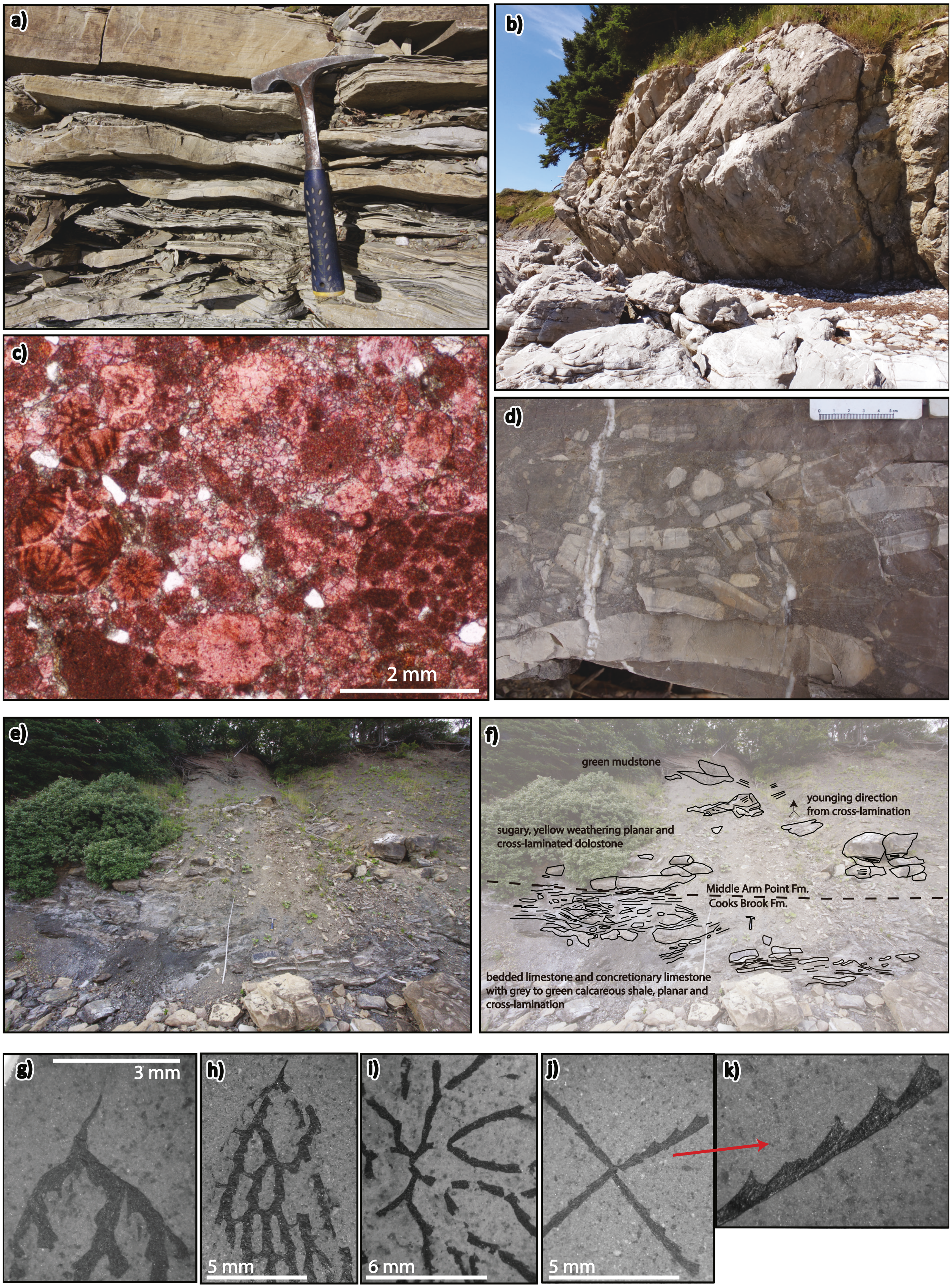
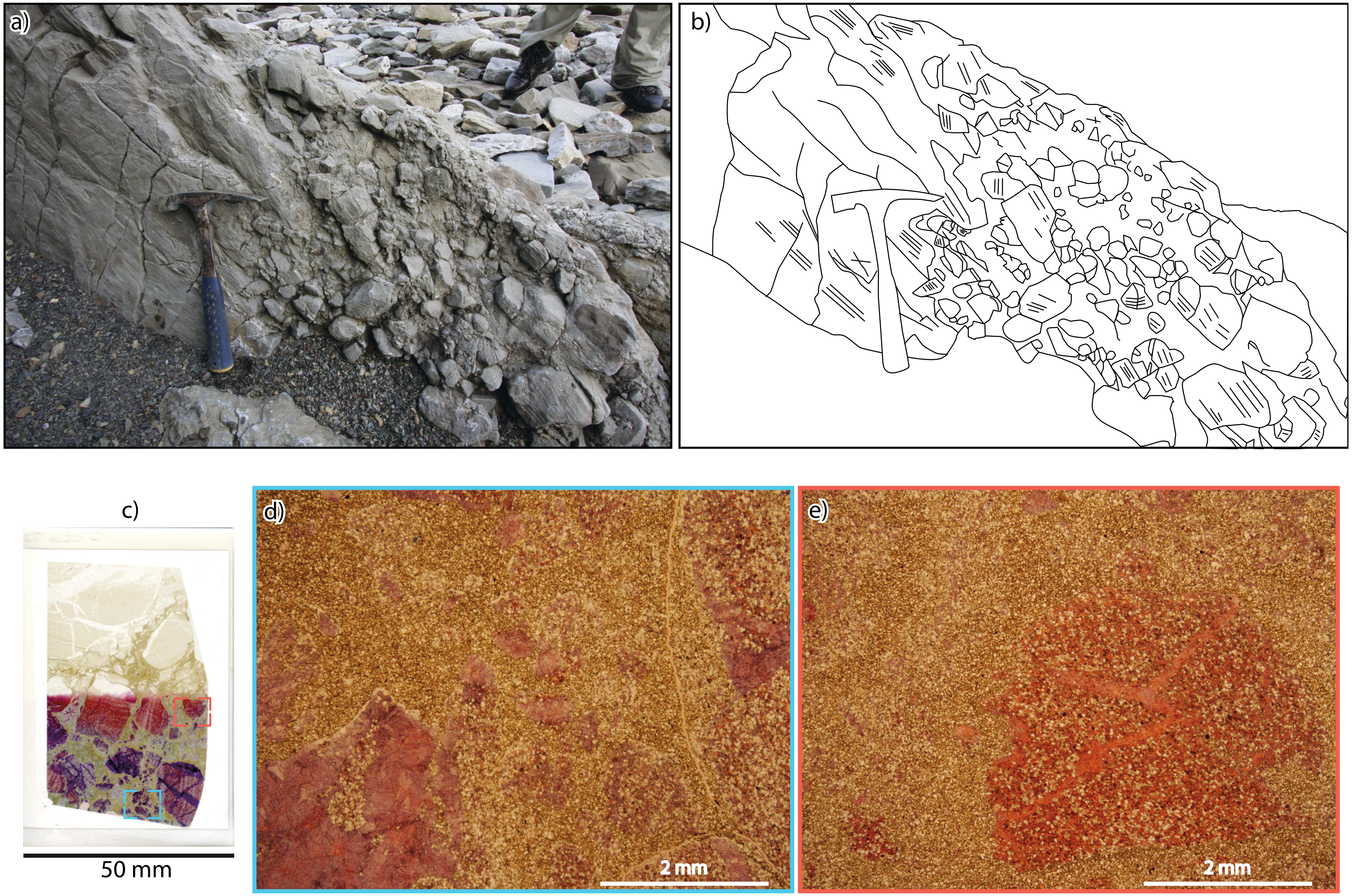

a)
b)
c)
2 mm
d)
e)
f)
green mudstone
younging direction
from cross-lamination
sugary, yellow weathering planar and
cross-laminated dolostone
Middle Arm Point Fm.
Cooks Brook Fm.
bedded limestone and concretionary limestone
with grey to green calcareous shale, planar and
cross-lamination
g)
3 mm
h)
5 mm
i)
6 mm
j)
5 mm
k)

Figure 3.6: Autobrecciation texture.

(a) (left) extensional fractures crosscutting the surface (right) of autobrecciated or rubbly limestone conglomerate at Piccadilly Slant and (b) annotation of figure. (c) Thin-section showing autobrecciated limestone; the bottom half of the thin section is stained with alizarin red-S and potassium ferricyanide to distinguish carbonates and iron content respectively. Carbonates are stained pink to purple. (d-e) Photomicrographs of thin-section shown in (c), locations are marked. Photomicrographs in plane-polarized light, limestone clasts are stained pink to purple; surrounding silty matrix contains primarily dolomite, quartz and clays.


a)
b)
c)
50 mm
d)
2 mm
e)
2 mm

regular episodic supply of carbonate sediment. This alternation of shale and limestone, combined with the internal sequence of sedimentary structures, is consistent with turbidity current deposition. Fine-grained, graded, and thinly bedded limestone commonly displaying cross-lamination, less common planar lamination, and lacking massive intervals are all characteristic features of distal turbidites (Flügel, 2010). The fine-grained nature of the limestone and relative rarity of coarser grained or conglomeratic beds, when compared to more proximal beds of the Cow Head Group north of Bonne Bay (Figure 3.1), may suggest deposition involved lower energy, in a deeper water environment. Beds of coarser material in the Cooks Brook Formation are likely the result of either platform progradation or regression, delivering higher-energy, farther-travelled turbidity currents to distal portions of a turbidite fan as proposed by Botsford (1987).

3.3.4. Cow Head Group: Middle Arm Point Formation

Lithology and Location: The Middle Arm Point Formation on Port au Port Peninsula is dominated by red, green, and less commonly grey, siliceous mudstone and shale (Figure 3.7). Locally this unit contains thin to medium beds (scale of Ingram 1954) of red or green radiolarian chert (Figure 3.7c), minor packages of ribbon limestone, intermittent silty dolostone (as yellow laminae or as interbeds) (Figure 3.7a), and minor lenses of carbonate conglomerate (Figure 3.7e). Bioturbation is common on basal bedding surfaces (Figure 3.7b). The Middle Arm Point Formation also contains abundant pyrite nodules up to 10 cm across (Figure 3.7d).

A 200 m section at Black Point North (Figure 3.1, Appendix A) represents the largest and most complete section of Middle Arm Point Formation in the Port au Port region. A lithologically similar section of Middle Arm Point Formation is found at Shoal Point South (Figure 3.4). Contrasting sections are found along the coast north of the mouth of Victors Brook, near the base of the allochthon at Black Point South, and north of West Bay Quarry (Figure 3.1, 3.4). The various mapped sections closely resemble the Middle Arm Point Formation of Botsford (1987) who included the section at Black Point North as part of his Middle Arm Point Formation.

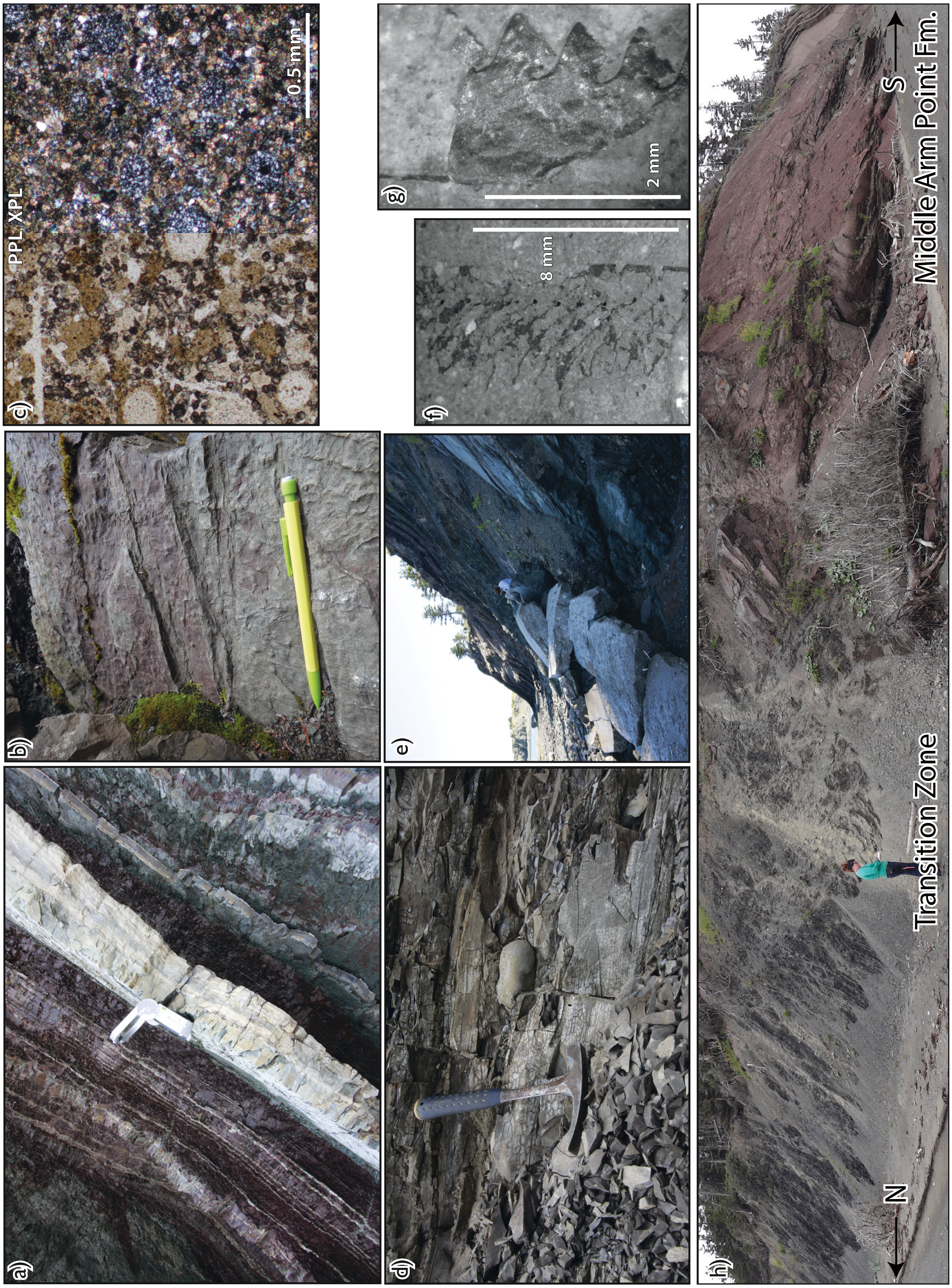
The section at Black Point North is dominated by green, red, and minor grey siliceous mudstone, chert, and shale passing upward into an interval of chert and yellow dolomitic laminae. Above the chert, this section transitions back into predominantly red siliceous mudstone and shale. Grey, thinly bedded to parted sandy limestone beds with grey shale interbeds are present in minor amounts. Near the middle of the section are two pebble- to cobble-sized limestone conglomerate beds, ~20 cm thick, that pinch out laterally (Figure 3.7e; Appendix A). Very thin beds (scale of Ingram 1954) of granule limestone conglomerate are also observed within the Middle Arm Point Formation along the coast at Shoal Point South (Figure 3.4). Overlying the highest red siliceous mudstone at Black Point North is a section of grey to green grey mudstone and shale with very thin to thin (scale of Ingram 1954) interbeds of calcareous silt.

At Tea Cove a 35 m thick section of the Middle Arm Point Formationis dominated by red shale containing numerous shear zones, and is overlain by a ~15 m interval of red and green, bioturbated siliceous mudstone and chert. Up section is an interval dominated by grey/green mudstone with minor interbedded calcareous siltstone. This section contains a single medium bed of crystalline limestone, one single limestone concretion, and one thick bed of lime mudstone. This grey mudstone probably represents the top of the Middle Arm Point Formation and may correlate with the section at Black Point North (Figure 3.1; Appendix A). Similarly, the coastline north of the mouth of Victors Brook (Figure 3.4) displays a distinctive section of grey, with minor green mudstone and shale, which hosts one bioturbated silty dolostone bed and an abundance of pyrite nodules up to 15 cm in diameter (Figure 3.7). This ~12 m section of shallowly dipping strata strikes along the coastline and can be correlated with other grey mudstone and shale sections found at the top of the Middle Arm Point Formation at both Black Point North and Tea Cove (Figure 3.1; Appendix A).

Other distinctive sections of Middle Arm Point Formation are present at Black Point South and on the coast near West Bay Quarry (Figure 3.1) just above the platform-allochthon contact; at these locations, the Middle Arm Point Formation comprises thick intervals of grey, blocky, nodular or boudinaged chert, with thin shale partings (Figure 3.7f).

Figure 3.7: Typical lithologies, graptolites, and transition zone within the Middle Arm Point Formation.

(a) Red, green, and yellow shale mudstone and chert at Black Point North. (b) Bioturbated bottom surface in Harry Brook. (c) Photomicrograph of radiolarian chert from Black Point. (d) Grey shale and mudstone with large pyrite concretion along the coast near Victors Brook. (e) Limestone bed within the Middle Arm Point Formation at Black Point North. (f-g) Graptolite species *Didymograptus* (Expansograptus) *pennatulus* collected from the Middle Arm Point Formation at Black Cove North. g) Transition zone at the top of the Middle Arm Point Formation at Black Point. All localities can be found in Figure 3.1 or Figure 3.4.



a)
b)
c)
PPL XPL
0.5 mm
d)
e)
f)
8 mm
g)
2 mm
h)
N
S
Transition Zone
Middle Arm Point Fm.

Stratigraphic Contacts: The lower contact of the Middle Arm Point Formation is not well exposed on Port au Port Peninsula; the best exposure of the lower contact is in a highly disrupted and attenuated section at Piccadilly Slant (Figure 3.4; 3.5e; 3.5f). At this section, parted sandy limestone beds and concretionary limestone, interpreted as Cooks Brook Formation, are overlain by sandy dolostone, thought to represent the Woman Cove Member; which sits at the base of the Middle Arm Point Formation in the Bay of Islands area (Botsford 1987). The contact here is poorly exposed and interpreted to be a deformed stratigraphic contact. The presence of scaly shale, containing blocks with polished surfaces, as well as the proximity of this outcrop to a major high-angle fault, are indicative of a high degree of deformation. The upper contact of the Middle Arm Point Formation with the overlying Eagle Island Formation is best exposed in the coastal section at Black Point North (Figure 3.1). Here, grey shale and calcareous siltstone, assigned to the Middle Arm Point Formation, transition up-section into thinly bedded (scale of Ingram 1954), very fine to fine grained, variably calcareous sandstone and grey shale of the Eagle Island Formation (Figure 3.7). Following Botsford (1987), the upper contact of the Middle Arm Point Formation is placed at the base of the first sandstone bed (Appendix A).

Biostratigraphy: Graptolites were recovered from this unit at Black Cove (Figure 3.1). They include *Didymograptus (Expansograptus) pennatulus,* placing this unit within the P. fruticosis zone of Floian age (Figure 3.7, 3.2). This age, along with lithologic characteristics, and the observed lower contact with the underlying Cooks Brook Formation, all support a correlation with the Middle Arm Point Formation as mapped in the Bay of Islands area. The Middle Arm Point Formation is time-correlative with the upper part of the autochthonous St. George Group (Catoche and Aguathuna formations) (Figure 3.2).

Interpretation: Thick silty dolostone beds found above the Cooks Brook Formation at Piccadilly Slant (Figure 3.4; 3.5), and inland along multiple brook traverses, are similar to those seen within the Woman Cove member of the Middle Arm Point Formation in the Bay of Islands (Botsford, 1987) where they are of Tremadocian age. These silty dolostone beds overlie parted limestone and shale of the Cooks Brook Formation and are likely age equivalent to a period of dominantly peritidal carbonate deposition in the St. George Group upslope (Figure 3.2). The sudden thick influx of silt-sized dolomite into the basin is interpreted by Knight (1978) and Boyce (1983) to correlate with a period of subaerial exposure on the platform correlating to the Boat Harbour disconformity.

Radiolarian chert, abundant shale, and siliceous mudstone sitting stratigraphically higher in the Middle Arm Point Formation are indicative of deep water, pelagic to hemipelagic deposition. This period of deposition is synchronous with a period of relative sea level rise and subtidal carbonate deposition on the platform (Knight and James, 1987); as a result, less detritus was shed into the deeper basin. Minor limestone conglomerate and parted limestone intervals within the Middle Arm Point Formation probably represent farther-travelled, high-energy sediment gravity flows shed from the platform during regressive intervals in this period of overall transgression. The transition upward through the Middle Arm Point Formation from silty dolostone beds near the base of the unit to more siliceous beds near the top suggests a change from dominantly turbiditic peri-platform deposition to a more quiescent deep-water, pelagic depositional environment. A greater proportion of chert beds near the top of the Black Point North section (Figure 3.1; Appendix A) may suggest that isolated sections of nodular chert found along the coast near West Bay Quarry and at Black Point South (Figure 3.1) are correlative with upper portions of the Middle Arm Point Formation. The transition to grey/green mudstone and shale near the top of the Middle Arm Point Formation may indicate a switch to primarily hemipelagic sedimentation. Intermittent limestone and dolostone beds represent the last gasp of platform-derived sedimentation into the deep basin before the Eagle Island Formation was deposited (Figure 3.2).

3.3.5. Western Brook Pond Group: Eagle Island Formation

The Eagle Island Formation is best exposed at Black Point North (Figure 3.1). Two facies are present here; the first, at the base of the Eagle Island Formation at Black Point North, is dominated by grey mudstone and shale with thin beds of fine to very fine, variably calcareous sandstone

Figure 3.8: Typical lithologies and structures found in the Eagle Island Formation.

(a) Loaded beds at the top of facies 1, base of facies 2 at Black Point North; facies 1: (b) thinly bedded cross-laminated sandstone in mudstone. Facies 2: (c) amalgamated sandstone beds with pebble lag at the base of a graded bed, younging to the left of the photo (west) at Black Point North. (d) Coarse sand to pebble conglomerate, poorly cemented at Black Point North. (e) De-watering structures at Tea Cove. (f) Conglomerate bed eroded into underlying sandstone at Black Point North; clasts are dominantly green and red siliceous mudstone containing yellow dolomitic lamination. (g) Red and green siliceous mudstone and chert and; (h) friable mudstone clast at Black Point North. (i) calcite concretions at Tea Cove.


a)
b)
c)
d)
e)
f)
g)
h)
i)

displaying planar, cross, or convolute lamination (Figure 3.8b). Grey sandstone beds are variably calcareous and commonly weather red or yellow. The second, more prominent facies of the Eagle Island Formation overlies the first at Black Point North along an undulatory surface characterized by large load features (Figure 3.8a). This facies is dominated by poorly cemented and typically friable grey sandstone of medium-sand size or coarser and common intervals of pebble conglomerate with both clast-dominated and sand-matrix-dominated varieties (Figure 3.8; Appendix A). Poor sorting is evident throughout this unit and clasts are commonly angular or subangular. Dominant clast lithologies include chips of shale, siliceous mudstone, dolostone, and chert (Figure 3.8f;3.8g;3.8h); sandstone and pebble conglomerate units have a speckled arkosic appearance. Beds here are dominantly very thick to massive (scale of Ingram 1954), graded, and commonly amalgamated (Figure 3.8c); interbedded grey shale is rare. Basal surfaces of beds within this dominant facies of the Eagle Island Formation are often sharp and undulatory with clear load structures and abundant flute and groove casts (Figure 3.8); pebble lags are also common above basal surfaces (Figure 3.8c). Isolated outcrops of the Eagle Island Formation in Harry Brook are dominated by coarse-pebble to cobble size carbonate clasts within a friable matrix of coarse sand (Figure 3.4). Dewatering structures (Figure 3.8e) and calcareous concretions (Figure 3.8i) are common and one sandstone dyke was observed on Port au Port Peninsula along the coastline south of the mouth of Harry Brook (Figure 3.4). In the Bay of Islands area, sandstone dykes are a common feature near the base of the Eagle Island Formation marking the transition zone with underlying Middle Arm Point Formation strata (Botsford, 1987).

Stratigraphic contacts: Botsford (1987) assigned the base of the Eagle Island Formation to the base of the first sandstone bed; this contact with the underlying Middle Arm Point Formation is transitional. This transitional contact is best exposed at Black Point North (Figure 3.1; Appendix A). Here, massive amalgamated coarse sandstone beds with intermittent pebble conglomerate are assigned to the Eagle Island Formation; a sharp, undulatory contact places this coarse sandstone package overtop of grey shale and thinly bedded fine to very fine sandstone. The base of the Eagle Island Formation is placed at the base of the lowest sandstone bed where it is in contact with grey shale and silt of the underlying Middle Arm Point Formation (Figure 3.2; Appendix A). No upper contact of the Eagle Island Formation is exposed on Port au Port Peninsula or in equivalent strata in the Bay of Islands (Botsford 1987; Waldron & Palmer 2000; Figure 3.1).

Biostratigraphy: No fossils were recovered from this formation on Port au Port Peninsula. This unit however occurs stratigraphically above the Middle Arm Point Formation at both Black Point North and Tea Cove (Figure 3.1), indicating that it is Floian or younger. Graptolites collected by Botsford (1987) in the Bay of Islands (Figure 3.1) included *Isograptus victoriae victoriae,* place the Eagle Island Formation within the Castlemanian 2 (Ca2) biozone of Dapingian age (Figure 3.2). This allows the Eagle Island Formation to be distinguished from the younger Goose Tickle Group (Darriwilian 3) overlying the platform succession (Chapter 2).

Interpretation: The large, angular clasts in the Eagle Island Formation suggest deposition close to the sediment source. A variety of recognizable clast lithologies in this unit bear a striking resemblance to the underlying Middle Arm Point Formation which suggests that the Middle Arm Point Formation was a dominant sediment source during deposition. Graded bedding and sharp undulatory, scoured basal bedding surfaces suggest high-energy deposition from rapid sediment suspension events in a deeper-water depositional environment. Amalgamated sandstone and conglomerate beds at Black Point show minimal interbedded shale and indicate that constant, high-energy currents removed any underlying fine grained sediment. Dewatering structures within the Eagle Island Formation also indicate that sediment was rapidly deposited. Sandstone dykes at the basal contact are likely the result of infilling of extensional fractures by sand. These observations are consistent with turbidite deposition in front of an advancing allochthonous mass into an under-filled basin. Pelagic and hemipelagic sedimentation continued between turbidity current events. The change in character of the Eagle Island Formation between Tea Cove and Black Cove is interpreted as a function of their relative distance from the sediment source, representing respectively, more distal and more proximal portions of a turbidite fan. The Eagle Island is commonly overlain by mélange and broken formation consistent with truncation, shortly after deposition, by the front of the advancing Humber Arm Allochthon.

Distinguishing Western Brook Pond Group from Goose Tickle Group: A distinction between the Goose Tickle Group and Western Brook Pond Group is made on the basis of stratigraphic relationships, facies relationships, and lithology; biostratigraphy is locally useful. The Black Cove and American Tickle formations of the Goose Tickle Group are most easily distinguished from other sandstone turbidite dominated units by an abundance of shale (usually 70% or more) (Quinn, 1995); the abundance of platform-derived carbonate conglomerate facies contained in the American Tickle Formation is not found in any of the other units (Chapter 2) (Figure 3.3). The Mainland Formation is more difficult to distinguish from the Western Brook Pond Group as it also contains medium to coarse, occasionally amalgamated, sandstone beds displaying basal pebble lags, flutes and grooves; a shale-chip conglomerate facies is however, distinctive (Chapter 2) (Figure 3.3). The Western Brook Pond Group is most easily distinguished from the Mainland Formation by its stratigraphic continuity with the underlying Cow Head Group, the coarser grain size (coarse sand to pebble), the angular and often friable nature of clasts (Figure 3.8h), poorer sorting, and overall immaturity. The Western Brook Pond Group can also be distinguished in the presence of dewatering structures (Figure 3.8e); these features are indicative of rapid expulsion of water due to loading, probably associated with tectonic imbrication of the Western Brook Pond Group; they are not found in rocks of the Goose Tickle Group.

Units in the Western Brook Pond Group have yielded graptolite assemblages equivalent to the Darriwilian 1 Zone in the case of the Lower Head Formation (James and Stevens, 1986) and the Castlemanian 2 Zone in the case of the Eagle Island Formation (Botsford, 1987). Graptolites have only been successfully collected from the basal portion of these two units and as such, they may extend up section into younger ages. The Goose Tickle Group, however, commonly yields graptolites equivalent to the younger, Darriwilian 3 Zone (Chapter 2).

Tectonically bounded or otherwise isolated sections of sandstone can be difficult to assign to either unit. One such section, at Tea Cove, places deformed thin to medium beds of sandstone and shale above the Middle Arm Point Formation and tectonically below a prominent cliff of more intact sandstone containing dewatering structures and assigned to the Eagle Island Formation (Figure 3.4). Graptolites collected from this small, shale-dominated section are indicative of the Darriwilian 3 graptolite zone; and we therefore assign it to the Goose Tickle Group rather than the Eagle Island Formation. The implication of this discovery is that the Goose Tickle Group likely unconformably overlies the Middle Arm Point Formation at Tea Cove where it is interleaved with the allochthon (Figure 3.4); a similar relationship has been observed by Lacombe (Chapter 2) in other parts of Port au Port Peninsula.

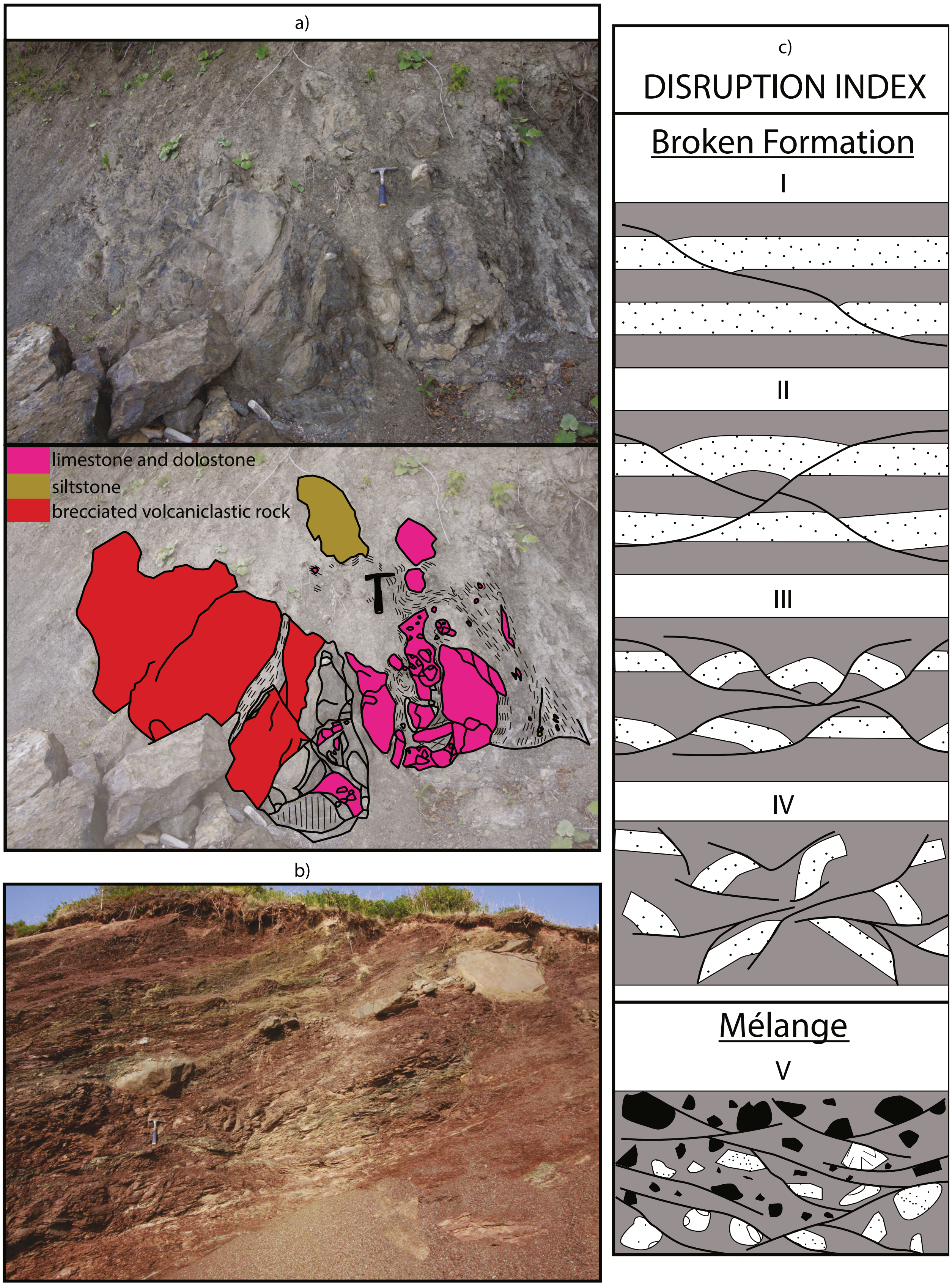
3.3.6. Mélange and igneous units

Most of the Humber Arm Allochthon on Port au Port Peninsula has previously been mapped as mélange (Williams and Cawood, 1989). However our mapping (Figure 3.4) shows that the allochthon is composed predominantly of sedimentary rocks of the Cow Head and Western Brook Pond groups. Therefore, the presence of exotic igneous blocks can be used to indicate areas of mélange. On Port au Port Peninsula, mafic igneous material is found in a number of localities (Figure 3.4). The two largest outcrops of exotic material are exposed along Piccadilly Slant, and within Harry Brook. Outcrops range in size from boulder-size blocks situated in a scaly-shale matrix, to whole outcrops up to 5 m across. Igneous material is commonly found mixed with scaly shale and/or blocks from the Cooks Brook and Middle Arm Point formations (Figure 3.9a). Scaly shale is characterized by a large number of anastomosing, bedding-parallel fracture planes that are commonly polished and slickensided suggesting that fabric formed by shearing of original fissility. The combination of originally fissile rocks containing an abundance of fracture planes commonly results in extremely friable outcrop.

Poor exposure makes the nature of contacts between outcropping igneous material and the surrounding stratigraphy difficult to discern. The composition of these igneous blocks is variable; some appear crystalline while others are volcaniclastic with abundant small clasts. Mafic igneous blocks are found within zones mapped as mélange throughout western Newfoundland. Igneous

Figure 3.9: Photographs of typical mélange outcrop and disruption index.

(a) Unannotated and annotated outcrop photo of mélange containing igneous blocks and sedimentary blocks mixed together at Piccadilly Slant. (b) A second type of mélange where two sedimentary units are mixed within scaly shale; here a string of sandstone blocks of characteristic Eagle Island Formation llithology is mixed with red shales and siliceous mudstone blocks of the Middle Arm Point Formation at Black Point.


a)
limestone and dolostone
siltstone
brecciated volcaniclastic rock
b)
c)
DISRUPTION INDEX
Broken Formation
I
II
III
IV
Mélange
V

blocks sampled on Port au Port Peninsula are similar in lithology to those from mélange zones bounding large structural slices of allochthonous strata in the Bay of Islands area (Waldron, 1985) (Figure 3.1). Preliminary geochemical analyses of igneous blocks collected from Port au Port Peninsula show a mixture of results suggesting that some blocks are sourced from arc magmatism while others are ocean island basalts (N. Holden, University of Alberta, personal communication). Similar igneous blocks studied in the Bay of Islands area (Figure 3.1), much closer to possible sources for igneous material, show a similar dichotomy of geochemical sources (Langille, 2009). The Skinner Cove Formation (Baker, 1978; Williams, 1995), Woods Island Succession (Waldron et al., 2002), Little Port Complex (Williams and Malpas, 1972) and Bay of Islands Complex (Dewey and Casey, 2013) are all possible sources for igneous material that sit structurally above the Curling Group and Cow Head Group (Figure 3.2).

At Black Point South (Figure 3.1), red shale and chert of the Middle Arm Point Formation have, incorporated within them, sandstone blocks of inferred Eagle Island Formation lithologies (Figure 3.9b; 3.2). Similarly, in Harry Brook, a large cliff exposes mixed siliceous mudstone and limestone blocks within a scaly shale matrix; these lithologies are representative of the Middle Arm Point Formation and Cooks Brook Formation respectively (Figure 3.4; 3.2). These sections at Black Point South and Harry Brook (Figure 3.1; 3.4) are also considered mélange (disruption index V) because, although they lack igneous blocks, they contain blocks from multiple formations and cannot be assigned to any single stratigraphic unit for mapping purposes.

Areas of mélange on Port au Port Peninsula are commonly found structurally below thrusted portions of the Cow Head Group or in structurally high positions either above the Cow Head Group or above the Eagle Island Formation. The contact between Cow Head Group and Eagle Island Formation has been observed in a few localities on Port au Port Peninsula; in other areas it appears the Eagle Island Formation is thinned or non-existent and the Cow Head Group is directly overlain by mélange.

3.4. Structure

3.4.1. Methods

3.4.1.1. Field mapping

The shaly and commonly friable nature of disrupted allochthonous rocks on Port au Port Peninsula has led to poor exposure; outcrops are almost exclusively found along coastal sections and brooks. The amount of disruption within these outcrops varies across the peninsula, probably as a result of both low-angle emplacement-related faults and high-angle platform-cutting faults. Within less disrupted strata, outcrop-scale folds are common and in some cases, multiple phases of deformation are indicated by fold overprinting relationships. The lack of cleavage development makes the exact chronology of fold generations difficult to determine. We attempt here to piece together a chronology of deformation from scattered outcrops.

3.4.1.2. Field characterization of disrupted units

The origin and classification of mélange has been reviewed by Festa et al. (2010) and Festa et al. (2012). Following these reviews we treat mélange and broken formation as endmembers in a range of deformation styles. Raymond (1975) defines mélange as a mappable unit of deformed rock which contains both native and exotic blocks commonly in a scaly, disrupted matrix. An exotic block is then defined as any extraformational block not lithologically associated with the surrounding material (Berkland et al. 1972). Broken formation, on the other hand, is entirely intraformational, involving stratal disruption without mixing between units (Hsü K. J., 1968; Festa et al., 2012).

Disruption at outcrop scale within the Humber Arm Allochthon was assessed using a 0-V disruption index (Figure 3.9c), modified from Waldron & Palmer (2000), to give a qualitative assessment of how pervasively an outcrop had been disrupted by faulting. A disruption level of 0 was used in areas where outcrops were either too poorly exposed, or lacked marker beds for disruption assessment. A disruption level of I is assigned where marker beds are present and relatively undisrupted (Figure 3.9c). Level II disruption is assigned to outcrops that display fractured marker beds and minor offset, such that beds are still continuous (Figure 3.9c). Level III disruption is assigned where marker beds have become fragmented into non-contiguous pieces but are still sufficiently aligned to be traceable across an outcrop (Figure 3.9c). Level IV disruption is assigned where marker beds are fragmented and disturbed such that individual beds are untraceable across an outcrop (Figure 3.9c). Disruption indices of II-IV involve various levels of stratal disruption with no obvious incorporation of exotic material and therefore constitute 'broken formation' (Figure 3.9c) in the classification of Festa et al. (2012). A disruption level of V has similar characteristics as level IV but contains 'exotic' or extraformational blocks that indicate both stratal disruption and mixing have occurred (Figure 3.9c); this level of disruption therefore designates mélange in the Festa et al. (2012) classification. While a level I-V disruption may indicate a progression of stratal disruption as a result of extension, other mechanisms for mixing material into a mélange are also considered.

3.4.1.3. Volumetric block proportions

Within highly disrupted areas, showing IV or V disruption, scanlines were used to assess the proportion of blocks to scaly shale matrix. 15 scanlines ranging in length from 1.5 to 9 m were assessed within disrupted rocks along the coast at Piccadilly Slant and Black Point where exposure was best (Figure 3.1; 3.4). All blocks were measured to the nearest half-centimetre using a minimum cutoff size of 0.5 cm. Block sizes here may be biased by arbitrary cutoffs which limit sizes to >0.5 cm, and to less than the length of the scanline; these cutoffs may influence estimates of volumetric block proportions.

3.4.1.4. Sample collection and description

Collecting samples of mélange is difficult due to the brittle and friable nature of the scaly shale matrix. In an attempt to keep a sample intact for transport and petrographic analysis we developed a technique using expanding foam in which a pillar was chipped out of the outcrop, an open-ended box was then placed over the pillar, and expanding foam was sprayed around the pillar. The edges of the box were marked to show the sample orientation. Once the foam had set, the pillar was broken off at the bottom and the bottom of the sample was encased in foam. Once transported, the samples were cut along oriented planes, dried, and set with blue epoxy so that oriented thin sections could be cut. Thin sections were cut from four samples in the inferred direction of transport (perpendicular to foliation in the shale and parallel to a lineation indicating slip direction, if present). PA014A was the first sample collected and cut; thin sections cut from this sample retain the normal thickness of 30 µm. Thin sections cut from samples SC026A, SA024A, and PF051B were ground to 10 µm so that more detail could be observed in these fine grained rocks. Although significant voids were opened during sample collection, the samples remained sufficiently coherent for study. Structures present in each of the samples are measured as clockwise (CW) rakes down from either the SE or NE strike line of each thin-section.

3.4.1.5. Microscopy

Reflected light microscopy was used to distinguish sulphide minerals from bitumen. Bitumen is black under reflected light while sulphides appear shiny and metallic. Fluorescence microscopy was used as a thermal maturity indicator for organic matter within thin-section samples; fluorescence was observed by N. Harris (University of Alberta) and O. Ardakani (Geological Survey of Canada). In this technique, hydrogen-rich organic matter absorbs UV-blue light and re-emits longer wavelength light. For liptinite macerals, fluorescence color changes from green to greenish yellow to yellow to orange in reflected blue light; these colors correspond to thermal maturity ranging from immature, to early oil window, to middle oil window respectively (Hackley and Cardott, 2016). Mature and over-mature organic matter do not fluoresce as intensely, or at all, due to a diminished hydrogen component.

3.4.2. Results: Coherent stratigraphic units

3.4.2.1. Shoal Point North

Along the northeastern and northwestern coastline at Shoal Point North (Figure 3.4) are low-lying outcrops of ribbon to parted limestone mapped as the Cooks Brook Formation. The strata here are steeply dipping to vertical; opposing younging directions within adjacent, almost parallel limestone beds suggests the presence of steeply plunging, isoclinal or tight folds. A few sections of outcrop along the beach here (Figure 3.10) expose fold overprinting relationships. F1 folds are tight and steeply plunging. F1 axial surfaces are gently refolded about a NW-SE striking, steeply dipping axial surface creating a SE closing, steeply plunging fold (interpreted below as F3) (Figure 3.10a). In another outcrop (Figure 3.10b) are two generations of folds in gently dipping strata; a gentle fold (interpreted as F2 below) with a NE-SW trending axial trace is gently refolded about a NW-SE striking axial surface into a downward closing, gently plunging, upright fold (F3).

Interpretation: Three generations of folding are required to generate the folds at Shoal Point (Figure 3.4; 3.10). Tight to isoclinal F1 folds are considered to have formed during emplacement of the Humber Arm Allochthon, probably as overturned fault-propagation folds along low-angle thrust faults. F1 folds must have been refolded in order to tilt the F1 fold hinges into a vertical orientation (Figure 3.10a); this was probably facilitated by folding about a NE-SW F2 fold axial surface (Figure 3.10b). A NW-SE strike direction for F3 fold axial surfaces is observed in both outcrops at Shoal Point (Figure 3.4). Here, they overprint both F1 (Figure 3.10a) and F2 folds (Figure 3.10b). These observations are consistent with isoclinal folds being subjected to type 3 (NE-SW F2 folds) and later type 2 fold interference (NW-SE F3 folds) (Ramsey and Huber, 1987). The strike of F2 axial surfaces is coincident with NE-SW striking faults (Piccadilly Bay and Piccadilly Head faults) which have been mapped further south (Chapter 2) and are thought to run offshore near the tip of Shoal Point (Figure 3.4). We suggest that F2 folds may have been related to fault inversion, similar to folded strata observed at Piccadilly Slant along the Piccadilly Head Fault by Lacombe (Chapter 2). NW-SE striking F3 axial surfaces are observed in outcrops at Shoal Point (Figure 3.10; Figure 3.4). F3 Axial surfaces are perpendicular to the previously mentioned offshore faults. We suggest that F3 folding is related to strike-slip movement on these faults consistent with sinistral slickenlines on the Piccadilly Bay Fault described by Lacombe (Chapter 2).

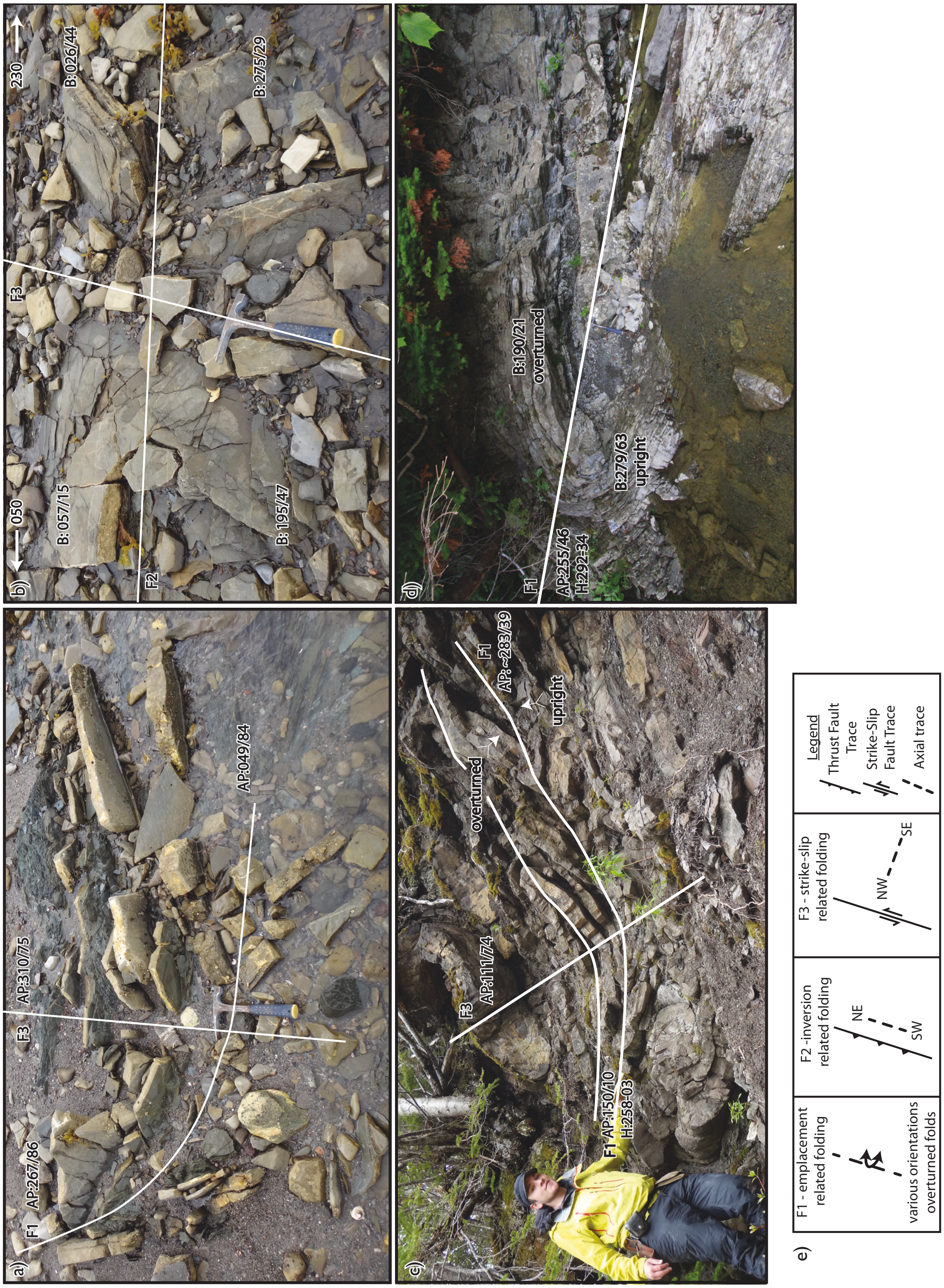
3.4.2.2. Harry Brook

Inland along Harry Brook, at the southern extremity of the Lourdes Thrust Sheet (Figure 3.4), red siliceous mudstone and shale mapped as Middle Arm Point Formation (Figure 3.10c) are separated from an outcrop of grey limestone and shale mapped as the Cooks Brook Formation (Figure 3.10d) by 60 m of poor exposure. The outcrop of Middle Arm Point Formation (Figure 3.10c) shows isoclinal F1 folds that are gently inclined to the SW or NE and plunge gently to the SW; F1 folds are gently refolded about an F3 axial surface which strikes ESE and dips steeply to the SW creating gently plunging F3 fold hinges. F1 folds are downward facing in the SW limb of this F3 fold. The Cooks Brook Formation outcrop (Figure 3.10d) contains a single tight, moderately plunging, downward facing, antiformal syncline.

Interpretations: Tight and isoclinal folds F1 folds are similar in style to those at Shoal Point and are emplacement-related. Downward facing folds are present in outcrops within Harry Brook indicating at least two phases of folding. F1 folds are refolded about a steeply dipping NE-SW striking axial surface in a similar orientation to F3 folds observed at Shoal Point North (Figures 3.10a; 3.10b) We therefore suggest that F3 folds in Harry Brook are also a result of strike-slip movement on nearby faults.

Figure 3.10: Outcrop photographs showing fold overprinting relationships.

(a-b) Fold overprinting relationships at Shoal Point North within the Cooks Brook Formation and; (c-d) Fold overprinting relationships in Harry Brook (c) Cooks Brook Formation and (d) Middle Arm Point Formation. (e) Map-view schematic summarizing three generations of folds observed on Port au Port Peninsula and how they might relate to local NE-SW trending fault traces. Abbreviations: AP=Axial Plane, H=Hinge, B=Bedding, F1, F2, F3 indicates fold generation.



a)
F1
AP:267/86
F3
AP:310/75
AP:049/84
b)
050
B: 057/15
B: 195/47
F2
F3
230
B: 026/44
B: 275/29
c)
F3
AP:111/74
F1 AP:150/10
H:258-03
overturned
upright
F1
AP: ~283/39
d)
F1
AP:255/46
H:292-34
B:279/63
upright
B:190/21
overturned
e)
F1 - emplacement related folding
various orientations overturned folds
F2 -inversion related folding
NE
SW
F3 - strike-slip related folding
NW
SE
Legend
Thrust Fault Trace
Strike-Slip Fault Trace
Axial trace

3.4.3. Results: Disrupted units

3.4.3.1. Volumetric Block Proportions

Map relationships commonly place areas of mélange either structurally below the Cooks Brook Formation or structurally above the Eagle Island Formation on Port au Port Peninsula. Accessible areas, mapped as disruption level IV or V (mélange), were chosen for scanline analysis to provide an estimation of the block size distribution and the proportion of blocks to scaly matrix. In total 183 blocks were measured across 15 scanlines. Measured block sizes range from 0.5 cm (the lower cutoff) to 158 cm; of these, the majority of blocks (177 of 183) were measured to be <45 cm in diameter and 140 of those were <10 cm (Figure 3.11). Block proportions from this small sample set within disrupted rocks range from 20% to 80%, with a majority of scanlines showing a 30% to 40% proportion of blocks to scaly shale (Figure 3.11). When all the line lengths are added together, and divided by the sum of the block lengths, the average proportion of blocks to scaly shale amongst the lines is ~24%.

3.4.3.2. Sample results: Photomicrographs

PA014B: Sample PA014B (Figure 3.12) was collected on the beach north of West Bay Quarry (Figure 3.4) in a section of scaly shale which sits just above the Table Head Group (Figure 3.2). This sample location is mapped as IV on the disruption index. This section is from the West Bay Thrust Sheet (Figure 3.3). The thin-section cut from this sample (Figure 3.12a) was cut in an orientation of 337/90; a cover slip on this thin-section makes fluorescence results unreliable. This sample is very fine-grained silt and clay containing ~75% light brown clay, ~23% very fine silt-sized quartz and carbonate grains, ~1% medium-silt size quartz grains, and ~1% opaques. Color variation is from dark beige to brown or black; boundaries appear transitional or irregular and locally follow fracture orientation, possibly suggesting that the brown to black portion of this sample was stained by fluids (Figure 3.12a). Fractures commonly contain either calcite, or an opaque fill interpreted as bitumen (Figure 3.12b). Numerous discreet fracture planes crosscut the section and are only noticeable through changes in extinction angle on either side of the fracture as the stage is rotated (Figure 3.12c). Oblique shear fractures in this sample show both top-to-NW and top-to-SE geometries (Figure 3.12e; 3.12f; 3.12g) suggesting coaxial strain, a trait commonly associated with mélange formation (Festa et al., 2012).

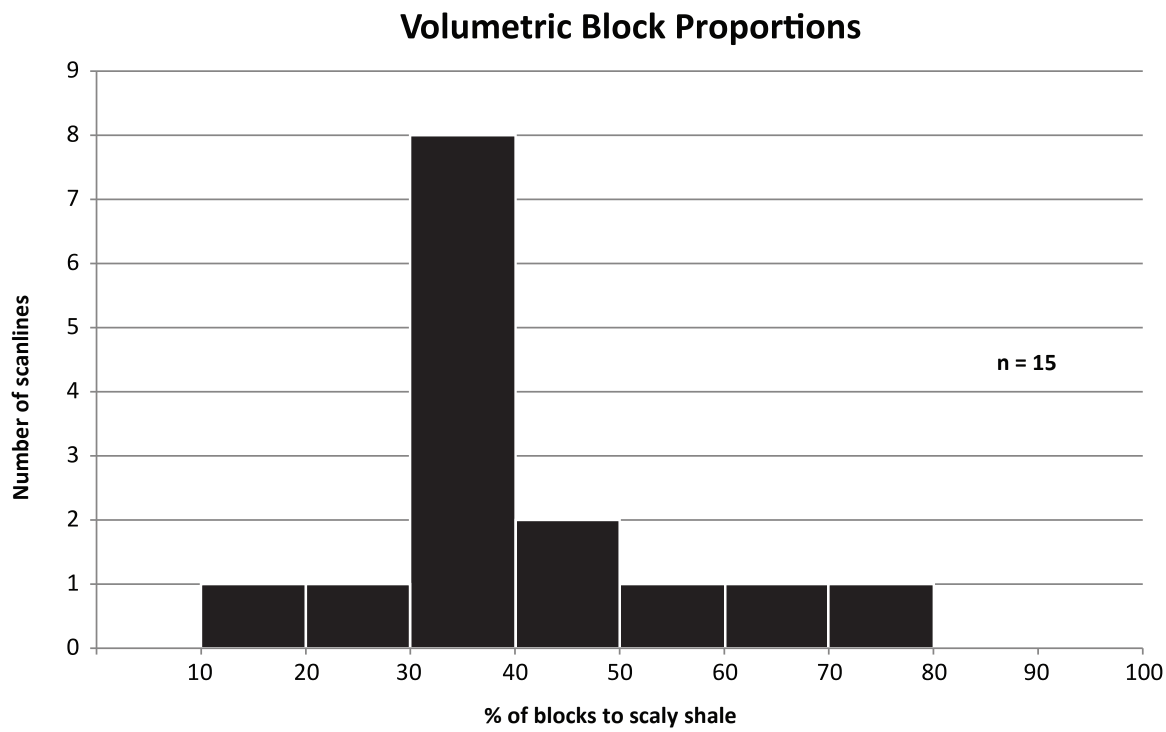
SA024A: Sample SA024A (Figure 3.13) was collected at Black Point (Figure 3.1) from a disrupted section mapped as mélange at outcrop scale comprising scaly red and green shale and blocks of siliceous mudstone. Volumetric block proportions at this sample location indicate a 30% block to 70% scaly shale ratio. A few larger blocks are folded. A fold observed in this outcrop, where the sample was taken, is tight to isoclinal and is therefore interpreted as related to other F1 folds. Although the West Bay Thrust Sheet and Lourdes Thrust Sheet cannot be separated this far east, the sample is probably from the base of the Lourdes Thrust Sheet (Figure 3.3).

SA024A shows very fine silt to clay-size material in the heavily fractured outer portions of the thin section (Figure 3.13); compositionally this appears to be mainly quartz. A disrupted bed, identified as a folded block in outcrop, sits in the center of this thin-section (Figure 3.13) and consists of fine-silt-size or smaller carbonate grains and minor chert (up to 20%). Distinctive white laminae comprise coarser grained carbonate and minor quartz. Many of the fractures in this sample have a light to dark brown or black coating along their margins which extends into the host rock up to 1 cm along smaller fractures and laminae and is closely associated with framboidal pyrite (Figure 3.13b; 3.13c). We suggest that light to dark brown staining along fractures and laminae is bitumen that has migrated from fractures to permeate the adjoining rock. Pyrite framboids, a crystal shape commonly formed in organic rich sediments, supports the interpretation that this represents an organic fluid (Sawlowicz, 1993). Fluorescence did not yield any results (N. Harris, University of Alberta, *personal communication*) which may be indicative of bitumen of higher thermal maturity.

The outer, quartz-rich zone is crosscut by numerous inconspicuous fracture planes. The inner carbonate-rich bed is crosscut by two conspicuous curvilinear fractures; one of which offsets

Figure 3.11: Charts illustrating numerical measurements in disrupted zones.

(top) Percentage of blocks to scaly shale present in each scanline (volumetric block proportions) and; (bottom) the distribution of block sizes measured along scanlines.


Volumetric Block Proportions
Number of scanlines
% of blocks to scaly shale
n = 15
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100

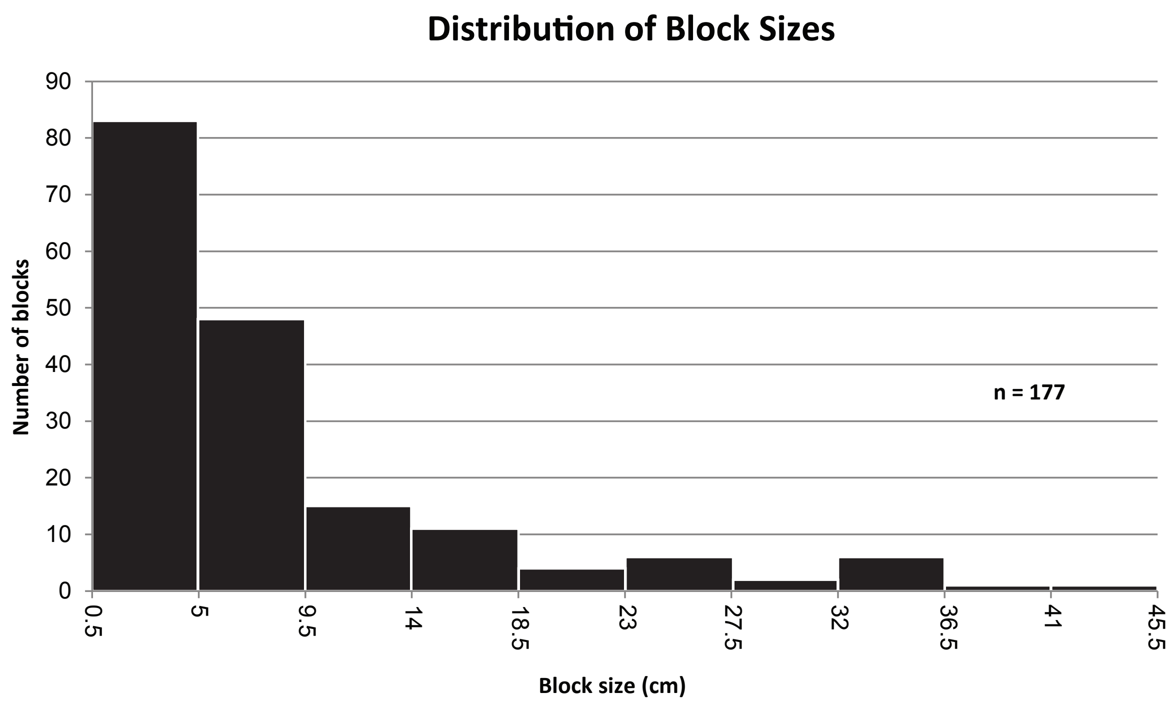

Distribution of Block Sizes
Number of blocks
Block size (cm)
n = 177
0
10
20
30
40
50
60
70
80
90
0.5
5
9.5
14
18.5
23
27.5
32
36.5
41
45.5

Figure 3.12: Photomicrographs of orientated sample PA014A.

(a) Scan of thin-section PA014B-1 with orientation marked, cut surface is oriented along a vertical plane striking 157^0. Locations of the following photomicrographs are indicated. (b) Plane-polarized light: extensional fracture traces filled with bitumen and other opaques identified as pyrite in reflected light. (c) A set of discreet fracture traces viewed with the lambda accessory plate. (d) A siliceous block surrounded by extensional fracture traces. (e) Two sets of extensional fracture traces raking 025^0 and 140^0 in the thin-section plane are sinistral, top-to-NW and dextral, top-to-SE respectively. (f) Dextral, top-to-SE and (g) sinistral, top-to-NW extensional fractures with calcite and bitumen fill. All clockwise rakes are measured from the strike (horizontal) of the thin-section plane (157^0).

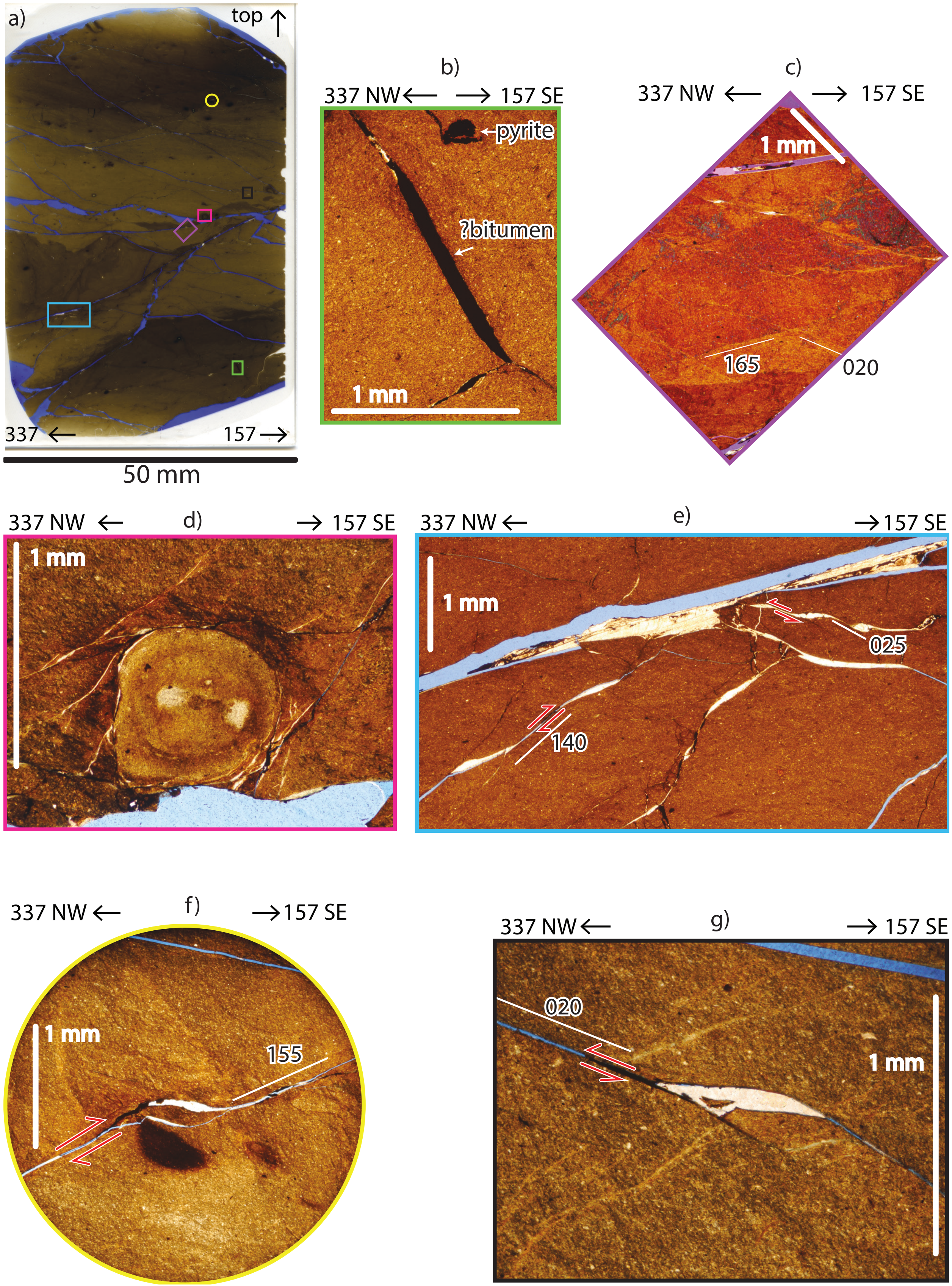
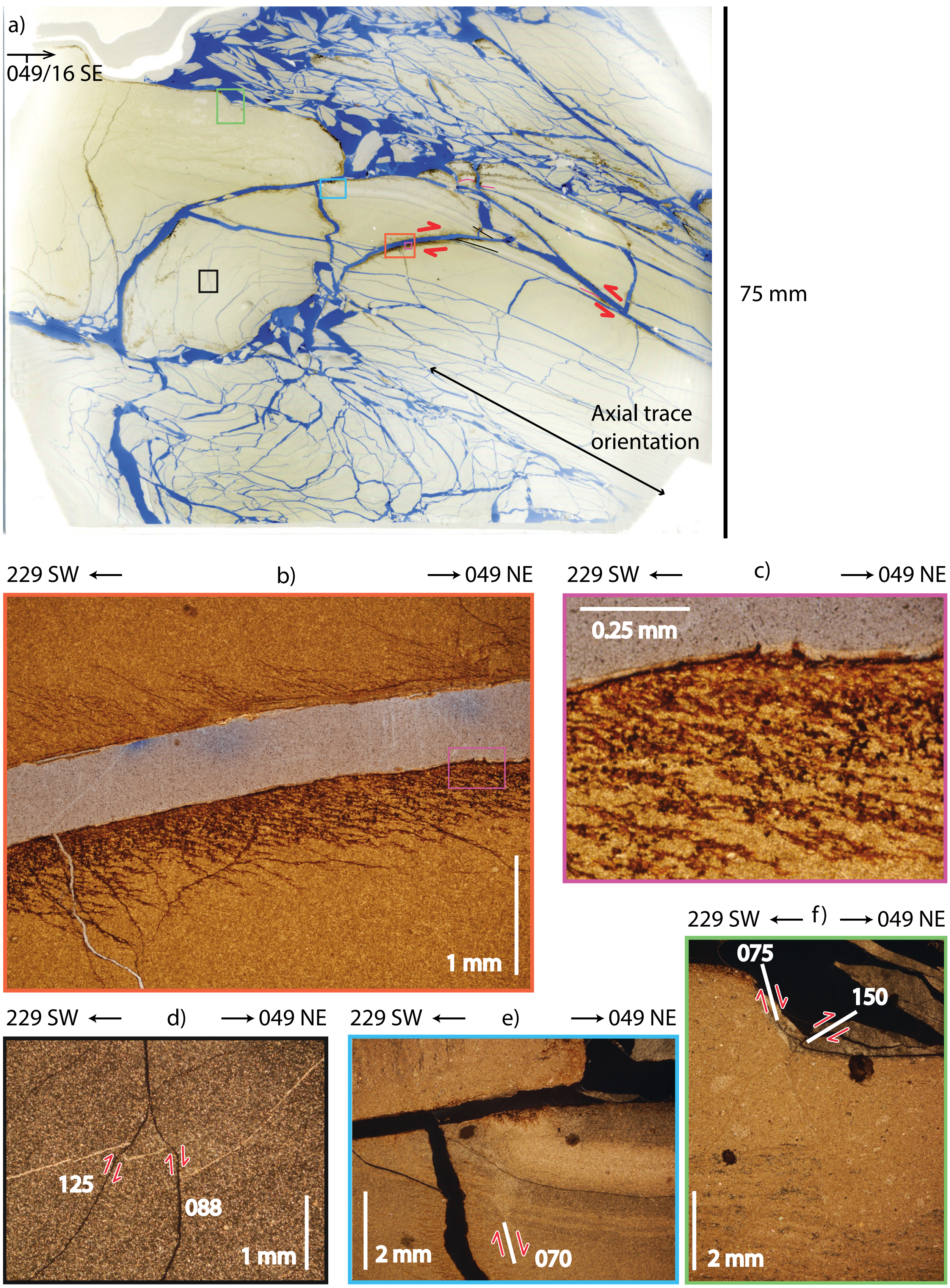

a)
top
337
157
50 mm
b)
337 NW
157 SE
pyrite
?bitumen
1 mm
c)
337 NW
157 SE
1 mm
165
020
d)
337 NW
157 SE
1 mm
e)
337 NW
157 SE
1 mm
025
140
f)
337 NW
157 SE
1 mm
155
g)
337 NW
157 SE
020
1 mm

Figure 3.13: Photomicrographs of oriented sample SA024A.

(a) Scan of thin-section SA024A with orientation of thin-section marked and locations of the following photomicrographs indicated. 2 fractures are evident from the offset of one marker lamina, red arrows show sense of movement; one (black lines) shows sinistral, top-to-SW offset and one (pink lines) shows dextral, top-to-NE offset. Fluid staining appears black around fracture edges. (b) Plane-polarized light: fluids around fracture edges have migrated into the rock along lamination; location of (c) is indicated. (c) Plane-polarized light: framboidal pyrite present as small, round opaques within fluid stained areas. (d) Cross-polarized light: lamina offset by 2 factures, both show dextral top-to-NE symmetry. (e) Cross-polarized light: lamina crosscut along 070^0 fracture trace shows dextral top-to-NE symmetry. (f) Cross-polarized light: a pair of fractures both showing dextral, top-to-NE symmetry; the fracture raking 075^0 in the plane of section is crosscut and offset clockwise by the fracture raking 150^0 in the plane of section. All clockwise rakes are measured from the strike (horizontal) of the thin-section plane (049^0).



a)
049/16 SE
Axial trace orientation
75 mm
229 SW
b)
049 NE
1 mm
229 SW
c)
049 NE
0.25 mm
229 SW
f)
049 NE
075
150
2 mm
229 SW
d)
049 NE
125
088
1 mm
229 SW
e)
049 NE
2 mm
070

the laminae with dextral, top-to-NE symmetry while the other shows a sinistral, top-to-SW offset (Figure 3.13a). Kinematic indicators are rare in this sample; three areas were found that show laminae offset by fractures. All four fractures observed show dextral, top-to-NE symmetry (Figure 3.13d; 3.13e; 3.13f). Curvilinear, conjugate fractures (Figure 3.13a) are oriented parallel to the axial trace of the fold possibly suggesting that they were formed during the same shortening event. A compressional fracture raking 150^{0} in this section, similar to one of the conjugate fractures, crosscuts and offsets an extensional fracture raking 075^{0} (Figure 3.13f). This crosscutting relationship suggests that an earlier phase of extension (Figure 3.13d; 3.13e; 3.13f) pre-dated contractional fractures related to folding. A tectonic event which provided the regional NW dip in this area, and which is thought to have rotated the fold in outcrop, would also have rotated these fractures from their original orientation; the original directions of extension and subsequent shortening are therefore ambiguous.

PF051B: Sample PF051B (Figure 3.14) was collected from Piccadilly Slant (Figure 3.4), from a disrupted siltstone unit, mapped within an area of mélange. The thin-section (figure 3.14a) was cut along an orientation of 308/71 NE. Sample PF051B contains one lithology; ~65% of the section is made up of light-brown pleochroic, undistinguishable clay while 35% is composed of coarsesilt; of this 35%, ~74% is quartz grains, ~25% is carbonate grains and ~1% is opaques. This sandy lithology is consistent with either the Western Brook Pond Group or the Goose Tickle Group. Opaques disseminated throughout the rock, commonly round and clustered, are pyrite framboids (Figure 3.14f). Weak planar lamination is defined by coarser grained laminae. Opaque material situated along fracture margins, or as vein fill, is likely bitumen; opaque material along fractures, thought to be bitumen from reflected light examination, did not yield any results from fluorescence; this may be indicative of bitumen at higher thermal maturity (N. Harris, University of Alberta *personal communication*). Inconspicuous fracture planes, similar to those identified in other samples, are also observed in portions of this sample. Carbonate-filled shear fractures are common; fractures in this sample show a consistent dextral, top-to-SE symmetry (Figure 3.14b; 3.14c; 3.14d; 3.14e; 3.14g). This sample was collected from adjacent to the Piccadilly

Head Fault; this faultstrikes SW and is SE-vergent. Carbonate veins commonly raking 130^0 to 135^0 in the thin-section plane were formed en-echelon to the Piccadilly Head Fault during inversion (Figure 3.14b; 3.14d; 3.14e). Crosscutting fractures all show dextral, top-to-SE movement also consistent with inversion on this fault (3.14c; 3.14e). The lack of west-vergent structures, as would be expected from the Humber Arm Allochthon, would be more easily explained if this sample instead belongs to the underlying Goose Tickle Group and was therefore less affected by low-angle features related to emplacement.

SC026A: Sample SC026A (Figure 3.15) was collected from Piccadilly Slant (Figure 3.4) in an area of mélange defined by scaly shale and the presence of limestone and chert blocks. Volumetric block proportions measured near the sample location show an average of 40% blocks to 60% scaly shale This sample location is in the footwall of the Piccadilly Head Fault and may have undergone rotation as the fault was inverted (Chapter 2). The thin-section cut was cut in an orientation of 302/76 NE (Figure 3.15a). This sample contains two dominant lithologies that appear as light brown to beige, and dark brown; both are fine-grained and composed primarily of fine silt or clay (Figure 3.15). The light brown to beige lithology, corresponding with scaly shale matrix observed in outcrop, contains <5% identifiable grains of coarse-silt-size; these grains are primarily quartz, carbonate, and minor pyrite. The dark brown lithology, (Figure 3.15b) described in outcrop as a block, is similar in composition but contains abundant framboidal pyrite (up to 20%), commonly concentrated within dark red-brown laminae (Figure 3.15b). Planar lamination is very well developed within this domain. Other subordinate lithologies are present as blocks within the light brown to beige lithology; these blocks are composed of either coarse-silt to sand-size chert, or coarse carbonate crystals, and are extraformational (Figure 3.15c; 3.15d; 3.15e). The presence of such blocks confirms the outcrop-scale interpretation that this is mélange.

The brown to red coloration of the laminae is the result of fluid staining (Figure 3.15b) and displays pale-yellow fluorescence (N. Harris, University of Alberta, *personal communication*). Pale-yellow fluorescence is consistent with immature kerogen or organic fluids within the early

Figure 3.14: Photomicrographs of oriented sample PF051B

(a) Scan of thin-section PF051B with orientation of thin-section marked, locations of the following photomicrographs are indicated. (b) Trace of a carbonate vein raking 140^0 from horizontal in the thin-section plane; shows sinistral, top-to-SE symmetry. (c) Trace of lamination raking 139^0 is crosscut by a 098^0 fracture trace and offset with sinistral, top-to-SE symmetry. (d) Trace of a carbonate vein showing sinistral, top-to-SE symmetry. (e) Fracture traces raking 093^0 crosscutting and rotating carbonate veins with sinistral, top-to-SE offset. (f) hydrocarbons (?bitumen) within a fracture as opaque fill. Other opaques, disseminated within the rock, are pyrite framboids. (g) Trace of a carbonate vein showing sinistral, NW block up symmetry. All clockwise rakes are measured from the SE strike direction (horizontal) of the thin-section plane (128^0).

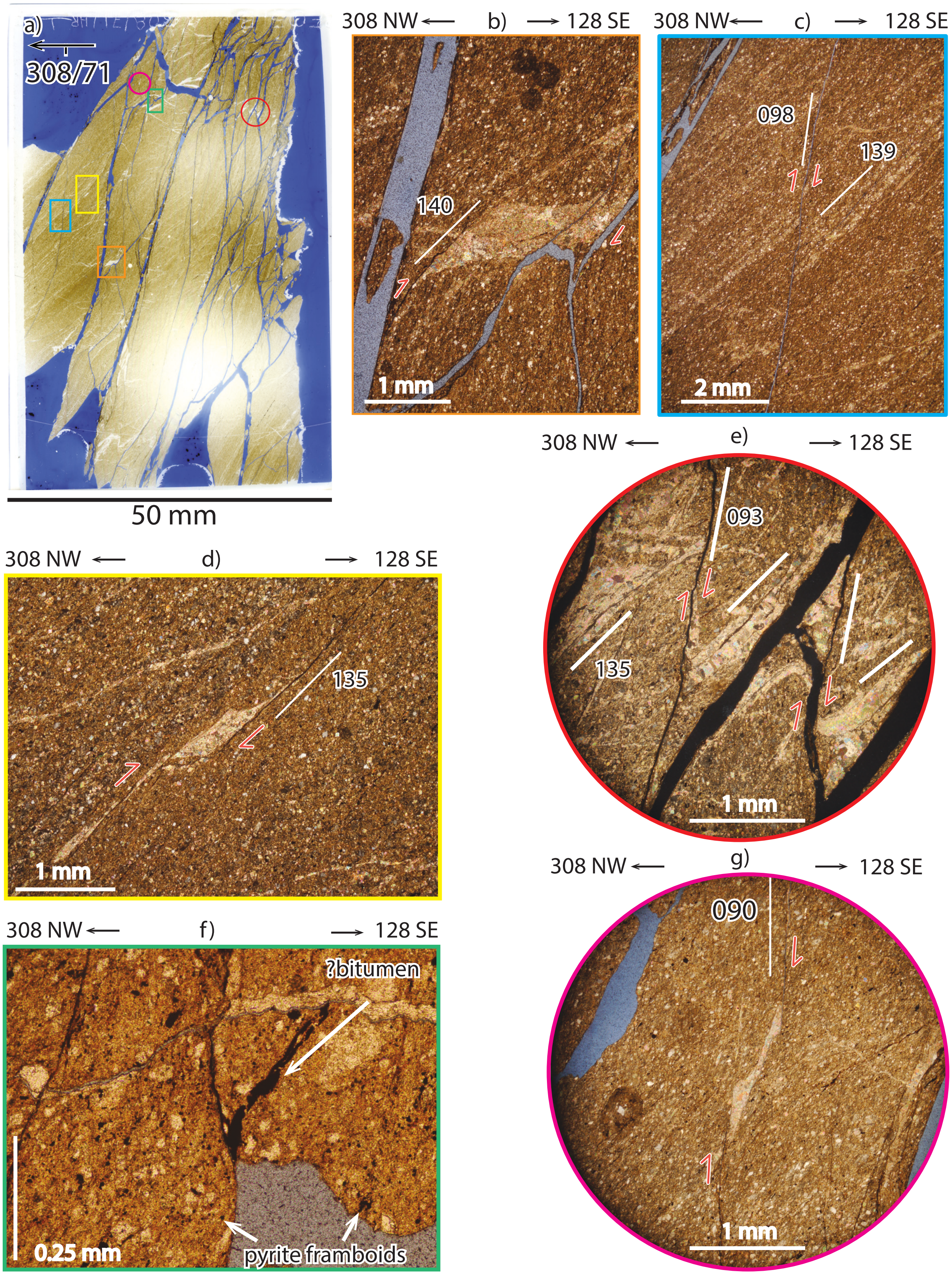
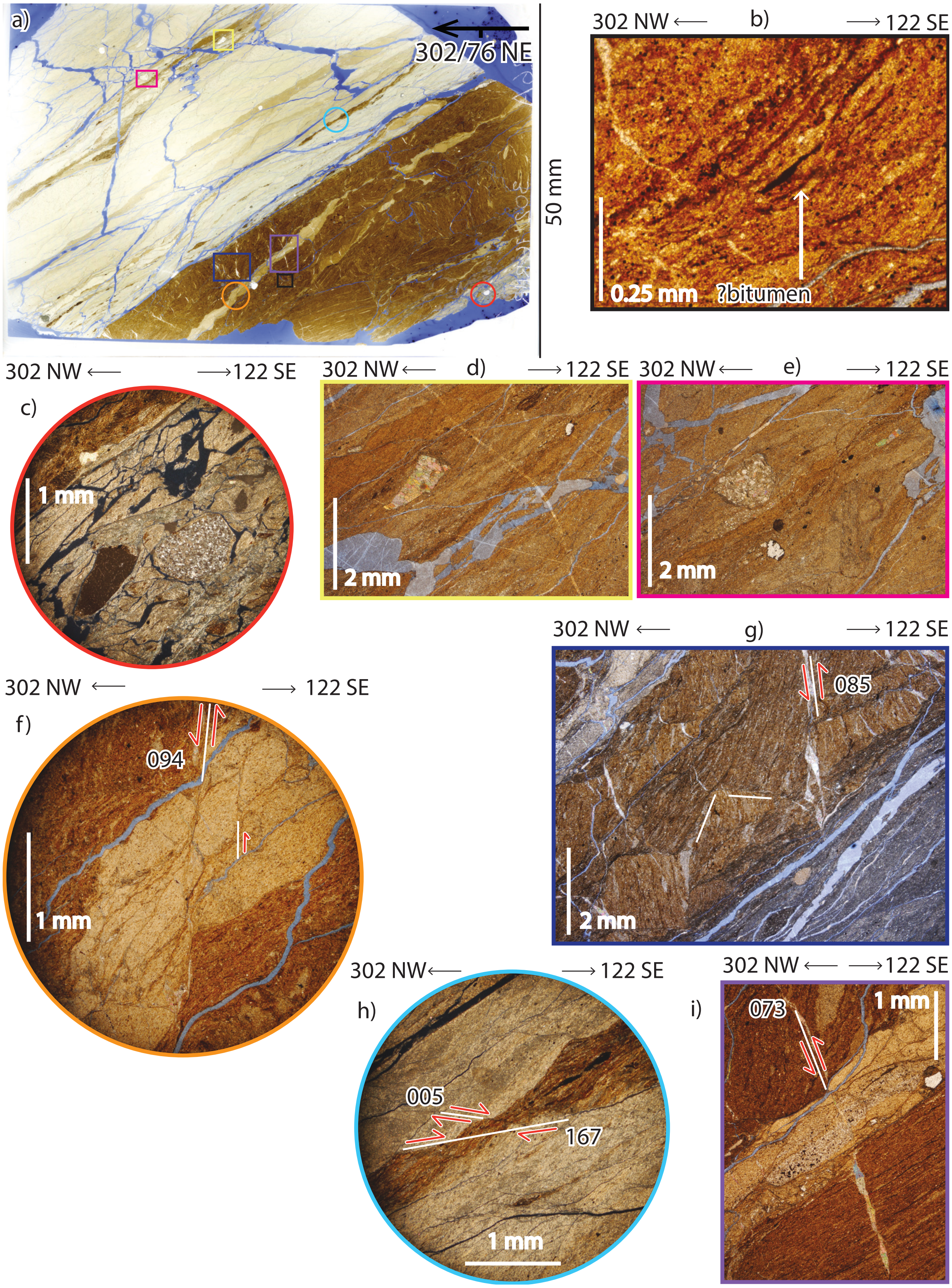

a)
308/71
50 mm
308 NW
b)
128 SE
140
1 mm
308 NW
c)
128 SE
098
139
2 mm
308 NW
e)
128 SE
093
135
1 mm
308 NW
d)
128 SE
135
1 mm
308 NW
g)
128 SE
090
1 mm
308 NW
f)
128 SE
?bitumen
0.25 mm
pyrite framboids

Figure 3.15: Photomicrographs of oriented sample SC026A.

(a) Scan of thin-section SC026A with orientation of thin-section marked, locations of the following photomicrographs are indicated. (b) Photomicrograph of dark brown lithology, lamination defined by hydrocarbon fluid staining; round, disseminated opaques are pyrite framboids (c) Cross-polarized light and (d-e) plane-polarized light photomicrographs of chert, coarse carbonate, and shale blocks contained within a shale matrix. (f) Plane-polarized light: pinch-and-swell structures, crosscutting fractures show sinistral, top-to-NW displacement. (g) Cross-polarized light: highly disrupted dark brown lithology; 3 fractures are highlighted where lamination changes orientation, a top-to-NW oblique shear fracture (085^0 rake) is marked. (h) Plane-polarized light: extensional reverse fracture (167^0 rake) and extensional fracture (005^0 rake) associated with pinch-and-swell features within lamina. Both fractures show dextral, top-to-SE displacement. (i) Plane-polarized light: light brown lithology crosscut by sinistral, top-to-NW fracture. All clockwise rakes measured from the SE strike direction (horizontal) of the thin-section plane (122^0).


a)
302/76 NE
50 mm
302 NW
b)
122 SE
0.25 mm
?bitumen
302 NW
122 SE
c)
1 mm
302 NW
d)
122 SE
2 mm
302 NW
e)
122 SE
2 mm
302 NW
g)
122 SE
085
2 mm
302 NW
122 SE
f)
094
1 mm
302 NW
122 SE
h)
005
167
1 mm
302 NW
122 SE
i)
073
1 mm

oil window; framboidal pyrite is closely associated with organic fluid in this sample. The two dominant lithologies are interlaminated but typically discontinuous, displaying pinch-and-swell structures as a result of a number of cross cutting fractures (Figure 3.15f; 3.15h; 3.15i). Laminae within the dark brown lithology are disrupted and display clear changes in orientation at fracture boundaries (Figure 3.15g). Sinistral, top-to-NW symmetry on fractures is common (Figure 3.15h; 3.15g; 3.15i). Dextral, top-to-SE symmetry (Figure 3.15f) is observed along one fracture. . This fracture cuts laminae at a low-angle and extends them; we therefore associate it with creation of the pinch-and-swell geometry found within this sample. This pinch-and-swell geometry is indicative of coaxial extension (Festa et al., 2012).

3.5. Discussion

As a result of new mapping and better characterization of mélange zones, presented here for Port au Port Peninsula, it is possible to put together a structural history for the area:

The variety of igneous blocks within mélange on Port au Port Peninsula suggests that multiple block sources were present early in the deformation history of the Humber Arm Allochthon; we do not see evidence of blocks from associated underlying metamorphic units. We suggest that a stack of thrust slices containing a variety of igneous material from outboard sources was thickened and imbricated with sedimentary units at its base early in the assembly of the Humber Arm Allochthon (Figure 3.16a). Tilting led to erosion of multiple thrust slices; material shed towards the Laurentian margin was distributed across the top of the Cow Head Group as an early formed, olistostomal, foreland basin deposit (Figure 3.16a). Later stratal disruption and mixing were likely facilitated by tectonic mixing as the olistostomes were overridden by, and incorporated into, the allochthon.

Deposition of the Western Brook Pond Group began in the Dapingian as allochthonous rocks impinged on the Laurentian slope (Figure 3.16b). Due to the lithologic association of contained clasts, we suggest that deposition of the Western Brook Pond Group was associated with the earliest uplift of distal Cow Head Group strata, within the allochthonous wedge, to an erosional level (Figure 3.16b). This switch from olistostromes, including igneous material, to turbidites of the Western Brook Pond Group was likely transitional as lower thrust slices were uplifted and eroded; both units overlie and onlap the Cow Head Group (Figure 3.2). During approximately the same interval (Dapingian), loading of the Laurentian margin caused a Taconian peripheral bulge to migrate through the platform creating the St. George Unconformity (Jacobi, 1981) (Figure 3.16b).

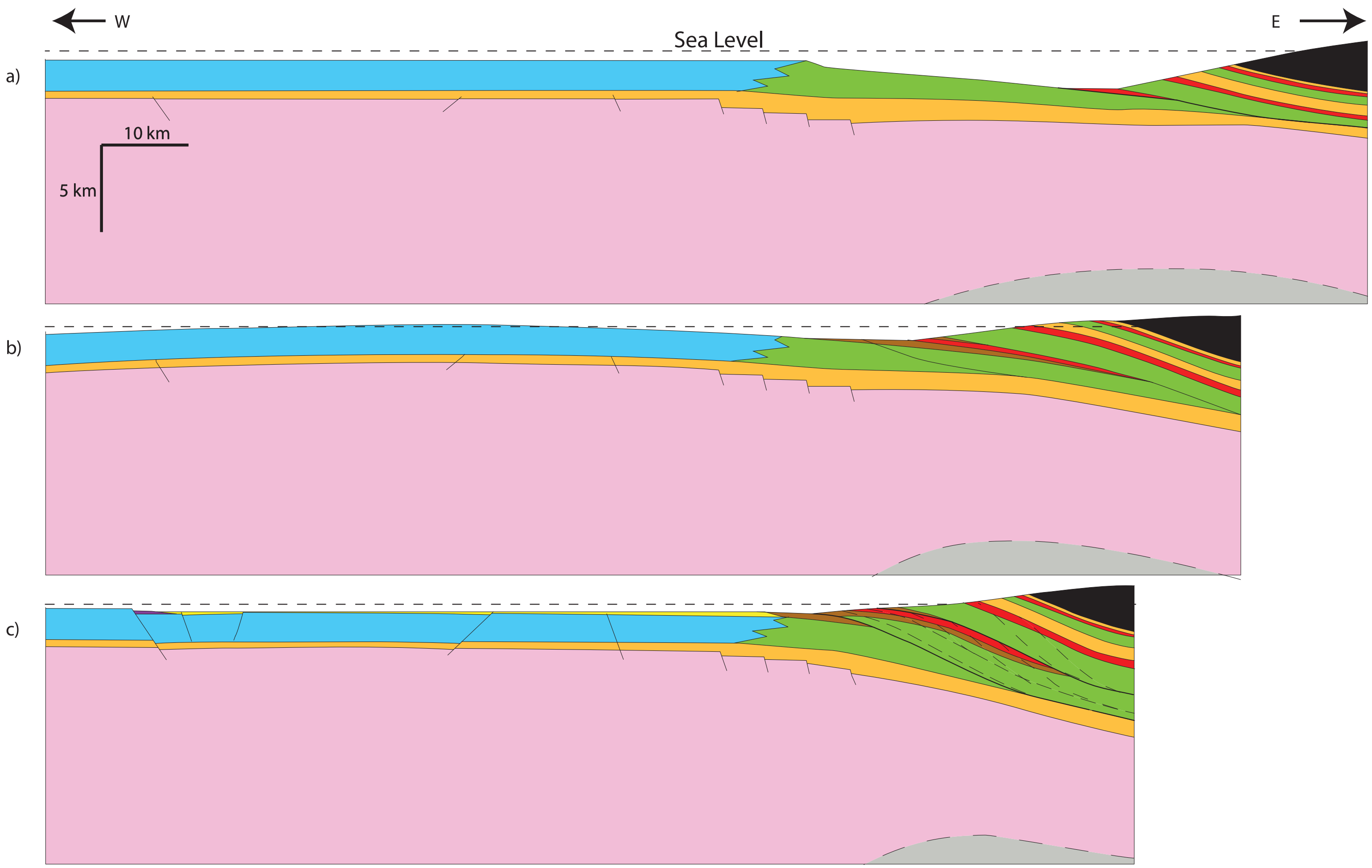
The Eagle Island Formation is thinned or non-existent above the Cow Head Group in some areas of Port au Port Peninsula where the Cow Head Group is directly overlain by mélange (Figure 3.4). The Eagle Island Formation and early mélange were likely structurally interleaved as thrusting continued (Figure 3.16c). The mélange appears to be folded with the stratigraphy of other units suggesting that it was overprinted by later folding events (Figure 3.4).

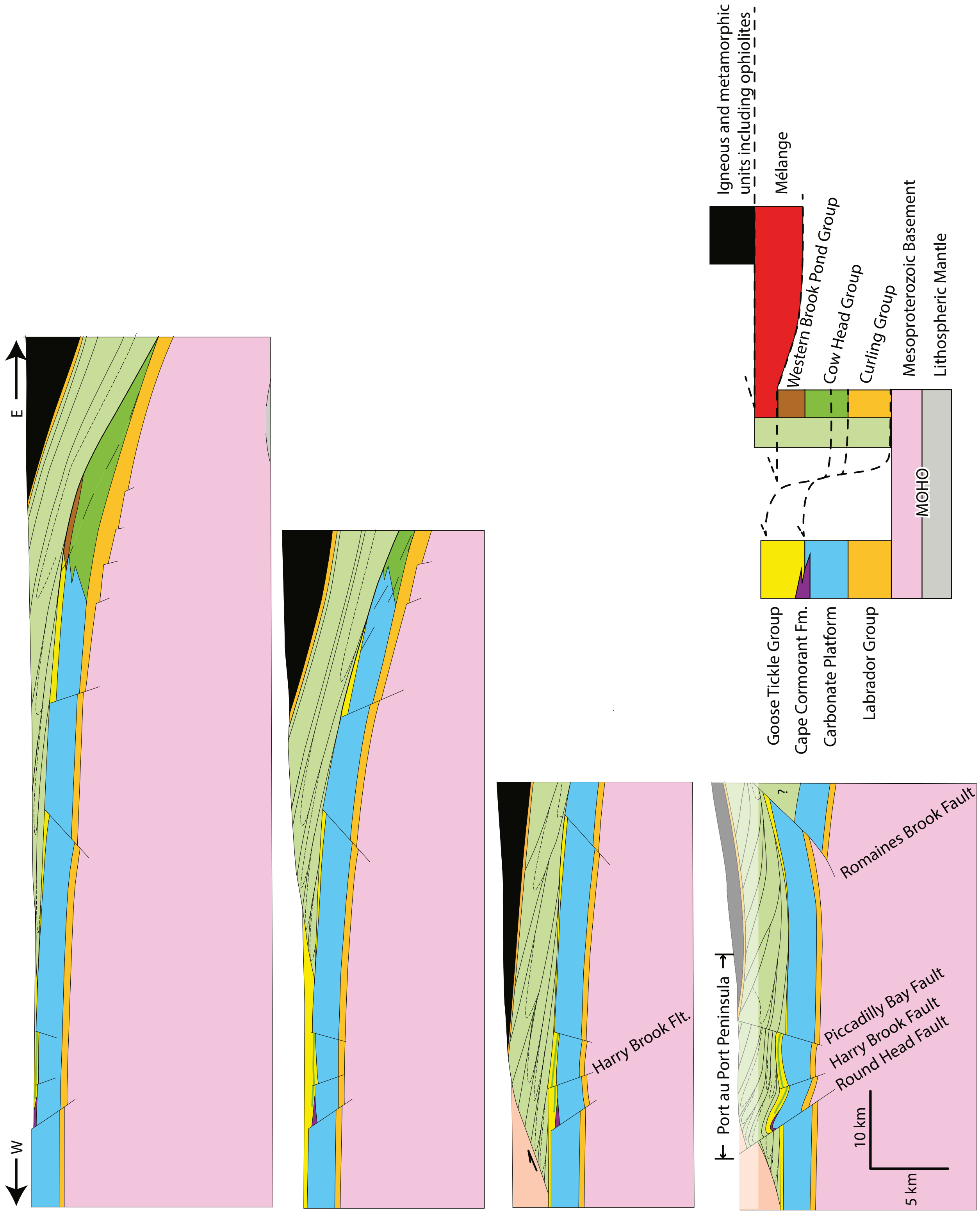
After the peripheral bulge had passed, subsidence on the platform led to the deposition of the Table Head Group during the Darriwilian. Extensional faults such as the Round Head Fault, possibly reactivating earlier rift-related faults, were activated in the wake of the peripheral bulge (Bradley and Kidd, 1991; Stockmal et al., 2004) further influencing local subsidence rates (Figure 3.16c). Far travelled, fine-grained turbidites of the Goose Tickle Group were deposited across the platform (Figure 3.16c; 3.2). The allochthonous Cow Head Group, Western Brook Pond Group and mélange continued to be imbricated below the allochthon as the wedge was thickened (Figure 3.16c).

The early tip of the allochthon, represented by the West Bay Thrust Sheet, is thin (20 m in places) on Port au Port Peninsula (Figure 3.4). Age constraints suggest emplacement of the West Bay Thrust Sheet occurred entirely within the Darriwilian 3 Biozone of the Ordovician (Chapter 2). On Port au Port Peninsula, mapped units within the allochthon commonly display an auto-brecciation texture (Figure 3.6); this texture is explained by fluid overpressure whereby finer-grained rocks underwent liquefaction and more competent beds underwent hydraulic

Figure 3.16: Schematic cross-sections through western Newfoundland from the Early Ordovician to Late Devonian.

(a-d) Middle Ordovician: early emplacement of the Humber Arm Allochthon showing earliest deposition into the foreland basin of olistostromal mélange (red) with subsequent foreland basin deposition (brown and yellow) occurring later; emplacement of the West Bay Thrust Sheet and reduced wedge taper is shown in (d). (e-g) ?late Middle Ordovician to Early Devonian: Increased wedge taper through internal deformation and emplacement of the Lourdes Thrust Sheet across Port au Port Peninsula; early inversion of the Harry Brook Fault (f) and subsequent inversion of the Round Head Fault, Piccadilly Bay Fault and Romaines Brook Fault (g) are shown.




d)
e)
f)
g)
W
E
Harry Brook Flt.
Romaines Brook Fault
Piccadilly Bay Fault
Harry Brook Fault
Round Head Fault
Port au Port Peninsula
10 km
5 km
?
MOHO
Goose Tickle Group
Cape Cormorant Fm.
Carbonate Platform
Labrador Group
Igneous and metamorphic units including ophiolites
Mélange
Western Brook Pond Group
Cow Head Group
Curling Group
Mesoproterozoic Basement
Lithospheric Mantle

fracturing. Dewatering structures and sandstone dykes, commonly associated with the Eagle Island Formation, also attest to this overpressure. Local overpressure features seen on Port au Port Peninsula are similar to those described in Taconic mélanges in the Humber Zone of Quebec (Cousineau, 1998). thinning of the West Bay Thrust Sheet was at least partially accomplished through high fluid pressure within the allochthon during this time; the critical taper of the encroaching allochthon was decreased as the wedge extended horizontally across the platform (Waldron et al., 1988; Dahlen and Suppe, 1988) (Figure 3.16d).

Portions of the Cow Head Group have long been considered source rocks for hydrocarbon generation in western Newfoundland (Fowler et al. 1995, and references therein). Mélange samples collected during this study contain material from the Cow Head Group and either mature bitumen, common as fracture fill; or organic fluids along laminae, indicative of a source within the early oil window. A thin section collected from the West Bay Thrust Sheet shows hydrocarbon-filled fractures and staining of the surrounding rock; oblique shear fractures within this sample are filled with both carbonate and bitumen and give both a clockwise and counterclockwise sense of shear (Figure 3.12). The opposite sense of shear observed in this sample along with pinch-and-swell geometries observed in other sections is indicative of coaxial extension, a viable mechanism for rapid emplacement and thinning of the West Bay Thrust Sheet. We suggest that increased burial depth within the imbricate thrust stack likely led to the expulsion of hydrocarbons, further increasing fluid pressure and allowing forward movement and thinning of the wedge through coaxial extension (Dahlen and Suppe, 1988) (Figure 3.16d). Mackay (2015) described a similar model in the Canadian Rocky Mountains whereby wedge taper is modified by high fluid pressures resulting from hydrocarbon generation. Fluid pressure contributed to the formation of extensional fractures leading to the development of broken formation, and, locally, mélange (Figure 3.9). This process of mélange generation in Newfoundland is similar to that described by Stevens (1970) and Waldron et al. (2003) (Figure 3.16a).

Later in the Darriwilian, the leading edge of the allochthon was down-dropped and buried by continued extension on high-angle faults within the basin preserving the West Bay Thrust Sheet (Figure 3.16e). Subsequently, the allochthonous wedge was built back up through internal deformation and continued its emplacement across Port au Port Peninsula shedding shale-chip sandstones and conglomerates into the Victors Brook Member (Chapter 2) (Figure 3.16e). The Harry Brook Fault, previously a Taconian extensional fault, was reactivated as a reverse fault prior to emplacement of the Lourdes Thrust Sheet (Figure 3.16f). The remaining Upper Ordovician to Lower Devonian foreland basin units were deposited during this time (Figure 3.16f). The Lourdes Thrust Sheet was emplaced to its final position during or after the Emsian as a result of Acadian orogenesis forming the triangle zone offshore (Stockmal et al., 2004); the Lourdes Thrust appears to cut up section to the west across the Harry Brook Fault (Figure 3.16f).

A number of other previously extensional faults including the Round Head Fault were reactivated with thrust sense and crosscut the base of the Lourdes Thrust Sheet (Figure 3.16g). Inversion on Port au Port Peninsula is associated with NE-SW trending fold axes in both the allochthon and underlying platform and is likely responsible for the regional NW dip of strata on the peninsula. These NE-SW trending folds overprinted earlier tight to isoclinal, emplacement-related folds (Figure 3.16g; 3.10). One of our oriented thin sections, taken from the footwall of the Piccadilly Head Fault shows en-echelon veins and top-to-SE fracture offsets consistent with this inversion event (Figure 3.14). Inversion of the Round Head Fault truncated the Lourdes Thrust Sheet (Waldron and Stockmal, 1991; Waldron et al., 1993; Stockmal et al., 2004) (Figure 3.16g). A later phase of strike slip-motion on some of these high-angle faults is associated with a third generation of NW-SE trending folds found within the Lourdes Thrust Sheet (Figure 3.10).

3.6. Conclusion

The Humber Arm Allochthon on Port au Port Peninsula has been mapped and subdivided into a broken stratigraphy in which individual units closely resemble the formations described by Botsford (1987) in the Bay of Islands area. Only the most disrupted outcrops, those in which both stratal disruption and mixing are identified, are classified as mélange. Three generations of folds are identified within more coherent portions of the allochthon; the first generation is emplacement-related while the latter two more localized generations are related to crosscutting high-angle faults. A new method of collecting oriented mélange samples has allowed more detailed study of the most highly disrupted portions of the allochthon. Thin-sections of these samples contain early mature and possibly over-mature bitumen. The development of extensional features within the allochthon was encouraged by this fluid overpressure which was likely aided by hydrocarbon expulsion. During emplacement of the allochthon, periods of high fluid pressure resulted in rapid forward movement and thinning of the wedge through coaxial extension.

Wells drilled on Port au Port Peninsula into the Humber Arm Allochthon have attempted, with minor success, to extract hydrocarbons. Map-scale, outcrop scale, and thin-section scale observations show that the Humber Arm Allochthon is extremely variable. We show that mélange is present at multiple scales. Volumetric block proportions in mélange at outcrops scale show a wide distribution in block sizes and variable proportions of blocks to shale. These sections are scattered amongst more coherent strata at map-scale making potential petroleum sources and reservoirs highly compartmentalized and unpredictable.

3.7. References

Baker, D.F., 1978, Geology and geochemistry of an alkali volcanic suite (Skinner Cove Formation) in the Humber Arm Allochthon, Newfoundland: Memorial University of Newfoundland.

Batten Hender, K.L., and Dix, G.R., 2008, Facies development of a Late Ordovician mixed carbonate-siliciclastic ramp proximal to the developing Taconic orogen: Lourdes Formation, Newfoundland, Canada: Facies, v. 54, p. 121–149.

Bergstrom, S.M., Riva, J., and Kay, M., 1974, Significance of conodonts, graptolites, and shelly faunas from the Ordovician of western and north-central Newfoundland: Canadian Journal of Earth Sciences, v. 11, p. 1625–1660.

Berkland, J., Raymond, L.A., Kramer, J., Montomoli, C., and O'Day, M., 1972, What is Franciscan? American Association of Petroleum Geologists Bulletin, v. 56.

Botsford, J.W., 1987, Depositional history of Middle Cambrian to Lower Ordovician deep water sediments, Bay of Islands, western Newfoundland: Memorial University of Newfoundland, 543 p.

Boyce, W.D., 1983, Early Ordovician trilobite faunas of the Boat Harbour and Catoche formations (St. George Group) in the Boat Harbour - Cape Norman area, Great Northern Peninsula, western Newfoundland: Memorial University of Newfoundland, 311 p.

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

Bradley, D.C., and Kidd, W.S.F., 1991, Flexural extension of the upper continental crust in collisional foredeeps: Geological Society of America Bulletin, v. 103, p. 1416–1438.

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

Burden, E.T., Quinn, L., Nowlan, G.S., and Nill, L.A.B., 2002, Palynology and micropaleontology of the Clam Bank Formation (Lower Devonian) of western Newfoundland, Canada: Palynology, v. 26:1, p. 37–41.

Cawood, P.A., and Botsford, J.W., 1991, Facies and structural contrasts across Bonne Bay cross-strike discontinuity, western Newfoundland: American Journal of Science, v. 291, p. 737–759.

Cawood, P.A., McCausland, P.J.A., and Dunning, G.R., 2001, Opening Iapetus: Constraints from the Laurentian margin in Newfoundland: Geological Society of America Bulletin, v. 113, p. 443–453.

Cawood, P.A., and Nemchin, A.A., 2001, Paleogeographic development of the east Laurentian margin: Constraints from U-Pb dating of detrital zircons in the Newfoundland Appalachians: Geological Society of America Bulletin, v. 113, p. 1234–1246.

Chow, N., 1985, Sedimentology and diagenesis of Middle and Upper Cambrian platform carbonates and siliciclastics, Port au Port Peninsula, western Newfoundland: Memorial University of Newfoundland, 458 p.

Chow, N., and James, N.P., 1987, Cambrian Grand Cycles : A northern Appalachian perspective: Geological Society of America Bulletin, v. 98, p. 418–429.

Cooper, M., Weissenberger, J., Knight, I., Hostad, D., Gillespie, D., Williams, H., Burden, E.T., Porter-Chaudhry, J., Rae, D., and Clark, E., 2001, Basin evolution in western Newfoundland : New insights from hydrocarbon exploration: American Association of

Petroleum Geologists Bulletin, v. 85, p. 393–418.

Cousineau, P. a., 1998, Large-scale liquefaction and fluidization in the Cap Chat Mélange, Quebec Appalachians: Canadian Journal of Earth Sciences, v. 35, p. 1408–1422.

Dahlen, F.A., and Suppe, J., 1988, Mechanics, growth, and erosion of mountain belts: Geological Society of America Special Papers, v. 218, p. 161–178.

Dewey, J.F., and Casey, J.F., 2013, The sole of an ophiolite: the Ordovician Bay of Islands Complex, Newfoundland: Journal of the Geological Society, v. 170, p. 715–722.

Festa, A., Dilek, Y., Pini, G.A., Codegone, G., and Ogata, K., 2012, Mechanisms and processes of stratal disruption and mixing in the development of mélanges and broken formations: Redefining and classifying mélanges: Tectonophysics, v. 568–569, p. 7–24.

Festa, A., Pini, G. a., Dilek, Y., and Codegone, G., 2010, Mélanges and mélange-forming processes: a historical overview and new concepts: International Geology Review, v. 52, p. 1040–1105.

Flügel, E., 2010, Microfacies of carbonate rocks - analysis, interpretation and application: Springer-Verlag Berlin Heidelberg, 984 p.

Fowler, M.G., Hamblin, A.P., Hawkins, D., Stasiuk, L.D., and Knight, I., 1995, Petroleum geochemistry and hydrocarbon potential of Cambrian and Ordovician rocks of western Newfoundland: Bulletin of Canadian Petroleum Geology, v. 43, p. 187–213.

Hackley, P.C., and Cardott, B.J., 2016, Application of organic petrography in North American shale petroleum systems: A review: International Journal of Coal Geology, v. 163, p. 8–51.

Hibbard, J., Van Staal, C.R., and Rankin, D.W., 2007, A comparative analysis of pre-Silurian crustal building blocks of the northern and the southern Appalachian orogen: American Journal of Science, v. 307, p. 23–45.

Hicks, L., and Owens, J. The history of petroleum exploration in western Newfoundland: , p. 24, http://www.nr.gov.nl.ca/nr/energy/pdf/history_petroleum_exploration_western_nl.pdf (accessed March 2017).

Hsü K. J., 1968, Principles of melanges and their bearing on the Franciscan-Knoxville paradox: Geological Society of America Bulletin, v. 79, p. 1063–1074.

Ingram, R.L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geological Society of America Bulletin, v. 86, p. 937–938.

Jacobi, R.D., 1981, Peripheral bulge-a causal mechanism for the Lower/Middle Ordovician unconformity along the western margin of the Northern Appalachians: Earth and Planetary Science Letters, v. 56, p. 245–251.

James, N.P., and Stevens, R.K., 1986, Stratigraphic correlation of the Cambro-Ordovician Cow Head Group, western Newfoundland: Geologic Survey of Canada Bulletin, v. 366, p. 143.

Johnson, H., 1941, Paleozoic lowlands of northwestern Newfoundland: The New York Academy of Sciences, Transactions, Series II, v. 3, p. 141–145.

Kindle, C.H., and Whittington, H.B., 1958, Stratigraphy of the cow head region, Western Newfoundland: Bulletin of the Geological Society of America, v. 69, p. 315–342.

Knight, I., 1978, Platformal sediments on the Great Northern Peninsula: Stratigraphic studies and geological mapping of the north St. Barbe district, *in* Gibbons, R.V. ed., Report of Activities for 1977. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-1, p. 140–150.

Knight, I., and Boyce, W.D., 1991, Deformed Lower Paleozoic platform carbonates, Goose Arm–Old Man's Pond: Newfoundland Department of Mines and Energy, Geological Survey Branch, v. Report 91-, p. 141–153.

Knight, I., and Boyce, W.D., 1987, Lower to middle Cambrian terrigenous-carbonate rocks of Chimney Arm, Canada Bay: Lithostratigraphy, preliminary biostratigraphy and regional significance: Current Research (1987) Newfoundland Department of Mines and Energy, Mineral Development Division, v. Report 87-, p. 359–365.

Knight, I., and James, N.P., 1987, The stratigraphy of the Lower Ordovician St. George Group, western Newfoundland: the interaction between eustasy and tectonics: Canadian Journal of Earth Sciences, v. 24, p. 1927–1951.

Knight, I., James, N.P., and Lane, T.E., 1991, The St. George Unconformity, northern Appalachians: The relationship of plate convergence at the St. Lawrence Promontory to the Sauk/Tippecanoe: Geological Society of America Bulletin, v. 103, p. 1200–1225.

Langille, A., 2009, Petrology and Geochemistry of volcanic rocks in the Humber Arm Allochthon, Bay of Islands, western Newfoundland: Memorial University of Newfoundland, 84 p.

Lindholm, R.M., and Casey, J.F., 1989, Regional significance of the Blow Me Down Brook Formation , western Newfoundland : New fossil evidence for an Early Cambrian age: Geological Society of America Bulletin, v. 101, p. 1–13.

Mackay, P. a., 2015, The role of fluid pressure in contractional systems: examples from the Southern Canadian Rocky Mountains: From:Richards, F. L., Richardson, N. J., Rippington, S. J.,Wilson,R.W.&Bond, C. E. (eds) Industrial Structural Geology: Principles, Techniques and Integration. Geological Society, London, Special Publications, 421, v. 421, p. 69–82.

Maletz, J., Egenhoff, S., Böhme, M., Asch, R., Borowski, K., Höntzsch, S., Kirsch, M., and Werner, M., 2011, A tale of both sides of Iapetus – upper Darriwilian (Ordovician) graptolite faunal dynamics on the edges of two continents: Canadian Journal of Earth Sciences, v. 48, p. 841–859.

Palmer, S.E., Burden, E.T., and Waldron, J.W.F., 2001, Stratigraphy of the Curling Group (Cambrian), Humber Arm Allochthon, Bay of Islands: Newfoundland Department of Mines and Energy, Geological Survey, v. Report 200, p. 105–112.

Palmer, S.E., Waldron, J.W.F., and Skilliter, D.M., 2002, Post-Taconian shortening, inversion and strike slip in the Stephenville area, western Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 39, p. 1393–1410.

Peng, S., Babcock, L.E., and Cooper, R.A., 2012, The Cambrian Period, *in* Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G. eds., The Geologic Time Scale 2012, Elsevier B.V., v. 1–2, p. 437–488.

Quinn, L., 1992b, Diagenesis of the Goose Tickle Group, western Newfoundland: A Report for Mobil Oil,.

Quinn, L., 1992a, Foreland and trench slope basin sandstones of the Goose Tickle Group and Lower Head Formation, western Newfoundland: Memorial University of Newfoundland, 574 p.

Quinn, L., 1995, Middle Ordovician foredeep fill in western Newfoundland, *in* Hibbard, J.P., van Staal, C.R., and Cawood, P.A. eds., Current perpecives in the Appalachian-Caledonian orogen: Geological Association of Canada, Special Paper 41, p. 43–64.

Quinn, L., Bashforth, a R., Burden, E.T., Gillespie, H., Springer, R.K., and Williams, S.H., 2004, The Red Island Road Formation: Early Devonian terrestrial fill in the Anticosti Foreland Basin, western Newfoundland: Canadian Journal of Earth Sciences, v. 41, p. 587–602.

Quinn, L., Harper, D.A.T., Williams, S.H., and Clarkson, E.N.K., 1999, Late Ordovician foreland basin fill: Long Point Group of onshore western Newfoundland: Bulletin of Canadian Petroleum Geology, v. 47, p. 63–80.

Ramsey, J.G., and Huber, M.I., 1987, The Techniques of modern structural geology. Vol. 2:

Academic Press.

Raymond, L.A., 1975, Tectonite and mélange — a distinction: Geology, p. 7–9.

Sawlowicz, Z., 1993, Pyrite framboids and their development: a new conceptual mechanism: Geologische Rundschau, v. 82, p. 148–156.

Schuchert, C., and Dunbar, C.O., 1934, Introduction and summary: Geological Society of America Memoirs, v. 1, p. 118.

Schwangler, M., Harris, N., and Waldron, J.W.F., 2017, Oil to source correlation in western Newfoundland: University of Alberta, v. in prep.

Stenzel, S.R., 1991, Carbonate sedimentation in an evolving Middle Ordovician foreland basin, western Newfoundland: Memorial University of Newfoundland, 612 p.

Stevens, R.K., 1970, Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a Proto-Atlantic Ocean, *in* Lajoie, J. ed., Flysch Sedimentology in North America. Geological Association of Canada, Special Paper 7, p. 165–177.

Stevens, R.K., 1965, Geology of the Humber Arm Area, West Newfoundland: Memorial University of Newfoundland.

Stockmal, G.S., Slingsby, A., and Waldron, J.W.F., 2004, Basement-involved inversion at the Appalachian structural front , western Newfoundland : an interpretation of seismic reflection data with implications for petroleum prospectivity: Bulletin of Canadian Petroleum Geology, v. 52, p. 215–233.

Stockmal, G.S., Slingsby, A., Waldron, J.W.F., and Lin, H., 1998, Deformation styles at the Appalachian structural front, western Newfoundland: implications of new industry seismic reflection data: Canadian Journal of Earth Sciences, v. 35, p. 1288–1306.

Stockmal, G.S., and Waldron, J.W.F., 1990, Structure of the Appalachian deformation front in western Newfoundland: Implications of multichannel seismic reflection data: Geology, v. 18, p. 765–768.

Stockmal, G.S., and Waldron, J.W.F., 1993, Structural and tectonic evolution of the Humber Zone, western Newfoundland, 1. Implications of balanced cross sections through the Appalachian structural front, Port au Port Peninsula: Tectonics, v. 12, p. 1056–1075.

Streel, M., Higgs, K., Loboziak, S., Riegel, W., and Steemans, P., 1987, Spore stratigraphy and correlation with floras in the type marine Devonian of the Ardenne-Rhenish regions: Review of Palaeobotony and Palynology, v. 50, p. 211–229.

Waldron, J.W.F., 1985, Structural history of continental margin sediments beneath the Bay of Islands Ophiolite , Newfoundland: Canadian Journal of Earth Sciences, v. 22, p. 1618–1632.

Waldron, J.W.F., Anderson, S.D., Cawood, P.A., Goodwin, L.B., Hall, J., Jamieson, R. a, Palmer, S.E., Stockmal, G.S., and Williams, P.F., 1998, Evolution of the Appalachian Laurentian margin: Lithoprobe results in western Newfoundland: Canadian Journal of Earth Sciences, v. 35, p. 1271–1287.

Waldron, J.W.F., Barr, S.M., Park, A.F., White, C.E., and Hibbard, J., 2015, Late Paleozoic strike-slip faults in Maratime Canada and their role in the reconfiguration of the northern Appalachian orogen: Tectonics, v. 34, p. 24.

Waldron, J.W.F., Henry, A.D., and Bradley, J.C., 2002, Structure and polyphase deformation of the Humber Arm Allochthon and related rocks west of Corner Brook, Newfoundland: Current Research (2002) Newfoundland Department of Mines and Energy, Geological Survey, Report 02-1, p. 47–52.

Waldron, J.W.F., Henry, A.D., Bradley, J.C., and Palmer, S.E., 2003, Development of a fold-ed thrust stack: Humber Arm Allochthon, Bay of Islands, Newfoundland Appalachians:

Canadian Journal of Earth Sciences, v. 40, p. 237–253.

Waldron, J.W.F., Hicks, L., and White, S.E., 2012, Stratigraphy, tectonics and petroleum potential of the deformed Laurentian margin and foreland basins in western Newfoundland: Geological Association of Canada–Mineralogical Association of Canada Joint Annual Meeting, Field Trip Guidebook B3. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Open File NFLD/3172, p. 131.

Waldron, J.W.F., and Palmer, S.E., 2000, Lithostratigraphy and structure of the Humber Arm allochthon in the type area, Bay of Islands, Newfoundland: Newfoundland Department of Mines and Energy, Geological Survey, Report, v. 2000–1, p. 279–290.

Waldron, J.W.F., and Stockmal, G.S., 1991, Mid-Paleozoic thrusting at the Appalachian deformation front: Port au Port Peninsula, western Newfoundland: Canadian Journal of Earth Sciences, v. 28, p. 1992–2002.

Waldron, J.W.F., Stockmal, G.S., Corney, E., and Stenzel, S.R., 1993, Basin development and inversion at the Appalachian structural front, Port au Port Peninsula, western Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 30, p. 1759–1772.

Waldron, J.W.F., Turner, D., and Stevens, K.M., 1988, Stratal disruption and development of melange , Western Newfoundland : effect of high fluid pressure in an accretionary terrain during ophiolite emplacement: Journal of Structural Geology, v. 10, p. 861–873.

White, C.E., Palacios, T., Jensen, S., and Barr, S.M., 2012, Cambrian-Ordovician acritarchs in the Meguma terrane, Nova Scotia, Canada: Resolution of early Paleozoic stratigraphy and implications for paleogeography: Bulletin of the Geological Society of America, v. 124, p. 1773–1792.

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

Williams, H., 1975, Structural Succession, Nomenclature, and Interpretation of Transported Rocks in Western Newfoundland: Canadian Journal of Earth Sciences, v. 12, p. 1874–1894.

Williams, H., and Hiscott, R.N., 1987, Definition of the lapetus rift-drift transition in western Newfoundland: Geology, v. 15, p. 1044–1047.

Williams, H., and Malpas, J., 1972, Sheeted dikes and brecciated dike rocks within transported igneous complexes , Bay of Islands , western Newfoundland: Canadian Journal of Earth Sciences, v. 9, p. 1216–1229.

Zhang, S., and Barnes, C.R., 2004, Arenigian (Early Ordovician) sea-level history and the response of conodont communities, western Newfoundland: Canadian Journal of Earth Sciences, v. 41, p. 843–865.

Williams, H. (Ed.), 1995, Geology of the Appalachian-Caledonian orogen in Canada and Greenland: Geological Society of America.

Chapter 4: Conclusion

The Humber Arm Allochthon and Middle Ordovician foreland basin units have been mapped on Port au Port Peninsula (Figure 4.1). New identification of foreland basin units in areas previously mapped as mélange allow us to distinguish the West Bay Thrust Sheet from the younger, out-of-sequence Lourdes Thrust Sheet (Figure 4.2; 4.3) and identify seven high-angle platform-cutting faults on Port au Port Peninsula (Figure 4.1). Emplacement of the Humber Arm Allochthon onto Port au Port Peninsula was a multi-stage, dynamic process involving at least three deformation events in the Middle Ordovician (Taconian), Devonian (Acadian), and Carboniferous. Deformation involved the interplay between movement on NE-SW trending, high-angle, platform cutting faults, and low-angle faults along which the Humber Arm Allochthon was emplaced (Figure 4.4).

The Humber Arm Allochthon is separated into the Cooks Brook, Middle Arm Point, and Eagle Island formations (Figure 4.3) and a mélange unit. A disruption index applied during mapping has allowed for a distinction between outcrops which have undergone stratal disruption, and can be mapped as broken formation; and outcrops which have undergone stratal disruption and mixing with extraformational blocks, fitting the criterion for mélange (Figure 4.5). Mélange is present at all scales on Port au Port Peninsula and is shown to contain hydrocarbons; the variability of mélange at all scales increases the risk of attempting to extract hydrocarbons from these rocks.

The thinned front edge of the Humber Arm Allochthon (the West Bay Thrust Sheet) was emplaced across Port au Port Peninsula rapidly during the Middle Ordovician with the aid of high fluid pressures possibly related to the expulsion of hydrocarbons within the allochthon (Figure 4.4). High fluid pressures facilitated thinning of the wedge through coaxial extension, allowing it to spread rapidly onto the Laurentian margin where it overlies a lower layer of foreland basin clastic strata (Goose Tickle Group) (Figure 4.2; 4.3). The West Bay Thrust Sheet, representing the early deformation front, is preserved unconformably below an upper unit of foreland basin strata containing fault scarp detritus (Figure 4.4). NE-SW striking high-angle faults greatly influenced the geometry of the foreland basin; extension, inversion, and later strike-slip movement on some of these faults is recorded by the distribution and deformation of rocks assigned to both the foreland basin and Humber Arm Allochthon (Figure 4.4). Timing relationships suggest that high-angle extensional faults were active after emplacement of the West Bay Thrust Sheet but may have begun to be inverted prior to emplacement of the Lourdes Thrust Sheet (Figure 4.4). These relationships better constrain the timing of emplacement and deformation in western Newfoundland.

Figure 4.1: Geological map of a portion of Port au Port Peninsula.

Key localities are shown including graptolite locations and igneous block locations. Abbreviations: WBT=West Bay Thrust, LT=Lourdes Thrust, Brk=Brook, Flt.=Fault, Gp.=Group, Fm.=Formation, Mbr.=Member

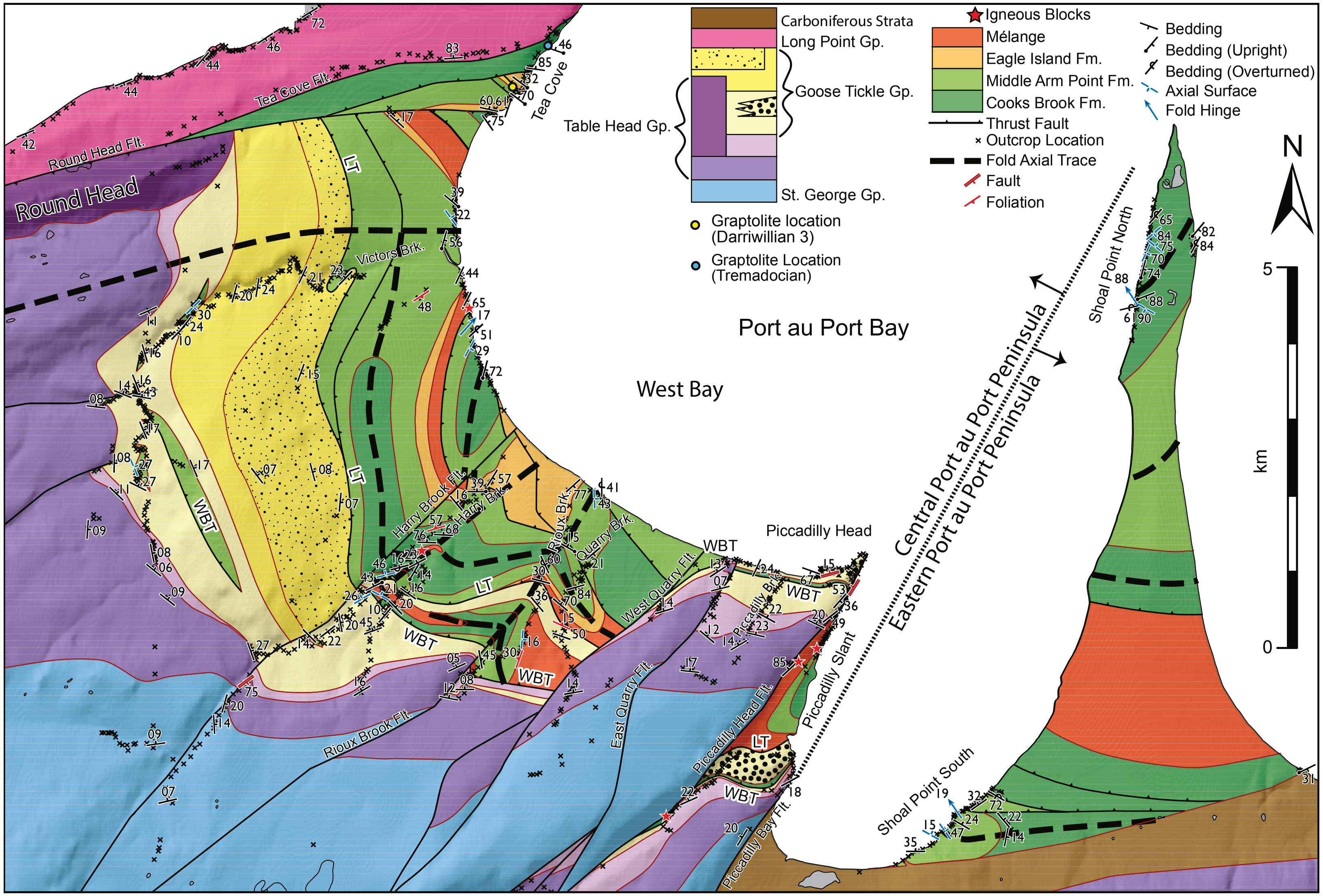


Figure 4.2: Summary of Middle Ordovician stratigraphic relationships.

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

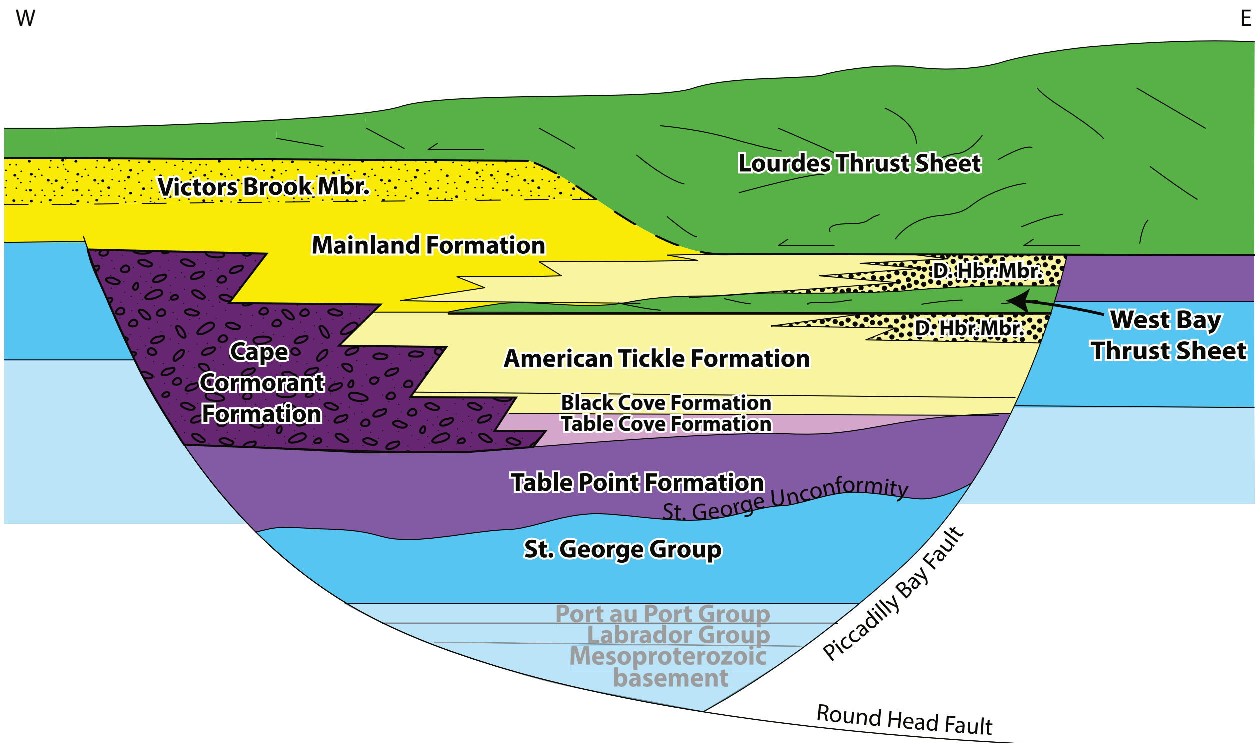


Figure 4.3: Stratigraphy of western Newfoundland.

Compilation of biostratigraphic ages (a-z) included in Chapters 2 and 3.

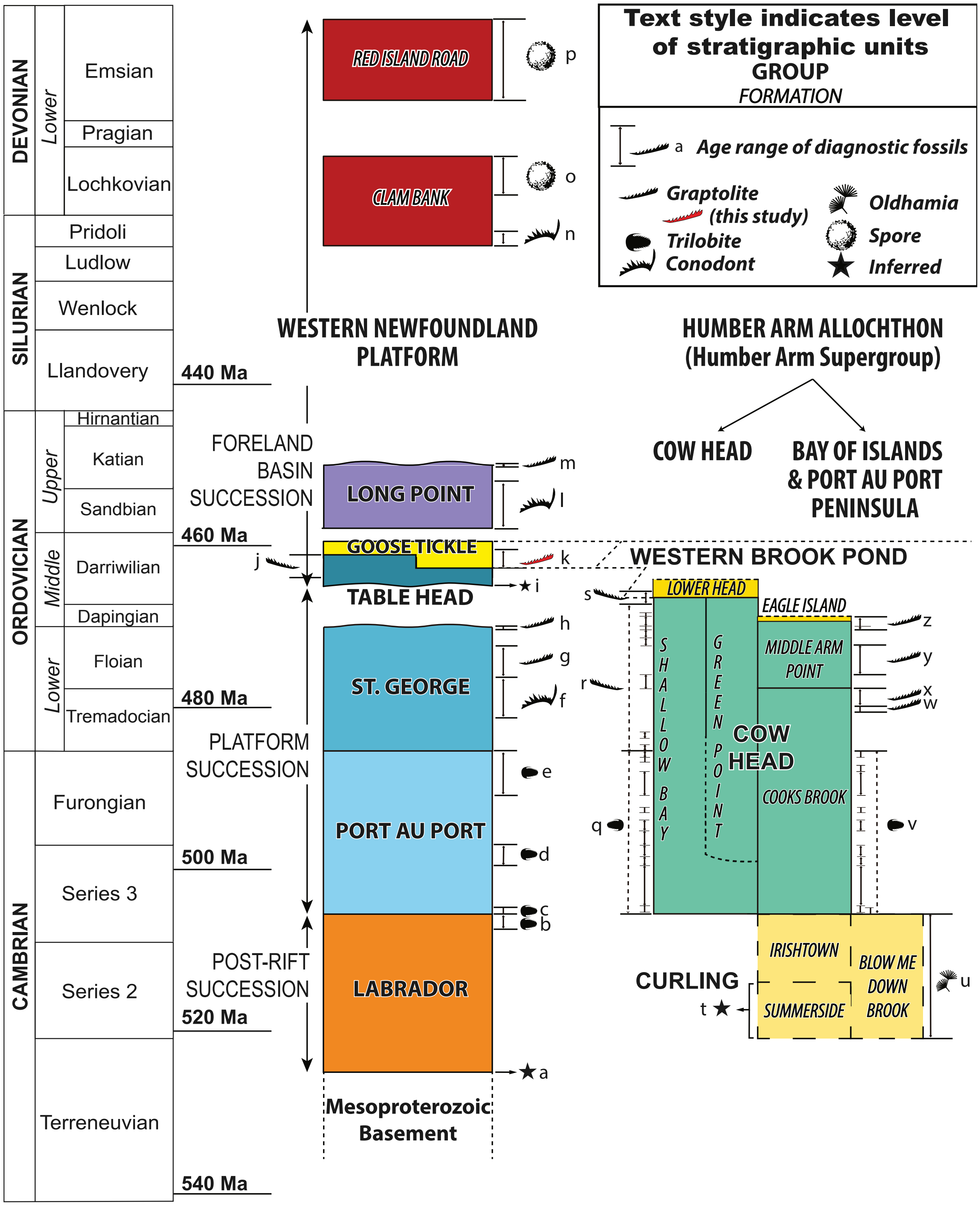
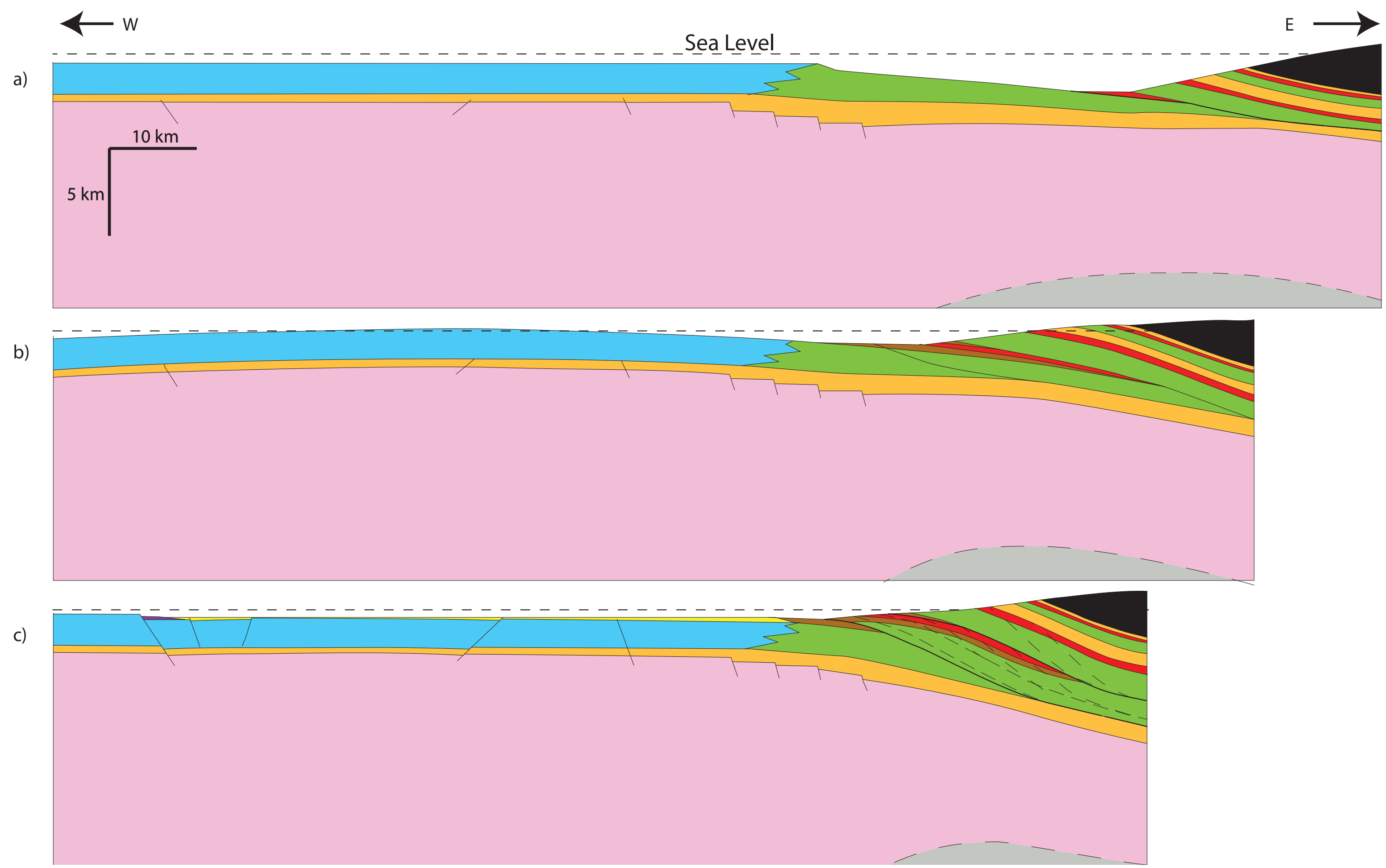
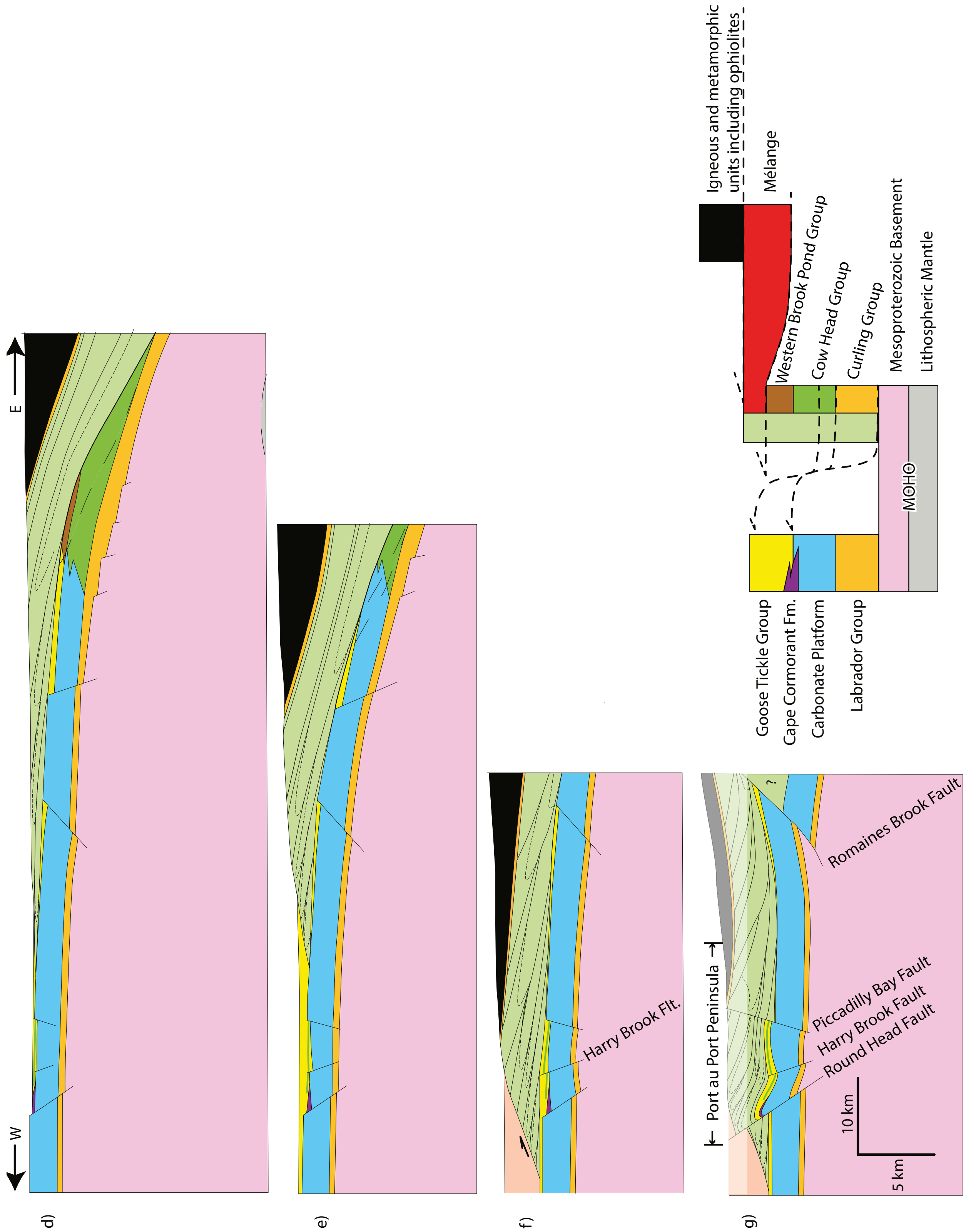


Figure 4.4: Schematic cross-sections through western Newfoundland from the Early Ordovician to Late Devonian.

(a-d) Middle Ordovician: early emplacement of the Humber Arm Allochthon showing earliest deposition into the foreland basin of olistostromal mélange (red) with subsequent foreland basin deposition (brown and yellow) occurring later; emplacement of the West Bay Thrust Sheet and reduced wedge taper is shown in (d). (e-g) ?late Middle Ordovician to Early Devonian: Increased wedge taper through internal deformation and emplacement of the Lourdes Thrust Sheet across Port au Port Peninsula; early inversion of the Harry Brook Fault (f) and subsequent inversion of the Round Head Fault, Piccadilly Bay Fault and Romaines Brook Fault (g) are shown.

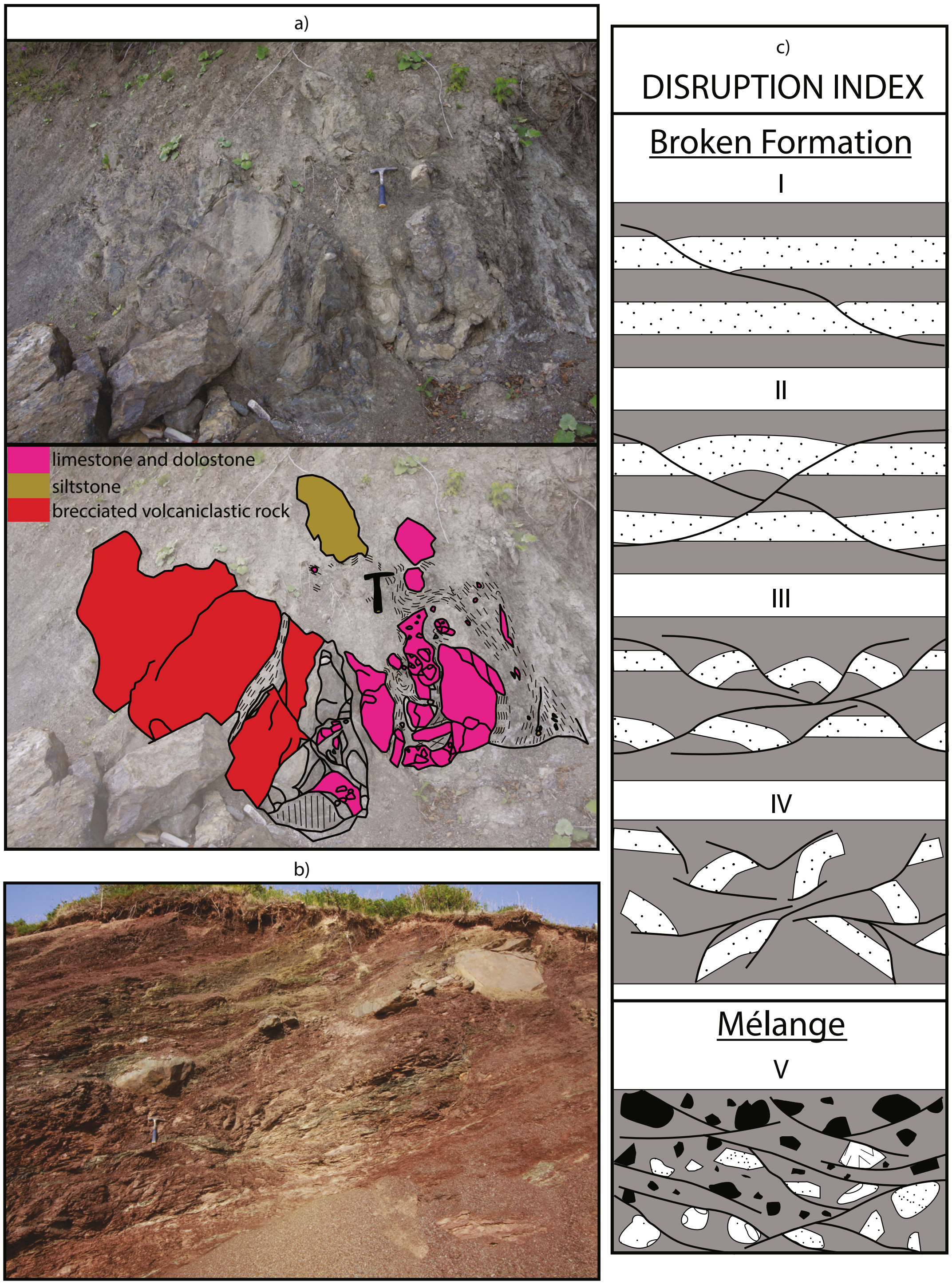




d)
e)
f)
g)
W
E
Harry Brook Flt.
Port au Port Peninsula
Piccadilly Bay Fault
Harry Brook Fault
Round Head Fault
Romaines Brook Fault
10 km
5 km
?
Goose Tickle Group
Cape Cormorant Fm.
Carbonate Platform
Labrador Group
Igneous and metamorphic units including ophiolites
Mélange
Western Brook Pond Group
Cow Head Group
Curling Group
Mesoproterozoic Basement
Lithospheric Mantle
MOHO

Figure 4.5: Photographs of typical mélange outcrop and disruption index.

(a) Unannotated and annotated outcrop photo of mélange containing igneous blocks and sedimentary blocks mixed together at Piccadilly Slant. (b) A second type of mélange where two sedimentary units are mixed within scaly shale; here a string of sandstone blocks of characteristic Eagle Island Formation lithology is mixed with red shales and siliceous mudstone blocks of the Middle Arm Point Formation at Black Point.



Full bibliography of all works cited

Baker, D.F., 1978, Geology and geochemistry of an alkali volcanic suite (Skinner Cove Formation) in the Humber Arm Allochthon, Newfoundland: Memorial University of Newfoundland.

Batten Hender, K.L., and Dix, G.R., 2008, Facies development of a Late Ordovician mixed carbonate-siliciclastic ramp proximal to the developing Taconic orogen: Lourdes Formation, Newfoundland, Canada: Facies, v. 54, p. 121–149.

Bergstrom, S.M., Riva, J., and Kay, M., 1974, Significance of conodonts, graptolites, and shelly faunas from the Ordovician of western and north-central Newfoundland: Canadian Journal of Earth Sciences, v. 11, p. 1625–1660.

Berkland, J., Raymond, L.A., Kramer, J., Montomoli, C., and O'Day, M., 1972, What is Franciscan? American Association of Petroleum Geologists Bulletin, v. 56.

Botsford, J.W., 1987, Depositional history of Middle Cambrian to Lower Ordovician deep water sediments, Bay of Islands, western Newfoundland: Memorial University of Newfoundland, 543 p.

Boyce, W.D., 1983, Early Ordovician trilobite faunas of the Boat Harbour and Catoche formations (St. George Group) in the Boat Harbour - Cape Norman area, Great Northern Peninsula, western Newfoundland: Memorial University of Newfoundland, 311 p.

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

Bradley, D.C., and Kidd, W.S.F., 1991, Flexural extension of the upper continental crust in collisional foredeeps: Geological Society of America Bulletin, v. 103, p. 1416–1438.

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

Burden, E.T., Quinn, L., Nowlan, G.S., and Nill, L.A.B., 2002, Palynology and micropaleontology of the Clam Bank Formation (Lower Devonian) of western Newfoundland, Canada: Palynology, v. 26:1, p. 37–41.

Cawood, P.A., and Botsford, J.W., 1991, Facies and structural contrasts across Bonne Bay cross-strike discontinuity, western Newfoundland: American Journal of Science, v. 291, p. 737–759.

Cawood, P.A., McCausland, P.J.A., and Dunning, G.R., 2001, Opening Iapetus: Constraints from the Laurentian margin in Newfoundland: Geological Society of America Bulletin, v. 113, p. 443–453.

Cawood, P.A., and Nemchin, A.A., 2001, Paleogeographic development of the east Laurentian margin: Constraints from U-Pb dating of detrital zircons in the Newfoundland Appalachians: Geological Society of America Bulletin, v. 113, p. 1234–1246.

Chow, N., 1985, Sedimentology and diagenesis of Middle and Upper Cambrian platform carbonates and siliciclastics, Port au Port Peninsula, western Newfoundland: Memorial University of Newfoundland, 458 p.

Chow, N., and James, N.P., 1987, Cambrian Grand Cycles : A northern Appalachian perspective: Geological Society of America Bulletin, v. 98, p. 418–429.

Cooper, M., Weissenberger, J., Knight, I., Hostad, D., Gillespie, D., Williams, H., Burden, E.T., Porter-Chaudhry, J., Rae, D., and Clark, E., 2001, Basin evolution in western Newfoundland : New insights from hydrocarbon exploration: American Association of

Petroleum Geologists Bulletin, v. 85, p. 393–418.

Cooper, R.A., Sadler, P.M., Hammer, O., and Gradstein, F.M., 2012, The Ordovician Period, in Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G. eds., The Geologic Time Scale 2012, Elsevier B.V., v. 1–2, p. 489–523.

Cousineau, P. a., 1998, Large-scale liquefaction and fluidization in the Cap Chat Mélange, Quebec Appalachians: Canadian Journal of Earth Sciences, v. 35, p. 1408–1422.

Dahlen, F.A., and Suppe, J., 1988, Mechanics, growth, and erosion of mountain belts: Geological Society of America Special Papers, v. 218, p. 161–178.

Dewey, J.F., and Casey, J.F., 2013, The sole of an ophiolite: the Ordovician Bay of Islands Complex, Newfoundland: Journal of the Geological Society, v. 170, p. 715–722.

Festa, A., Dilek, Y., Pini, G.A., Codegone, G., and Ogata, K., 2012, Mechanisms and processes of stratal disruption and mixing in the development of mélanges and broken formations: Redefining and classifying mélanges: Tectonophysics, v. 568–569, p. 7–24.

Festa, A., Pini, G. a., Dilek, Y., and Codegone, G., 2010, Mélanges and mélange-forming processes: a historical overview and new concepts: International Geology Review, v. 52, p. 1040–1105.

Flügel, E., 2010, Microfacies of carbonate rocks - analysis, interpretation and application: Springer-Verlag Berlin Heidelberg, 984 p.

Fowler, M.G., Hamblin, A.P., Hawkins, D., Stasiuk, L.D., and Knight, I., 1995, Petroleum geochemistry and hydrocarbon potential of Cambrian and Ordovician rocks of western Newfoundland: Bulletin of Canadian Petroleum Geology, v. 43, p. 187–213.

Hackley, P.C., and Cardott, B.J., 2016, Application of organic petrography in North American shale petroleum systems: A review: International Journal of Coal Geology, v. 163, p. 8–51.

Harland, W.B., and Gayer, R.A., 1972, The Arctic Caledonides and earlier oceans: Geological Magazine, v. 109, p. 289–314.

Hibbard, J., Van Staal, C.R., and Rankin, D.W., 2007, A comparative analysis of pre-Silurian crustal building blocks of the northern and the southern Appalachian orogen: American Journal of Science, v. 307, p. 23–45.

Hibbard, J., and Waldron, J.W.F., 2009, Truncation and translation of Appalachian promontories: Mid-Paleozoic strike-slip tectonics and basin initiation: Geology, v. 37, p. 487–490.

Hicks, L., and Owens, J. The history of petroleum exploration in western Newfoundland: , p. 24, http://www.nr.gov.nl.ca/nr/energy/pdf/history_petroleum_exploration_western_nl.pdf (accessed March 2017).

Hsü K. J., 1968, Principles of melanges and their bearing on the Franciscan-Knoxville paradox: Geological Society of America Bulletin, v. 79, p. 1063–1074.

Ingram, R.L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geological Society of America Bulletin, v. 86, p. 937–938.

Jacobi, R.D., 1981, Peripheral bulge-a causal mechanism for the Lower/Middle Ordovician unconformity along the western margin of the Northern Appalachians: Earth and Planetary Science Letters, v. 56, p. 245–251.

James, N.P., and Stevens, R.K., 1986, Stratigraphic correlation of the Cambro-Ordovician Cow Head Group, western Newfoundland: Geologic Survey of Canada Bulletin, v. 366, p. 143.

Jenner, G. a., Dunning, G.R., Malpas, J., Brown, M., and Brace, T., 1991, Bay of Islands and Little Port complexes, revisited: age, geochemical and isotopic evidence confirm supra-subduction-zone origin: Canadian Journal of Earth Sciences, v. 28, p. 1635–1652.

Johnson, H., 1941, Paleozoic lowlands of northwestern Newfoundland: The New York Academy of Sciences, Transactions, Series II, v. 3, p. 141–145.

Kindle, C.H., and Whittington, H.B., 1958, Stratigraphy of the cow head region, Western Newfoundland: Bulletin of the Geological Society of America, v. 69, p. 315–342.

Klappa, C.F., Opalinski, P.R., and James, N.P., 1980, Middle Ordovician Table Head Group of western Newfoundland: a revised stratigraphy: Canadian Journal of Earth Sciences, v. 17, p. 1007–1019.

Knight, I., 1978, Platformal sediments on the Great Northern Peninsula: Stratigraphic studies and geological mapping of the north St. Barbe district, in Gibbons, R.V. ed., Report of Activities for 1977. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-1, p. 140–150.

Knight, I., Azmy, K., Boyce, W.D., and Lavoie, D., 2008, Tremadocian carbonate rocks of the lower St. George Group, Port au Port Peninsula, western Newfoundland: lithostratigraphic setting of diagenetic, isotopic and geochemistry studies: Newfoudland and Labrador Department of Natural Resources Geological Survey, v. Report 08-, p. 115–149.

Knight, I., and Boyce, W.D., 1991, Deformed Lower Paleozoic platform carbonates, Goose Arm–Old Man's Pond: Newfoundland Department of Mines and Energy, Geological Survey Branch, v. Report 91-, p. 141–153.

Knight, I., and Boyce, W.D., 1987, Lower to middle Cambrian terrigenous-carbonate rocks of Chimney Arm, Canada Bay: Lithostratigraphy, preliminary biostratigraphy and regional significance: Current Research (1987) Newfoundland Department of Mines and Energy, Mineral Development Division, v. Report 87-, p. 359–365.

Knight, I., and James, N.P., 1987, The stratigraphy of the Lower Ordovician St. George Group, western Newfoundland: the interaction between eustasy and tectonics: Canadian Journal of Earth Sciences, v. 24, p. 1927–1951.

Knight, I., James, N.P., and Lane, T.E., 1991, The St. George Unconformity, northern

Appalachians: The relationship of plate convergence at the St. Lawrence Promontory to the Sauk/Tippecanoe: Geological Society of America Bulletin, v. 103, p. 1200–1225.

Langille, A., 2009, Petrology and Geochemistry of volcanic rocks in the Humber Arm Allochthon, Bay of Islands, western Newfoundland: Memorial University of Newfoundland, 84 p.

Lindholm, R.M., and Casey, J.F., 1989, Regional significance of the Blow Me Down Brook Formation , western Newfoundland : New fossil evidence for an Early Cambrian age: Geological Society of America Bulletin, v. 101, p. 1–13.

Loydell, D.K., 2012, Graptolite biozone correlation charts: Geological Magazine, v. 149, p. 124–132.

Mackay, P. a., 2015, The role of fluid pressure in contractional systems: examples from the Southern Canadian Rocky Mountains: From:Richards, F. L., Richardson, N. J., Rippington, S. J.,Wilson,R.W.&Bond, C. E. (eds) Industrial Structural Geology: Principles, Techniques and Integration. Geological Society, London, Special Publications, 421, v. 421, p. 69–82.

Maletz, J., and Egenhoff, S., 2011, Graptolite biostratigraphy and biogeography of the Table Head and Goose Tickle Groups of western Newfoundland, in Gutierrez-Marco, J.C., Rabano, I., and Garcia-Bellido, D. eds., Ordovician of the World, Cuadernos del Museo Geominero, 14. Instituto Geológico y Minero de España, Madrid, 3-9.

Maletz, J., Egenhoff, S., Böhme, M., Asch, R., Borowski, K., Höntzsch, S., Kirsch, M., and Werner, M., 2011, A tale of both sides of Iapetus – upper Darriwilian (Ordovician) graptolite faunal dynamics on the edges of two continents: Canadian Journal of Earth Sciences, v. 48, p. 841–859.

Palmer, S.E., Burden, E.T., and Waldron, J.W.F., 2001, Stratigraphy of the Curling Group (Cambrian), Humber Arm Allochthon, Bay of Islands: Newfoundland Department of Mines and Energy, Geological Survey, v. Report 200, p. 105–112.

Palmer, S.E., Waldron, J.W.F., and Skilliter, D.M., 2002, Post-Taconian shortening, inversion and strike slip in the Stephenville area, western Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 39, p. 1393–1410.

Peng, S., Babcock, L.E., and Cooper, R.A., 2012, The Cambrian Period, in Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G. eds., The Geologic Time Scale 2012, Elsevier B.V., v. 1–2, p. 437–488.

Quinn, L., 1995, Middle Ordovician foredeep fill in western Newfoundland, in Hibbard, J.P., van Staal, C.R., and Cawood, P.A. eds., Current perpecives in the Appalachian-Caledonian orogen: Geological Association of Canada, Special Paper 41, p. 43–64.

Quinn, L., 1992a, Foreland and trench slope basin sandstones of the Goose Tickle Group and Lower Head Formation, western Newfoundland: Memorial University of Newfoundland, 574 p.

Quinn, L., 1992b, Diagenesis of the Goose Tickle Group, western Newfoundland: A Report for Mobil Oil,.

Quinn, L., Bashforth, a R., Burden, E.T., Gillespie, H., Springer, R.K., and Williams, S.H., 2004, The Red Island Road Formation: Early Devonian terrestrial fill in the Anticosti Foreland Basin, western Newfoundland: Canadian Journal of Earth Sciences, v. 41, p. 587–602.

Quinn, L., Harper, D.A.T., Williams, S.H., and Clarkson, E.N.K., 1999, Late Ordovician fore-land basin fill: Long Point Group of onshore western Newfoundland: Bulletin of Canadian Petroleum Geology, v. 47, p. 63–80.

Ramsey, J.G., and Huber, M.I., 1987, The Techniques of modern structural geology. Vol. 2: Academic Press.

Raymond, L.A., 1975, Tectonite and mélange — a distinction: Geology, p. 7–9.

Sawlowicz, Z., 1993, Pyrite framboids and their development: a new conceptual mechanism: Geologische Rundschau, v. 82, p. 148–156.

Schillereff, S., and Williams, H., 1979, Geology of the Stephenville map area, Newfoundland, in Current Research, Part A, Geological survey of Canada, Paper 79-1A, p. 327–332.

Schuchert, C., and Dunbar, C.O., 1934, Introduction and summary: Geological Society of America Memoirs, v. 1, p. 118.

Schwangler, M., Harris, N., and Waldron, J.W.F., 2017, Oil to source correlation in western Newfoundland: University of Alberta, v. in prep.

Searle, M.P., and Stevens, R.K., 1984, Obduction processes in ancient, modern and future ophiolites: Geological Society, London, Special Publications, v. 13, p. 303–319.

Van Staal, C.R., Dewey, J.F., Niocaill, C.M., and McKerrow, W.S., 1998, The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus: Geological Society, London, Special Publications, v. 143, p. 197–242.

Stenzel, S.R., 1991, Carbonate sedimentation in an evolving Middle Ordovician foreland basin, western Newfoundland: Memorial University of Newfoundland, 612 p.

Stenzel, S.R., Knight, I., and James, N.P., 1990, Carbonate platform to foreland basin: revised stratigraphy of the Table Head Group (Middle Ordovician), western Newfoundland: Canadian Journal of Earth Sciences,.

Stevens, R.K., 1970, Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a Proto-Atlantic Ocean, in Lajoie, J. ed., Flysch Sedimentology in North America. Geological Association of Canada, Special Paper

7, p. 165–177.

Stevens, R.K., 1965, Geology of the Humber Arm Area, West Newfoundland: Memorial University of Newfoundland.

Stockmal, G.S., Slingsby, A., and Waldron, J.W.F., 2004, Basement-involved inversion at the Appalachian structural front , western Newfoundland : an interpretation of seismic reflection data with implications for petroleum prospectivity: Bulletin of Canadian Petroleum Geology, v. 52, p. 215–233.

Stockmal, G.S., Slingsby, A., Waldron, J.W.F., and Lin, H., 1998, Deformation styles at the Appalachian structural front, western Newfoundland: implications of new industry seismic reflection data: Canadian Journal of Earth Sciences, v. 35, p. 1288–1306.

Stockmal, G.S., and Waldron, J.W.F., 1993, Structural and tectonic evolution of the Humber Zone, western Newfoundland, 1. Implications of balanced cross sections through the Appalachian structural front, Port au Port Peninsula: Tectonics, v. 12, p. 1056–1075.

Stockmal, G.S., and Waldron, J.W.F., 1990, Structure of the Appalachian deformation front in western Newfoundland: Implications of multichannel seismic reflection data: Geology, v. 18, p. 765–768.

Streel, M., Higgs, K., Loboziak, S., Riegel, W., and Steemans, P., 1987, Spore stratigraphy and correlation with floras in the type marine Devonian of the Ardenne-Rhenish regions: Review of Palaeobotony and Palynology, v. 50, p. 211–229.

Waldron, J.W.F., 1985, Structural history of continental margin sediments beneath the Bay of Islands Ophiolite , Newfoundland: Canadian Journal of Earth Sciences, v. 22, p. 1618–1632.

Waldron, J.W.F., Anderson, S.D., Cawood, P.A., Goodwin, L.B., Hall, J., Jamieson, R. a, Palmer, S.E., Stockmal, G.S., and Williams, P.F., 1998, Evolution of the Appalachian Laurentian margin: Lithoprobe results in western Newfoundland: Canadian Journal of Earth Sciences,

v. 35, p. 1271–1287.

Waldron, J.W.F., Barr, S.M., Park, A.F., White, C.E., and Hibbard, J., 2015, Late Paleozoic strike-slip faults in Maratime Canada and their role in the reconfiguration of the northern Appalachian orogen: Tectonics, v. 34, p. 24.

Waldron, J.W.F., Henry, A.D., and Bradley, J.C., 2002, Structure and polyphase deformation of the Humber Arm Allochthon and related rocks west of Corner Brook, Newfoundland: Current Research (2002) Newfoundland Department of Mines and Energy, Geological Survey, Report 02-1, p. 47–52.

Waldron, J.W.F., Henry, A.D., Bradley, J.C., and Palmer, S.E., 2003, Development of a folded thrust stack: Humber Arm Allochthon, Bay of Islands, Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 40, p. 237–253.

Waldron, J.W.F., Hicks, L., and White, S.E., 2012, Stratigraphy, tectonics and petroleum potential of the deformed Laurentian margin and foreland basins in western Newfoundland: Geological Association of Canada–Mineralogical Association of Canada Joint Annual Meeting, Field Trip Guidebook B3. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Open File NFLD/3172, p. 131.

Waldron, J.W.F., and Palmer, S.E., 2000, Lithostratigraphy and structure of the Humber Arm allochthon in the type area, Bay of Islands, Newfoundland: Newfoundland Department of Mines and Energy, Geological Survey, Report, v. 2000–1, p. 279–290.

Waldron, J.W.F., Schofield, D.I., and Murphy, J.B., 2017, Diachronous Paleozoic accretion of Peri-Gondwanan terranes at the Laurentian margin: Geological Society of London Special Publication, submitted, p. 42.

Waldron, J.W.F., and van Staal, C.R., 2001, Taconian orogeny and the accretion of the Dashwoods block : A peri-Laurentian microcontinent in the Iapetus Ocean: Geology, v. 29,

p. 811–814.

Waldron, J.W.F., and Stockmal, G.S., 1991, Mid-Paleozoic thrusting at the Appalachian deformation front: Port au Port Peninsula, western Newfoundland: Canadian Journal of Earth Sciences, v. 28, p. 1992–2002.

Waldron, J.W.F., Stockmal, G.S., Corney, E., and Stenzel, S.R., 1993, Basin development and inversion at the Appalachian structural front, Port au Port Peninsula, western Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 30, p. 1759–1772.

Waldron, J.W.F., Turner, D., and Stevens, K.M., 1988, Stratal disruption and development of melange , Western Newfoundland : effect of high fluid pressure in an accretionary terrain during ophiolite emplacement: Journal of Structural Geology, v. 10, p. 861–873.

White, C.E., Palacios, T., Jensen, S., and Barr, S.M., 2012, Cambrian-Ordovician acritarchs in the Meguma terrane, Nova Scotia, Canada: Resolution of early Paleozoic stratigraphy and implications for paleogeography: Bulletin of the Geological Society of America, v. 124, p. 1773–1792.

Williams, H., 1978, Tectonic lithofacies map of the Appalachian orogen: Memorial University of Newfoundland,.

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

Williams, H., 1985, Humber Arm Allochthon and nearby groups between Bonne Bay and Portland Creek, western Newfoundland, in Geological Survey of Canada Current Research, p. 399–406.

Williams, H., 1975, Structural Succession, Nomenclature, and Interpretation of Transported Rocks in Western Newfoundland: Canadian Journal of Earth Sciences, v. 12, p. 1874–1894.

Williams, H., and Hiscott, R.N., 1987, Definition of the lapetus rift-drift transition in western Newfoundland: Geology, v. 15, p. 1044–1047.

Williams, H., and Malpas, J., 1972, Sheeted dikes and brecciated dike rocks within transported igneous complexes , Bay of Islands , western Newfoundland: Canadian Journal of Earth Sciences, v. 9, p. 1216–1229.

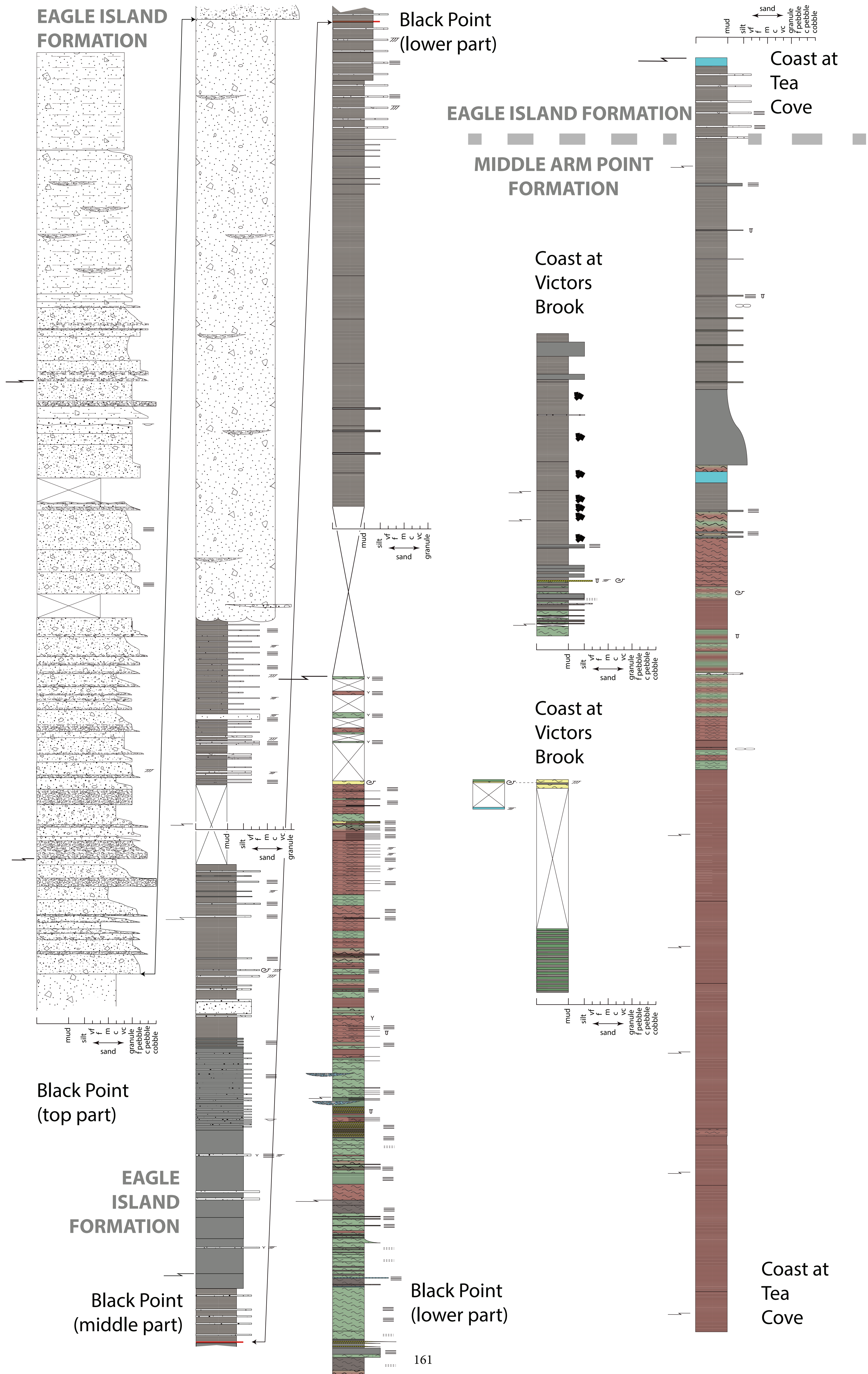
Williams, H. (Ed.), 1995, Geology of the Appalachian-Caledonian orogen in Canada and Greenland: Geological Society of America.

Wilson, J.T., 1966, Did the Atlantic close and then re-open? Nature,.

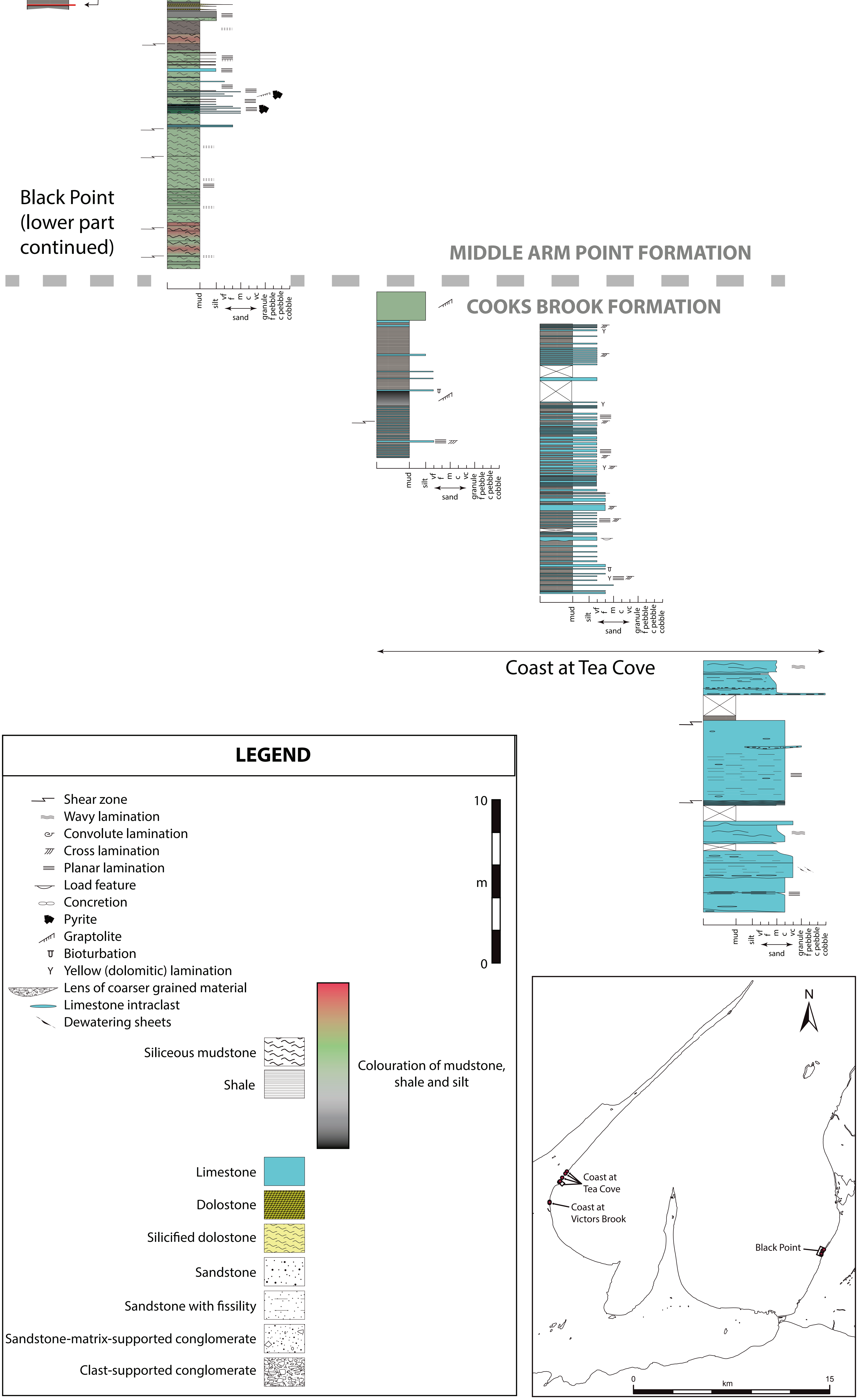
Zhang, S., and Barnes, C.R., 2004, Arenigian (Early Ordovician) sea-level history and the response of conodont communities, western Newfoundland: Canadian Journal of Earth Sciences, v. 41, p. 843–865.

APPENDIX A: MEASURED SECTIONS

This Appendix accompanies Chapter 3. It shows measured sections through more coherent sections of stratigraphy within the Humber Arm Allochthon on Port au Port Peninsula.



EAGLE ISLAND FORMATION
Black Point (lower part)
Coast at Tea Cove
EAGLE ISLAND FORMATION
MIDDLE ARM POINT FORMATION
Coast at Victors Brook
Coast at Victors Brook
Black Point (top part)
EAGLE ISLAND FORMATION
Black Point (middle part)
Black Point (lower part)
Coast at Tea Cove
mud
silt
vf
f
m
c
vc
granule
f pebble
c pebble
cobble
sand


Black Point
(lower part
continued)
MIDDLE ARM POINT FORMATION
COOKS BROOK FORMATION
mud
silt
vf
f
m
c
vc
sand
granule
f pebble
c pebble
cobble
Y
Coast at Tea Cove
LEGEND
Shear zone
Wavy lamination
Convolute lamination
Cross lamination
Planar lamination
Load feature
Concretion
Pyrite
Graptolite
Bioturbation
Yellow (dolomitic) lamination
Lens of coarser grained material
Limestone intraclast
Dewatering sheets
Siliceous mudstone
Shale
Colouration of mudstone, shale and silt
Limestone
Dolostone
Silicified dolostone
Sandstone
Sandstone with fissility
Sandstone-matrix-supported conglomerate
Clast-supported conglomerate
10
m
0
N
Coast at
Tea Cove
Coast at
Victors Brook
Black Point
0
km
15