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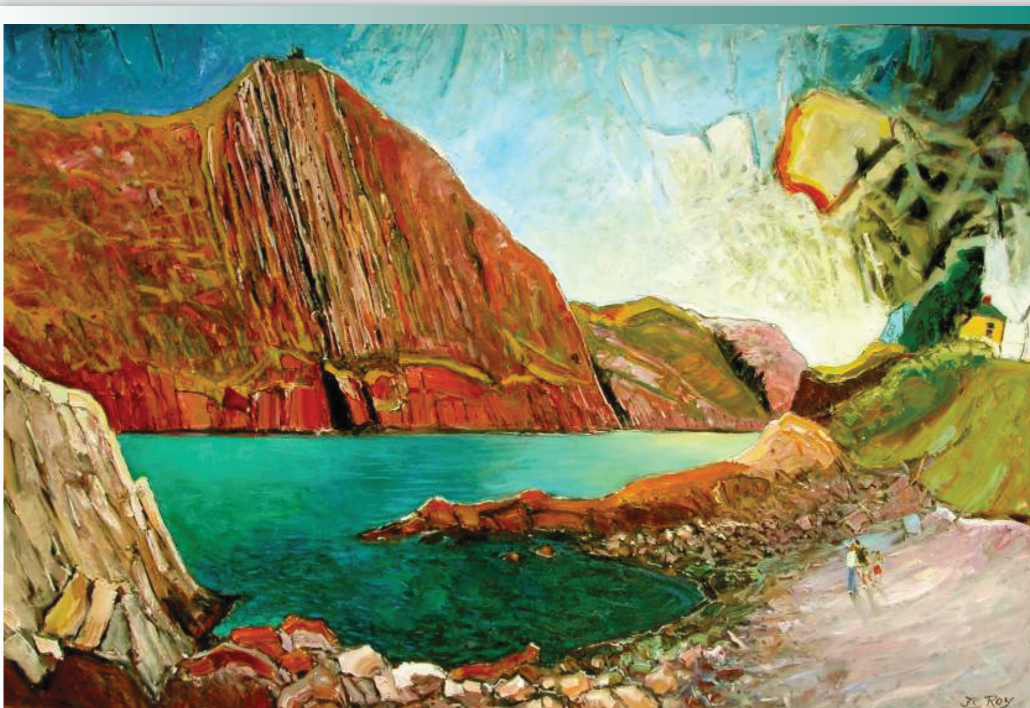

Jean Claude Roy, *Signal Hill from Fort Amherst*, oil on canvas / huile sur toile, 48" x 72", 2006

FIELD TRIP GUIDEBOOK - B3

STRATIGRAPHY, TECTONICS AND PETROLEUM POTENTIAL OF THE DEFORMED LAURENTIAN MARGIN AND FORELAND BASINS IN WESTERN NEWFOUNDLAND

Leaders: John W.F. Waldron, Larry Hicks and Shawna E. White

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FIELD TRIP GUIDEBOOK – B3

STRATIGRAPHY, TECTONICS AND PETROLEUM POTENTIAL OF THE DEFORMED LAURENTIAN MARGIN AND FORELAND BASINS IN WESTERN NEWFOUNDLAND

FIELD TRIP LEADERS

John W.F. Waldron[1], Larry Hicks[2] and Shawna E. White[1]

[1]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB
[2]Petroleum Resource Division, Newfoundland and Labrador
Department of Natural Resources, St. John's, NL A1B 4J6

May, 2012

OVERVIEW OF THE FIELD TRIP

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 record, with an emphasis on facies variations now telescoped by deformation, and the implications of regional structure and stratigraphy for petroleum exploration. This is a place where you can step from the peritidal zone, down the continental slope, and into the abyssal plain in just a few outcrops, while you gaze across the water at towering ophiolite mountains. The itinerary includes parts of Gros Morne National Park, and also the rich fossil localities of the Port-au-Port Peninsula and Table Point. For anyone interested in Paleozoic stratigraphy and tectonics, this field trip is an ideal excursion.

Recommended citation:

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SAFETY INFORMATION

General Information

The Geological Association of Canada (GAC) recognizes that its field trips may involve hazards to the leaders and participants. It is the policy of the Geological Association of Canada to provide for the safety of participants during field trips, and to take every precaution, reasonable in the circumstances, to ensure that field trips are run with due regard for the safety of leaders and participants. GAC recommends steel-toed safety boots when working around road cuts, cliffs, or other locations where there is a potential hazard from falling objects. GAC will not supply safety boots to participants. Some field trip stops require sturdy hiking boots for safety. Field trip leaders are responsible for identifying any such stops, making participants aware well in advance that such footwear is required for the stop, and ensuring that participants do not go into areas for which their footwear is inadequate for safety. Field trip leaders should notify participants if some stops will require waterproof footwear.

The weather in Newfoundland in May is unpredictable, and participants should be prepared for a wide range of temperatures and conditions. Always take suitable clothing. A rain suit, sweater, and sturdy footwear are essential at almost any time of the year. Gloves and a warm hat could prove invaluable if it is cold and wet, and a sunhat and sunscreen might be just as essential. It is not impossible for all such clothing items to be needed on the same day.

Above all, field trip participants are responsible for acting in a manner that is safe for themselves and their co-participants. This responsibility includes using personal protective equipment (PPE) when necessary (when recommended by the field trip leader or upon personal identification of a hazard requiring PPE use). It also includes informing the field trip leaders of any matters of which they have knowledge that may affect their health and safety or that of co-participants. Field Trip participants should pay close attention to instructions from the trip leaders and GAC representatives at all field trip stops. Specific dangers and precautions will be reiterated at individual localities.

Specific Hazards

Some of the stops on this field trip are in coastal localities. Access to the coastal sections may require short hikes, in some cases over rough, stony or wet terrain. Participants should be in good physical condition and accustomed to exercise. The coastal sections contain saltwater pools, seaweed, mud and other wet areas; in some cases it may be necessary to cross brooks or rivers. There is a strong possibility that participants will get their feet wet, and we recommend waterproof footwear. We also recommend footwear that provides sturdy ankle support, as localities may also involve traversing across beach boulders or uneven rock surfaces. On some of the coastal sections that have boulders or weed-covered sections, participants may find a hiking stick a useful aid in walking safely.

Coastal localities present some specific hazards, and participants MUST behave appropriately for the safety of all. High sea cliffs are extremely dangerous, and falls at such localities would almost certainly be fatal. Participants must stay clear of the cliff edges at all times, stay with the field trip group, and follow instructions from leaders. Coastal sections elsewhere may lie below cliff faces, and participants must be aware of the constant danger from falling debris. Please stay away from any overhanging cliffs or steep faces, and do not hammer any locations immediately beneath the cliffs. In all coastal localities, participants must keep a safe distance from the ocean, and be aware of the magnitude and reach of ocean waves. Participants should be aware that unusually large "freak" waves present a very real hazard in some areas. If you are swept off the rocks into the ocean, your chances of survival are negligible. If possible, stay on dry sections of outcrops that lack any seaweed or algal deposits, and stay well back from the open water. Remember that wave-washed surfaces may be slippery and treacherous, and avoid any area where there is even a slight possibility of falling into the water. If it is necessary to ascend from the shoreline, avoid unconsolidated material, and be aware that other participants may be below you. Take care descending to the shoreline from above.

Other field trip stops are located on or adjacent to roads. At these stops, participants should make sure that they stay off the roads, and pay careful attention to traffic, which may be distracted by the field trip group. Participants should be extremely cautious in crossing roads, and ensure that they are visible to any drivers. Roadcut outcrops present hazards from loose material, and they should be treated with the same caution as coastal cliffs; be extremely careful and avoid hammering beneath any overhanging surfaces.

The hammering of rock outcrops, which is in most cases completely unnecessary, represents a significant "flying debris" hazard to the perpetrator and other participants. For this reason, we ask that outcrops not be assaulted in this way; if you have a genuine reason to collect a sample, inform the leaders, and then make sure that you do so safely and with concern for others. Many locations on trips contain outcrops that have unusual features, and these should be preserved for future visitors. Frankly, our preference is that you leave hammers at home or in the field trip vans.

Subsequent sections of this guidebook contain the stop descriptions and outcrop information for the field trip. In addition to the general precautions and hazards noted above, the introductions for specific localities make note of specific safety concerns such as traffic, water, cliffs or loose ground. Field trip participants must read these cautions carefully and take appropriate precautions for their own safety and the safety of others.

PART 1. OVERVIEW OF THE GEOLOGY OF WESTERN NEWFOUNDLAND

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 (Figures 1, 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 (Figure 3).

During the early Paleozoic Era, these rocks lay on the north or northwest 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 3). During these events, the margins of Iapetus were telescoped, with the result that contrasting sedimentary facies are now juxtaposed by faults, deformed by folds, and metamorphosed. Ophiolites, probably representing oceanic crust formed in arc-related settings, 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.

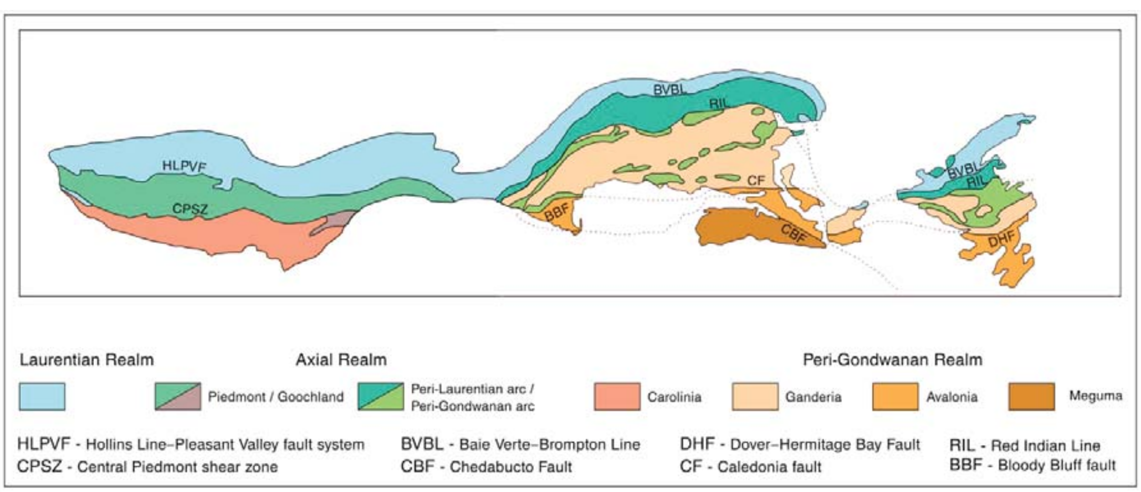


Figure 1. *Map of the Appalachian orogen, after Hibbard* et al. *(2006).*

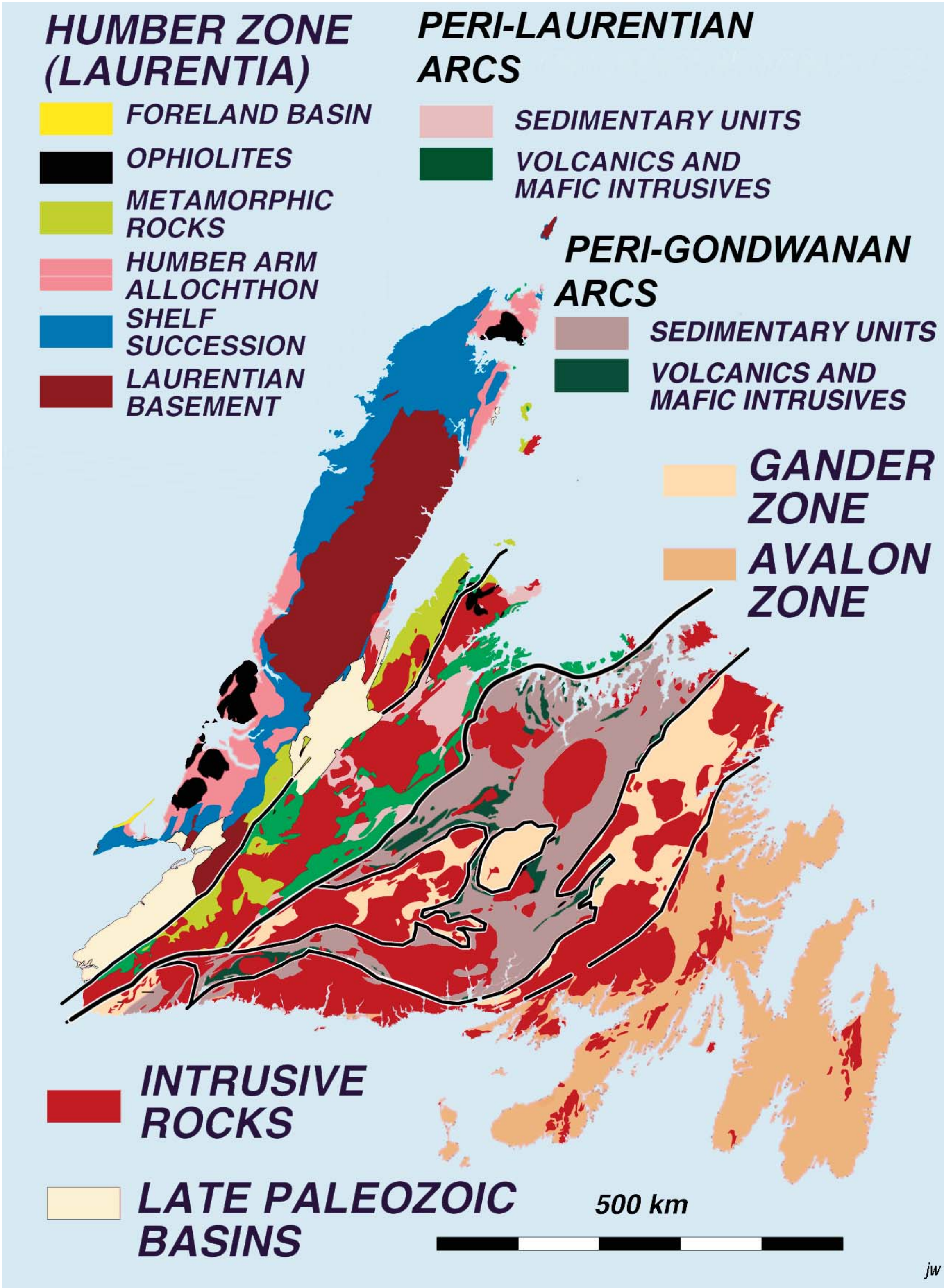


Figure 2. *Summary geological map of Newfoundland, showing main tectonic units.*

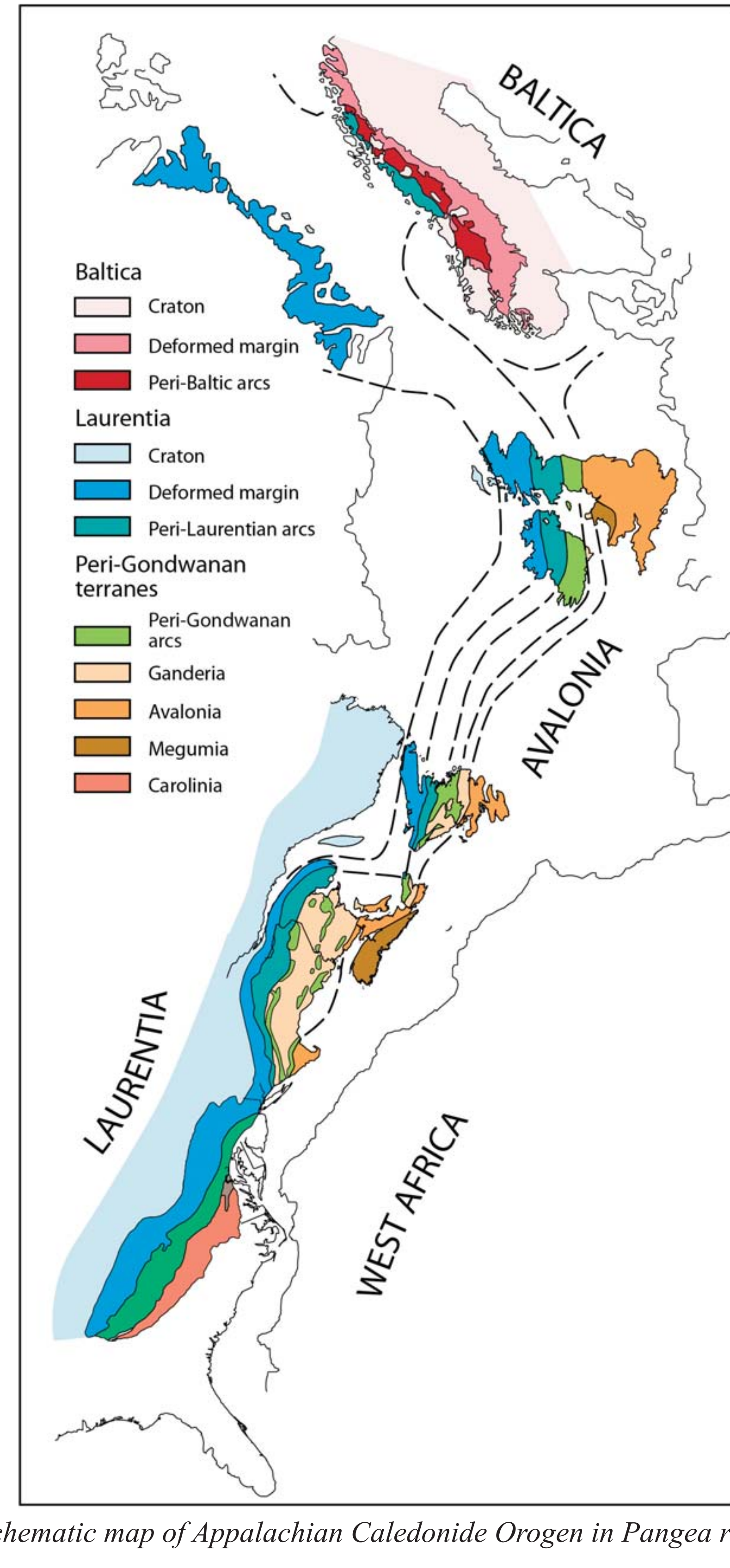


Figure 3. *Schematic map of Appalachian Caledonide Orogen in Pangea reconstruction.*

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**. Our focus will be the mainly sedimentary rocks of the external Humber Zone, within which several large-scale assemblages of rock can be recognized (Figure 2).

- **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** was deposited on this 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.
- **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**. These units, together with **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 **Humber Arm Allochthon**. Although they were undoubtedly formed well to the 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.
- **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.

Orogenic History

Western Newfoundland shows a complex structural history, which has analogues throughout the Humber Zone of the northern Appalachians. Taconian (Ordovician) thrusts and mélange belts have been overprinted by later deformation, typically attributed in older work to Acadian (Devonian) orogenesis (*e.g.*, Cousineau and Tremblay, 1993). Folding and thrusting beneath the Gulf of St. Lawrence and on the Port au Port Peninsula have been clearly shown to affect rocks as young as Early Devonian, demonstrating an Acadian component to the deformation (Cawood and Williams, 1988; Stockmal and Waldron, 1990; Waldron and Stockmal, 1991). However, elsewhere for onshore Newfoundland, there is little sedimentary record of the interval from Middle Ordovician to Early Carboniferous. Hence, the history of deformation following the Taconian Orogeny is poorly known in the weakly metamorphosed, western ("external") portion of the Humber Zone. Offshore evidence from the foreland basin suggests significant Late Ordovician loading of the Laurentian margin (Waldron *et al.*, 1998). Farther east, in metamorphic rocks of the "internal" Humber Zone, Cawood *et al.* (1994) use isotopic evidence to demonstrate an important episode of Salinian (Silurian) deformation.

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) and in the adjacent rocks of shallow marine facies (Knight and Boyce, 1991; Knight, 1994a, b, 1995, 1996a; Cawood and van Gool, 1998) that neither the allochthon nor the platform rocks are tabular in their present-day configuration, and that the contact between them is both faulted and folded, locally tightly. This later folding is responsible, for example, for the current distribution of Humber Arm Allochthon to the west of the shelf succession (Figure 2), despite clear evidence that the deep-water environments originally lay to the east.

Following the discovery of oil beneath Port au Port Peninsula (Cooper *et al.*, 2001), interest has focused on the sedimentary units of the Humber Arm Allochthon as potential source rocks for petroleum. In addition, Lithoprobe seismic profiles (Quinlan *et al.*, 1992) show reflectors beneath the allochthon that may represent inverted basins in structurally underlying platform rocks (Waldron *et al.*, 1998), encouraging interest in possible deeply buried petroleum reservoirs.

STRATIGRAPHY

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 (Figures 4a, 4b, 5). They are exposed in restricted areas of western Newfoundland, of which by far the largest is the Long Range Inlier of the Northern Peninsula (Figures 2, 6, 7). 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. 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 5). The basalts are associated with thick terrestrial clastic units assigned to the Bradore Formation of the Labrador Group (Figures 4a, 4b). On

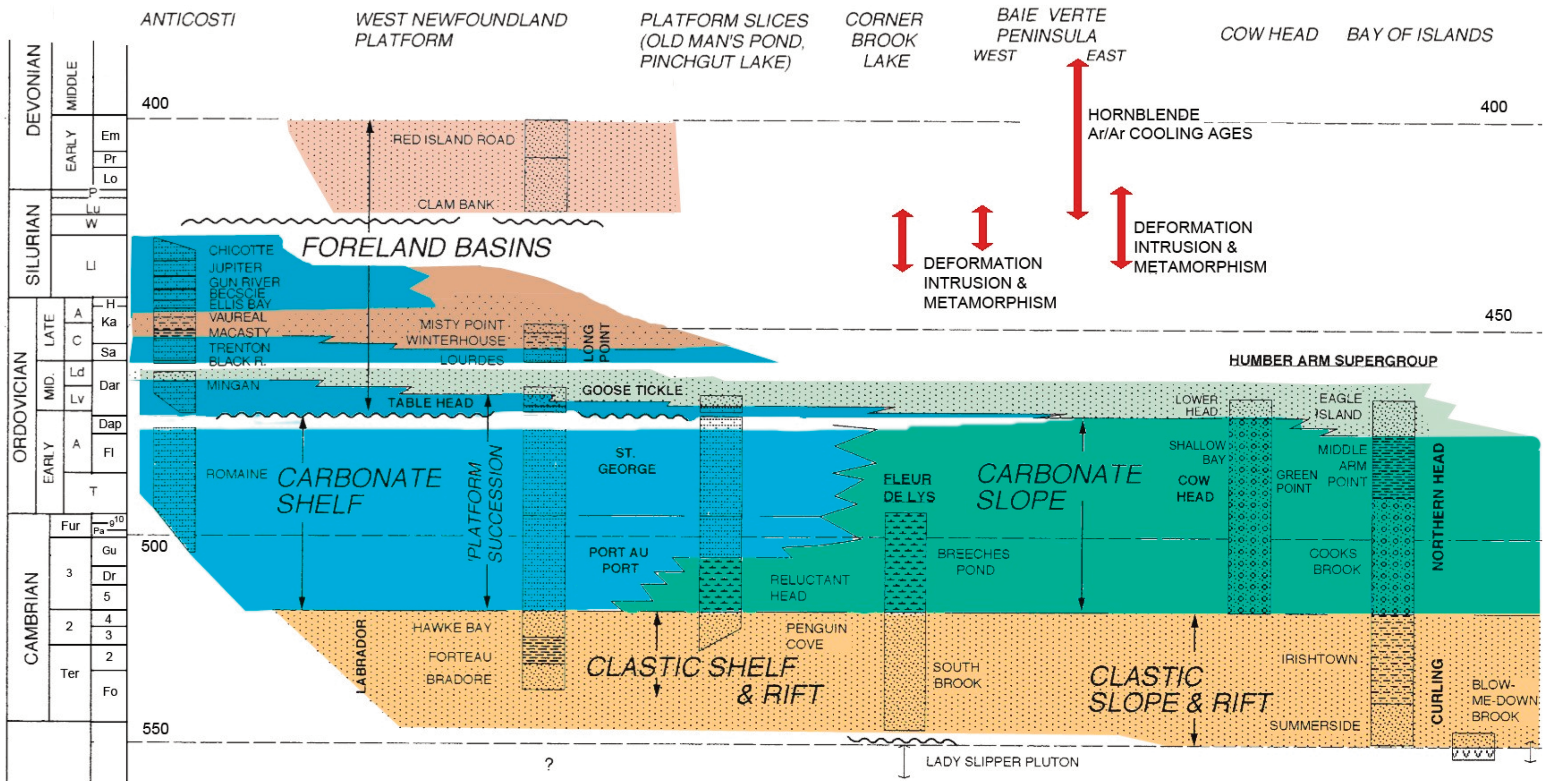


Figure 4a. *Diagram showing principal stratigraphic units of the Laurentian margin, plotted with time on the vertical axis, in inferred original paleogeographic relationships, modified from Waldron* et al. *(1998).*

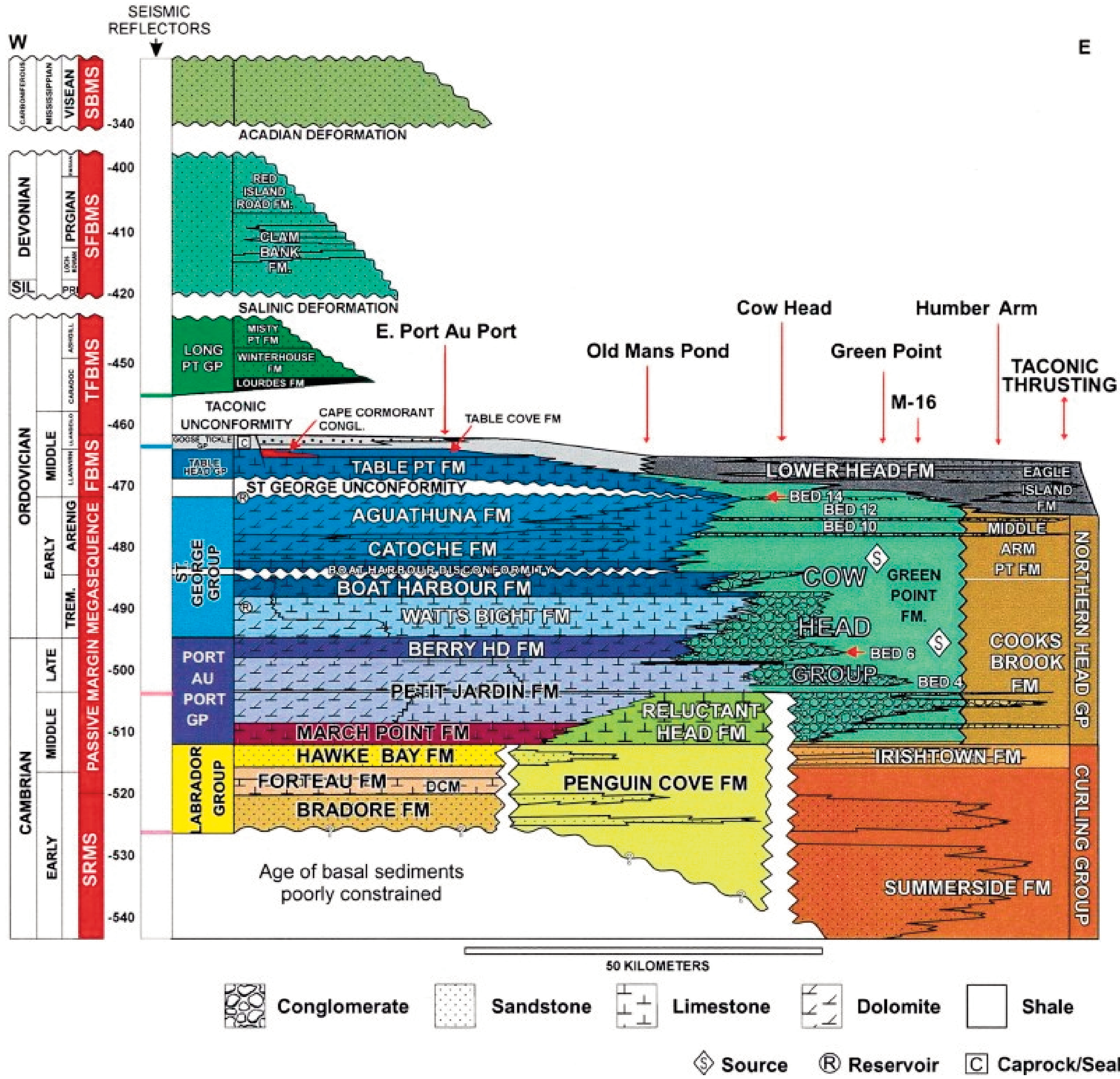


Figure 4b. *Stratigraphic Column for western Newfoundland (from Cooper* et al.*, 2001).*

adjacent horsts, these rift successions are much thinner or entirely absent. Eventually, Rodinia broke up into smaller continental masses, and ocean-floor spreading commenced in the newly formed Iapetus Ocean. Western Newfoundland lay on one margin of this ocean, on the edge of the newly formed continent Laurentia. 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).

The breakup of Rodinia placed Western Newfoundland on a passive continental margin. Following the start of ocean-floor spreading in the newly-formed Iapetus Ocean, the continental margin underwent slow thermal subsidence. The changeover from rifting to thermal

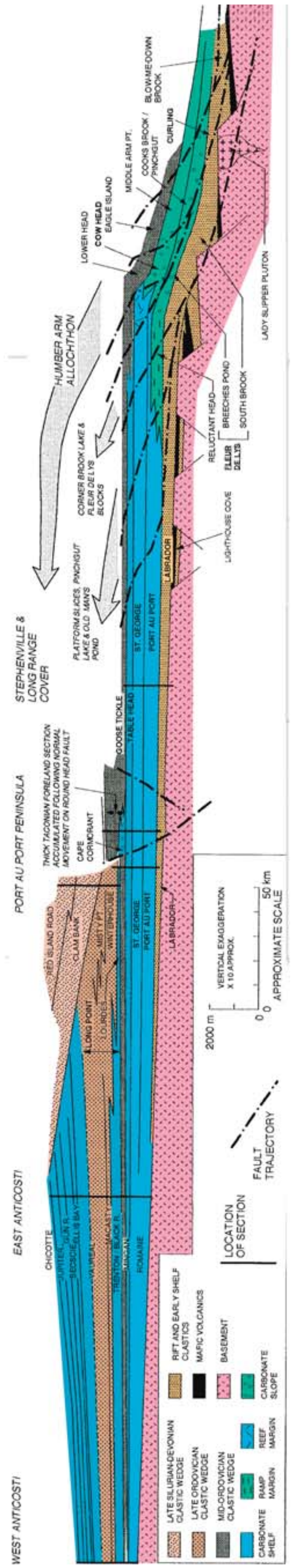


Figure 5. *Diagram showing principal stratigraphic units of the Laurentian margin, plotted with thickness on the vertical axis, using the top of the 'platform' succession (top of the Table Point Formation) as a datum, after Waldron* et al. *(1998).*

subsidence is marked by a breakup unconformity above which the sedimentary succession shows a much more 'layer-cake' style (Williams and Hiscott, 1987) (Figure 5). Above the unconformity the Forteau Formation (Figure 8) consists of shales and limestones deposited in shallow-marine shelf environments, while the quartz-rich sandstones of the Hawke Bay Formation formed in higher-energy shelf conditions (Figure 9). Both formations were deposited during the late Early Cambrian (~517–509 Ma in the timescale of Shergold and Cooper, 2004). 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 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) (Figures 10a, 10b, 11, 12). 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. Parts of this carbonate succession display excellent porosity, and they have a high potential as petroleum reservoir rocks. This succession of carbonate sedimentary rocks can be traced, in general terms, from Alabama in the present south-

Figure 6. *Precambrian rocks of the Long Range massif at Western Brook Pond form an impressive scarp. The rocks are migmatite, felsic and mafic gneiss, felsic and mafic intrusions, and mafic dykes related to Iapetus rifting.*

Figure 7. *Precambrian/Cambrian unconformity (~500 Myr time gap) along Route 430, Gros Morne National Park. Dark colored Bradore Fm. (left) overlies lighter colored Precambrian metamorphic rock (right).*

Figure 8. *Interbedded shale, siltstone and limestone of the Forteau Fm. (Labrador Group) along Route 430, Gros Morne National Park.*

Figure 9. *Moderate to well sorted, locally porous, Hawke Bay Fm. (Labrador Group) quartz arenites at Marches Point, Port au Port Peninsula.*

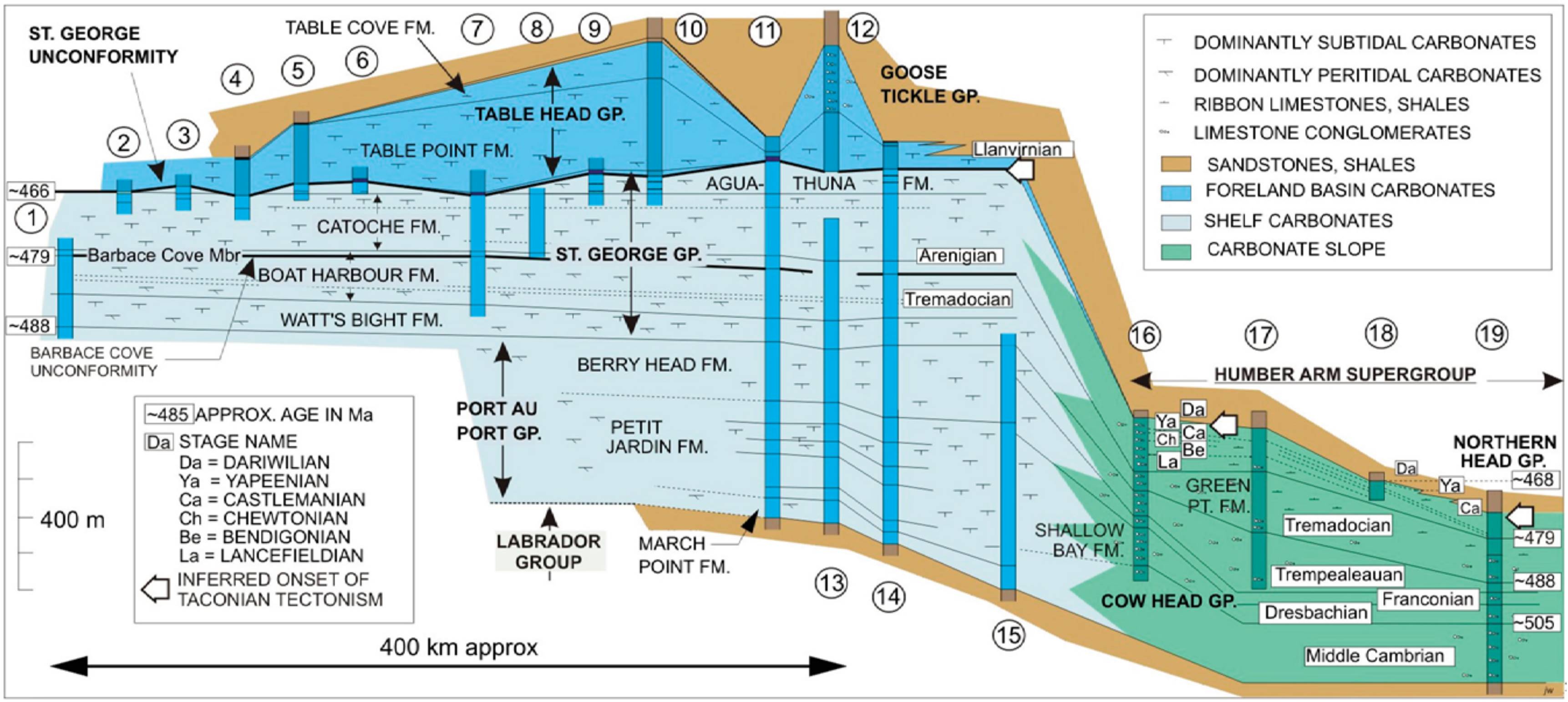


Figure 10a. *Stratigraphic columns for Middle Cambrian through Middle Ordovician strata of western Newfoundland, showing inferred correlation of shelf and slope units. Location map for numbered stratigraphic sections shown in Figure 10b. Data sources:* see *Waldron and van Staal (2001).*

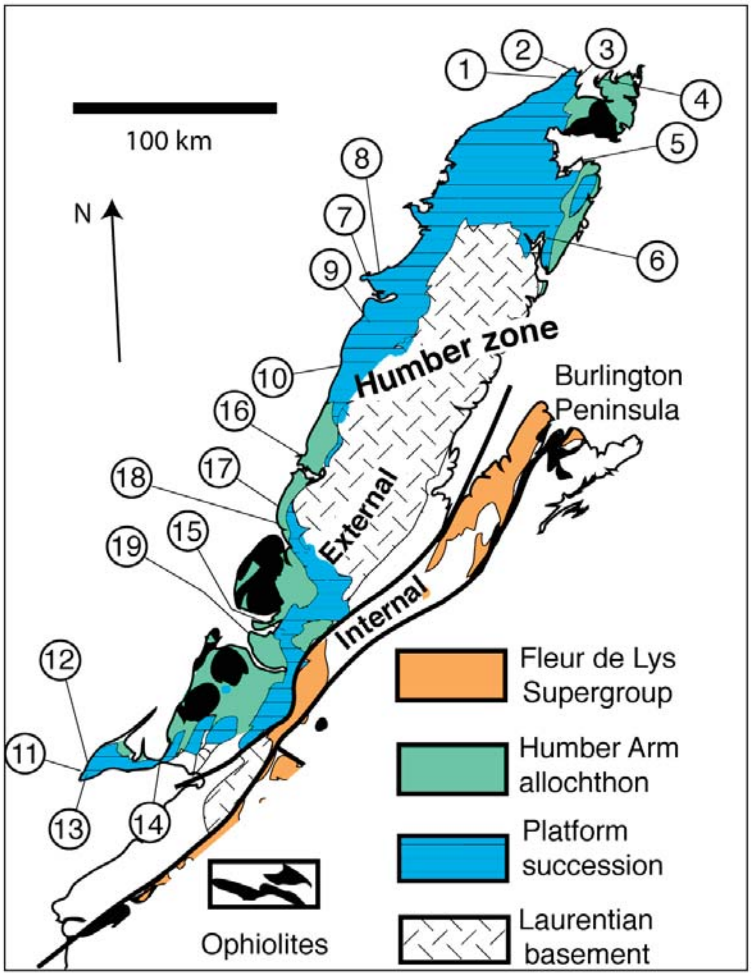


Figure 10b. *Summary geological map of western Newfoundland showing location of Humber Arm Allochthon and correlative units of Laurentian margin. Numbers show location of stratigraphic sections in Figure 10a.*

Figure 11. *Interbedded Port au Port Group limestone, dolostone and shale at Marches Point, Port au Port Peninsula.*

Figure 12. *Interbedded St. George Group limestone and dolostone at Table Point, near Bellburns, Northern Peninsula.*

west, through Atlantic Canada, into northwest Scotland and on into Greenland, areas which formed a continuous belt prior to the opening of the modern Atlantic (James *et al.*, 1989) (Figure 3).

Taconian Foreland Basin

Table Head Group

Eventually, the passive margin of Laurentia came into collision with an island arc–trench system that encroached from the southeast (present-day coordinates) (Figure 13). The first effect of this collision was the appearance, at the end of the Early Ordovician, of arc-derived material in the deep-water succession of the Humber Arm Supergroup. Slightly after this, the shelf succession underwent a subtle uplift, due to the passage of a 'peripheral bulge', before subsiding rapidly in a foreland basin formed as the arc advanced onto the continental margin (Jacobi, 1981, Knight *et al.*, 1991). The passage of the peripheral bulge resulted in an erosion surface – a disconformity known as the St. George Unconformity – at the top of the St. George Group (Figures 10a, 14).

The overlying Middle Ordovician foreland basin (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 from the highly productive tropical shallow sea was able to keep pace with subsidence (Figures 10a, 15). Because of the similarity of facies, these first foreland basin rocks are sometimes grouped with the underlying shelf carbonates as the "platform succession". Eventually, sediment production failed to keep pace with subsidence, and deeper water limestones and graptolitic shales of the Table Cove Formation (Table Head Group) were deposited (Figures 10a, 16). The transition from platform carbonates to more shaly lithologies corresponds to a major reflection, the top-of-platform reflection, in offshore seismic profiles.

It is clear that significant faulting accompanied the subsidence of the foreland basin. Initially, the faults were extensional, normal faults. One very large fault in the Port au Port area, the Round Head Fault (Figures 17, 18), exposed at least 500 m of platform stratigraphy in its scarp; carbonate conglomerates including huge boulders were deposited on the downthrown hanging wall, where they are assigned to the Cape Cormorant Formation (also Table Head Group) (Stenzel *et al.*, 1990, Waldron *et al.*, 1993) (Figure 19).

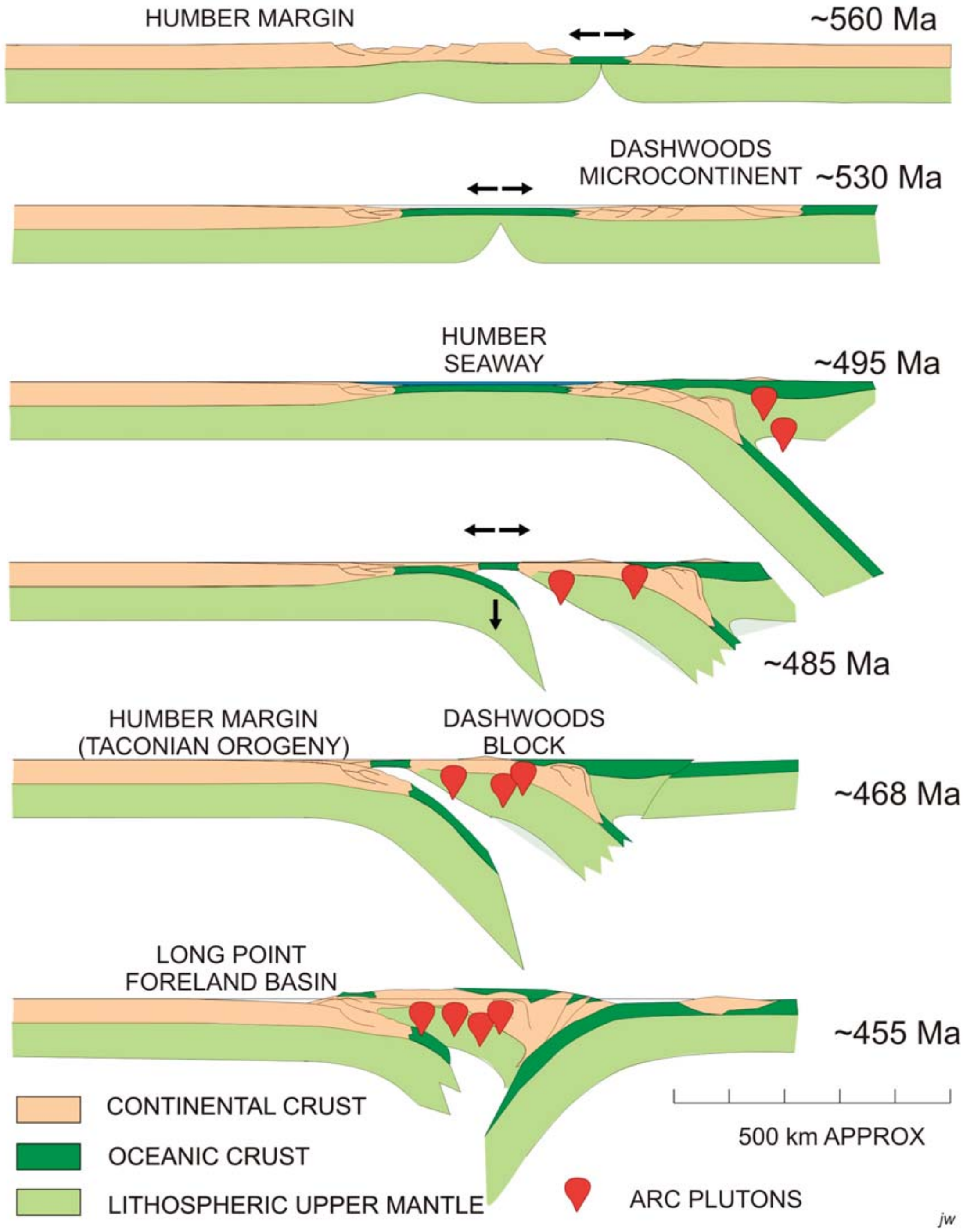


Figure 13. *Continental collision and subduction leading to the formation of the Humber Margin during the Taconian Orogeny.*

Figure 14. *St. George Unconformity exposed at Aguathuna Quarry; grey Table Head Group limestone (top), tan St. George Group dolostone (bottom).*

Figure 15. *Dark grey, thick bedded, massive limestone of the Table Point Formation (Table Head Group) at Aguathuna Quarry.*

Figure 16. *Thin bedded, deep water ribbon limestone and shale, Table Cove Formation (Table Head Group) at West Bay Beach, Port au Port Peninsula.*

Goose Tickle Group

Eventually, carbonate sedimentation gave way to clastic sediments. The overlying Goose Tickle Group comprises sandstones and shales derived from the advancing arc and from thrust sheets of continental margin origin that were by now being thrust onto the shelf edge (Figure 19).

Laurentian Slope and Rise: Humber Arm Supergroup

To the south of the Laurentian shelf (or, in present-day coordinates, to the southeast) a continental slope and rise developed. Sedimentary rocks deposited on this slope and rise are assigned to the Humber Arm Supergroup. Our knowledge of the slope and rise successions is a little more fragmentary than the shelf, because they have been more severely af-

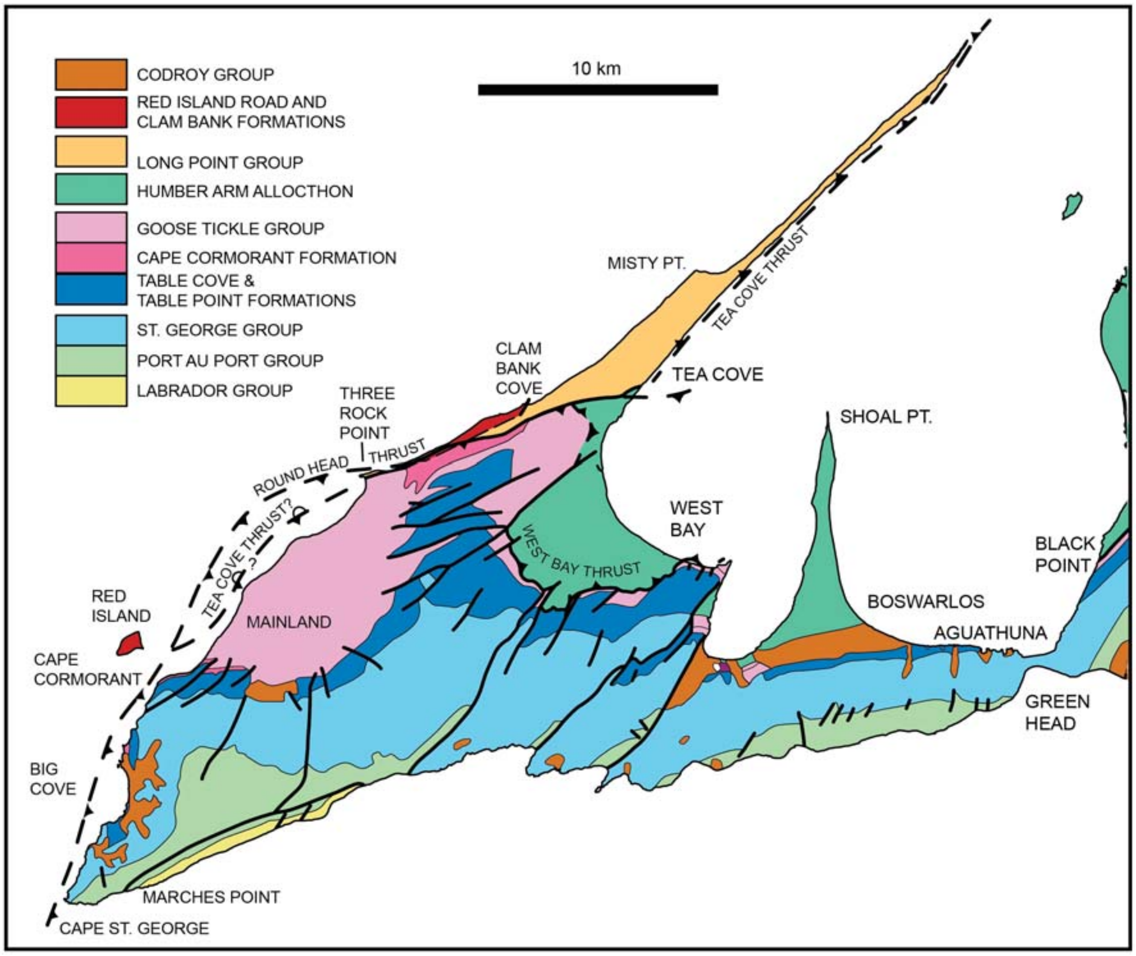


Figure 17. *Geological map of the Port au Port Peninsula based on Stockmal* et al.*, 1998 and Knight* et al.*, 2007.*

fected by later collisions. The preserved fragments are now tectonically emplaced above the shelf succession. Nonetheless the basic elements of the stratigraphy can be pieced together (Figure 20).

Platform Edge: Watsons Brook Succession

Distinctive platform-margin stratigraphic units were identified to the south of Corner Brook by Williams and Cawood (1986). Carbonate units were assigned by them to the Pinchgut group; adjacent clastic rocks were designated the Whale Back formation. Cawood and Van Gool (1998) reduced the unit to formation status, defining a Pinchgut Formation including both the clastic rocks and the carbonates. The carbonates were mapped in greater detail as the Pinchgut Lake Group by Knight (Knight, 1995, 1996a, b), who interpreted them as a separate thrust sheet. Waldron *et al.* (2003) recognized apparent stratigraphic con-

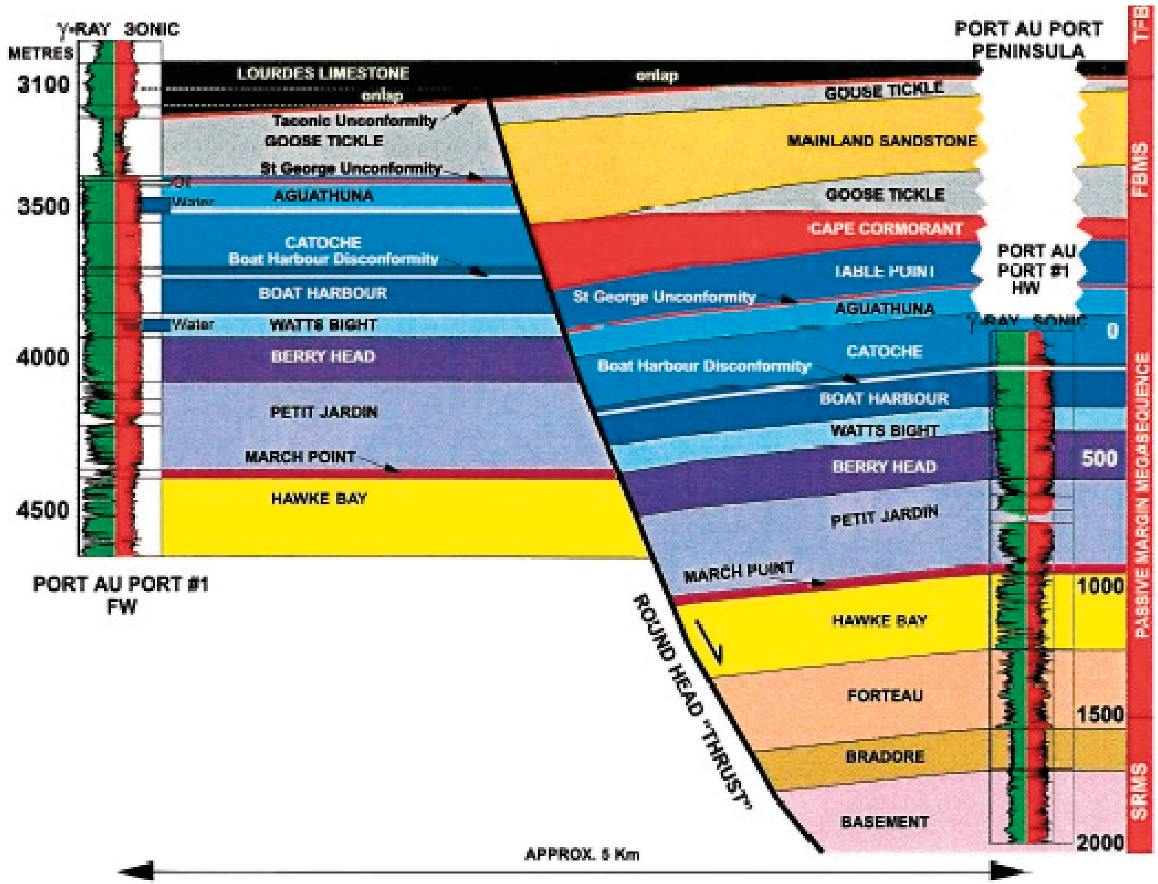


Figure 18. *Extensional Round Head Fault before inversion, Port au Port area. Note approximate 500 m of displacement between the footwall and hanging wall blocks (from Cooper* et al.*, 2001).*

Figure 19. *Interbedded sandstone and shale of the Mainland Formation (Goose Tickle Group) overlying limestone conglomerate and shale of the Cape Cormorant Formation (Table Head Group).*

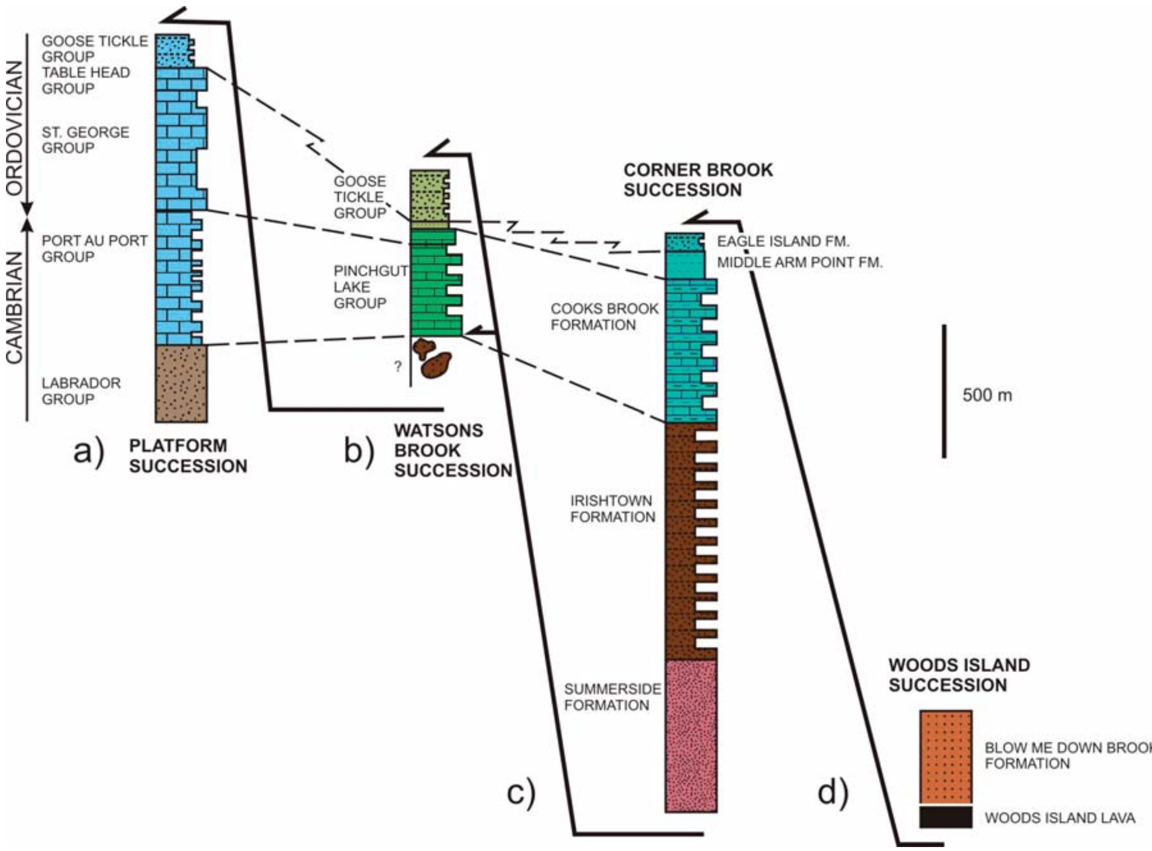


Figure 20. *Stratigraphic columns representative of the four successions described in the Bay of Islands area, including platform and Humber Arm Allochthon.*

tinuity from carbonate rocks, upward through bioturbated slates, into grey-green cleaved sandstones and slates identical to the Goose Tickle Group at the top of the platform (Figure 20, column b). We follow Knight in retaining the term Pinchgut Lake group for the carbonate succession, together with interbedded and overlying slates, and map the overlying coarser clastic units as the Whale Back formation of the Goose Tickle Group.

The Pinchgut Lake group and its cover appear to represent environments transitional between platform and slope. The carbonates were correlated generally with the upper Port au Port Group and Lower St. George Group by Knight (Knight, 1996b) and inferred to represent platform-margin environments. The overlying bioturbated slates resemble in facies the Middle Arm Point formation of the Corner Brook succession (*see* below). These possibly represent an interval of "starved" slope or "drowned" platform environments, at the edge of the former shelf.

At one locality close to the inferred tectonic basal surface of the Pinchgut Lake group, we observed blocks in mélange of interlaminated argillite and white quartzose sandstone, with ripple cross-laminations. These blocks contrast with other clastic rocks in the area in lacking distinctly graded sandstone turbidite beds; finer and coarser sands and silts are gradationally interlaminated, suggesting shelf rather than slope environments. We infer that these blocks may represent the unit originally underlying the Pinchgut Lake group, the inferred equivalent of the Labrador Group in the platform succession (Figure 20, column b).

Proximal Slope and Rise: Cow Head Succession

Farther north, in Gros Morne Park and at Cow Head, a slightly different slope succession is preserved as the Cow Head Group (James and Stevens, 1986) (Figure 21). In this area, the basal clastic succession (Curling Group equivalents) are absent; presumably they were 'left behind' when the Cow Head Group was thrust over the shelf, as the succession is everywhere terminated at its base by a thrust fault (Figure 5). The sediments of the Cow Head Group are similar in character to those of the Northern Head Group but are consistently coarser grained, representing either a more proximal part of the slope to the continental margin, or a portion of the margin that received coarser-grained debris because of sedimentary processes. The Group is divided into two formations: the most proximal, coarsest boulder conglomerates and interbedded sediments constitute the Shallow Bay Formation. Somewhat more distal successions (more closely resembling the Curling Group) are assigned to the Green Point Formation (Figures 21, 22, 23).

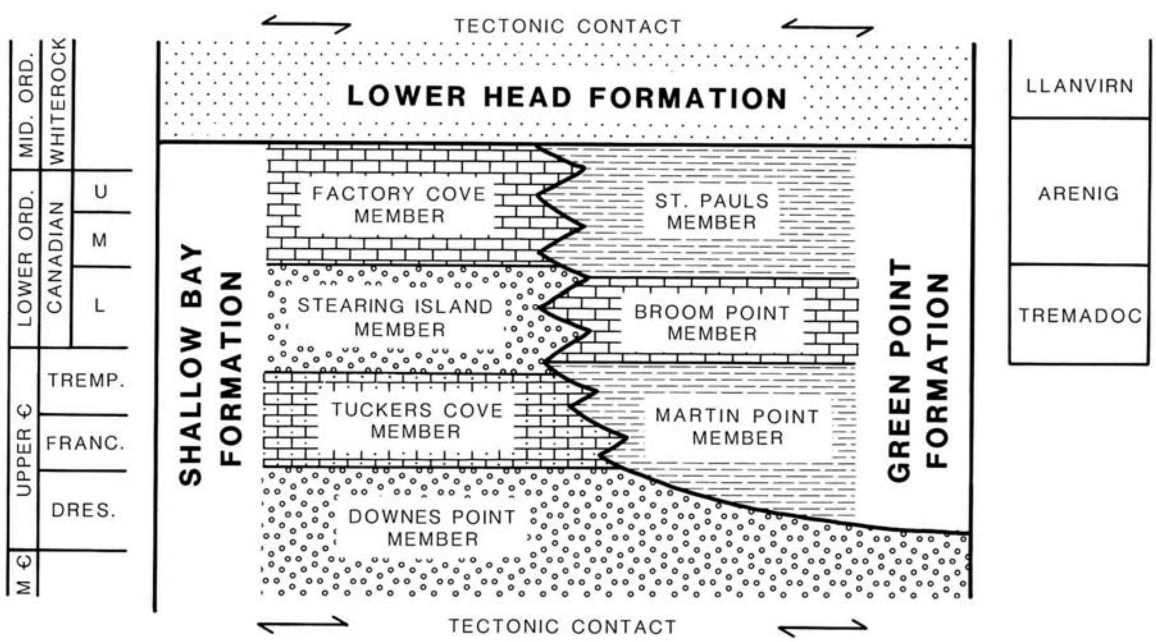


Figure 21. *Simplified diagram of the different stratigraphic units which comprise the Cow Head Group (after James and Stevens, 1986).*

Figure 22. *Limestone conglomerate/breccia, parted /ribbon limestone and shale, Shallow Bay Formation (proximal) (Cow Head Group) at Cow Head.*

Figure 23. *Shale, parted/ribbon limestone and minor limestone breccia, Green Point Formation (distal), (Cow Head Group) at Green Point.*

The Humber Arm Supergroup of the Port au Port Peninsula has been less thoroughly mapped and measured than the equivalent units in the Bay of Islands. Generally, the sedimentary rocks have been classified using the Cow Head stratigraphy, and assigned to the Green Point Formation. However, in some places they more closely resemble the strata of the Bay of Islands, and might just as easily be assigned to the Cooks Brook and Middle Arm Point Formations of the Northern Head Group.

Distal Slope and Rise: Corner Brook Succession

The most complete slope and rise successions are found in the Bay of Islands. Mapping on the shores of Humber Arm has confirmed major elements of the deep-water stratigraphy (Figure 20, columns c and d) identified and outlined by Stevens (Stevens, 1965, 1970) and Bruckner (1966) comprising the Summerside, Irishtown, Cooks Brook, and Middle Arm Point formations named by Bruckner (1966), together with the overlying Eagle Island formation clastics named by Botsford (1988; Boyce *et al.*, 1992).

The **Summerside Formation** consists of maroon and green slate interbedded with subordinate pale quartzose to arkosic metamorphosed sandstone. The Summerside Formation is probably of Early Cambrian age, based on the presence of Early Cambrian fossils in the overlying Irishtown Formation, and the occurrence of abundant bioturbation structures in the fine-grained rocks. The overlying **Irishtown Formation** consists of interbedded quartzose turbiditic sandstone, conglomerate, and grey to black, locally pyrite-bearing slate. Rare clasts in some of the conglomerates have yielded Early Cambrian trilobites. The Summerside and Irishtown Formations together constitute the **Curling Group**, and 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 (Figure 24).

The **Cooks Brook Formation** consists of grey slate and shale, slope limestone, and limestone conglomerate (Figure 25), representing Middle Cambrian to Early Ordovician continental slope environments located offshore of the Laurentian shelf, on which contemporary carbonates of the Port au Port and St. George Group were deposited. The overlying **Middle Arm Point Formation** consists mainly of grey-green slate and mudstone, bedded chert, and fine-grained dolostone (Figure 26). It is of Early Ordovician age and represents a sediment-starved offshore equivalent of the St. George Group in the shelf succession. The reason for the lack of coarse carbonate debris is unknown; most likely, a change in the character of the shelf margin cut off the supply of coarse material to parts of the slope. The Cooks Brook and Middle Arm Point Formations together constitute the **Northern Head Group**. They are approximately equivalent to the Green Point Formation of the Cow Head Group, and represent a significant potential petroleum source.

The **Eagle Island Formation** consists of turbiditic sandstone, shale and slate of Early Ordovician age, derived from thrust sheets that advanced on the Laurentian margin at the start of the Taconian Orogeny. Although previously included in the Northern Head Group, logically it seems more appropriate to include all the Early Ordovician syn-tectonic "flysch" units in the Goose Tickle Group, regardless of their tectonic position, as recommended by Waldron *et al.* (2003).

Allochthonous Sandstone Basin: Woods Island Succession

Large areas of massive, somewhat arkosic sandstone (Figure 27) occur in the western part of Woods Island, on Governor's Island, in the Blow Me Down Brook area, and elsewhere in a broad area extending from Bonne Bay in the north to Two Guts Pond, south of Fox Island river in the south. These were named the Blow Me Down Brook Formation by Bruckner (1966). The Woods Island succession comprises the Blow Me Down Brook Formation together with underlying or intercalated mafic lava units. Locally, the upper part of the Blow Me Down Brook Formation contains the Early Cambrian trace fossil *Oldhamia* (Figure 28).

Note, however, that the term "Blow Me Down Brook" was applied inconsistently in older literature. Lindholm and Casey (1989) determined that Bruckner had confused two

Figure 24. *Interbedded shale, sandstone and conglomerate of the Irishtown Formation, Curling Group along Route 440, Bay of Islands.*

Figure 25. *Limestone conglomerate, Cooks Brook Formation, Northern Head Group exposed on Route 440, Bay of Islands.*

Figure 26. *Grey green mudstones of the Middle Arm Point Formation, Northern Head Group, north of Middle Arm, Bay of Islands.*

Figure 27. *Poorly sorted, grey-green sandstone of the Blow Me Down Brook Formation, Curling Group on Route 450, Bay of Islands.*

Figure 28. *Photograph of the trace fossil* Oldhamia antiqua*.*

distinct units in the original descriptions of the Formation: one with the Early Cambrian trace fossil *Oldhamia*, and another with Early Ordovician graptolites. The type area at Blow Me Down Brook was within the older of these two units, which therefore retained the name. The younger unit became the Eagle Island Formation of the Corner Brook succession.

Post-Taconian Foreland Basin Successions

Long Point Group

The Taconian collision was probably followed by a reversal in the polarity of subduction (Figure 13), with the result that western Newfoundland now lay on an active continental margin (one coinciding with a plate boundary). 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 early Silurian Salinian Orogeny.

Following the Taconian collisional events, 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) (Figures 17, 29). It is also a prominent reflector in offshore seismic profiles. Carbonate sedimentation was short-lived, however, and younger units of the Late Ordovician Long Point Group (Winterhouse and Misty Point formations) are dominated by clastic sedimentary rocks deposited in a rapidly subsiding basin (Quinn *et al.*, 1999) (Figures 30, 31). The origin of this, second episode of foreland basin subsidence (Figure 4a) is rather poorly understood. Recent work suggests it may be related to thrust emplacement farther along the margin to the southwest, in the Appalachians of New England and Québec.

There is little record of deformation due to the Salinian Orogeny on 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 during this interval.

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 Bank Formation (Burden *et al.*, 2002) (Figure 32). Although this unit is identified

Figure 29. *Medium grey, highly fossiliferous limestone, Lourdes Formation, Long Point Group, at Long Ledge, Port au Port Peninsula.*

Figure 30. *Interbedded sandstone and shale, Winterhouse Formation, Long Point Group, at Clam Bank south, Port au Port Peninsula.*

Figure 31. *Vertical to overturned beds of the Misty Point Formation, Long Point Group, north side of Clam Bank Cove, Port au Port Peninsula.*

Figure 32. *Overturned beds of the Clam Bank Formation, south side of Clam Bank Cove, Port au Port Peninsula.*

over a vast area offshore, on land it is confined to a very narrow coastal strip of Port au Port Peninsula, 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 (Figures 33, 34). It consists largely of conglomerates with abundant rhyolite cobbles of unknown origin, 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 (Figures 4a, 4b).

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 southwest 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, demonstrating the largely post-tectonic nature of the Carboniferous sediments in this area (Figure 35). 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.

Figure 33. *Early Devonian Red Island Road Fm., Red Island, offshore western Port au Port Peninsula.*

Figure 34. *Red Island Road Formation conglomerate, Red Island, offshore western Port au Port Peninsula.*

STRUCTURE

Rifted Margin Structures

Structures representing the rifted margin of Iapetus have mostly been overprinted by later deformation and are difficult to find. The best mapped examples are in the far north of the Northern Peninsula where several mapped graben contain thick successions of Labrador Group clastic sedimentary rock (Bradore Formation) and mafic volcanic rock (Lighthouse Cove Formation) that are not present on adjacent horsts (Figure 5).

Figure 35. *Table Point Formation strata unconformably overlain by lighter coloured Carboniferous age rock, north side Port au Port Peninsula.*

On Port au Port Peninsula there is indirect evidence that the Round Head Fault (Figure 17), active in the Taconian and Acadian deformations, had an earlier rift-phase history. The Port au Port #1 (Garden Hill) well penetrated unexpectedly thick Labrador Group clastics in the hanging wall of the fault, indicating that it was controlling sedimentation as early as the early Cambrian.

Humber Arm Allochthon

Structurally, the Humber Arm Allochthon has had a complex history, and 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 (Figures 36a, 36b). 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 Eagle Island formation (*see* Botsford, 1988). Elsewhere in the Eagle Island formation, there are folded sandstone beds having strongly thickened hinges (*e.g.*, Waldron, 1985), indicating deformation while sand was liquefied (Waldron and Gagnon, 2011). However, Taconian deformation started very soon after deposition of the Eagle Island formation; 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

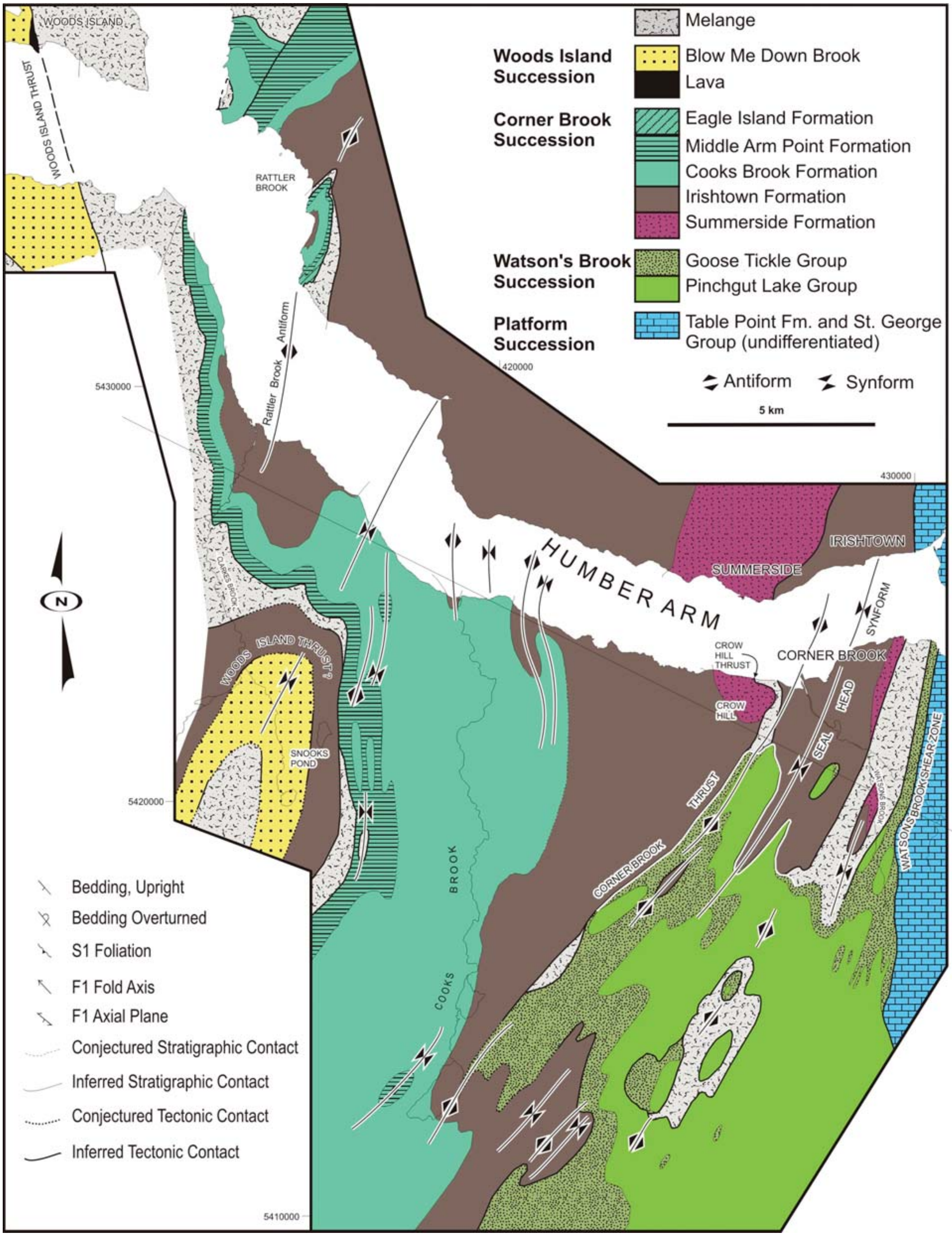


Figure 36a. *Geological map of the Humber Arm Allochthon and adjoining units in the Corner Brook and surrounding area, showing distribution of stratigraphic units, thrust sheets, and F_2 folds (after Waldron* et al.*, 2003).*

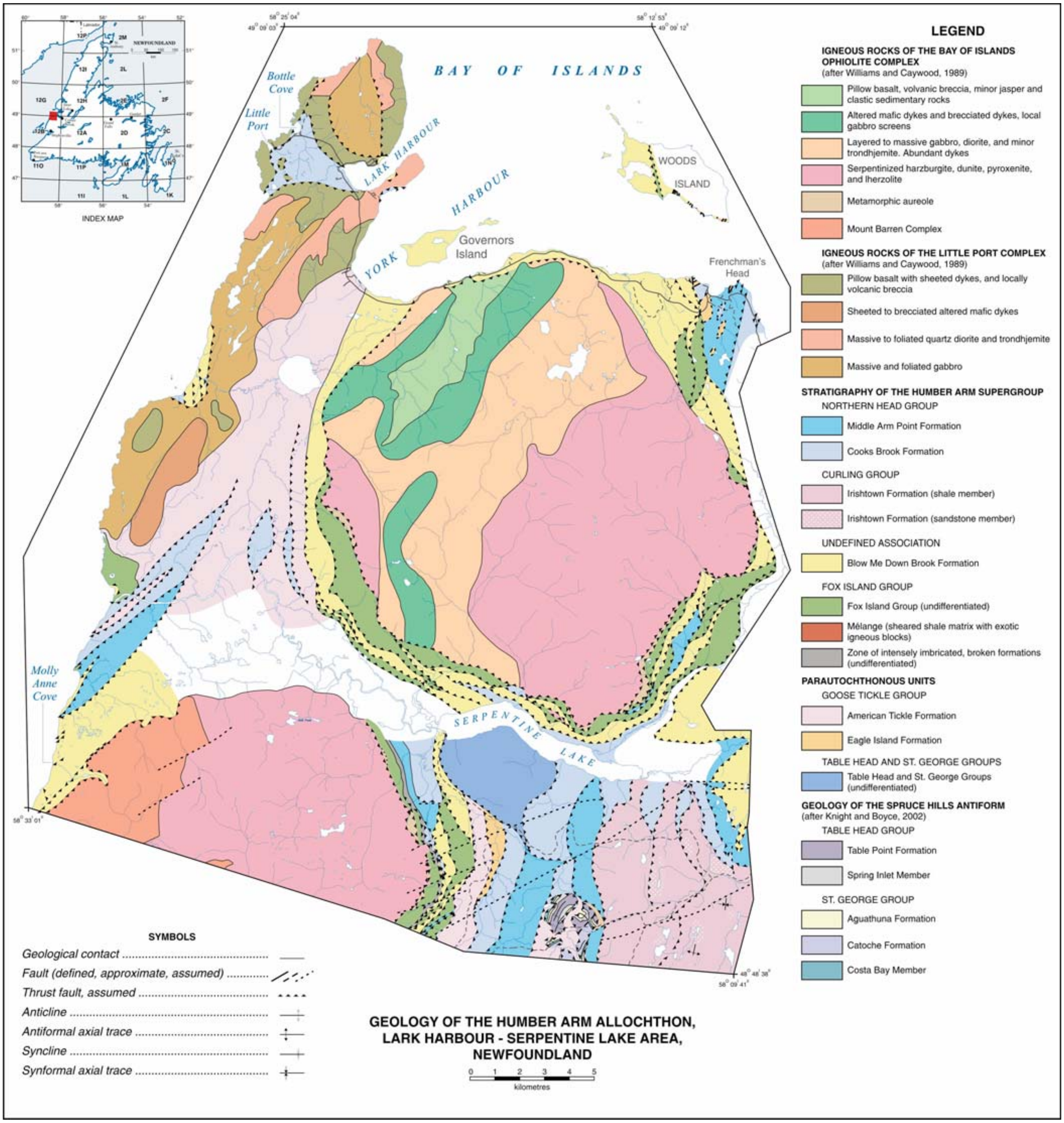


Figure 36b. *Geological map of the Humber Arm Allochthon, Lark Harbour–Serpentine Lake Area, Newfoundland (after Burden* et al.*, 2006).*

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" or "broken formation". They typically display scaly foliations that resemble those described in modern accretionary wedges (Waldron, 1985; Waldron *et al.*, 1988). Waldron *et al.* (2003) and Burden *et al.* (2005) restrict the term mélange to those outcrops where tectonic mixing at formation level can be demonstrated. Polylithic sedimentary rocks derived from one formation are not classified as mélange; areas where bedding is disrupted but the protolith is a single formation are described as broken formation. The structures responsible for these configurations are grouped as D_1.

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. 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 (Figure 37).

In the Summerside formation, early fabric development appears to be different. Bed-parallel foliation is widespread in mudrocks, but 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 (Figure 38).

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. In the Watsons Brook and Corner Brook Assemblages, F_1 folds are overprinted by F_2 folds, a feature also noted by Cawood and Van Gool (1998).

Figure 37. *Outcrop showing blocks in a scaly shale matrix, Black Point, northwest of Stephenville.*

Figure 38. *Pressure solution cleavage cutting bedding in Summerside Formation sandstone, Summerside area.*

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. In some cases the orientation of scaly fabric surrounding, and in some cases within, the blocks, appears axial planar to the folds. However, in other examples, the bed-parallel fissility appears folded. Elsewhere, in highly disrupted zones, the scaly fabric, together with trains of bed-fragments, is itself folded, indicating that folding post-dated boudinage and fragmentation.

Thrusts

Within the area of mapping, all the successions (with the possible exception of the Woods Island succession) are present in more than one structural unit. In general, the tectonic contacts between units are sub-parallel to stratigraphy; they are inferred to represent D_1 thrust faults that formed during the telescoping of the continental margin. Faults across which contrasting successions are juxtaposed are inferred to represent more major thrust surfaces. On this basis we recognize four major sheets, corresponding to the four stratigraphic successions outlined above (Figure 20). Within the sheets, smaller thrusts juxtapose parts of the same stratigraphic succession; we term the bounded units within sheets "slices". Figure 39 shows the inferred geometry of slices and sheets.

Farther north, in the Cow Head region, the Humber Arm Allochthon shows a contrasting structural style. In place of the disorganized mélanges and broken formation, the Cow Head region displays a series of regularly imbricated thrust sheets resembling those of typical

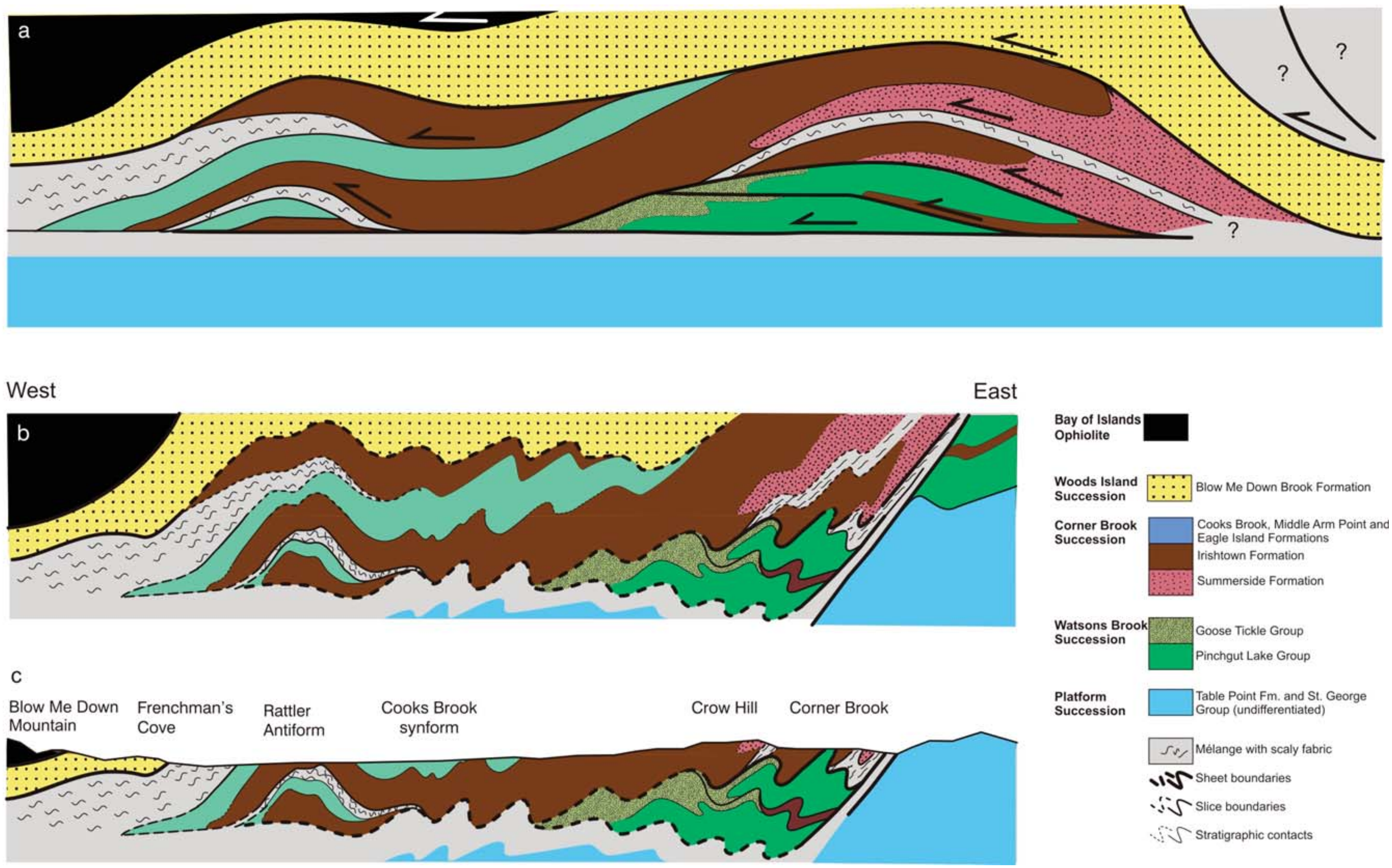


Figure 39. *Schematic cross section through the Corner Brook area illustrating inferred structural relationships. Top: inferred general geometry after Taconian thrust emplacement. Middle: inferred geometry after F_2 folding and D_3 shearing. Bottom: present day inferred geometry.*

foreland fold and thrust belts. Most of these sheets contain a carbonate-dominated Cow Head Group succession overlain by allochthon-derived sandstone of the Lower Head Formation. Because of the mafic detritus in the latter, it has significantly higher magnetic susceptibility than the underlying carbonate succession. The alternation of the two units in the imbricated stack of thrust slices creates a well defined pattern of magnetic anomalies, which can be used to map the thrust sheets in poorly exposed inland areas, such as that around Parson's Pond (Figures 40, 41).

There is little firm evidence for the timing of the imbricate thrusting in the Cow Head Group. However, the lack of intervening younger rocks suggests that initial stacking of the thrust slices occurred in the Ordovician, Taconian collisional event. Major thrusts that cut basement are interpreted, by analogy with the Port au Port Peninsula, as Acadian features, although again, there is no direct evidence of their age.

Early Thrusts in the Platform Succession

In western parts of the external Humber Zone, transitional into the internal zone, the shelf succession and overlying Table Head Group are duplicated in stacked thrust sheets. These have been mapped, for example, in the Pinchgut Lake area between Corner Brook and Stephenville by Knight (1995, 1996a, 1997) and Ferguson (1998). The age of this thrusting is not well known, but it is clearly overprinted by the regional S_2 cleavage, so it is inferred to be Ordovician.

Regional S_2 Cleavage and Associated Structures

S_2 Cleavage

The eastern part of the area mapped is affected by penetrative cleavages that strike consistently north-south to northeast-southwest; 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 western half of the area, S_2 is only sporadically developed, taking the form of a variably spaced crenulation of S_1. In the eastern part of the map area shown in Figure 36, S_2 cleavage is intense, locally phyllitic, and dips gently to moderately west.

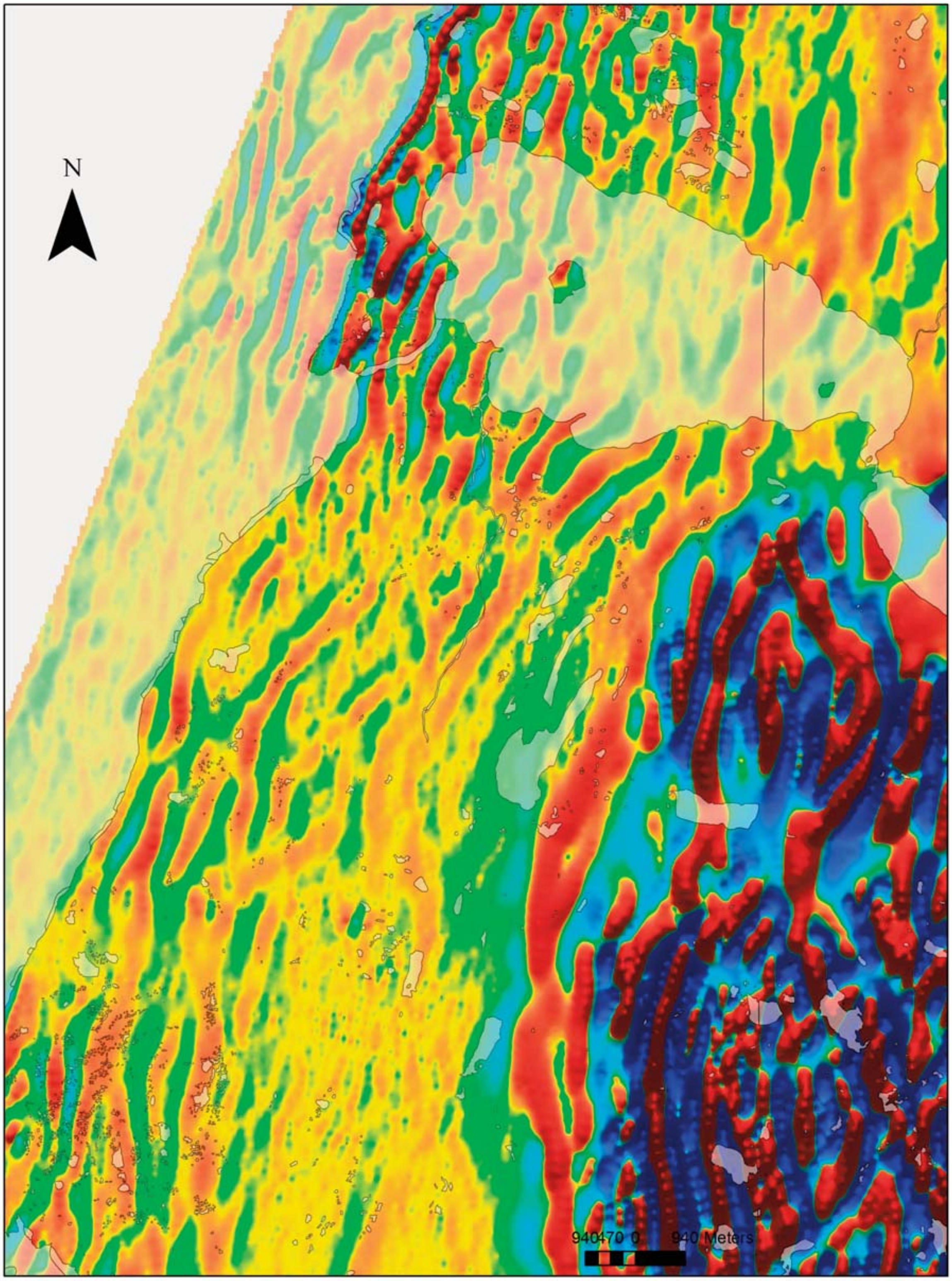


Figure 40. *First vertical derivative magnetic anomaly map of the area between Parson's Pond and Portland Creek.*

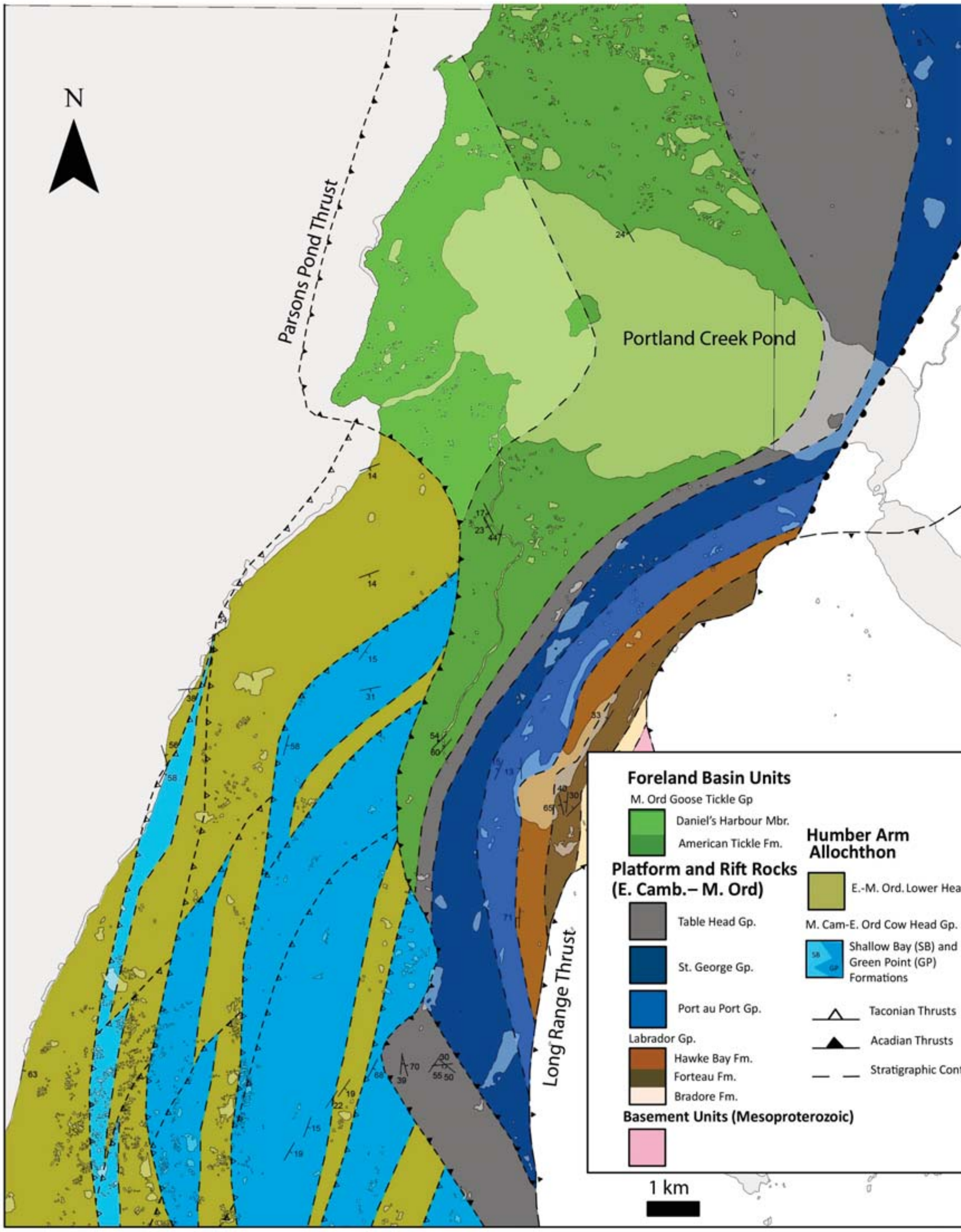


Figure 41. *Preliminary geological map showing relationships of thrust slices in the area between Parson's Pond and Portland Creek, based in part on interpretation of aeromagnetic data.*

F_2 Folds

F_2 folds are present at both outcrop and map scale. Folds at outcrop scale are typically open to tight, with axial surfaces striking north-south or north-northeast–south-southwest. 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 39).

At a number of localities we have seen folds in outcrop that have strongly curved hinges over distances of 50 cm to 5 m. In the Watson's Brook sheet, such folds show 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).

Shear Zones and Later Structures

Intensely sheared, mylonitic limestones were seen at a number of locations within the Pinchgut Lake group limestones of the Watsons Brook sheet and are especially evident close to its eastern edge. We infer that the boundary between the Platform and Watsons Brook sheet is marked by a broad west-dipping shear zone.

At outcrop scale, all the ductile indicators found in the Pinchgut Lake group display normal sense, top-to-the-west movement. In thin sections cut parallel to the lineation, kinematic indicators are found to show opposing senses of movement, sometimes in the same thin section. Structures showing brittle deformation are also abundant. The majority show thrust movement, but in one example normal sense slip was recorded. In some cases, brittle thrust planes follow and reactivate mylonitic normal-sense shear zones; thrust-sense brittle fracturing postdates ductile shearing. The repeated overprinting of brittle and ductile structures in these rocks indicates that they passed through the brittle-ductile transition several times. This was most likely due to variations in fluid pressure during deformation. The simplest history that can explain the array of structures involves an early episode of mainly ductile normal-sense shearing on west-dipping surfaces. Subsequently, thrust-sense shearing occurred in response to horizontal shortening. F_2 folds appear to be tightened and rotated into reclined orientations in the mylonitic zones. Based on relationships farther east the shear zones are tentatively interpreted as D_3 structures.

In the Corner Brook and Irishtown areas, two lineations L_4 and L_5 can be seen on S_2 surfaces. The second, steep, crenulation cleavage (S_5) strikes south-southwest, crenulating both S_2 and S_4 and distorting the L_4 crenulation lineations. It may reasonably be correlated with the episode of thrust sense motion late in the history of the shear zones described above.

Post-Taconian Appalachian Structures

Post-Taconian deformation has undoubtedly affected the Newfoundland Appalachians, but because of the general scarcity of post-Taconian, pre-Carboniferous rocks in most of western Newfoundland it is difficult to identify younger structures. The situation is different in Port au Port Peninsula, where two post-Taconian sedimentary successions are preserved. These are the Upper Ordovician Long Point Group and the (?Silurian) – Lower Devonian Clam Bank – Red Island Road succession. Both these units extend offshore into the foreland basin beneath the Gulf of St. Lawrence. Waldron *et al.* (2002) were able to use the magnetic signature of units in the Long Point Group to correlate the onshore succession with that imaged in offshore seismic profiles.

Both successions are deformed offshore above the west-dipping contact which separates them from underlying Humber Arm Allochthon, leading Stockmal and Waldron (1990) to propose that the Humber Arm Allochthon had been remobilized in an Acadian thrusting event, and that the basal contact of the Long Point Group, previously interpreted as an undeformed unconformity, is a thrust, named the Tea Cove Thrust (Waldron and Stockmal, 1991). Below the thrust, the Humber Arm Allochthon was remobilized westward in a tectonic wedge or triangle zone, above its basal contact, the West Bay Thrust. The two thrusts meet in the subsurface at the 'blind' tip of the tectonic wedge, which is imaged in numerous offshore seismic profiles (Figures 42, 43).

Farther south on Port au Port Peninsula, the thrust geometry becomes more complicated. A second, southeast dipping structure cuts through the Tea Cove Thrust, the Round Head Thrust, placing Ordovician carbonate rocks above the Lower Devonian clastic rocks (Figure 44). Both the hanging wall and footwall successions are steeply dipping to overturned in map-scale folds close to the Round Head Thrust (Figure 45). Exploration of the subsurface with seismic reflection has shown that another thrust, the St. George Thrust, is present below

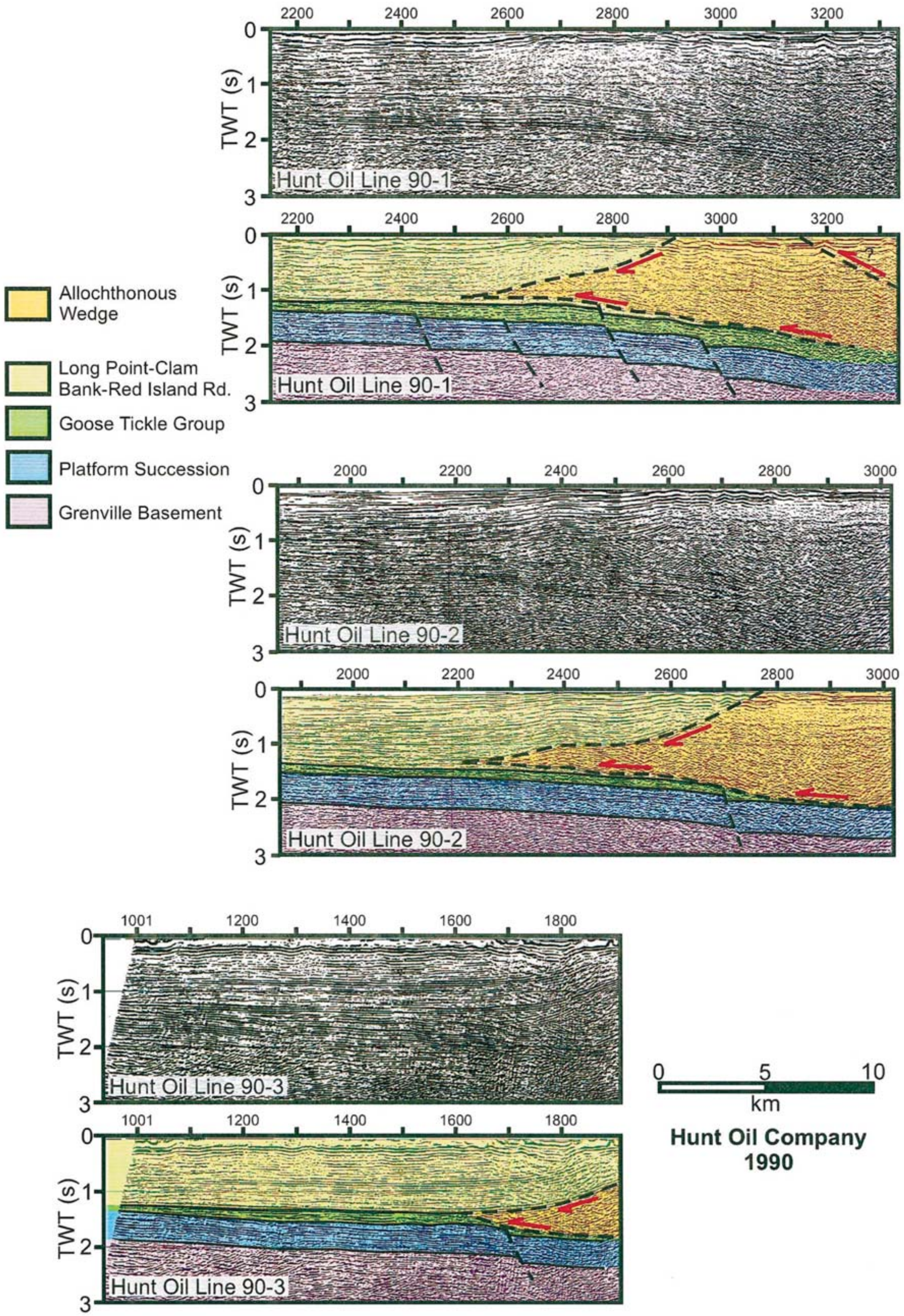


Figure 42. *Geometry of thrusts North of the Port au Port Peninsula (after Stockmal* et al. *1998).*

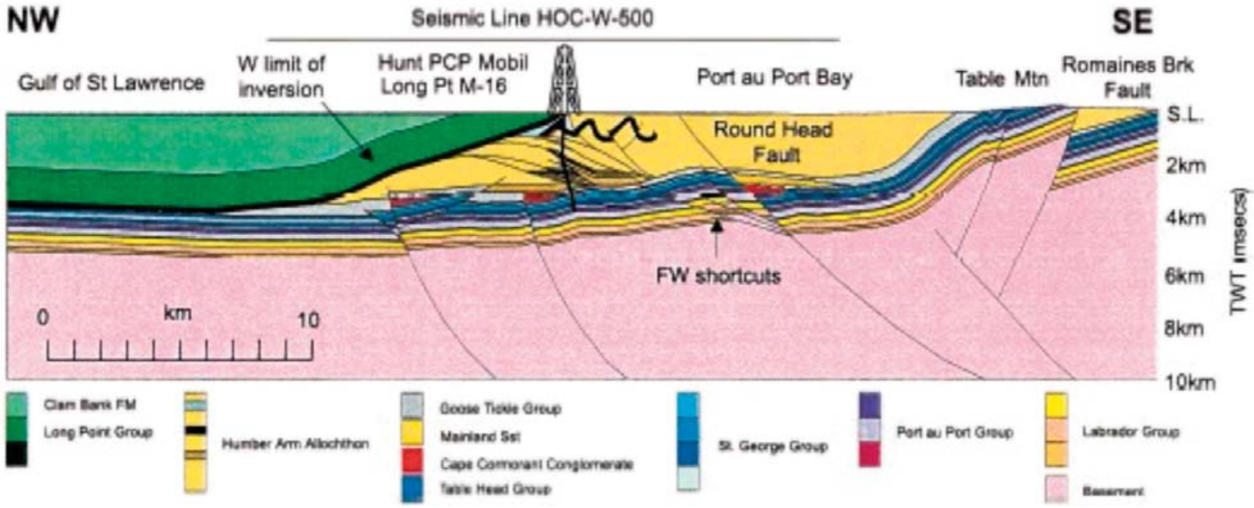


Figure 43. *Triangle zone as seen along Seismic Line HOC-W-500 (from Cooper* et al.*, 2001).*

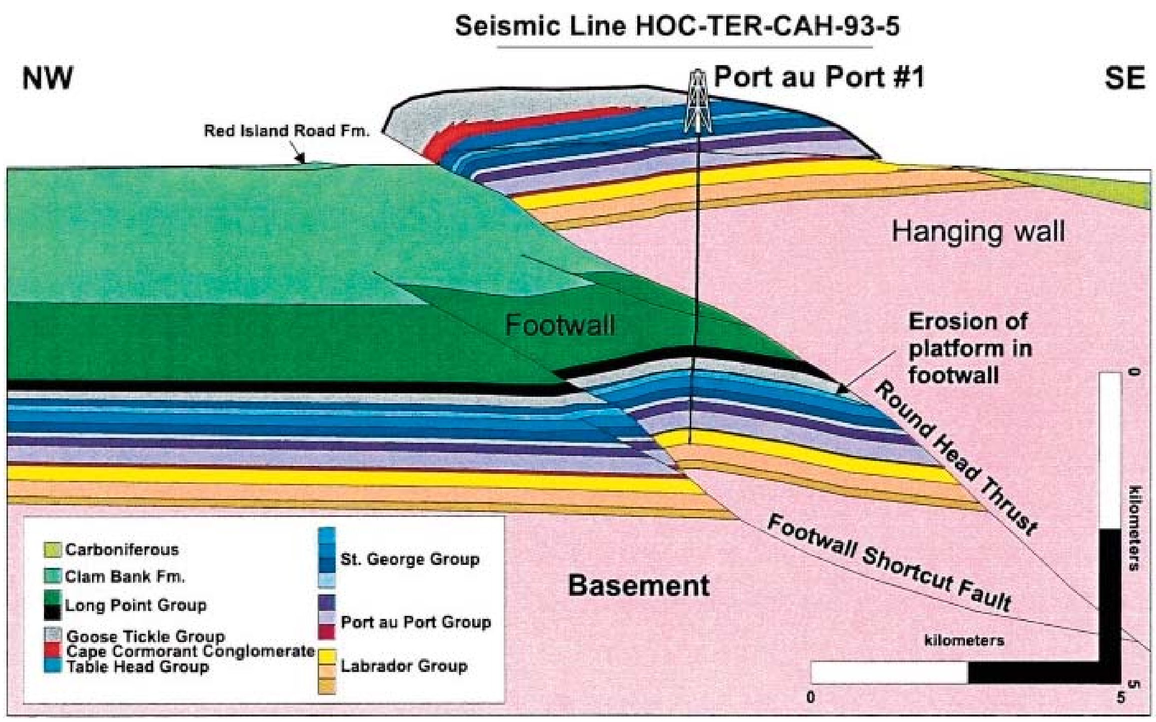


Figure 44. *Structural cross section through the Port au Port #1 well based on surface geology, seismic data, and dip and well formation data (from Cooper* et al.*, 2001).*

Figure 45. *Overturned, east to southeast dipping Lourdes Formation limestone (Long Point Group), Route 463, east of Clam Bank Cove.*

the Round Head Thrust, and that this third thrust also forms a tectonic wedge farther south (Figure 46). These structures involve potential reservoir rocks of the platform succession and therefore have been of great interest in attempts (so far unsuccessful) to extract economic quantities of petroleum from the Port au Port #1 (Garden Hill) oil well.

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 (Figure 47). It is possible that thrust movement occurred during the Tournaisian Epoch (earliest Mississippian) but thrust motion on a fault with east-north-

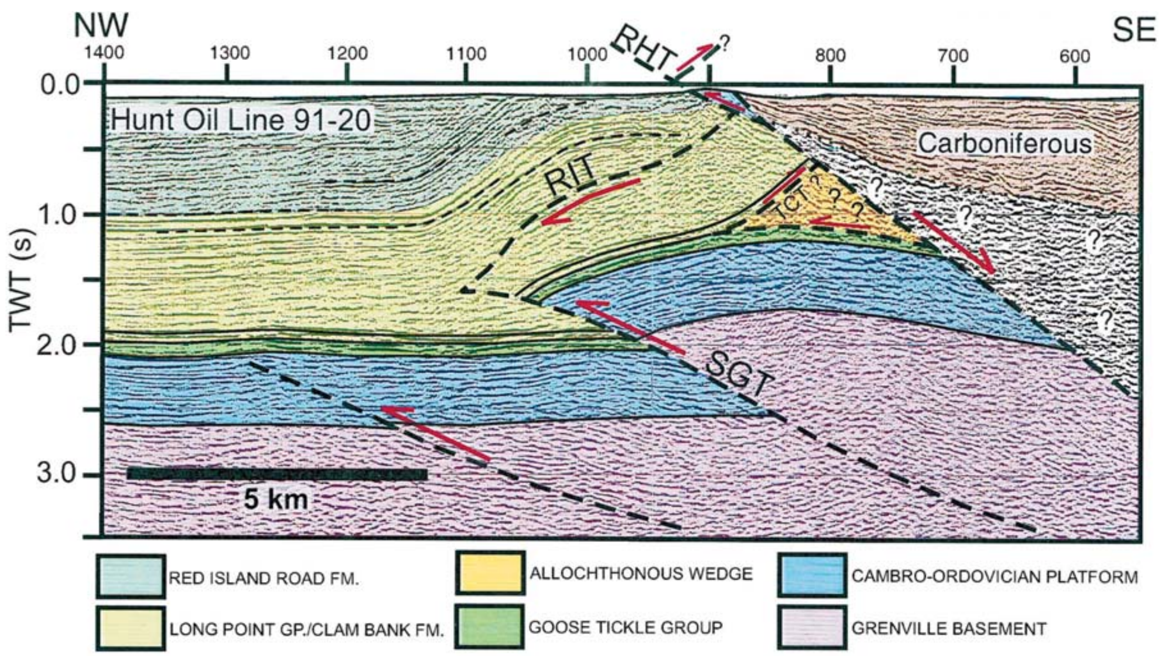


Figure 46. *Geometry of thrusts southwest of Port au Port Peninsula. RHT = Round Head Thrust; SGT = St. George Trust; RIT = Red Island Thrust (after Stockmal* et al.*, 1998).*

Figure 47. *Subhorizontal carboniferous rock filling an incised paleovalley cut into steeply dipping Table Head Group, dipping towards the camera in the lower part of the cliff.*

east 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.

Farther north the evidence for post-Taconian thrusting is equivocal. Major basement-cutting thrusts along the west edge of the Long Range Mountains on the Northern Peninsula, the Long Range Thrust and the Parson's Pond Thrust, have a similar style to the Round Head Thrust, and are generally interpreted as Acadian structures (Figure 41).

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 southwest Newfoundland, and in the Deer Lake Basin. Both basins are interpreted as transtensional pull-apart basins formed in association with southwest-northeast 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

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 (Figure 13). 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 48).

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 at around 490 Ma, the very start of the Ordovician period. 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 (2003) to suggest that an offshore microcontinent, the Dashwoods microcontinent, was the first to experience the Taconian collision (Figure 13).

Somewhat later, in the Middle Ordovician around 475 Ma, the main Humber margin started to be deformed. The major effect of the encroaching arc system was the subsidence of the margin, which killed off carbonate sedimentation, and led to the deposition of the clastic Goose Tickle Group above the old margin. Shortly afterwards, rocks of the former continental slope and rise were thrust up over the 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 Structures

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. The origin of D_2 has long been a puzzle in the geometry of the allochthon. Cleavage varies from generally upright and east-dipping in the vicinity of the Cooks Brook synform (Figure 36a), where it is sporadically developed and weak, to west-dipping in the Corner Brook area where it is more penetrative and locally phyllitic. These relationships would be consistent with development in association with shortening above an east-vergent detachment, but there is no obvious location for a "root zone" for a basal detachment associated with D_2 deformation. However, the Acadian tectonic wedge at the thrust front almost certainly post-dates the cleavage within the allochthon; hence, at the time of cleavage development the allochthon may have been located significantly east of its present location. The cleavage may have developed at the time of west-dipping subduction, east-vergent thrusting, and accretion in central Newfoundland (van Staal and de Roo, 1996; van Staal *et al.*, 1998) (Figure 13 - last stage).

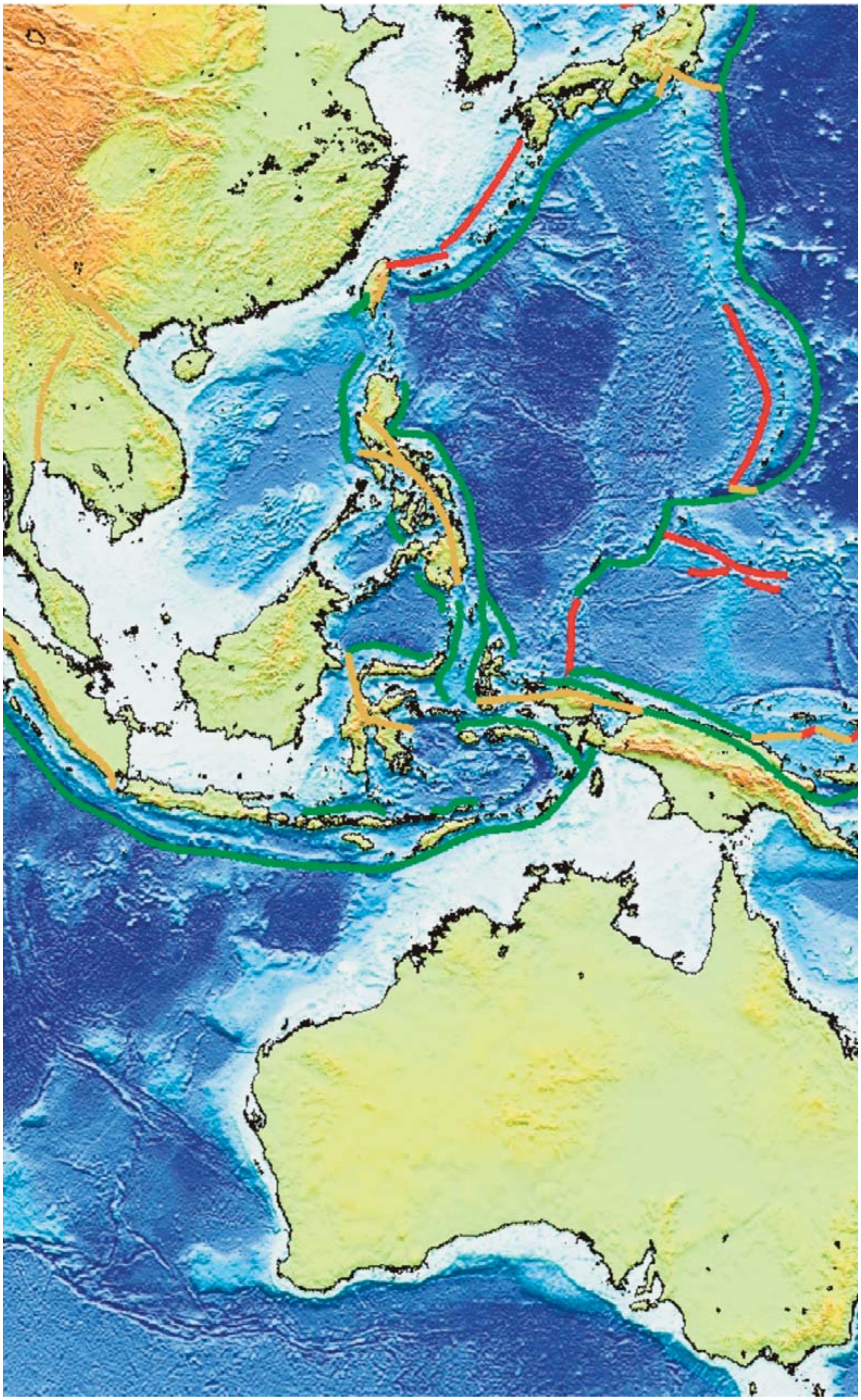


Figure 48. *The present-day collision between Australia and Papua New Guinea is a good analogue for the Taconian deformation of the Laurentian margin.*

Shear zones along the eastern edge of the Watsons Brook sheet 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), and has been attributed to "extensional collapse" of the orogen following Salinian (Silurian) shortening.

Acadian Thrusting and Development of the Offshore 'Triangle Zone'

Later shortening, recorded by thrust-sense brittle shear zones and tension gashes, can reasonably be related to shortening at the thrust front, that 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. Thrusting during Acadian deformation was critical in creating the Garden Hill structure and other prospects beneath the Port au Port Peninsula, by placing carbonate reservoir rocks from the shelf succession, formerly deeply buried in the thrust stack, into a position where they could receive a hydrocarbon charge from potential source rocks in the Humber Arm Allochthon and/or Goose Tickle Group (Figure 44).

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. In the older, already-deformed Early Paleozoic rocks, late brittle fractures are probably the main product of Carboniferous deformation. However, it is likely that the whole area was buried by Carboniferous, and probably Mesozoic sediments. These have subsequently been removed, but their blanketing effect must be taken into account in modelling the thermal history of the area, and the potential maturation history of hydrocarbons.

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 uplift due to 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.

PART 2. PETROLEUM EXPLORATION HISTORY

EARLY HISTORY TO 1987

Parson's Pond

According to historical documents (English records only), hydrocarbon seeps have been noted in western Newfoundland since 1812. It is reported that a gentleman by the name of Mr. Parsons collected oil from around the shoreline of Parson's Pond and used this seep oil as an external cure for rheumatism. This seep oil remained a source of curiosity until 1867 when John Silver, a Nova Scotia sawmill operator who upon hearing the oil rumours came to the area and by utilizing a steam powered drill put down a 700 foot (213.4 m) well on the south shore of the pond. It was reported that oil and gas was encountered over three intervals, but further drilling and attempts to produce were not pursued at that time. In fact, no further petroleum activity took place for approximately another twenty-five years.

In the early 1890's, individuals prospecting along the shoreline at Parson's Pond identified a number of oil shows and based on these discoveries, one of these prospectors, George A. Pippy, took the lead role in the formation of the Newfoundland Oil Company in 1893. In the spring of 1894 representatives of the Newfoundland Oil Company travelled to the Oil Springs area in Ontario and obtained a drilling plant and two experienced drillers. Upon their return and following a series of start-up difficulties in 1894 the company managed in 1895 to complete their first hydrocarbon-bearing well and then re-enter and deepen this well in 1896, while later in the same year commencing a second well closer to the shoreline.

Following these early attempts, word of mouth from local residents indicates that over the next thirty years a number of Colonial Newfoundland and British companies drilled an additional twenty to twenty-five shallow to intermediate-depth holes around the pond, most of which encountered oil and gas shows. Although no written records exist, it is speculated that anywhere from 5,000 to 10,000 barrels of oil may have been produced during this timeframe. The most productive period was the early 1920's when General Oilfields Ltd., under the direction of J.D. Henry, a widely recognized and acclaimed British oil expert, had at one time three wells drilling and four wells in production. All of this oil was used locally in the drilling operations or sold to fisherman up and down the coast for fuel to power their motorboats.

After 1925, it appears no further drilling took place at Parson's Pond until sometime between 1952 and 1954. A consortium headed by American entrepreneur John Fox sank two wells, obtaining oil and gas shows in both. Mixed drilling results however, in combination with a fire that destroyed their field office and records, discouraged the company, and they departed western Newfoundland in early 1954.

The last historic drilling attempt at Parson's Pond was in 1965 by NALCO (Newfoundland and Labrador Company). They drilled one well (Nalco I-65) and according to drill records and their lithological log, encountered ten zones (total of 34.7 m net pay) of 43.40 API "sweet" oil and a number of gas-bearing zones before losing the well at 1302 meters. NALCO also produced around 75,000 gallons of oil from a nearby abandoned well while drilling at the I-65 location.

St. Paul's Inlet

A few kilometres to the south, at St. Paul's Inlet, one well was drilled to a depth of 1700 feet (518.3 m) in the fall of 1896 and winter 1897 by the Canadian-Newfoundland Oil Company. Oil shows were encountered over three intervals and the well was pumped for a brief period of time. No further activity took place until 1952 to 1953 when the John Fox consortium drilled three wells and achieved mixed results from their efforts. A number of shallow water wells drilled in the 1970's had to be abandoned due to contamination from hydrocarbons.

Port au Port Peninsula

Approximately 160 km south of St. Paul's Inlet, hydrocarbon seeps were first noted in 1865 on the Port au Port Peninsula (Figure 49) by Alexander Murray, the first government geologist for Newfoundland. In his report for that year, Murray states, *"whilst in the neighbourhood of Port au Port, I was informed that a bituminous substance, resembling petroleum had been observed on the middle long point (Shoal Point) on the west side of the bay"*. These shows were evaluated in 1874 by Murray's assistant, government geologist James P. Howley, and according to him, *"the bituminous limestones where broken are characterized by the presence of a set of drusy cavities lined with crystals of calc spar, which are often filled with petroleum in a semi-liquid state of about the consistency of tar, while exposed surfaces are pitted with small cells, encrusted with bitumen. On the west side of the Point this substance exudes through the sand and at low water is sometimes found in small depressions, where it has been gathered by visitors"*.

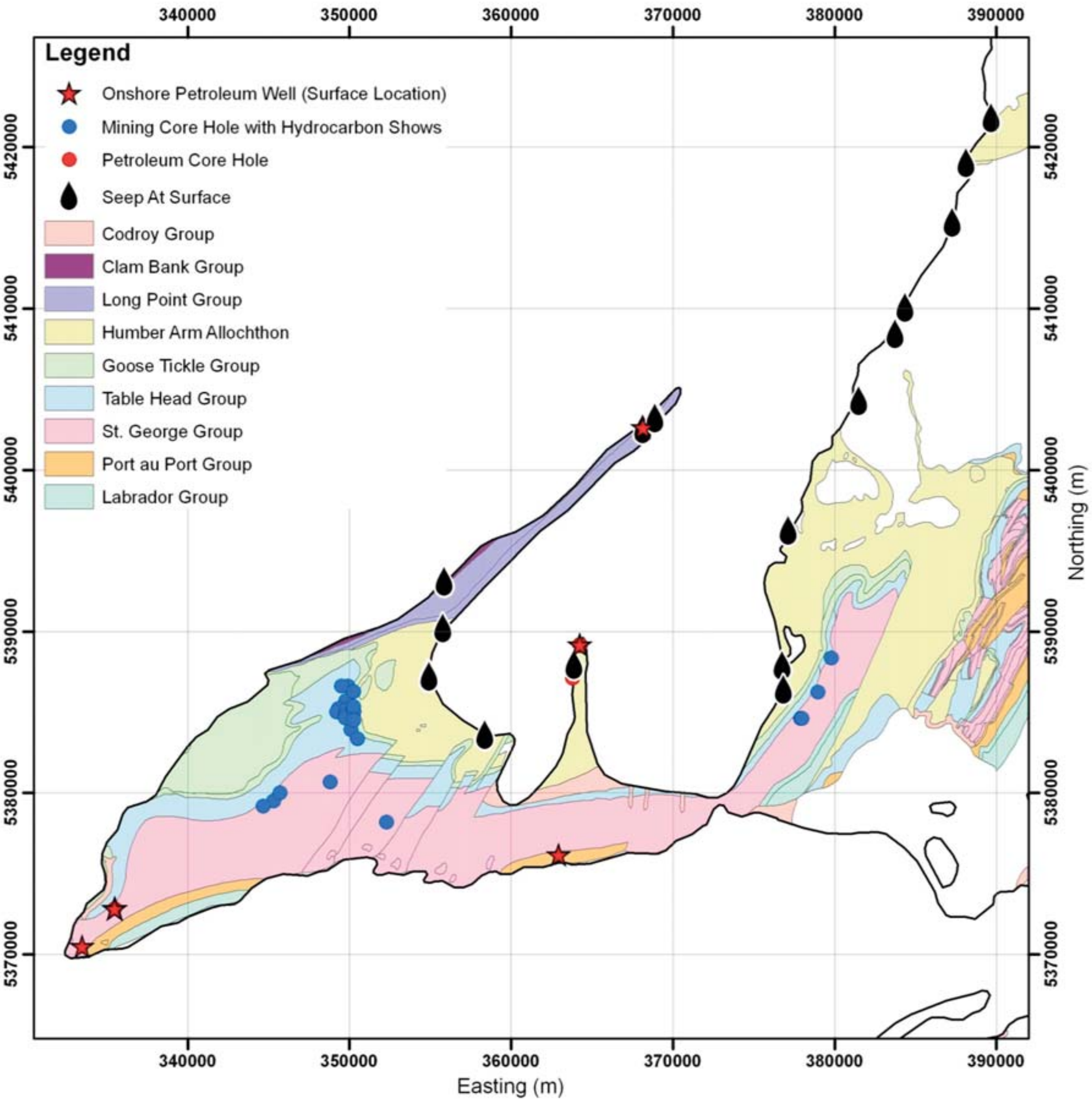


Figure 49. *Simplified geology map of the Stephenville / Port au Port area showing locations of known surface oil seeps / shows, mining core holes with shows and petroleum wells with shows.*

After these early references to the regions petroleum potential, there is no further mention of petroleum-related activity until 1898. Commencing in that year and intermittently up to 1901, the Western Oil Company Limited (Figure 50), incorporated in New Brunswick, put down at least four shallow holes at Shoal Point. These wells reportedly ranged in depth from 51 to 200 m and were said to have produced anywhere from 10 to 20 barrels of oil per day. No production records exist for this drilling activity. After this first drilling attempt, the Newfoundland Oil (Parent) Syndicate Limited, a British based company, supposedly drilled at Shoal Point around 1911. No details exist for this drilling activity and it is unclear

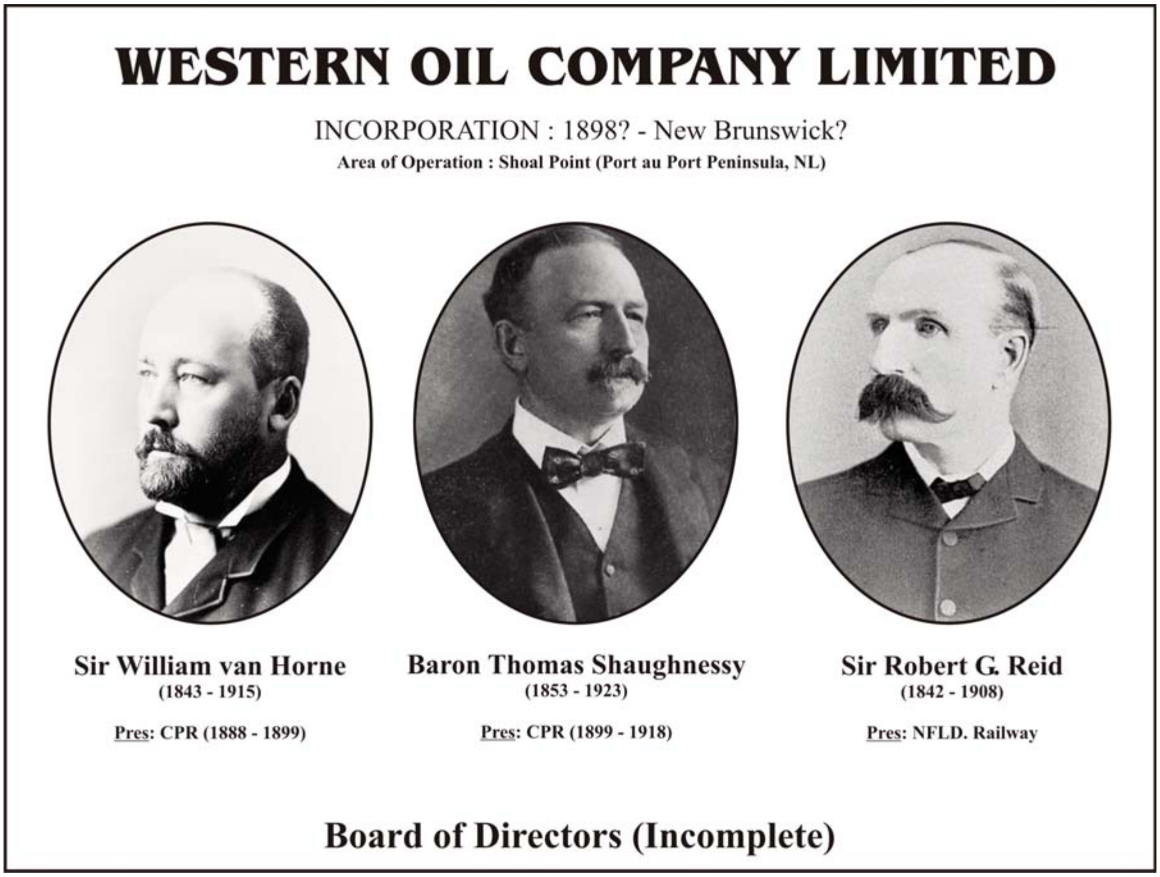


Figure 50. *Board of Directors (partial representation), Western Oil Company Limited.*

what wells, if any, they drilled. Over the next seventeen years there are no records to indicate further drilling; however a report written by government geologist Baker in 1928 states “at least eleven wells had been drilled at Shoal Point”.

The last episode of historic petroleum activity commenced in 1964 when British Newfoundland Exploration Limited (Brinex) and Golden Eagle Oil and Gas Limited undertook a joint exploration program throughout the Port au Port Peninsula. A detailed geological examination of the Peninsula was made by H. Corkin, and based on his recommendations two wells were drilled at Shoal Point in 1965 in order to obtain stratigraphic and structural information. The Shoal Point #1 well which was spudded at the tip of the Point encountered limited porosity development and examined cuttings exhibited only minor to trace amounts of oil staining and fluorescence. Shoal Point #2, spudded a few kilometers to the south, penetrated numerous zones with live and dead oil shows described as varying from 'trace' to 'good'.

RECENT PETROLEUM ACTIVITY (1987 – PRESENT)

The recent era of petroleum activity (Figure 51) for western Newfoundland has arbitrarily been chosen to coincide with the creation of the Newfoundland and Labrador Department of Energy in 1987, which evolved into the current Department of Natural Resources, Energy Branch. The below section summarizes the petroleum history and recent drilling activity for the onshore portion of the Anticosti Basin.

Port au Port Area (Anticosti South)

The first petroleum drilling utilizing a conventional rotary petroleum rig took place on the Port au Port Peninsula during the mid 1990's, when Hunt / PanCanadian spudded the Port au Port #1 Garden Hill well in September 1994. This well attracted the attention of the Province and petroleum industry in the spring of 1995 when a flare from the well lit up the sky along the southwestern part of the Port au Port Peninsula. The well encountered several reservoirs, one of which was hydrocarbon bearing. Two intervals within the hydrocarbon-bearing zone flowed 1528 and 1742 barrels per day of high quality (510 API) oil and 2.6 and 2.3 million cubic feet per day of natural gas, respectively, plus associated water. An extended test on one of the intervals produced a total of 5,012 barrels oil over a nine day period.

After the drilling of Port au Port #1, in September 1995 Hunt / PanCanadian spudded the Long Point M-16 well at the tip of Long Point and followed this up in May 1996 with their St. George's Bay A-36 offshore well, located approximately six km southwest of Cape St. George. There were no shows recorded in the Long Point well, but minor live oil and numerous bitumen occurrences were reported from the St. George's Bay hole. This well also had good porosity development in the Watts Bight and Hawke Bay formations. In between the Hunt / PanCanadian wells, Talisman *et al.* in February 1996 spudded their Long Range A-09 well approximately 3 km south of the Port au Port #1 well. This well upon completion was plugged and abandoned.

Inglewood Resources commenced the Man O'War I-42 well near Campbell's Creek on the southern Port au Port Peninsula in November 1998 in order to evaluate the hydrocarbon potential of a faulted, anticlinal structure located beneath St. George's Bay. The well reached a depth of 676.7 m and was terminated due to drill-related problems in thinly bedded,

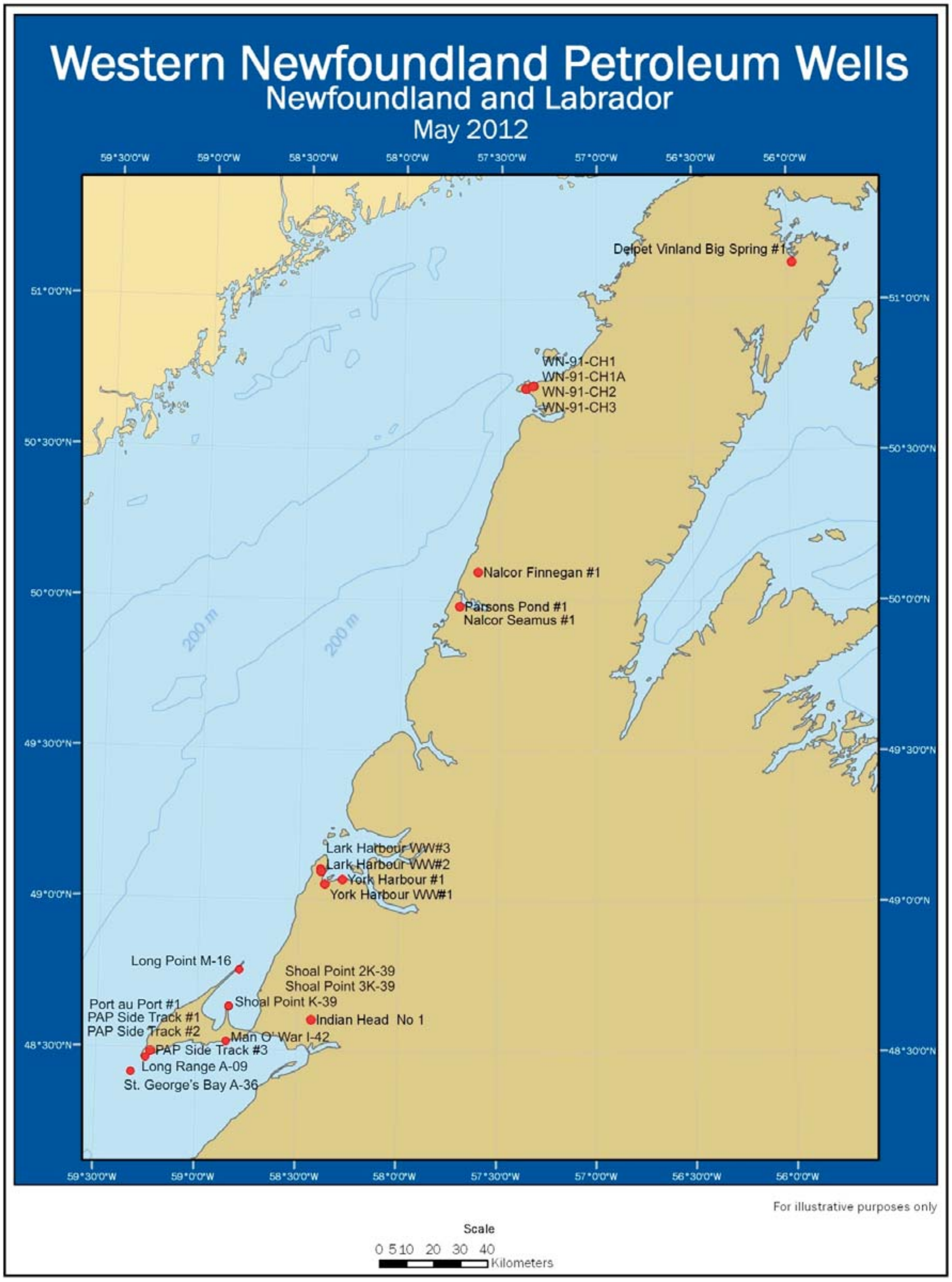


Figure 51. *Onshore well location map for the Anticosti Basin; includes all recent (since 1990) petroleum wells and shallow stratigraphic holes.*

Forteau Formation (Labrador Group) shales and carbonates. No hydrocarbon shows were noted in the drilled section.

In 1999, PanCanadian Petroleum and partners Hunt Oil, Mobil and Encal Energy spudded the Shoal Point K-39 well on the tip of Shoal Point adjacent to the 1965 Shoal Point #1 drillsite. The well was directionally drilled to a depth of 3035 m to test a large structure located beneath Port au Port Bay. In May 1999, Pan Canadian announced that the well had tested water and would be abandoned. In the fall of 2000, Memorial University's Earth Science Department acquired additional seismic data around the Shoal Point area and subsequent analysis of this data suggests the well may have missed its intended target.

Also in 1999, Canadian Imperial Venture Corporation (CIVC) farmed into the Hunt / PanCanadian Garden Hill project and conducted additional pressure and flow testing of the reservoir zones.

In August 2001, CIVC spudded Port au Port #1 sidetrack #1 in order to earn their farm-in with Hunt/PanCanadian. The original PAP #1 well was re-entered and kicked off in a northwesterly direction in order to penetrate the Garden Hill reservoir further updip in the oil bearing zone. Unfortunately, the upper Aguathuna Formation which was dolomitized and possibly karsted in the original well contained tight limestones in the sidetrack well. Minor oil shows however were present in dolostones of the lower Aguathuna Formation. Following the sidetrack well, CIVC spudded their Indian Head #1 well north of Stephenville (Black Duck Siding) in November 2001 and terminated the well in early 2002 after encountering approximately 805 m of Precambrian basement rock. Also within this timeframe, CIVC drilled a second sidetrack well in a northeast direction from the original PAP #1 well during the summer of 2002 and announced that this well flowed at 195 bopd, with 1.2 million cubic feet per day of natural gas. They also announced there was no produced water with the test and the pressures were constant. However, in 2003 CIVC experienced financial difficulties and sought court protection from their creditors. After a long series of legal maneuverings, PDI Productions Inc. became primary operator for the lease in 2008.

Meanwhile, CIVC re-entered the PAP #1 sidetrack #2 in late 2006 / early 2007 to conduct an extended well test that produced over 3500 bbls of oil and 15 MMscf of gas. In 2008 PDIP drilled PAP#1 sidetrack #3. Over 6000 barrels of oil were produced during drilling operations and subsequent flow testing.

Just north of the Port au Port Peninsula, Enegi Inc. is the representative for offshore block EL-1070. One of their partners, Shoal Point Energy Ltd, drilled the 2K-39 well in the summer of 2008 from the same drilling pad as the original K-39 well. A preliminary interpretation of the logs in the St. George's Group did not identify the presence of any economic hydrocarbons. However, significant shows of gas were encountered while drilling the Green Point shale of the Humber Arm Allochthon in the intermediate hole section.

In 2011, Shoal Point Energy and partners returned to the Shoal Point Peninsula to test the Green Point Formation oil-in-shale play. The 3K-39 well reached a depth of approximately 1715 m before being suspended due to rig and hole problems. Shoal Point Energy returned with a workover rig in early 2012 in order to deepen the hole to its intended 2200 m target depth. As of this writing, work is still ongoing at the drillsite.

Overall, approximately 35,000 barrels of oil and 120 MMscf of gas have been produced from the original Port au Port #1 wellbore and sidetracks, and the Port au Port Peninsula has attracted the greatest interest from exploration companies. However, sustained production has remained elusive.

Bay of Islands (Anticosti Central)

A little further to the north, within the Bay of Islands, in 1996 Mobil Oil Canada Properties contracted East Coast Drilling to put down a shallow stratigraphic test hole in order to acquire geological information on known or suspected source and reservoir rocks in the Humber Arm Allochthon. The York Harbour #1 well spudded in December 1996 and was continuously cored to a depth of 299.3 m TVD (total vertical depth). Stratigraphically, the well penetrated multiple, stacked, fining upward, greenish-grey, fine to coarse grained sandstone to pebbly sandstone sequences with subordinate pebble conglomerates and shale, all belonging to the Lower Cambrian Blow Me Down Brook Formation of the Humber Arm Supergroup. Sandstone beds were mostly tight, but locally exhibited poor to fair intergranular porosity. Porous intervals invariably exhibited a weak to good, pale brown oil stain. The cored section also exhibited numerous cross-cutting fractures, most of which were infilled by calcite and/or pyrobitumen. Fluids extracted and analysed upon well completion indicate an API oil gravity between 260 and 350.

Concurrent with the drilling of York Harbour #1, Mobil Oil Canada Properties contracted D. A. Construction Ltd. to drill three shallow (water) wells in the communities of

York Harbour, Lark Harbour and Little Port, the purpose being to collect geological information from potential source rocks in the area. York Harbour Water Well #1 encountered hole stability problems and was abandoned at 50.3 m. Lark Harbour Water Well #2 went to 123.4 m and encountered dark shales in the bottom hole section. Total organic carbon (TOC) values ranged from 0.6% to 1.5%, with an average around 0.80%. Acritarch alteration index (AAI) values fall within the range 2.3 to 2.7, implying that strata are still within the oil window (medium mature to condensate stage). The Little Port Water Well #3 encountered mostly red shales down to 152 m. Twenty-seven samples analysed for TOC content all returned values <0.3%. AAI values ranged from 2.7 to 3.4, suggesting strata in this area are mostly overmature for oil and fall within the condensate to dry gas zone.

Northern Peninsula (Anticosti North)

The first petroleum-related drilling activity under the new Department of Energy in the Anticosti Basin occurred in 1991 when BHP Petroleum Ltd. contracted Longyear Canada Inc. to continuously core four shallow stratigraphic test holes, with a mining rig, near the community of Port au Choix on the Northern Peninsula, to evaluate reservoir quality and assess the overall hydrocarbon potential of Catoche Formation (St. George Group) dolostones. These were shown to be locally porous (intercrystalline, vuggy and solution enhanced) and occasionally heavily bitumen stained, so much so that many now consider this hydrocarbon occurrence to be an exhumed oilfield.

In May 1997, Delpet Vinland spudded the Big Springs #1 well near the community of Croque in the Hare Bay area on the Northern Peninsula. The play concept was an anticlinal structure located within a foreland fold and thrust duplex structure. Anticipated reservoir rocks included vuggy, Catoche formation dolostones (primary target) and secondary targets consisting of porous units within Table Head carbonates and clastic reservoirs within the Goose Tickle flysch sequences. Post drill analysis suggests that the well encountered approximately 1397 m (surface to TD) of Port au Port Group carbonates. Only very minor gas shows were encountered throughout this well.

The greatest exploration interest on the Northern Peninsula has been in the area of the original 19th century production at Parson's Pond. In January 2004 Contact Exploration of Calgary and partners, used a water well rig to spud the Parsons Pond #1 well at Parson’s Pond in order to test a large thrusted feature identified on seismic data which had been acquired by Labrador Mining and Exploration in the mid 1990’s. This was the first well to be drilled in this area since the Nalco I-65 well in 1965 and the first to be drilled based on seismic information. Several companies, including the Newfoundland based juniors Deer Lake Oil and Gas and Vulcan Minerals partnered with Contact in this endeavor. The well was suspended in April 2004 prior to the planned drill depth due to drill related problems encountered while trying to penetrate a shear zone.

In 2009 Nalcor Energy Corporation acquired a majority interest in three permits located immediately north of Gros Morne National Park on the Northern Peninsula. The three permits had previously been held by Leprechaun Resources Inc., who in their evaluation had identified three potential prospects located along a north – south trending structural high. In February 2010 Nalcor and partners spudded the Seamus #1 well in the southern permit and followed this towards the north in September 2010 with Finnegan #1. After completion, some of the well partners announced a number of gas zones had been penetrated in both wells from upper sections. Information on both wells remains confidential until May 2012 (Seamus #1) and late 2012 (Finnegan #1).

PART 3. FIELD TRIP STOPS (Figure 52)

DAY 1 (Figure 53). EARLY PALEOZOIC LAURENTIAN MARGIN

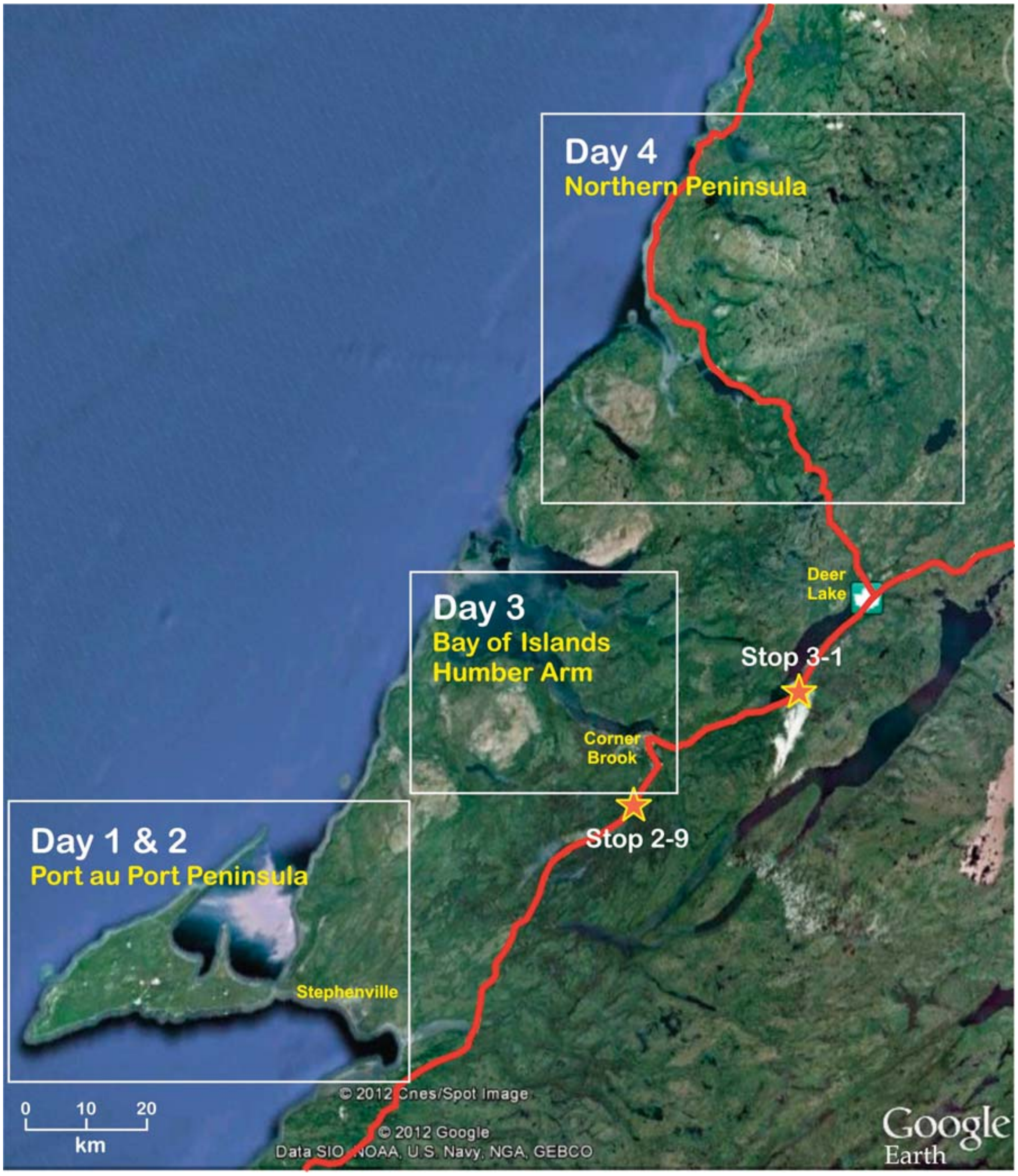


Figure 52. *Regional map for western Newfoundland highlighting field areas for Days 1 to 4.*

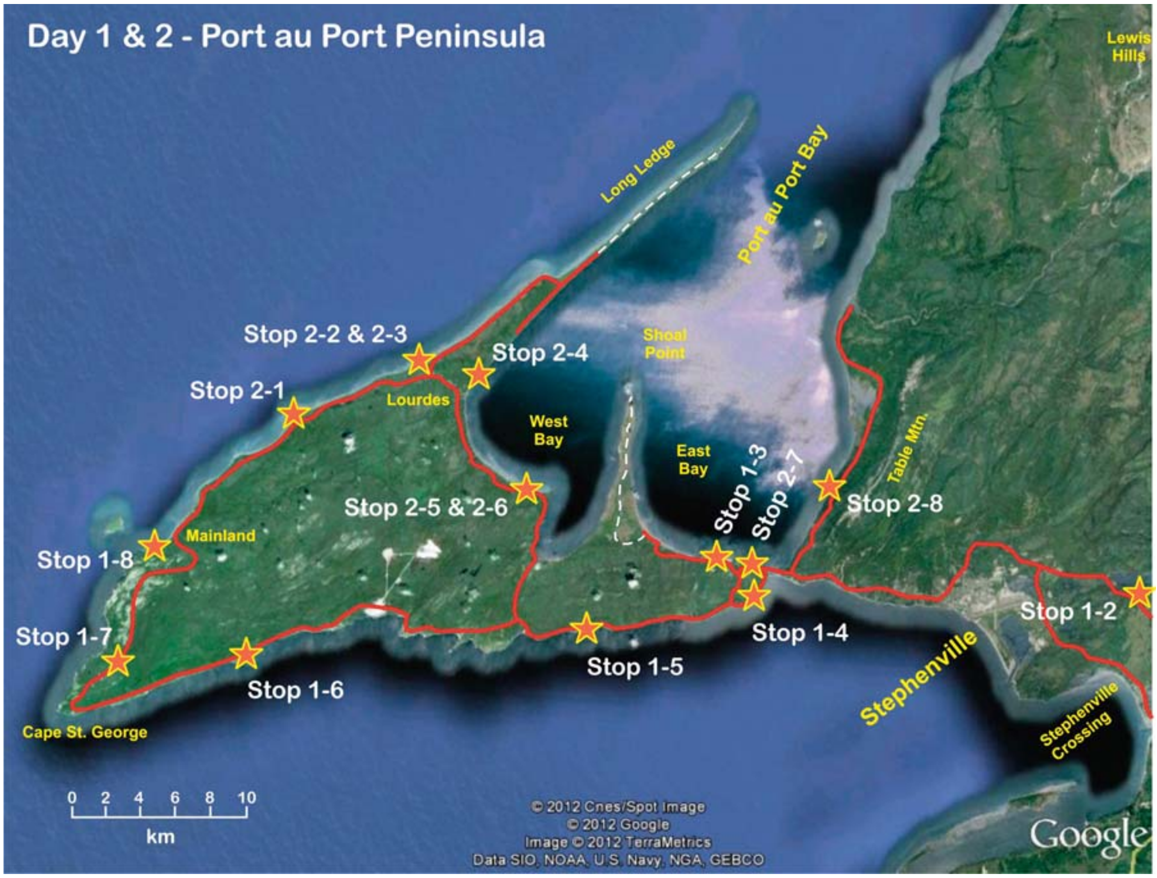


Figure 53. *Port au Port Peninsula Field Stop Map for Days 1 and 2.*

STOP 1.1: Corner Brook TCH Lookout

From this viewpoint (Figure 54) it is possible to see many of the main geological elements of the Newfoundland Humber Zone. Immediately to the southeast are limestone hills that represent the carbonate platform succession formed on the Laurentian continental shelf. These are often described as 'autochthonous' but it is important to remember that all the rocks in view have been deformed and probably thrust multiple times, in the development of the orogen. The only truly autochthonous rocks are deep in the subsurface below us, and far to the west, offshore, beneath the Gulf of St. Lawrence.

At this stop, we stand approximately on the boundary between platform succession and Humber Arm Allochthon rocks, which underlie the entire area visible to the west. Although these rocks are exposed to our west, they were originally deposited well east of their current position, having been thrust westward during the Taconian and Acadian orogenies. Subsequent erosion exposed these allochthonous rocks.

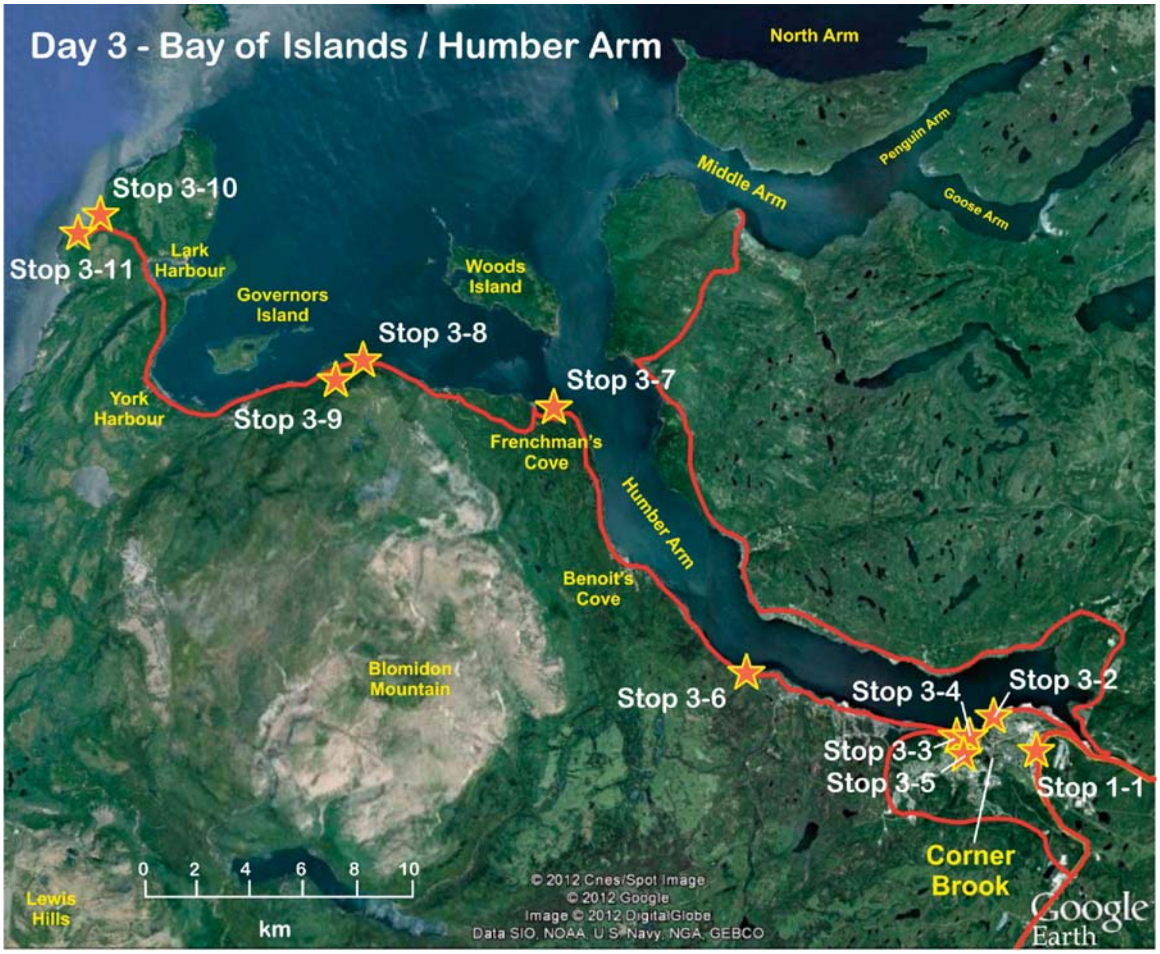


Figure 54. *Bay of Islands Field Stop Map for Day 3.*

Within the Humber Arm Allochthon, remnants of contrasting stratigraphic successions derived from the continental margin are recognized, preserved in separate thrust sheets (Waldron *et al.*, 2003) (Figures 20, 39). In the area of the present view, it is generally the case that more distal, far travelled units are exposed to the west of more proximal, less transported units. The structurally lowest thrust sheet is the platform sheet, representing ancient Laurentian shelf and its foreland cover. Immediately to the west, and structurally higher, are rocks of the Watson's Brook sheet (Pinchgut Lake Group and its foreland basin cover) (Knight 1996b). This is well exposed to the southwest in highway cuts but at this location it is largely hidden in the subsurface, appearing only in an anticline close to Wilfred Grenfell College campus. Above the Watson's Brook sheet are several thrust slices of the Corner Brook sheet that display dominantly turbiditic slope sediments of the Corner Brook Succession – often regarded as the most typical Humber Arm succession (Stevens, 1970). These occupy the ground between the stop location and the mouth of Humber Arm at Frenchman's Cove. Structurally above and farther west lies the Woods Island sheet, dominated by the early Cambrian Blow Me Down Brook Formation (Lindholm and Casey, 1989). Finally, the highest thrust contains ocean floor rocks of the Bay of Islands ophiolite. These rocks make up the range of hills on the horizon (Blow Me Down Mountain). Depending on the weather and time of day, it may be possible to make out the distinctive orange weathering of the upper mantle peridotites that form the eastern part of Blow Me Down Mountain.

STOP 1.2: Indian Head

This short roadside stop will be to review the oldest rock units in western Newfoundland, the gneisses and granitoids of Proterozoic age that formed the basement upon which continental margin rocks were deposited in Paleozoic time (Figures 55, 56, 57, 58). Gneiss and granitoid basement rocks give ages (where dated) corresponding broadly to those of the Grenville Orogen of mainland North America. The basement rocks in western Newfoundland are therefore often informally referred to as 'Grenvillian'. In the Stephenville area, this relatively small mass of basement rock is termed the Indian Head Range.

A highly variable assemblage of Mesoproterozoic Indian Head Complex rocks outcrop along this section. Major rock types include pink and grey feldspathic gneiss, massive to foliated granite, granodiorite, gabbro and anorthosite, plus associated pegmatite pods or lenses. Mafic dykes and disseminated to massive magnetite lenses are common throughout the Complex. The magnetite bodies have been the focus of intense mineral exploration and several attempts have been made to mine the ore.

Historical Note – Indian Head Iron Mines

Mining operations at Indian Head took place over two distinct time intervals during the last century. In 1914, just before the outbreak of WWI, a Dr. Elizabeth Ingraham arrived from the United States with a diamond drill and a crew of twelve drillers (Martin 1983). Their purpose was to outline the extent of an iron deposit on Indian Head. However, the complete crew vanished at the start of WWI leaving many of the local residents wondering whether they were German spies.

A second attempt at mining the ore lenses occurred during the Second World War. Fearing disruption of iron ore shipments from Bell Island to the DOSCO (Dominion Steel and Coal Company) steel mills in Nova Scotia, DOSCO decided to mine the higher grade ore at Indian Head and ship to Nova Scotia, because the ore was located closer to the mills and the company had a large supply of miners and equipment located a few miles away at the

Figure 55. *Precambrian leucocratic anorthosite exposed at Indian Head, near Stephenville.*

Figure 56. *Pegmatitic anorthite (light) and pyroxene (dark) within Indian Head anorthosite, Indian Head Quarry, near Stephenville.*

Figure 57. *Epidotized, coarse grained granite (Precambrian) intruded into slightly older Indian Head Range gneiss and mafic volcanics, near Stephenville.*

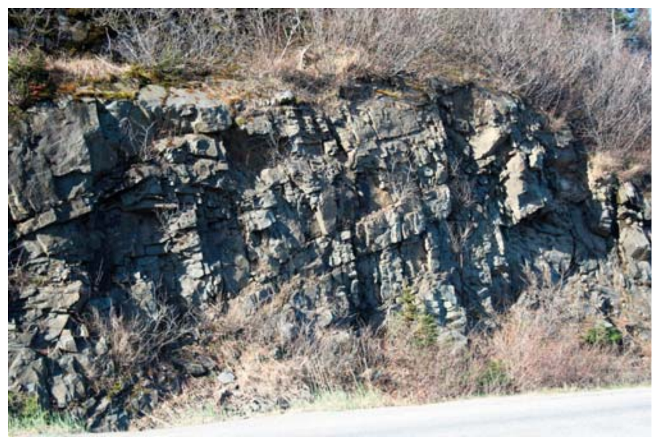


Figure 58. *Precambrian mafic volcanic rocks exposed along Route 490 between Stephenville and Stephenville Crossing.*

Aguathuna limestone quarry. Mining began in 1941 and up to 1944, DOSCO operated four separate open pit mines at Indian Head. Years later, miners of the era recall how they had to use welding torches to remove ore from the pit walls or cut apart manageable blocks for transport to Aguathuna for shipment (Martin 1983). Due to the iron shortages encountered during the war, the ore cars were modified to operate with wooden wheels. DOSCO never intended the mine to be open for any extended period, so in 1944 the mines closed and have not re-opened since.

STOP 1.3: Aguathuna

Warning: *keep away from old machinery and steep rock faces in this disused quarry. Be careful crossing the road.*

See Figure 53 for stop locations on the Port au Port Peninsula.

The St. George Unconformity forms a major sequence boundary in the Appalachians, marking the Early-Middle Ordovician boundary and separating the Sauk and Tippecanoe sequences of Sloss (1963). It also marks the contact of underlying carbonates of the St. George Group (deposited on the Laurentian passive margin) with those of the overlying Table Head Group (deposited in the Taconian foreland basin). The boundary is believed to represent the westward passage of a peripheral forebulge across the margin and is coincident with a eustatic sea level fall (Knight *et al.*, 1991).

Units of the St. George Group below the unconformity are best exposed in the inner quarry. The top of the Catoche Formation and the base of the Aguathuna Formation are exposed. On the Port au Port Peninsula, the Catoche Formation consists of three units: a lower limestone, a middle dolostone (the Pine Tree unit), and an upper clean-white limestone (the Costa Bay Member, locally known as the White Hills unit, (Knight and James, 1987). The Pine Tree unit and Costa Bay Member occur in the inner quarries. Note the massive bedded nature of the Costa Bay Member, where it is composed mostly of peloidal grainstones. Elsewhere in western Newfoundland, it is host to extensive dolomitization and impressive porosity (*e.g.*, at Port au Choix, an exhumed petroleum reservoir, Baker and Knight, 1993; Knight *et al.*, 2007). The unit is also host to the Daniel's Harbour zinc mine (Lane, 1990). In the western part of the Port au Port Peninsula, the Costa Bay Member changes its facies character reflecting a deeper water shelf setting (Boyce *et al.*, 2000) in contrast to the high-energy lime-sand shoal setting of the member observed throughout the eastern two thirds of the Peninsula).

Stromatolitic limestone, dololaminite and green shale interbeds are observed in the base of the Aguathuna Formation and occur on the northern face of the quarry. Paleocaves and collapse breccias occur throughout the inner quarry. The reservoir potential of the cave system in this area is reduced by clogging with green shale that was most likely derived from subsurface washout of interbedded shale units of the Aguathuna Formation during exposure of the overlying unconformity surface.

The unconformity (Figure 59) 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. The surface displays a variety of karstic features including small karren, a basal conglomeratic lag, and local cave deposits. Such caves are likely important reservoirs in the Garden Hill well.

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.

STOP 1.4: Green Head

Notes at this stop based in part on Knight et al. *(2007).*

On the Port au Port Peninsula, the Watts Bight Formation, the lowest most unit of the St. George Group, is dominated by subtidal bioturbated limestone with storm layers of intraclastic conglomerate and high energy thrombolitic mound complexes. The carbonates were deposited on the western Newfoundland shelf during the earliest Tremadocian, during flooding and later regression. This locality is famous for the spectacular thrombolitic mounds, mounds being common features of the formation throughout western Newfound-

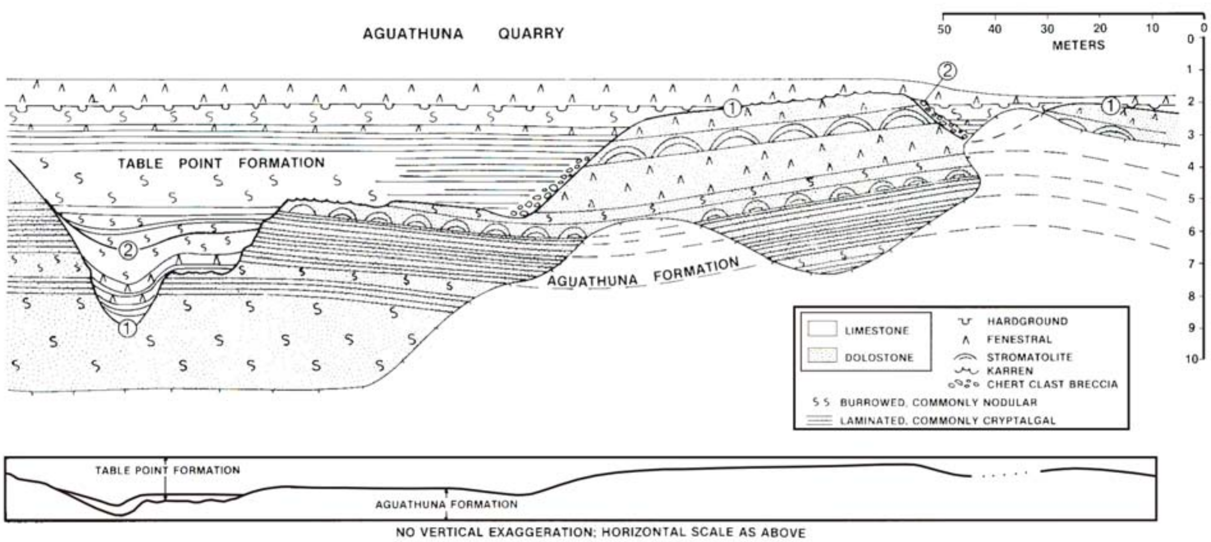


Figure 59. *Diagram of the St. George Unconformity at Aguathuna Quarry (after Knight* et al.*, 1991).*

land (Pratt and James, 1982) (Figure 60). The mounds are represented by subtidal cryptalgal microbialites with clotted and digitate structure that also hosted sponges, primitive corals (Lichenaria) and stromatoporoids. The mounds are associated with channel fills and beds of grainstone and exhibit truncation surfaces, implying that the shelf had shallowed into the surf zone. Both the mounds and the carbonate sand are partially dolomitized. The finely sucrosic dolostones have pinpoint porosity.

Tracing the section to the north, the Watts Bight Formation is overlain by the lowest beds of the Boat Harbour Formation (Figure 61). The unit consists of metre-scaled peritidal limestone-dolostone sequences capped by a thick interval of dolostone. Bioturbated limestone overlain by dololaminite reflects the gradual shallowing of the shelf into the intertidal zone. Small pockets of breccia, long fissure cracks and sheet cracks, and the widespread presence of chert all point to a disconformity at the top of the thick dolostone just beside the ladder to the inn. This is supported by marked changes in the micro and macro faunas at this point in the stratigraphy. This disconformity represents a regional episode of subareal exposure. Elsewhere in western Newfoundland this interval is characterized by large scale development of collapse breccias, producing potential reservoirs. Above the dolostone unit, the middle Boat Harbour Formation is characterized by peritidal limestone and dolostone (Note the superb stromatolite mounds just north of the ladder).

From this location, it is possible to walk north along the shoreline to observe repeated peritidal cycles. En route to the Boat Harbour Disconformity, there are exquisite microbial thrombolite mounds, some of which are eroded by deeply incised, coastal paleo-karst and associated grainstone infill. Above the disconformity, the succession consists of Arenig strata forming the second of two megacycles that characterize the St. George Group (Knight and James, 1987), including the upper, Barbace Cove Member of the Boat Harbour Forma-

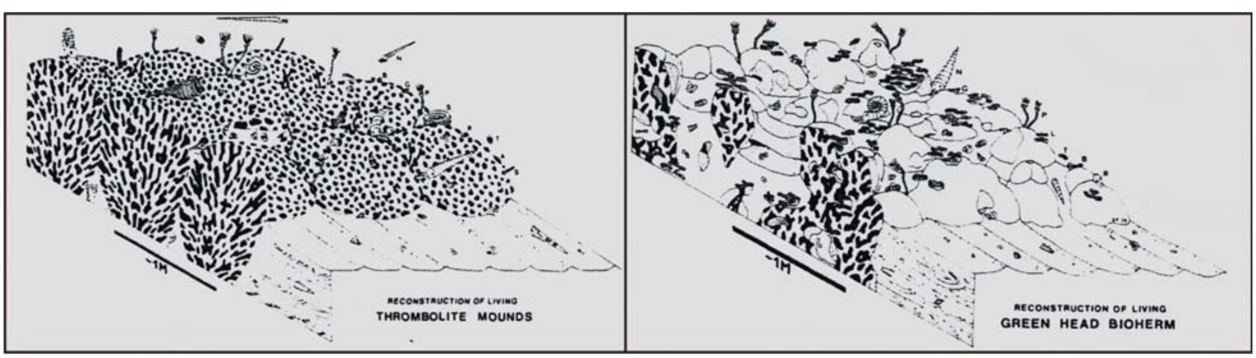


Figure 60. *Model of the Early Ordovician Green Head mound complex, Isthmus Bay (from Pratt and James, 1982).*

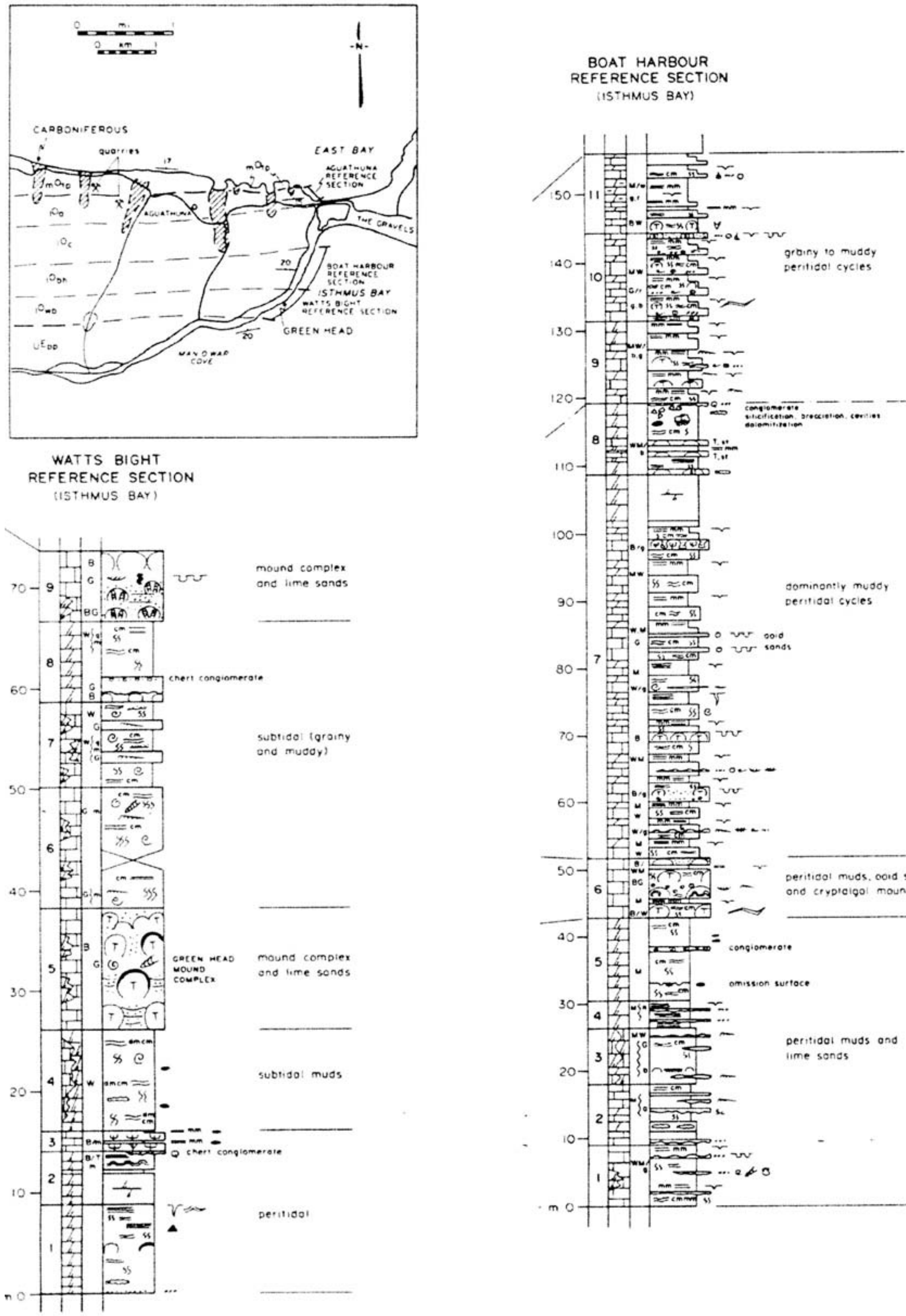


Figure 61. *Schematic measured section through the Watts Bight and Boat Harbour formations along the shore of Isthmus Bay (from Knight and James, 1987).*

tion, overlain by a succession of bioturbated and fossiliferous, subtidal limestone of the Catoche Formation.

STOP 1.5: Campbell's Creek

Caution: *The roadside stop is on a narrow highway. Keep off the road and be aware of the traffic hazard. The same relationships can be seen on the shore, where there are hazards from overhanging cliffs and where it is important to be aware of the state of the tide.*

The south coast of the Peninsula exposes generally lower parts of the shelf succession, including the Port au Port Group. At Campbell's Creek, and several other places along the south coast, the succession of Cambrian dolostones and limestones are abruptly interrupted by red conglomerates of the Carboniferous (Mississippian) Codroy Group. Clasts in the conglomerate range up to boulder size locally. The unconformity below the Codroy Group is clearly highly irregular and locally steeply dipping. The Carboniferous rocks were clearly deposited in karstic gorges cut into the underlying lower Paleozoic strata.

STOP 1.6: Marches Point

The lowest units exposed on the Port au Port Peninsula are clastic rocks of the uppermost Labrador Group of early Cambrian age, overlain by the lowest Middle Cambrian unit of the Port au Port Group. The Labrador Group is here represented by the Hawke Bay Formation (Figure 62), consisting of cross-bedded and locally highly bioturbated, quartz-cemented quartz-rich sandstones (orthoquartzites). Locally the sandstones display abundant subvertical pipes, the trace fossil Skolithos. The sandstones are thought to represent a shallow-marine shelf environment.

A disconformity, marked by a conglomeratic lag, separates the Hawke Bay formation from the overlying March Point Formation (Figure 63). The overlying March Point formation is lithologically varied, including quartz-rich and glauconitic sandstone, dark shale, and bioturbated limestone. Like the underlying Hawke Bay Formation, the March Point represents a shallow-marine shelf environment; however, the boundary between the two represents a margin-wide transition from a clastic-dominated shelf to the carbonate-dominated shelf succession seen at the previous stops.

Figure 62. *Hawke Bay Formation (Labrador Group) quartz arenites exposed along the southern shore of the Port au Port Peninsula, near Marches Point.*

Figure 63. *Contact between the Port au Port Group and underlying Hawke Bay Formation at Marches Point, southern Port au Port Peninsula.*

STOP 1.7: Garden Hill

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 44) 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.

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.

STOP 1.8: Cape Cormorant

Warning: *Use extreme caution when approaching the cliff, especially the near-vertical bedding planes and boulder conglomerates of the Cape Cormorant Formation, which are extremely unstable; be alert for hazards from falling rocks and landslides; choose safe places to examine the outcrops. Protective headgear is strongly recommended.*

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) (Figures 64, 65) and the upper parts of the underlying Cape Cormorant Formation (Table Head Group) (Figures 66, 67, 68, 69).

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. Trace fossils may also be seen on some bedding surfaces.

Figure 64. *Steep, northwest dipping beds of Mainland Sandstone and shale (extreme left side of photo), Cape Cormorant Formation shale and debris flows (mid–right side of photo).*

Figure 65. *Steeply dipping beds of Mainland Sandstone; sandstone beds display partial Bouma sequences, at Cape Cormorant.*

Figure 66. *Very steeply dipping to slightly overturned interbedded shale and debris flow conglomerate of the Cape Cormorant Formation.*

Figure 67. *Close up view of Cape Cormorant Formation debris flow conglomerates and thinly interbedded ribbon limestone and shale.*

Figure 68. *Close up view of fossiliferous, organic-rich, Cape Cormorant graptolitic shale, at Cape Cormorant.*

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. 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.

Figure 69. *Steep, west to northwest dipping Cape Cormorant Formation interbedded shale, ribbon limestone, and debris-flow conglomerate exposed at Cape Cormorant.*

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.

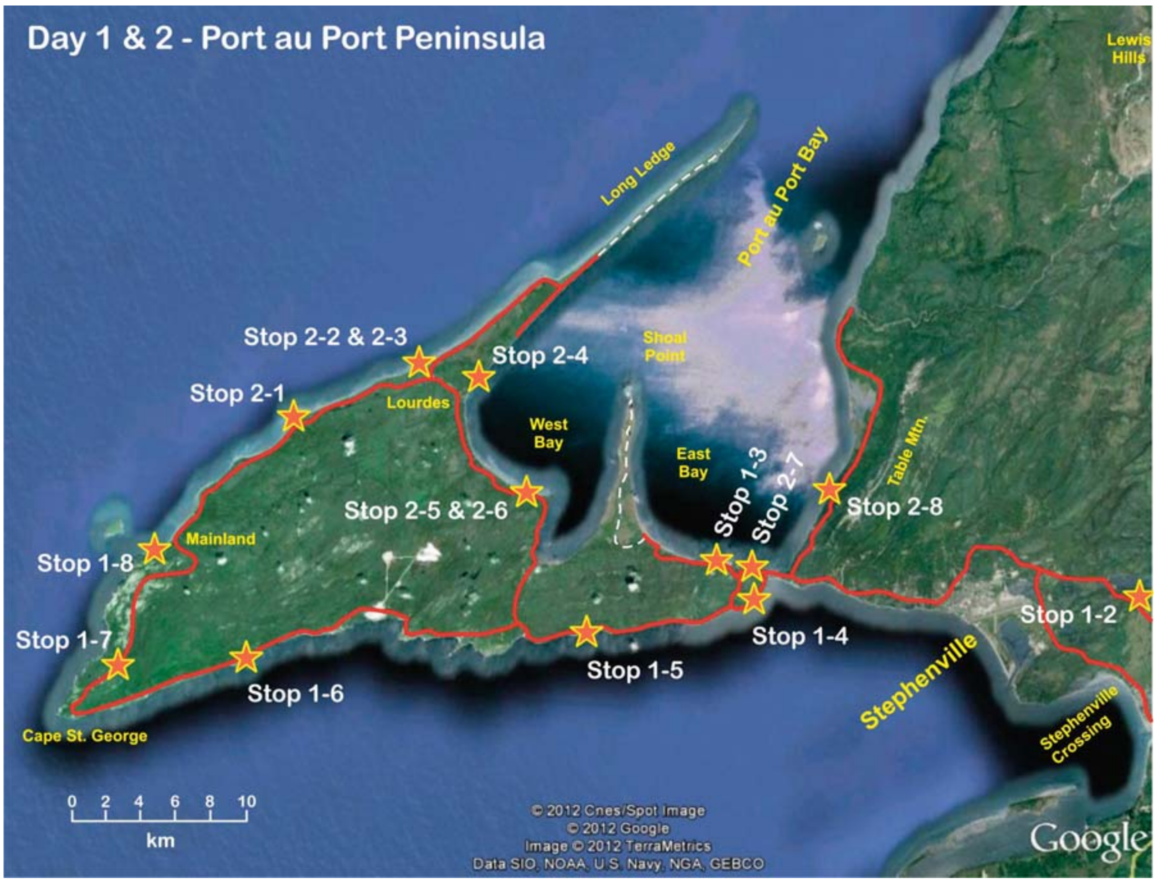
Inland, along Caribou Brook and on other exposures along the western edge of the Peninsula, the formation disconformably overlies the Table Point Formation. However, these conglomerates lens out rapidly in just a few kilometres to the east. Ribbon limestones and shales of the Table Cove Formation occupy an equivalent position in the stratigraphy in the eastern two-thirds of the peninsula, although in some places equivalent strata are absent and in places the Goose Tickle Group directly overlie 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 to 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, and was intersected by the Port au Port #1 (Garden Hill) well (Figure 44).

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.

DAY 2 (Figure 53). FORELAND BASINS TO HUMBER ARM ALLOCHTHON



STOP 2.1: Three Rock Cove

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

At this locality (Figure 70), 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 southwest of this location, between it and the grey-green sandstones of the Mainland Formation that occur in the cliffs farther southwest. However, it is also possible (Stockmal and Waldron, 1993) that this outcrop lies in the hanging wall of the Round Head Thrust, which would necessarily run offshore somewhere to the northeast, 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.

Figure 71 shows a view northeast towards Round Head. The Round Head Thrust in this view passes through the grassy notch in the skyline, between the steep scarp of Round Head to the right (Ordovician conglomerate; Cape Cormorant Formation) and the grey and red rocks of the Devonian Clam Bank Formation in the low sea cliff to the left.

STOP 2.2: Clam Bank Cove (north end)

Clam Bank Cove is situated in some of the youngest rocks of the foreland basin successions on the Port au Port Peninsula (Figures 30, 72, 73). 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.

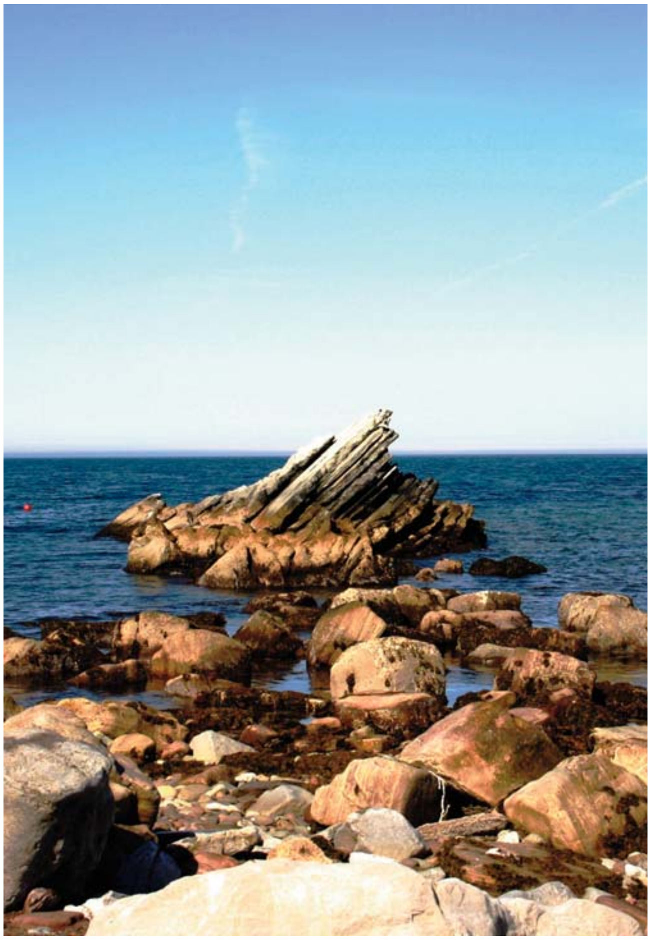


Figure 70. *Southeast dipping, overturned, thin, fine grained beds of Lourdes Formation limestone (Long Point Group), at Three Rock Cove.*

Figure 71. *View north from Three Rock Cove; the Round Head Thrust trends along the base of the steep scarp face.*

Figure 72. *Overturned, east to southeast dipping Winterhouse Formation shelf sandstone and shale, north side of Clam Bank Cove.*

Figure 73. *Overturned, east to southeast dipping, fluvial to shallow marine Misty Point Formation redbeds, north side of Clam Bank Cove.*

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 red strata of the Misty Point Formation. Sedimentary structures in both units indicate that they are overturned, and that the strata young seaward. Stratigraphically, the Misty Point Formation therefore overlies the Winterhouse Formation. 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 regressive sequence indicates progressive filling of the foreland basin as sediment supply from the orogen exceeded the subsidence rate.

STOP 2.3: Clam Bank Cove (south end)

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

At the southwest end of the cove (Figure 74), probable Ordovician redbeds of the 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 (Figure 75), 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,

Figure 74. *Wide view of Clam Bank Cove south; foreground strata (left) Misty Point Formation redbeds; background strata, shallow marine to terrestrial Clam Bank Formation sediments.*

Figure 75. *Overturned, east to southeast dipping, grey to red clastic sediments and limy, fossiliferous grainstones of the Clam Bank Formation.*

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 the contact has been interpreted as a fault. 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 'Salinian' unconformity.

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; Figures 33, 34). These red sedimentary rocks have yielded Emsian spores (Quinn *et al.*, 2004).

STOP 2.4: Tea Cove

Caution: *Be aware of the potential for falling rocks and wear protective headgear if examining the steep cliffs. The shoreline outcrops and the approach can be slippery. This outcrop is best approached on a falling tide, close to low tide,, as access is limited when the tide is high.*

The walk to Tea Cove is across varied units of the Humber Arm Supergroup, most of which are turbiditic limestone and shale that have been assigned to the Green Point Formation of the Cow Head Group (although assignment to the laterally equivalent Cooks Brook Formation of the Northern Head Group is also possible) (Figures 76, 77, 78, 79). The presence of abundant graptolites in some units indicates that the rocks are of Ordovician age. The rocks are significantly more deformed than most of the shelf succession and overlying foreland basin rocks of the Table Head Group. Extensional structures are common, and in places the beds show 'chocolate tablet' boudinage indicating that they were extended in all directions during emplacement of the Humber Arm Allocthon. Veins formed in the extensional voids that opened between blocks of the more competent beds typically contain calcite but locally also contain pyrobitumen, indicative of the oil-rich character of the Humber Arm Allochthon during emplacement.

The contact with the overlying Lourdes Limestone, marking the mapped Tea Cove thrust at the top of the Humber Arm Allochthon, is poorly exposed and typically requires digging out (Figure 80). The contact zone contains sheared shales and sandstones that may be derived from either of the juxtaposed units. Waldron and Stockmal (1991) extracted samples from the surface and showed that they bore slickenlines plunging down the dip of the surface, indicating tectonic movement on what had previously been mapped as an unconformity. Although the map and subsurface seismic relationships require significant deformation in this zone, it is quite likely that the contact originated as an unconformity that was a plane of weakness during later deformation. West-dipping sandstones and limestones of the Lourdes Formation of the Long Point Group occur in the hanging wall of the thrust and form the scarp to the north, along the east shore of Long Point.

The Tea Cove thrust represents the top of the Humber Arm Allochthon. Down dip to the northwest, the Tea Cove thrust meets the West Bay thrust (representing the base of the Allochthon) at the 'blind' tip of a tectonic wedge or triangle zone.

STOP 2.5: West Bay Quarry

Caution: *Be careful when crossing this busy road. In the quarry be aware of the potential for falling rocks and wear protective headgear if examining the steep surfaces.*

The quarry in West Bay (Figure 81) is well known for the abundance of fossils found in rocks of the Table Head Group. At the back (south) wall of the quarry, the uppermost beds of the Table Point Formation can be recognized by their thick bedded, bioturbated facies. These are overlain by a succession of interbedded fine-grained fossiliferous ribbon limestone and shale of the Table Cove Formation. The fossils include graptolites, the trilobite *Cybelurus mini* (Billings, 1865) and inarticulate brachiopods. The fauna are Darriwilian (Middle Ordovician) in age. These were deposited in slope or basin settings adjacent to remaining horsts of platform carbonates in the Taconian foreland basin, which was dissected by faults. The Table Cove Formation is contemporary with the much coarser conglomeratic rocks of the Cape Cormorant Formation. The Black Cove Formation (Goose Tickle Group), which overlies the ribbon limestone, is a dark grey, organic rich shale that is a potential source rock with TOC of up to 2%. Thin Daniel's Harbour Member occurs in the upper ter-

Figure 76. *Thickly bedded, coarse grained, greyish-green, greywacke sandstone (Humber Arm Allochthon) near Rocky Point, West Bay.*

Figure 77. *Thinly interbedded, northwest dipping, ribbon limestone and black shale (Humber Arm Allochthon), West Bay.*

Figure 78. *Folded Humber Arm Allochthon black shales and calcarenites, north of Rocky Point, West Bay.*

Figure 79. *Thick, moderately west dipping sequence of Lourdes Formation limy sandstone (base) and limestone, north of Rocky Point, West Bay.*

Figure 80. *Tea Cove Thrust contact between foreland basin Lourdes limestone (top unit) and Humber Arm Allochthon (bottom unit), at Tea Cove.*

Figure 81. *Thinly bedded, Table Cove Formation ribbon limestone and organic-rich black shale exposed at West Bay Quarry.*

race of the west face of the quarry (Figure 82). An oil seep is reported in the southeast corner of the quarry.

STOP 2-6: West Bay Shoreline

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

The Table Cove Formation is well exposed at the mouth of the small stream that descends to the shoreline west of the store (Figure 83). 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 basal units of the 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 Cove Formation 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) is marked by highly deformed, black and green scaly shales of the Humber Arm Supergroup (Figure 84). 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 later 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 Northern Head Group, or the laterally equivalent Green Point Formation 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 (Figures 85, 86). The stratigraphic affinity of these units is not known for certain. They could be the youngest unit of the Humber Arm Allochthon (Eagle Island Sandstone), or they could be a tectonically incorporated slice of Goose Tickle Group. The two units (Eagle Island and Goose Tickle) can be lithologically very similar but are of slightly different age; unfortunately no graptolites have been found. However, the tectonic state of the unit and the observed lithological differences from the Goose Tickle Group located at the west end of the section favour assignment to the Eagle Island Sandstone.

Figure 82. *Black Cove Formation organic-rich black shales overlain by Daniel's Harbour Member limestone conglomerate, West Bay Quarry.*

Figure 83. *Table Cove Formation strata (right) in thrust contact with Humber Arm Allochthon mélange (left), West Bay Beach.*

Figure 84. *Shaly mélange and breccia (foreground) overlain by siliceous chert, Humber Arm Allochthon, West Bay Beach.*

Figure 85. *Tightly folded Eagle Island (?) sandstone and shale in fault contact with shaly mélange, West Bay Beach.*

Figure 86. *Tightly folded Eagle Island (?) sandstone and shale within Humber Arm Allochthon, West Bay Beach.*

STOP 2.7: Gushue's Cove

At this locality, carbonate and clastic sequences of the Upper Mississippian (Carboniferous), Big Cove Formation unconformably overlie karsted limestones of the Table Head Group. The erosional surface is clearly visible on both sides of the cove (Figure 87).

To access this site, proceed approximately 200 m beyond Our Lady of Mercy Church and then follow the dirt track (north side of paved road) approximately 300 m to the cove. Note that recent trail construction may have slightly changed the access route. If so, follow the Gravels Trail directional signs.

The Upper Mississippian strata seen at Gushue's Cove belong to one of numerous Carboniferous outliers that unconformably overlie carbonate strata of the Port au Port, Table Head and St. George Groups and the Humber Arm Allochthon from West Bay to Piccadilly and at Romaine's Brook near Stephenville.

On the Port au Port Peninsula, the Carboniferous rocks have been assigned based on lithological variation to the Big Cove and Lower Cove formations. The Big Cove Formation is prevalent along the northeast coast between Boswarlos and the Gravels, while Lower Cove strata outcrop mainly along the southern shore. The type section for the Big Cove Formation is located north of Cape St. George at Big Cove (Dix and James, 1988). Lithologically, the Big Cove Formation consists of an intercalated sequence of bedded biohermal limestone, calcareous sandstone and sandy limestone breccia. The strata appear to be very discontinuous, with the best exposures and most complete sections found along the northeast coast at Lead Cove, Bellman's Cove and Gushue's Cove. A general lithology characterized by a break in sedimentation, permits grouping the formation into an Upper and Lower sequence (Dix, 1981).

Figure 87. *East and West views of Gushue's Cove; highlighting the unconformity separating medium brown Carboniferous (Mississippian) strata from underlying dark grey Table Point Formation (Table Head Group) carbonates.*

The Big Cove Formation strata at Gushue's Cove fall within the Lower sequence, an intercalated package of carbonate, calcareous sandstone and sandy breccia, with or without bioherms. Located immediately above the unconformity is a very thin layer of grey to green-grey arenaceous lime mudstone, overlain by grey to beige, massive, unbedded bryozoan mounds, intermound bedded skeletal to pelletal packstone and/or grainstone and well developed biolithites of similar lithology to mounds, but lacking internal bedded sediment (Dix, 1981). Biolithites developed primarily along the steep walls of the erosional surface (Table Head strata) and built outwards into depressed areas. Lithologically, the mounds and biolithites exhibit tiny colloform structures with cores of bryozoans, algae and serpulid-type worm tubes. Associated fauna include brachiopods (Beecheria, Martinia galataea – Bell 1948), pelecypods and large cylindrical worm tubes (Dix, 1981). Mound and biolithite structures are overlain by and intercalated with bedded packstones, grainstones and thin black shaley limestones which may slope up to 30° towards the center of the cove. Calcareous sandstone and sandy breccia overlie and locally intercalate with the underlying sequence.

STOP 2.8: Black Point

Caution: *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 (Figures 88, 89, 90, 91, 92). 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 two stratified formations of the Humber Arm Supergroup. The Middle Arm Point formation (laterally equivalent to the upper part of the Green Point Formation) consists of fine-grained red and green shale, siliceous shale and chert, with rare carbonate beds. These are probably time-equivalents of the upper part of the St. George Group in the shelf succession, with which they present a striking contrast. 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 sec-

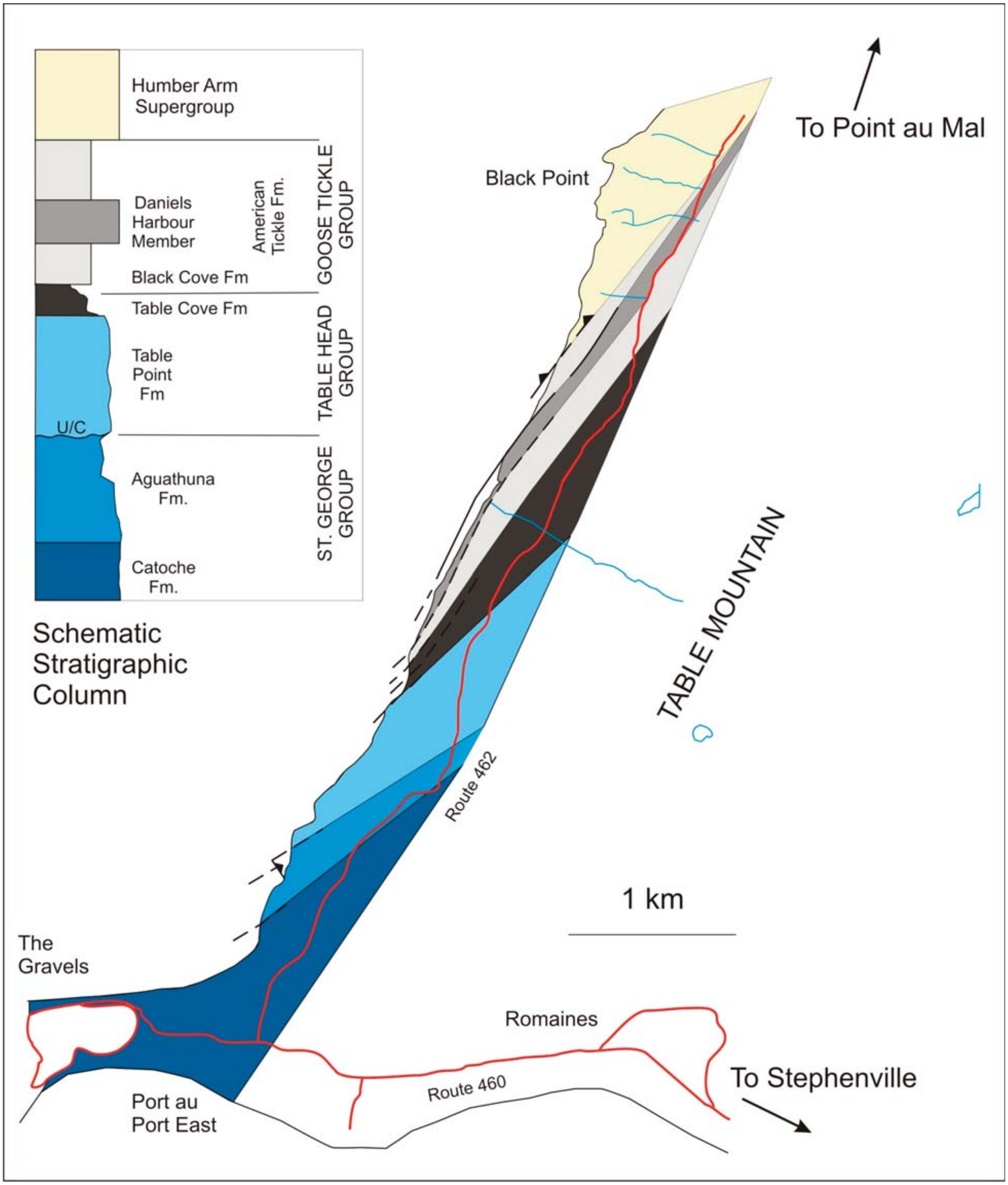


Figure 88. *Simplified geology map for the eastern side of East Bay, Port au Port Bay area.*

Figure 89. *Goose Tickle Group strata tectonically beneath Humber Arm allochthonous rocks, Black Point.*

Figure 90. *Highly sheared, Humber Arm Allochthon (Middle Arm Point? Formation) red and green shale exposed at Black Point.*

Figure 91. *Dark grey-green, Eagle Island Formation sandstone structurally juxtaposed with red and green Middle Arm Point Formation sheared shale, Black Point.*

Figure 92. *Spectacular, asymmetric folds within Middle Arm Point Formation red and green, siliceous shale, Black Point.*

tions which mostly trend northeast-southwest. 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 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.

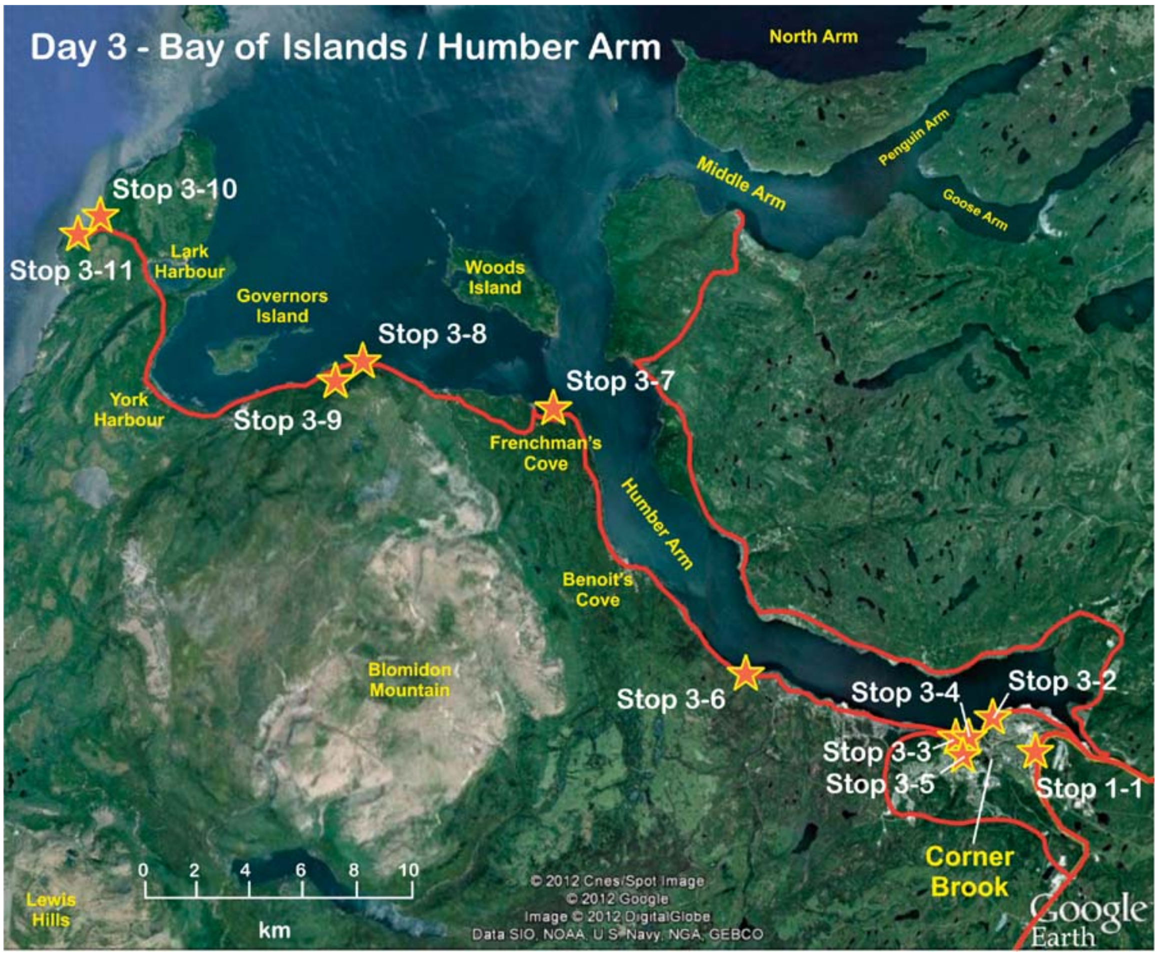
STOP 2.9: Trans-Canada Highway near Pinchgut Lake (Pinchgut Lake Group)

Keep off the highway at all times. If you have to cross the highway, make sure there is no traffic and do not follow a group across.

Roadside outcrops on the Trans Canada Highway display the Pinchgut Lake Group, part of the Watson's Brook Succession, the tectonic slice of the Humber Arm Allochthon that originated closest to the platform edge. The succession is significantly metamorphosed, and age control is poor. The rocks are deformed impure limestones, including thick limestone conglomerate units, with interbedded ribbon dolostone and phyllite.

The outcrops are of interest because of their variety of deformation features. West dipping shear zones show kinematic indicators of west-side-down, normal sense ductile shearing, but these are overprinted by brittle thrust faults with slickenfibre lineations. The normal sense shear zones could be D_3 extensional features, or they could be D_1 (Taconian) thrusts that have been folded into their current orientation by F_2 folds.

DAY 3 (Figure 54). BAY OF ISLANDS



STOP 3.1: Pasadena Off Ramp

For the first segment of travel, the Trans Canada Highway (Route 1) trends southwest and parallels the structural trend of the rocks in the region, in predominantly metamorphic rocks of the Internal Humber zone (Williams, 1978). The lowermost unit the Corner Brook Lake Complex consists of Grenvillian gneissic rocks and forms the basement rock to the overlying cover succession (Cawood and van Gool 1998). Metamorphic rocks with Neoproterozoic igneous protoliths included granodioritic gneiss and amphibolite of the Lady Slipper Pluton, which in turn, are unconformably overlain by a metaclastic sequence, the Mount Musgrave Group, and a conformable upper carbonate dominated succession. Exposures observed along the way are metamorphic rocks, mostly fine (pelitic) to coarse (psammitic) grained schists derived from shale and greywacke sandstone protoliths representing sediments deposited along the margin of the juvenile Iapetus Ocean. These rocks are thought to be very latest Precambrian to potentially lower Ordovician and they comprise part of the South Brook Formation, Mount Musgrave Group. The schists are muscovite mica and/or quartz-feldspar rich and they have been subjected to at least three episodes of deformation. Tight to open macro-folds, smaller scale chevron to kink folds, high angle faults, thrust faults and ductile shear zones are some of the deformation features visible in the cliff faces (Figure 93).

Travel: *Pasadena to Corner Brook*

Marble Mountain

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 / gorge 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 lime-

Figure 93. *Pelitic and psammitic metasediments of the South Brook Formation (Mount Musgrave Group) exposed along the TCH near Pasadena.*

Figure 94. *Vertically dipping Reluctant Head Formation (left) and Port au Port Group strata (right) exposed along Trans-Canada Highway, west of Marble Mountain.*

stone, limestone conglomerate, dark grey slate and phyllite (Figure 94). 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).

Limestone Junction Quarry

Dolomitic and calcareous, white to cream marble has been quarried (Figure 95) intermittently since the late 1880's, when it was first used as a source for building stone and a few years later as ballast along the railway line. Following construction of the Grand Falls paper mill in 1905, the stone was used for a number of years in their chemical pulping process and later between 1925 and 1943 it was utilized at the Corner Brook paper mill. The quarry was abandoned in 1943 due to difficulties quarrying in the fractured rock and risks posed by rock debris to the adjacent railway and highway. After 1943, limestone for the Corner Brook mill was obtained from the Dormston and Leonard House Quarries both located a few kilometres from the mill.

Just west of the quarry site, near Shellbird Island, the Reluctant Head Formation is exposed once again in the core of the Bear Head Anticline. The roadside exposure (south side of highway) adjacent to Duncan's Brook is fine grained, thinly bedded, ribbon banded limestone and phyllite and displays close to isoclinal folds (Figure 96).

Old Man in the Mountain

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"** (Figure 97). Legend has it that pirates had at one time sailed into the outer Bay of Islands and hid for a short period of time behind one of the many islands to escape detection from naval ships. To avoid capture and run the risk of losing their plundered treasure, they decided to sail further up the bay into Humber Arm and bury their treasure on Shellbird Island, which lay a few kilometres from the mouth of the Humber River. In order to locate their treasure at some future time, the pirates marked its location by carving an old man's face into the cliff, positioning it to stare remorsely down on the treasure location. According to local folktales, many attempts have been made to locate the pirate riches, but to this day it has escaped detection.

Farther west the highway exits Humber gorge and intersects the Riverside Drive overpass, where the excursion will follow the off-ramp and continue along Riverside Drive into downtown Corner Brook. Just beyond (west) the turn-off to Riverside Drive the TCH begins an uphill climb to the Confederation Drive exit into the city. 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 east-west and northeast-southwest striking, steep oblique-slip and strike-slip faults. The fault surfaces, exhibit metre scale undulations and parallel slickenlines (Figure 98).

Riverside Drive off-ramp

The succession of Port au Port and St. George Group carbonates (Figure 99) is sporadically exposed along Riverside Drive between the Trans-Canada Highway off-ramp and the contact with Humber Arm Allochthon. 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 (Figure 100).

Across the river (to the northeast) near Brakes Cove, a 50 m high gravel terrace can be seen at the base of Mount Patricia. This wave-cut terrace is the remnants of a glacial outwash delta formed at approximately 12.5 ka, when melting glaciers located in Wild Cove valley and Humber valley were discharging large volumes of sediment into Humber Arm. Today the gravel terrace is site for the Mount Patricia cemetery.

Figure 95. *Abandoned limestone / marble quarry at Limestone Junction, TCH west of Marble Mountain.*

Figure 96. *Close to tight folds within Reluctant Head Formation strata; near Duncan's Brook, Humber gorge.*

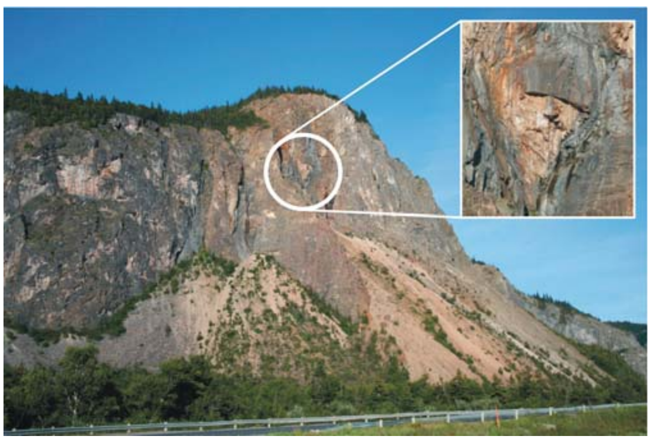


Figure 97. *Vertically dipping Port au Port Group / Reluctant Head Formation strata at Bear Head, Humber gorge; Insert – Old Man in the Mountain.*

Figure 98. *Well defined fault plane near Riverside Drive off-ramp; slickensides indicate oblique-slip motion.*

Figure 99. *Moderately west-dipping limestone / dolostone beds of the carbonate shelf succession along Riverside Drive.*

Figure 100. *Mount Patricia (High Knob) synclinal F2 fold, north of the Humber River at Riverside Drive.*

Brakes Cove

At Brakes Cove, the route crosses a major shear zone (Watsons Brook Shear Zone) separating carbonate platform rocks from strata of the Humber Arm Allochthon. A narrow zone of shaly mélange is encountered just before the LaFarge Gypsum operation (Figure 101). This mélange in turn is in tectonic contact with a narrow sliver of Summerside Formation slate. The slate is overlain by quartzose sandstones and shales of the Irishtown Formation (Figure 102). Atlantic Ready Mix produces concrete products and sand / gravel aggregate at a facility here (Figure 103).

STOP 3.2: Seal Head Syncline

Caution: *Take care crossing the road, and do not attempt to stand close to the foot of the cliff where falling rocks are a hazard.*

See Figure 54 for stop locations in the Bay of Islands area.

There are four cross-sections through the F_2 Seal Head syncline in the city of Corner Brook. This stop is at the northernmost of these, beside the former railway yards now occupied by various parking and industrial lots along the shore of Humber Arm. The view of the cliff (Figure 104) displays a magnificent syncline in the quartz-rich sandstone and conglomerate of the Irishtown Formation (Lower Cambrian). Although the fold appears symmetric in the southwest-northeast cutting, this is an illusion; the hinge actually trends north-south, so the view in the cliff is very oblique, and the dips are apparent. A profile view reveals that this is an overturned fold, with a near-vertical to overturned west limb and a much gentler east limb. The cleavage dips moderately west, and is axial planar to the fold, making it an F_2 fold, formed after the original stacking of thrust slices onto the continental margin. The syncline can be traced through the hill and is exposed in three more cross-sections to the south: both sides of the deep Lewin Parkway cutting, and on the southwest side of Hospital Hill behind the Glynmill Inn hotel.

STOP 3.3: 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 at this site.*

Monument site

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.

Figure 101. *Shaly mélange exposed along Riverside Drive just west of Brakes Cove.*

Figure 102. *Interbedded quartzose sandstone / slate of the Irishtown Formation (Curling Group), east of Seal Head.*

Figure 103. *Atlantic Ready Mix aggregate / concrete products operation at Brakes Cove, Riverside Drive.*

Figure 104. *East verging, close to tight, F2 synclinal fold at Seal Head, Corner Brook waterfront.*

The hilltop is a monument commemorating the surveying work of the British Admiralty, and in particular Captain James Cook (Figures 105, 106), 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 Summerside Formation (Figure 107), 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 which have oriented themselves 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 get younger 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 is said to face down on the cleavage planes. 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.

View East

To the east (Figure 108), 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.

View North

To the north, the view is across the Humber Arm. The eastern part of the view is occupied by Irishtown Formation of the Corner Brook Slice around the community of Irishtown. To the west, the community of Summerside rests on Summerside Formation, which produces somewhat 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.

View West

To the west (Figure 109), most of the forested ground in the middle distance is occupied by the Humber Arm Allochthon, Corner Brook sheet, in which rocks are disposed in a broad

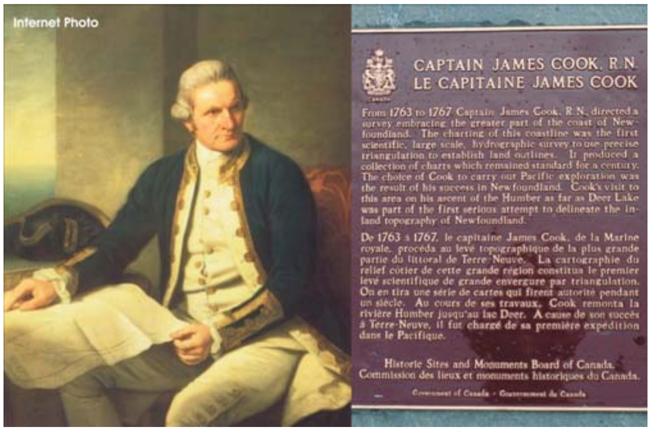


Figure 105. *Portrait of Captain James Cook; information plaque.*

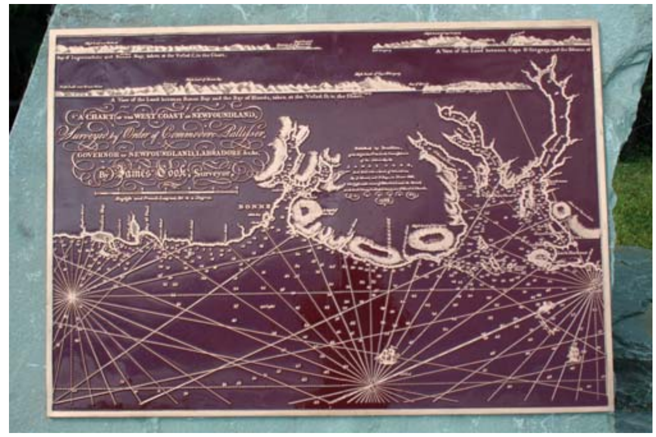


Figure 106. *Plaque depicting Captain James Cook navigational chart for Bay of Islands & Bonne Bay.*

Figure 107. *Steeply dipping, interbedded quartzose sandstone / shale of the Summerside Formation (Curling Group), top of Crow Hill.*

Figure 108. *Panoramic view of the inner Humber Arm; foreground - Corner Brook pulp & paper mill; background – lower structural slices of Humber Arm Allochthon and carbonate platform succession.*

Figure 109. *Panoramic view of the outer portion of Humber Arm; background higher elevation – Bay of Islands Complex (ophiolite: foreground – lower structural slices of the Humber Arm Allochthon.*

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 ocean floor of the Iapetus Ocean, or one of its branches.

STOP 3.4: Atlantic Avenue, South of Crow Hill

Safety: *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 (Figure 110) 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 westward 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.

STOP 3.5: Lewin Parkway (below Crow Hill)

Caution: *Park at Quarry Road and walk along Curling Street to the west. This is a busy street with no sidewalk. Watch out for traffic and walk facing the oncoming traffic if possible. Depending on the number of participants, the traffic situation, and timing, this stop may be omitted.*

The rocks in the roadcut here are mainly maroon slate (Figure 111) of the Summerside Formation with cleavage dipping west. At this point it is possible to find recumbent west-facing folds in the cliff that are probably F_1 (Taconian) folds related to the emplacement of the allochthon. In places the pressure solution cleavage in the sandstone appears to be axial planar to these folds and may therefore also be an S_1 Taconian cleavage. However, the slaty cleavage crosscuts the folds and is probably S_2. To the east, it is possible to walk through the thrust contact (Crow Hill Thrust) with the Irishtown Formation below (Figure 112).

Beyond Barry's Fish Plant, faulted and folded, interbedded quartzose sandstones and shale belonging to the Irishtown Formation (Figure 113) are sporadically exposed in roadside outcrops up to Giles Point.

Travel: *Giles Point to Halfway Point*

From Giles Point (east of Cook's Brook) to Halfway Point (west of Cook's Brook) there is a near continuous sequence of Northern Head Group, Cook's Brook Formation exposed along the south side of the highway and within the stream bed of Cook's Brook. Ribbon to parted limestones, shale and limestone conglomerate are the dominant lithologies (Figure 114). According to Bosworth (1985), strata are generally west dipping and cut by numerous

Figure 110. *Crow Hill thrust fault exposed near the southern end of Atlantic Avenue, Corner Brook.*

Figure 111. *Maroon colored, Summerside Formation slates exposed at Quarry Hill road, Lewin Parkway.*

Figure 112. *Crow Hill thrust fault beneath Crow Head, placing Summerside Formation over Irishtown Formation.*

Figure 113. *Faulted, interbedded shales and thickly bedded quartzose sandstones of the Irishtown Formation exposed along Griffin Drive.*

west-facing normal faults. The section is folded by small amplitude, moderate to tight cleavage generation folds. These folds are extremely asymmetric with long west-dipping limbs.

STOP 3.6: Cooks Brook

Caution: *Take care crossing the road, if necessary. The rocks in the brook may be slippery.*

Enter the brook on the north side of the road and work downstream to see typical sections near the base of the Cooks Brook Formation and the top of the underlying Irishtown Formation. There are substantial sections of dark grey to black shale in both the uppermost Irishtown Formation and the lower Cooks Brook Formation, and there is the possibility of structural repetitions complicating the stratigraphy. The Cooks Brook Formation here represents the Middle Cambrian deep-water equivalents of the Port au Port Group and lower part of the St. George Group of the shelf succession. Thin beds of limestone represent carbonate turbidites that flowed down the continental slope. Finer-grained limestones may also represent the deposition of shelf muds that were suspended in major storms and then settled in deeper water. Locally, the Cooks Brook Formation contains substantial layers of limestone conglomerate derived from slope failures at the platform edge or higher up on the continental slope. One of these is visible in the highway cut about 400 m west of Cook's Brook (Figure 115).

STOP 3.7: Frenchman's Cove Mélange

To access this stop, travel east along the beach at Frenchman's Cove out to the first headland before Frenchman's Head. The fragmented rock on this coastline has been variously described as mélange or broken formation, or as a synsedimentary olistostrome produced by down-slope sliding. It probably occurs between the Corner Brook and Woods Island sheets of the Humber Arm Allochthon. Despite early claims that the Bay of Islands mélanges were "ophiolitic", most outcrops of disrupted lithologies contain only sedimentary protoliths. Here sandstone, thin-bedded limey shale, and dark grey shale blocks suggest derivation from Cook's Brook, Middle Arm Point and Eagle Island formations, embedded in a black to green shaly matrix (Figure 116).

Travel: *Frenchman's Cove (middle) to Saltwater Cove Road*

Broken formation in the highway cuts on this section of the route have been variously mapped as mélange or as Eagle Island Formation. West of Frenchman's Cove Route 450 takes a sharp switchback and follows a south-southeasterly trending ridge uphill for approximately ½ kilometre before turning to the southwest and then north-northwest, to roughly parallel the northwest-southeast face of Blow Me Down Mountain. Black, fissile Eagle Island Formation shale is sporadically exposed on both sides of the road on the uphill and summit section to Saltwater Cove road (Figure 117). Immediately west of Frenchman's Cove the road crosses the Woods Island thrust and passes onto the highest thrust sheet of the Humber Arm Allochthon in this area, the Woods Island sheet, dominated by massive sandstones of the Blow Me Down Brook Formation.

Figure 114. *Thin bedded (<20 cm), parted limestone / shale of the Cook's Brook Formation along Route 450, west of Cook's Brook (south shore Bay of Islands).*

Figure 115. *Thick bedded, Cook's Brook Formation limestone conglomerate exposed along Route 450, west of Cook's Brook.*

Figure 116. *Highly disrupted, shale and thin bedded limestone of the Middle Arm Point Formation (Northern Head Group) at Frenchman's Cove (east side).*

Figure 117. *Eagle Island Formation shales exposed along Route 450, immediately south of Frenchman's Cove.*

STOP 3.8: Candlelight Bay Inn

Notes on this stop are based on descriptions by E. Burden, in *Hicks* et al. *(2010), and by Gillis (2006).*

The Blow Me Down Brook formation (Figure 27) occupies a belt of thick-bedded grey-green coarse-grained arkosic sandstone extending from Bonne Bay in the north to perhaps as far south as the east shore of Port au Port Bay. In the east, strata are sharply delimited by the Woods Island Thrust; in the west, the rocks apparently extend to the vicinity of the Little Port volcanic complex. Neither the top nor the bottom of this formation is well defined (Figure 20).

Sandstones show a combination of thick- and thin-bedded deposits of coarse and pebbly rocks that may be massive, graded, and cross bedded. Finer interbeds include black, green and red shale and siltstone. In a few places a carbonate boulder conglomerate is seen in the middle of the formation (Gillis and Burden 2006).

The Blow Me Down Brook formation was originally interpreted as Early Ordovician flysch positioned at the top of the Humber Arm Supergroup (Stevens, 1970). However, the discovery of the trace fossil *Oldhamia* in the shaly strata of the formation (Figure 28) indicates that it is Early Cambrian and therefore should be placed at the base of the Humber Arm Supergroup (Lindholm and Casey, 1990; Cawood *et al.*, 1988).

From palynomorph studies Lavoie *et al.* (2003) suggest the Blow Me Down Brook formation may be laterally correlative to the Summerside and Irishtown formations of the Curling Group with the Labrador Group of the shelf successuon.

Stratigraphic and petrographic studies completed by Gillis (2006) and in part summarized in Gillis and Burden (2006) indicate the Blow Me Down Brook formation contains 4 to 6 distinctive units. Red beds in contact with Fox Island volcanics, and exposed on the western flank of the Lewis Hills, may be the lowest interval of the formation. *Oldhamia* is relatively common in some of the shale beds of the upper parts of this succession.

The Blow Me Down Brook formation is interpreted as a deep marine deposit, formed on a rifted continental margin. Paleoflow measurements taken at numerous locations suggest a southerly trend, and possibly down the axis of a graben. Channels, dewatering structures, conglomeratic units and partial Bouma sequences support the submarine fan interpretation.

However, it is likely that the coarse arkosic unit was deposited in a shallower marine setting. In contrast, the upper parts of the formation contain more quartzose sandstones likely sourced from mature coastal sands, which tend to have a little more porosity and may be petroliferous (Figure 118) (Hicks *et al.*, 2010).

STOP 3.9: York Harbour Mine Adit

Caution: *Do not attempt to enter mine workings.*

The Bay of Islands Complex consists of a lower assemblage of serpentinized ultramafic rocks (harzburgite, dunite, pyroxenite and lherzolite), overlain by layered to massive, intermediate to mafic intrusive rocks (diorite, trondhjemite and gabbro), which in turn are overlain by a Lower Basalt unit (characterized by highly altered basalt flows, pillow lava, pillow breccia and sheeted dykes), a middle pyroclastic-sedimentary horizon (characterized by coarse andesitic agglomerate with minor interbedded felsic tuffaceous beds, chert-pyrite horizons and thin hematite–iron formation) and a less altered Upper Basalt unit (mainly undeformed basalt flows, pillow lavas and pillow breccias, with interstitial red jasper).

The York Harbour deposit (Figures 119, 120) is a stratabound, Cyprus-type volcanogenic Cu–Zn ± Ag, Au massive sulphide deposit hosted by these ophiolitic mafic volcanic rocks (NLDNR MODS ID# 1775). The deposit consists of multiple, small (*e.g.*, <60,000 tonnes), irregular lenses of Cu–Zn rich ore contained within the upper altered Lower Basalt unit. Mineralization consists of massive pyrite, sphalerite and chalcopyrite with minor pyrrhotite

Figure 118. *Pyrobitumen stained fracture surfaces within Blow Me Down Brook Formation sandstones, shoreline near Candlelite Bay Inn.*

Figure 119. *Sealed portal entrance (adit) located northeast from the abandoned York Harbour Copper Mine.*

Figure 120. *Hematitized and epidotized pillow basalts of the Bay of Islands Complex volcanic rocks, adjacent to York Harbour mine adit.*

and galena. Silver and gold values are sporadic throughout the deposit. The massive sulphide ore lenses are typically brecciated and are underlain by variably developed stringer-stockwork zones, typically associated with intense hydrothermal brecciation, quartz-carbonate veining, sulphidization and chloritization. The favorable horizon occurs over a 100 m width and appears associated with high angle, north-northwest to southeast trending shear zones. In contrast, the hanging wall contacts are sharp and overlying basalts are unaltered and contain on average less than 1% disseminated pyrite.

History

Historical details of this site mainly after Martin (1983).

The York Harbour copper deposit was discovered near the top of Blow Me Down Mountain in 1893 by prospector Daniel Hendersen. Mr. Hendersen received monetary support from St. John's merchant A.J. Harvey in return for part ownership of the property. Mining began in 1897 with Hedley Smythe as mine manager and Charles Rendell as mine captain. The company sank four shafts and constructed a makeshift chute and pulley contraption to transport pork barrels of ore down the cliff to the coast. By 1899 the company had raised only 500 tons of ore and in their frustration the directors fired Rendell and leased the property to the York Harbour Copper Company.

The new mine captain James Hooper appears to have had little mining experience and worse still, very little luck. A fire destroyed the mine site, an epidemic rendered everyone sick for a period of time and the miners were constantly harassed in their efforts to build a tramway and pier by the French navy. By the time the property lease expired (late 1901 – early 1902), the York Harbour Copper Company had raised a meagre 100 tons of ore. Based on these results, A.J. Harvey refused to extend the lease and in 1902 he formed the Western Copper Company Limited with Charles Willis of the Humber Consolidated Mining & Manufacturing Company and the original discoverer Daniel Hendersen.

The Western company leased the property to Willis who then leased it in 1902 to the Humber Company. Between 1902 and 1905, about 15,000 tons of ore was shipped to the United States. As a result of a shortage of funds and a legal dispute, the property was awarded back to the Western Copper Company in 1906. The Western company optioned the property in 1909 to a group of British mining engineers and merchants, who formed the York Harbour Mine (Newfoundland) Limited, producing copper until 1913. The Newfoundland government considered financing the erection of a smelter on site, however, the smelter was never built and by 1913 the mine was running out of known reserves. In July 1913 the last load of ore left York Harbour for the United States and by September 1913 the mine was closed. In total the York Harbour Mine (Newfoundland) Limited shipped approximately 15,000 tons of ore.

In 1950 when the property was optioned by Independent Mining Corp. Limited. In 1953, as a result of geophysical surveys and further drilling they estimated total reserves at 93,000 tonnes grading 2.38% Cu and 6.80% Zn. In 1955, the mining rights were acquired by Big Nama Creek Mines Ltd. who calculated reserved at 176,000 tonnes grading 2.65% Cu and 8.25% Zn. In 1965 an adit was collared east of Mine Brook with the intent to intersect the old mine workings along the Lower Basalt / Upper Basalt contact (Figures 119, 120). Work was halted in 1966 when fire destroyed the diesel-electric plant and surface buildings. New reserve calculations reported 198,000 tonnes grading 2.68% Cu and 8.25% Zn.

Between 1968 and 1990 a number of companies conducted various levels of exploration work at the York Harbour site: Brinex in 1968, Long Lac Mineral Exploration Ltd. in 1969, Noranda in 1974, Labrador Mining and Exploration Company Ltd. in 1975, York Consolidated Exploration Ltd. (formerly Big Nama) in 1977, Lacana-Corona in 1987 to 89 and finally Noranda Exploration Ltd. in 1990.

In 1990, Noranda Exploration acquired the rights to the York Harbour property and began an exploration program with joint venture partner Cumberland Resources. A company report from 1991 lists estimated reserves at 200,000 tonnes grading 2.68% Cu, 8.25% Zn, 1–2 oz/t Ag and <1.0 g/t Au. Despite interest and involvement in the property by several other companies, no development of the mine has occurred.

STOP 3.10: Bottle Cove

Notes on this stop are based on descriptions by E. Burden, in *Hicks* et al. *(2010) and by Strowbridge (2001).*

The Little Port Complex represents the leading, westernmost edge of the ophiolites that cap the Humber Arm Allochthon. The Little Port Complex includes mafic volcanics and more felsic intrusive units, and displays a complex history of deformation and intrusion. It includes some of the oldest known ophiolitic units in the Allochthon. Interpretations of the tectonic environment of formation of the Little Port Complex have varied. It has been suggested that it may represent a transform fault, for example. However, most modern interpretations suggest that the Complex represents an island arc in the Iapetus Ocean, and that the younger Bay of Islands Complex formed by spreading within this arc environment, above a subduction zone.

Little Port volcanics are typically overlain by sedimentary strata. Typically stata with relatively well defined stratigraphic relationships with the volcanics are overlain by fault panels separated by minor breaks, then by strata that are intensely folded, faulted and phacoidally cleaved. Collectively, the sediments are loosely called the Little Port Assemblage. Genetically, they are thought to have formed in the same tectonic unit as the Little Port igneous complex, and represent an episode of deep water marine sedimentation after volcanism ended.

At Bottle Cove (Figures 121, 122) the volcanic rocks are mainly dark green pillowed flows with porphyritic and amygdular textures, subordinate massive flows, and volcanic

Figure 121. *Panoramic view (towards southwest) of Bottle Cove.*

Figure 122. *Bottle Cove (northwest side: showing fault contact between Little Port Complex volcanics (left) and Northern Head Group sediments (right).*

breccia. Pillow lavas, near the unconformity, locally contain pockets of both red chert and pink recrystallized limestone in the interstices. Red chert and shale locally also form the matrix of the volcanic breccias.

There are two slightly different unconformable contacts with sedimentary rocks of the Little Port assemblage (Figures 123, 124). The unconformity at the top the volcanics is an irregular undulating to folded surface with variable dip. The unconformity is overlain by a 0.5-6 m unit of grey to pink limestone with minor lenses of partially recrystallized limestone breccia. The limestone is bitumen stained (Figures 125, 126). Lenses (10-50 cm thick) of thinly bedded red chert occur in the upper portion of the unit. A package of siliceous grey, purple and black shale at least 15 m thick overlies the limestone. It contains near its top thin beds of brown-weathering sandstone with cross lamination. Locally, the limestone is missing and red shale and chert directly overlie the volcanic rocks.

The succession is truncated by a steeply east dipping fault in the northwestern corner of the cove. To the east is a 60 m wide, strongly deformed section of green and black siliceous and rusty pyritiferous shale interbedded with thin boudinaged sandstone and chert. A poorly sorted volcanic conglomerate with clasts of chert lies in the core of a south-plunging anticline in the western part of this section.

STOP 3.11: Little Port

Notes on this stop are based on descriptions by E. Burden, in *Hicks* et al. *(2010) and by Strowbridge, 2001).*

Little Port volcanics on the west shore of the harbour are dark green adjacent to the wharf and elsewhere in this bay, crudely pillowed basaltic lavas pass into irregular bodies of pillow breccia. The volcanic rocks are locally non-conformably overlain by volcanic agglomerate grading to sedimentary conglomerate with contacts dipping moderately east (Figure 127). Volcaniclastic strata are interbedded with green, coarse-grained sandstone lenses (Figures 128, 129, 130).

On the southwest side of Little Port Harbour an unconformable contact exists between the Little Port volcanics and an overlying succession of volcaniclastic sediments, cherty shale, ribbon limestone and shale of the Little Port Assemblage (Figure 131). Immediately above the contact the strata are relatively little deformed. Farther away from the contact,

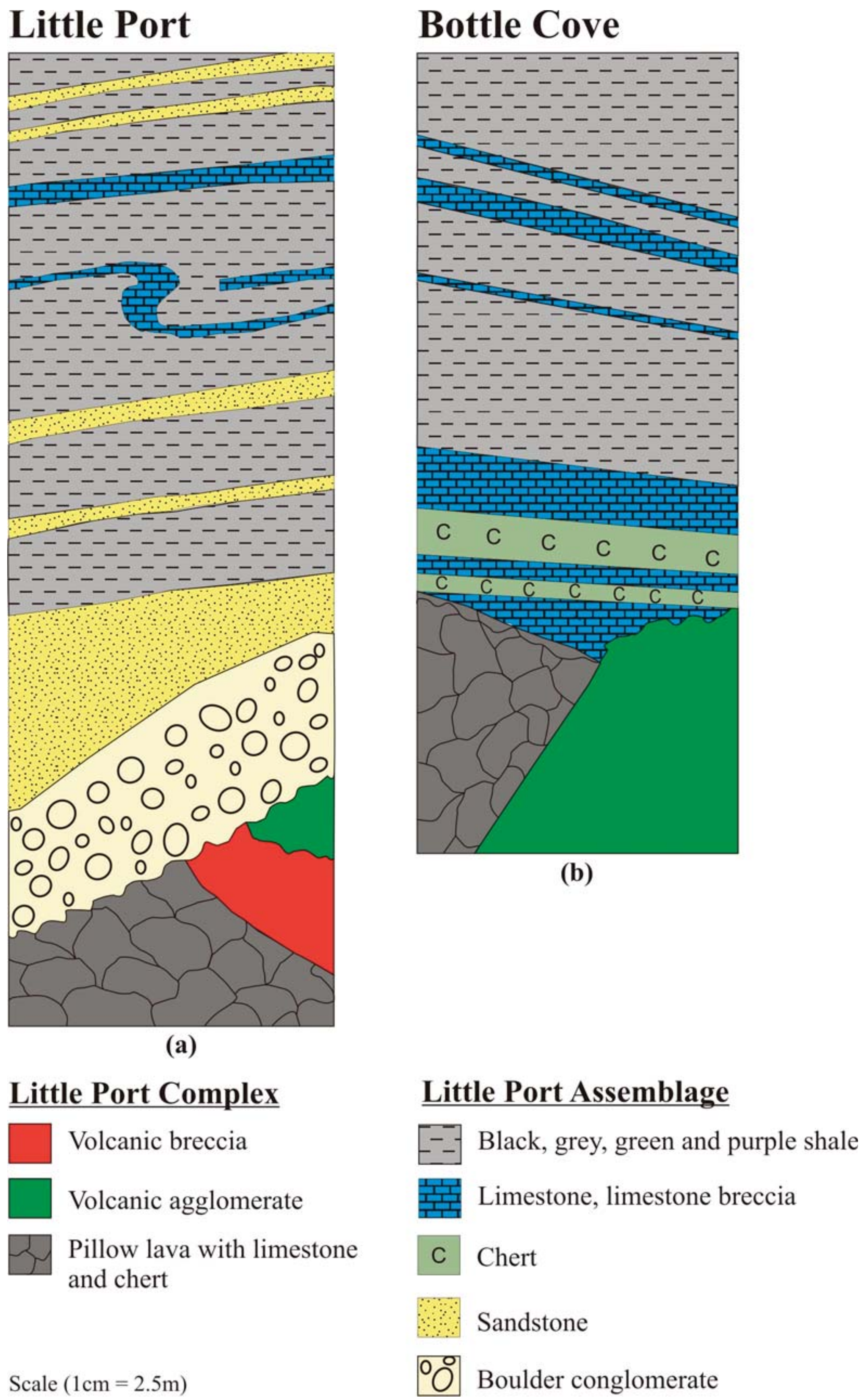


Figure 123. *Schematic stratigraphic sections showing the main features for the successions examined at (a) Little Port and (b) Bottle Cove.*

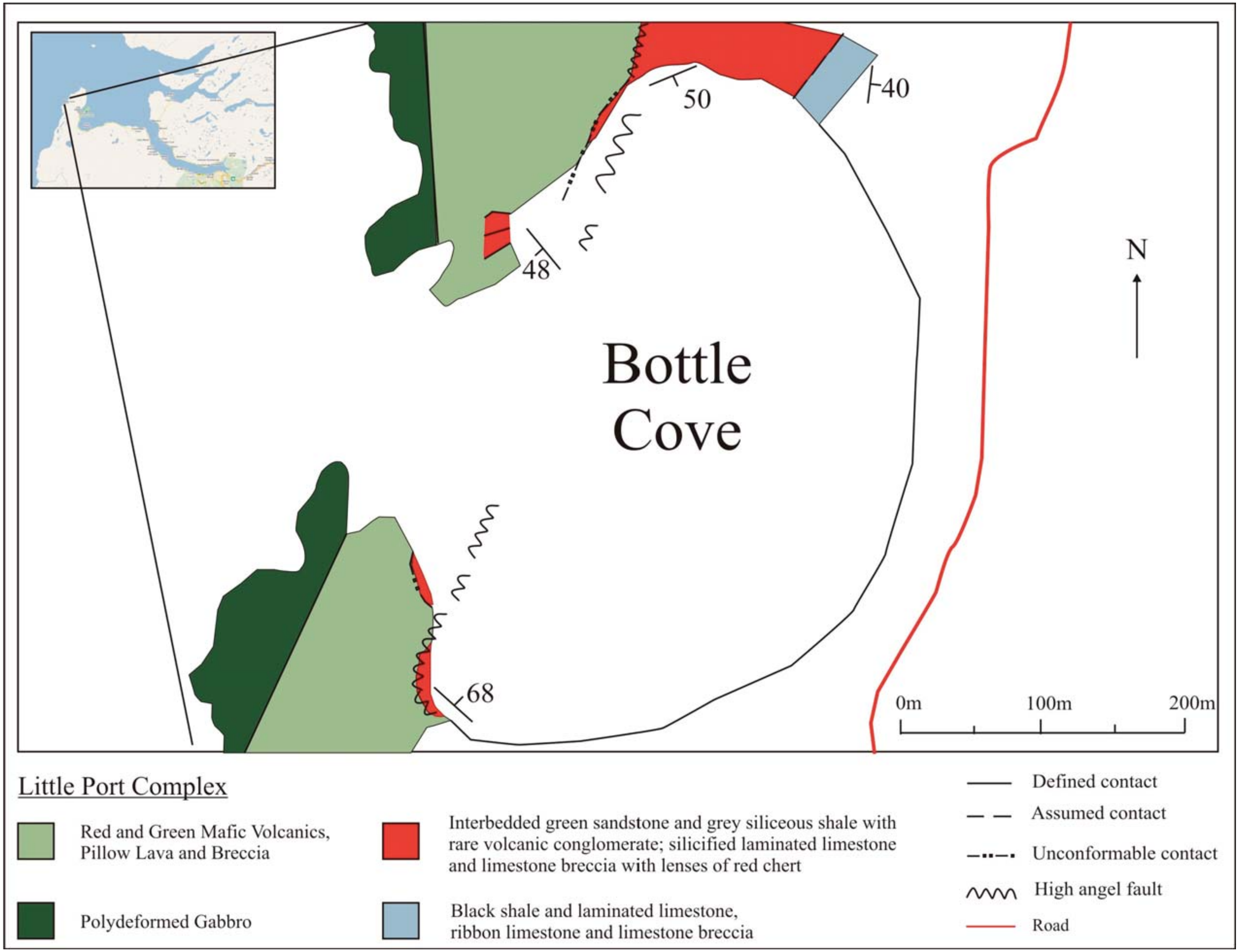


Figure 124. *Geological map showing strata and structures for strata surrounding Bottle Cove (taken from Hicks* et al.*, 2010).*

Figure 125. *Pyrobitumen vein (approx. 2–3 cm thick) cutting Little Port Complex volcanic rocks, northwest side of Bottle Cove.*

Figure 126. *Pyrobitumen coated fracture surfaces within Little Port Complex pillow basalts, Bottle Cove.*

Figure 127. *Unconformity contact between volcanic strata and very large boulder conglomerate, southwest corner of Little Port Harbour. Area to the left (south) shows the transition into a folded limestone succession.*

Figure 128. *View of Little Port (southwest side: showing Little Port Complex volcanic rocks.*

Figure 129. *View of Little Port (northeast side: showing Little Port Complex volcanic rocks.*

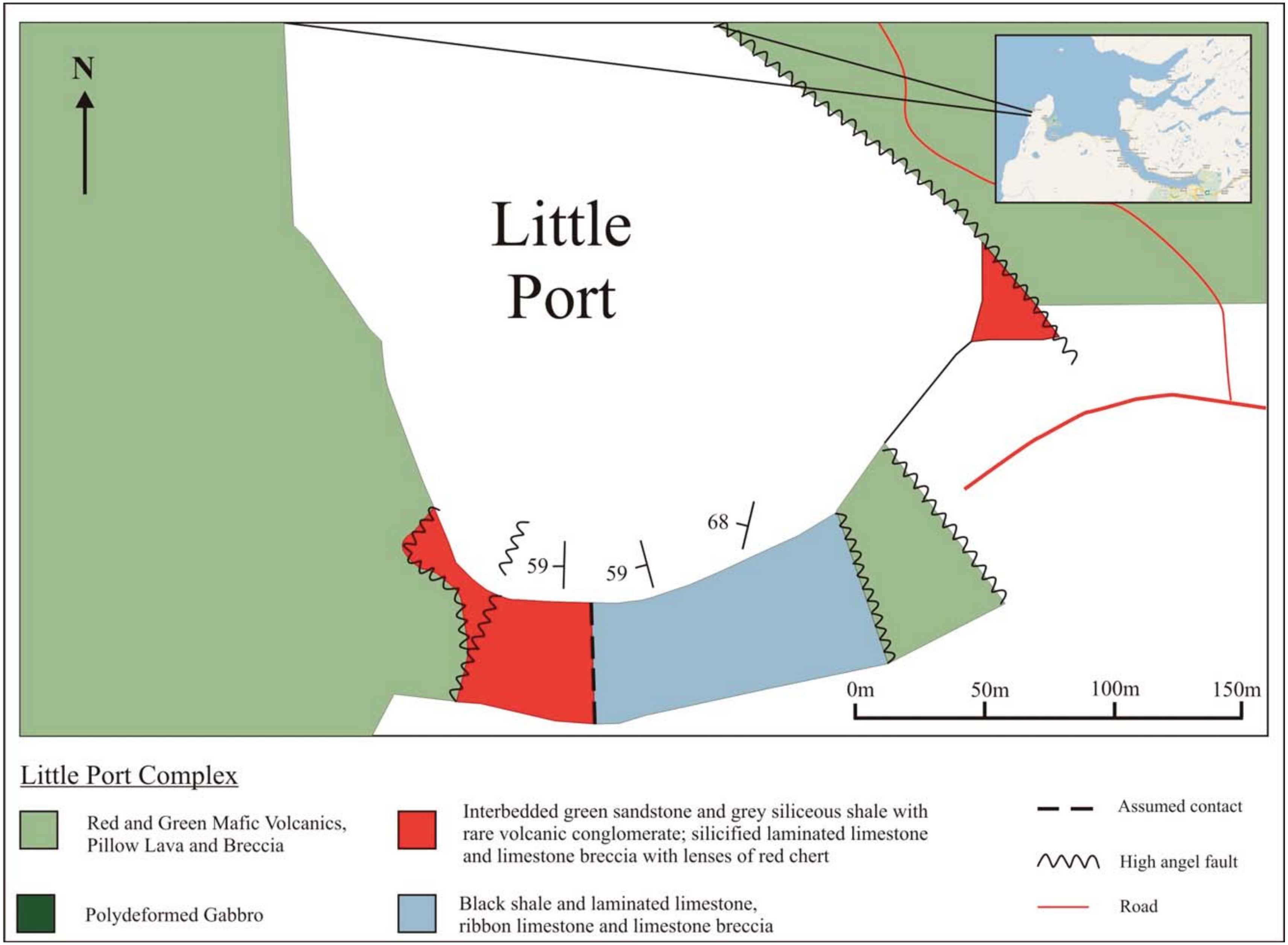


Figure 131. *Geological map showing strata and structures for strata surrounding Little Port Harbour (taken from Hicks* et al.*, 2010).*

Figure 130. *View of Little Port (south corner: showing thinly bedded shales / limestones and silty limestones of the Northern Head Group.*

Figure 132. *Live oil show / bitumen staining within sedimentary units exposed along beach, northeast side of Little Port.*

the overlying beds become significantly and progressively deformed. The sedimentary succession here is quite different from the one recorded in Bottle Cove (Figure 123).

Higher in the section is a 5-6 m layer of boulder conglomerate. The conglomerate is unsorted and clast supported with a highly variable and hematized matrix. Clasts are mainly mafic volcanics, occasional fresh and epidotized gabbro, felsic igneous lithologies, and chert. Clast size decreases up-section. The boulder conglomerate is overlain by 4 to 5 m of medium- to thick-bedded, coarse-grained, laminated, green sandstone. These rocks pass into a narrow interval of green and black siliceous shale that contains metre-sized lenses of volcanic breccia. In the northwestern part of the exposure, the sandstone and shale beds are truncated to the west by a steep fault contact with mafic volcanics.

The conglomerate, sandstone and shale succession is fault-bounded to the east with a prominent high-angle sinistral reverse fault (175/86 E). Farther east are faulted rusty brown shale, laminated limestone and several limestone breccia horizons, with a large intrafolial fold interpreted as a syn-sedimentary slump fold. Despite the fact that the shale-limestone unit lies within a sheared panel, it is inferred to form the upper part of the succession.

A small occurrence of oil stained sedimentary rock is also located on the northeastern side of Little Port harbour (Figure 132). The rocks include an oligomictic volcanic conglomerate with a thickness of 2-3 m lying within a package of shale and sandstone. This unit unconformably overlies massive and pillowed basaltic flows.

DAY 4 (Figure 133). NORTHERN PENINSULA

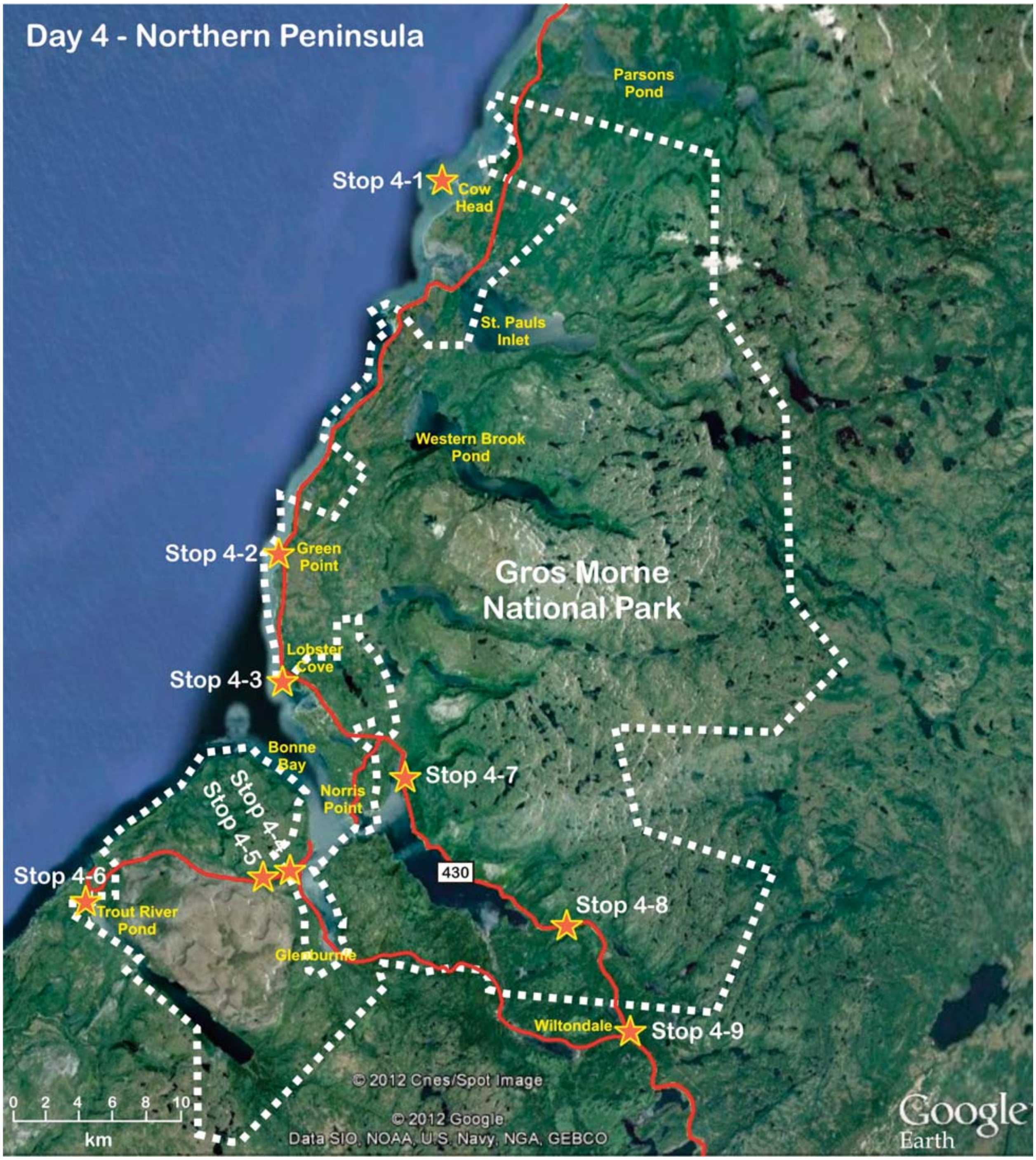


Figure 133. *Northern Peninsula Field Stop Map for Day 4.*

STOP 4.1: Cow Head Peninsula

Information on this stop is modified from James et al. *(1988) and S.H. Williams* et al. *(2001).*

See Figure 133 for stops on the Northern Peninsula.

The section on Cow Head Peninsula is virtually continuous and represents a complete section of the Cow Head Group (Figure 134) which has traditionally been divided into 14 beds, following Kindle and Whittington (1958). A complete tour around the peninsula crosses beds 1-14. Depending on the availability of time and the state of the tide we will visit only part of the stratigraphy.

Beachy Cove (Beds 1–5)

The oldest beds at Cow Head form the cliffs and low tide platform at Beachy Cove. Older conglomerates (late Middle Cambrian) are exposed on White Rock Islets to the north in Shallow Bay). The strata at Beachy Cove are earliest Furongian (Late Cambrian) in age, equivalent to the lower part of the Petit Jardin Formation of the carbonate platform.

Bed 1: Conglomerate composed of small equant to tabular clasts, including conspicuous tabular slabs of fossiliferous grainstone.

Bed 2: Thin, resistant conglomerate bed with similar small clasts but exhibiting a calcite spar cement.

Bed 3: A lower green shale overlain and partly cut out by a thick megaconglomerate, present both as a recessive channel in the low tide zone and as the cliff on the south side of the cove. The chaotic megaconglomerate has a shale matrix and contains huge coherent but folded masses of parted slope limestone that grade laterally into boulder conglomerate. This unit is capped sporadically by graded calcarenite. It can be traced for almost 500 m along strike.

Bed 4: Two conglomerate gravity flows separated by a thin parted mudstone to packstone. Conglomerates are composed of relatively small clasts, and have a buff-weathering dolomitic matrix, but exhibit occasional large boulders.

Bed 5: A series of similar small-clast conglomerates, locally separated by parted mudstone and shale. The top of the unit is cut by a fault and part of the section is repeated to the west.

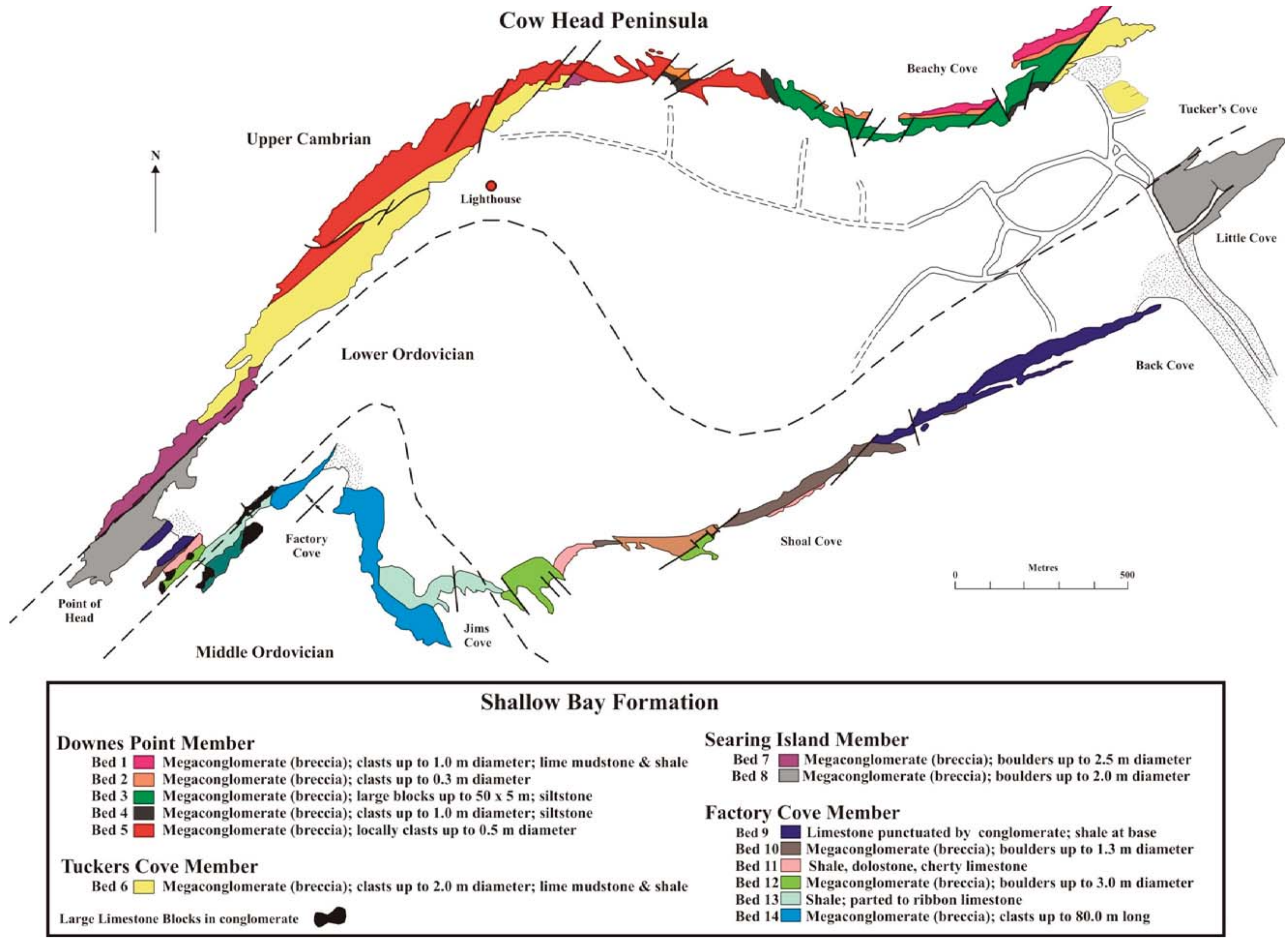


Figure 134. *Shoreline geology – Cow Head Peninsula (Kindle and Whittington, 1958).*

Lighthouse Flats (Bed 6)

Bed 6: The low erosional platform opposite the lighthouse is formed by Bed 6, a continuous section some 70 m thick, though broken and repeated by faulting. It is characterized by a wide variety of lithologies but few massive conglomerates. This section is characterized by abundant quartz-rich sand, locally forming as thick sandstone layers. The upper half of bed 6, which is cliff-forming, exhibits more thick conglomerate, fewer graded calcarenites and more parted to ribbon mudstones. The age of bed 6 ranges from middle to latest Late Cambrian.

Point of Head (Beds 7–9)

Bed 7: Upward in bed 6 there is a gradual increase in the number of conglomerates containing large boulders of white limestone. This culminates in bed 7, a cliff-forming mass ~16 m thick, comprising 3 welded conglomerate units characterized by conspicuous, large, white limestone boulders (Figure 135). The white boulders are composed of *Epiphyton* and *Girvanella* together with internal sediment and cement. James (1981) interprets these blocks as fragments of a long-lasting upper slope shelf-margin facies. The unit cuts down ~4 m into underlying beds.

Bed 8: Bed 8, which is basal Ordovician forms the Point of Head. The lower part is composed of graded calcarenites similar to bed 6, yet punctuated by coarse conglomerates as in bed 7, while the upper part is more similar to overlying strata. For the first time, chert occurs both in beds and as clasts; distinct trace fossils are found in abundance; phosphate (collophane) granules are dispersed throughout many conglomerates, and brightly hued shales separate carbonate beds.

Bed 9: The cove east of the head is formed by a section of parted to ribbon limestones, equivalent in age to the Catoche Formation of the St. George Group. Evenly-bedded, parted to ribbon lime mudstone to wackestone layers are separated by black to green shale (Figure 22). Within the limestones are abundant sponge spicules, together with occasional inarticulate brachiopods, hexactinellid sponges and graptolites. Some beds are intensively burrowed and illustrate numerous U-shaped *Arenicolitea* (Jansa 1974) and rarer *Zoophycus*.

The parted to ribbon limestone/shale sequence found at the base of Bed 9 smells petroliferous when broken. Many of the thin limestone beds display live to dead oil staining along joint and fracture surfaces (Figure 136). Clasts within the conglomerates are also locally petroliferous.

Figure 135. *Megaconglomerate bed displaying large boulders of white limestone.*

Figure 136. *Oil stained fractures within parted limestones at Cow Head (Bed 9).*

The Ledge (Beds 10–14)

Bed 10: A mass flow deposit that exhibits great variation in thickness along strike. Clasts comprise varied limestones with large clasts up to 4 m across. The matrix is argillaceous and the fabric is chaotic. The bed is capped by grainstone. The uppermost surface displays a brown-weathering chert cap and large boulders where tops have been planed off flat, two features also found on the overlying conglomerates of beds 12 and 14,. There is a Dorset Eskimo site on the grassy terrace above bed 10.

Bed 11: This unit, like bed 9, consists mainly of fine-grained sediment. The basal part is distinctive thin-bedded, dark red to black siliceous shale, brown-weathering chert and lenticular phosphate conglomerate. The upper half of the bed is a series of parted to ribbon limestones. Punctuating the sequence are beds of buff-weathering, burrowed dolomite. The graptolite fauna indicates a latest Early Ordovician (Floian) to earliest Middle Ordovician (Dapingian) age.

Bed 12: This massive megabreccia with clasts up to 20 m in diameter is similar to bed 10. The matrix is, however, green shale. Clasts contain a diverse fauna of trilobites, brachiopods, gastropods, and sponges and indicate an earliest Dapingian (earliest Middle Ordovician) age.

Bed 13: The ribbon to parted limestones that characterize the lower part of bed 13 are peloidal to intraclastic grainstone, which are commonly spiculitic and have silicified tops. Synsedimentary dykes and other injection features are found in some localities.

Bed 14: This uppermost mass flow unit is much like bed 12 but thicker (15 m) and cuts down into underlying strata up to 4 m. Clasts vary from rounded shallow-water boulders to twisted masses of slope carbonate. Brachiopods and trilobites from boulders indicate an early middle Ordovician age. Deep Cove is formed by a syncline, with bed 14 and underlying strata appearing again on the south shore. The uppermost strata here are greywacke of the Lower Head Formation exposed in the cove only at lowest tide.

STOP 4.2: Green Point

Be careful of slippery rocks on the shoreline.

This is a protected site; collecting and hammering without appropriate permits are strictly prohibited.

Information on this stop is modified from James et al. *(1988), S.H. Williams* et al. *(2001) and Hicks and Knight (2008).*

The site is approached via the first side road north of the Green Point campground, ~6 km south of Sally's Cove; drive to parking area uphill from fishermen's huts, proceed to beach and walk northward.

This shoreline outcrop (Figure 137) shows a distal facies of the Cow Head Group, the Green Point Formation and spans the Upper Cambrian (Furongian) to Middle Ordovician (Darriwilian). This section includes the boundary between the Cambrian and Ordovician Systems. On June 1, 2001, the International Commission on Stratigraphy and Parks Canada held a formal ceremony here to unveil a plaque marking this site as the global stratotype section and point (GSSP) for the base of the Ordovician System. The boundary coincides with the first appearance of the conodont lapetognathus fluctivagus and is found 4.8 m below the earliest planktic graptolites. The boundary is located between two prominent limestone conglomerate beds.

Figure 137. *Green Point section showing location of Cambrian-Ordovician boundary.*

The strata at this locality are overturned. The stratigraphically lowest beds are shale, siltstone and sandstone turbidites, which are commonly rippled and cross-laminated, and ribbon lime mudstone and lenticular carbonate conglomerate in which clasts show imbrication. Upsection, dark green shale predominates, punctuated by beds of nodular ribbon lime-mudstone. Nodules are locally rimmed by coarse fibrous calcite spar. At the head of the cove the ribbon limestones take on a peculiar "wrinkled" aspect and are distorted and cracked into a series of cusps, with individual layers locally overlapping; the origin of this structure is uncertain. The bed is stratigraphically just above the Cambrian-Ordovician boundary.

The first point of land includes a substantial conglomerate. The point itself exposes a 30 m thick sequence of parted limestone containing numerous graptolites. Synsedimentary deformation is well illustrated by a slumped and contorted mass of parted limestone in an adjacent gully (Coniglio 1984). Eastward, these parted limestones are exposed along strike for about 0.5 km. The parted limestones are locally very petroliferous, exhibiting live to dead oil staining along multiple joint and fracture surfaces. At extreme low tide it is possible to see the lowest beds of the Darriwilian Lower Head Sandstone, representing the first influx of Taconian derived foredeep turbidites.

STOP 4.3: Lobster Cove Head

Be careful on the rocky shoreline which is locally seaweed-covered.

The lighthouse shore section, exposed between Lobster Cove Head and Yellow Point, is accessible by several paths that start at the lighthouse. The northern path leads to the base of the section (Figure 138).

This tectonically deformed succession of Lower to Middle Ordovician strata is a large, disrupted raft within the Rocky Harbour mélange which probably structurally overlies the Cow Head thrust complex to the north and west (Figure 139).

The basal part of the section can be correlated, both in terms of lithology and biostratigraphy with beds 9, 10 and part of bed 11 of the Cow Head Group at Cow Head Peninsula. The upper part of the section consists of interbedded buff dolostone and shale and is unlike other sections in the Cow Head Group, but resembles some sections in the Middle Arm Point Formation of the Bay of Islands. These upper beds are defined as the Lobster Cove Member of the Shallow Bay Formation (James *et al.*, 1987) and are interpreted to have been deposited as dilute turbidites of mud and detrital dolomite under dysaerobic conditions. The

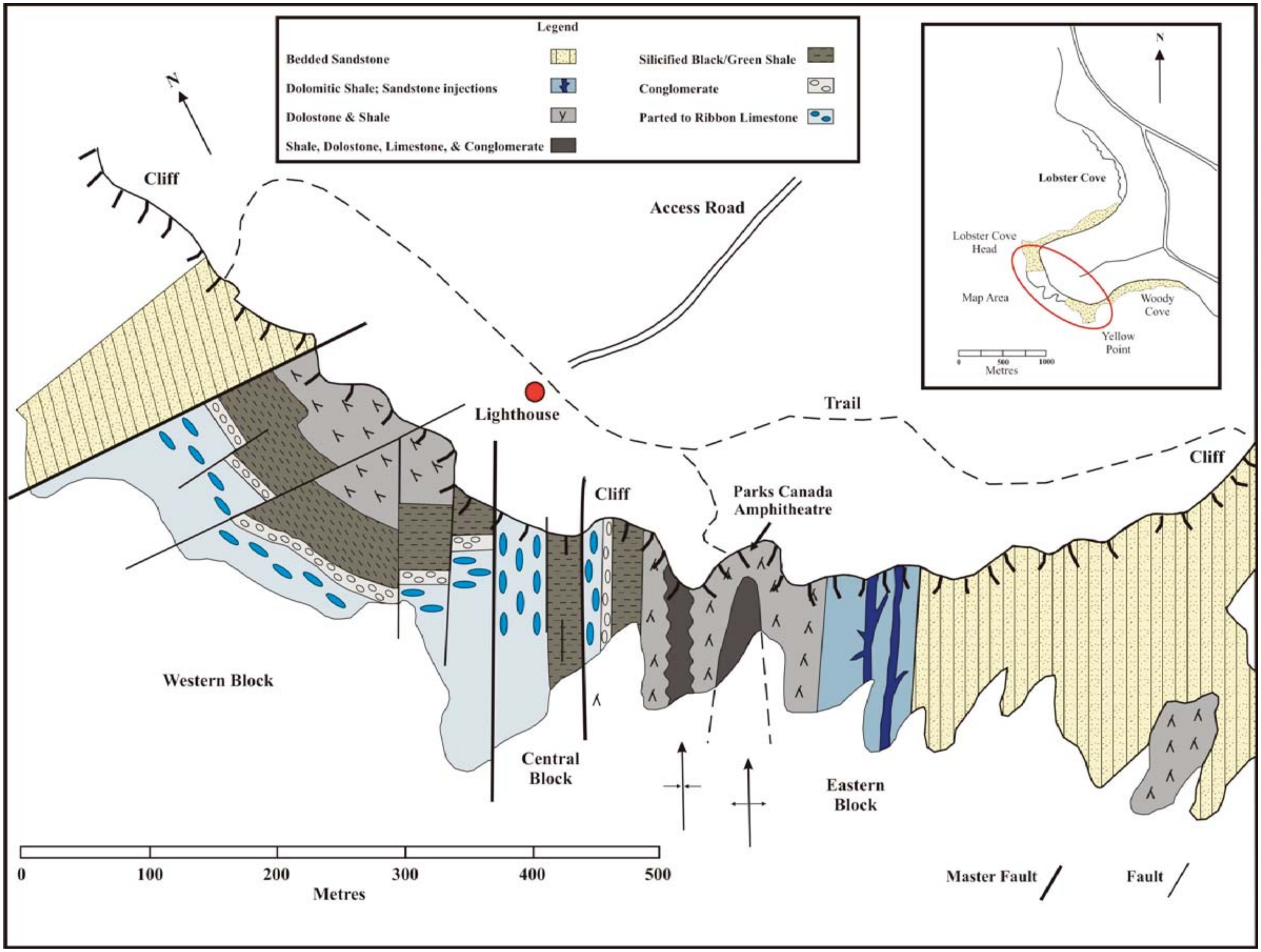


Figure 138. *Geological map of shoreline section beneath Lobster Cove Lighthouse (after James et al. 1987).*

contact between the two sedimentary packages is marked by a faunal break and coincides with emplacement of megaconglomerate Bed 12 at Cow Head.

This break marks the change from a relatively uniform to more complex platform paleogeograpy and is interpreted to be the result of synsedimentary faulting. According to James *et al.* (1987) the margin upslope from Cow Head remained in shallow water during the final stages of Cow Head Group deposition whereas, upslope from Lobster Cove Head, the margin was drowned and shed little sediment into deep water. This synsedimentary faulting coincides with the onset of the Taconic Orogeny; most of the Lobster Cove Member was deposited during the interval missing at the St. George Unconformity at the top of the shelf succession.

The rocks show an interesting deformation history. Lenticular, limestone concretions of the Cow Head Group are cut by extensional fractures which are typically filled by dark bitumen-bearing calcite, or by shale, attesting to an early episode of extension possibly associated with the development of the surrounding mélange (Figure 140). Hydrocarbons from surrounding source rocks were probably leaking into these fractures as they opened. The extensional structures are overprinted by folds and minor thrust faults. These contractional structures are also associated locally with calcite veins but the calcite is white and appears free of bitumen (Figure 141).

Upper beds of the Lobster Cove Member probably pass up into graded sandstone and shale of the Lower Head Formation. The section is faulted but can be reconstructed by correlation of

Figure 139. *Ribbon limestones, debris flow conglomerate and interbedded buff dolomite and shale exposed along the shoreline at Lobster Cove (beneath Lighthouse), Gros Morne National Park.*

Figure 140. *Brittle extensional fractures cut carbonate concretions in the upper part of the Cow Head Group at Lobster Cove Head. Fractures are filled by dark calcite and by shale that has flowed from surrounding beds.*

beds across faults. Basal beds of the Lower Head contain bedded intervals of dolostone and shale, locally tilted and rotated as blocks and displaying later injections of sandstone. This type of synsedimentary deformation is common at the base of the Lower Head and Eagle Island sandstones elsewhere in the Humber Arm Allochthon.

Route: *South from Rocky Harbour*

From Rocky Harbour to Deer Lake there are two routes that can be taken south. In the first, we travel by ferry (Bonne Bay Water Shuttle) from Norris Point to Woody Point, permitting a side trip to see upper mantle rocks of Table Mountain (the tablelands). The alternative route retraces our steps through Gros Morne park, visiting additional stops in the platform succession on the way.

Woody Point Route: *Trout River turn-off*

North of the turn-off to Trout River, weakly altered mafic volcanic rocks are exposed along the west side of the road. They have been assigned to the Little Port Complex, an assemblage of mostly intermixed intrusive and extrusive igneous rocks that are found structurally below the Bay of Islands Complex (oceanic crust /mantle rocks).

Views to the east display a magnificent panorama of the north side of Bonne Bay. The large, isolated dome shaped hill towards the centre of this view is Gros Morne, the highest peak in the park at 806 m and the second highest point on the island of Newfoundland (Figure 142).

Figure 141. *Folds and brittle thrusts duplicate beds in upper Cow Head Group at Lobster Cove Head. Calcite vein fills developed in this phase are mostly white.*

Figure 142. *Gros Morne Mountain. In French, 'Gros' means 'big' and Morne stands for 'dismal or gloomy'.*

Geologically the top of Gros Morne is capped by a thick bedded unit of gently dipping Early Cambrian quartzite of the Hawke Bay Formation. Lower slopes are underlain by the underlying Forteau Formation and by Grenville basement of the Long Range massif (Figure 143).

STOP 4.4: Discovery Centre

Exit onto Trout River road and proceed uphill to the Discovery Centre. Exposures observed along the north side of the road are similar in appearance and rock type (weakly altered mafic volcanic rocks) to those seen immediately before turning onto the Trout River road.

The Discovery Centre, which opened in the spring of 2000, overlooks the South Arm of Bonne Bay. The centre serves the southern portion of the park and provides a facility for visitor information, interpretation, exhibition, theatrical events (musicians, storytellers, craftspeople, *etc*.) educational training, meetings, administration and a host of other functions.

Immediately west of the Discovery Centre there is a very large exposure of deformed Little Port Complex intrusive rocks. Gabbro and diabase are the most common rock types, but more felsic trondhjemites are present locally.

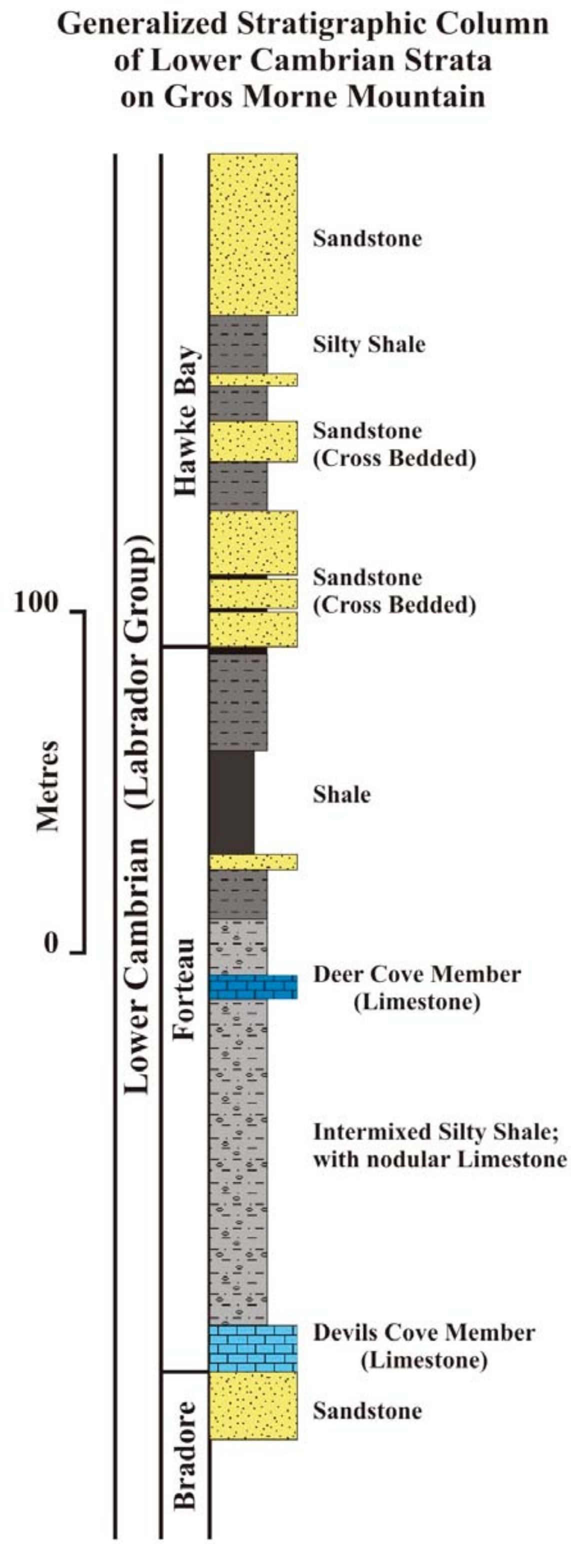


Figure 143. *Generalized stratigraphic column of Lower Cambrian strata exposed along the north face of Gros Morne Mountain after Knight* et al. *(2007).*

STOP 4.5: Tablelands Viewpoint Area

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

Opposite the Tablelands Viewpoint, note the long exposure of 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.

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 and is famous for its ultramafic rocks of the lithospheric upper mantle. The mantle section is mainly peridotite, iron and magnesium rich, low silica rocks. In fact, oxidation of iron is responsible for the dun to medium brown colour characteristic of the weathered surfaces, characteristic of most ultramafic rocks (Figure 144). On fresh surfaces, the rocks are typically dark green, reflecting their high percentage of olivine and pyroxene minerals. The unusual chemical compositions of these rocks inhibit plant growth in soils that develop over them. In addition to peridotites, the ultramafic suite on Table Mountain includes dunite and pyroxenite.

Peridotites typically 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 host ultramafic rocks. Calcium is selectively dissolved adjacent to the fractures and olivine is converted to serpentine, sometimes in the form of chrysotile asbestos. The dissolved calcium is locally precipitated around springs to form whitish surface travertine deposits.

Tablelands Viewpoint to Trout River

Beyond the Tablelands Viewpoint, the road travels through a glacially carved valley (referred to as “The Gulch”) that displays a remarkable contrast in landscape character and geology. The central region of the valley is floored by mélange and flanked to the south by barren, ultramafic rocks of the Tablelands ophiolite and to the north by vegetation covered, structurally underlying Little Port Complex mafic intrusive and extrusive igneous rocks (Figure 145). There are few outcrops along this section of road, but the surrounding hillsides exhibit a wide variety of glacial erosive and depositional features.

Figure 144. *Brown colored, mantle derived peridotites (Tablelands) located to the south of Bonne Bay, western Newfoundland.*

Figure 145. *Trout River road, view towards Woody Point; crustal rock (left), mantle rock (right), separated by a major shear zone.*

The town of Trout River itself sits within a glacially carved, landlocked fiord (Trout River Pond) and it is built on and around a large terrace of sand and gravel that separates the Pond from the sea. This terrace is a classic ice-marginal marine delta, deposited by meltwater flowing west from a glacier that existed in what is now the Trout River Valley. The top of the delta is approximately 35 m above present day sea level and its height corresponds with the base of a raised seastack of amphibolite on the opposite side of Trout River.

STOP 4.6: Trout River Pond

Drive to the Trout River Pond day use parking lot or alternately follow the same road a few hundred extra metres uphill to get a panoramic view of Trout River Pond (Figure 146). The landscape, towards the northeast is dominated by the barren, brown weathered, mantle rocks of the Tablelands. Numerous expanses of grey coloured rock represent gabbro, remnants of the lowest layer of oceanic crust. The contact between the two contrasting rock types therefore represents the Mohorovicic discontinuity (Moho), the boundary between the oceanic crust and underlying mantle (Figure 147). Not all the brown/grey contacts seen across the pond however are bonafide Moho boundary zones, some of the brown/grey juxtapositions are fault or shear induced.

A major southeast-northwest trending fault underlies the glacially carved valley of Trout River Pond. To the southwest, the mafic upper crustal section of the North Arm Mountain ophiolite massif is characterized by lush, vegetated terrain, which stands in stark contrast to the barren, brown weathering ultramafic rocks of the Table Mountain massif to the northeast.

Figure 146. *Looking east up Trout River Pond; dun brown mantle rock (left), dark grey crustal rock (right).*

Figure 147. *Crust / mantle transition (MOHO) located along the north shore of Trout River Pond.*

Travel: *Woody Point to Wiltondale*

From Trout River it is necessary to return to Woody Point before following highway 431 to Wiltondale. Numerous bedrock and Quaternary features can be seen on the way.

Woody Point to Glenburnie

Between the Trout River turn-off at Woody Point and Glenburnie the road follows the shoreline of South Arm. Over this 8 km distance, the road cuts through three, raised, glacial outwash deltas; one at Winterhouse Brook, one near Bailey's Point (1/2 km north of Shoal Brook) and the last at Glenburnie. The delta tops which are approximately 35 m above present sea level give some indication to the amount of isostatic rebound that has taken place since the end of the last glacial period.

Medium to coarse grained, massive, greenish grey sandstone units with or without pebbly bases and individual pebbly conglomerate beds are observed at one location between Shoal and Winterhouse Brooks. The units appear to be debris flow channel deposits laid down in deep water along the Iapetus continental slope. They are probably equivalents of the Blow Me Down Brook Formation seen in the Bay of Islands.

Glenburnie to Barters

Outcrops of phyllite and/or shale belonging to the Curling Group or associated chaotic mélange units are exposed along the south side of the road, just southeast of the community of Glenburnie. The road crosses McKenzie's Brook approximately 0.8 km inland from the head of South Arm. McKenzie's Brook valley and South Arm are both part of a once continuous valley which channelled glacial ice and meltwater. The valley is floored by a thick veneer of unconsolidated, glacial drift which, due to isostatic rebound, is being incised rapidly by McKenzie's Brook.

The road begins a 4.5 km steep ascent locally called "the Struggle". Rock exposures along the way are part of the Cambrian Curling Group, mostly shale, siltstone, minor quartzites and conglomerates, similar to those in the Bay of Islands. Approximately 1.5 km west of Barters Pond, on the north side of the road, a large exposure of clastic sedimentary rock is probably equivalent to the Lower to early Middle Cambrian 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.

Barters Pond to Wiltondale

The westernmost exposures along this section are mostly black shale and phyllite with minor thin limestone beds. These rocks have an uncertain affinity but may correlate with the Goose Tickle Group or the mélanges at the base of the the Humber Arm Allochthon.

To the east the road passes on to deformed carbonate rocks of the platform succession, that include mostly medium to thick bedded, medium to dark grey and white limestones, and grey to buff dolostones. The limestones are locally strongly bioturbated, occasionally cherty, and in places, smell faintly petroliferous when broken. The rocks have been assigned to the Lower Ordovician St. George and Table Head Groups (unseparated in this area).

In this area, to the south of the highway, Bonne Bay Little Pond and the Lomond River sit within another large glacial valley that was active during Wisconsin glaciation and quite possibly earlier.

At Wiltondale, the highway re-joins the northern peninsula highway 430.

Alternative Route: *South from Rocky Harbour*

If the ferry from Norris Point to Woody point is not taken, instead return to highway 430 and travel south toward Wiltondale.

STOP 4.7: Forteau Formation

Highway 430 follows the coast of Deer Arm and East Arm of Bonne Bay. A number of outcrops of the early Cambrian Forteau Formation occur in highway cuts, displaying open folds and variable axial planar cleavage (probably the regional S_2). The Forteau Formation consists of about 70 to 100 m of thin to thick, locally fossiliferous shales, siltstones and lime wackestones to packstones. Limestones locally contain a rich assemblage of Salterella cones. Locally there are large trilobite fragments or complete fossils (Figures 148, 149).

STOP 4.8: Precambrian/Cambrian Unconformity

Caution: *this is a major highway. Keep off the road surface and be alert for traffic; parking is available at Southeast Brook Falls 150 m to the northwest.*

At this location [NAD 83 UTM – 452433E, 5479228N], Precambrian crystalline basement rocks (around 1150 Ma) are unconformably overlain by an exposed section of Bradore and Forteau formation strata (around 530 Ma). The unconformity represents a time gap of about 500 Myr (Figure 150).

At the east end of the outcrop is green weakly foliated metabasic to intermediate gneiss. Coarser parts have pink feldspar and leaf green retrograded ferromagnesian minerals (including much chlorite and epidote). The gneiss is intruded by granitic pegmatite dykes. The contact with the overlying sedimentary rocks is a diffuse zone of cobbles in a dark grey

Figure 148. *Large trilobite fossil in Forteau Formation shale, near the Head of Deer Arm, Gros Morne National Park.*

Figure 149. *Open fold in Labrador Group strata along the north side of East Arm.*

wacke matrix representing the weathered regolith and overlying basal conglomerate of the Bradore Formation. The overlying dark green sandstone shows only faint bedding at the base but becomes more distinctly bedded and laminated up section to the west. The Bradore Formation is here only about 6 m thick, and dips at ~42° to the west.

The Bradore Formation is overlain by impure limestone , minor sandstone, and cleaved mudstone of the Forteau Formation. Limestones occur as beds of lenticular concretions. Approximately 8 m of the Forteau Formation is exposed on the north side of the highway, but to the west there is continuous outcrop on the south side of the highway for ~100 m. Cleavage in the mudstones anastomoses around the limestone concretions, where it forms discrete stylolytic surfaces.

STOP 4.9: Wiltondale Turn-off

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 and have been subjected to more than one episode of deformation, as indicated by cleavage planes that cross-cut the axial surfaces of folds (Figure 151).

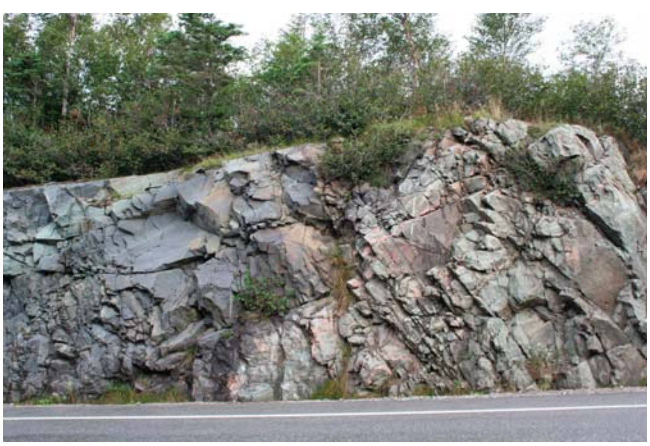


Figure 150. *The Cambrian-Precambrian Unconformity exposed near Southeast Hills (within photo - dark colored Forteau and Bradore formations to the left and lighter colored Precambrian gneiss to the right).*

Figure 151. *Close to tight folds in Port au Port Group strata, Wiltondale, highway 430.*

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Western Newfoundland has been a classic field trip area for decades and we are 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 ours. We would particularly like to acknowledge the contributions of Noel James (James *et al.*, 1988), Ian Knight (Knight *et al.*, 2007), and Elliott Burden (Hicks *et al.*, 2010).

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Paul Myrow and Guy Narbonne

FT-A4 **Mistaken Point: A Potential World Heritage Site for the Ediacaran Biota**
Richard Thomas

FT-A5 **Neoproterozoic Epithermal Gold Mineralization of the Northeastern Avalon Peninsula, Newfoundland**
Sean J. O'Brien, Gregory W. Sparkes, Greg Dunning, Benoît Dubé and Barry Sparkes

FT-A9 **Cores from the Ben Nevis and Jeanne d'Arc Reservois: A Study in Contrasts**
Duncan McIlroy, Iain Sinclair, Jordan Stead and Alison Turpin

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