TECTONICS OF THE WEST NEWFOUNDLAND APPALACHIANS: A FIELD GUIDE

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OVERVIEW

Western Newfoundland is a classic area for the development of the latest Precambrian to Middle Ordovician succession of the Laurentian passive continental margin. It also provides a world-class record of the foundering of the continental shelf, emplacement of allochthons including oceanic crustal rocks, and subsequent deformational events from Ordovician to Devonian. The region is also an active area for petroleum exploration, although it has yet to yield major discoveries. This field trip explores the fascinating sedimentary and igneous records, with an emphasis on facies variations now telescoped by deformation. The itinerary includes parts of Gros Morne National Park, and also the rich fossil localities of the Port-au-Port Peninsula and Table Point. This is a place where you can step from the peritidal zone, down the continental slope, and onto the ocean floor in just a few outcrops.

ACKNOWLEDGMENTS

The author is grateful to the Canadian Tectonics Group, a division of the Geological Association of Canada (GAC), and the Newfoundland and Labrador section of the Geological Association of Canada, for making this trip possible. Nalcor Exploration, Marathon Gold, the Geoscience Education Trust of Newfoundland and Labrador (GET-NL), and Memorial University of Newfoundland provided generous sponsorship. I thank the Newfoundland and Labrador Department of Natural Resources, Geological Survey Branch, for logistical and transportation support and for the printing of this guide. We are also grateful to Parks Canada for supporting us in our visit to Gros Morne National Park.

Western Newfoundland has been a classic field trip area for decades and I am grateful to those who have preceded us and passed on their knowledge. Inevitably a field guide such as this draws on this knowledge, and in some places we have explicitly used descriptions from previous guides in constructing this one. I acknowledge the contributions of John Malpas (1987), Hank Williams and Peter Cawood (Cawood et al. 1988), Noel James (James et al. 1988), Ian Knight (Knight et al. 2007) Larry Hicks, (Hicks et al. 2010). I am particularly grateful to Andrew Kerr, who generously shared information from his forthcoming guide to the ophiolitic rocks (Kerr 2019).

I also acknowledge grant support for research leading to this field trip from the Petroleum Exploration Enhancement Program of Newfoundland and Labrador, and from the Natural Sciences and Engineering Research Council of Canada.

SAFETY CONSIDERATIONS

Field trips may involve hazards to the participants and leaders. For your safety as well as the safety of others, observe the following precautions on the trip.

Weather is unpredictable and participants should be prepared for a wide range of temperatures. Always take suitable clothing. A rain suit, sweater, sturdy footwear is essential. Remember to take gloves and a warm hat. However, bright sunshine is equally possible, in which case make sure you have sunscreen.

Inform field trip leaders of any health concern that may affect your health and safety or that of co-participants.

Act in a manner that is safe for yourself and other participants. You are the most important factor in your own safety. Be aware of your surroundings and do not do anything that could be unsafe.

Several stops may be adjacent to highways. Wear high-visibility vests. Take care when exiting the field trip vehicles. If it is necessary to cross the road, remember that groups straggling across a highway are particularly vulnerable; cross together if possible and avoid situations where groups travel on both sides of the highway, creating a bottleneck for traffic. Except when crossing, stay off the paved highway at all times. Each individual must take responsibility for their own safety and for that of the group.

Take care while walking along shorelines. Rocks are often slippery and waves may be troublesome. Slippery rocks, tree roots and moss covered rocks / roots may also pose hazards during non-shoreline traversing.

Watch out for loose rock on slopes. On slopes be aware that those below you are vulnerable to displaced rocks. Do not walk straight down steep slopes especially if others are also on the slope below you. Instead, proceed down slopes at an angle, and stay in a tight group. Walk at the pace of the slowest member. Warn those below clearly and immediately if you displace an object that may be hazardous.

Do not attempt to enter old mine workings.

Do not approach wildlife.

Do not wander away from the main group while at field trip stops.

Several stops are on tidally influenced shorelines. Be aware of the state of the tide, and work on a falling tide if possible. Stay with the group.

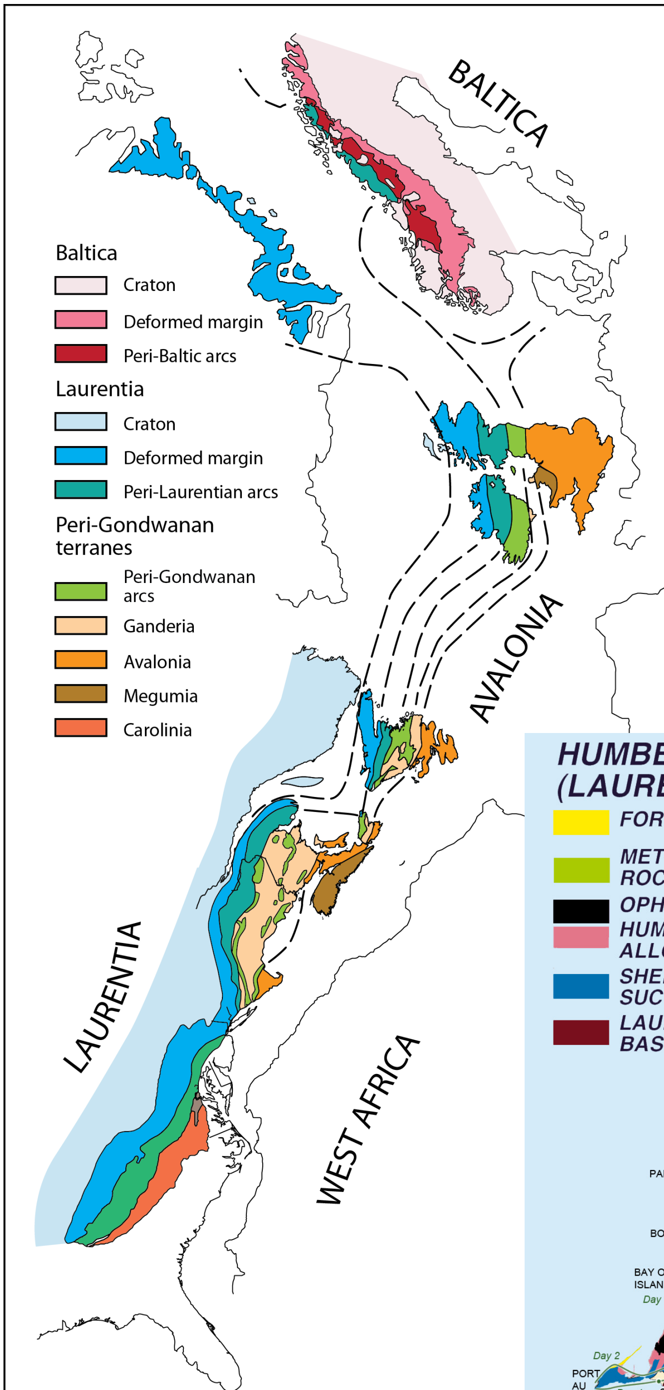


Figure 1 Schematic map of Appalachian-Caledonide Orogen in Pangea reconstruction.

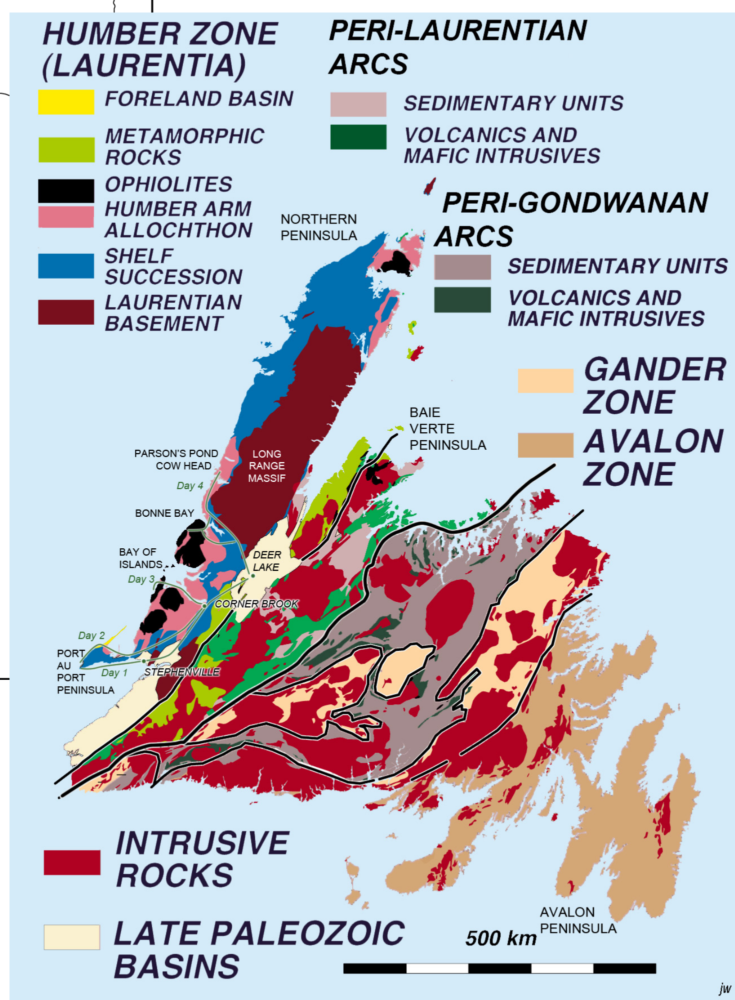


Figure 2. Summary geological map of Newfoundland, showing main tectonic units.

INTRODUCTION

Significance of West Newfoundland Geology

Western Newfoundland has had a huge influence on the development of Appalachian geology. The Humber Arm, one of several spectacular fjords that meet in the Bay of Islands, has given its name to the Humber Zone of the Appalachians (Williams 1979), representing the margin of the Laurentian continent, that can be traced along the full length of the Appalachians (Figure 1, Figure 2). Correlative rocks can be found in the northwest highlands of Scotland (which lay close to Newfoundland before the opening of the Atlantic in the Mesozoic) and in Greenland.

During the early Paleozoic Era, these rocks lay on the N or NW margin of the Iapetus Ocean. The progressive closing of the Iapetus Ocean, the accretion of a number of exotic terranes from the margin of Gondwana, and eventually the assembly of Pangea, resulted in the development of the Appalachian-Caledonide orogen (Figure 1). During these events, the margins of Iapetus were telescoped, with the result that contrasting rocks from contrasting tectonic and sedimentary environments are now juxtaposed by faults, deformed by folds, and metamorphosed. Ophiolites, probably representing oceanic crust formed in arc-related settings within the Iapetus Ocean, were emplaced onto the margin. Episodes of foreland basin subsidence that occurred during the building of the Appalachians are recorded in the deposition of Ordovician to Devonian sedimentary rocks.

Major geological subdivisions

Within the Humber Zone, our focus will be the least metamorphosed, western portion, distinguished as the **external Humber Zone**. To the east, metamorphic rocks dominate the **internal Humber Zone**. In the external Humber Zone, several large-scale assemblages of rock can be recognized (Figure 3).

Grenville basement

- In the stratigraphically and structurally lowest position are Mesoproterozoic metamorphic and igneous rocks of the **Grenville basement**, that record the assembly of the earlier supercontinent Rodinia at ~1 Ga during the Grenville orogeny. These form the foundation on which the Laurentian margin was built.

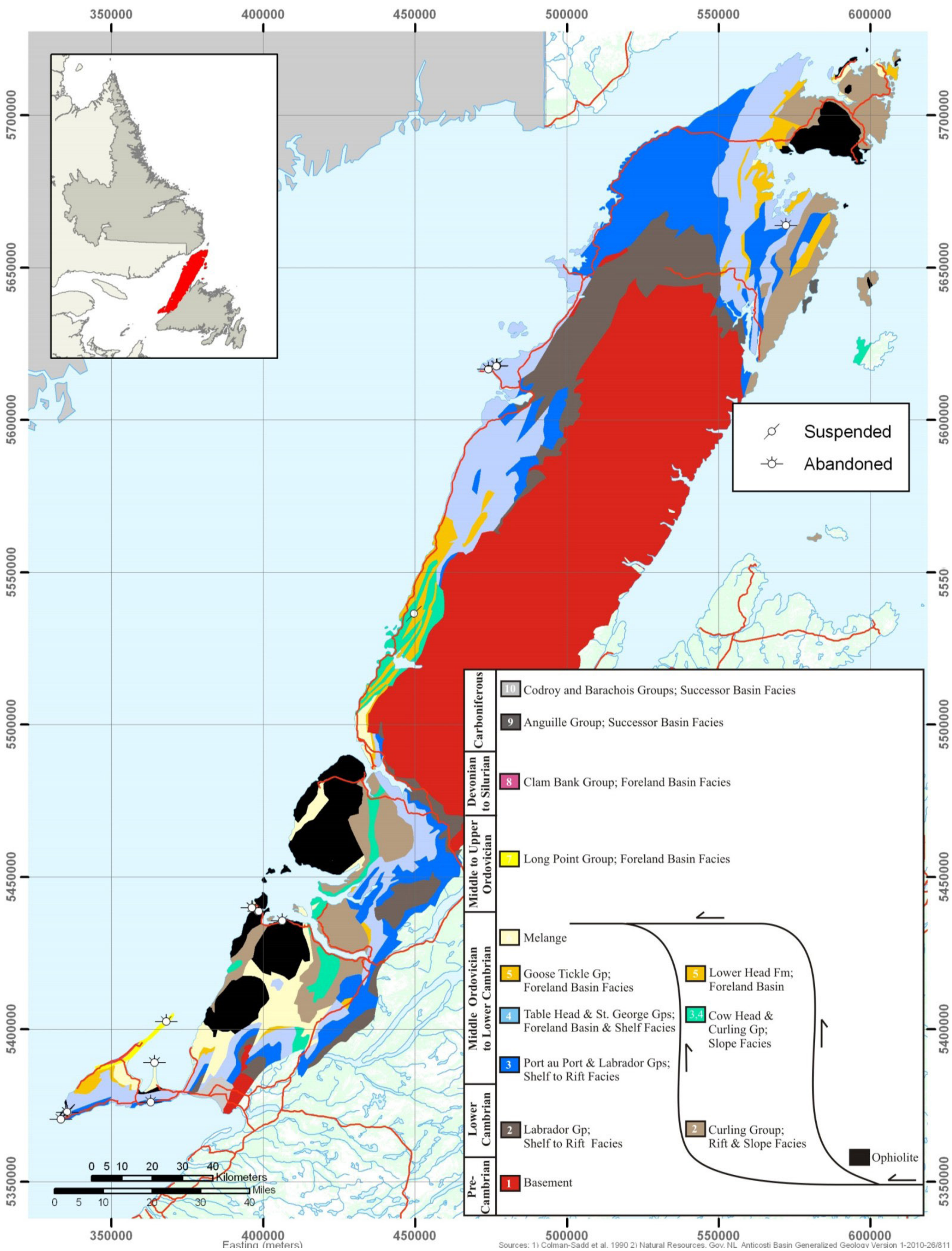
The Laurentian margin rift and shelf succession...

- The Laurentian margin rift and shelf succession was deposited on Grenville basement between latest Neoproterozoic (~600 Ma) and Early Ordovician (~470 Ma). Early Cambrian clastic sedimentary rocks are overlain by a thick carbonate-dominated succession deposited on the tropical shelf of Laurentia (Figure 4, Figure 5).

Humber Arm Allochthon:

- Contemporary with these predominantly shallow-water sedimentary rocks, deeper-water facies were deposited on the continental slope and rise. These are now preserved in the **Humber Arm Supergroup** (Figure 4, Figure 5).
- **Ophiolitic rocks** of the Bay of Islands and Little Port Complexes, representing oceanic island arcs that encroached on the margin from the southeast, comprise the upper slices of the **Humber Arm Allochthon.** Although they were undoubtedly formed well to the

Figure 3. Summary geological map of western Newfoundland showing location of Humber Arm Allochthon and correlative units of Laurentian margin (Waldron and Hicks 2011).



southeast of the Laurentian shelf, they are now found in a highly deformed state, tectonically emplaced above the shelf succession.

Foreland basins:

- In Middle Ordovician time, this shelf succession underwent rapid subsidence as thrust sheets of the Humber Arm Allochthon were emplaced onto the margin during early stages of the Taconian Orogeny. These events are recorded by a **Taconian foreland basin succession.** After the Taconian Orogeny, the margin continued to subside intermittently, first during the Late Ordovician, and then again during the latest Silurian to Early Devonian. The driving force for this subsidence, like that during the Taconian Orogeny, was probably loading by the mountain belt that had been built upon the continental margin. The subsidence is recorded in **post-Taconian foreland basin successions,** which underlie a huge area of sea-floor beneath the Gulf of St. Lawrence to the west, despite their limited extent on land (Figure 4, Figure 5).

Late Paleozoic Maritimes Basin:

- Overlying these deformed rocks of the Appalachians are non-marine clastic sedimentary rocks, marine limestone, evaporites, and coal or Carboniferous (Mississippian and Pennsylvanian) age. These represent the fill of a large successor basin, the Maritimes basin, which straddled the entire Appalachian orogen. The thickest development of these rocks is in the Bay St. George basin in southwest Newfoundland. Although a fascinating study in themselves, they will not be a major focus for our field trip.

Quaternary deposits:

- In addition to the above units of consolidated rock, western Newfoundland displays a fascinating record of Quaternary history recorded by spectacular glacial valleys, raised beaches, glacial, and periglacial sediments. We will remark on these where their distribution affects bedrock outcrop and human history, but like the Carboniferous record, they will not be a major focus of our trip.

ROCK UNITS

Laurentian Basement

The oldest rocks in western Newfoundland are metamorphic and intrusive igneous rocks from the Grenville Orogen, dated at 1 Ga or older. These Precambrian rocks formed during the assembly of an even older supercontinent, termed Rodinia. They form the basement to the Newfoundland Appalachians, on which the sedimentary rocks of main interest in this field trip were deposited. They are exposed in restricted areas of western Newfoundland, of which by far the largest is the Long Range Inlier of the Northern Peninsula (Figure 3). Smaller areas of Grenville basement rock are exposed farther south, including in the Indian Head Range just east of Stephenville.

Shelf succession: passive margin of Laurentia

Labrador Group

The supercontinent Rodinia began to break up during the Neoproterozoic. Rifting led to the intrusion of mafic dykes, and the deposition thick terrestrial clastic units (Bradore Formation) and basaltic lava flows (Lighthouse Cove Formation), assigned to the of the Labrador Group, which are confined to graben in the Grenville basement (Figure 6). On adjacent horsts, these rift successions are much thinner or entirely absent. Eventually ocean-floor spreading commenced in the new Iapetus Ocean. Western Newfoundland lay on the edge of the newly formed continent Laurentia.

Following the start of ocean-floor spreading in the Iapetus Ocean, the continental margin underwent slow thermal subsidence. The changeover from rifting to thermal subsidence is marked by a breakup unconformity (Williams and Hiscott 1987) above which the sedimentary succession shows a much more 'layer-cake' style (Figure 5). Above the unconformity, shale and limestone (Forteau Formation; Figure 6) followed by quartz-rich sandstone (Hawke Bay Formation) were deposited in shelf conditions during Cambrian epoch 2 (~ 521-509 Ma). They are assigned, together with the underlying rift-related sediments, to the Labrador Group.

Port au Port and St. George groups

In Middle Cambrian time (Figure 6) the continental shelf underwent a transition to predominantly carbonate sedimentation, recorded in the Port au Port Group (middle to late Cambrian) and the overlying St. George Group (Early Ordovician). During this time, what is now the eastern margin of Laurentia lay more or less east-west in the southern tropics. Clear tropical waters provided an ideal environment for the deposition of carbonate sediments, now preserved as limestones and dolostones. This succession of carbonate sedimentary rocks can be traced, in general terms, from Alabama in the present southwest, through Atlantic Canada, into NW Scotland and on into Greenland, areas which formed a continuous belt prior to the opening of the modern Atlantic (James et al. 1989) (Figure 1).

Laurentian slope and rise: Humber Arm Supergroup

To the SE of the Laurentian shelf (in present-day coordinates) a continental slope and rise developed during the Cambrian and Early Ordovician. Sedimentary rocks deposited there are assigned to the Humber Arm Supergroup. The preserved fragments are now tectonically emplaced above the shelf succession in the lower parts of the Humber Arm Allochthon. The stratigraphy in Figure 6 has to be pieced together from multiple tectonic slices.

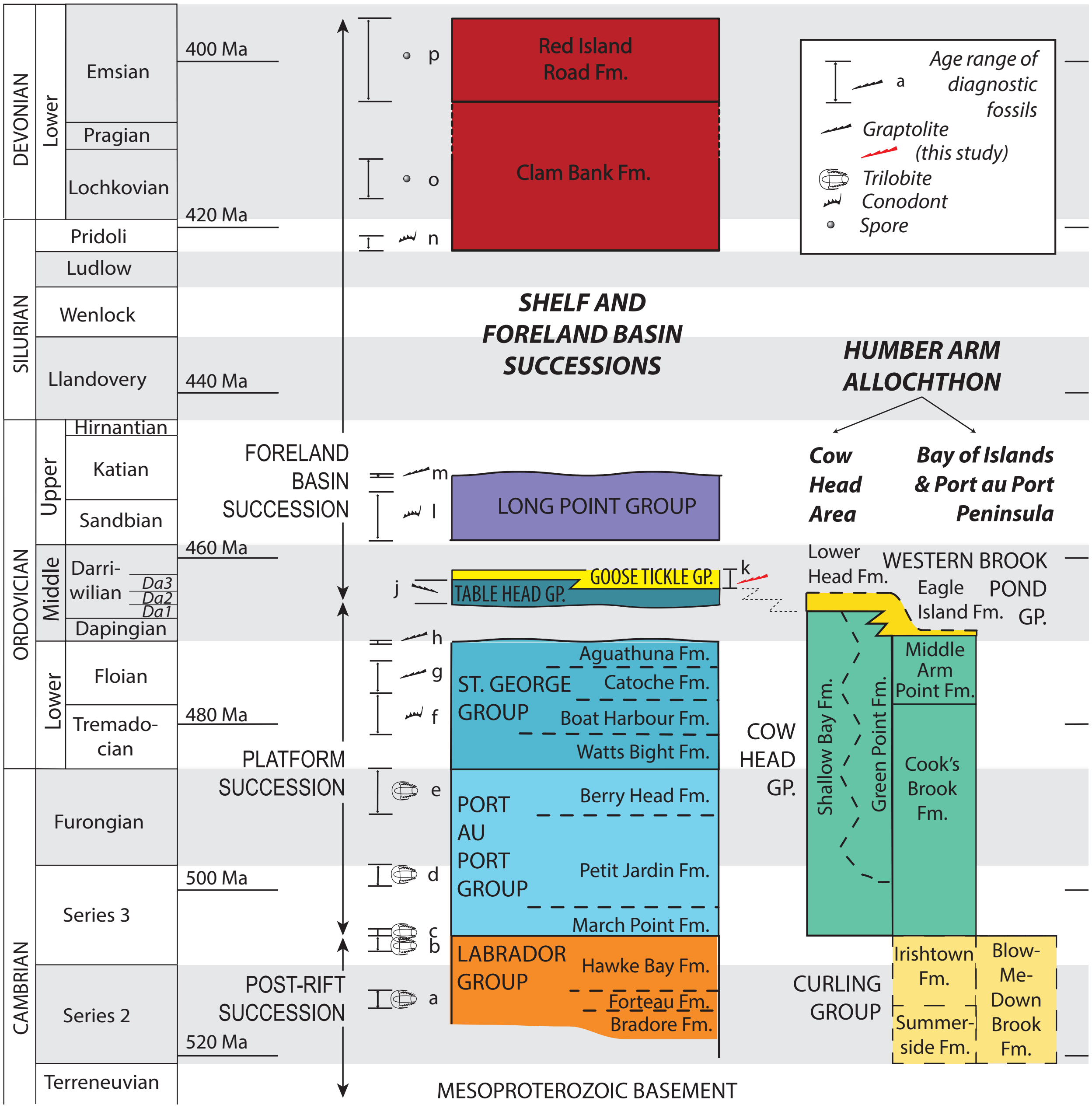
Curling Group

The most complete slope and rise successions are found in the Bay of Islands. The Cambrian Curling Group, well exposed around the City of Corner Brook, consists of interbedded sandstone and slate, with less common conglomerate. These represent deep-water equivalents of the Labrador Group of the shelf succession. Sedimentary structures formed by turbidity currents attest to deposition in a deep-water, slope environment.

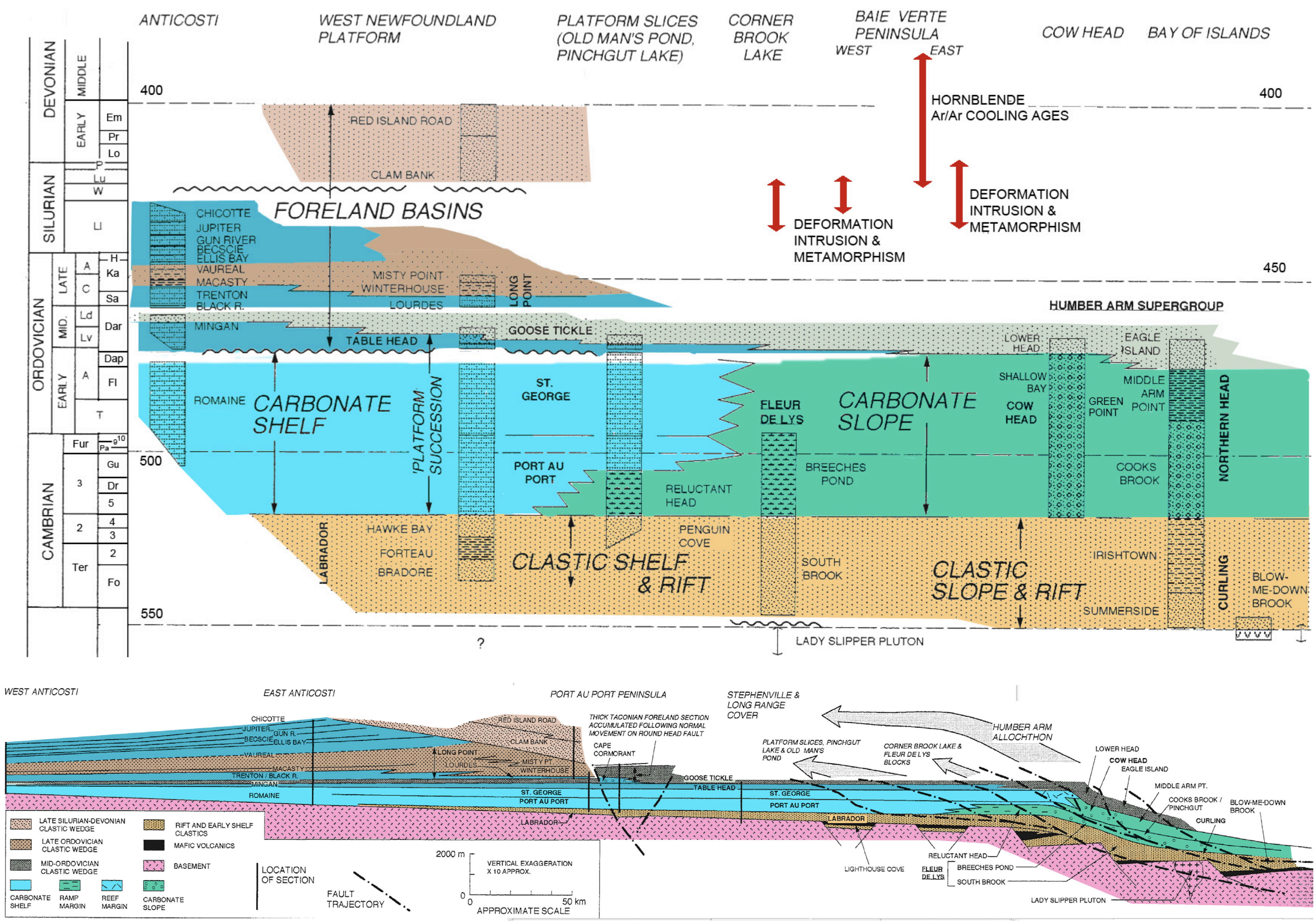
Cow Head Group

The Cambrian to Early Ordovician Cow Head Group consists of slope limestone, limestone conglomerate, shale and chert, representing Middle Cambrian to Early Ordovician slope

Figure 4 Stratigraphic columns for major units of Laurentian margin (Lacombe et al. 2019a).



environments located offshore of the Laurentian shelf, laterally equivalent to the Port au Port and St. George Groups of the shelf succession. It is well exposed north of Bonne Bay (Figure 3), where it includes the international Cambrian-Ordovician boundary stratotype at Green Point. Historically, equivalent rocks in the Bay of Islands were assigned to a different group (Northern Head Group) but the rocks are closely similar, and we (Lacombe et al. 2019b, White et al. 2019b) have recently argued that all should be assigned to the same group.


ANTICOSTI
WEST NEWFOUNDLAND PLATFORM
PLATFORM SLICES (OLD MAN'S POND, PINCHGUT LAKE)
CORNER BROOK LAKE
BAIE VERTE PENINSULA
WEST
EAST
COW HEAD
BAY OF ISLANDS
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
400
450
500
550
HORNBLENDE Ar/Ar COOLING AGES
DEFORMATION INTRUSION & METAMORPHISM
DEFORMATION INTRUSION & METAMORPHISM
RED ISLAND ROAD
CLAM BANK
FORELAND BASINS
CHICOTTE
JUPITER
GUN RIVER
BECSCIE
ELLIS BAY
VAUREAL
MACASTY
TRENTON
BLACK R.
MINGAN
MISTY POINT
WINTERHOUSE
LOURDES
LONG POINT
GOOSE TICKLE
TABLE HEAD
HUMBER ARM SUPERGROUP
ROMAINE
CARBONATE SHELF
'PLATFORM SUCCESSION
ST. GEORGE
PORT AU PORT
CARBONATE SLOPE
FLEUR DE LYS
BREECHES POND
RELUCTANT HEAD
LOWER HEAD
SHALLOW BAY
COW HEAD
GREEN POINT
EAGLE ISLAND
MIDDLE ARM POINT
COOKS BROOK
NORTHERN HEAD
LABRADOR
HAWKE BAY
FORTEAU
BRADORE
CLASTIC SHELF & RIFT
PENGUIN COVE
SOUTH BROOK
CLASTIC SLOPE & RIFT
IRISHTOWN
SUMMERSIDE
CURLING
BLOW-ME-DOWN BROOK
LADY SLIPPER PLUTON
WEST ANTICOSTI
EAST ANTICOSTI
PORT AU PORT PENINSULA
STEPHENVILLE & LONG RANGE COVER
THICK TACONIAN FORELAND SECTION ACCUMULATED FOLLOWING NORMAL MOVEMENT ON ROUND HEAD FAULT
CAPE CORMORANT
PLATFORM SLICES, PINCHGUT LAKE & OLD MAN'S POND
CORNER BROOK LAKE & FLEUR DE LYS BLOCKS
HUMBER ARM ALLOCHTHON
MIDDLE ARM PT.
COOKS BROOK / PINCHGUT
LIGHTHOUSE COVE
LATE SILURIAN-DEVONIAN CLASTIC WEDGE
LATE ORDOVICIAN CLASTIC WEDGE
MID-ORDOVICIAN CLASTIC WEDGE
CARBONATE SHELF
RAMP MARGIN
REEF MARGIN
CARBONATE SLOPE
RIFT AND EARLY SHELF CLASTICS
MAFIC VOLCANICS
BASEMENT
LOCATION OF SECTION
FAULT TRAJECTORY
2000 m
VERTICAL EXAGGERATION X 10 APPROX.
0
50 km
APPROXIMATE SCALE

Ophiolites

Western Newfoundland is perhaps best known geologically for its ophiolitic rocks, which were amongst the first to be identified as preserved fragments of oceanic lithosphere, thrust onto continents during convergent tectonic events. Early interpretations of ophiolites correlated them with typical ocean floor formed at mid-ocean spreading ridges. Subsequently, it was found geochemically that almost all ophiolites show at least some influence of volcanic-arc magmatism. The ophiolites of W Newfoundland are now interpreted as having formed in settings ranging from volcanic arc to back-arc basin settings.

Figure 7 Map of western Newfoundland showing the principal ophiolitic units, after Dewey and Casey (2013)

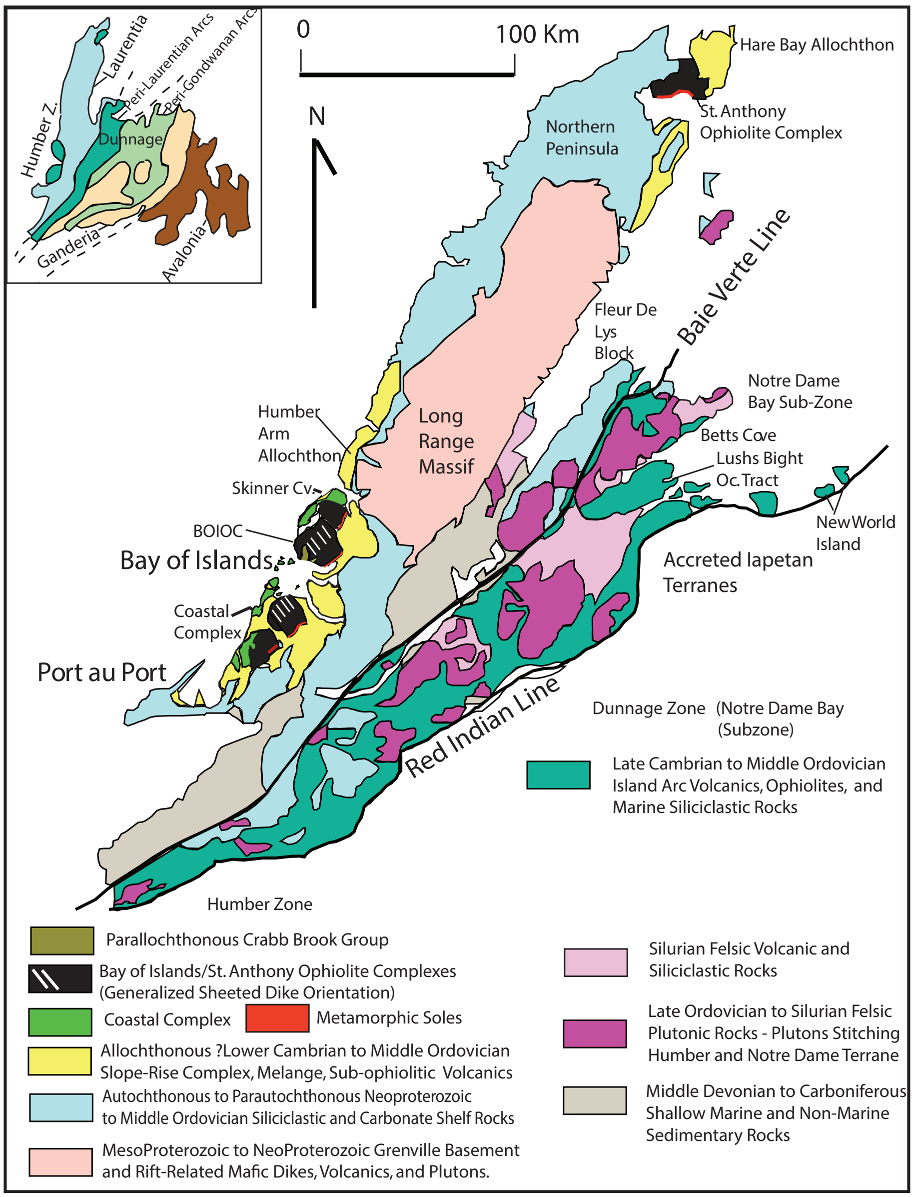


Figure 5 Principal stratigraphic units of the Laurentian margin, plotted with time on the vertical axis, in inferred original paleogeographic relationships, modified from Waldron et al. (1998)

Figure 6 Principal stratigraphic units of the Laurentian margin, plotted with thickness on the vertical axis, using the top of the 'platform' succession (top of the Table Point Formation) as a datum, after Waldron et al. (1998).

Little Port Complex / Coastal Complex

Two distinct ophiolite suites are found along the coast of W Newfoundland (Figure 7). The older of the two is the Little Port Complex, occurring around the town of Woody Point and along the coast to the south, where it forms the chain of islands that gives the Bay of Islands its name. The Little Port Complex consists of a series of foliated gabbro, amphibolite, and plagiogranite (trondhjemite) with more arc-like chemistry. In many areas, earlier, foliated mafic and ultramafic rocks are cut by dykes which are interpreted as feeders for less deformed pillow lava successions, some of which are interbedded with radiolarian chert. The trondjemitic rocks have been dated at 504–508 Ma (Jenner et al. 1991), which in corresponds to Cambrian Series 3.

Bay of Islands Complex

The younger, and more famous, ophiolite assemblage is the Bay of Islands Complex, one of the first ophiolites to be interpreted as ancient ocean floor following the development of plate tectonics in the 1960s. The Bay of Islands Complex consists of four rugged massifs, from N to S, Table Mountain or the Tablelands, North Arm Mountain, Blow Me Down Mountain, and the Lewis Hills. The Complex is a complete ophiolite suite (Figure 8, Figure 9), comprising upper mantle peridotite, overlain successively (but gradationally) by gabbro, diabase in sheeted dykes, pillow basalt, and ocean-floor sediment. Sheeted dykes are oriented E-W, perpendicular to the margin-parallel orientation predicted by a simple history of ocean opening followed by closing. The geochemistry of the Bay of Islands Complex shows less arc influence than the Little Port Complex, but there is boninite, thought to be typical of the early stages of arc development. Dates from the Bay of Islands Complex (Jenner et al. 1991) are close to the Cambrian-Ordovician boundary (485 Ma) and notably younger than the Little Port Complex. This age is also younger than the earliest interactions between arc rocks and the Laurentian margin, which occurred prior to 488 Ma in the Dashwoods block of SW Newfoundland (Waldron and van Staal 2001). Thus the Bay of Islands Complex must have formed by ocean-floor spreading within arcs that were already involved in the developing Taconic orogeny.

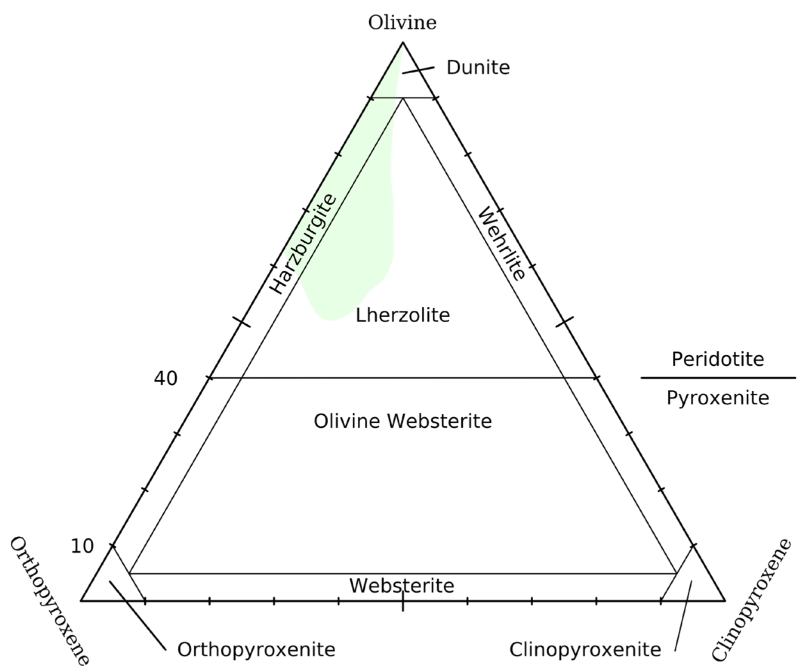


Figure 8: Classification of ultramafic rocks: https://en.wikipedia.org/wiki/Peridotite , accessed 2019/09/21

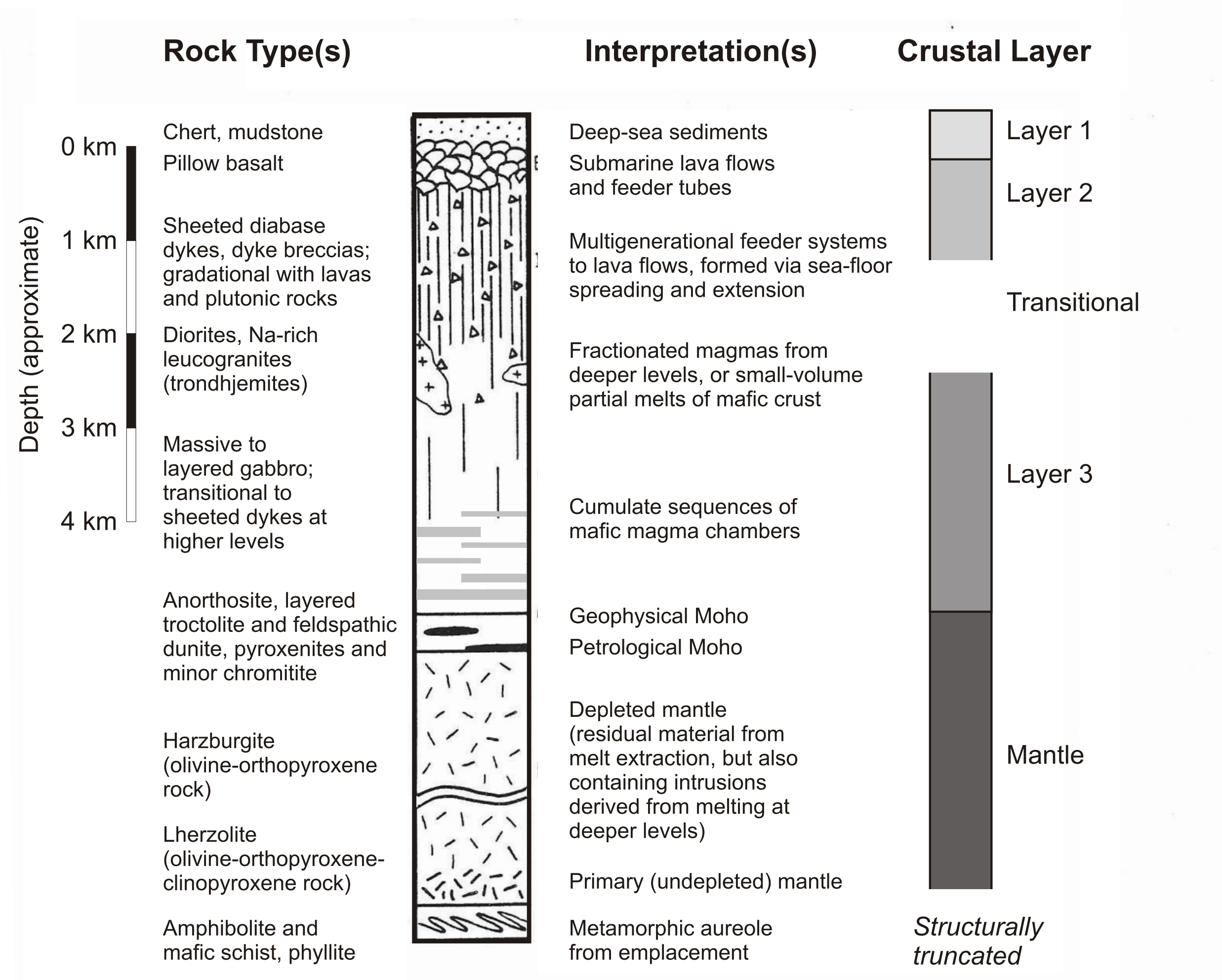


Figure 9 Subdivisions of an ideal ophiolite suite (Kerr 2019)

Relationships of ophiolitic units

The relationships of the two ophiolitic complexes have been controversial. They were originally mapped by Williams (1973) as separate thrust sheets (the Little Port below the Bay of Islands), and this is the relationship in the area between Woody Point and Trout River where we shall see them. However, Karson and Dewey (1978) argued strongly that the two represent the intersection of a ridge with an oceanic transform fault. In support of this hypothesis, Karson and Dewey (1978) included the western part of the Lewis Hills with the Little Port rocks in an expanded "Coastal Complex". They showed that younger intrusive rocks of the Bay of Islands Complex intrude older foliated rocks of the Coastal Complex. This reclassification has not been accepted by all authors (Jenner et al. 1991).

Isotopic dating has complicated the arguments, making it unlikely that the two units formed at a simple ridge – transform fault intersection as envisaged by Karson and Dewey. Most modern interpretations envisage formation of the Little Port (or Coastal) complex in an arc that subsequently collided with an offshore Laurentian microcontinent (the Dashwoods block) where it was deformed. The arc was then rifted apart to form the Bay of Islands Complex in a small ocean basin, in a process that may have involved transform faults (e.g. Figure 10). Spreading centres are actually quite common in closing oceans (e.g. in the Mediterranean or SE Asia) so this suggestion is not unreasonable.

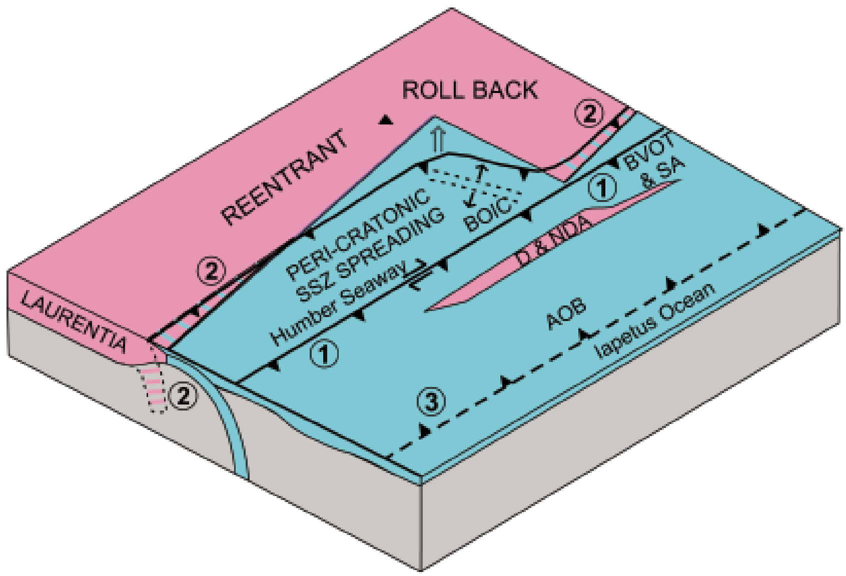


Figure 10 Scenario for spreading of the Bay of Islands ophiolite within the developing Taconian orogen at a re-entrant in the Laurentian margin, after van Staal et al. (2007)

Taconian foreland basin

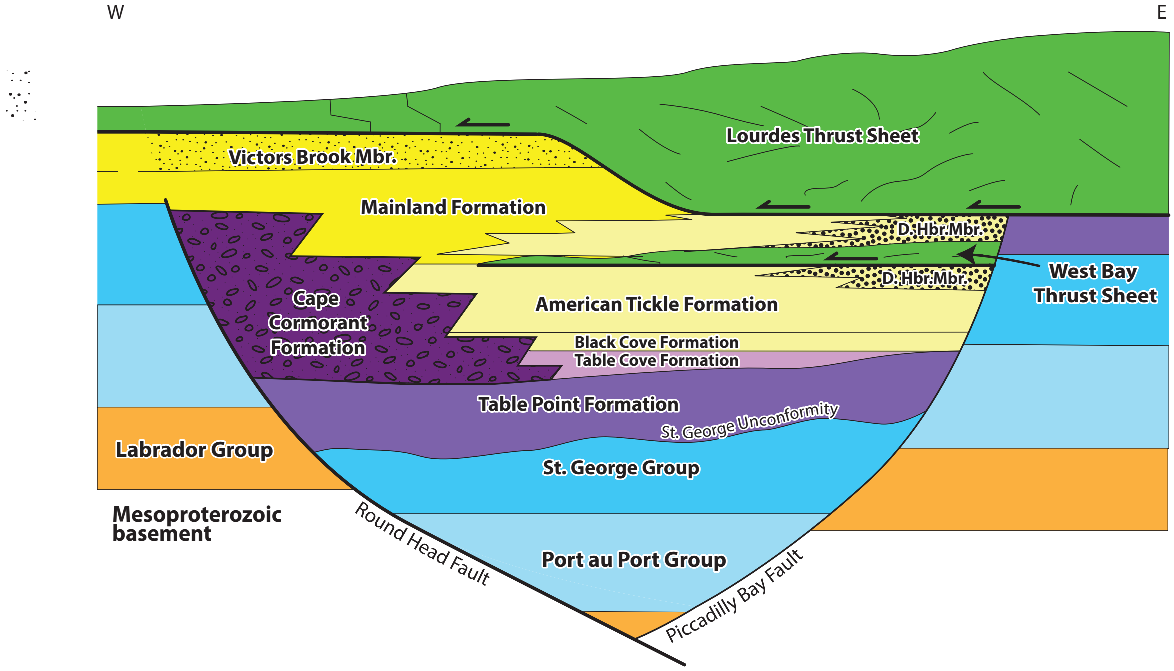
Western Brook Pond Group

Eventually, the passive margin of Laurentia came into collision, starting in the Late Cambrian, with an arc – trench system that encroached from the SE (in present-day coordinates; in the Ordovician the Laurentian margin was probably oriented ~E–W, so the allocthon advanced from the S). The first effect of this collision in the external Humber Zone was the appearance, at the end of the Early Ordovician, of turbidites including arc-derived material, at the top of the deep-water succession of the Humber Arm Supergroup. These sedimentary rocks are sometime described using the older term 'flysch'. (This term is derived from the Alps, where turbidites were similarly derived from advancing thrust sheets during the late Mesozoic and Cenozoic.) Different formation names have been applied up and down the coast. We have recently suggested (Lacombe et al. 2019b, White et al. 2019b) that for convenience all the syntectonic clastic units within the Humber Arm Allocthon be included in the Western Brook Pond Group.

Table Head Group

Slightly after this, the shelf succession underwent a subtle uplift, due to the passage of a 'forebulge' or 'peripheral bulge', before subsiding rapidly in a foreland basin formed as the arc advanced onto the continental margin (e.g. Jacobi 1981, Knight et al. 1991). The passage of the forebulge resulted in an erosion surface - a disconformity known as the St. George Unconformity - at the top of the St. George Group.

Figure 11 Schematic diagram of stratigraphic relationships in the faulted foreland basin preserved on Port au Port Peninsula (Lacombe et al. 2019a).



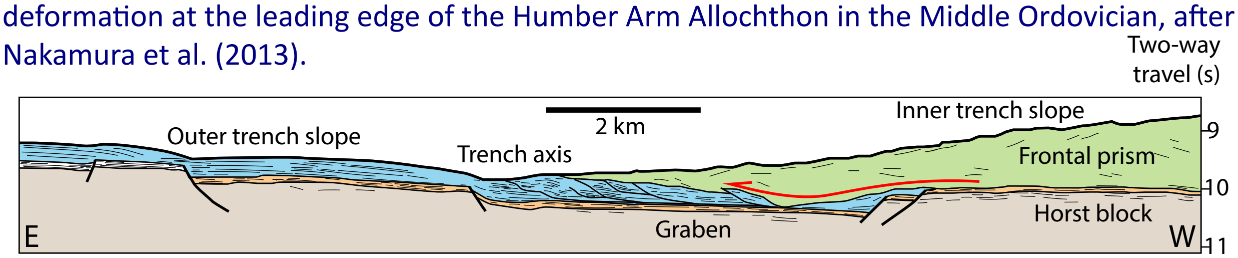
The overlying Middle Ordovician foreland basin (Klappa et al. 1980, Stenzel et al. 1990) succession is initially very similar in character to the underlying shelf rocks - bioturbated subtidal limestones of the Table Point Formation (Table Head Group) - and formed as carbonate deposition was able to keep pace with subsidence. Because of the similarity of facies, these first foreland basin rocks are sometimes grouped with the underlying shelf carbonates as the "platform succession". The top of the platform succession is a major reflection in offshore seismic profiles.

Eventually, sediment production failed to keep pace with subsidence, and graptolite-bearing deeper water limestones and shales of the Table Cove Formation (Table Head Group) were deposited.

Goose Tickle Group

Eventually, carbonate sedimentation gave way to clastic sediments. The overlying Goose Tickle Group comprises "flysch" sandstone and shale derived from thrust sheets of continental margin origin and the advancing arc, that were by now being thrust onto the shelf edge). This is a few million years (a few graptolite zones) later than on the continental slope succession, indicating that the allochthons were coming in from the SE (present-day coordinates.)

Figure 12: Cross section through the Japan Trench oriented to show possible environment of deformation at the leading edge of the Humber Arm Allochthon in the Middle Ordovician, after Nakamura et al. (2013).



Limestone conglomerate units interbedded with both the Table Head Group and the Goose Tickle Group indicate that the foredeep was dissected by fault scarps, similar to the geometry of the present-day Japan Trench (Nakamura et al. 2013, Chester and Moore 2018).

Post-Taconian foreland basin successions

Long Point Group

The Taconian collision was probably followed by a reversal in the polarity of subduction, with the result that western Newfoundland now lay on an active continental margin.

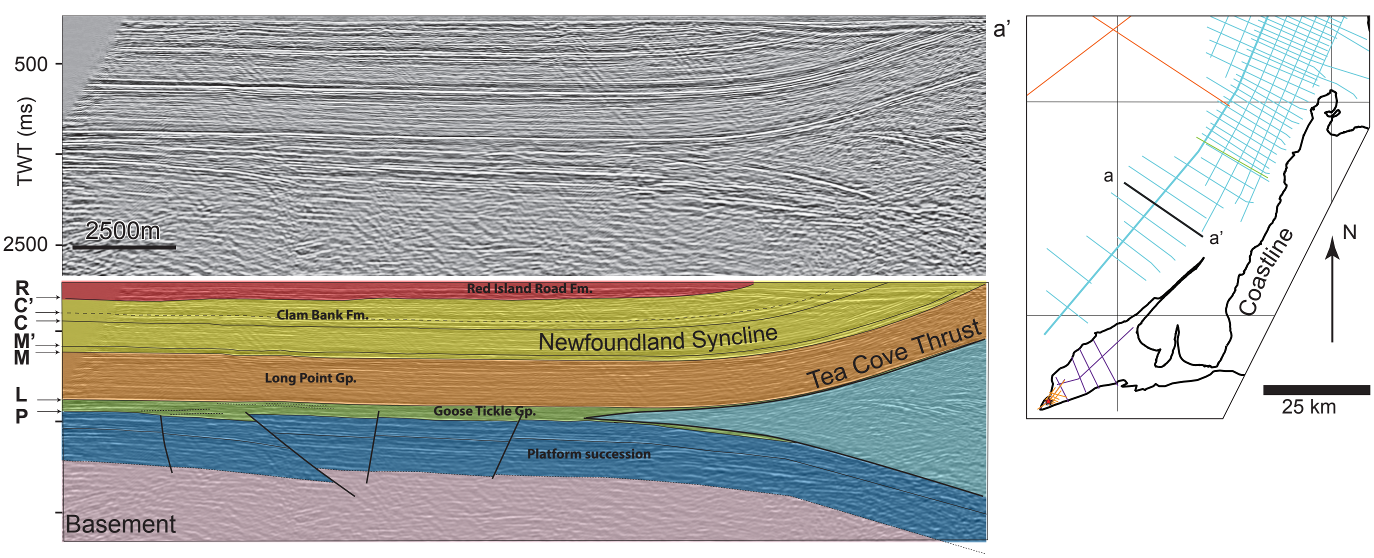
Shallow marine carbonate sedimentation returned in the Late Ordovician. The Lourdes Limestone (Long Point Group) is a distinctive unit containing localized patch reefs that forms the axis of 'the Bar' on Port au Port Peninsula (Batten Hender and Dix 2006). It is also a prominent reflector in offshore seismic profiles (Figure 11). Carbonate sedimentation was short-lived, however, and younger units of the Late Ordovician Long Point Group are dominated by clastic sedimentary rocks deposited in a rapidly subsiding basin (Quinn et al. 1999). Recent work (White et al. 2019b, 2019a)suggests that this, second episode of foreland basin subsidence may be related to thrust emplacement farther along the margin to the southwest, in the Appalachians of New England and Québec.

Continuing subduction and collision to the east of and beneath the former continental margin resulted in deformation, metamorphism, and intrusion in central Newfoundland during the Silurian Salinian Orogeny. There is little record of deformation due to the Salinian Orogeny in Port au Port Peninsula or the adjacent offshore. However, most of the Silurian section is missing, suggesting that the area was subject to regional uplift.

Clam Bank – Red Island Road succession

Sedimentation resumed in the late Silurian or (more likely) earliest Devonian, with the deposition of red and grey marginal marine clastic sediments and minor carbonates of the Clam

Figure 13: Seismic profile offshore of western Newfoundland (White et al. 2019b).



Bank Formation (Burden et al. 2002). Although this unit is identified over a vast area offshore (Figure 11), on land it is confined to a very narrow coastal strip of Port au Port Peninsula (Figure 13), in the footwall of the Round Head Thrust.

Even more restricted in area is the succeeding Red Island Road Formation, which occurs only on offshore Red Island. It consists largely of conglomerate with abundant rhyolite cobbles, and has yielded Early Devonian fossils (Quinn et al. 2004). The Clam Bank and Red Island Road Formations probably represent a third foreland basin developed in advance of thrusts associated with the Devonian Acadian Orogeny.

Maritimes basin: Carboniferous rocks

The youngest sedimentary rocks in the Port au Port area are Mississippian carbonates and clastics of the Codroy Group, part of the Carboniferous Maritimes Basin that extends from SW Newfoundland to New Brunswick. Locally, flat-lying Mississippian conglomerates overlie near-vertical Ordovician rocks of the Table Head Group that were deformed in the hanging wall of the Round Head thrust (Figure 13), demonstrating the largely post-tectonic nature of the Carboniferous sediments in this area. Farther south, both the Codroy Group and the underlying Anguille Group are significantly deformed, but this deformation is believed to be related to Carboniferous strike-slip movements that post-dated the Acadian Orogeny.

STRUCTURE

Early mapping and syntheses of the geology in the Bay of Islands area by Rogers and Neale (1963) Williams (1973), and by Dewey (1974) and co-workers, painted a relatively simple picture of the structure of the Humber Arm Allochthon as a stack of roughly tabular sheets overlying the shelf succession, emplaced in the Middle Ordovician Taconian orogeny. However, it is clear from more detailed studies in both the allochthon (Bosworth 1985, Waldron 1985, Waldron et al. 2003) and in the adjacent rocks of shallow marine facies (Knight and Boyce 1991, Knight 1994a, 1994b, 1995, 1996, Cawood and van Gool 1998) that neither the allochthon nor the platform rocks are tabular in their present-day configuration, and that the contacts between them were both faulted and folded in Salinic and/or Acadian deformation. This later folding is responsible, for example, for the current distribution of Humber Arm Allochthon to the west of the shelf succession (Figure 3), despite clear evidence that the deep-water environments originally lay to the east.

The Humber Arm Allochthon presents challenges to the mapping geologist because in some areas the spacing of faults is closer than the spacing of outcrops. Also, because the metamorphic grade is low, and brittle structures predominate, it is difficult to distinguish a clear overprinting sequence of structures. Nonetheless, it has been possible to separate generations (D_1, D_2 etc.) of structures based on overprinting criteria in favorable outcrops, especially those along coasts and highways adjacent to Humber Arm. However, in small inland outcrops identification of structures as D_1, D_2 etc., is necessarily based on analogies of structural style with better exposed sections.

Synsedimentary and penecontemporaneous structures

Structures formed by deformation when sediments were still unconsolidated are relatively common. Many turbidite sandstone and limestone beds show load structures, convolute lamination or ball-and-pillow structure. A widespread zone of sandstone injection is found at the base of the Western Brook Pond Group (Botsford 1987). Elsewhere in the Western Brook

Pond Group, there are folded sandstone beds having strongly thickened hinges (Waldron 1985), indicating deformation while sand was liquefied (Waldron and Gagnon 2011). However, Taconian deformation started very soon after deposition of the Western Brook Pond Group; hence it cannot be assumed that soft-sediment structures are necessarily truly syn-sedimentary. Thus, in some cases it is not possible to unequivocally distinguish "early" folds as either F_0 (slump folds) or F_1 (early tectonic folds).

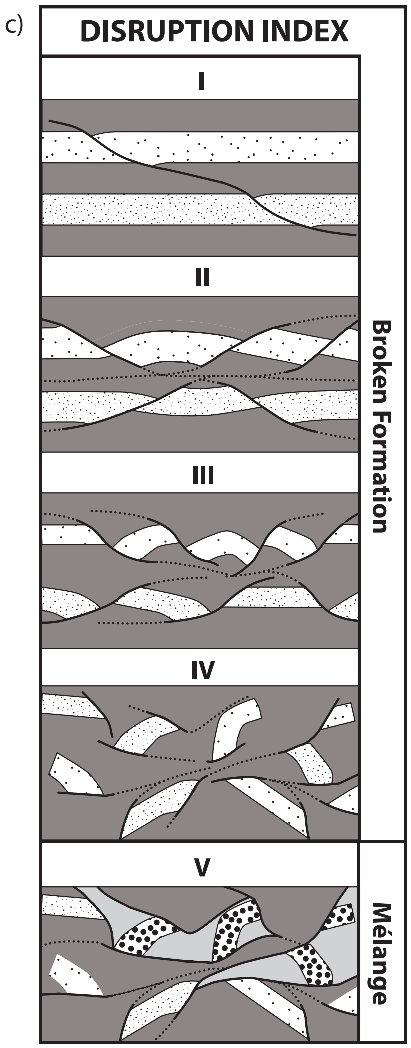
Fragmentation and mélange

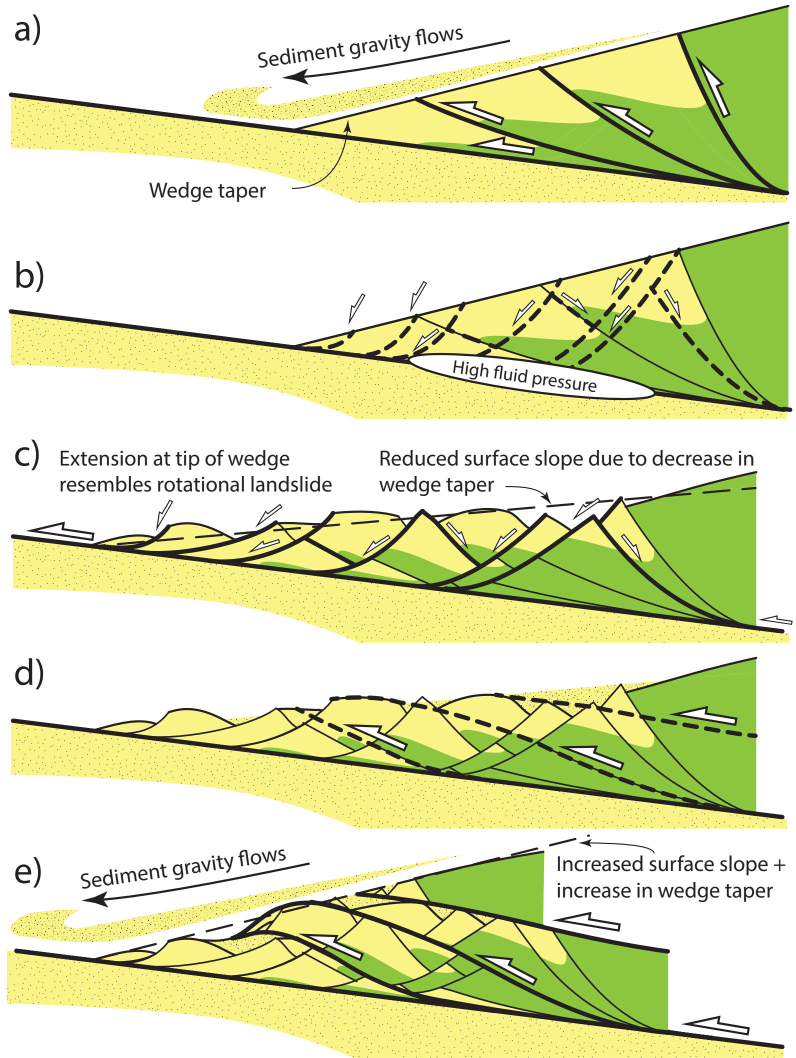
The most characteristic deformational features of the sedimentary portion of the Humber Arm Allochthon are zones where stratification has been disrupted, producing blocks of competent lithologies (sandstone, limestone) immersed in a matrix of deformed shale. All stages in the progressive boudinage of sandstone and limestone beds can be observed; typically the beds are disrupted by brittle extension and shear fractures. Zones where bedding has been largely disrupted by faults and shear zones that are too closely spaced to map have variously been described as "mélange" (Figure 14) or "broken formation". They typically display scaly foliations that resemble those described in modern accretionary wedges (Waldron 1985, Waldron et al. 1988, Lacombe et al. 2019b). Waldron et al. (2003), Burden et al. (2005) and Lacombe et al. (2019b) restrict the term mélange to those outcrops where tectonic mixing at formation level can be demonstrated. Areas where bedding is disrupted but the protolith is a single formation are described as broken formation (Figure 15). The structures responsible for these configurations are grouped as D_1. Our recent work on mélanges in the area of Port au Port Peninsula (Lacombe et al. 2019b) confirms the hypothesis of Waldron et al. (1988) that the formation of mélange and broken formation was driven by high fluid pressure, which episodically weakened the thrust

Figure 14: Typical outcrop appearance of mélange.

Figure 15: Field classification of mélange and broken formation (Lacombe et al. 2019b).

Figure 16: Development of broken formation and mélange in an accretionary wedge or thrust belt subject to fluid-pressure variation (Lacombe et al. 2019b)





wedge such that its critical taper was reduced; gravity spreading led to widespread extensional features. Steepening of the wedge following fluid expulsion caused contractional structures, further adding to the chaotic style of deformation (Figure 15).

Fabrics

Most of the coherently bedded fine-grained sedimentary rocks of the Humber Arm Supergroup display a strong bed-parallel fissility, which probably represents the original compactional fissility of the shales, enhanced by D_1 tectonic deformation. In mélange and some broken formation, the S_1 fabric is anastomosing and scaly (Figure 14). Polished slickenside surfaces are common; they branch around lenticular domains in which the fissility fabric has variable orientation. This scaly fabric is interpreted as a composite fabric produced by cataclastic flow of already fissile shale.

In the oldest parts of the Curling Group, early fabric development appears to be different. Sandstones typically show an S_1 pressure-solution cleavage characterized by seams of recessively weathered, quartz-poor material, spaced at 5 mm to 5 cm apart. Pressure-solution processes dominated the Taconian deformation of the more deeply-buried Summerside formation, in contrast to the cataclastic flow that affected the remaining units of the allochthon.

The eastern part of the area is affected by penetrative S_2 cleavage that strikes consistently N-S to NE-SW; the intensity of the cleavage decreases westward. Although the cleavage appears slaty and penetrative in many samples, in most outcrops it is possible to find S_1 surfaces preserved in the finest-grained lithologies; there, S_2 is responsible for finely spaced crenulation lineations on the S_1 surfaces. In contrast, in silty and sandy lithologies, pressure solution at the margins of coarse grains has obliterated the S_1 cleavage. In the eastern part of the map area shown in Figure 16, S_2 cleavage is intense, locally phyllitic, and dips gently to moderately west.

Folds

F_1 folds are found at a number of locations in the Humber Arm Supergroup, though they are not as conspicuous as the pervasive F_2 folds (see below). Typically, F_1 folds are isoclinal, intrafolial, asymmetric fold pairs with axial surfaces parallel to the regional envelope of bedding and S_1. Folds are also apparent in zones where bedding is disrupted by boudinage and even in mélanges. In some cases, tight to isoclinal folds are found within blocks, indicating that folding occurred before fragmentation. However, in other examples the scaly fabric, together with trains of bed-fragments, is itself folded, indicating that folding post-dated boudinage and fragmentation.

F_2 folds are present at both outcrop and map scale. Folds at outcrop scale are typically open to tight, with axial surfaces striking N-S or NNE-SSW. Axial plunges are extremely variable. In some cases F_2 folds have gentle plunges north or south, but elsewhere the fold hinges display steeper rakes, ultimately leading to the development of reclined folds. In general, there is a tendency for folds in the west to show shallow axial rakes, whereas steeper rakes and reclined folds are most abundant in the east. At map scale, all the boundary surfaces between D_1 slices and sheets are strongly folded, with the result that original relationships at thrust faults are locally inverted (Figure 17, Figure 18).

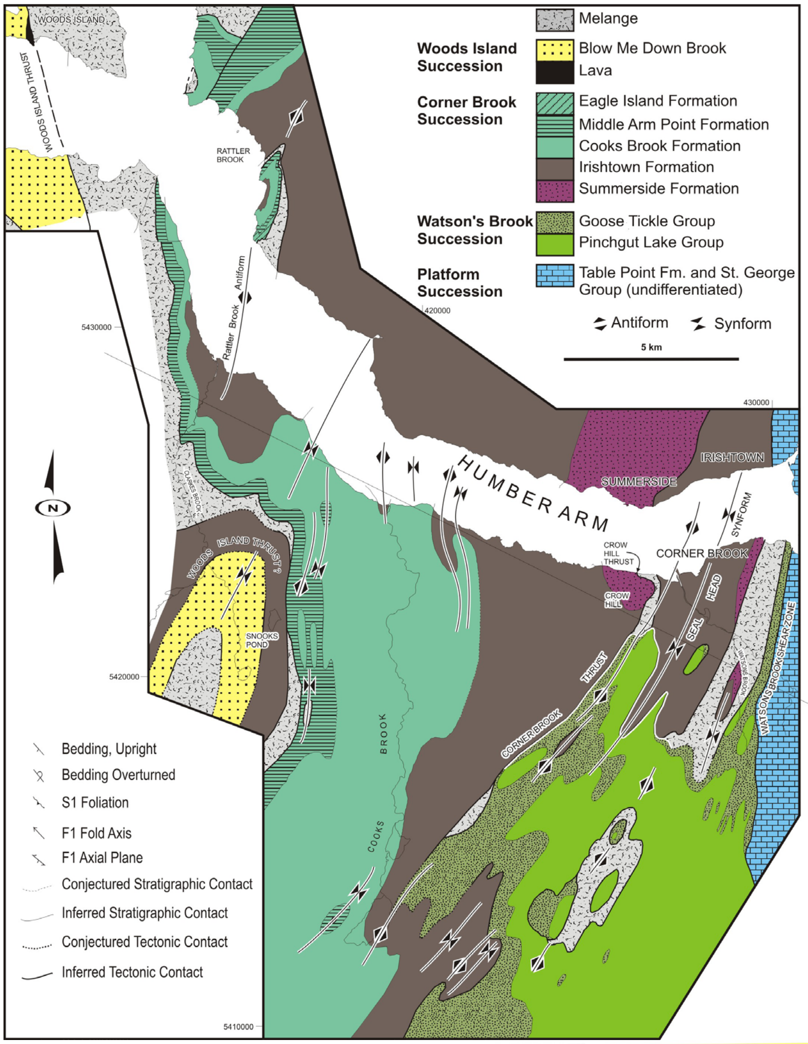


Figure 17: Map of part of the Bay of Islands showing F2 folds refolding D1 thrust sheets (Waldron et al. 2003)

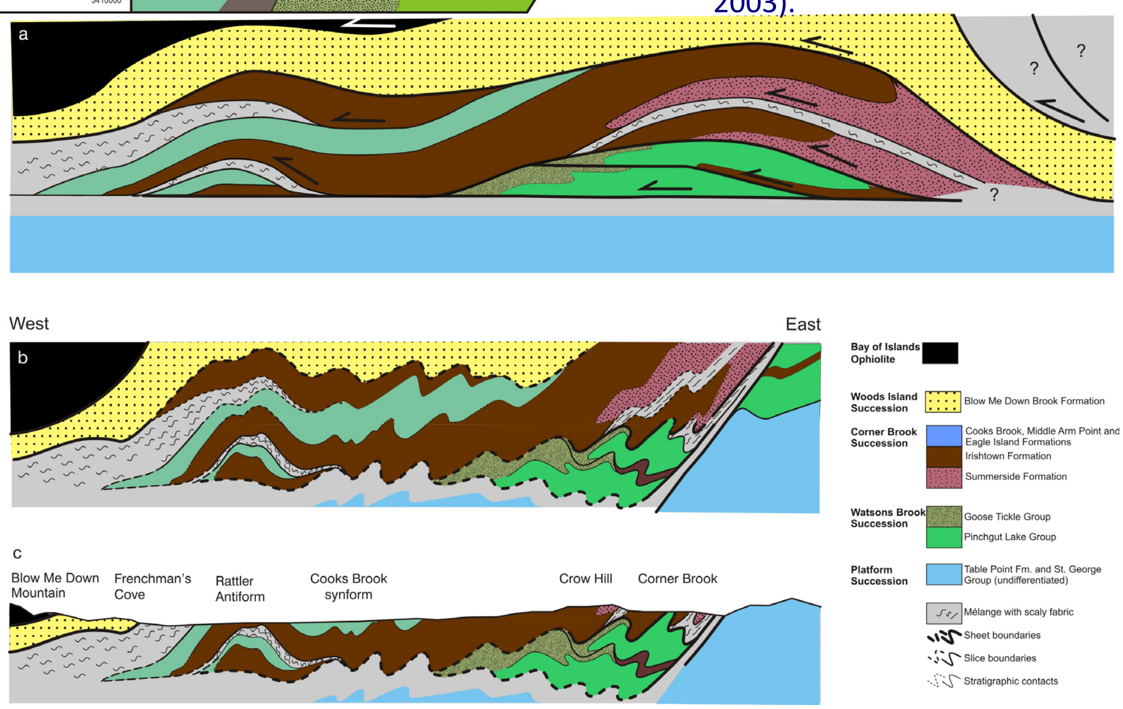


Figure 18: Highly schematic cross-section through the Bay of Islands (Waldron et al. 2003).

At a number of localities we have seen folds in outcrop that have strongly curved hinges over distances of 50 cm to 5 m. Such folds show up to 90° variations in hinge rake, approaching the geometry of sheath folds. F_2 folds are locally seen refolding F_1 folds, producing fold interference patterns that are generally of type 3 in the classification of Ramsay (1967).

Map-scale faults

In addition to the closely spaced, locally extensional, faults that affect the Humber Arm Allochthon, it is clear from the stratigraphic record documented by Lacombe et al. (2019a) that normal faults were active in the foreland basin ahead of the advancing Humber Arm Allochthon. The geometry was probably similar to that of the modern Japan Trench (Nakamura et al. 2013) (Figure 12). The principal evidence for these faults is the presence on their hanging walls, of pockets of platform-derived limestone conglomerate, interspersed with more normal "flysch" shale and sandstone. The largest of these faults, the SE-dipping Round Head Fault, shed several hundred metres of coarse, platform-derived boulder conglomerate into the basin on its hanging wall, forming the Cape Cormorant Formation. This fault was subsequently inverted during the Acadian orogeny, so that its hanging-wall now lies >3km higher than the source area of these conglomerates.

Vertical strata in the hanging wall of the Round Head Thrust are overlain with spectacular angular unconformity by subhorizontal Viséan strata of the Mississippian Codroy Group, demonstrating that movement of the Round Head Thrust was post-Emsian (Early Devonian) but pre-Viséan. It is possible that thrust movement occurred during the Tournaisian Epoch (earliest Mississippian) but thrust motion on a fault with ENE strike of the Round Head thrust is difficult to reconcile with what we know of Tournaisian deformation elsewhere in Atlantic Canada, so most geologists prefer to interpret the Round Head Thrust as an Acadian, mid-Devonian feature.

Comparable faults occur along the western edge of the Long Range Mountains on the Northern Peninsula, where they also probably reactivate Taconic or older normal faults. These Acadian thrusts have an out-of-sequence relationship with an imbricate thrust belt that characterizes the Humber Arm Allochthon in the Cow Head area. There is little firm evidence for the age of this earlier imbricate thrusting. However, the lack of intervening younger rocks suggests that initial stacking of the thrust slices occurred in the Ordovician, Taconic collisional event. Major thrusts that cut basement are interpreted, by analogy with the Port au Port Peninsula, as Acadian features (White and Waldron 2019).

Carboniferous structures

Carboniferous (Mississippian-Pennsylvanian) deformation affected western Newfoundland and other parts of Atlantic Canada. Major dextral strike-slip faults and associated structures are seen in the Bay St. George and Codroy areas of SW Newfoundland, and in the Deer Lake Basin (e.g. Knight 1983, Hyde et al. 1988, Waldron et al. 2015). Both basins are interpreted as transtensional pull-apart basins formed in association with SW-NE dextral strike-slip faults. A variety of brittle fractures and other structures are seen in the earlier Paleozoic rocks, but little penetrative deformation of these rocks apparently occurred in the Carboniferous.

TECTONIC DEVELOPMENT OF THE OROGEN

Opening of the Iapetus

The Laurentian margin probably formed as a result of a 3-way break up between components of Rodinia: Lauentia, Baltica, and Amazonia – West Africa. The first indications of rifting in western Newfoundland and adjacent Labrador took place around 615 Ma (Stukas and Reynolds 1974, Kamo et al. 1989, Kamo and Gower 1994), with the intrusion of mafic dykes, and the eruption of basaltic lava flows of the Lighthouse Cove Formation, which are confined to graben structures produced by rifting of the formerly continuous Grenville basement (Figure 6). There is not complete certainty as to the location of the conjugate margin that rifted away from Laurentia. Most reconstructions suggest that the opposite margin of the Iapetus Ocean is preserved in South America as part of the Amazonian craton (e.g. Cawood et al. 2001).

Taconian arc-continent collision

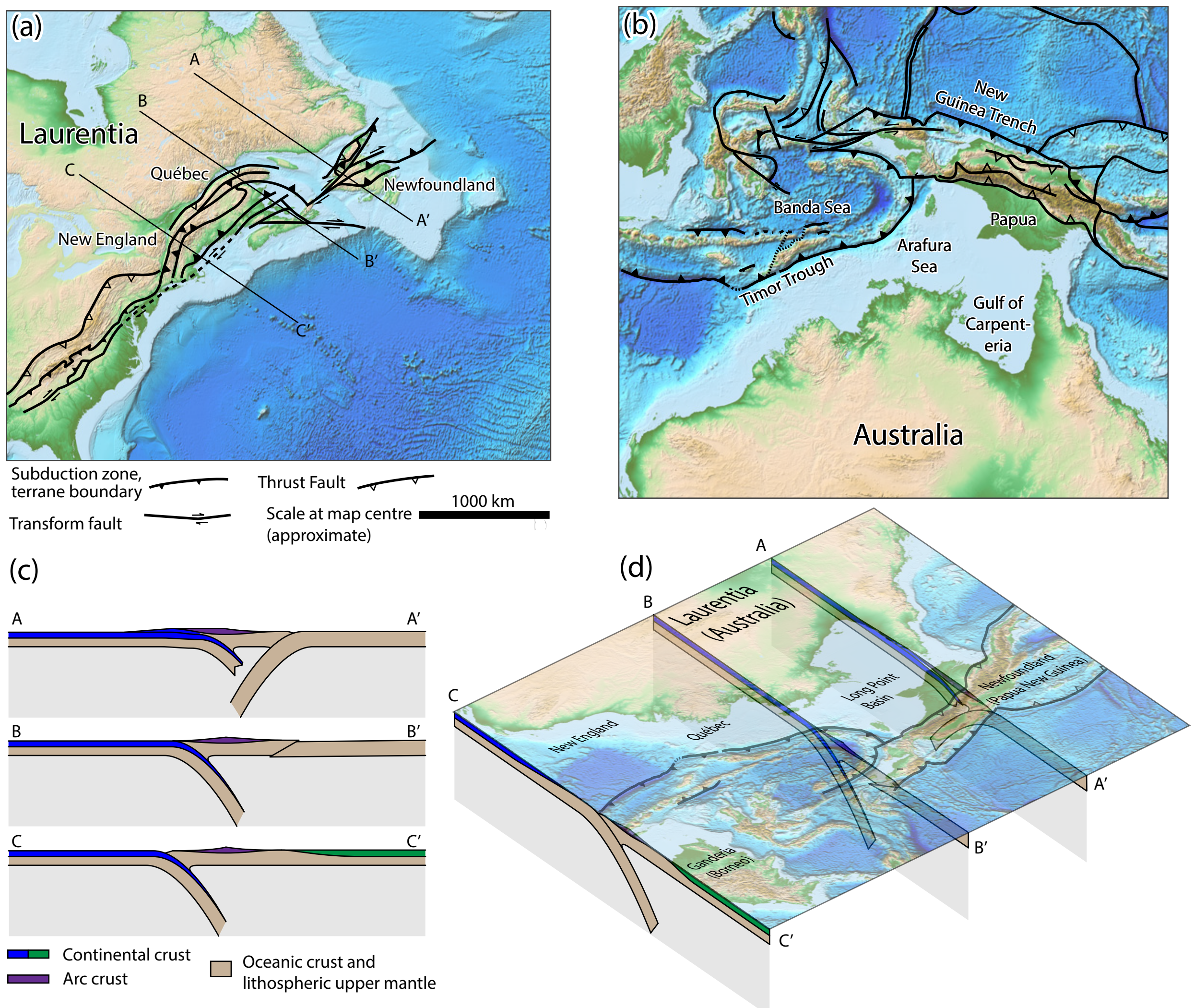
There is general agreement that the Taconian orogeny in Newfoundland was the result of a collision between the eastern passive continental margin of Laurentia and a west-facing subduction zone and its associated island arc. In the Middle Ordovician, western Newfoundland represented a situation very like the present-day northeastern margin of Australia, where the tropical, carbonate-dominated margin of the Australian Continent is starting to be deformed in collision with oceanic arcs that run through Papua New Guinea (Figure 19).

The collision was not simple, however. The first indications of collision are found well to the southeast, in the Dashwoods subzone of the Newfoundland Appalachians, where continental margin rocks started to be deformed in the latest Cambrian around 490 Ma. At this time, the part of the Laurentian margin in the Bay of Islands was still definitely a passive margin. This led Waldron and Van Staal (2001) to suggest that an offshore micro-continent, the Dashwoods block, was the first to experience the Taconian collision.

Subsequent to this collision, somewhere near the margin, the Bay of Islands Ophiolite formed by spreading within an arc system. The spreading axis appears to have been at a high angle to the margin. Van Staal et al. (2007) have made the reasonable suggestion that this might have occurred in association with a transform offset in the margin, as shown in Figure 10.

Somewhat later, in the Middle Ordovician around 470 Ma (Floian to Dapingian), the main Humber margin started to be deformed. The first effect of the encroaching arc system was a change in the chemistry of shales followed by the deposition of allochthon-derived sandstone ("flysch" of the Western Brook Pond Group) in the most distal parts of the continental slope. Brief uplift of the forebulge was followed by subsidence of the margin in the Early Darriwilian (~467 Ma), which killed off carbonate sedimentation. Shortly afterwards (~463 Ma), rocks of

Figure 19: Comparison of Ordovician Laurentian margin with present-day N margin of Australia. (White et al. 2019b)



the former continental slope and rise were thrust over the former shelf as the Humber Arm Allochthon. Oceanic and arc rocks of the Bay of Islands and Little Port complexes acted as the ‘bulldozer’ pushing the allochthonous sedimentary rocks in front of and beneath them. The Bay of Islands and Little Port complexes thus ended up on the top of the thrust stack.

Post-Taconian folds and fabrics

At some time later, either near the end of the Ordovician period or very early in the Silurian, the whole edifice was deformed again by F_2 folds. Cleavage varies from generally upright and east-dipping in the vicinity of the Cooks Brook synform (Figure 16), where it is sporadically developed and weak, to west-dipping in the Corner Brook area where it is more penetrative and locally phyllitic. The cleavage may have developed at the time of west-dipping subduction, east-vergent thrusting, and accretion in central Newfoundland (e.g. van Staal and de Roo 1996, van Staal et al. 1998, Waldron et al. 2019).

Shear zones along the eastern edge of the Humber Arm Allochthon record normal sense motion that post-dates D_2, followed by later shortening. Normal-sense motion late in the sequence of structures appears widespread in the area east of Corner Brook (Waldron and Milne 1991, Cawood and van Gool 1998) (Waldron and Milne 1991; Cawood and van Gool, 1998), and has been attributed to “extensional collapse” of the orogen following Salinic (Silurian) shortening.

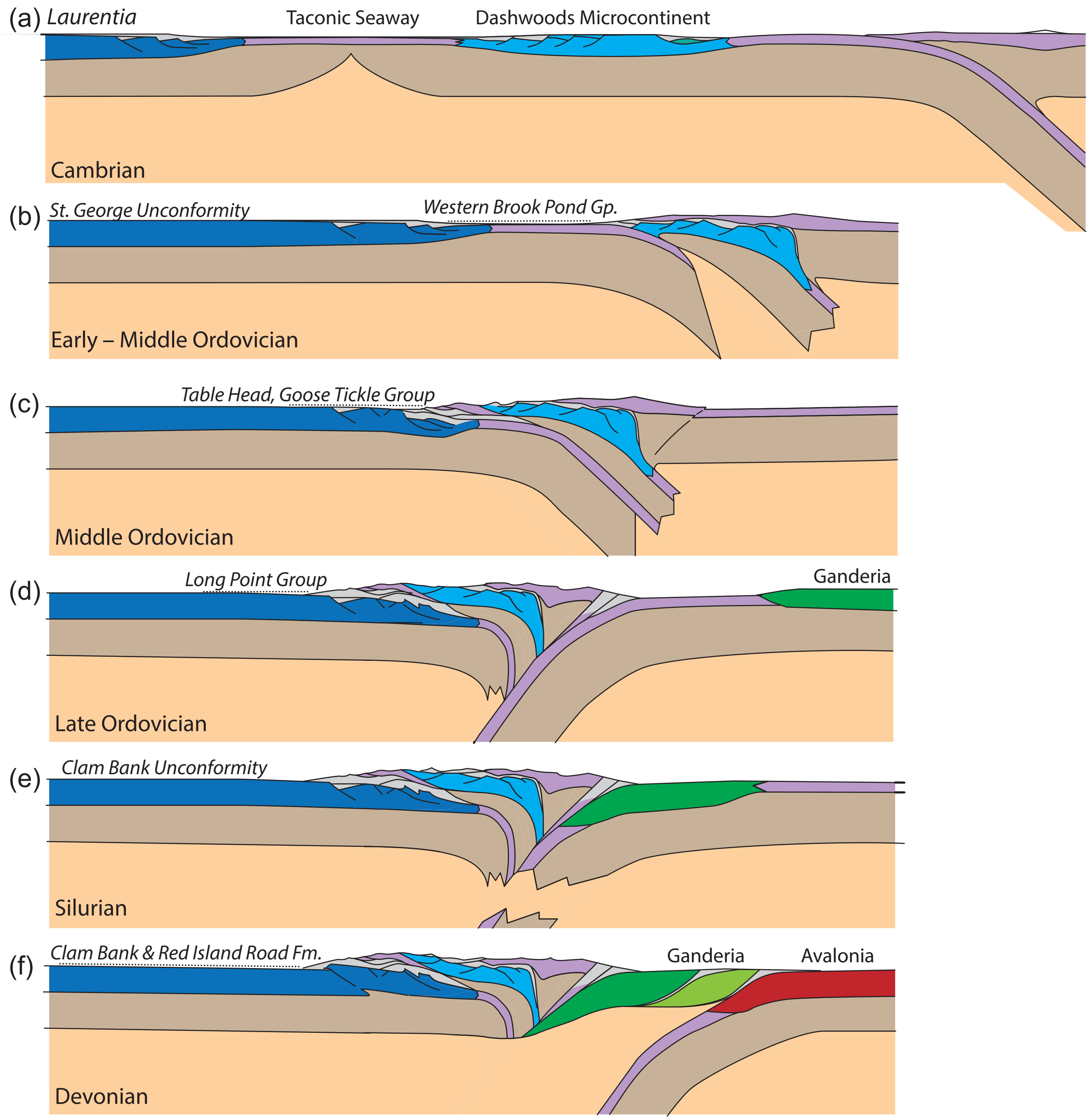
Acadian thrusting and development of the offshore ‘triangle zone’

Later shortening, recorded by thrust-sense brittle faults post-dates the Devonian Red Island Road Formation, but pre-dates the Mississippian Codroy Group. This deformation led to the formation of a tectonic wedge or triangle zone, extending from offshore Bonne Bay south to the Port au Port Peninsula (Figure 11).

Post-Acadian deformation

Subsequently, the region was deformed again, this time by mainly strike-slip faults, in the Carboniferous Period. This deformation produced the deep sedimentary Bay St. George and Deer Lake basins. The most recent process to have left its mark on the landscape of the Bay of Islands was Quaternary glaciation. The valleys of the Humber River and other streams that now flow into the Gulf of St. Lawrence were repeatedly dammed and occupied by valley glaciers, which were responsible for eroding the large U-shaped valleys and fjords (or “arms”) that dominate the region’s landscape. Once the weight of ice was removed, in the last 12000 years, the area underwent isostatic rebound. Many of the coastal communities around the Bay of Islands are built on low and narrow coastal plains that represent old wave-cut platforms, backed by former sea cliffs, now raised above sea-level by isostatic rebound.

Figure 20: Cartoons showing sequential development of the Appalachian orogen during the Paleozoic Era. Caution! This diagram omits important along-strike variations and movements that were not orthogonal to the margin! (White et al. 2019b)



DAY 1 FIELD STOPS: OPHIOLITES ON THE LAURENTIAN MARGIN, GROS MORNE NATIONAL PARK

Day 1 includes stops (Figure 21) on all the main units of the west Newfoundland Appalachians, but the focus is on ophiolitic rocks of the Bay of Islands and Little Port complexes. Depending on time and weather conditions, and the amount of hiking desired, some stops may be skipped.

Locations are UTM coordinates, zone 21, using the NAD 83 datum.

Trip 1: Rocky Brook to Tablelands

Stop 1-1 Rocky Brook Cabins: Carboniferous Rocky Brook Formation

467676 5456938

Take care on slippery rocks and do not cross the barrier

The start of the field trip is at Rocky Brook Cabins, where a fine section in oil shale of the Mississippian Rocky Brook Formation is exposed in Rocky Brook.

Travel: Drive W to Highway 430 and turn N. Park on side road at 462881 5458450 and walk 400 m NW OR Park on dirt road at 462289 5458938 and walk 400 m SE

The next three stops are on dangerous highways. Wear high-visibility vests. Take care when exiting the field trip vehicles. If it is necessary to cross the road, remember that groups straggling across a highway are particularly vulnerable; cross together if possible and avoid situations where groups travel on both sides of the highway, creating a bottleneck for traffic. Except when crossing, stay off the paved highway at all times.

Stop 1-2 Highway 430 at Rocky Pond. Basement of the Grenville Orogen

462692 5458692

The highway here intersects the southernmost extremity of the Long Range Inlier, representing the Mesoproterozoic basement of the Laurentian margin, formed during the assembly of Rodinia. This region is mapped by Owen (1990) as >1550 Ma granitic to granodioritic rocks locally intruded by ~1023 to 970 Ma biotite ± hornblende granite. Knight (2010) reports that this part of the Long Range Inlier was locally deformed and altered during Paleozoic deformation.

Follow Highway 430 N to Wiltondale

Stop 1-3: Highway 430 at Wiltondale. Port au Port Group.

455798 5471692

At the Wiltondale turn-off highway 430 meets highway 431 from Woody Point. Exposures seen around the intersection form part of the Cambrian Port au Port Group and consist mostly of interbedded phyllite, white to beige dolostones to dolomitic marbles and marble. The rocks are spectacularly folded. Cleavage planes locally cross-cut the axial surfaces of folds suggesting more than one episode of deformation.

Return S to the junction with highway 431. Turn W and follow highway 431

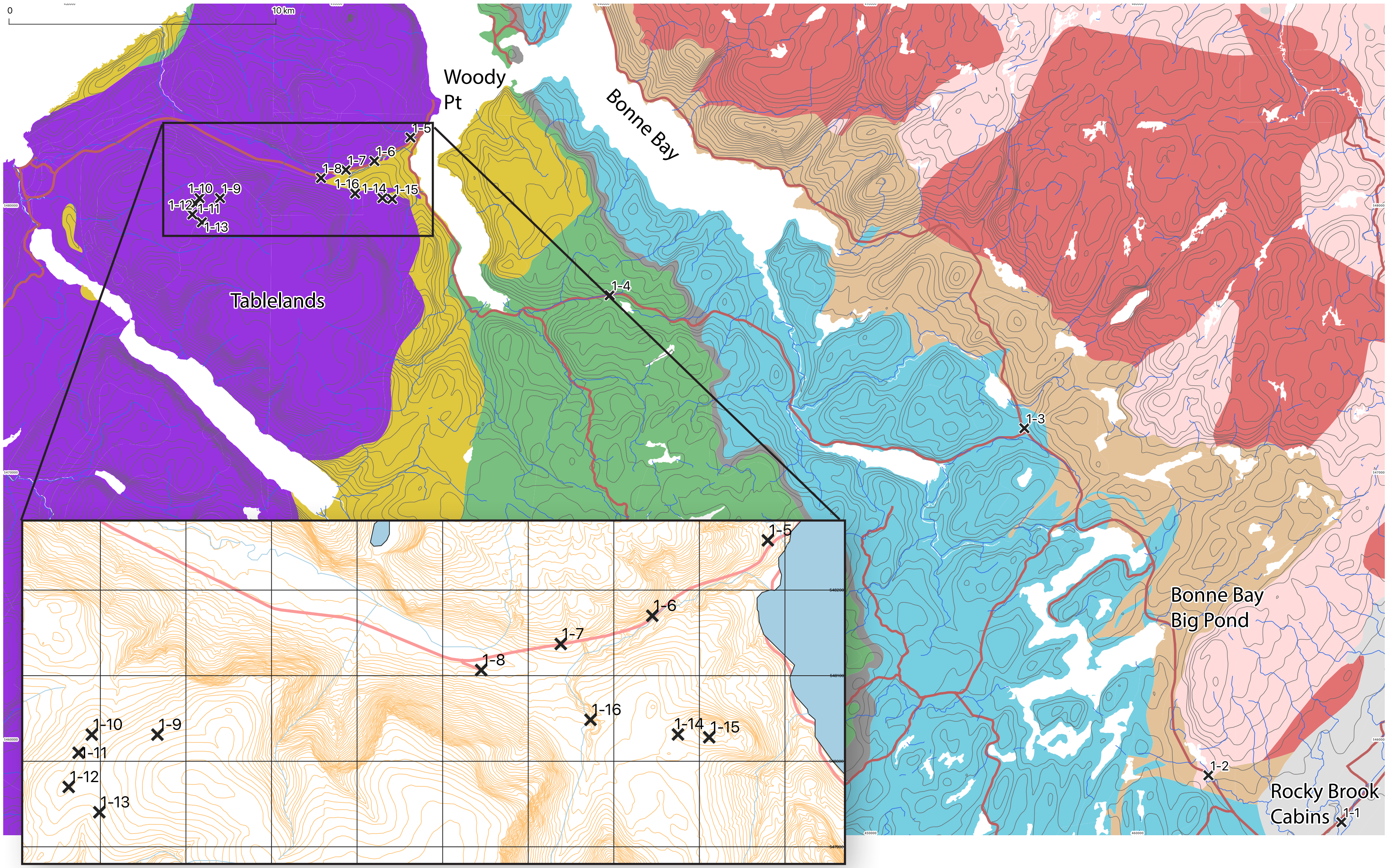


Figure 21: Map of field trip stops on Day 1. Legend: see Figure 23

Stop 1-4 Highway 431 Curling Group of Humber Arm Allochthon

440265 5476672

From this point onward you are within the boundary of Gros Morne National Park. NO HAMMERING OR SAMPLING IS ALLOWED. NATURAL OBJECTS MAY NOT BE REMOVED FROM A NATIONAL PARK WITHOUT A PERMIT. The penalties are large.

Rocks exposed on the north side of the highway are part of the Curling Group, equivalent to the Irishtown Formation. The outcrop contains a lower section of quartz-rich turbidite sandstone, and shale which is cut into by spectacular conglomerate units that fill erosional channels into the underlying bedded sediments.

Continue W on highway 431, descending a long hill (localy known as "the struggle" – presumably by those travelling in the other direction). At 433333 5482980 turn sharp left (sign to Trout River) to stay on 431. If you find yourself in Woody Point you've gone too far.

Stop 1-5 Discovery Centre

432800 5482581

The Discovery Centre is one of two large exhibits in Gros Morne National Park. Here you can see a display on the geology of the park, talk to the interpreters about about plants & animals, get espresso and hot soup, as well as advice on travel within the park area.

Here you can see displays on the geology, natural environments, and human history of the park, and get advice on travel within the park area.

Continue W on highway 431.

Stop 1-6 Highway 431: mafic lava and deep-water sedimentary rocks.

Between the Discovery Centre and Tablelands viewpoint area is a long outcrop on the north side of the road at 431450 5481700.

There is no easy parking place near this outcrop as the road is narrow and guarded on the S side with a barrier. If you stop, make sure you can be seen. With a large group this stop may be skipped.

This outcrop is mostly greenish, altered pillow basalt and diabase dykes. The pillows represent ocean-floor lava flows, whereas the diabase dikes are feeder conduits representing crustal extension at a spreading ridge.

Continue W and park at the Tablelands viewpoint on the S side of the road 430380 5481370

Stop 1-7 Tablelands Viewpoint

Opposite the Tablelands Viewpoint. 430380 5481370

Take care when crossing highway 431. Make sure you can be seen by traffic from both directions, and look both ways before crossing. A group should cross together. Do not stray onto the highway pavement while looking at the rocks. Do not create a traffic bottleneck by standing in two groups on both sides of the highway.

Weakly altered mafic volcanic rocks are exposed along the west side of the road. They are part of the Little Port Complex, an assemblage of mostly intermixed intrusive and extrusive arc-related igneous rocks that are found structurally below the Bay of Islands Complex.

The long exposure includes intercalated pillow lava, pillow breccia, red shale, and chert. This outcrop is variably altered and contains a prominent rusty zone towards its centre, which may represent a hydrothermal alteration zone.

Travel W to the Parks Canada parking lot for the Tablelands Trail.

Stop 1-8 Tablelands Trail: Lithospheric upper mantle harzburgite

Starting at 429450 5481065. Follow the trail east if you are intending to do trip 1b, below.

From the Tablelands Viewpoint, the view south displays the main massif of Table Mountain, the northernmost of four ophiolite massifs that make up the Bay of Islands Complex. Table Mountain displays a deep section through oceanic lithosphere (Figure 9) and is famous for its ultramafic rocks of the lithospheric upper mantle. The mantle section is mainly peridotite. Oxidation of iron is responsible for the rust colour characteristic of the weathered surfaces. On fresh surfaces, the rocks are typically dark green, reflecting their high percentage of olivine and pyroxene, and lack of feldspar. However, in most samples, the olivine is largely altered to serpentine-group minerals. The unusual chemical compositions of these rocks inhibit plant growth, resulting in a relatively barren landscape.

The peridotite is mainly tectonite harzburgite, consisting mainly of olivine (now mostly serpentine) and orthopyroxene. The orthopyroxene crystals stand out on weathered surfaces against the recessive olivine/serpentine. The harzburgite has a tectonite fabric: it is foliated, and the grain-size of the olivine has been reduced by ductile deformation, leaving the orthopyroxene mostly as porphyroclasts. It represents the lithospheric upper mantle of an oceanic plate, and formed as the solid residue of partial melting beneath a spreading centre.

Locally there are dykes of either dunite or pyroxenite. Dunite is an olivine-only rock, smooth and orange on weathered surfaces. Pyroxenite appears dark brown and may contain both ortho- and clinopyroxene. The pyroxenite probably represents partial melt formed during spreading, remnants of magma that was mostly extracted to form the mafic rocks of the crustal section above. The origin of the dunite is harder to explain as pure dunite should have a melting point higher than the surrounding harzburgite. Most likely it formed as a residual crystal mush from an extracted magma; olivine crystals remained in the dykes after the more mafic magma was squeezed out.

Peridotites locally exhibit a scaly, snakeskin-like appearance on weathered surfaces. This pattern develops as a result of meteoric waters moving through cracks and fractures in the Calcium is selectively dissolved adjacent to the fractures and olivine is converted to serpentine, locally in the form of chrysotile asbestos. There are also deposits of white metasomatic rock containing carbonate and calc-silicate minerals.

From here, two routes may be taken. The more demanding hike (1a) goes to see the Moho preserved on the Tablelands high plateau, and involves ~400 m elevation gain. The total horizontal distance (if all outcrops are included) is about 7.5 km. The easier hike (1b) stays on relatively low ground and focusses on the base of the Tablelands ophiolite massif. the total distance out and back is ~7 km but the elevation gain is gradual, amounting to 150 m.

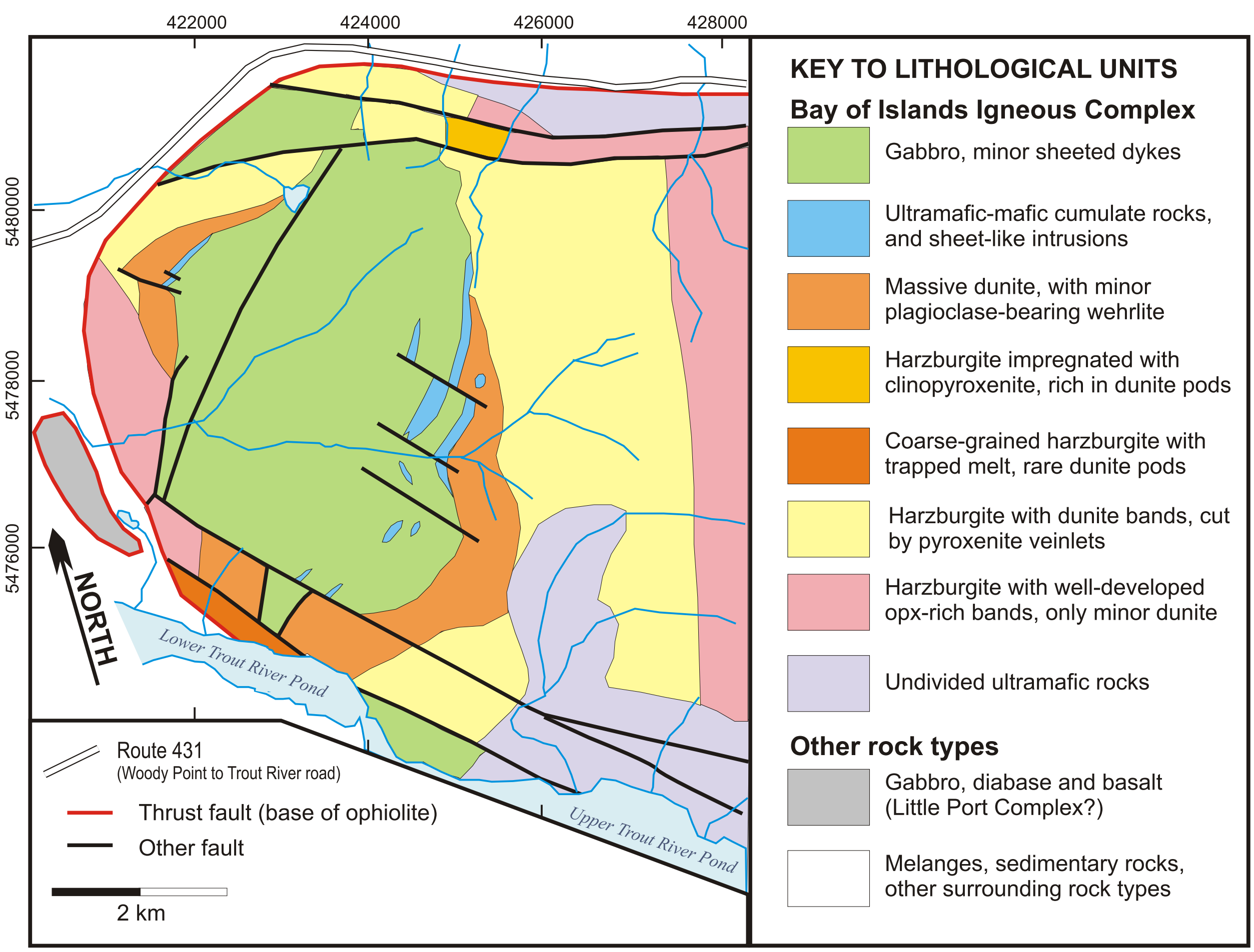
1a: Tablelands traverse to the Moho

Drive west and park at 426247 5482185.

Ascend the slope towards the southwest

No hammering or sampling allowed. The next 5 stops involve an elevation gain of approximately 400 m over a distance of 3.5 km each way. Be aware that because of the bouldery ground, the descent may be as arduous as the ascent. Do not attempt this traverse in foul weather. Wear hiking boots and take warm and waterproof clothes, a hat and gloves. Sunscreen and insect repellant are advisable. Watch out for loose rock on slopes. On slopes be aware that those below you are vulnerable to displaced rocks. Do not walk straight down steep slopes especially if others are also on the slope below you. Instead, proceed down slopes at an angle, and stay in a tight group. Walk at the pace of the slowest member. Warn those below clearly and immediately if you displace an object that may be hazardous. Remain in sight of the leaders. If you take shelter for a "pit stop" let somebody know so that you do not become separated from the group.

Figure 22: Schematic geologic map of the Tablelands (Kerr 2019)



Stop 1-9 Peridotite of the upper mantle succession

425667 5481801

This spot makes a convenient rest stop. The rocks in this area are upper mantle peridotites similar to those at stop 1-9.

Stop 1-10 Moho

424900 5480311

This location is the northernmost outcrop where the Moho is well exposed. To the west, the landscape is dominated by grey gabbro, which gets its colour from dark pyroxene and white-weathering plagioclase. The gabbro is locally layered, reflecting crystal accumulation on the floor of a magma chamber beneath a spreading ridge.

To the east, the landscape is dominated by orange-weathering peridotite. The peridotite differs from that seen at stop 1-9, however, in that it shows a cumulate fabric as opposed to a tectonite fabric. Olivine and pyroxene crystals are of comparable sizes (typically around 1 mm) but are interlayered in varying proportions.

At this location, gabbro and peridotite are interlayered in subequal proportions representing a gradational contact. The Moho is therefore a zone perhaps 50 m wide. This is the geophysical, or "true" moho that is identified beneath the ocean floor by geophysical means. Seismic p-waves travel much faster in olivine-rich peridotite than in feldspar-rich gabbro.

Follow the Moho 250 m SSW.

Stop 1-11 Moho - folded cumulates

424746 5480099

Layered gabbro in this region exhibits isoclinal folds, with axial surfaces parallel to the overall layering, that probably resulted from high-temperature deformation in the oceanic ridge environment.

Depending on the stamina of the participants, walk 400 m SSW following the strike of the Moho.

Stop 1-12 Moho - folded cumulates

424630 5479700

In traversing parallel to the Moho you may notice apparent offsets in the layering. These could be the result of faulting, but there is little direct evidence of faults. An alternative explanation is that multiple small magma chambers are present, and the level of the changeover from gabbro to peridotite varies from one magma chamber to the next.

The cumulates in this area show some photogenic folds.

From this point, a 450 m walk across roughly level ground crosses mostly float of peridotite

Stop 1-13 Petrological "Moho"

In this area there is a very subtle change from layered cumulate peridotite and dunite, to tectonite peridotite similar to that at stop 1-9, with pyroxene porphyroblasts in a foliated groundmass of serpentinized olivine. The two rocks are almost identical in colour, but the tectonites can be identified by croscutting dunite and pyroxenite dykes that served as feeders to the cumulate succession above. Unfortunately, real outcrop is sparse in this area; the change has to be picked out from the composition of float.

This boundary, though inconspicuous, marks an important boundary in terms of petrologic process. Above, the peridotite is igneous, formed by crystal accumulation in a magma chamber, whereas below, the it is metamorphic, the solid residue of the partial melting that formed the overlying igneous units. For this reason it is sometimes called the petrological Moho, though it's important to stress that it's difficult to detect seismically beneath the modern oceans, because cumulate and tectonite peridotite have similar elastic properties

1b: Base of the ophiolite

From the trailhead at 1-9 Continue across barren harzburgite along the signposted Tablelands Trail, which coincides with the old Trout River Highway.

No hammering or sampling allowed. Wear hiking boots and take warm and waterproof clothes, a hat and gloves. Sunscreen and insect repellant are advisable. If you take shelter for a "pit stop" let somebody know so that you do not become separated from the group.

At 430617 548000 the trail diverges from the old road. Follow the old road by fording Winterhouse Brook. Continue to 431000 5480275. From there, hike due E towards a small hill that appears greyer than the surrounding harzburgite barrens.

Stop 1-14 Lherzolite

431750 5480313

The greenish-weathering peridotite in this vicinity has two distinct pyroxene minerals and is therefore a lherzolite. The presence of Ca-bearing clinopyroxene makes this a more enriched mantle sample, in contrast to the highly depleted harzburgite. This may represent a remnant of the asthenosphere, caught up at the base of the ophiolite, or more likely a part of the lithospheric mantle that underwent a lower degree of partial melting.

Hike ESE over barren ground to about 432050 5480200. Climb the ridge to the north to a series of grey outcrops near the ridge crest

Stop 1-15 Sub-ophiolite amphibolite

432115 5480280

These rocks, though unspectacular in appearance, are significant tectonically as they represent thinned and mylonitized mafic rocks (possibly underlying oceanic rocks) that were deformed as the ophiolite was emplaced. Though they are better exposed elsewhere, this is the only area where they can be easily accessed without boat or helicopter transportation. Though fine-grained, the rocks here are strongly foliated, and locally strongly lineated, as a result of their deformation during thrusting of the ophiolite onto the continental margin.

Other exposures of the sub-ophiolite metamorphic rocks contain visible garnet and orthopyroxene which can be used for pressure-temperature (P-T) determinations; conditions of 750–850°C and 10-11 kbar have been estimated (Jamieson and Strong 1981, McCaig 1983). The age of metamorphism is poorly known; the only available date is 469 Ma from Ar-Ar on Hornblende from Dallmeyer & Williams (1975), but Dewey and Casey (2013) suggest that metamorphism was likely earlier.

Stop 1-16 Xonotlite

This stop lies downstream from the junction of a tributary brook with Winterhouse Brook, and it is marked by a prominent wall-like feature extending across the brook. The description here is derived with thanks from a forthcoming field guide by Andrew Kerr (2019) The location marks the contact of the ophiolite with the sedimentary rocks to the north.

The contact of igneous and sedimentary rocks here is a fault, and there are no sub-ophiolite metamporphic rocks preserved. However, boulders of metamorphic rocks that resemble those of Stop 1-15 can be located in the stream bed. The ultramafic rocks in this area are pervasively altered, and few original textures or minerals are preserved. The contact itself is marked by a resistant, pale grey unit that resembles a bed. This is commonly referred to as the "xonotlite layer", after a rare mineral that it contains. It is actually a metasomatized ultramafic rock that also contains Ca-rich prehnite, calcite and wollastonite. The metasomatism of the ultramafic rocks at the contact may have occurred during emplacement of the ophiolite, but could equally well reflect fluid migrations associated with later faulting. Xonotlite is an unusual mineral with the formula $Ca_6Si_6O_{17}(OH)_2$. It is relatively hard (6.5 in the Moh's hardness scale) which accounts for the resistant nature of this layer. It is named for a place called Tetela de Xonotla, in the state of Pueblo, Mexico. The Winterhouse Brook locality was the first xonotlite to be described in Canada.

DAY 2 FIELD STOPS: LAURENTIAN MARGIN DEFORMATION HISTORY: PORT AU PORT PENINSULA

Locations are UTM coordinates, zone 21, using the NAD 83 datum.

Rocky Brook to Port au Port

Exit to Highway 430 and turn south to Deer Lake. At the intersection with highway 1 (Trans-Canada Highway TCH) turn west towards Corner Brook, and continue past the Marble Mountain Ski area.

Marble Mountain to Corner Brook

The Marble Mountain ski hill is underlain by upper Proterozoic to lower Cambrian (Cawood and van Gool 1998), pelitic and psammitic schistose rocks of the South Brook Formation, Mount Musgrave Group. Immediately west of the ski slopes, the internal and external domains are separated by a structural front, the Humber River Fault (Williams and Cawood 1989).

Beyond the ski chalet parking area, the TCH enters the Humber River gorge and parallels the river for several kilometres. This section of highway provides multiple opportunities to view shelf succession lithologies.

Upon entering the gorge, the steep cliff face on the left exposes a vertically dipping, thinly bedded succession of Reluctant Head limestone, dolomitic limestone, ribbon limestone, limestone conglomerate, dark grey slate and phyllite. Close examination of the thinly bedded limestones reveal small scale F_1 folds and a well developed, axial planar cleavage in slaty to phyllitic lithologies (Cawood and van Gool 1998). The Reluctant Head formation is conformably overlain by a thick succession of Port au Port Group dolostone, dolomitic marble, and grey to white calcareous marble (Knight 1995).

Above the steep talus slope and about halfway up the cliff face at Bear Head, there occurs within the limestone strata a natural rock feature locally referred to as the “Old Man in the Mountain”.

A near continuous succession of folded Port au Port Group strata is overlain by St. George and Table Head Group lithologies exposed towards the top. Port au Port Group strata exposed on the south side of the highway just past the Riverside Drive turn-off locally contain E – W and NE – SW striking, steep oblique-slip and strike-slip faults. The fault surfaces, exhibit metre scale undulations and parallel slickenlines.

An upright, close to tight, F_2 syncline (Mount Patricia syncline) is exposed in the high, cliff face located directly across the river from the Route 440, North Shore highway bridge.

At exit 6 take highway 450A Lewin Parkway towards Corner Brook.

At the first traffic lights (Toyota dealer on the left) turn left on Confederation Drive.

Follow Confederation Drive south for 1.7 km and turn right (west) on West Valley Road.

Continue 1.2 km and turn left (west) on O’Connel Drive.

Continue 2.5 km west and turn right (north) on Bliss St. (This is an easy intersection to miss. If you miss it, it’s possible to take any of the next three exits to the right, which will take you to Country Road where you can travel back east to regain the route.)

Follow Bliss St. north 300 m and turn right (east) on Country Road.

In 200 m turn north on Atlantic Avenue.

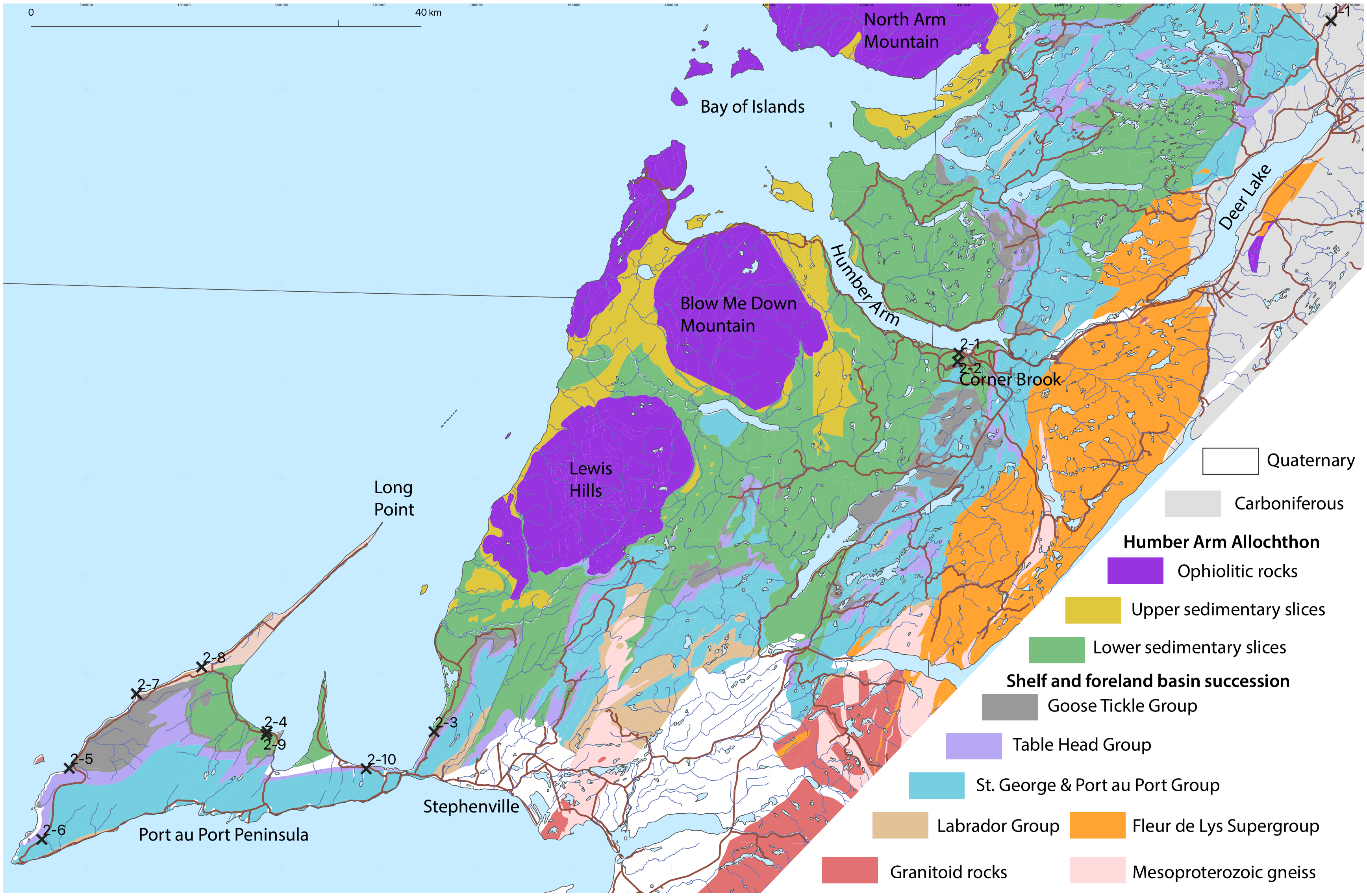


Figure 23: Map of field trip stops on Day 2

Follow Atlantic 650 m northeast and take the first left, Mayfair Avenue.

In 75 m turn right (north) at the T-junction and continue to the James Cook Monument.

Stop 2-1: Captain Cook's Lookout

***Caution**: Do not attempt to cross the barriers constructed to protect the public from the precipitous cliff on the north side of the hill. No hammering is allowed in the site.*

429505 5422848

Crow Hill overlooks the City of Corner Brook and, on a clear day, provides panoramic views of the city, the carbonate-dominated terrane to the east, the Humber Arm to the north, and the Bay of Islands ophiolite to the west.

The hilltop is a monument commemorating the surveying work of the British Admiralty, and in particular Captain James Cook, who subsequently achieved fame for his exploits in the Pacific Ocean. The monument itself is constructed of a variety of local rock-types. Perhaps the most notable are ripple-laminated shales and sandstones from the Carboniferous Anguille Group of the Deer Lake Basin to the east.

Cook's Monument itself is built on Curling Group, and sits just above the Crow Hill thrust, which places older Cambrian Summerside Formation on top of younger (but still Early Cambrian) rocks of the Irishtown Formation. The Summerside Formation here consists of interbedded arkosic sandstone and maroon to brown slate, weakly metamorphosed, with cleavage dipping to the west. In the fine-grained rocks (originally mudstone, now slate) the cleavage is a slaty cleavage, defined by flakes of sheet silicate minerals oriented perpendicular to the shortening direction. In the sandstones, the cleavage is defined by seams along which quartz has been preferentially dissolved - it is a pressure solution cleavage.

The structure at the top of the hill is notable because the beds dip and young to the west (as shown by graded bedding and rare cross-bedding) but the cleavage planes pass downward through the beds in this direction - the bedding faces down on cleavage. This is an unusual situation and shows that these rocks have been deformed twice - once during westward thrusting (D_1) in the Taconian Orogeny, and then again during the deformation (D_2) that produced the cleavage, which probably transported higher rocks back towards the east. The age of the cleavage-forming event is poorly constrained, but some preliminary Ar-Ar data suggest that it was Late Ordovician or Early Silurian.

To the east, the low ground occupied by the City of Corner Brook is mainly underlain by Irishtown Formation of the lowermost slice in the Corner Brook Sheet of the Humber Arm Allochthon. This extends across the valley, and includes the hill through which the cutting of Lewin Parkway passes. This hill represents a succession of resistant quartz-rich sandstone and conglomerate within the slates of the Irishtown Formation that are folded in a syncline (Seal Head Syncline). Farther away is the boundary between the Humber Arm Allochthon and the limestone and dolostones of the shelf succession. At the contact, approximately marked by line of the Trans Canada Highway, these dip towards us; presumably present at depth beneath our feet.

To the north, the view is across the Humber Arm. The eastern part of the view is occupied by Irishtown Formation (upper Curling Group) around the community of Irishtown. To the west, the community of Summerside rests on Summerside Formation (lower Curling Group), which produces more rugged topography. The two types of terrain are separated by the Crow Hill Thrust, which can be picked out dipping to the west from the change in topography between the two communities.

To the west, most of the forested ground in the middle distance is occupied by the Humber Arm Allochthon, in which rocks are disposed in a broad synform, the Cooks Brook synform. In the far distance, the skyline is formed by the overlying mantle rocks of Blow Me Down Mountain, part of the Bay of Islands Ophiolite.

Retrace the route as far as the bottom of Atlantic Avenue

Stop 2-2 Atlantic Avenue, south of Crow Hill

429362 5421971

This is a busy street with no sidewalk. Watch out for traffic and walk facing the oncoming traffic if possible.

The outcrop on Atlantic Avenue displays highly deformed Irishtown Formation of the Crow Hill thrust. Locally, strongly lineated quartz bands attest to dip-slip motion on the contact. Technically, and from a purely local perspective, this fault zone might be described as a normal fault, because the hanging wall (the upper block) has probably moved down the present-day dip of the fault. However, that dip is almost certainly the result of later F_2 folding. When the fault first formed it probably dipped to the east, and brought older Summerside Formation over younger Irishtown Formation.

The fault has a complex history, and may have cut an unknown volcanic unit (perhaps at the base of the Summerside Formation), because a few hundred metres to the west of this locality a large block of mafic lava is present in the fault zone.

Retrace the route east along O'Connel Drive and West Valley Road. At the T-junction with Confederation Drive turn right (south). Continue to the TCH westbound (Confederatin Drive becomes the on-ramp.

Continue 47 km. Take Exit 3 Highway 460 west toward Stephenville

Continue 42 km to Port au Port East.

Turn Right on Highway 462 toward Fox Island River and Point au Mal

Continue 5.4 km to a private road to the coast. Park 376121 5384475 and walk to the coast (request permission to cross private land)

Stop 2-3: Black Point

375662 5384000

Be aware of cliffs on this traverse; do not stand under overhangs or anywhere where there may be a hazard from falling rocks. The coastal outcrop is only accessible close to low tide. Be aware of the rising tide and make sure you do not get cut off. Our route to or from the shore may involve crossing private property; please respect owners' rights and leave the area as you find it

A long coastal section on the east side of Port au Port Bay exposes a complete transition from shelf, through foreland basin, to the Humber Arm Allochthon. Our stop will focus on the Humber Arm Allochthon at Black Point. The Humber Arm Allochthon in this region can be subdivided, at least in areas of good exposure, into tectonic mélanges (blocks of varied lithologies in a matrix of sheared shale) and stratified formations of the Humber Arm Supergroup. The Middle Arm Point Formation consists of fine-grained red and green shale, siliceous shale and chert, with rare carbonate beds. At the Black Point location the formation displays spectacular cliff-high asymmetric folds. The hinges of these folds trend almost east-west and contrast with the regional trend of folds in the tectonically underlying shelf and foreland basin sections which mostly trend NE-SW. This unexpected orientation possibly indicates that the folded block was more or less 'floating' in mélange, and was rotated into its present orientation during intense deformation of the Humber Arm Allochthon. These folds are some of the most photographed in Canada, and have appeared in several textbooks and government publications. The best photographs have been obtained by walking out onto the wave-cut platform at low spring tide.

In addition to the Middle Arm Point Formation, there are fault-bounded exposures of very coarse sandstone of the Western Brook Pond Group (Eagle Island Formation), the youngest unit in the Humber Arm Allochthon. This unit was deposited during the early stages of Taconian deformation in the Early Ordovician, as sediment derived from arcs and continental slices farther offshore started to reach the continental margin of Laurentia.

Return to Highway 460, turn right and continue west. After 1.5 km turn left to stay on 460.

Continue 16.3 km to Abrahams Cove. Continue straight (north) onto Highway 463. Continue 8.5 km.

Port au Port Peninsula

Park at Parkview Variety 358555 5383972

Caution: The shoreline outcrops are typically extremely slippery. Choose your route to the shore carefully and take care to avoid overhanging cliffs.

Stop 2-4: West Bay Shoreline

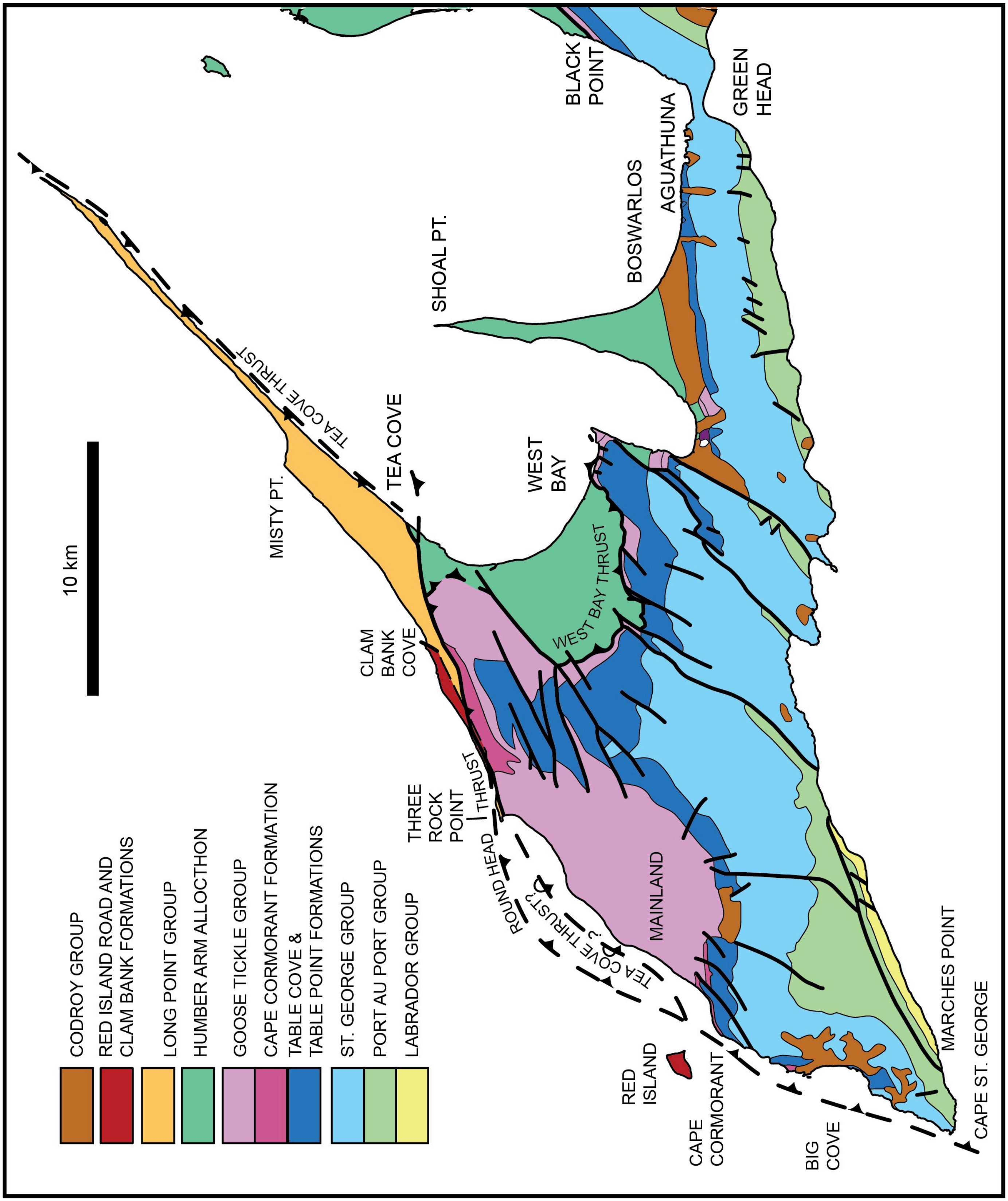
358536   5384013

The Table Cove Formation is well exposed at the mouth of the small stream that descends to the shoreline west of the store. West of the stream, at low tide, the succession passes up through ~5 m of dark shale of the basal Goose Tickle Group (Black Cove Formation) into overlying turbiditic sandstone of the Goose Tickle Group. However, to the east and in the base of the cliff the Goose Tickle Group is absent. Instead, the ribbon limestone and shale of the Table Head Group are increasingly fragmented, and distinctive black and green shale appears between the more competent blocks of limestone. The base of the Humber Arm Allochthon (West Bay thrust: Figure 26) is marked by highly deformed, black and green scaly shales of the Humber Arm Supergroup. These have distinctive green and black banding that contrasts with the consistently grey to black colour of the younger, but underlying, units of the Table Head and Goose Tickle groups. The West Bay thrust is here offset by several steep faults that change its level in the cliff.

Higher in the cliff, and to the east, there are distinctive nodular green chert and siliceous shale units of the Humber Arm Allochthon. They are most likely part of the Middle Arm Point Formation of the of the Cow Head Group. These siliceous sedimentary rocks are thought to have provided material for lithic tools of ancient peoples who inhabited western Newfoundland.
To the east, beyond a small point, is a tectonic contact with a spectacularly folded succession of turbiditic sandstones and shales, with asymmetric, west-facing folds that appear to refold a series of extensional faults (Figure 25). The stratigraphic affinity of these units was long in doubt. The recent discovery of Darriwilian 3 graptolites (Lacombe et al. 2019a) shows that this is Goose Tickle Group.

Continue west to Mainland 28 km. At the south end of the community, turn off to follow the dirt road along the shore. Park at the end of the road 338518 5380495 Taking care not to block access to boats or fishing cabins.

Figure 24: Geological map of Port au Port Peninsula after Knight et al. (2007).



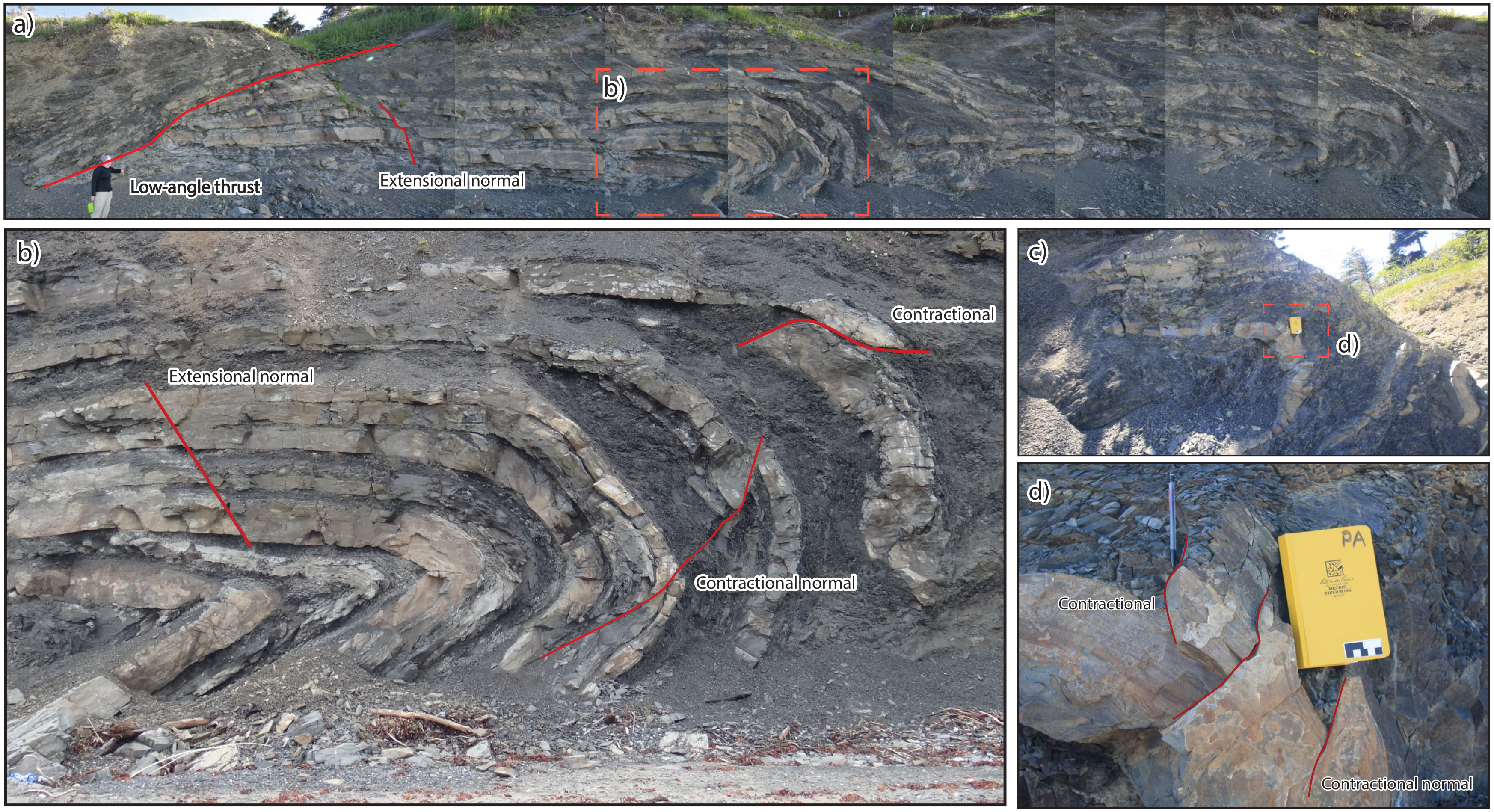


Figure 25: Folds on shoreline of West Bay, Stop after Lacombe et al. (2019a).

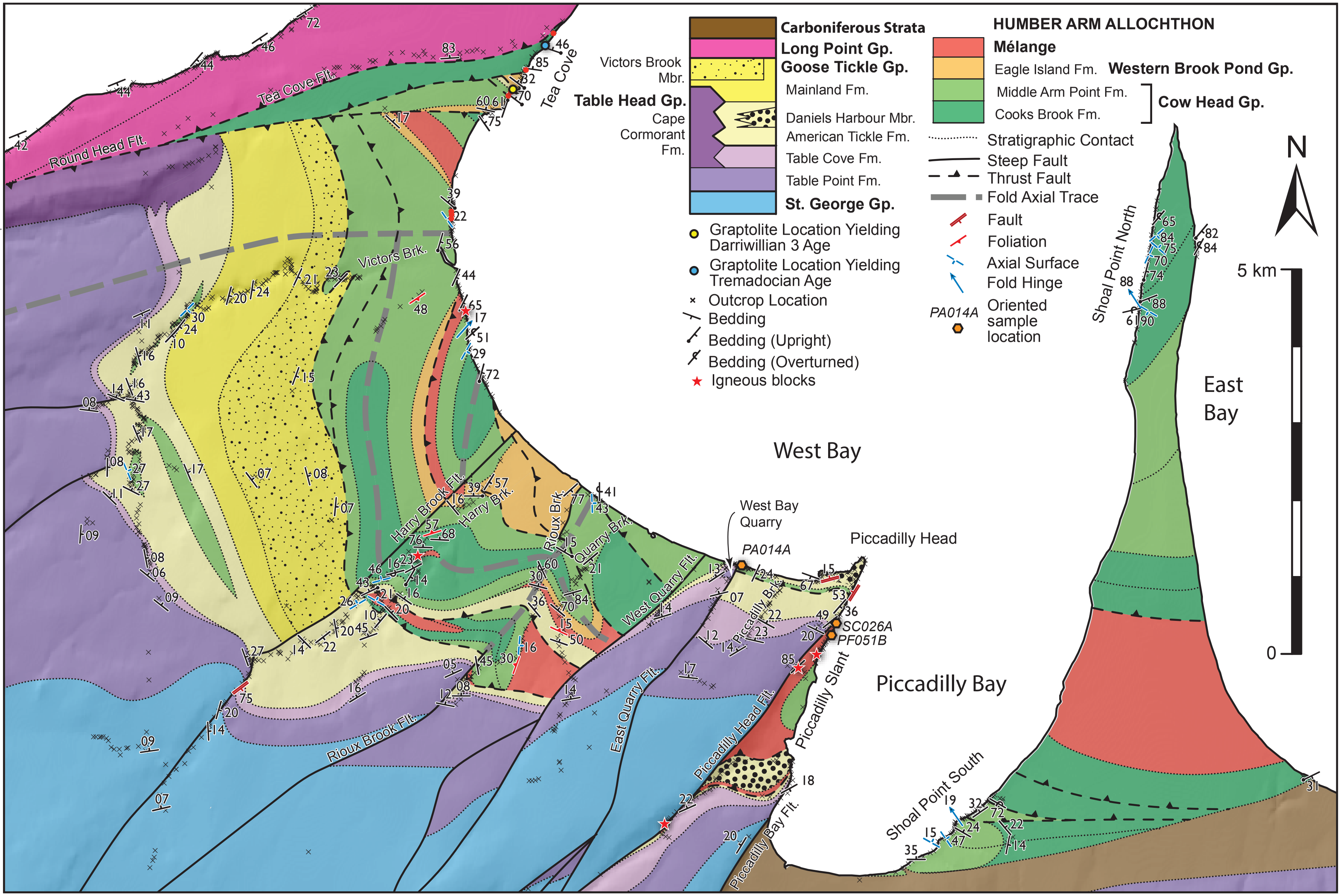


Figure 26: Detailed map of Humber Arm Allochthon on Port au Port Peninsula after Lacombe et al. (2019a).

Walk SW along the shore to the start of the section.

Stop 2-5: Cape Cormorant

338239 5380256

Do not approach the cliff without protective headgear. The near-vertical bedding planes and boulder conglomerates of the Cape Cormorant Formation are extremely unstable; be alert for hazards from falling rocks and landslides; choose safe places to examine the outcrops.

The classic section at Cape Cormorant provides an opportunity to view the effects of the Taconian orogeny at the top of the platform succession. Steeply dipping beds form a cliff that is a strike-section, younging towards the sea. From the parking place at the end of the road it is possible to walk gradually down-section through the Mainland Sandstone (Goose Tickle Group) and the upper parts of the underlying Cape Cormorant Formation (Table Head Group).

The Mainland Sandstone consists of interbedded sandstone and shale and represents syntectonic sedimentation of turbidites ("flysch") deposited as Taconian allochthons advanced onto the now buried edge of the continental shelf to the east. The Mainland Sandstone is represented by interbedded turbiditic sandstone and shale. The sandstone beds exhibit normal grading, and partial Bouma sequences including parallel and ripple cross-lamination. Graptolites are locally present in the shales and finer sandstones, and may show preferred orientation parallel to current flow. Paleocurrent structures measured in the Mainland Sandstone suggest sediment transport to the north-northwest (Quinn 1995). Trace fossils may also be seen on some bedding surfaces.

To the south, the Mainland Sandstone overlies the uppermost strata of the Cape Cormorant Formation, marked by limestone conglomerate units. The contact is gradational. The Cape Cormorant Formation is a 200 m succession of shale, ribbon limestone, calcarenite and polymictic limestone conglomerate rich in angular debris derived from the underlying upper Cambrian to Middle Ordovician carbonate platform successions (Stenzel et al. 1990). Conglomerate beds ranging from discrete pebble debris sheets to very thick beds of amalgamated, pebble to boulder conglomerate. Many of the conglomerates are disorganized and matrix-supported, indicating deposition by debris flows. Fine-grained, thin-bedded limestone and some beds of lithoclastic grainstone also occur in the succession and are interbedded with dark grey to green-grey, shales, containing Middle Ordovician fossils including graptolites, bivalves, and trilobites.

337600 5379760

Conodonts, recovered from many clasts in the conglomerates (Stenzel et al. 1990), indicate that much of the debris was shed from Early and Middle Ordovician carbonates of the St. George Group and Table Point Formation. Scattered clasts of dark grey sucrosic dolostone were probably derived from the Watts Bight and/or Catoche formations of the St. George Group. Clasts of oolitic grainstone and various types of dolostone indicate source strata as old as the late Cambrian Port au Port Group. Older clasts generally become more abundant up-section, suggesting progressive erosion of a source area in the carbonate platform.

Inland, along Caribou Brook and on other exposures along the western edge of the Peninsula, the formation disconformably overlies the Table Point Formation. However, these conglomerates lens out rapidly in just a few kilometres to the east. Ribbon limestones and shales of the Table Cove Formation occupy an equivalent position in the stratigraphy in the eastern two-thirds of the peninsula, although in some places equivalent strata are absent and the Goose Tickle Group directly overlies the Table Point Formation.

The enormous grain size, highly localized distribution, and polymictic composition of the Cape Cormorant Conglomerate Formation strongly suggest derivation from a contemporary Middle Ordovician fault scarp. However, there is no obvious source area on land; the St. George and Port au Port groups are largely intact, and the Cape Cormorant Formation fines rapidly eastward. Hence, we must infer that the material came from a major fault scarp that lay to the west. Increasingly older clasts occur up-section, indicating that the fault scarp was progressively incised by erosion and/or collapse as it developed.

The section contains a number of minor faults and associated folds, most of which are contractional (they shorten strata). At the northernmost portion of this outcrop in Mainland, Port au Port, the sandstone is folded into subhorizontal, overturned, angular folds. Fold hinges are typically sub-parallel the coastline. Overall, the strata of the Cape Cormorant Formation progressively steepen toward the west, in a fold interpreted to be related to a major east-dipping reverse fault, the Round Head Thrust, inferred to intersect the seafloor just offshore. The fault is imaged at depth in seismic profiles shot on the high ground to the east of the coastal section (Figure 27), and was intersected by the Port au Port #1 (Garden Hill) well.

The timing of reverse-sense movement on the Round Head Thrust is constrained between the youngest rocks cut, which are Early Devonian, and the flat-lying Early Carboniferous (Viséan) strata that unconformably overlie the near-vertical Cape Cormorant Formation. Regional relationships suggest that within this bracket, movement on the thrust is most probably Acadian (mid-Devonian). There is a striking coincidence between the distribution of these Devonian structures and the distribution of the Ordovician Cape Cormorant Formation. This coincidence led Waldron et al. (1993) to suggest that the Round Head Thrust had an earlier incarnation as the normal fault scarp from which the Cape Cormorant conglomerates were derived; Acadian contraction led to its inversion, producing the present-day reverse offset.

Return to the vehicles and continue 14 km along Highway 463 to Garden Hill

Stop 2-6: Garden Hill

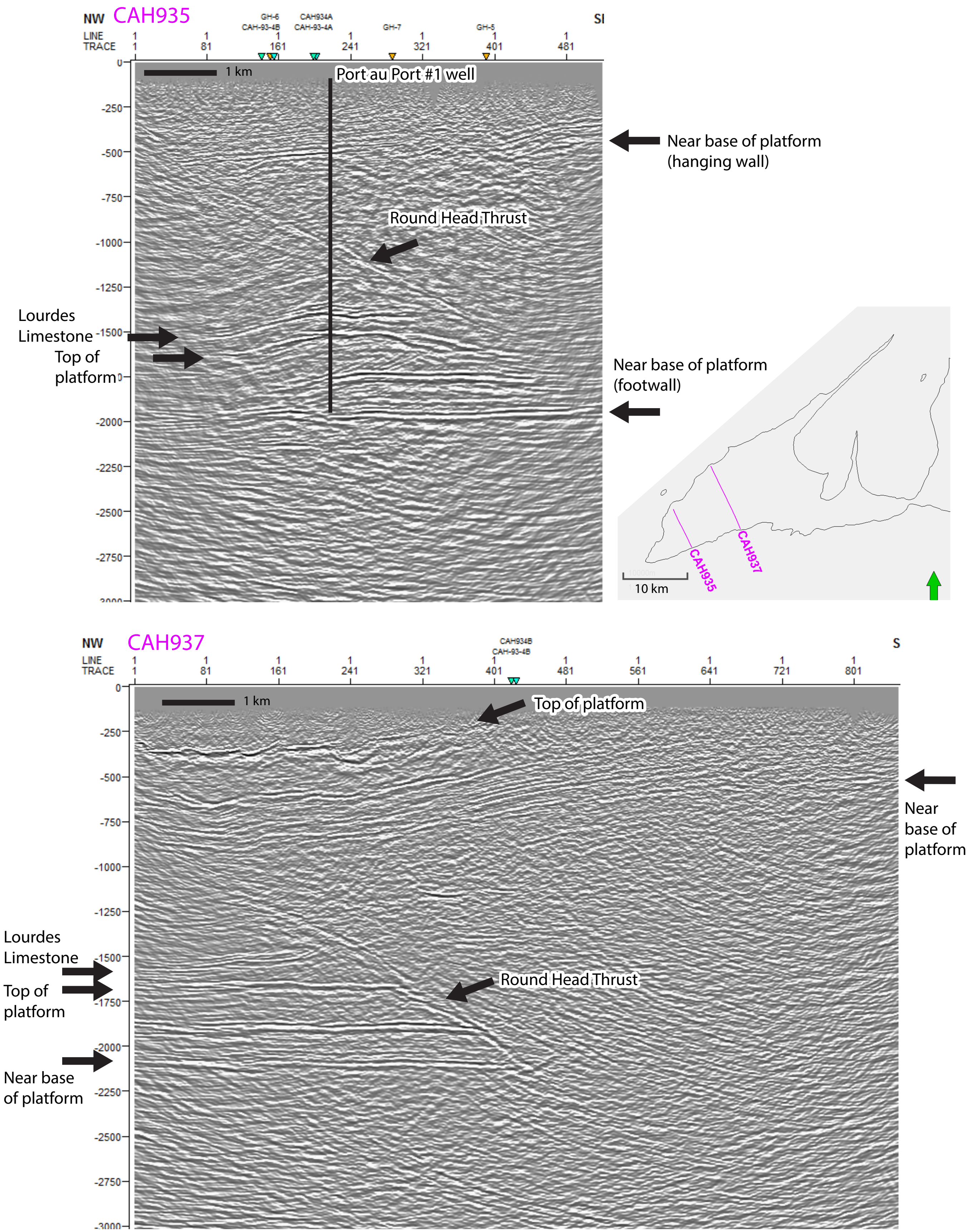
335420 5372963

Do not attempt to enter enclosed parts of the well site

The Port au Port #1 well (Cooper et al. 2001) can be visited at the top of Garden Hill. The well-head is located in an area of widespread outcrop of the Catoche Formation of the St. George Group. The well was drilled (Figure 27) through underlying St. George, Port au Port, and thick Labrador Group sedimentary rocks, entering Grenville gneiss 1710 m below the surface. After drilling through basement rocks for 615 m, the well passed through a major reverse fault (the Round Head Fault) at 2325 m and back into Paleozoic sediments of the Long Point Group.

The hole hit platform limestones of the Table Head Group (Table Point Formation) at 3445 m, and re-entered the St. George Group at 3472 m below the surface, in an anticline between the Round Head Thrust and a footwall shortcut fault. Hydrocarbons were encountered in 3 zones in the Aguathuna Formation, including at least some cavernous porosity (paleo-caves) associated with vuggy sucrosic dolostones in a zone 18.5 m thick. Water saturated zones occur in Catoche Formation dolostones and in cavernous zones in the Watts Bight Formation.

Figure 27: Seismic profiles through Round Head thrust on Port au Port Peninsula.



The hole was continued, penetrating the entire St. George and Port au Port Group a second time, presumably to investigate the sandstones of the Labrador Group (Hawke Bay Formation) which were also completely penetrated. Drilling was suspended in the top of the underlying Forteau Formation at a total depth of 4697.5 m.

Return N on Highway 463 25 km.

Stop 2-7: Three Rock Point

Park at the Community Centre building and walk to the point at

345126   5387902

Be careful of overhanging cliffs and slippery rocks at this location.

At this locality, the Late Ordovician Lourdes Limestone, the basal unit of the Long Point Group, appears on the shoreline, to the north of a long interval of Mainland Sandstone. The Lourdes Limestone displays characteristic fossiliferous, fine grained, nodular facies, locally interbedded with crossbedded grainstones and intraformational conglomerates. Trace fossils are common; local isolated stromatoporoids indicate that the unit is inverted.

Williams (1985) and Stockmal and Waldron (1990) interpreted these rocks as lying in the overturned *footwall* of the Round Head Thrust, in which case the trace of the thrust runs to the SW of this location, between it and the grey-green sandstones of the Mainland Formation that occur in the cliffs farther SW. However, it is also possible that this outcrop lies in the *hanging wall* of the Round Head Thrust, which would necessarily run offshore somewhere to the NE, between these outcrops of Lourdes Limestone and the red cliffs of Early Devonian Clam Bank Formation visible in the distance. If this is the case, the Lourdes Formation originally may have rested disconformably upon the Mainland Sandstone. Both possible locations for the trace of the Round Head Thrust are marked by exposure gaps; current work is aimed at resolving the ambiguity by relating outcrop exposure to the subsurface seismic profiles, in which the Lourdes Limestone is a conspicuous reflector.

Continue 7.5 km NE and turn left to the coast.

Stop 2-8: Clam Bank Cove

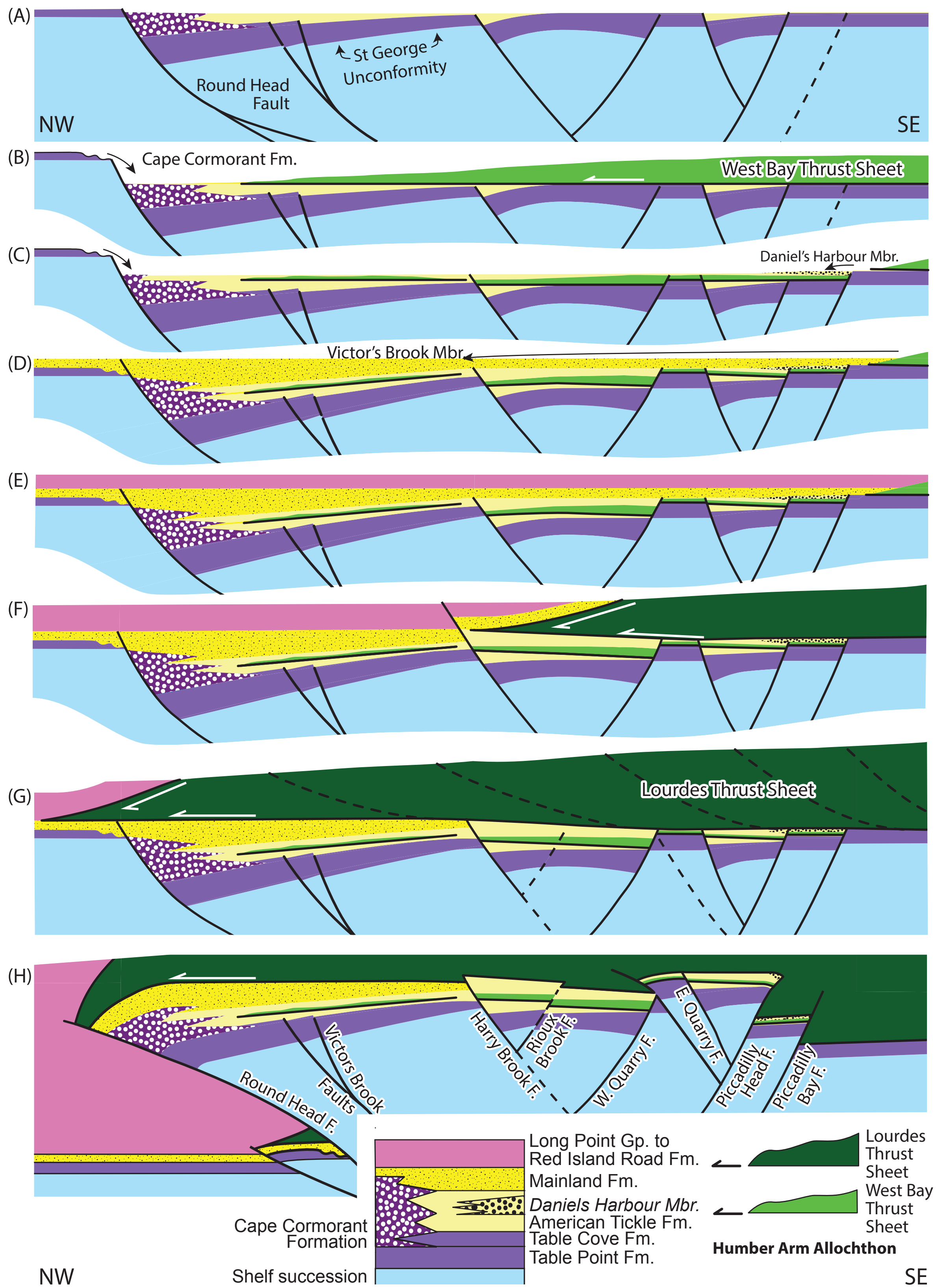
351826   5390648

Be careful of overhanging cliffs and slippery rocks at this location. This outcrop is best examined on a falling tide, as outcrops SW of the cove are cut off by the rising tide.

Clam Bank Cove is situated in some of the youngest rocks of the foreland basin successions on the Port au Port Peninsula. There are two sections, best exposed at opposite ends of the cove. Both sections are overturned in the immediate footwall of the Round Head Thrust. These stratigraphic sections were once confused but distinct stratigraphic units can now be recognized.

The northern outcrops display units of the Long Point Group that overlie the Lourdes Limestone. Steeply dipping, grey clastic sedimentary rocks of the Winterhouse Formation are in contact with by red strata of the Misty Point Formation. Sedimentary structures in both units indicate that they are overturned, and that the strata young seaward. Both units are part of the Late Ordovician Long Point Group, representing post-Taconian foreland basin fill. The Winterhouse Formation is interpreted to represent storm-influenced shelf conditions, while the overlying Misty Point Formation ranges from fluvial to shallow marine (Quinn et al. 1999). The overall

Figure 28: Schematic diagram showing faulting history of Port au Port Peninsula.



regressive sequence indicates progressive filling of the foreland basin as sediment supply from the orogen exceeded the subsidence rate.

At the southwest end of the cove, probable Ordovician redbeds of the Long Point Group (Misty Point Formation) are exposed in a northwest-younging section in the cliff. These are separated by a small exposure gap from red and grey, generally finer-grained clastic rocks and minor carbonates of the younger Clam Bank Formation, which are intensely bioturbated, and contain local bivalves and echinoderm fragments. The fossils represent restricted marine environments, and the age of the Clam Bank Formation has been debated, with estimates ranging from late Silurian to Early Devonian. The most recent work (Burden et al. 2002) favours an Early Devonian age.

Between the Misty Point Formation and the overlying Clam Bank Formation is a time gap of at least 30 million years. Unfortunately the on-land exposure is insufficient to determine whether the boundary is a fault or a stratigraphic contact, although bedding measurements on either side of the boundary suggest small angular discordance, and aeromagnetic data suggest a fault (White et al. 2019b). In offshore seismic profiles the two units can be seen to have an almost concordant relationship with the Clam Bank overlying the Misty Point Formation. However, a subtle truncation can be detected in the longest seismic lines, suggesting that a regional uplift without major internal deformation was the cause of this 'Salinic' unconformity (White et al. 2019b).

The youngest rocks of the post-Taconian foreland basin fill are exposed as a gently dipping, upright succession of red, fluvial conglomerates and pebbly sandstones of the Red Island Road Formation on Red Island (seen offshore to the south). These red sedimentary rocks have yielded Emsian spores (Quinn et al. 2004).

Return along Highway 463, 10 km to Parkview Variety

<u>*Stop 2-9: Quarry at West Bay*</u>

358425 5383706

This outcrop is very close to 2-4 but can be done later in the day as it is not tide-dependent.

Cross highway 463 with care as this is a busy spot. Do not approach the quarry face without a hard hat.

In the quarry, the contact between burrow-mottled limestone of the Table Point Formation and the overlying ribbon limestone and shale of the Table Cove Formation is exposed. The boundary marks the time during the Darriwilian when carbonate productivity became unable to keep pace with foreland-basin subsidence induced by the Humber Arm Allochthon which was advancing westward toward this point. Both formations are fossiliferous, and the Table Cove is particularly rich in graptolites.

Travel 8.6 km south to Abraham's Cove; continue onto Highway 460.

Continue 13 km east and turn left onto Father Joy's Road.

In 2 km turn left onto Main St.

Continue 2 km to Aguathuna Quarry

Stop 2-10: Aguathuna Quarry

368694 5380200

Do not approach the quarry face without protective headgear. Keep away from old machinery and steep rock faces in this disused quarry. Be careful crossing the road.

The St. George Unconformity marks the Early-Middle Ordovician boundary, separating the Sauk and Tippecanoe sequences (Sloss 1963). It also marks the contact of the St. George Group (Laurentian passive margin) with the overlying Table Head Group (Taconian foreland basin). The boundary is believed to represent the westward passage of a peripheral forebulge across the margin but coincides with a eustatic sea level fall (Knight et al. 1991).

Units of the St. George Group below the unconformity are best exposed in an inner quarry. The top of the Catoche Formation and the whole of the Aguathuna Formation are exposed.

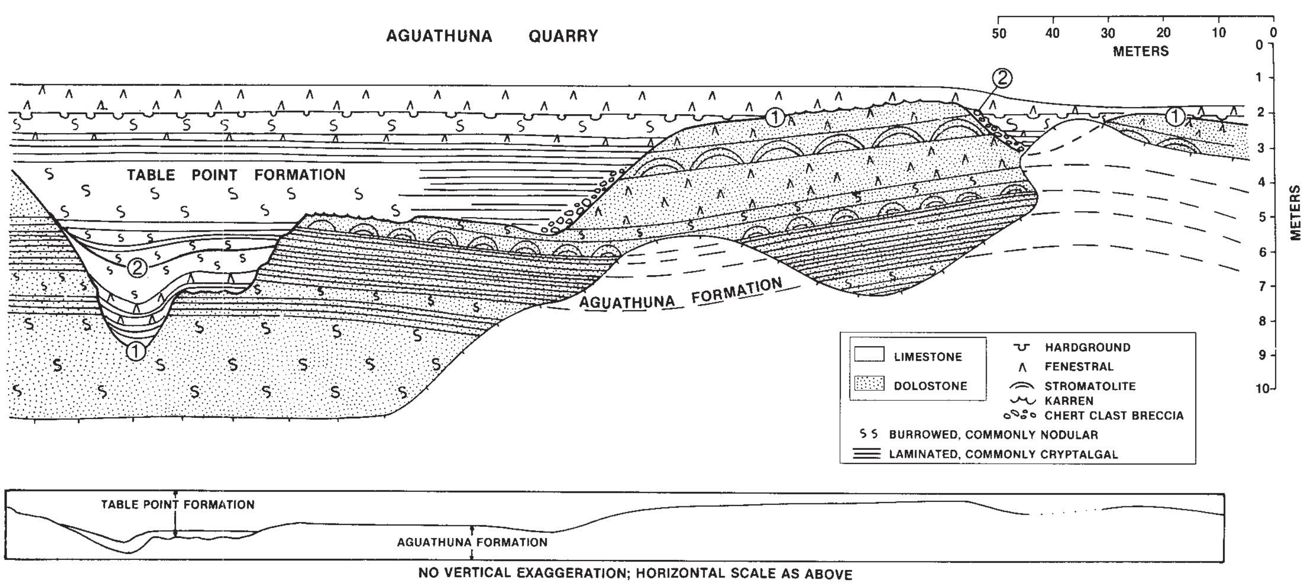
The unconformity itself is well exposed in the face of the outer quarry where it has an erosional relief of several metres, cutting down into the predominantly burrowed and laminated dolostones of the Aguathuna Formation, St.George Group (Figure 29). The surface displays a variety of karstic features including small karren, a basal conglomeratic lag, and local cave deposits.

The overlying Table Point Formation consists mainly of dark grey bioturbated limestone. A thin member of nodular limestone, grainstone and fenestral limestone, locally with dolostone interbeds, occurs immediately above the unconformity; it is known as the Spring Inlet Member (Ross and James 1987). This unit was deposited upon the unconformity as the Middle Ordovician sea drowned the underlying platform.

In the centre of the quarry a small upstanding area displays Carboniferous rocks of the Codroy Group, in places including abundant brachiopods and tube worms. These probably represent the fill of a karst system eroded in the Ordovician carbonates during the Carboniferous, and were left behind during quarrying of the surrounding dolostone. They are locally mineralized with barite and celestite, leading to the suggestion that these were deposits associated with a geothermal spring around which a specialized biota flourished.

Return to Deer Lake 160 km

Figure 29: St. George unconformity at Aguathuna Quarry, after Knight et al. (1991).



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