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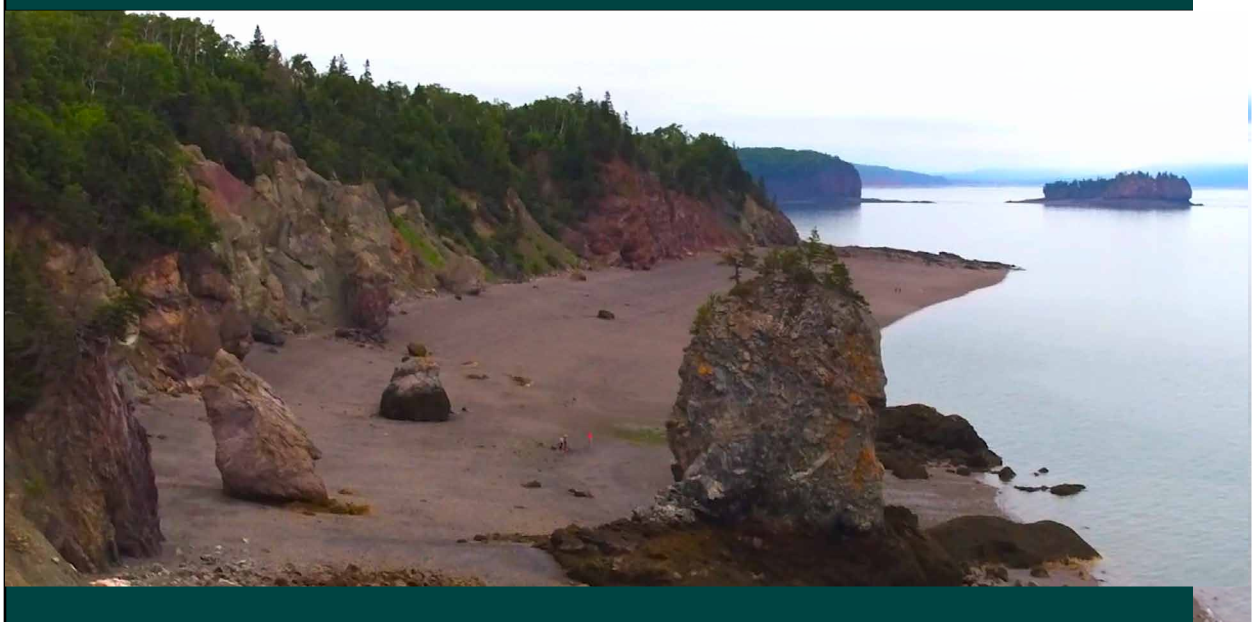

FIELD TRIP GUIDEBOOK – A1

Salt Tectonics along a Late Paleozoic Transform Fault, Nova Scotia

Leaders: John Waldron, Morgan Snyder, Alison Thomas

GEOLOGICAL ASSOCIATION OF CANADA / ASSOCIATION GÉOLOGIQUE DU CANADA

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SAFETY AND HEALTH CONSIDERATIONS

Field trips may involve hazards to the participants and leaders. Each participant must be aware of their own safety and for that of the group, and refrain from any action that might endanger themselves or others. For your safety as well as the safety of others, observe the following precautions on the trip.

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

Inform field trip leaders of any health concerns that may affect your health and safety or that of co-participants. Washrooms are available at museum and other indoor stops, as indicated in the appropriate sections of this guide. During longer drives, it may be possible to make a stop at a gas station or convenience store where washrooms are available to customers. Please inform your driver well in advance if you need a washroom break. Do not wander away from the main group while at field trip stops, without telling the leaders.

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

Shorelines. Rocks are often slippery and waves may be troublesome. Several stops are on tidally influenced shorelines. The tidal range on Bay of Fundy shorelines is up to 15 m. The rising tide advances rapidly. Be aware of the state of the tide, and work on a falling tide if possible. Stay with the group.

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

Slopes: Watch out for loose rock on slopes. On slopes be aware that those below you are vulnerable to displaced rocks. Do not walk straight down steep slopes especially if others are also on the slope below you. Instead, proceed down slopes at an angle, and stay in a tight group. Walk at the pace of the slowest member. Warn those below clearly and immediately if you displace an object that may be hazardous. Slippery rocks, tree roots and moss covered rocks / roots may also pose hazards during non-shoreline traversing.

Old mine workings are dangerous; do not attempt to enter.

Do not approach wildlife.

First aid kits are available at the rear of each van.

Salt tectonics along a late Paleozoic transform fault, Nova Scotia: a field guide

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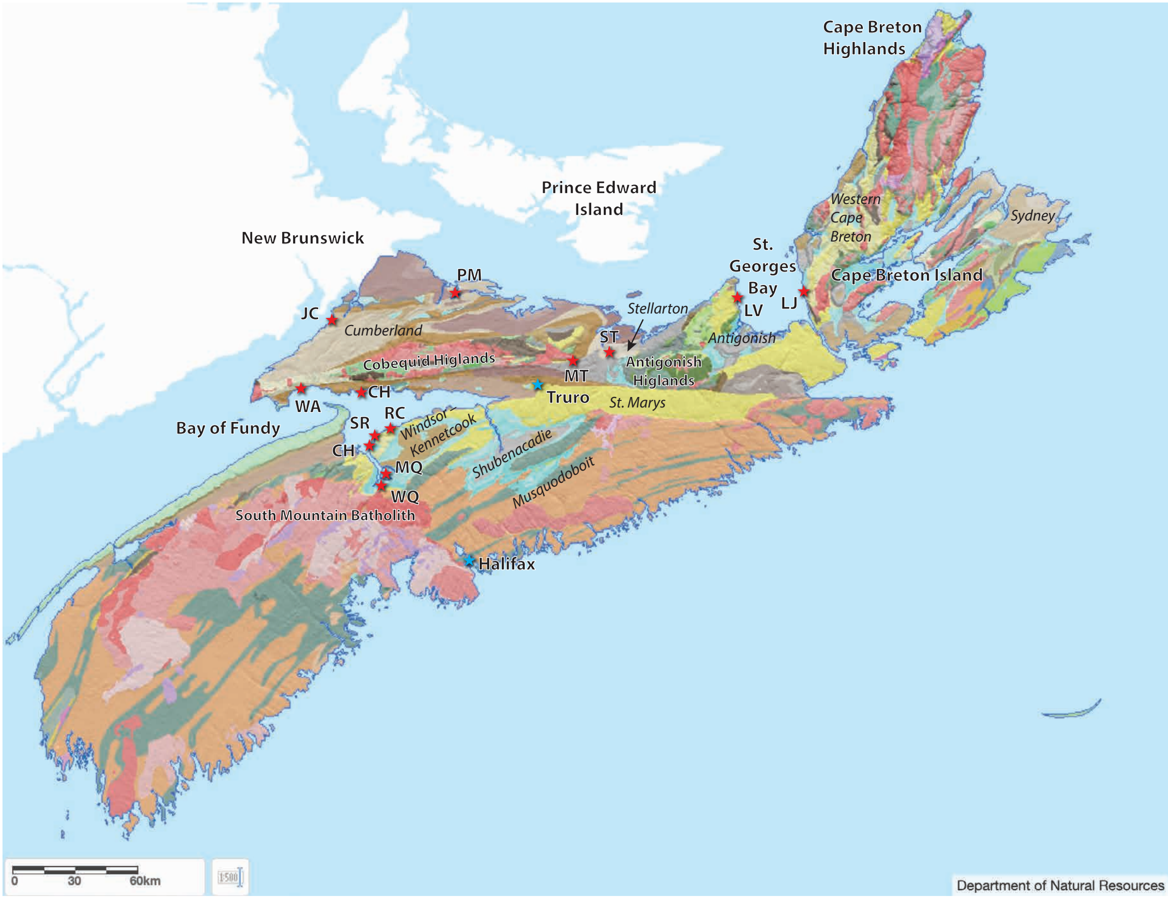
OVERVIEW

This field trip will visit spectacular coastal sites in Carboniferous rocks of the Maritimes Basin that were influenced by salt tectonics, transtension, and transpression during final stages in the assembly of the supercontinent Pangea. The trip will be of interest to structural, sedimentary, and resource geoscientists working in tectonically active sedimentary basins. It will visit distinctive features of Nova Scotia geoheritage, including the Joggins Fossil Centre, the Cliffs of Fundy Geopark, and the Pictou Coalfield.

Many stops involve complex geology and spectacular exposure: a small number of long stops is envisaged on each day to allow full appreciation of the complex interactions between sedimentation, strike-slip tectonics, and salt movement. Principal challenges include the preponderance of coastal outcrops only accessible at low tide; low tide occurs late in the day during the scheduled time of field trip.

Participants should read the safety considerations carefully, and not venture beyond their comfort level with the conditions. Every effort will be made to provide alternative media for anyone unable to access an individual field stop.

Figure 1. Field trip stops (stars) superimposed on Nova Scotia geology (Keppie 2000). Sub-basin names shown in italics. Source, with full legend, at: https://novascotia.ca/natr/meb/download/dp043.asp



Acknowledgements

We acknowledge, and ask participants to remember that the field trip takes place in Mi'kma'ki, the ancestral and unceded territory of the Mi'kmaq People, who have occupied this land far longer than settler populations that have had a large impact on the landscape.

We thank Sandy Lunn, CGC Inc, Dane Henderson, Windsor Salt, and Alex MacKay, Nova Scotia Department of Natural Resources and Renewables, for access to their operations.

We are grateful for discussions with multiple Earth scientists over many years for insights that have contributed to the view of Maritimes Basin geology presented here. They include: Sandra Barr, Bob Boehner, John Paul Brown, John Calder, Fred Chandler, Paddy Chesterman, Ian Davison, Paul Durling, Lauren Eggleston, Martin Gibling, Peter Giles, Jim Hibbard, Sue Johnson, Stan Johnston, Pierre Jutras, Fraser Keppie, Steven Hinds, Ellie MacInnes, Paul MacKay, Brendan Murphy, Sarah Palmer, Adrian Park, Georgia Pe-Piper, David Piper, David Hope-Simpson, Jared Kugler, Reg Moore, Carlos Roselli, Bob Ryan, Rob Naylor, Brian Roulston, Mike Rygel, Paul Schenk, Clint St. Peter, Amy Tizzard, Chris White, and Joe White, and an anonymous reviewer. John Waldron was supported by NSERC Discovery Grant RGPIN-2020-04171.

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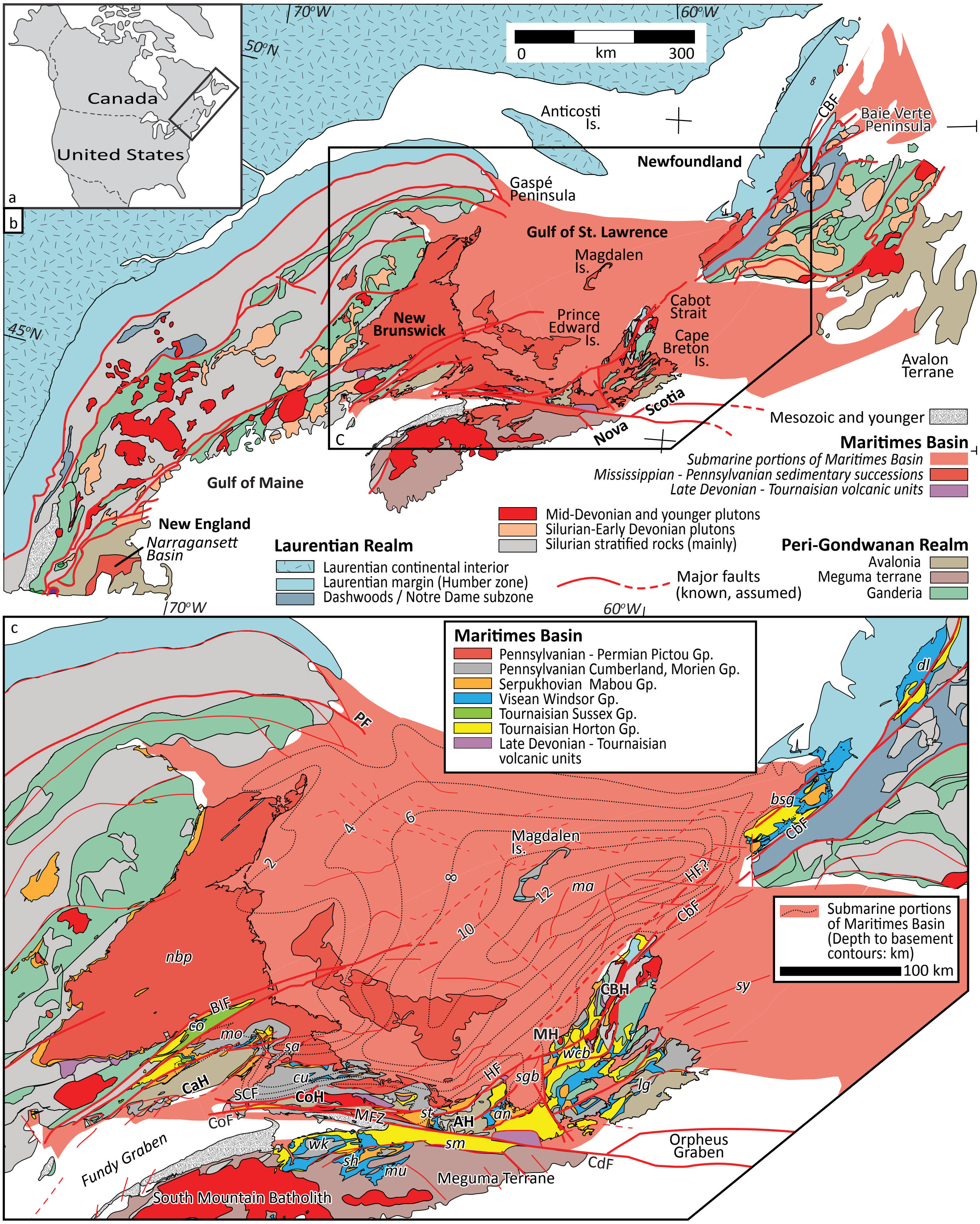


Figure 2. Regional map of the Maritimes Basin in the context of the northern Appalachians of North America (a, b). Enlarged view of central area of (b) shown in (c). Terranes and massifs (boldface): AH = Antigonish Highlands, CaT = Caledonia terrane; CoH = Cobequid Highlands; IHK = Indian Head inlier. Carboniferous basins (lower case italic): an = Antigonish; bsg = Bay St. George; co = Cocagne; cu = Cumberland; dl = Deer Lake; lg = Lomond-Glengarry; ma = Magdalen (Gulf of St. Lawrence); mo = Moncton; mu = Musquodoboit; nbp = Central

(continued opposite)

INTRODUCTION: THE MARITIMES BASIN

Regional geologic setting

The Maritimes Sedimentary Basin (Figure 2) is a large (~150,000 km^2) and deep (>12 km) late Paleozoic sedimentary basin that straddles all the early Paleozoic zones of the Appalachian Orogen in Atlantic Canada, from the Humber Zone in the west of Newfoundland to the Meguma Zone in the south of Nova Scotia. Gibling et al. (2019) provide a recent account of the stratigraphy of the Maritimes Basin, in much greater depth than is possible here.

As you will see from the map, the majority of the Maritimes Basin, including the deepest part, is concealed under the Gulf of St. Lawrence and other areas of the continental shelf of Atlantic Canada. The lithologies are of course best known from on-land areas, and as you can see, these areas are highly faulted. Most of these faults were active during development of the basin and deposition of its fill. Additional complexity comes from the widespread presence of evaporites and their propensity to flow. The field trip will focus on these exciting but challenging aspects of the Maritimes Basin.

Rock units

Classically, major depositional episodes have been recognized in the Maritimes Basin by the identification of six major groups: Fountain Lake, Horton, Windsor, Mabou, Cumberland, and Pictou. However, most of the units in the basin are somewhat diachronous, and lateral facies changes abound. In addition, sedimentation has been influenced by cyclic changes in sedimentary environments, with the result that similar facies are found in multiple stacked units. To cope with some of these complexities, additional group names have been defined within, or extrapolated into, the area of the Maritimes Basin (e.g., Moncton, Sussex, Percé, Morien, Anguille, Codroy, Deer Lake...) creating a potentially confusing nomenclature. Furthermore, authors have differed in their strategies for dealing with lateral facies changes. Some versions of the lithostratigraphy have used correlation of unconformities (allostratigraphy) and fossil zones (biostratigraphy) to supplement information purely based on rock type (lithostratigraphy) in arriving at a group-level nomenclature. In some cases, this has resulted in inconsistent nomenclature across provincial borders. There is less controversy about the definition of formations, but unfortunately the number of formations is extremely large. Figure 3 attempts to lay out a commonly used version of the group-level stratigraphy, and we will attempt to adhere to the nomenclature therein during the field trip. However, participants reading beyond this document may encounter differences of opinion on the assignment of formations to groups within much of the basin. For more complete discussion of the intricacies of lithostratigraphy see Gibling et al. (2019) and Waldron et al. (2017).

Carboniferous (New Brunswick) platform; sa = Sackville; sgb = St. Georges Bay; sh = Shubenacadie; sm = St. Marys; st = Stellarton; sy = Sydney; wcb = Western Cape Breton Island; wk = Windsor-Kennetcook. Fault and other abbreviations (plain text): AF = Aspy fault; BIF = Belleisle fault; CbF = Cabot fault; CoF = Cobequid fault and CdF = Chedabucto fault (Minas Fault Zone, MFZ); HF = Hollow fault; KF = Kennebecasis fault. PF = Percé fault. Is. = Island. Modified from Waldron et al. (2015), and references therein.

Fountain Lake Group: lava and clastic sediments

The oldest rocks of the Maritimes Basin are mixed volcanic and sedimentary successions of the Fountain Lake Group, and correlative units. These are predominantly Late Devonian but in their type area in the Cobequid Highlands (Figure 2) the highest units are early Carboniferous. The volcanic rocks, and associated intrusions, show predominantly bimodal, within-plate geochemical signatures, transitioning from older subduction and collision-related magmatism that occurred during the Early to Middle Devonian Acadian Orogeny.

Horton Group and correlatives: clastic sediments in a basin-and-range environment

Clastic sedimentary rocks of the Horton Group overlie, and are partially laterally equivalent to, the Fountain Lake Group. In its type area, in the Windsor–Kennetcook sub-basin (Figure 2), the Horton Group has a three-fold subdivision, with coarse clastic rocks at the base and top, and finer mud-dominated successions in between. Other sub-basins show similar successions, but the available palynological evidence suggests that they may not all be synchronous. Available seismic profiles through the sub-basins suggest the presence of multiple internal unconformities, and maps show that the group was deposited in grabens and half-grabens.

The Horton Group is commonly interpreted as fluvio-lacustrine, but indications of marine influence have been found locally (Gibling et al. 2019), leading to alternative interpretations as marginal marine deposits. The abundance of active faults, lateral facies changes, and local unconformities suggest a basin-and-range tectonic environment.

The equivalent rocks in the Bay St. George sub-basin of SW Newfoundland are assigned to the Anguille Group. In southern New Brunswick a marked unconformity divides the lower, clastic part of the Maritimes Basin succession, and the upper part, mostly, but not entirely, younger than the Horton Group in its type area, is distinguished as the Sussex Group (St. Peter and Johnson 2009).

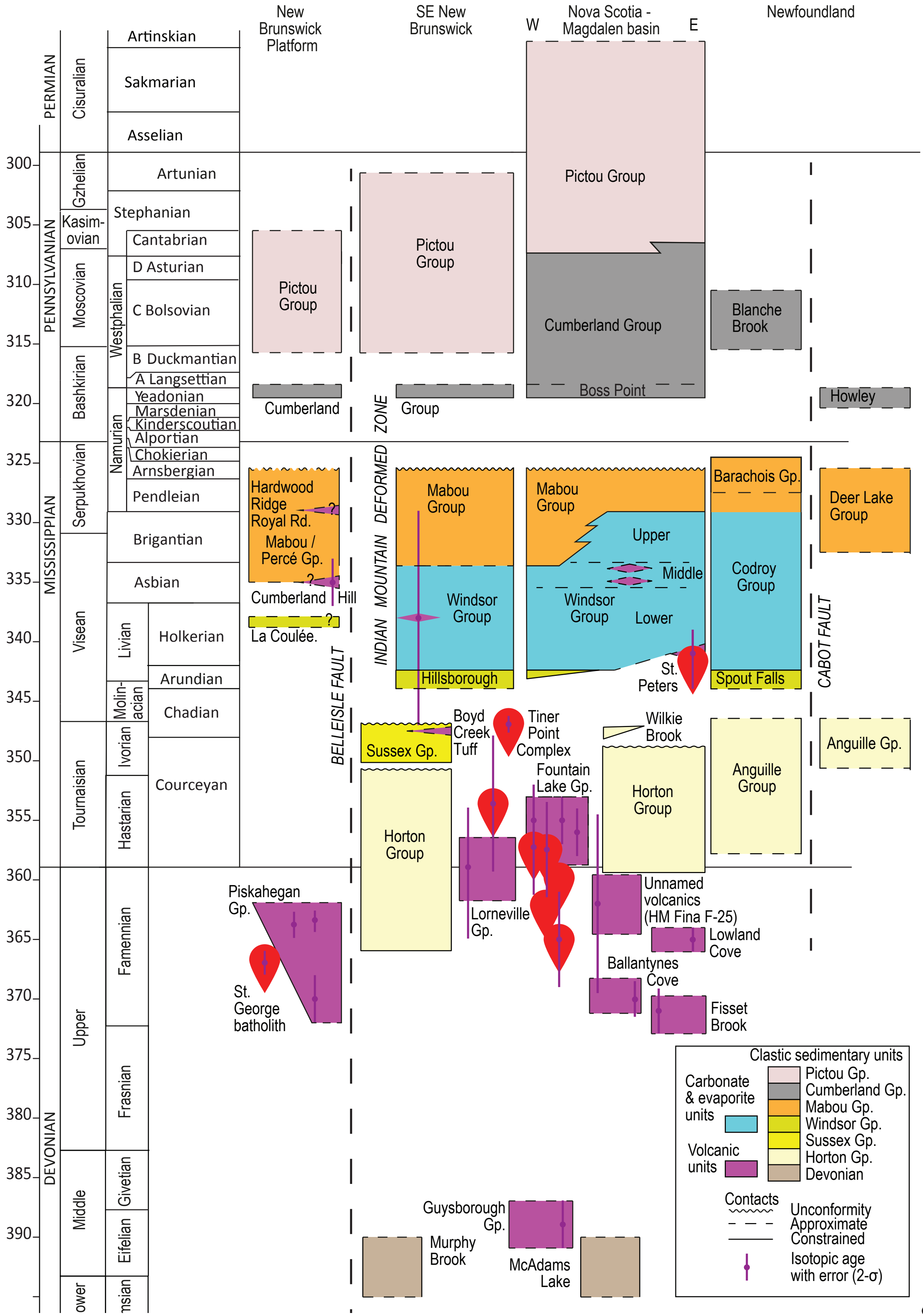
Palynological evidence suggests that the Horton Group and its equivalents range from Late Devonian to late Tournaisian in age.

Windsor Group: carbonates, evaporites and shale

An overlying succession that includes most of the fully marine sedimentary rocks in the Maritimes Basin is assigned to the Windsor Group in Maritime Canada and to the Codroy Group in Newfoundland (Figure 3). This succession overlies the Horton, Sussex, and Anguille Groups with a contact that varies from a disconformity to an angular unconformity. In many places, immediately above the unconformity, there is a unit of coarse clastic sedimentary rock, ranging from less than a metre thick to more than 100 m, that lithologically more closely resembles the underlying units, but which is variably included with the Windsor Group depending on local stratigraphic practice.

The Windsor Group has intrigued local geologists for more than a century. Outcrop successions are characterized by a thin basal limestone (Macumber Formation and

Figure 3. Simplified stratigraphic table for the Maritimes Basin, modified from Gibling et al. (2019).



equivalents), overlain by a thicker layer of gypsum (anhydrite in the subsurface). In the subsurface, the anhydrite is commonly overlain by a much thick layer of rock salt (Stewiacke Salt or "lower Windsor salt"), that in southern New Brunswick contains substantial potash deposits. This threefold package constitutes the *lower Windsor Group.* The age of the lower Windsor Group has been controversial (Waldron et al. 2017). Estimates range from late Chadian (about 345 Ma in modern time scales) to early Asbian (about 335 Ma). The biostratigraphic problem with the age of the lower Windsor Group is that typical facies were deposited in extremely restricted environments so that normal marine fossil groups are scarce. Palynological dating is possible, but its resolution is limited a single biozone (*pusilla-columbaris* sometimes referred to as "PC"*)* appears to span most of the Chadian to Asbian interval.

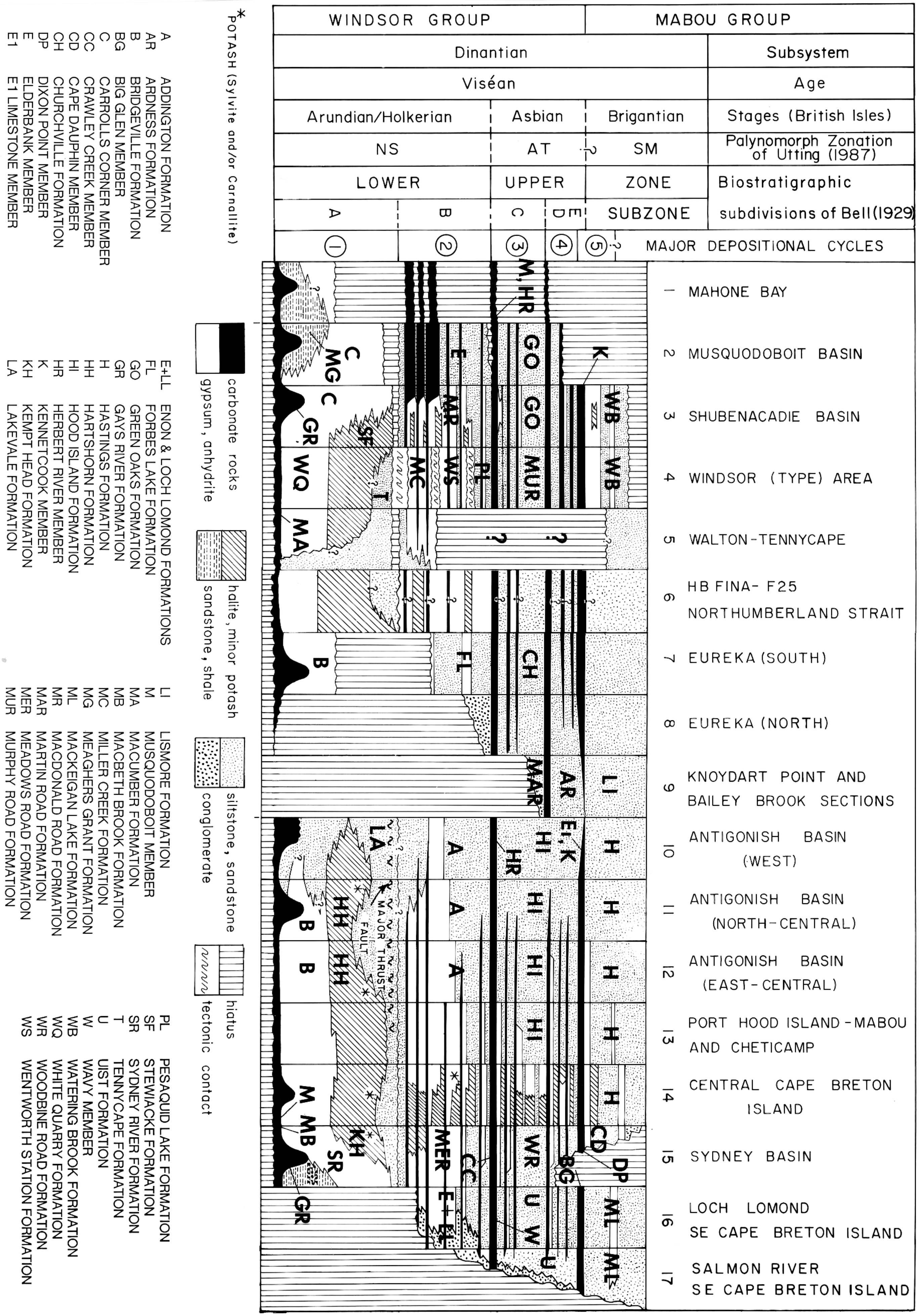
An overlying succession assigned to the *middle Windsor Group* consists of multiple repeating alternations of limestone-gypsum-mudstone, again with rock salt in the subsurface. The *upper Windsor Group* is also cyclic, but contains larger amounts of clastic sedimentary strata relative to evaporites. Although different formation names are used for the middle and upper Windsor Group rocks in different sub-basins, a distinctive feature of the stratigraphy is that individual limestone beds can be correlated basin-wide (Giles 1981, 2009), wherever the middle and upper Windsor Groups are found (Figure 4).

In Newfoundland, equivalent successions to the Windsor Group are included in the Codroy Group, which nonetheless has been defined slightly differently in the past, to include successions that extend above the highest marine limestone into the early Serpukhovian. Snyder and Waldron (2021) have recently suggested a redefinition of the Codroy Group to align more closely with the Windsor Group. Thus defined, the Windsor Group appears to fall entirely within the Visean Series of the Mississippian, or Lower Carboniferous.

Mabou Group: non-marine clastic sediments deposited in an arid environment

The Mabou Group (formerly Canso group) is a non-marine succession containing abundant redbeds that overlies the Windsor Group, typically without obvious unconformity. The group includes both grey and red clastic successions and, in addition, minor evaporites that are interpreted as non-marine. Marine carbonates are absent, but the boundary with the Windsor Group is strongly diachronous. In the Cumberland sub-basin and adjacent parts of New Brunswick lower parts of the Mabou Group contain the same late Visean palynoflora as the upper parts of the Windsor Group farther south and east. In some versions of the stratigraphy this lower, predominantly Viséan part of the non-marine succession is classified as belonging to the Percé Group, a unit defined in the Gaspé Peninsula of Québec (e.g. Jutras et al. 2007). In this document we follow the usage of the provincial surveys (e.g., Ryan et al. 1991), and the original definition of Belt (1969) in including the whole of the diachronous non-marine Visean to Serpukhovian succession in the Mabou Group.

Figure 4. Correlation of Windsor Group stratigraphic units (Boehner and Prime 1993). *(Facing page)*


WINDSOR GROUP
MABOU GROUP
Dinantian
Subsystem
Viséan
Age
Arundian/Holkerian
Asbian
Brigantian
Stages (British Isles)
NS
AT
SM
Palynomorph Zonation of Utting (1987)
LOWER
UPPER
ZONE
Biostratigraphic
A
B
C
D
E
SUBZONE
subdivisions of Bell (1929)
MAJOR DEPOSITIONAL CYCLES
1 MAHONE BAY
2 MUSQUODOBOIT BASIN
3 SHUBENACADIE BASIN
4 WINDSOR (TYPE) AREA
5 WALTON-TENNYCAPE
6 HB FINA- F25 NORTHUMBERLAND STRAIT
7 EUREKA (SOUTH)
8 EUREKA (NORTH)
9 KNOYDART POINT AND BAILEY BROOK SECTIONS
10 ANTIGONISH BASIN (WEST)
11 ANTIGONISH BASIN (NORTH-CENTRAL)
12 ANTIGONISH BASIN (EAST-CENTRAL)
13 PORT HOOD ISLAND-MABOU AND CHETICAMP
14 CENTRAL CAPE BRETON ISLAND
15 SYDNEY BASIN
16 LOCH LOMOND SE CAPE BRETON ISLAND
17 SALMON RIVER SE CAPE BRETON ISLAND
MAJOR THRUST FAULT
carbonate rocks
gypsum, anhydrite
halite, minor potash
sandstone, shale
siltstone, sandstone
conglomerate
hiatus
tectonic contact
* POTASH (Sylvite and/or Carnallite)
A ADDINGTON FORMATION
AR ARDNESS FORMATION
B BRIDGEVILLE FORMATION
BG BIG GLEN MEMBER
C CARROLLS CORNER MEMBER
CC CRAWLEY CREEK MEMBER
CD CAPE DAUPHIN MEMBER
CH CHURCHVILLE FORMATION
DP DIXON POINT MEMBER
E ELDERBANK MEMBER
E1 E1 LIMESTONE MEMBER
E+LL ENON & LOCH LOMOND FORMATIONS
FL FORBES LAKE FORMATION
GO GREEN OAKS FORMATION
GR GAYS RIVER FORMATION
H HASTINGS FORMATION
HH HARTSHORN FORMATION
HI HOOD ISLAND FORMATION
HR HERBERT RIVER MEMBER
K KENNETCOOK MEMBER
KH KEMPT HEAD FORMATION
LA LAKEVALE FORMATION
LI LISMORE FORMATION
M MUSQUODOBOIT MEMBER
MA MACUMBER FORMATION
MB MACBETH BROOK FORMATION
MC MILLER CREEK FORMATION
MG MEAGHERS GRANT FORMATION
ML MACKEIGAN LAKE FORMATION
MR MACDONALD ROAD FORMATION
MAR MARTIN ROAD FORMATION
MER MEADOWS ROAD FORMATION
MUR MURPHY ROAD FORMATION
PL PESAQUID LAKE FORMATION
SF STEWIACKE FORMATION
SR SYDNEY RIVER FORMATION
T TENNYCAPE FORMATION
U UIST FORMATION
W WAVY MEMBER
WB WATERING BROOK FORMATION
WQ WHITE QUARRY FORMATION
WR WOODBINE ROAD FORMATION
WS WENTWORTH STATION FORMATION

Cumberland Group: coal measures

A regional unconformity, ranging from a disconformity to an angular unconformity, separates the Mabou Group from the overlying Cumberland Group. The Cumberland Group includes predominantly grey beds, and in its broadest definition (Ryan et al. 1991), followed here, includes all the historically mined economic coal resources of Nova Scotia. However, thus defined, its upper boundary is diachronous and interfingers towards the NW with redbeds. This has led to differences of nomenclature both in the more arid region of northern Nova Scotia and adjacent New Brunswick, where transitional units assigned to the Cumberland Group in Nova Scotia are assigned to the Pictou Group, and in Cape Breton Island, where substantially younger coal-bearing units are assigned to the Morien Group.

Based on the broader definitions in Figure 3, the Cumberland Group ranges from mid-Bashkirian to the end of the overlying Moscovian (Upper Carboniferous or Pennsylvanian).

Pictou Group: redbeds

The Pictou Group may be characterized in Nova Scotia as the non-coal-bearing, redbed-dominated succession that overlies, and interfingers with the Cumberland Group (Ryan et al. 1991). However, inconstencies with this definition occur in the transition from Nova Scotia to New Brunswick; upper units assigned to the Cumberland Group in Nova Scotia (Malagash Fm.) are redbed-dominated, with only very minor coal, whereas the coal-bearing units (Minto Fm.) occur higher in the succession assigned to the Pictou Group in New Brunswick. The Pictou Group, as the term is currently used, is therefore better defined by the formations it contains (e.g., Waldron et al. 2017), most of which have unambiguous definitions. The youngest parts of the Pictou Group occur in Prince Edward Island, where they range into the Cisuralian (early Permian).

Structure

Many authors (e.g. Belt 1968, Bradley 1982, Murphy et al. 2011, Waldron et al. 2015) have noted the prevalence of steep faults in the Maritimes Basin (Figure 2). Many of these show evidence of dextral strike-slip motion, but that motion may be combined with either extension (producing an overall environment of transtension) or shortening (producing transpression), or both. Waldron et al. (2015) classified these faults into two dominant trends, and showed how they may have dissected the earlier geometry of the Appalachian Orogen. East-west faults were termed the *Minas trend* whereas a second group of NESW to ENE-WSW faults constitute the *Appalachian trend*.

In many parts of Atlantic Canada, the lowest units of the Maritimes basin appear to be deposited with a simple angular unconformity upon underlying, much more highly deformed rocks of the Appalachians. However, this relative simplicity is deceptive. Towards the faults that bound sub-basins, the rocks of the Maritimes Basin are highly deformed and locally cleaved and/or overturned. Moreover, in many areas the complexity increases up-section in the stratigraphy, which has caused previous

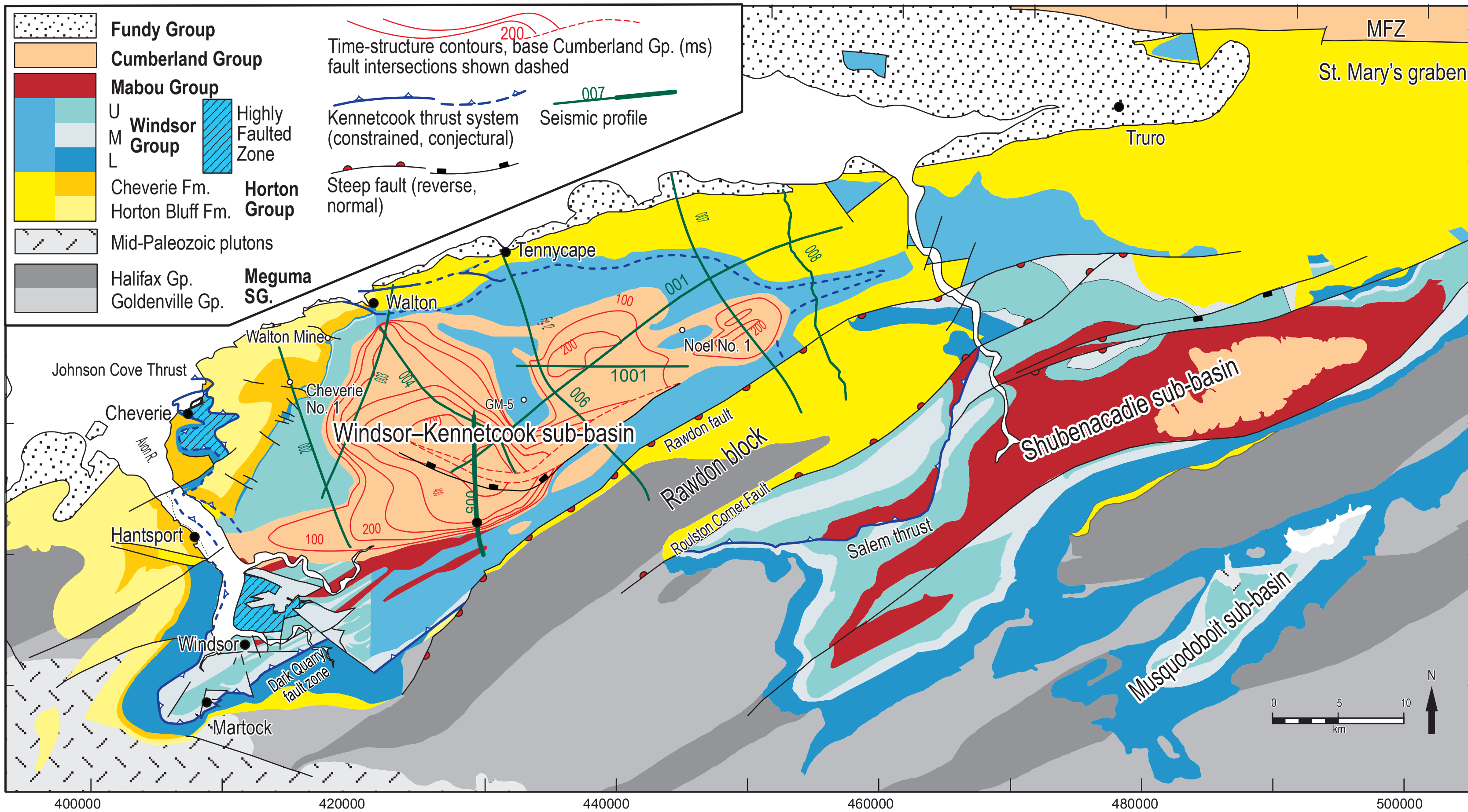


Figure 5. Simplified geological map of Maritimes Basin units overlying the Meguma terrane of the Appalachians (Waldron et al. 2010).

interpreters to struggle with map interpretation. We interpret many such unusual aspects of the structure as products of evaporite flow in the subsurface.

Structure of the Tournaisian basin

In the early stages of the development of the Maritimes Basin, Horton Group and equivalent strata were deposited in a series of graben and half-graben, mostly with ENE-WSW, Appalachian trend, that were clearly active during sedimentation. This is notable in a number of areas, and is most apparent in maps of the Windsor-Kennetcook, Antigonish, and Bay St. George sub-basins, where there are dramatic lateral changes in the thickness of the Tournaisian strata. Hibbard and Waldron (2009) and Waldron et al. (2015) suggested that this basin-and-range geometry was developed in a broad zone of transtension associated with strike-slip motion on Appalachian-trend faults that interacted with large swings (salients and recesses) in the Appalachians, inherited from the margin of early Paleozoic Laurentia (Thomas 1977).

In many cases, the thickest Horton Group and equivalent sections are found in blocks that are presently the most uplifted relative to the surrounding blocks. This phenomenon is notable in the Rawdon block of southern mainland Nova Scotia (Figure 5), the Antigonish sub-basin of northern mainland Nova Scotia (Figure 5), the Anguille Mountains in the Bay St. George sub-basin of SW Newfoundland (Figure 6) and in the Cockagne sub-basin of New Brunswick (Figure 2). These relationships strongly suggest contractional inversion of originally extensional faults, although the precise timing of inversion is in many cases uncertain. The Horton Group is particularly intensely deformed toward the major east-west Minas fault zone (MFZ) that includes the Cobequid and Chedabucto faults, and many smaller faults active at different times (Murphy et al. 2011). It locally includes recumbent folds that have been refolded to produce downward-facing folds (synformal anticlines and antiformal synclines) on their overturned limbs.

Structures involving the Visean-Serpukhovian Windsor and Mabou groups

The base of the Visean Windsor Group appears to cross-cut many of these structures, and the Windsor and Mabou Groups have sometimes been represented as a “post-rift” succession representing a thermal subsidence episode following Tournaisian rifting. However, the Windsor Group does not blanket the whole basin. The Cobequid and Antigonish Highlands were clearly islands in the Windsor sea, whereas the Windsor and Mabou groups fill half-graben structures beneath the Cumberland sub-basin (Waldron and Rygel 2005, Waldron et al. 2013) and in Cape Breton Island (Boehner and Prime 1993) show that active faulting continued. In many sub-basins the complexity of the Windsor Group paradoxically increases up-section, so that tabular lower Windsor Group rocks are overlain by middle and upper Windsor sections that show complex patterns of refolded recumbent folds.

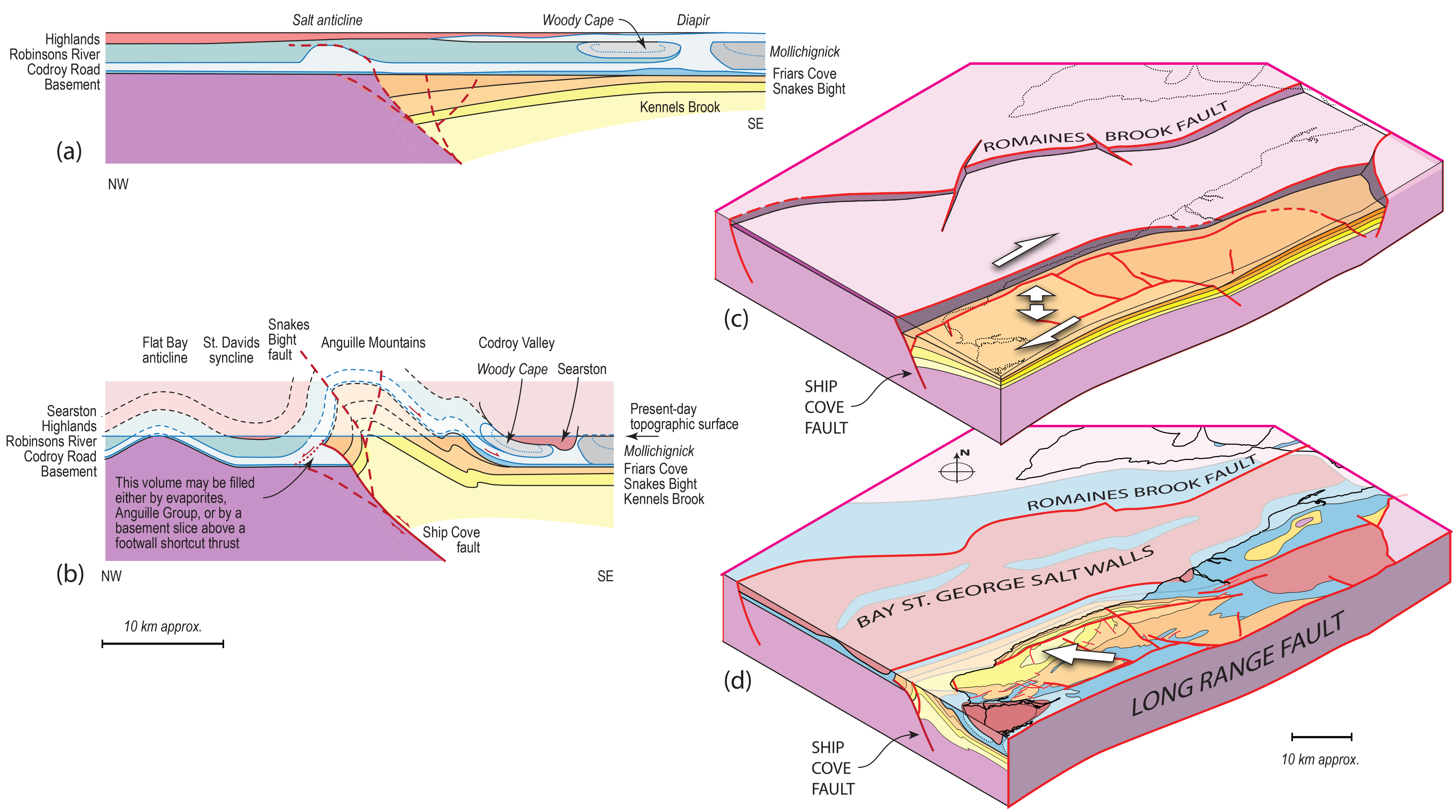


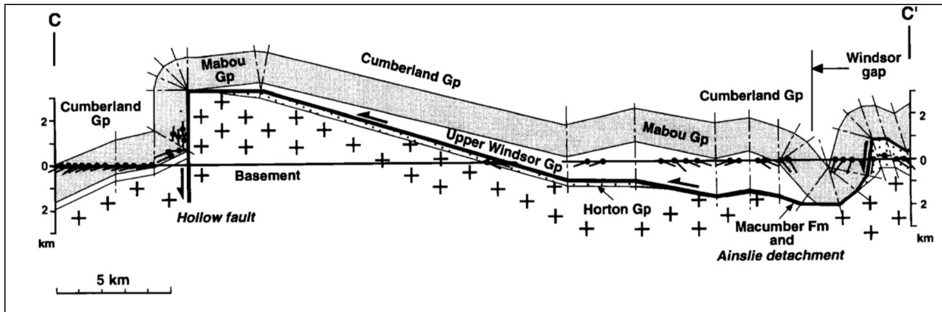
Figure 6. Simplified geological map and block diagram of the Bay St. George sub-basin in SW Newfoundland (Snyder and Waldron 2021).

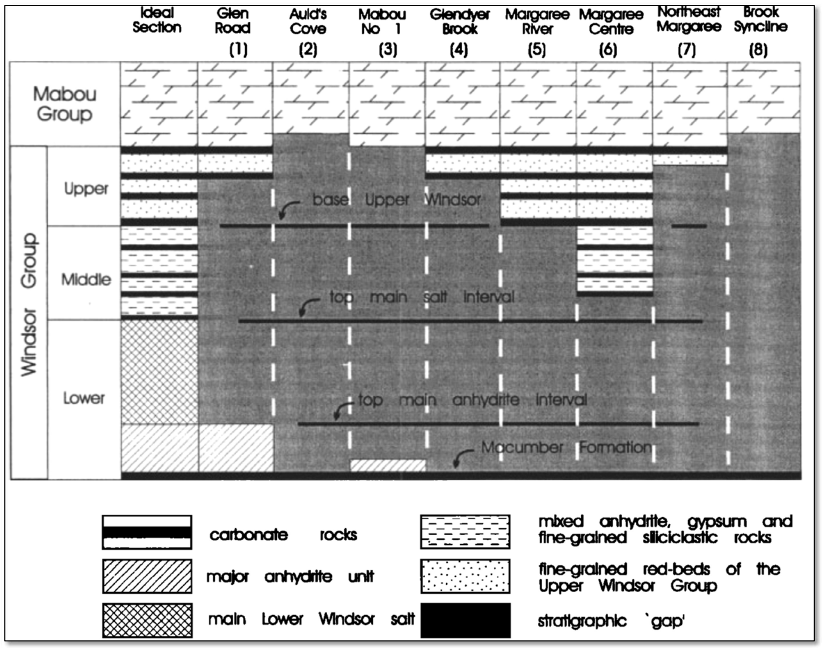
Although the basin-wide correlations of limestone units in the Windsor Group are remarkable, there are major lateral variations in the Windsor Group, for which a variety of explanations have been proposed. For example, in the Shubenacadie sub-basin a *Salem thrust* (Figure 5) was identified (Giles and Boehner 1982a), and in the Antigonish sub-basin, variations in the stratigraphic succession at the base of the group were explained (Boehner and Giles 1982, 1993) as being due to an *Antigonish thrust*. However, it was subsequently pointed out (Lynch and Giles 1995, Lynch et al. 1998) that thrusting would be expected to produce stratigraphic duplications, whereas the observed stratigraphic anomalies in the Antigonish sub-basin and adjoining areas of western Cape Breton Island were mostly omissions. Lynch and co-authors therefore proposed that a regional normal-sense detachment named the *Ainslie detachment* (Figure 7) was responsible (Lynch and Giles 1995, Lynch et al. 1998). They postulated ramps and flats on the detachment to explain the observed stratigraphic anomalies, and suggested 35 km of likely slip (minimum 9.5 km).

Subsequent work based on seismic data in conjunction with surface outcrop on the north margin of the Windsor–Kennetcook sub-basin (Waldron et al. 2007, 2010) identified a region where Horton Group was thrust over basal Windsor Group suggesting indeed that shortening at the *Kennetcook thrust* (Figure 5) had been important. Nonetheless, the interpreted thrust passes laterally into a bed-parallel surface where stratal disruption, but neither large-scale duplication nor omission is observed. However, Waldron et al. raised the possibility that the Salem thrust, farther south, represents a continuation of the Kennetcook thrust to the south of the younger Rawdon uplift (Figure 5). Structures identified by R.G. Moore, in unpublished maps of gypsum quarries near Windsor, show recumbent, overturned sheath-like folds consistent with major shortening and subhorizontal transport of higher units in the Windsor Group (Figure 8).

Work on the Cumberland sub-basin (Waldron and Rygel 2005, Waldron et al. 2013), using industry seismic profiles, revealed another aspect of structure in the Windsor Group. Seismic profiles through anticlines, cored by Windsor Group, in the Cumberland sub-basin revealed that at depths of several kilometres in the subsurface, the thickness of the Windsor Group diminished to zero on anticline flanks. This led to the hypothesis that the anticlines formed as evaporites were expelled from the adjoining synclines, which carry a stratigraphic record of the resulting differential subsidence.

Comparable structures have been well studied on passive continental margins. Surfaces along which evaporites have been expelled (and originally non-contiguous units juxtaposed) are known as *welds*. Types of welds are classified based on the origin and orientation of the evaporite body prior to its expulsion (Figure 9). The overlying subsident areas, in which accumulating sediments may record the history of evaporite expulsion, are *minibasins*.





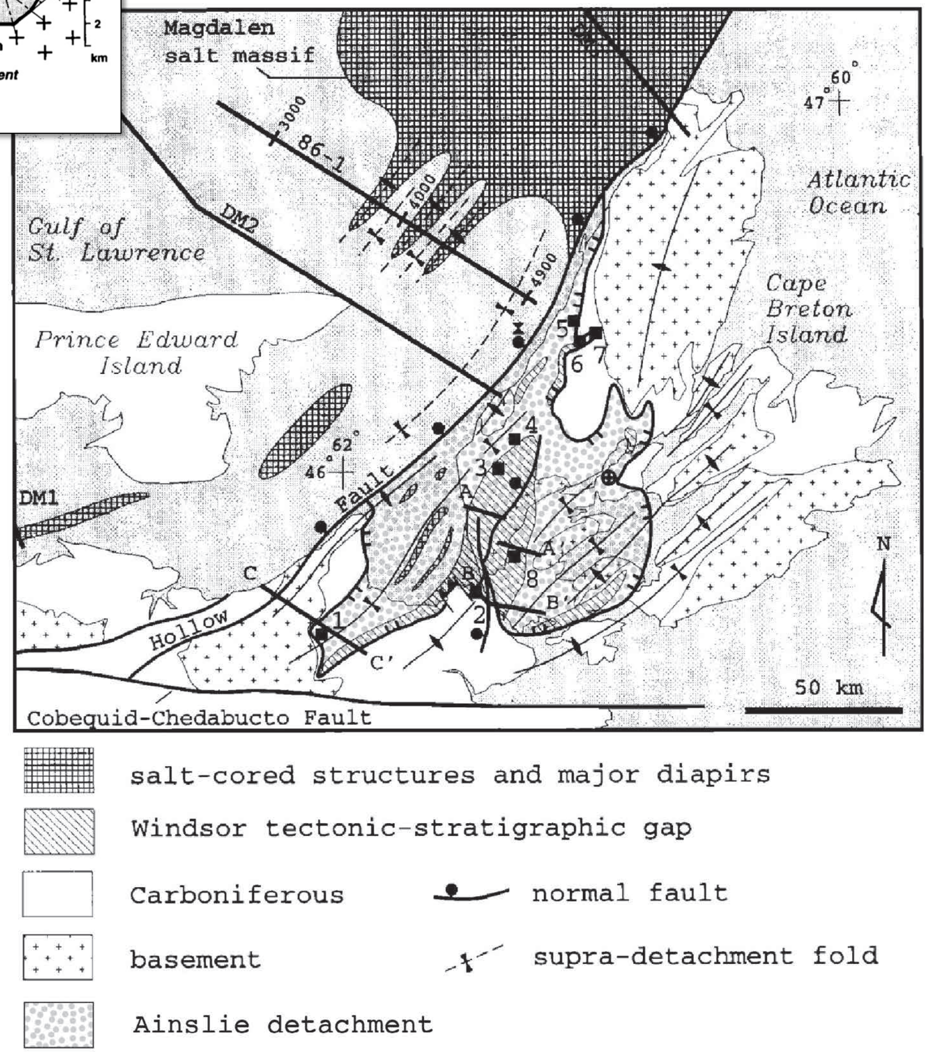


Figure 7. Map of proposed Ainslie detachment and diagram showing stratigraphic omissions from the Windsor Group (Lynch et al. 1998).

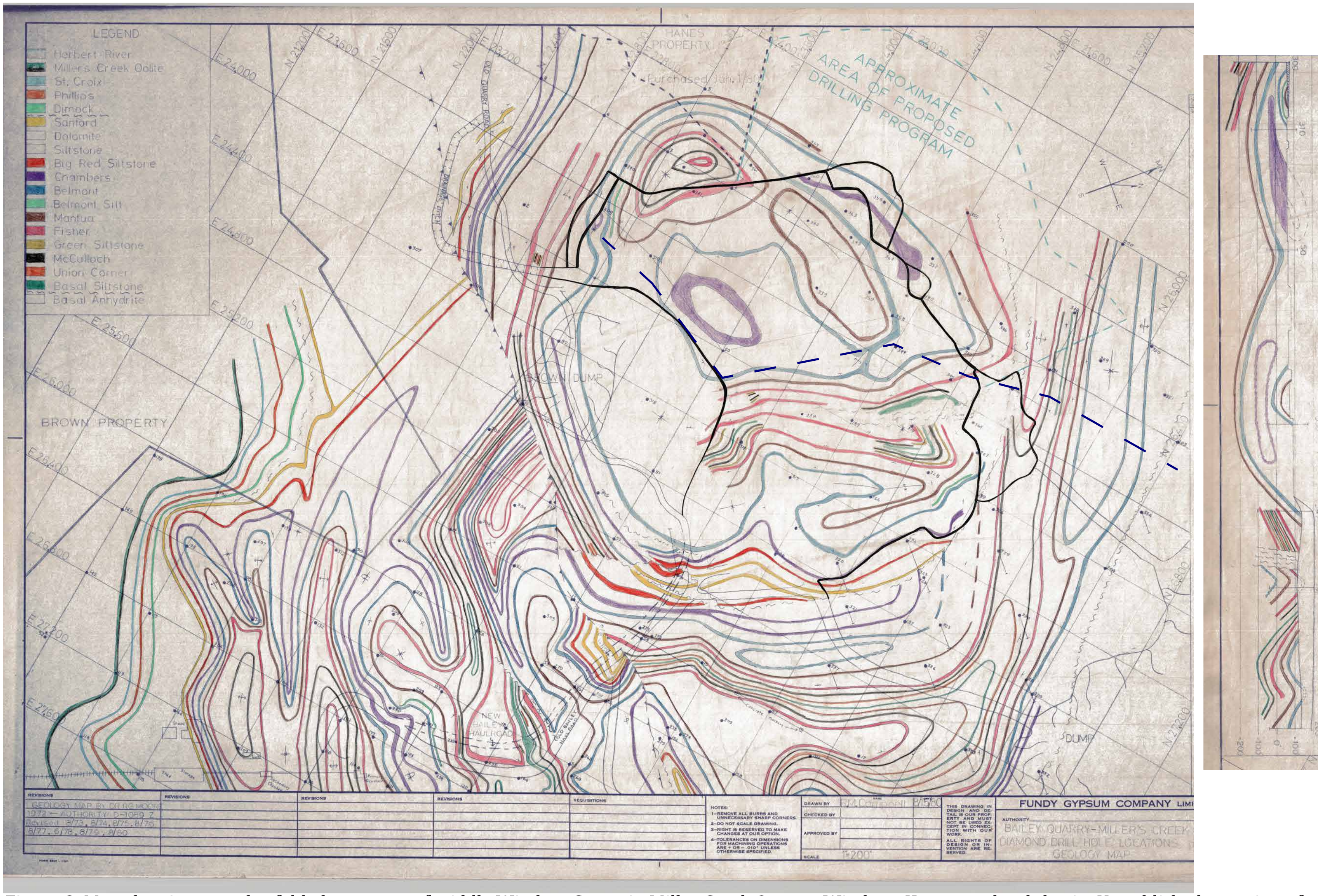
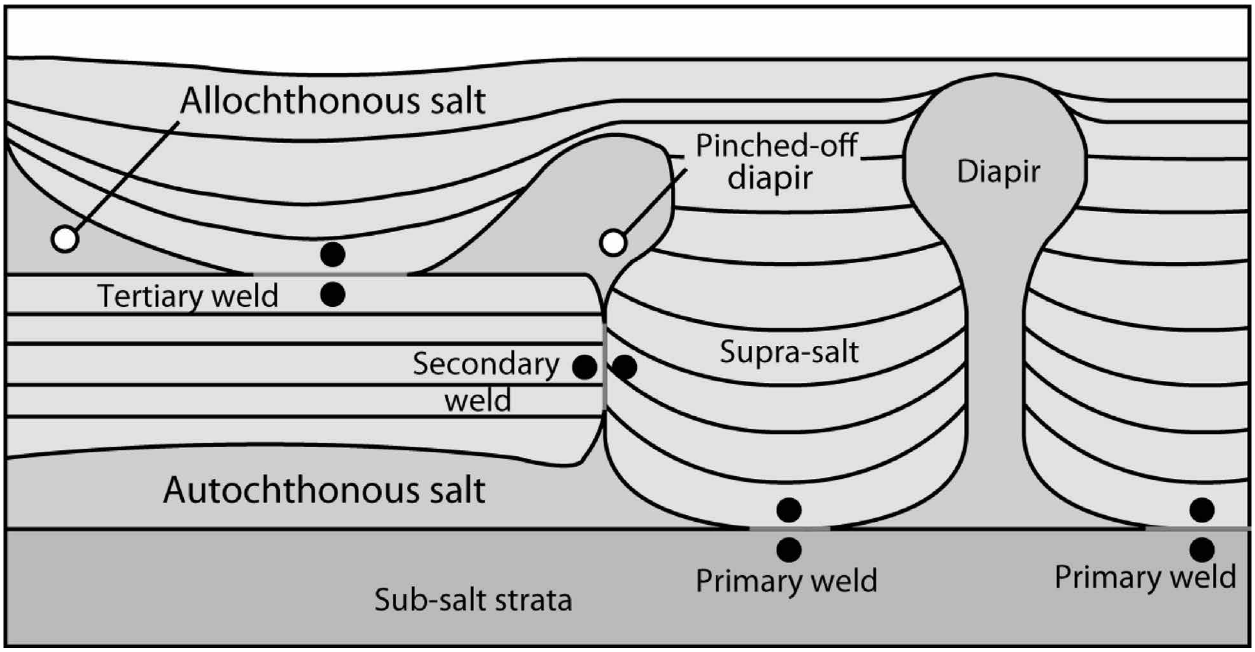


Figure 8. Map showing complex folded structure of middle Windsor Group in Miller Creek Quarry, Windsor–Kennetcook sub-basin. Unpublished mapping of R.G. Moore, students of Acadia University, and staff of Miller Creek and Bailey Quarries.

Figure 9. Typical features of evaporite welds and minibasins (Jackson et al. 2014). Primary salt welds record expulsion of autochthonous salt; secondary welds form as a result of expulsion from a steep diapir, and tertiary welds mark the position of previous allochthonous salt.



Analysis of the stratigraphic relationships seen the Cumberland sub-basin suggested that the subsidence histories of the eastern and western Cumberland basin were different. In the east, evaporite expulsion began at least as early as the Serpukhovian, in an environment of overall extension or transtension, and probably began in the Visean, as recorded by minibasin-like geometries imaged deep in the subsurface. However, the same history of salt movement did not occur in the west, where a thick (>2 km) succession of Windsor evaporites was not expelled until the Bashkirian. Expulsion of these evaporites led to rapid subsidence in the adjacent Athol syncline, a minibasin in which the rapid development of accommodation, and the accumulation of sediment, was an important factor in the preservation of upright trees in the famous Joggins fossil forests, now a UNESCO world heritage site (Waldron and Rygel 2005).

Comparison of the Cumberland sub-basin with other sub-basins of the Maritimes Basin suggests that the configuration in the eastern Cumberland sub-basin, where evaporite expulsion began early, in the Visean and Serpukhovian, is more normal (Thomas 2019, Snyder and Waldron 2021).

The hypothesis that evaporite movement, and mini-basin formation, began during deposition of the Windsor and Mabou Group helps to explain startling lateral facies changes and thickness variations in the Windsor Group, as between lower Windsor evaporites and clastic sediment of the Tennycape Formation (Figure 4), and in Newfoundland between contemporary evaporite-rich and evaporite-poor units (Snyder and Waldron 2021). However, it poses questions about both the previously described moderate thickness and “layer-cake” characteristics of the Windsor Group limestones (also seen in Figure 4). However, thickness estimates (< 1km) of the Windsor Group

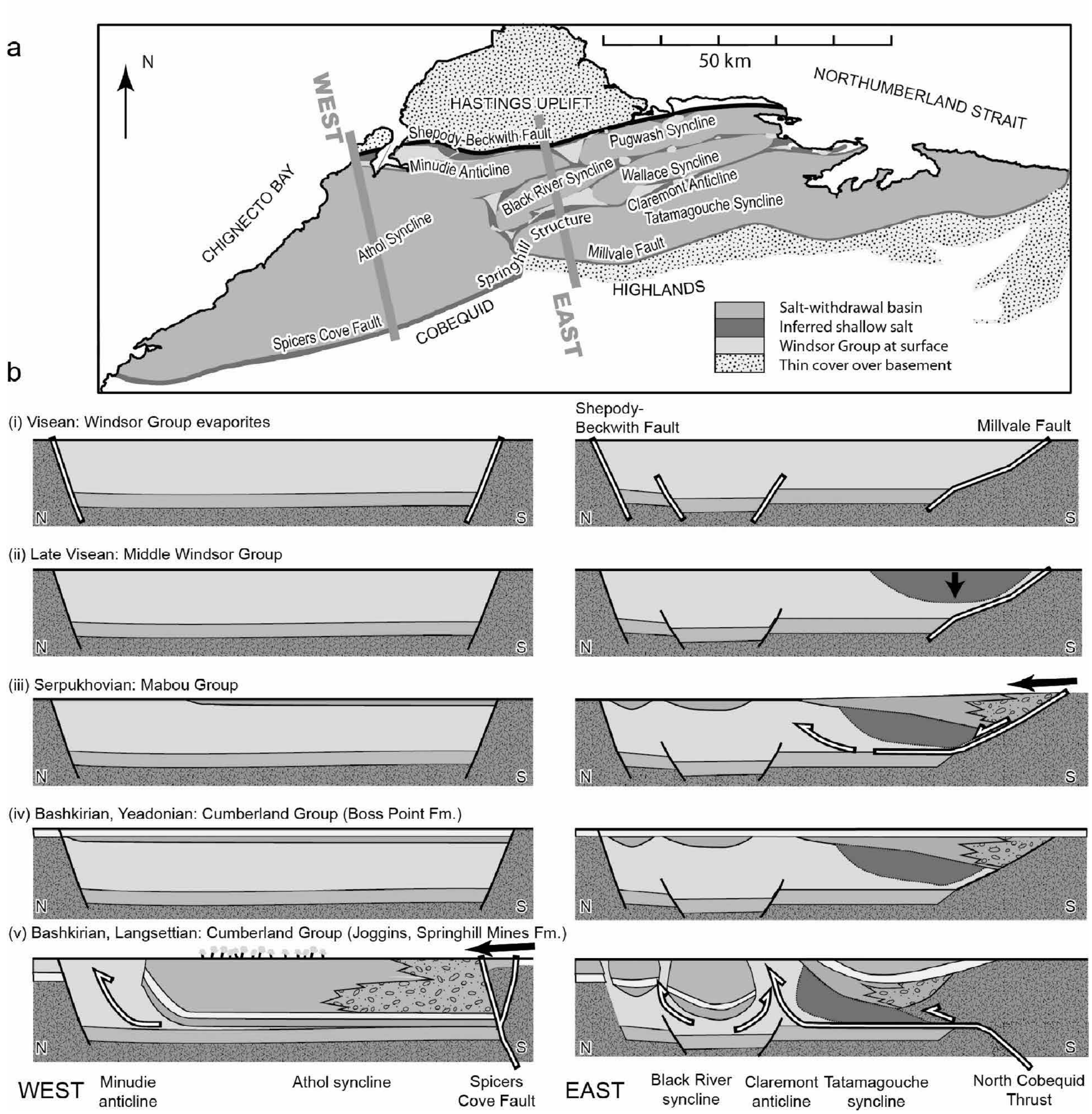


Figure 10. Map and interpretation of Cumberland sub-basin showing contrasting evolution of western and eastern sub-basins (Waldron et al. 2013).

are predominantly derived from the least deformed successions, particularly in the relatively shallow Musquodoboit and Shubenacadie sub-basins (Figure 1), and may well be unrepresentative. Much greater thicknesses of evaporite (2–3 km) are suggested by minibasin fills in the Cumberland sub-basin (Waldron and Rygel 2005), but cannot be confirmed because the remaining evaporites are too deformed for the measurement of sections.

What of the laterally continuous limestones, which have previously been interpreted to imply continuity of the various sub-basins during the Visean? Giles (2009) has suggested that orbital forcing associated with the development of Gondwanan ice sheets can explain the cyclic variations in facies seen in the middle and upper Windsor Groups through eustatic sea-level change. It is thus possible to envisage that a rising sea-level pulse would likely have simultaneously flooded minibasins in diverse parts of the Maritimes Basin, accounting for the deposition of similar, normal-marine carbonates in minibasins that were, at other times, disconnected from one another.

Basin inversion and younger structures

Dextral strike-slip motion along the Minas fault zone (MFZ) probably reached a peak in late Serpukhovian to earliest Bashkirian time (Murphy et al. 2011) when a regional "Miss.–Penn. unconformity" affects the basin. A corresponding unconformity in the southern Appalachian basin may be eustatic, but in the Maritimes Basin this unconformity locally removes too much section to be explained by eustasy alone; it must result from tectonic motion, probably involving convergence in addition to strike-slip (i.e., transpression).

Different portions of the Maritimes Basin probably experienced different tectonic regimes during this phase of basin development. The Stellarton sub-basin underwent extension, subsiding at a releasing bend or junction on strike-slip fault systems from Langsettian to Asturian time (late Bashkirian to late Moscovian, or, in older timescales, Westphalian A–D) before being affected by shortening late in its history. Many sections show a hiatus in the Duckmantian (Westphalian B). Relationships seen in seismic profiles on the north margin of the Cobequid Highlands (Figure 1) suggest that this hiatus may record transpression and tilting as the Cobequids were uplifted along steep faults and inserted as a tectonic wedge into the Cumberland sub-basin. Tectonic wedges appear to be widespread products of basin inversion in the Maritimes Basin. The start of this process may have triggered the expulsion of evaporites from the western, Athol syncline of the Cumberland sub-basin. If the Duckmantian unconformity is associated with transpression, it may well be diachronous. Restraining bends on strike slip faults produce pulses of uplift that migrate laterally over time.

Later tectonism was clearly relatively mild, except perhaps in SW New Brunswick where thrusting continued into at least into the Moscovian (Plint and Van de Poll 1984). Most Pictou Group strata are relatively flat-lying but in the Cumberland sub-basin tall evaporite diapirs, propagated from an underlying salt wall, pierce Pictou Group strata. The active Pugwash salt mine (PM – Figure 1) is located in a salt diapir.

Evolution of the Maritimes Basin

It is clear that the Maritimes Basin developed under the combined influence of strike-slip tectonics (including transtension and transpression) and evaporite flow. There are few well-studied models for such basins - it may be argued that the Maritimes Basin is one of the best, although of course many of the more soluble evaporites have been dissolved, in contrast to evaporitic basins in more arid climates.

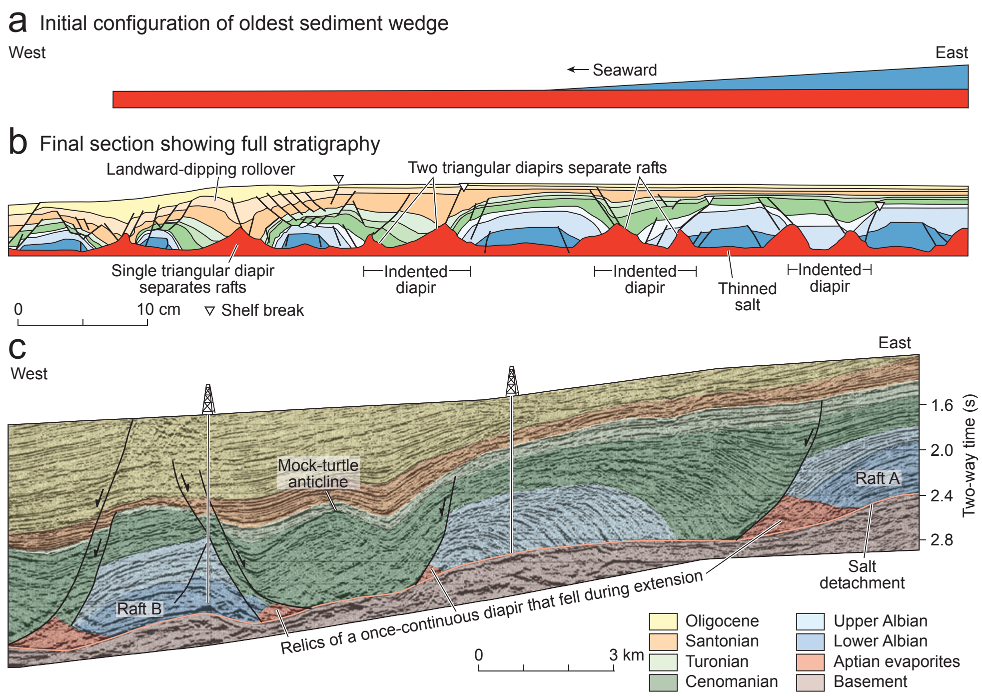
The role of strike-slip tectonics in the late Paleozoic of Atlantic Canada has been at least partially understood for many decades (e.g. Belt 1968, Bradley 1982, Nance 1987, Waldron 2004, Murphy et al. 2011). However, authors have differed on the amounts of shortening and extension that have occurred (e.g. Belt 1968, Martel 1987, McCutcheon and Robinson 1987, Durling et al. 1995a, Lynch and Giles 1995).

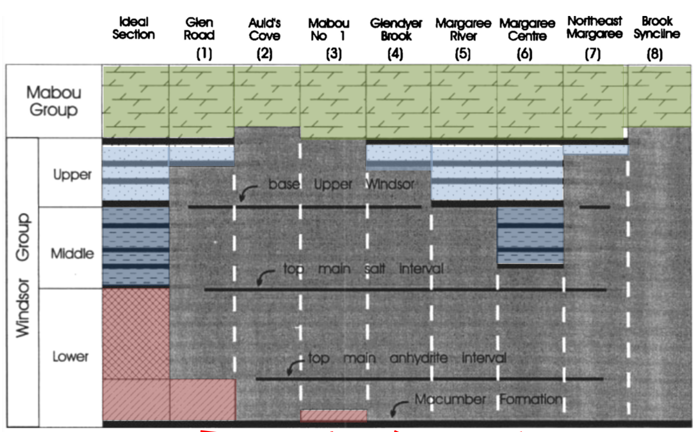
Early structural interpretations were hampered by over-adherence to discussions of *stress* (Anderson 1905, Anderson, 1951). Such *dynamic* analyses suggest that structures will fall neatly into three categories: horizontal compression, extension, and strike-slip, but neglect the fact that observed structures are cumulative products of stress that varied over time. More modern *kinematic* analyses have focussed on much more quantifiable *strain* measures, and have increasingly led to the recognition of mixed tectonic environments - transpression and transtension - in which strike-slip motion is combined with shortening or extension (e.g. Sanderson and Marchini 1984, Fossen et al. 1994, Dewey et al. 1998). Furthermore, such environments can be divided into simple-shear-dominated transtension and transpression (in which both the extension and shortening directions are horizontal) and pure-shear dominated variants in which the intermediate strain axis is horizontal as in a classical rift or thrust belt. Thus a wide variety of structural configurations are possible, combining aspects of rifts, strike-slip zones, and thrust belts. In this respect, the work of Belt (1968) was far ahead of its time in recognizing the difficulty of characterizing the tectonic style of the Maritimes Basin using a single model.

High-quality seismic reflection data from passive continental margins have led to a revolution in the understanding of salt tectonics, and particularly of its relationship to stratigraphy, since 1990 (e.g. Vendeville and Jackson 1992a, 1992b, Hudec et al. 2009, Jackson and Hudec 2017) (Figure 9, Figure 11a). These advances show that stratigraphic omissions similar to those associated with the postulated Ainslie detachment (Lynch et al. 1998) can be explained with much smaller horizontal movements if near-vertical expulsion of salt is taken into account (Figure 11b).

Early evolution of the Maritimes Basin, during deposition of the Late Devonian to Tournaisian Fountain Lake and Horton groups, was clearly dominated by extension. The most likely cause, however, was transcurrent movement between Laurentia and Gondwana along zone with Appalachian-trend (NE–SW) that was offset by a large releasing bend (Hibbard and Waldron 2009) inherited from the old, Appalachian Laurentian margin (Thomas 1977). The tectonic evolution is best understood as similar to the modern basin and range province in the western USA, or the Cenozoic Bohai Bay basin (Figure 13) in northern China (Allen et al. 1998, Gibling et al. 2019).

Figure 11. Salt-tectonic structures on the West African margin (Rouby et al. 2002, Jackson and Hudec 2017).





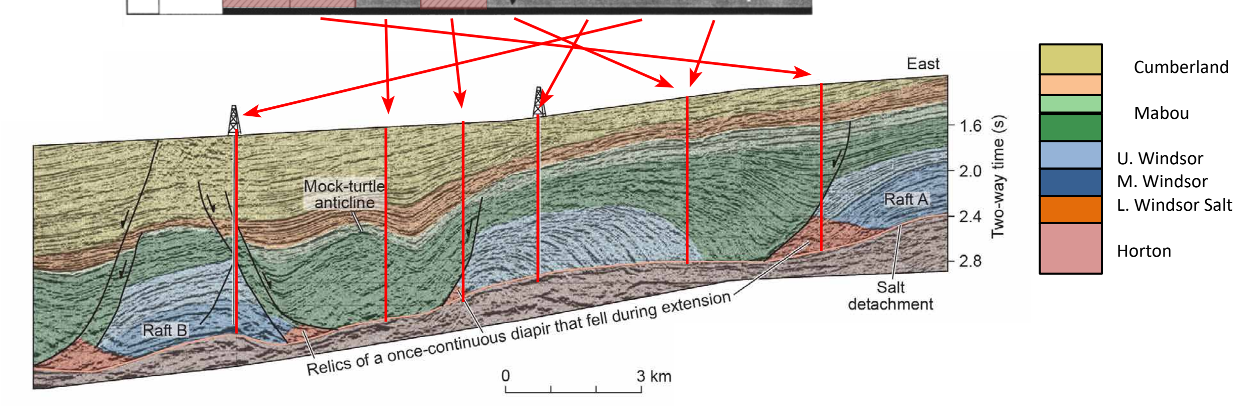
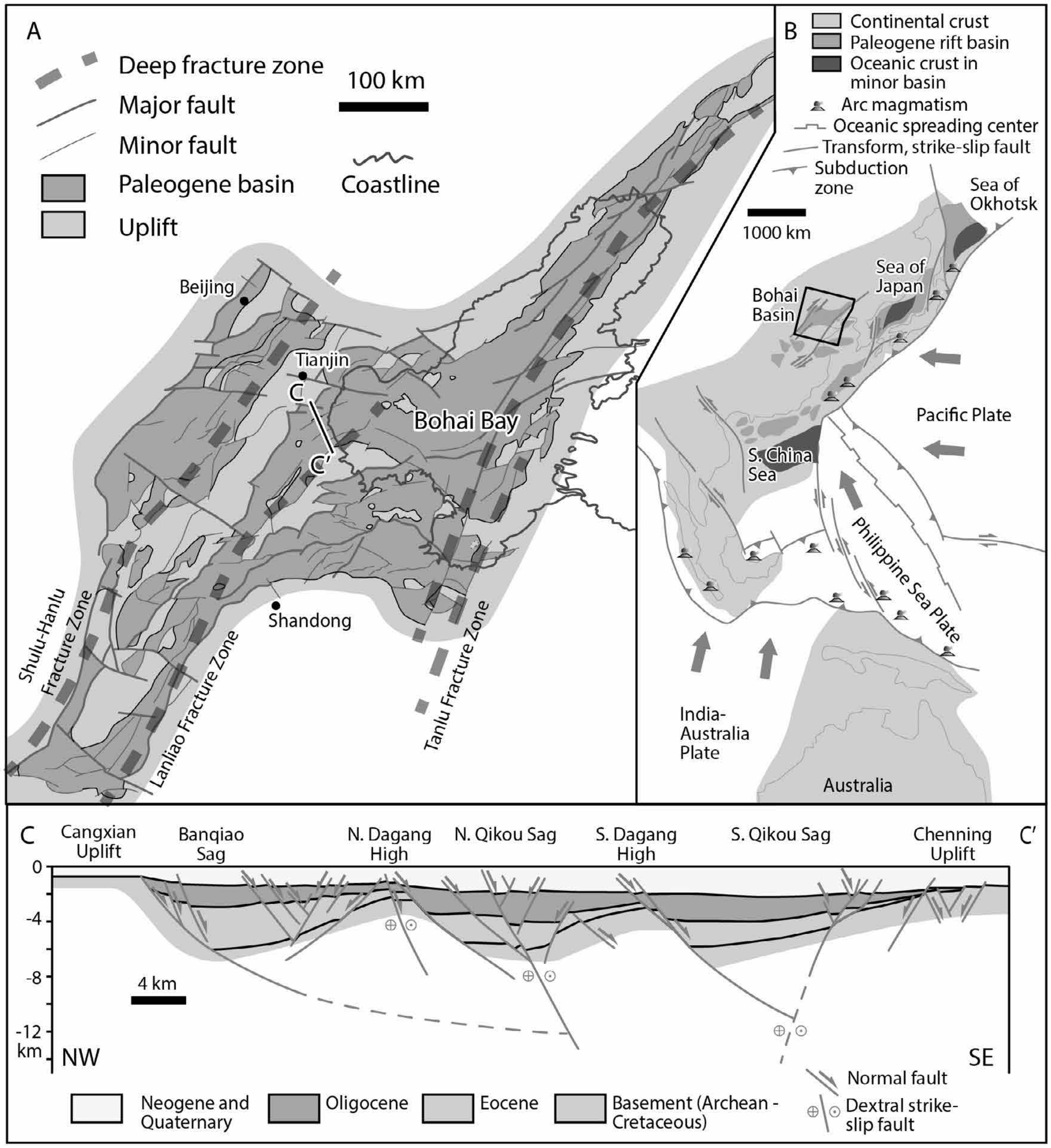


Figure 12. Reinterpretation of stratigraphy associated with the postulated Ainslie detachment (Lynch et al. 1998) using West African margin as an analogue.

Figure 13. Bohai Bay basin in northern China, a transtensional, obliquely rifted Cenozoic analogue for early stages in the development of the Maritimes Basin (Allen et al. 1998, Gibling et al. 2019 and references therein).



There was clearly a hiatus and a change of tectonic regime prior to deposition of the Windsor and conformably overlying Mabou groups, which blanket many of the earlier horst-and-graben structures. Cleavage development in the Cobequid Highlands (Murphy et al. 2011) and in the Lochaber–Mulgrave area of eastern mainland Nova Scotia probably occurred prior to the development of the Windsor Group during transpressional deformation along the Minas fault zone (Reynolds et al. 2004, Murphy et al. 2011). However, this is not the case for all such structures. Basin-margin facies and mapped relationships suggest that neither the Antigonish nor the Cobequid Highlands were covered, data from the Cumberland sub-basin show that the Mabou Group was deposited in an extensional half-graben along the north edge of the Cobequids (Waldron et al. 2013).

Stratigraphic relationships shown in Figure 12 suggest that lateral discontinuities in the Windsor–Mabou section were products of salt diapir formation in a broadly extensional environment. Abrupt changes in facies recorded in the Windsor and Codroy groups of the Windsor–Kennetcook and Bay St. George sub-basins, respectively, record the simultaneous subsidence of minibasins into the accommodation space created by expulsion of the thick lower Windsor salt (Snyder and Waldron 2021). Salt welds identified at Lakevale (LV – Figure 1) in the Antigonish sub-basin (Thomas 2019) and at Capelin Cove in the Bay St. George sub-basin (Figure 6) were probably developed during deposition of the Mabou Group.

A major upheaval took place following deposition of the Mabou Group, around the Mississippian–Pennsylvanian boundary ~318 Ma. This time (Figure 14) corresponded to deformation and mineralization (Figure 15) at many locations along the MFZ (Murphy et al. 2011, Pe-Piper et al. 2018). In the succeeding Bashkirian Stage, the basin was blanketed by a major incursion of fluvial sand, preserved in the Boss Point, Parrsboro, and Port Hood formations and their correlatives. Rapid expulsion of remaining thick salt occurred in the western Cumberland sub-basin, producing rapid sedimentation rates (over 1 km/Myr) in the Joggins succession with its famous preserved upright trees. Continued salt expulsion in Cape Breton Island led to the development of salt welds (Thomas 2019) at Little Judique and Port Hood Island, that involve Cumberland Group strata.

The trigger for this later phase of salt expulsion is not certain, but relationships seen in seismic profiles at the south margin of the Cumberland sub-basin strongly suggest that a tectonic wedge cored by Fountain Lake Group was inserted northward into the sub-basin by tectonic shortening. Salt was expelled northward, emerging upward in a salt wall near the north edge of the ub-basin. Although there is no direct evidence for the transcurrent component of motion, the simultaneous development of a transtensional pull-apart basin at Stellarton suggests that dextral strike-slip motion along the MFZ played a role. Variations in the strikes of basin-bounding faults could easily have placed the western Cumberland sub-basin in a restraining bend while the Stellarton sub-basin was on a releasing bend of the same fault system (Waldron 2004, Waldron et al. 2013). Tectonic movements are recorded into the late Moscovian but probably subsided into the Kasimovian–Gzhelian (latest Pennsylvanian) to Cisuralian (early Permian) interval. However, salt expulsion continued during, and probably after deposition of the Pictou Group, as shown by diapiric salt stocks in the northern Cumberland sub-basin (Pugwash area).

Figure 14. Compilation of isotopic ages along the Minas Fault Zone (Pe-Piper et al. 2018).

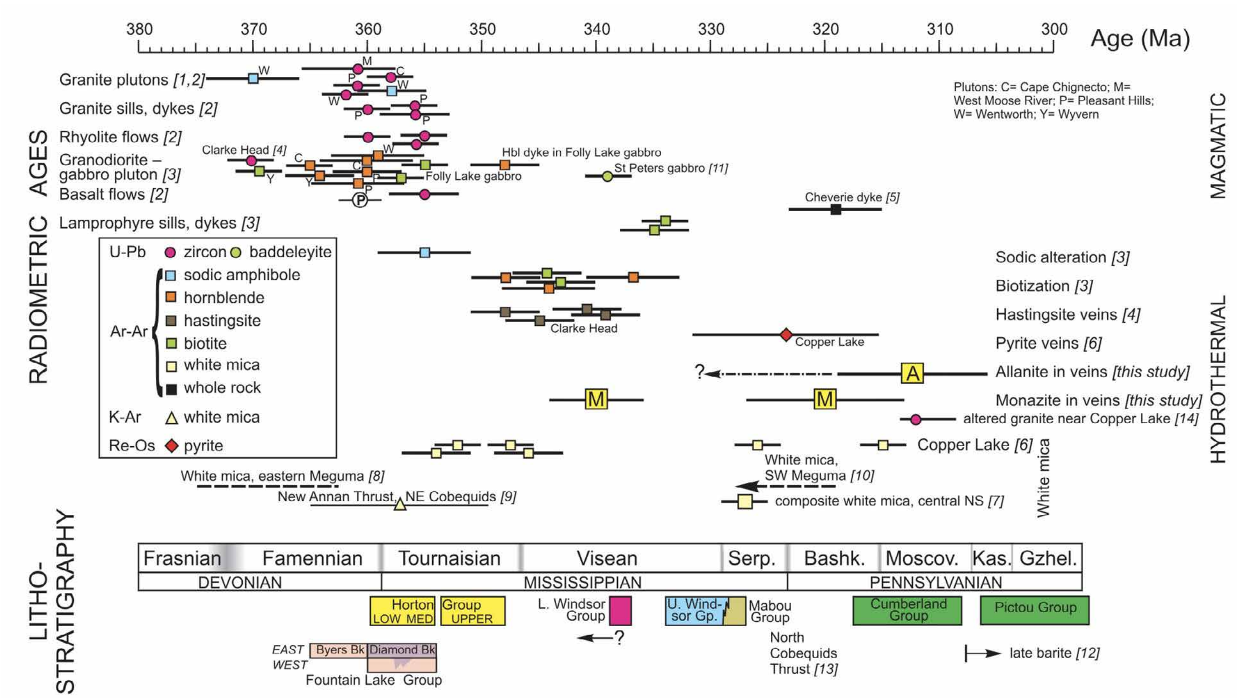
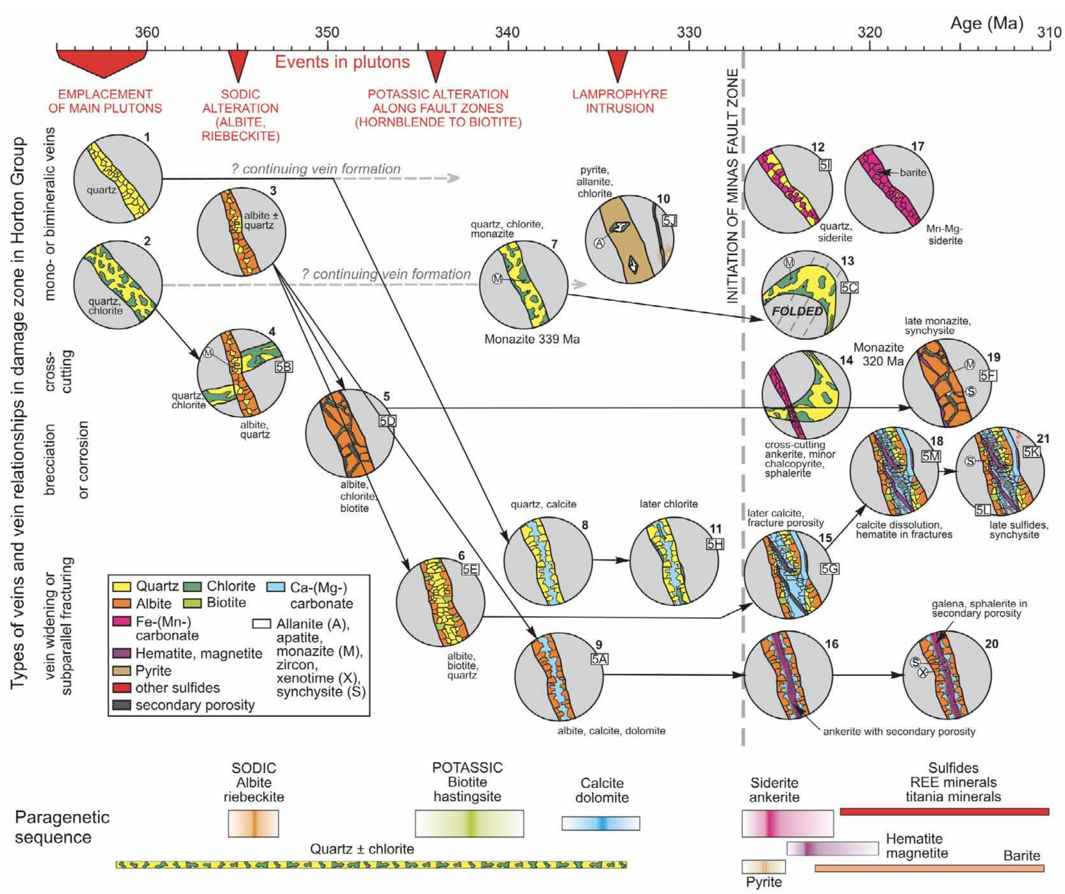


Figure 15. Diversity of vein types developed during movement along Minas Fault Zone (Pe-Piper et al. 2018).



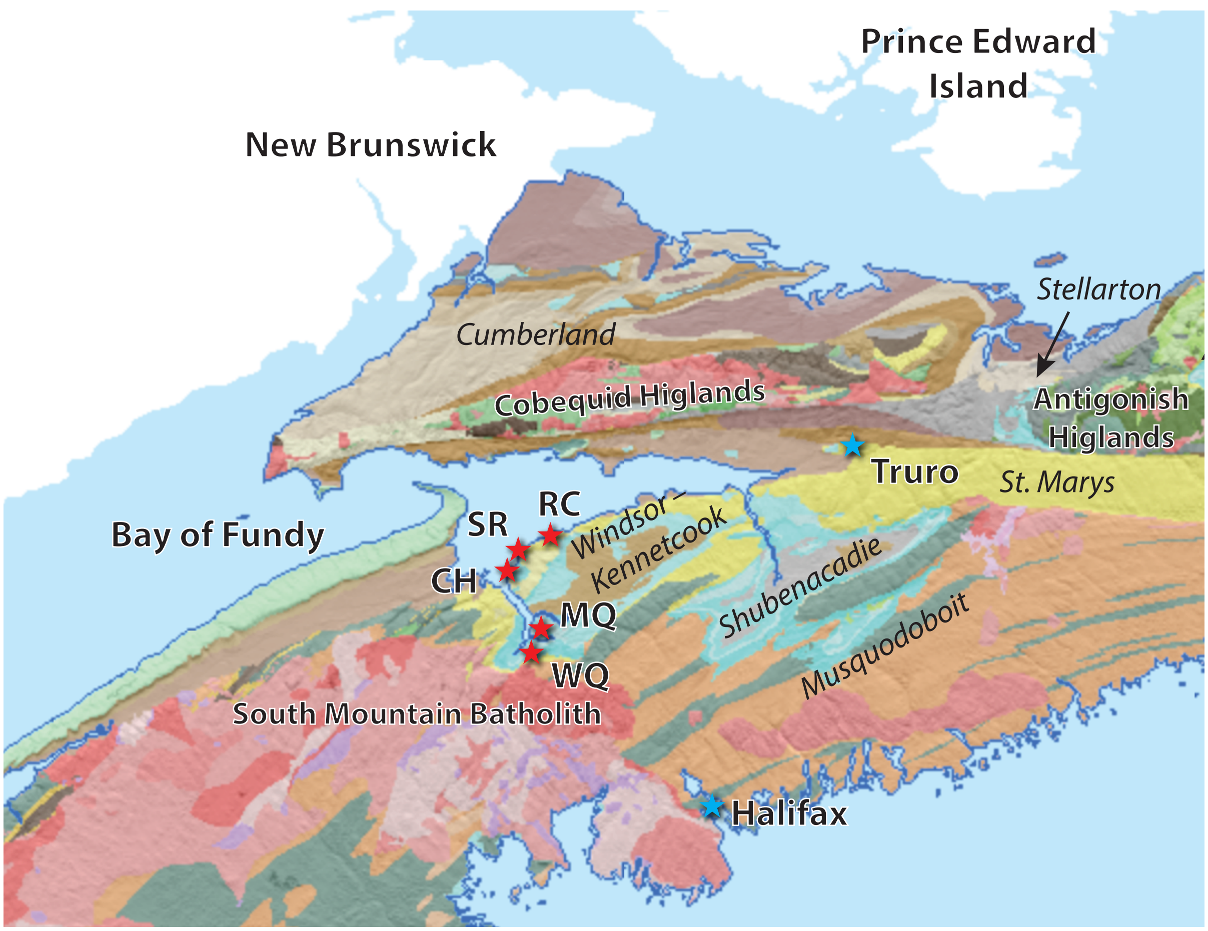
DAY 1 MINAS SHORE

Introduction to the day

The first part of today's drive is over Cambrian-Ordovician metaclastic rocks of the Meguma Supergroup and granitoids of the Devonian South Mountain Batholith. Meguma Supergroup in the aureole contains andalusite and locally (in an enclave) sillimanite. About at Exit 4 on highway 101, we cross an angular unconformity onto the late Paleozoic Maritimes Basin. The basal Horton Group is very thin at this point, so immediately NW of Exit 4 you will note outcrops of white gypsum on the roadside cuttings and nearby cliffs. This is the thick and relatively resistant White Quarry Formation, the local representative of the lower Windsor 'basal anhydrite'.

The Horton Group thickens to the north. In this area it is divided into a lower, mainly grey lacustrine unit named the *Horton Bluff Formation*, noted for spectacular soft-sediment deformation structures (Martel and Gibling 1993, Snyder and Waldron 2016) overlain by predominantly fluvial red and grey beds of the *Cheverie Formation*. Relatively undeformed strata characterize the type sections of the Horton Bluff and Cheverie Formations, respectively west and east of the Avon estuary (Figure 17). The overlying

Figure 16. Day 1 field stops. Source (Keppie 2000), with full legend, at: https://novascotia.ca/natr/meb/download/dp043.asp



Windsor Group has complex internal stratigraphy. At the base of the Windsor Group is a thin unit of laminated lime mudstone, the *Macumber Formation*. Overlying gypsum and anhydrite are assigned to the *White Quarry Formation*. However, in some sections the Macumber Formation is overlain by enigmatic breccia units, informally termed *Pembroke breccia,* that occur beneath the White Quarry Formation.

A subhorizontal discontinuity overlies the White Quarry Formation throughout the region that lies to the north, which features spectacular coastal exposures of the Tournaisian Horton and Visean Windsor groups. This discontinuity is partially exposed at several locations and is also seen in seismic profiles where it is termed the Kennetcook thrust (Keppie 1982, Waldron et al. 2010). In northern, coastal parts of the area, this contact places Horton Group above basal Windsor Group rocks, duplicating stratigraphy in a belt 5–10 km wide, which provides a rough minimum displacement. However, as we shall see on this day, rocks in the hanging wall are dramatically shortened by upright and recumbent folds, in places in complex overprinted patterns, whereas the footwall rocks are much less deformed. It is likely, therefore, that the displacement on the thrust decreases in the direction of transport, inferred to be roughly southeast.

The presence of Horton Group in a hanging wall ramp implies that there is a corresponding footwall ramp offshore to the north under the Bay of Fundy, or below Triassic rocks of the Fundy Group. However, this ramp is not exposed. To the south, the thrust passes into a zone where the hanging wall stratigraphy is largely constant (though highly deformed) suggesting a “flat-on-flat” relationship at the thrust, which follows the stratigraphic position of the lower Windsor salt. It is therefore likely that the salt (before it was expelled by halokinesis or removed by solution during exhumation) acted as a décollement surface.

Wentworth Quarry (WQ)

Drive 67 km, 0:50.
Start Halifax downtown. Drive north on Barrington or Robie Street and Massachusetts Avenue to NS-111 to Dartmouth via MacKay Bridge.
Pay toll.

Take exit 2W toward NS-7 following signs to Bedford, Lower Sackville. Fork right onto NS-33 still to Bedford, Lower Sackville. Exit left onto NS-101 westbound towards Windsor.
Continue to Exit 5A toward Wentworth Road. At roundabout take second exit. Continue to Wentworth Quarry entrance on left.

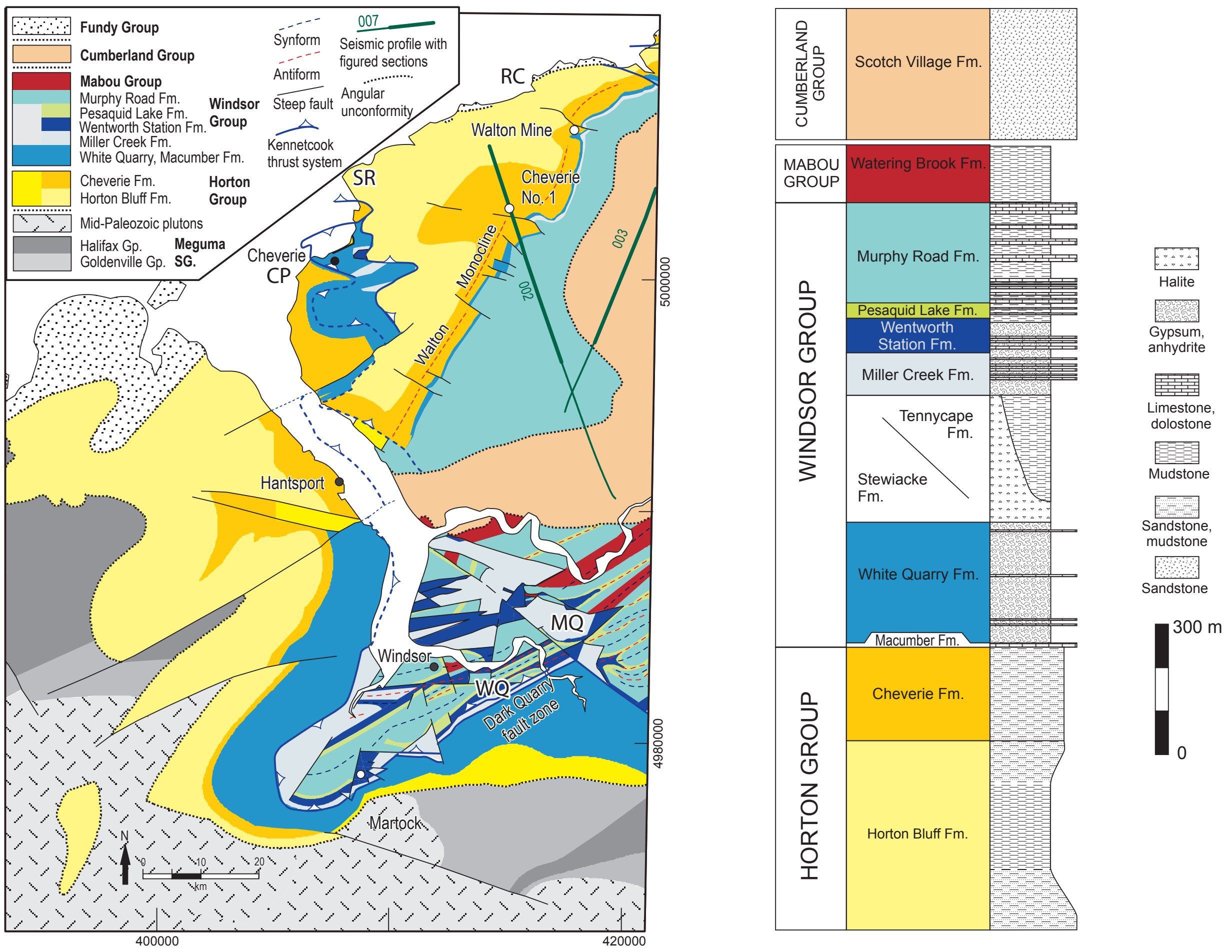
- 414009 4983018 (Locations are UTM grid zone 20T and use the WGS84 datum.)

Caution: Quarry is in ‘care and maintenance’. Safety vests and hard hats are required Active mining is not in progress but be aware that slopes are unstable rocks may fall. Do not enter tunnels, caves or other underground workings. Do not touch cables or discarded engineered materials, and be aware of the tripping hazards that these pose. Do not wander away from the group. Washrooms at quarry office.

Proceed with guidance from quarry staff to the access road at

- 4146434 982101

Figure 17. Map showing geology of western Windsor–Kennetcook sub-basin, including field stops (Waldron et al. 2010).



At this location, the N-dipping upper contact of the White Quarry Formation is exposed. Underlying rock is gently N-dipping weakly bedded white gypsum and blueish anhydrite of the White Quarry Formation. Above is middle Windsor Group, here assigned to the Miller Creek formation, consisting of rubbly gypsum including thin limestone marker beds. The deformed zone between the two, mapped as Dark Quarry fault zone (Moore and Ferguson 1986) is an important contact separating transported evaporites, above, from untransported evaporites below. It is likely the Kennetcook thrust horizon, although there is no duplication of stratigraphy. Note that the rocks above are shortened by upright to steeply inclined folds whereas the rocks below are not. The zone of deformation itself has been highly modified by rehydration of anhydrite to gypsum, and removal of all traces of the thick lower Windsor salt, which would occur in the subsurface at this level. From a kinematic point of view the zone of deformation is not particularly informative.

Miller Creek Quarry (MQ)

Drive 7 km. 0:07. Head east on Wentworth Rd toward Baxter Rd. Turn left onto Glooscap Trail/NS-14 E, 1.4 km. Turn left onto Avondale Rd 1.4 km. At the T junction, turn left to stay on Avondale Rd. Quarry entrance is on the right.

- 417413 4983846

Caution: Quarry is in 'care and maintenance'. Safety vests and hard hats are required Active mining is not in progress but be aware that slopes are unstable rocks may fall. Do not enter tunnels, caves or other underground workings. Be aware of tripping hazards including cables and discarded engineered materials. Do not wander away from the group. No washrooms.

Proceed with quarry staff to the face at

- 416585 4985996

The second gypsum quarry in the Windsor area is actually a combination of two pits, the eastern Miller Creek Quarry, now largely reclaimed, and the western Bailey Pit, still well exposed. Unpublished maps by R.G. Moore and students from Acadia University made in the late 20th century traced numerous marker limestones through the quarries and the associated drill holes, showing a highly convoluted structure with overturned sections and sheath folds (Figure 8). Because of the rubbly nature of the outcrops the structure is unclear in the present-day exposures, although the extent of the workings is impressive.

Cheverie (CV)

Drive 27 km, 00:23.
Head southeast on Avondale Rd toward Millers Creek Rd. Continue straight onto Lawrence Rd 2.5 km. Turn left to merge onto Glooscap Trail/NS-215. Continue 23.6 km. General store with washroom available at Centre Burlington en route. Turn left onto Leander Macumber Rd. Park at the end of the road taking care not to obstruct access.

- 406940 5000750

Do not trespass on private property. Rocky shoreline is locally very slippery when wet. Be especially careful on rocks with algae (seaweed). Section is tidal: do not venture out onto the tidal flats except on a falling tide. Low tide (Hantsport) 2022-05-12 16:49 ADT. No washrooms.

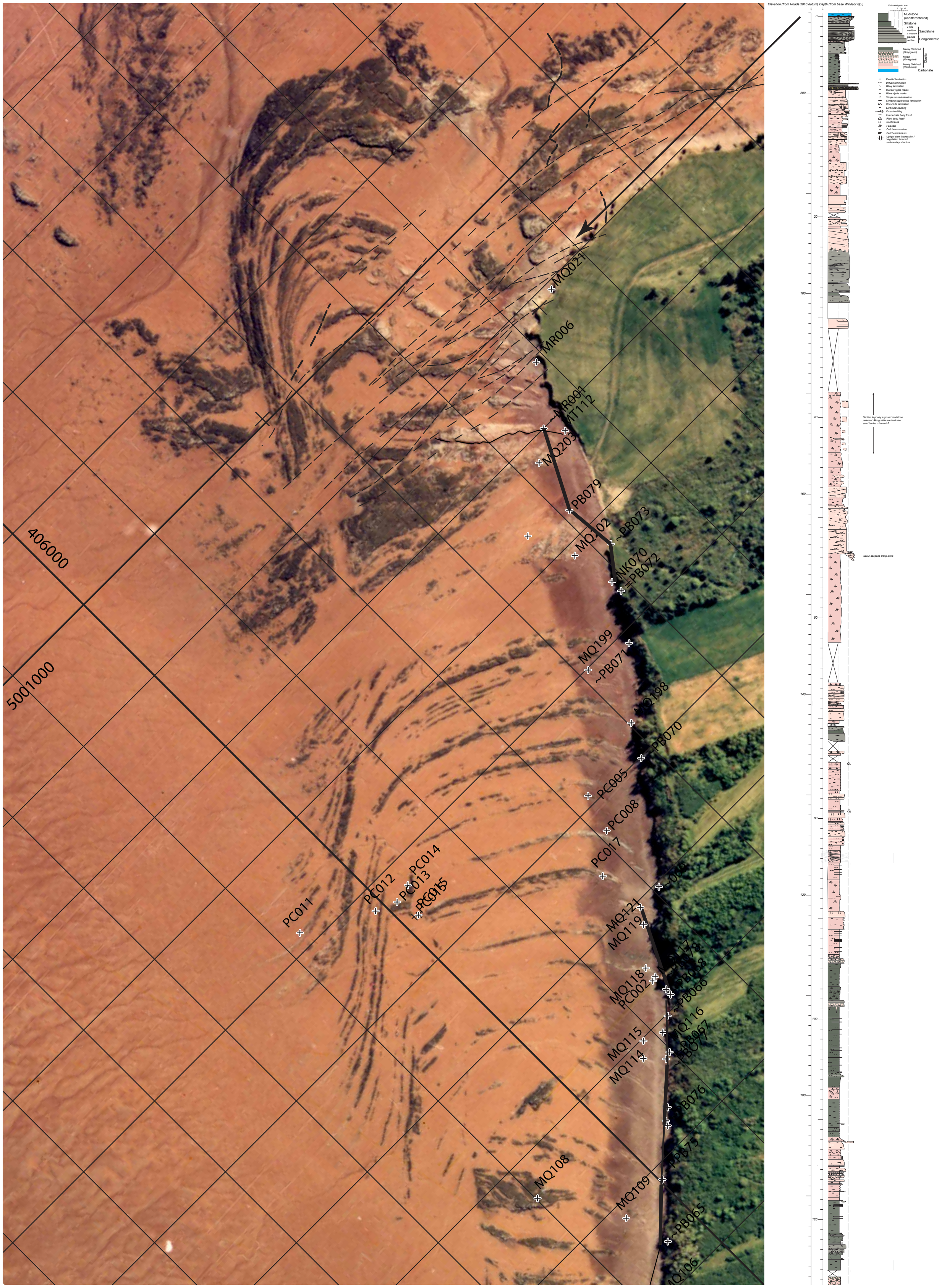
Walk W along the coast to the cliffs and wave-cut platform.

- 406500 5000900

On the wave-cut platform, the gently folded Cheverie and overlying Macumber Formation plunge beneath a broad region of Pembroke breccia. The Cheverie Formation (upper Horton Group) consists of red to yellow sandstone and mudstone. The laminated sandstone locally includes sedimentary structures such as cross-bedding and climbing-ripple cross-lamination. Mudstones locally display mudcracks, plant fragments, and yellowish carbonate concretions interpreted as caliche, which is locally reworked into lag deposits in channels. Both sandstone and mudstone locally contain upright fossil tree stumps and amphibian footprints, though typically not particularly well preserved. The Cheverie Formation is interpreted as a fluvial succession probably deposited in channels and arid floodplains.

Several different interpretations have been proposed for the overlying Macumber Formation limestone at the base of the Windsor Group, summarized by Lavoie et al. (1995); interpretations include intertidal algal mats (Schenk 1967), deep water

Figure 18. Air photo montage of Cheverie Point section, incorporating unpublished work by J. Noade (Dalhousie U.) and the current authors. Grid 100 m.



methane-vent bioaccumulations (Von Bitter et al. 1992), saline lake deposits (Schenk et al. 1994), and deep water microbial mats Lavoie et al. (1995). The Macumber Formation shows excellent exposures of reverse faults and associated fault-propagation folds. Scattered outcrops of highly deformed Windsor gypsum and anhydrite occur in adjacent coastal cliffs.

The Macumber Formation passes transitionally upward into a poorly understood unit known as the Pembroke breccia. It consists of variably sized, randomly oriented, elongate angular blocks of thinly laminated yellow weathered limestone, of Macumber Formation origin (Lavoie et al. 1995), typically in a limestone matrix. The origin of the Pembroke breccia is controversial. Four different processes may have contributed: (1) synsedimentary slumping produced a breccia of well bedded microbial mats, and slump folds in contorted mats (Lavoie et al. 1995). (2) Because of the absence of certain stratigraphic units above the Macumber, Lavoie et al. (1995) also proposed that some of the breccia is tectonic, formed by bedding-parallel extensional shear. Stratigraphic omissions were linked to the proposed Ainsley detachment positioned at the Macumber / evaporite boundary (Giles and Lynch 1994, Lavoie and Sangster 1995). (3) A late karstic breccia can incorporate both intact Macumber Formation and previously brecciated material of origins 1 and 2 (Lavoie et al. 1995). (4) Parts of the Pembroke breccia can also be interpreted as solution collapse breccia.

Highly deformed gypsum and anhydrite with internal layers of folded bituminous black limestone, attributed to the White Quarry Formation, occur farther east along the shore.

Johnson Cove – Split Rock (– Mutton Cove) shoreline hike (SR)

Drive 4.3 km, 0:06.
Head southeast on Leander Macumber Rd toward Glooscap Trail/NS-215 E. Turn left onto Glooscap Trail/NS-215 E. General store in Cheverie may has a washroom. In 3.1 km. Turn left onto Sherman Lake Rd. Park at the end of the road.

- 408581 5002953

This is an extended shoreline hike; carry spare weather-appropriate clothing, water and snacks. Wear a hard had if approaching cliffs and do not stand under overhangs. Rocky shoreline is locally very slippery when wet. Be especially careful on rocks with algae (seaweed). Section is tidal: do not venture out onto the tidal flats except on a falling tide. Low tide (Hantsport) 2022-05-12 16:49 ADT. No washrooms.

Walk north along the shore, moving down beach to ford the stream at a shallow point.

- 408400 5003282

SR-1 Johnson Cove: Uppermost Cheverie section

At the beach there are typical exposures of the Cheverie Formation, red to yellow sandstone and mudstone. The laminated sandstones locally include sedimentary structures such as cross-bedding and climbing-ripple cross-lamination. Mudstone locally displays mudcracks, plant fragments, and yellowish carbonate concretions interpreted as caliche. There are significant differences between this succession and that on the SW side of Cheverie Harbour, suggesting significant lateral variability.

SR-2 Basal Windsor section

The uppermost beds of the Cheverie Formation are calcareous sandstone. The transition to overlying pinkish grey fine limestones of the basal Windsor Group (Macumber Formation) is inconspicuous but sharp. The Macumber Formation consists of laterally continuous laminated limestone with a yellow to reddish orange oxidized weathering surface. The resistant limestone forms a distinctive linear outcrop on the shore. The overall stratigraphic thickness of the Macumber Formation is 2-3 m.

Above the Macumber Formation, only a short interval of Pembroke breccia is exposed. Locally, cavities within the breccia include soft red sandstone possibly derived by infiltration from younger Carboniferous or Triassic units above. To the north, there is sporadic exposure in the beach, including both Windsor and Horton lithologies. Bedding orientations appear chaotic, suggesting that there is a significant thickness of megabreccia, involving material from both groups. This zone, mapped by Moore et al (2000) as the Johnson Cove thrust, is interpreted as the local expression of the gently folded Kennetcook thrust, the base of "allochthonous" Horton Group.

SR-3 Horton Bluff Formation, and Triassic Fundy Group graben-fill

- 408344 5003639

At the start of continuous exposure there are Horton Group shale and thin sandstone that are tightly folded, with incipient axial planar cleavage in some beds. Immediately north, the sedimentary rocks are cut by a diabase dyke and sill, and by faults that bring down a small graben-like outcrop of the Triassic Fundy Group to beach level. The Fundy Group is much more friable than the adjacent Horton Group and is easily distinguished. A first interpretation might suggest that the intrusion is related to the graben formation. However, this seems not to be the case because the intrusion closely resembles others in the area that have been dated as mid-Carboniferous (Kontak et al. 2000), and appears quite unlike the Mesozoic basalts of the Fundy Group. Hence we have to regard the juxtaposition of the dyke and the graben either as a coincidence, or as a result of the localization of Mesozoic faults at pre-existing intrusions.

SR-4: Mid-Carboniferous intrusions

- 408222 3003692

An approximately homoclinal, gently dipping succession of Horton Bluff Formation is exposed on the south-facing cliff. Spectacular wave-ripple marks are visible on the rocky shore. Despite the apparent low degree of deformation, there is a steep cleavage in places, and intersection lineation is visible on bedding surfaces. The preservation of sedimentary structures suggests that the strain is low.

Close to the top of the cliff, a diabase sill is more resistant to weathering than most of the Horton Bluff lithologies. The sill is abruptly connected with a dyke, which cuts across stratigraphy before connecting with another sill-like segment, that disappears under the beach. Lenticular intrusions of diabase are present low in the cliffs, and suggest that the magma filled a series of generally *en-echelon* tension gashes, interconnected fractures, and bedding-plane cracks. This group of intrusions is one of several that occur within Horton Bluff Formation rocks in the area. Although the age relationships are unclear at this locality, about 2 km to the south, in Cheverie, Johnston (1999) was able to show in thin section that the intrusions clearly cross-cut the fabric of highly deformed shale, though they are themselves cut by faults (Figure 19). Kontak et al. (2000) used Ar-Ar methods to date another intrusion in this suite, located about 2 km inland, also cross-cutting structure in the Horton Group, at 315+/-4 Ma. These relationships indicate that the Horton Group was deformed prior to ~315 Ma. The sediments of the Horton Group would have been less than 40 Myr old at this time.

Figure 19: Thin section showing diabase intrusion cross-cutting fabric in shale. Both are cut by faults (Johnston 1999, Waldron et al. 2010).

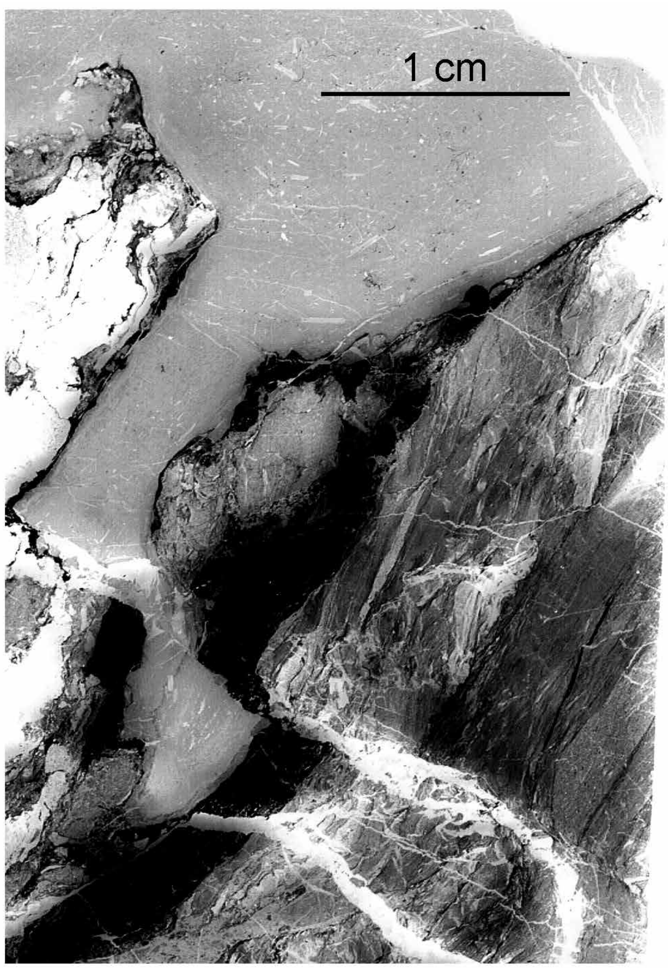
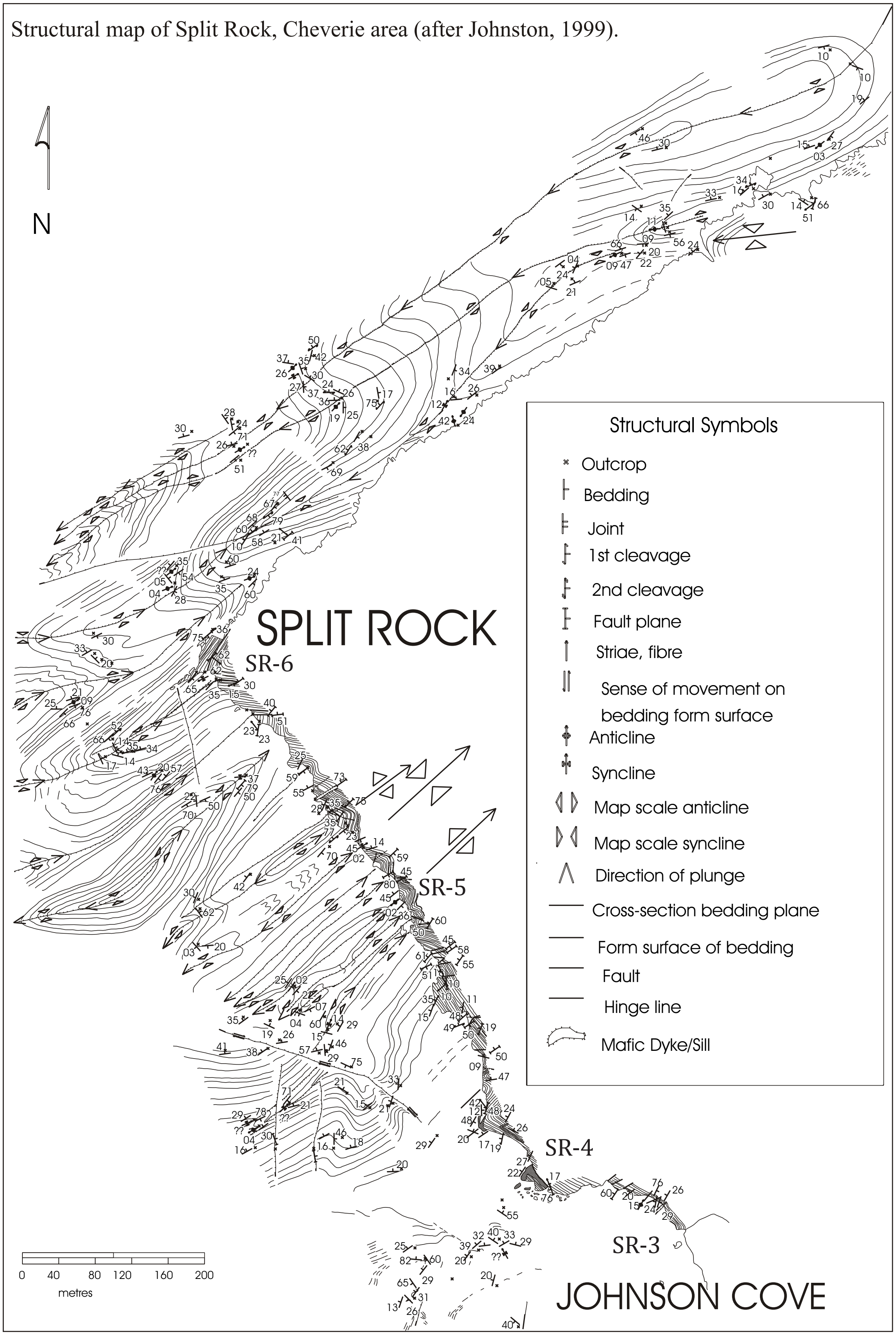


Figure 20. Detailed map of folds in Split Rock area, after Johnston (1999)



SR-5: Coastal section in folded Horton Bluff Formation

- 408033 5004033 to 407880 5004230

The coastal section to the north is unrivalled as a place to view folded sedimentary rocks. The folds are typically subhorizontal, upright to moderately inclined, with gently curved hinges that are locally spectacularly exposed in the beach (Figure 20). At some locations, folds are disharmonic, the shale intervals acting as detachment surfaces. Some folds are related to these detachments as detachment folds and fault-propagation folds.

Cleavage is weakly developed along this section of shore, though many bedding surfaces, especially in fissile shales, show a weakly developed crenulation lineation, parallel or sub-parallel with the main fold hinges.

Extensional structures are also much less conspicuous than those associated with shortening, but at numerous locations on this stretch of beach there are boudinage structures with axes either perpendicular to fold hinges or rotated slightly clockwise from this orientation.

Thin quartz and calcite veins mark some fractures, both parallel to layering and cross-cutting the bedding. Slickenfibres indicate the direction of slip. These have not been systematically investigated, but there appear to be veins that cross-cut the folds and veins that are folded, suggesting that several generations of fractures are present.

SR-6: Split Rock

- 407806 5004300

The syncline at Split Rock is one of the best exposed on the shore (Figure 21).

This syncline has a near-horizontal hinge, but because of the slope of the beach, it is possible to view the fold in 'axial projection' from a suitable (if muddy) vantage point on the foreshore. A bed that is characterized by large 'cannonball' concretions of dolomitic carbonate can be located easily on both sides of the main fold. North of the fold hinge, bedding is vertical to overturned, and cleavage becomes more intense. A penetrative slaty cleavage is developed in black mudrocks; weak spaced cleavage occurs in some sandstones.

The dependency of buckle fold wavelength on layer thickness is well illustrated in muddy sections just north of the main syncline. Thick sandstone layers show long-wavelength buckles whereas thin layers are folded at a much smaller scale.

Figure 21. Folds in Horton Bluff Formation, Split Rock

Mutton Cove (optional)

At this point, continue NE along the shore to Mutton Cove only if drivers are able to collect the group at Mutton Cove. Otherwise, return to the vehicles at the start of the traverse, Sheerman Lake Road.
Drive 3.5 km 6:00. Head southeast on Sherman Lake Rd, Turn left onto Glooscap Trail/NS-215 E. In 850 m Turn left onto Ocean Beach Rd. Park at end of road.

SR-7

- 408907 5004732

Wear a hard had if approaching cliffs and do not stand under overhangs. Rocky shoreline is locally very slippery when wet. Be especially careful on rocks with algae (seaweed). Section is tidal: do not venture out onto the tidal flats except on a falling tide. Low tide (Hantsport) 2022-05-12 16:49 ADT. No washrooms.

At the resumption of outcrop on the east side of Mutton Cove (Figure 22), folds are again prominent in the rocks of the wave-cut platform. Notice that the mudrocks are strongly cleaved, and there is a conspicuous, non-penetrative bedding-cleavage intersection lineation visible on the surfaces of sandstone beds. At several locations the cleavage is not parallel to the axial traces or hinges of the folds: the folds are 'transected' by the cleavage in a counter-clockwise sense.

There are two 'classical' interpretations for this phenomenon. In the first, the folds and cleavage are regarded as separate generations of structures. A second explanation involves dextral strike-slip or transpressional motion. Folds nucleated early, and underwent clockwise rotation with progressive deformation. Cleavage, on the other hand, reflects the bulk strain, acquired during the whole deformation history. Cleavage therefore undergoes less rapid clockwise rotation, and ends up transecting the folds in a counterclockwise sense. The presence of major strike-slip features just to the NE favours the second explanation.

Several faults cut the beach to the east of Mutton Cove (Figure 22, Figure 23), and can be traced into the cliffs where they are seen to have steep dips (Figure 24). Mineralized sheets with slickenfibres of quartz and calcite are found on the fault surfaces, and in some cases allow the sense of slip to be determined as predominantly dextral strike-slip. There do not appear to be any unambiguous piercing points that allow a clear evaluation of the amount of slip.

Folds are present in bedding adjacent to the largest, most continuous fault. The folds are oriented in an *en echelon* relationship to the fault, and die out into surrounding bedded sedimentary rocks. Cleavage is also present, oblique to the fault; cleavage planes curve to an orientation more nearly parallel to the fault in the immediately adjacent wall rocks.

Several fault-bounded slivers occur in the fault zone. One of these forms a prominent section of cliff, being “popped up” relative to the surrounding rocks, and forming a positive flower structure, a type of structure often interpreted at much larger scale in seismic profiles from strike-slip and transpressional basins.

Figure 22. Map of east side of Mutton Cove after Roselli (2004).

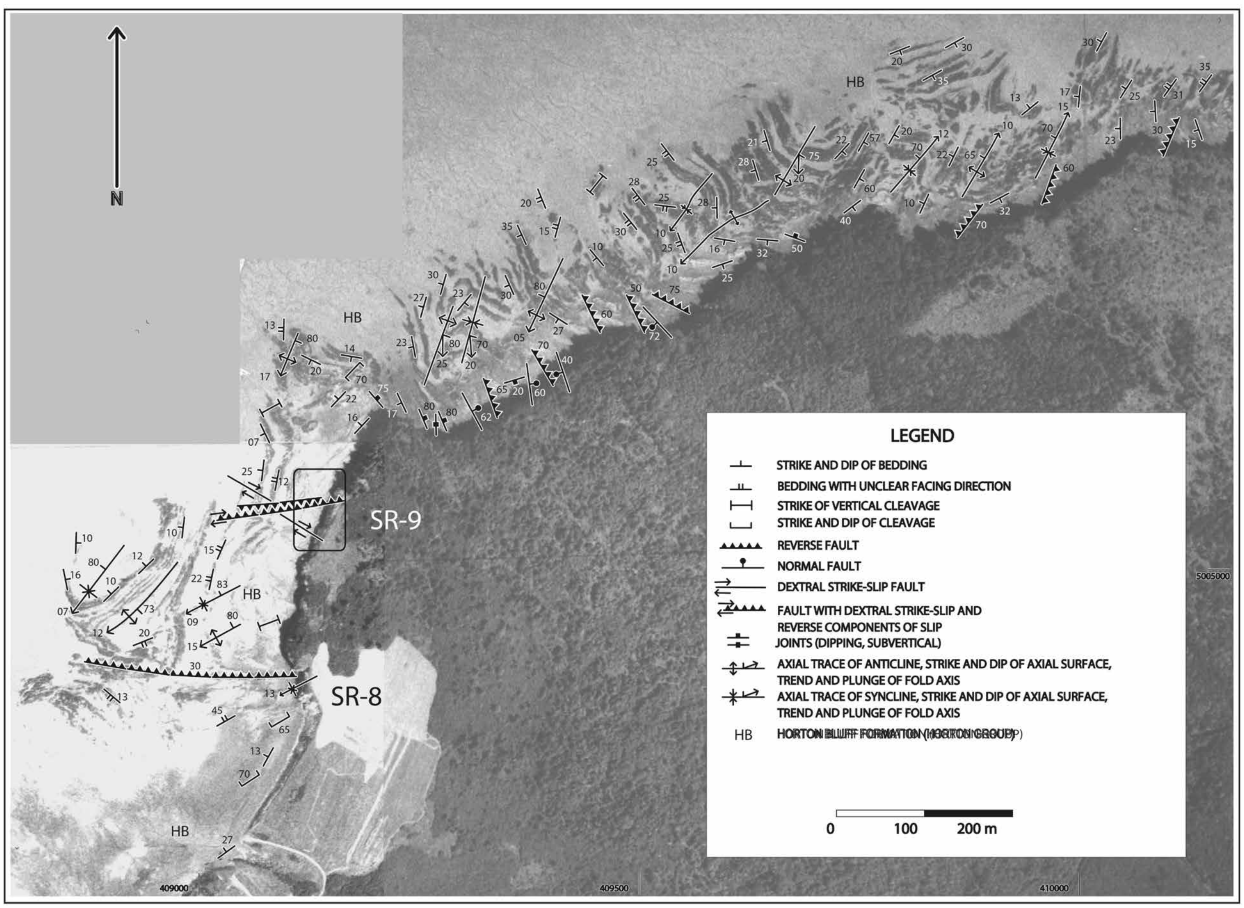


Figure 23. Enlarged map of fault relationships at Mutton Cove after Roselli (2004).

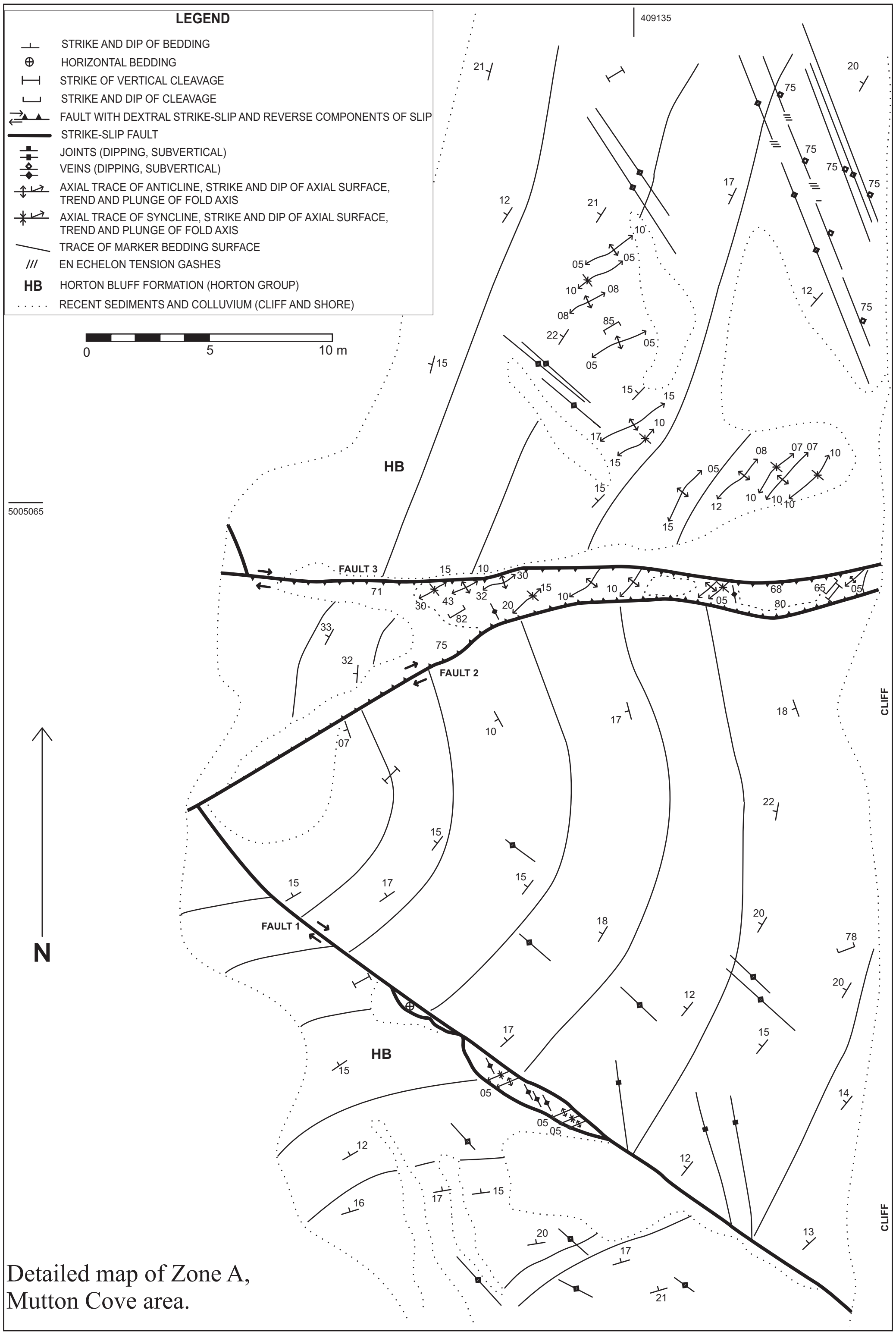
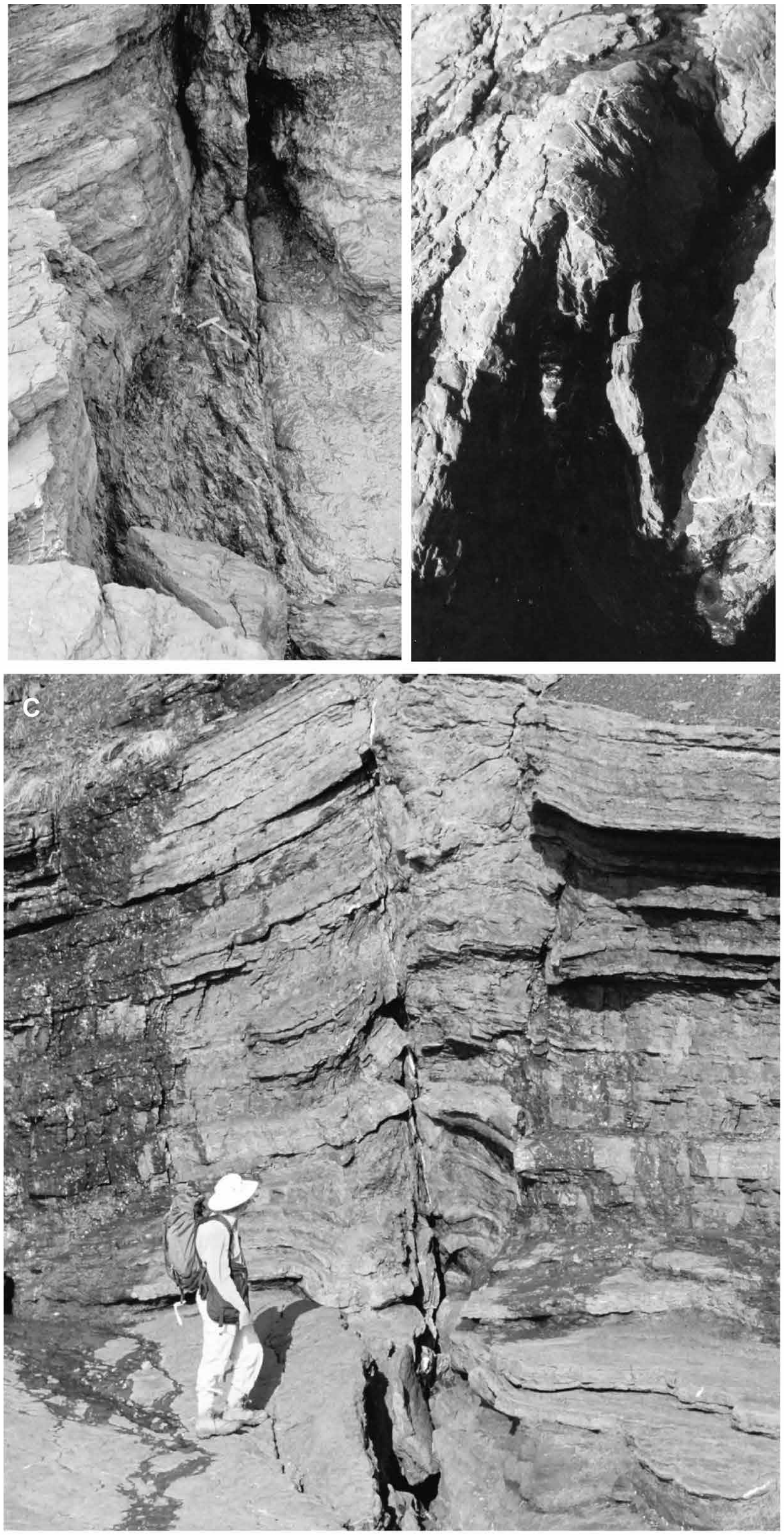


Figure 24. Outcrop photographs at Mutton Cove after Roselli (2004).



Zone A.

A) Restraining fault bends in Fault 1 contain folds and veins at the centimetre-scale (hammer for scale).

B)Transected cleavage observed in folds near flower structure (pencils for scale, parallel to fold axis and cleavage).

C)Traces of Faults 2 and 3 in the cliff mutually diverge, display strike-slip and reverse displacements. This fault zone is interpreted as a flower structure (person for scale).

Rainy Cove (RC)

Drive 11 km, 0:11.
Head south on Ocean Beach Rd. Turn left onto Glooscap Trail/NS-215 E. In 9.1 km Turn left onto Pembroke Wharf Rd.

- 416148 5008042

Wear a hard had if approaching cliffs and do not stand under overhangs. Rocky shoreline is locally very slippery when wet. Be especially careful on rocks with algae (seaweed). Section is tidal: do not venture out onto the tidal flats except on a falling tide. Low tide Walton 2022-05-12 16:31 ADT. No washrooms

The 400 m section at Rainy Cove is one of the best known in Nova Scotia, having been the subject of numerous student field trips from universities, high schools, and others. The section is particularly noted for spectacular exposures of downward facing folds (synformal anticlines and antiformal synclines) and for the angular unconformity between near-vertical Carboniferous rocks of the Horton Group and near-horizontal Triassic rocks of the Fundy Group.

Immediately west of the cove, the coastal section shows southwest-trending cliff-scale folds with weak axial-plane cleavage, somewhat similar to those at Cheverie, though the folds have been rotated into an orientation where their axial surfaces strike northwest-southeast. These folds overprint smaller, intrafolial folds that have very variable orientations, and strongly curvilinear hinges suggesting deformation while the sediments were still soft. These are designated F1 folds, and the cliff-scale, cleavage-related folds are F2. The difference in orientation of F2 between this section and that at Split Rock suggests the existence of a third generation of folds F3, though these cannot be observed directly on the west side of Rainy Cove.

The traverse along the east side of the cove shows a progression from upward facing F2 structures to downward facing structures, demonstrating the refolding of inclined to F2 folds by a more upright generation designated F3. By careful mapping of the shoreline (Roselli 2004) it has been possible to disentangle these two generations of structures.

RC-1: Upward-facing syncline and duplex structure

- 416000 5008158

The southernmost portion of the Rainy Cove section is a mainly north-dipping cliff section interrupted by several faults that make correlation difficult. Depending on the state of erosion of the beach, excellent examples of deformed mudcracks, groove casts, and fossil trees may be seen in the cliffs and on the beach.

A broad northeast-plunging syncline with a general box-fold shape (D, D1 and D2 in Figure 26) brings bedding to near horizontal. The north limb occupies 50 m of cliff section and is interrupted by a fault at the north end. The north limb of the fold is marked by repetition of bedding in a duplex of multiple horses and associated folds, indicative of significant shortening. Is this duplex an accommodation structure produced during folding or is it an earlier structure that has been refolded by fold D? The vergence of folds (Z-sense as viewed in the cliff) is inconsistent with the geometry of fold D, suggesting refolding.

Figure 25. Map of beach at Rainy Cove, after Roselli (2004).

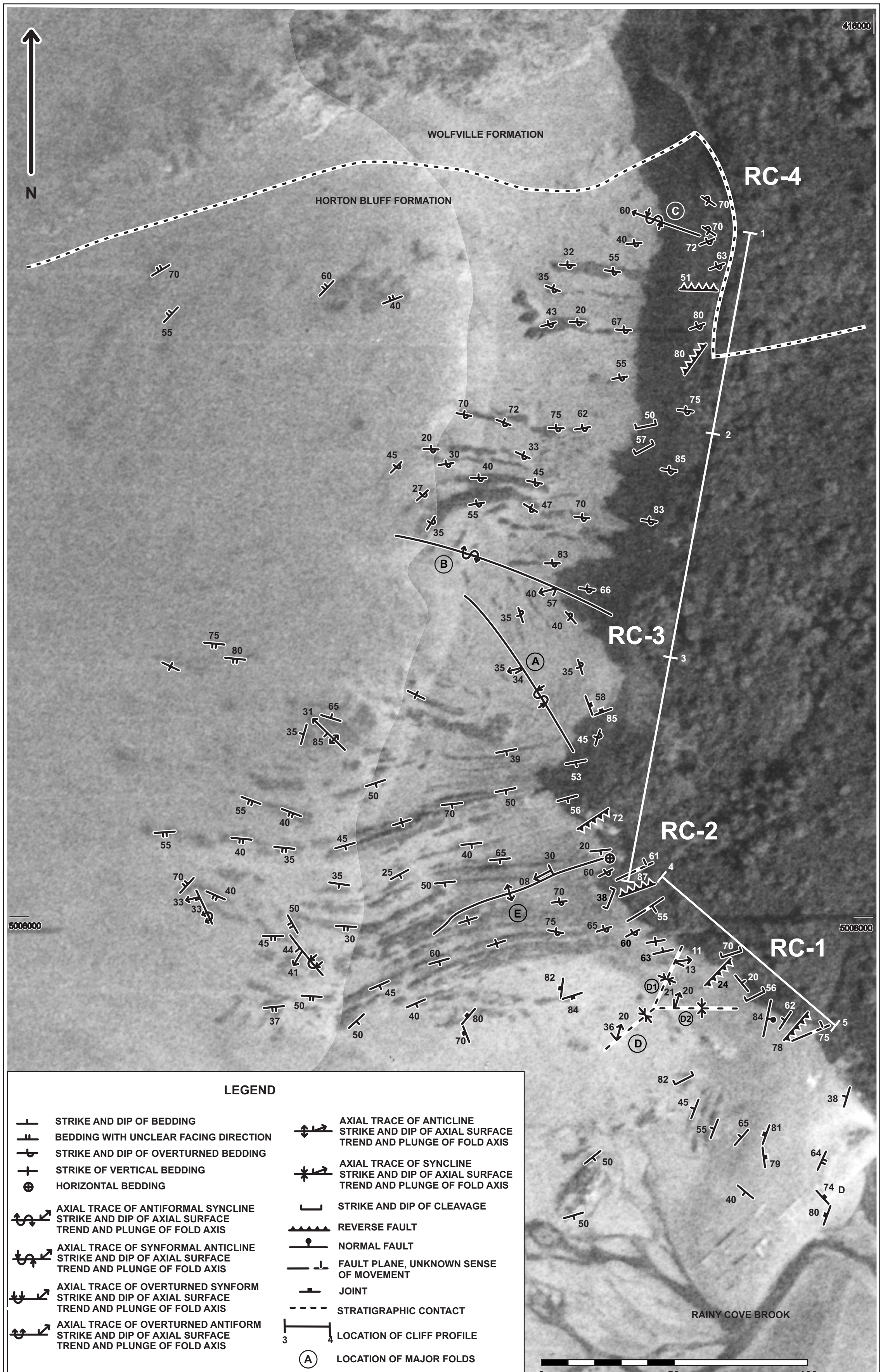


Figure 3.28: Map of the Rainy Cove area.

RC-2: Multiple upward-facing folds

- 415908 5008285

North of the fault, a section of cliff exposes near-continuous stratigraphy in a south-younging, steeply north-dipping overturned section. Towards the north end of this section, cascades of upward facing S-folds cut the strata. Locally there is a very weakly developed north-dipping cleavage that has a similar (not identical) orientation to the fold axial surfaces.

A conspicuous and complex anticlinal structure (Fold E in Figure 26) occurs in sandstone at the north end of this section. The central core of the fold is almost isoclinal, with tightly adpressed limbs. It is surrounded by a box-fold. Depending on the level of the beach, it may be possible to observe that a stratigraphically underlying shale section is much less tightly folded and much less shortened, demonstrating that the tight fold in the sandstone is a detachment fold.

RC-3: Downward-facing folds: synformal anticline and antiformal syncline

- 4159375008321

About 20 m north of fold E is the first of a series of cliff-scale folds which face downward. The first is an anticline A whose hinge can be seen in the cliff, plunging moderately southwest in an axial surface that dips southwest. The fold is a reclined fold - one in which the hinge is aligned down the dip of the axial surface. The facing direction in the axial surface is very slightly downward, towards the southeast.

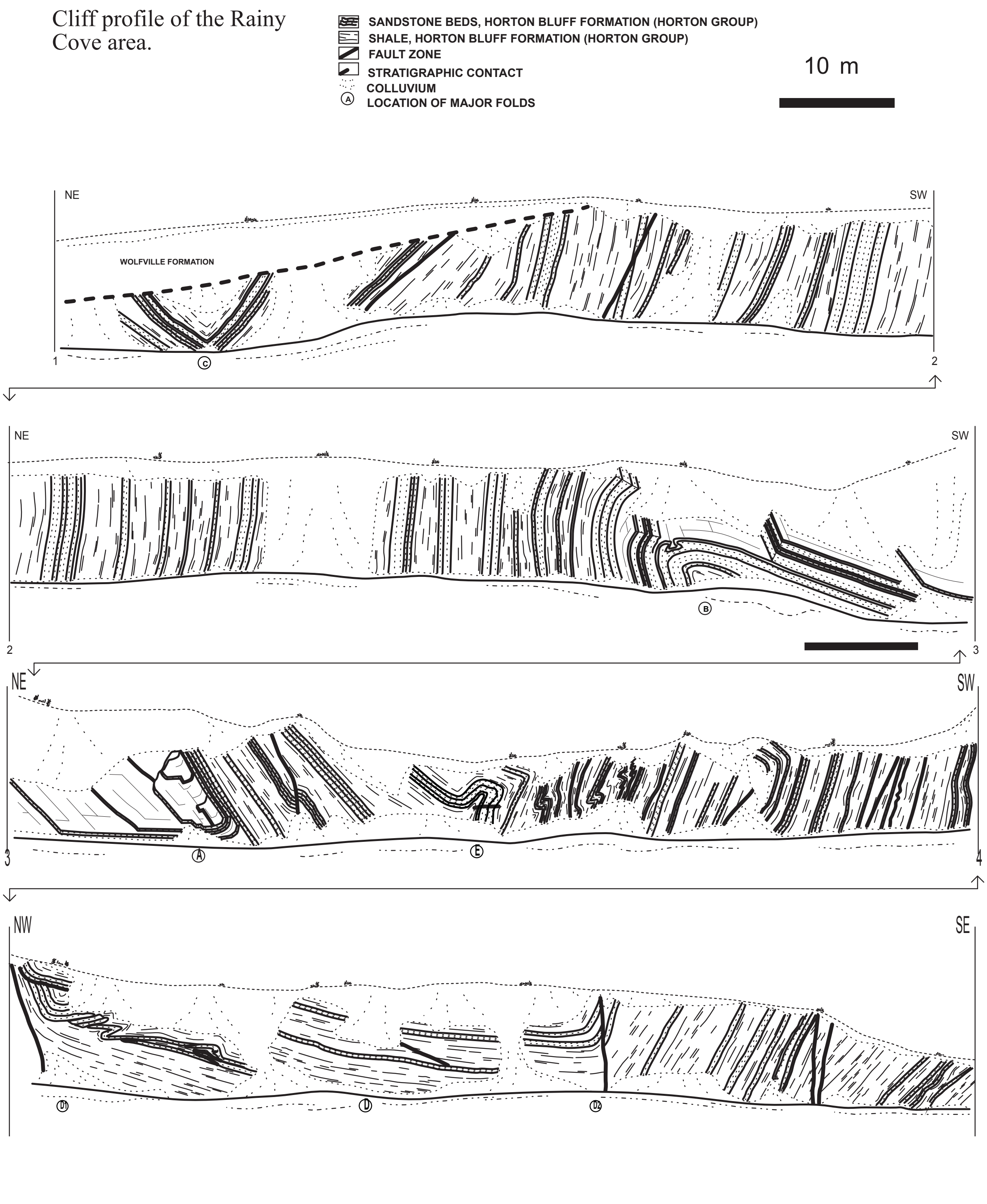
In the cliff, it is possible to see the folded under-surface of a sand bed bearing load casts, cut by a number of parasitic buckle folds and very weak crenulation lineations suggesting that this fold is related to the weak cleavage seen elsewhere in the shore. This fold is interpreted as an F2 fold.

About 40 m to the north is a second large downward-facing fold, antiformal syncline B (Figure 26). This fold plunges moderately west. The trace of folded bedding is picked out by seaweed-covered sand ridges on the foreshore. The axial surface is moderately inclined, dipping to the south-southwest. Facing direction is clearly steeply downward, into the cliff to the east, as indicated by cross-lamination on the north limb, and also by tracing the way-up from fold A (Figure 26).

Caution: because of the seaward-dipping bedding surfaces in the hinge region, this fold has been the site of numerous cliff-falls in the past. (The photograph Figure 27 shows its state approximately 20 years ago.) Beware of falling rocks. Do not stand close to the cliff and be especially aware of overhangs.

The axial traces of folds A and B converge offshore, raising the question of what happens when they meet; do the two folds merge or does one refold the other? Unfortunately the sand ridges are lost in the mud before this question can be resolved. However, based on cleavage orientations measured at intervals along the cliff, it seems likely that fold A is earlier, and is refolded by fold B.

Figure 26. Cliff profile at Rainy Cove after Roselli (2004).



RC-4: Unconformity and Mesozoic Fundy Group

- 415970 5008520

Caution: the remaining sections of the cliff are steep and prone to rock-falls. View the structures from a distance and in the wave-cut platform. Do not stand under the overhanging or vertical sections of the cliff!

North of fold B (Figure 26), there is a long (~100 m) homoclinal section of cliff with near-vertical bedding, younging south. Toward the top of the cliff, strata of the Triassic Wolfville Formation can be seen, dipping gently north, and resting with profound angular unconformity on the Horton Group below.

Several small folds can be seen both in the cliff and in the foreshore. In general, these cannot clearly be related to the large downward facing folds B and C; they are believed to pre-date the larger structures.

Fold C is a synform located in the cliff immediately below the Mesozoic unconformity. Tracing way-up from nearby accessible outcrops with cross-lamination shows that this fold is an anticline, a third major downward-facing fold in the profile. A smaller asymmetric fold on its south limb, with weak axial plane cleavage, has the wrong asymmetry to be a parasitic fold on fold C. It probably belongs to an earlier generation.

The main challenge in interpreting the Rainy Cove section is the interpretation of the downward facing folds A, B and C. In general, downward facing folds cannot be easily produced by a straightforward shortening of originally upright, horizontal stratigraphy; some kind of fold overprinting is required, either to invert stratigraphy before later folding, or to rotate already-formed folds into a downward-facing orientation.

Two geometries can explain the configuration of folds at Rainy Cove. In the first (Figure 28a), folds A, B, and C were produced in an early episode of recumbent, south-facing F2 folds, and these have been overprinted by upright F3 folds D and E, bringing them into their current downward facing orientation. In hypothesis 2 (Figure 28b), only fold A is a recumbent F2 fold. Folds B, C, D and E are all later, superimposed upright F3 folds; B and C end up with downward facing directions because they are overprinted on the already-overturned limb of fold A.

Scattered observations of cleavage along the section at Rainy Cove are roughly parallel to the folded axial surface of early fold A in hypothesis 2. In contrast, the cleavage observations, particularly the north-dipping cleavages observed near fold D, are not parallel to either set of axial surfaces in hypothesis 1. Hence we favour hypothesis 2: the downward facing folds B and C are developed in the overturned limb of a large recumbent anticline, the hinge of which is exposed as fold A.

Figure 27. Cliff-scale folds A, B, C at Rainy Cove.

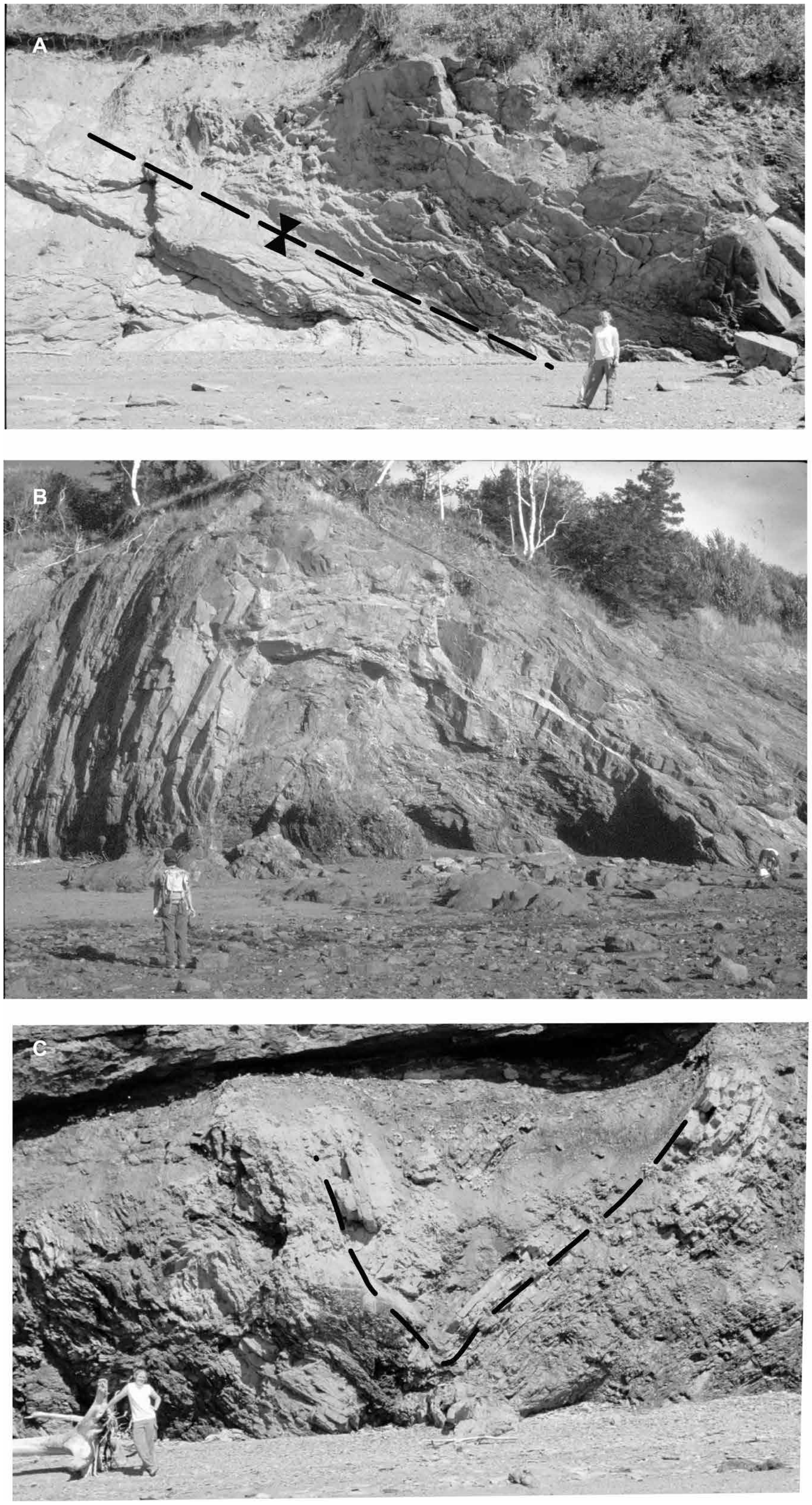
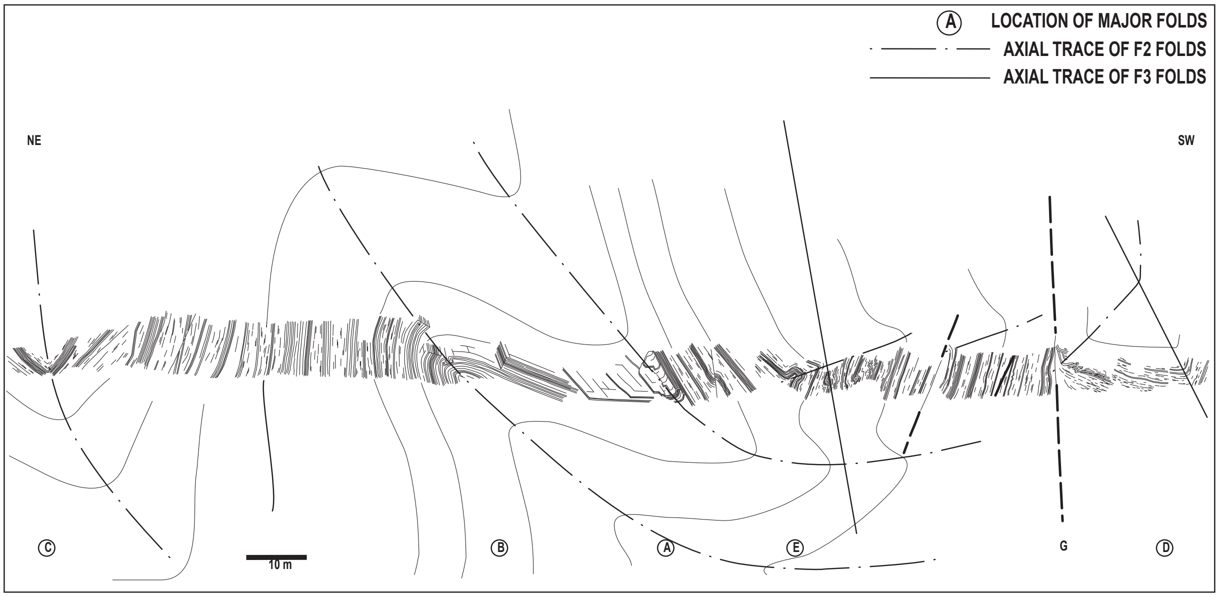
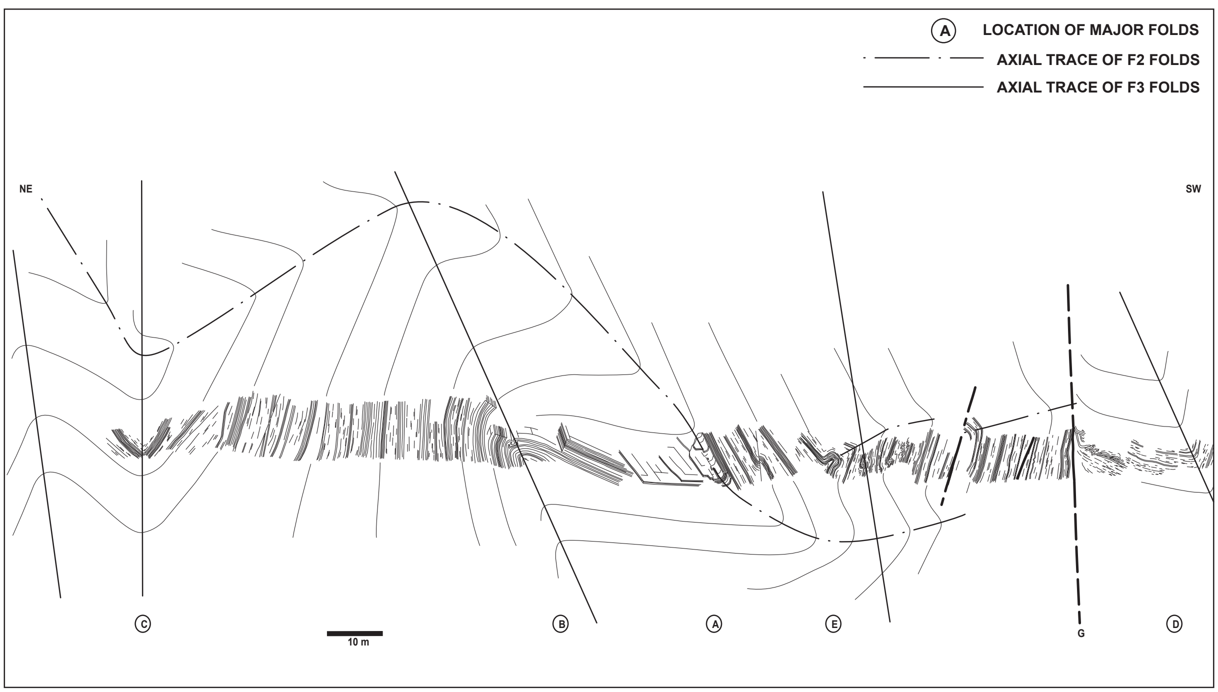


Figure 28. Alternative hypotheses for refolded fold structure at Rainy Cove after Roselli (2004). Cleavage measurements favour the hypothesis shown in the lower diagram.





Overnight Truro

Drive 85 km, 1:11.
Turn left onto Glooscap Trail/NS-215 E. Washrooms may be available in general stores in larger communities on NS-215. In 57.2 km turn left onto Hwy 236/Glooscap Trail/NS-236 E (signs for Truro/Princeport). In 3.0 km, Turn left to stay on Hwy 236/Glooscap Trail/NS-236 E (signs for Old Barns/Truro). In 19.0 km at the roundabout, take the 1st exit onto Nova Scotia Trunk 2 S. In 1.1 km turn left onto Marshland Dr. 2.0 km turn left onto Park St. 950 m Turn right onto Main St/NS-4 E. In 1.1 km. Turn left onto College Rd. Turn right onto Cumming Dr. Turn right onto Horseshoe Crescent. Overnight Dalhouse Agricultural Campus.

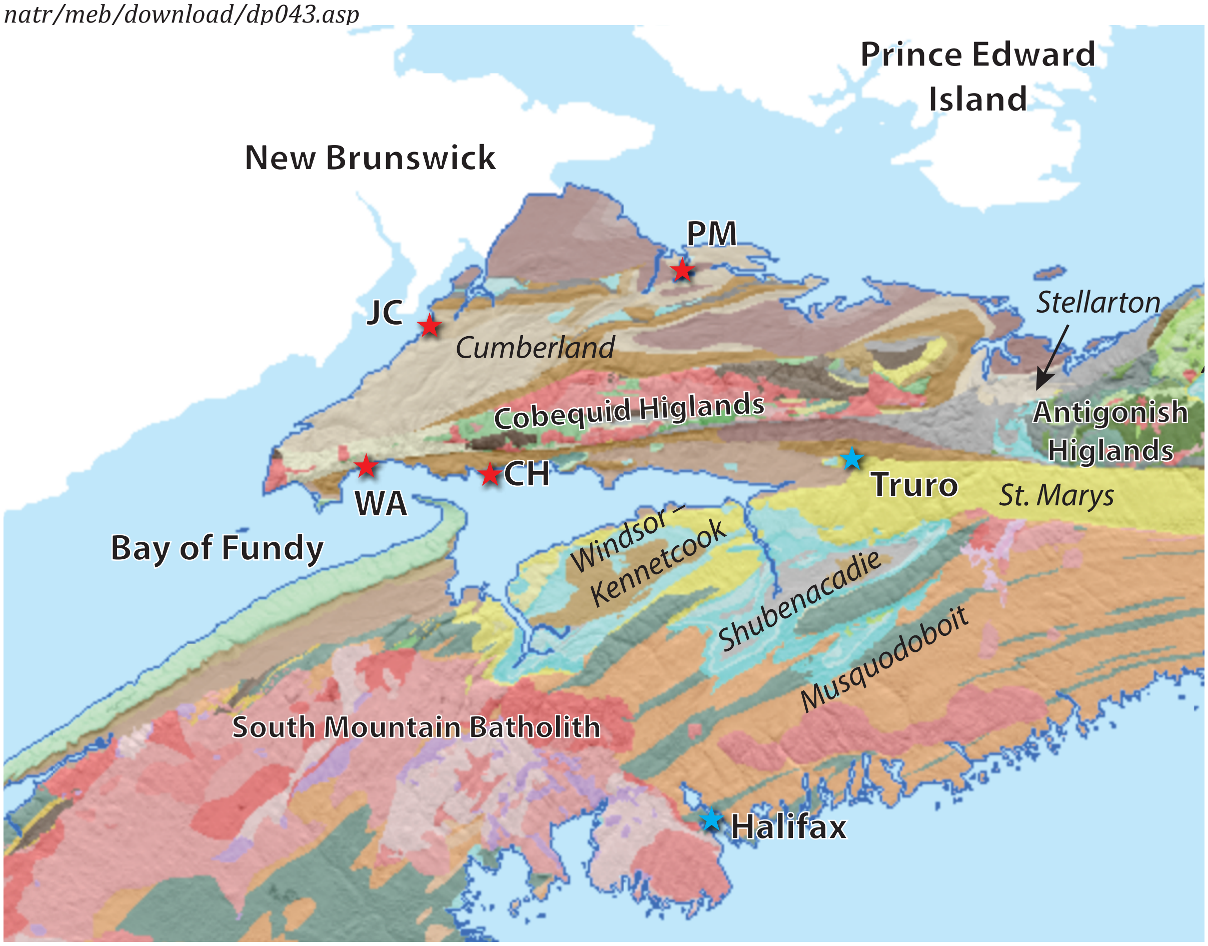
DAY 2: CUMBERLAND SUB-BASIN

Introduction to the day

Day 2 focusses on the geology of the Cumberland sub-basin and the Cobequid Highlands that bound it to the south. Although salt is nowhere exposed at the surface of the Cumberland sub-basin, movement of salt has had a profound effect on the geology and particularly on the economic resources of the sub-basin. Not only is salt mined at Pugwash, but also the extensive coalfields of the Springhill and Joggins areas were accumulated in rapidly subsiding wetlands where accommodation was created by salt expulsion. The intervening salt walls are identifiable in the landscape from the large numbers of sink holes that are developed above them.

The Cumberland sub-basin is bounded to the south by the Cobequid Highlands, that include some of the oldest rocks in the domain Avalonia of the Appalachian Orogen. The East-West Minas Fault Zone (MFZ) dissects the south margin of the Cobequids, including several major faults of which the most prominent is the Cobequid Fault, that forms a lineament easily visible from space. The MFZ was long-lived, separating the Meguma terrane of the Appalachians from Avalonia to the north, and undergoing major pulses of

Figure 29. Cumberland sub-basin location map. Source (Keppie 2000), with full legend, at: https://novascotia.ca/natr/meb/download/dp043.asp



activity in the mid-Pennsylvainian, and again close to the Mississippian–Pennsylvanian boundary. Most of the Paleozoic motion was probably dextral, but the faults were active again in the Mesozoic, when sinistral transtension was responsible for opening the Fundy graben.

Several stops during this day are subject to logistical uncertainties. Changes to the itinerary will be made as necessary.

Pugwash Mine (PM)

Drive 80 km 1:01
Return to the roundabout on NS-2 and take the 1st exit. Merge onto Nova Scotia Trunk 2 N/NS-102 toward Trans-Canada Hwy/NS-104/Amherst/New Glasgow
After 1.6 km Use the left lane to take exit 15W for Trans-Canada Highway/NS-104 W toward Amherst/New Brunswick
After 15.5 km take exit 11 for NS-4 toward Folly Lake/Wentworth
For 47.1 km Follow NS-4 northbound
At 17.3 km Keep right to continue on NS-307 N
After 8.7 km Turn left onto Fountain Rd (signs for Pugwash)
After 1.6 km Turn right onto NS-368 N (signs for NS-6/Sunrise Trail/Pugwash/Wallace)
After 7.1 km Turn left onto Sunrise Trail/NS-6 W (signs for NS-366/Pugwash/Amherst) After 5.9 km Turn left onto Crowley Rd.
Continue straight onto Sheas Island Rd. Park at Canadian Salt Co Ltd.

- 449177 5076821

A safety briefing, separate waiver, and approved safety equipment including steel-toed boots are required for entry to Pugwash mine. Pay attention to information provided by the mine organization, and follow all instructions meticulously. Do not wander away from the group. Do not approach mining machinery. Participants who do not wish to enter the mine may remain at the surface. Washrooms not available underground.

This stop is dependent on operations at the mine and may be cancelled at short notice.

Information from Pugwash Village web site (downloaded 2022 Jan 30) https://www.pugwashvillage.com/index.php/living-in-pugwash/industry.

> "Josh Allen accidentally discovered salt in 1953 when drilling for water at his lobster factory. The Canadian Salt Company Ltd. hoisted the first load in November, 1959. Shafts go down to one thousand feet to huge working corridors (30' x 55'). These corridors are well ventilated and well lit. Most of the mine runs under the Pugwash River with some under solid ground. No mining operations run under the village. The company employs approximately 210 people. The processing plant at the site produces industrial grades of salt. The refining process for this industrial salt is one of crushing, screening and sizing. The mine produces approximately 1,200,000 tonnes of salt per year. The mine's lifespan is estimated in excess of 100 years, possibly longer with advanced technology. Transportation of salt is either by road or from the company owned ship-loading facility."

Pugwash mine occupies several levels in a tall piercement style diapir rising from the Windsor Group. At the present-day surface it is surrounded by the Moscovian (Pennsylvanian: Westphalian C-D) Malagash Formation, though another salt diapir in the region pierces the overlying Balfron Formation of the Pictou Group. The salt diapir lies close to a lineament (Shepody Beckwith fault) that probably bounded the deep

Cumberland Basin during the Mississippian, and formed a locus for a wall of rising salt expelled from the basin during deposition of underlying parts of the Cumberland Group. Following initial development of the salt wall during the late Bashkirian interval, point-fed stock-like diapirs continued to rise during the succeeding Moscovian.

In the diapir, rock salt, with local potash, is interlayered with anhydrite in a complex sheath-folded structure. Mining removes the halite but leaves the anhydrite walls in place, with the result that mine plans clearly show the folded structure of the evaporites.

Joggins Fossil Cliffs (JC)

Drive 76 km, 1:05
Head southeast on Sheas Island Rd. Continue onto Crowley Rd
Turn left onto Durham St/NS-6 W
1.7 km Turn left to follow NS-6 W
In 8.8 km Turn left onto Beckwith Rd/Leicester Rd
In 16.0 km Turn right onto NS-204 W
In 14.4 km Turn left onto Fenwick Rd
In 9.6 km Turn left onto NS-302 S (signs for Maccan)
In 5.7 km Turn right onto Lower Maccan Rd/NS-242 W (signs for River Hebert/Joggins)
In 19 km Continue straight onto Main St and park at Joggins Fossil Cliffs

JC-1: Joggins Fossil Cliffs facility

Washrooms available

- 387155 5061123

The following account includes information from additional sources:

Joggins Fossil Cliffs https://jogginsfossilcliffs.net/

UNESCO World Heritage http://whc.unesco.org/en/list/1285

The Joggins coastal section has been famous for nearly 200 years (Rygel and Shipley 2005). The first accounts of the geology, including mention of upright tree fossils, appear in 1828–1829. In 1842 Abraham Gesner (famous for the discovery of a method of producing kerosene) and Charles Lyell visited Joggins as part of their research into the origin of coal. The following year, William Logan, on his way from the UK to take up his position as first director general of the Geological Survey of Canada, measured a succession of strata totalling 4441 m in thickness, pacing about 15 km of beach and converting to thickness using trigonometrical tables. This was effectively the first field project undertaken by the new organization. Lyell returned in 1853 with J. William Dawson. These two made some of the earliest fossil discoveries, including tetrapods, millipedes, and the earliest land gastropods. Other than the upright trees, the most famous of the Joggins fossils is the reptile *Hylonomus lyelli* Dawson, the earliest known amniote, which was discovered inside tree-stumps that were probably hollowed by forest fire. The Joggins site has yielded the richest known assemblage of fossils from the early Pennsylvanian, including 148 species in 96 genera, and 20 types of ichnofossils - mostly footprints.

Figure 30. Location map of the Pugwash – Oxford area (Ryan et al. 1990). *(Legend: Facing page)*

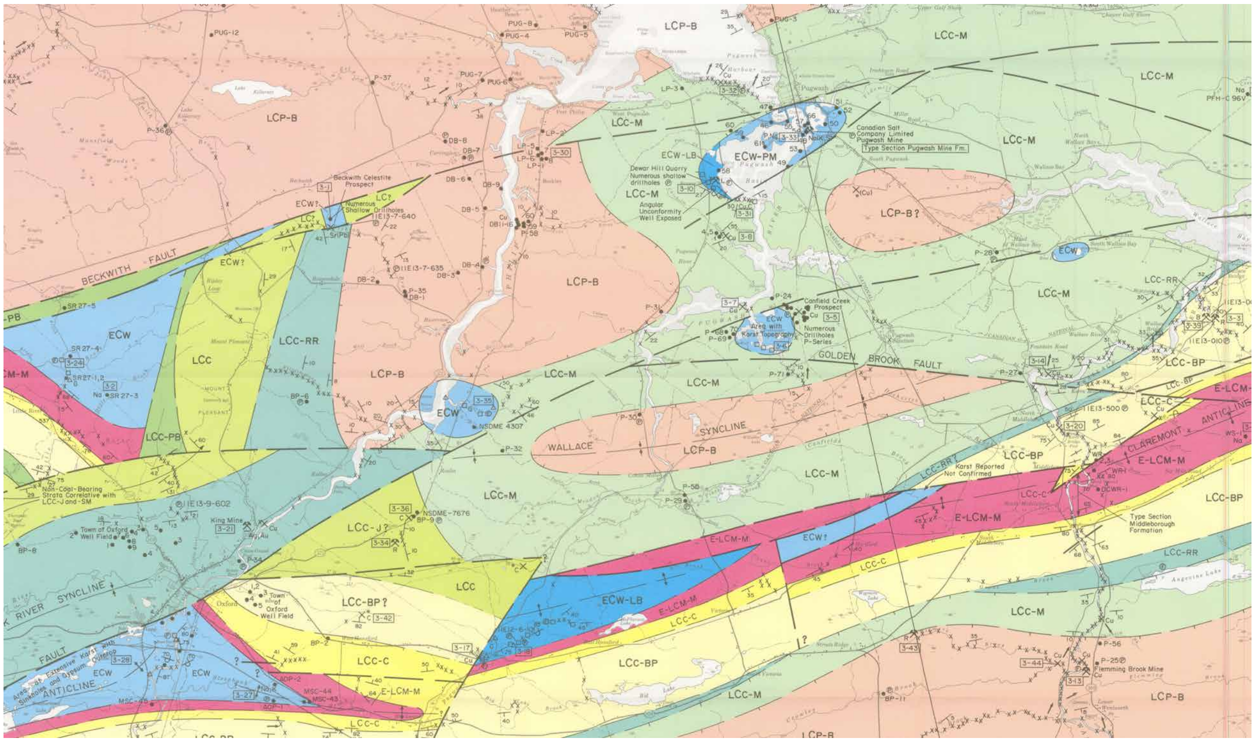
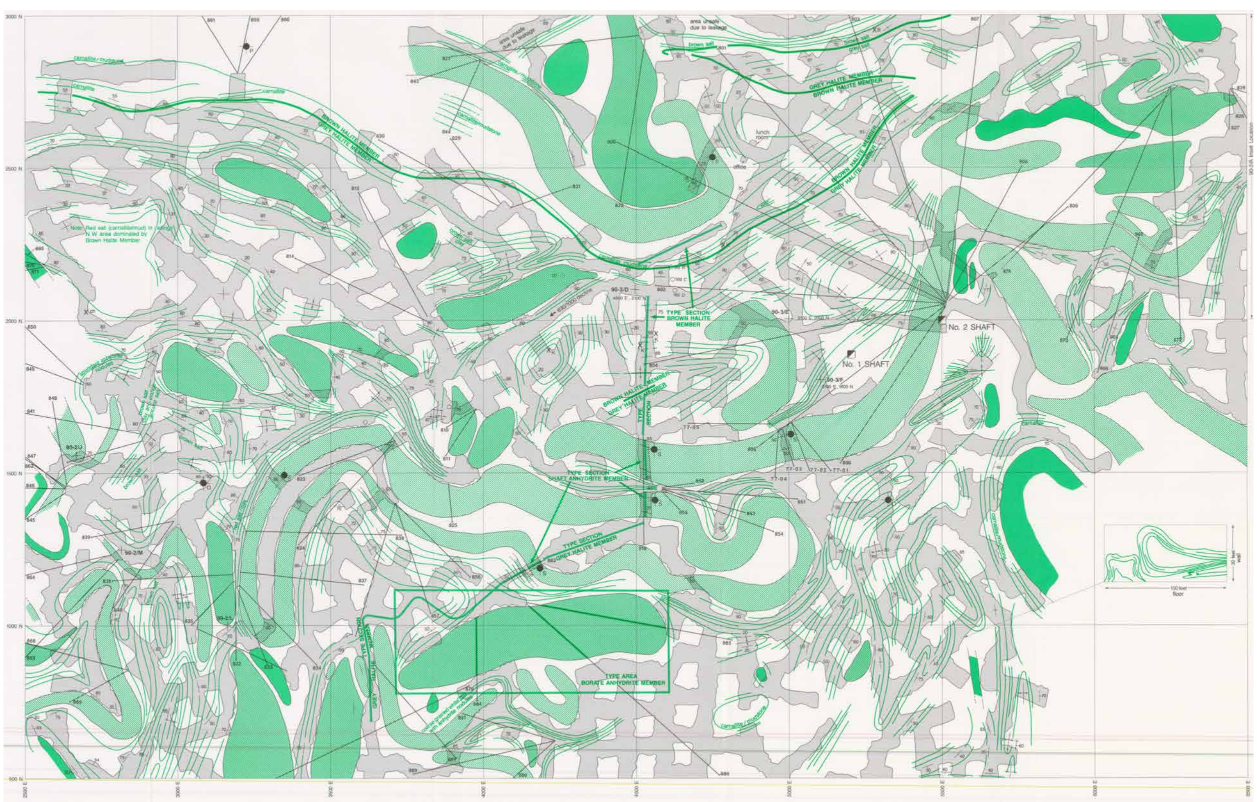
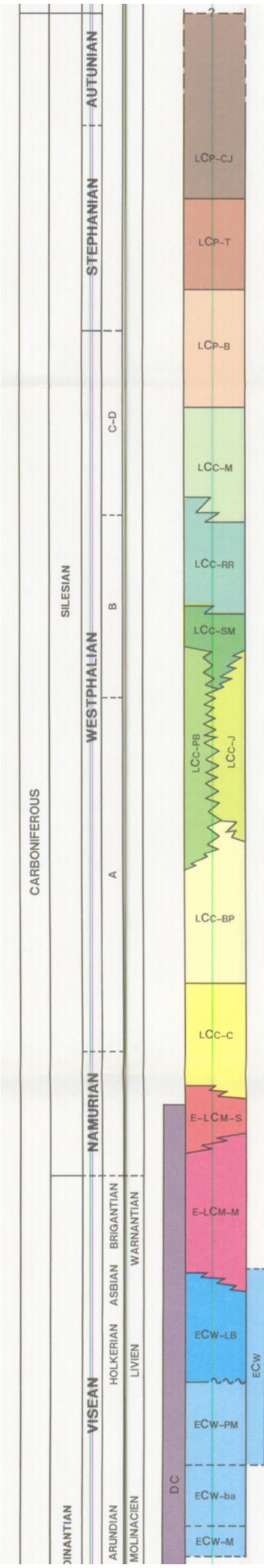


Figure 31. Mine plan of the Pugwash salt, 830 level, showing the folded structure (Carter 1990).





Note: This is a common legend for Nova Scotia Department of Mines and Energy Maps 90-11, 90-12, 90-13 and 90-14. All references unless otherwise stated refer to the entire Cumberland Basin.

CARBONIFEROUS

PICTOU GROUP (LCP = undivided):

CAPE JOHN FORMATION (LCP-CJ):
red-brown mudrock, pebbly arkosic sandstone, sandstone, minor calcareous mud-chip conglomerate; minor grey beds; rare, thin, laterally persistent limestone beds.
Fine / Coarse – 5 Thickness = 350–400+ m
paraconformity or conformable

TATAMAGOUCHE FORMATION (LCP-T):
red-brown mudrock, sandstone, calcareous mud-chip conglomerate; minor grey beds; rare pebbly sandstone; several thin, laterally persistent limestone beds; thick (up to 30 m) sandstones form sheet-like bodies that are laterally persistent for 10s of km.
Fine / Coarse – 3 Thickness = 300–350 m
paraconformity or conformable

BALFRON FORMATION (LCP-B):
red-brown sandstone, mudrock, minor pebbly sandstone, calcareous mud-chip conglomerate; minor grey beds; rare, thin, discontinuous limestone beds; thick (up to 40 m) sandstones form sheet-like bodies with a lateral extent of up to several km.
Fine / Coarse – 1 Thickness = 800–900 m
paraconformity – angular unconformity

CUMBERLAND GROUP (LCC = undivided or unassigned):
sandstone, grey, bodies up to 30 m thick with interstratified red mudrock and rare, thin coal.

MALAGASH FORMATION (LCC-M):
sandstone, grey and minor red; mudrock, red and grey; rare, thin coal seams and laterally persistent limestone beds.
Fine / Coarse – 0.5 Thickness = 100–400 m

RAGGED REEF FORMATION (LCC-RR):
grey pebbly sandstone, conglomerate, fine grained sandstone; subordinate mudrock, grey and red; rare, thin coal seams and bituminous limestone beds; mudrock may locally predominate.
Fine / Coarse – 0.7 Thickness = 0 (east) to 700–1000 m (west)

SPRINGHILL MINES FORMATION (LCC-SM):
sandstone, grey, sandstone bodies up to 22 m thick; mudrock, grey and sideritic, rarely red; significant coal seams (up to 4 m); thin cone-in-cone limestone locally; (SMM) MacCarrons River Member with poorly developed coal seams; red mudrock increases up section, numerous thin (less than 2 m) sandstones; rhythmic interstratification common.
Fine / Coarse – 0.7 to 4.3 Thickness = 0 (east) to 600–1000 m (west)

JOGGINS FORMATION (LCC-J):
mudrock, grey and minor red (predominant in lower half); subordinate sandstone, grey; numerous, thin (up to 1 m) coal seams closely associated with bivalve-bearing, bituminous limestone and shale.
Fine / Coarse – 2 Thickness = 0 (east) to 1100–1450 m (west)

POLLY BROOK FORMATION (LCC-PB):
red and grey polymictic ortho- and paraconglomerate, boulder – pebble; pebbly sandstone; rare mudrock; variable rounding and sorting; (PBL) Leamington Member with granule conglomerate and silty mudrock, grey with subordinate red, thinly interstratified, poorly sorted (transitional with the overlying *Springhill Mines Formation*).
Fine / Coarse – very low Thickness = 0 (east and north) to 0–1500? m (west)
conformable – angular unconformity?

BOSS POINT FORMATION (LCC-BP):
sandstone, grey to green-grey, medium- to coarse-grained, locally abundant plant debris; limestone (calcrete); calcareous mud-chip conglomerate; subordinate grey to minor red mudrock.
Fine / Coarse – 0.4 Thickness = 200–600 m (east) 700–1200 m (west)
local disconformity

CLAREMONT FORMATION (LCC-C):
red polymictic conglomerate, pebble to granule, arkosic, pebbly sandstone, weakly cemented, minor grey-green mottle.
Fine / Coarse – very low Thickness = 50–1500 m+
local disconformity ?

MABOU GROUP (E-LCM = undivided):

SHEPODY FORMATION (E-LCM-S):
red mudrock and red to grey sandstone with abundant plant debris.
Fine / Coarse – 0.7 Thickness = 0–250 m

MIDDLEBOROUGH FORMATION (E-LCM-M):
red mudrock, minor sandstone, rare fine conglomerate, interstratified; age and facies equivalent, in part, with the upper part of the Windsor Group.
Fine / Coarse = 2–3 Thickness = 200–500 m
local disconformity ?

WINDSOR GROUP (ECW = undivided):
interstratified redbeds, evaporites and carbonates.

LIME-KILN BROOK FORMATION (ECW-LB):
red mudrock, minor sandstone and fine conglomerate; interstratified fossiliferous marine limestone and dolostone; anhydrite, gypsum and locally salt (Borehole PFH C96v).
Fine / Coarse = high Thickness = 300–800 m
structural contact (fault-intrusive)

PUGWASH MINE FORMATION (ECW-PM):
interstratified halite, anhydrite, gypsum, grey and red mudrock; dominantly residual collapse breccia (cap rock) in near surface environment where these complexly-deformed diapiric rocks outcrop and are/were subject to dissolution by groundwater or formation water.
Thickness = 300–500 m+ ?

Basal Anhydrite (informal) (ECW-ba):
anhydrite with thin interstratified carbonate and mudstone; unit is inferred to be present (seismic data) but has not been confirmed in the map area.
Thickness = 100–200 m ?

MACUMBER FORMATION (ECW-M):

The Joggins Fossil Cliffs facility is built on the site of a former coal mine, which mined one of several productive coals seams in the Pennsylvainian Cumberland Group. The facility was built in conjuction with the establishment, in 2008, of the Joggins Fossil Cliffs UNESCO World Heritage site.

JC-2: Joggins Beach

Hammering and collecting prohibited. Wear a hard had if approaching cliffs and do not stand under overhangs. Rocky shoreline is locally very slippery when wet. Be especially careful on rocks with algae (seaweed). Do not attempt to enter old mine workings. Section is tidal: do not venture out onto the tidal flats except on a falling tide. Low tide Joggins 2022 May 13: 17:04.

- 387041 5061065 South access from the Joggins Fossil Cliffs centre
- 388403 5063623 North access from Lower Cove

The section between these two locations dips to the S at around 20°, and includes the upper part of the Little River Formation (Logan's division V), and most of the Joggins Formation (Logan's division IV). Both units were formerly included in the Joggins Formation. Both comprise predominant mudstone, with tabular and channel-filling beds of sandstone. However, the Little River Formation is predominantly red, whereas the Joggins Formation is mostly grey, representing a slightly more humid environment, and includes several coal seams, in some cases with thin overlying calcareous units which have been interpreted as marine incursions. Old mine workings can be seen on the beach. The transition to the overlying Springhill Mines Formation lies about 400 m to the south of the Joggins Fossil Cliffs facility.

The most spectacular paleobiological aspect of the cliffs is the presence of upright tree fossils, mainly lycopsids, that have been reported up to 20 m high, though most are less than 5 m - still unusual and impressive testaments to sedimentation rates.

Seismic profiles roughly parallel to and perpendicular to the coast allow these units to be traced inland. The Joggins and Little River formations show spectacular thinning towards the Springhill area, where an evaporite wall (Claremont anticline) brings Windsor Group to the surface. A second evaporite wall is developed to the north (Minudie anticline) although the Joggins formation has been eroded from the flank of that structure. Towards the Claremont anticline, the Joggins formation undergoes spectacular thinning to a small fraction of its thickness at the coast. The mud-rich flood-plain environment of deposition shows that the surface on which it accumulated was almost horizontal; therefore differential subsidence controlled the accommodation of the unit. Because the base of the Windsor group is almost horizontal in the seismic profiles, salt expulsion must have controlled these thickness variations (Waldron and Rygel 2005, Waldron et al. 2013).

Figure 32. Map of Joggins shore, from https://jogginsfossilcliffs.net.

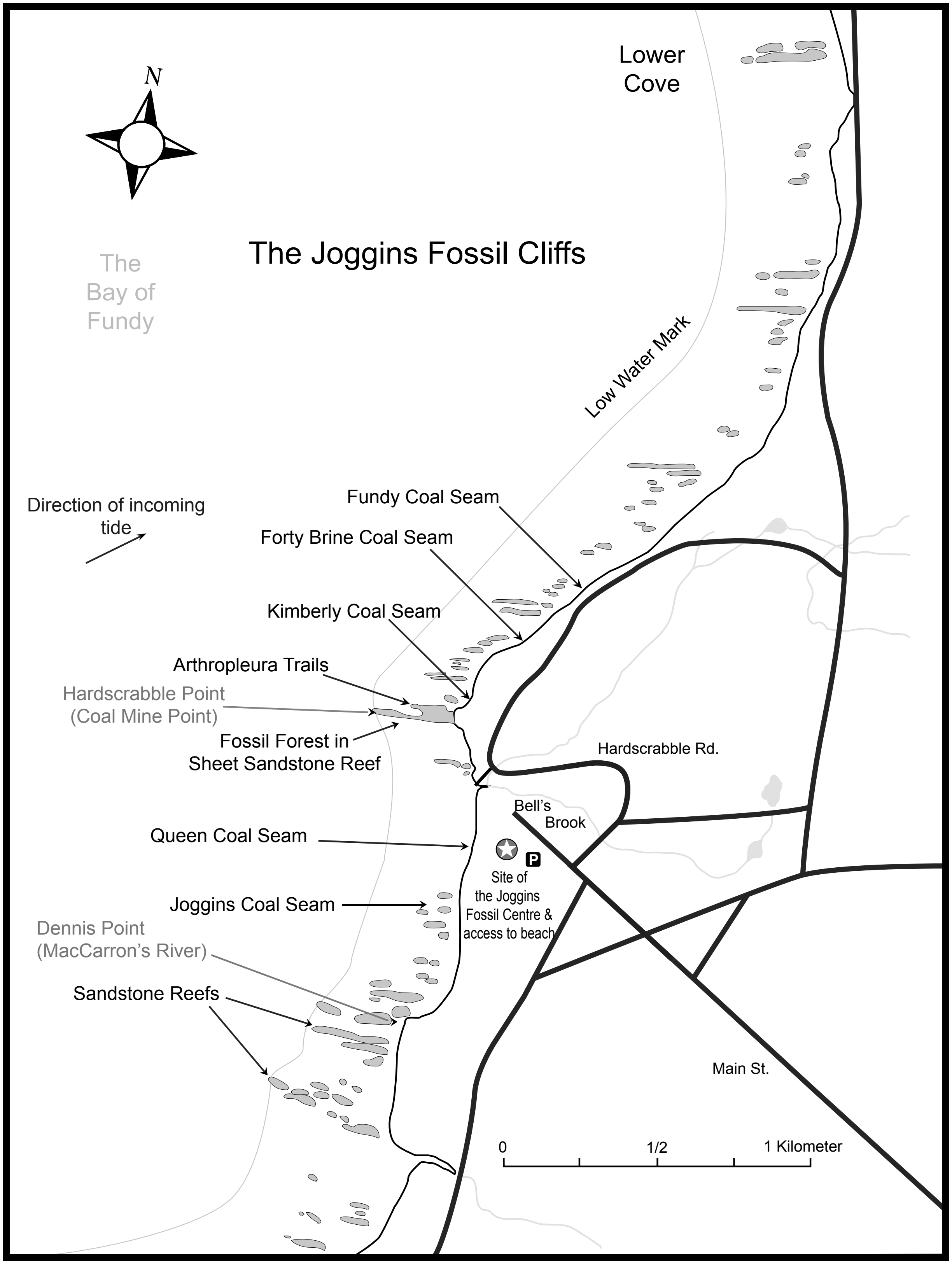
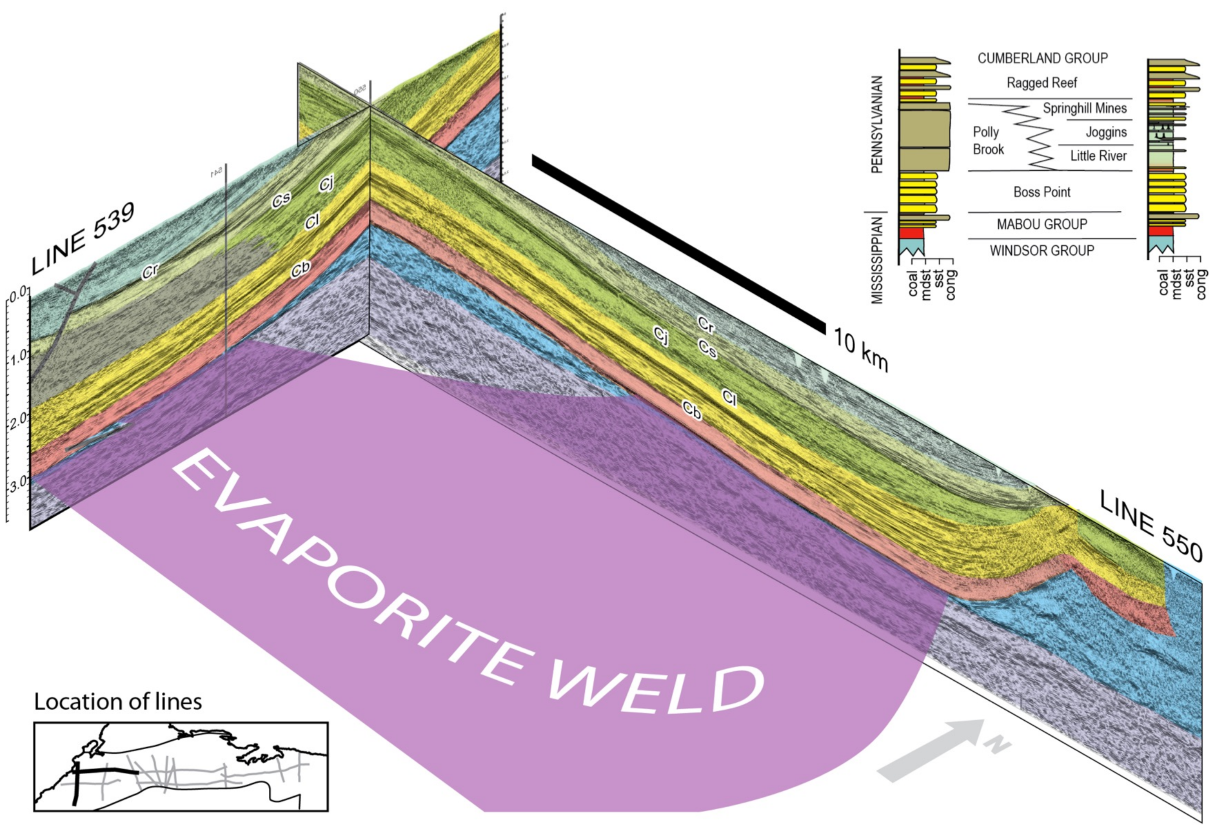


Figure 33. View of of the Joggins section, and upright lycopsid tree (https://jogginsfossilcliffs.net).

Figure 34. Interpreted seismic profiles in the Joggins area (Waldron et al. 2013).



West Advocate Cobequid fault (WA)

Drive 58 km 0:50
Return SE along Main St. to intersection with NS-209. Turn R. Follow N S-209 56.6 km. Turn right on W. Advocate Rd. and Park at Visitor Centre. Washroom available at visitor centre when open.

- 357087 5023484

Take care on the steep path to the beach. Wear a hard had if approaching cliffs and do not stand under overhangs. Section is tidal: do not venture out onto the tidal flats except on a falling tide.

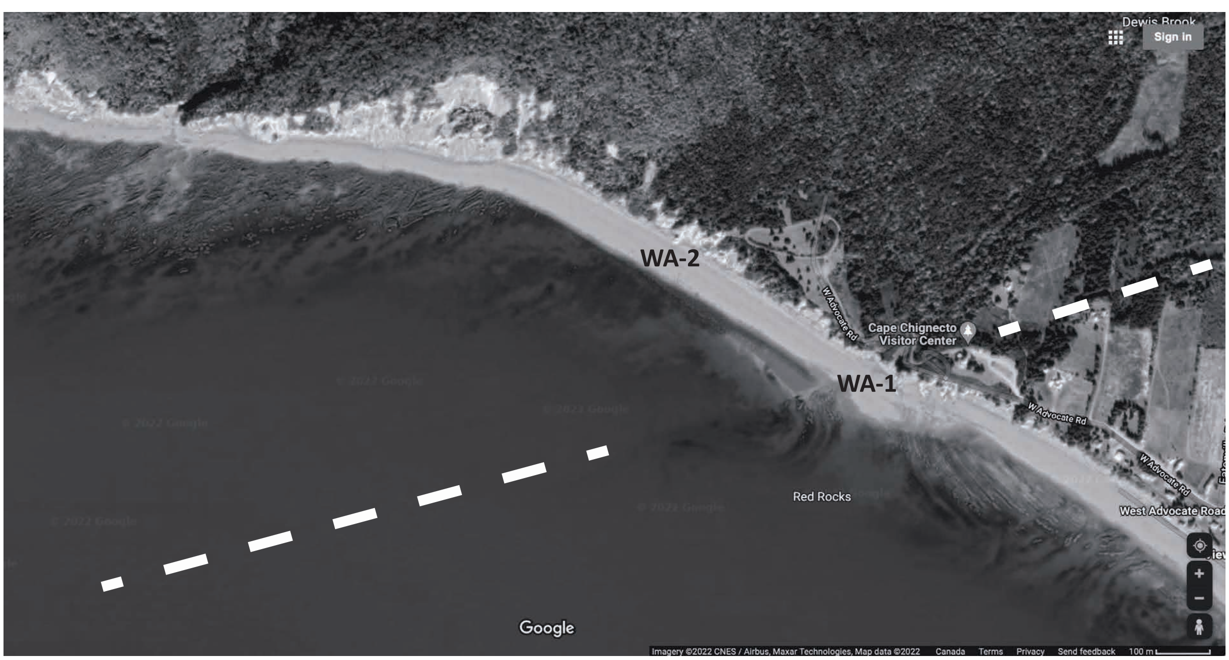
- 356934 5023454

The trace of the Cobequid Fault, the most prominent fault of the Minas Fault Zone, passes close to the visitor centre and crosses the beach at this point. To the south and east are mildly deformed red sandstone and conglomerate of the Triassic Wolfville Formation, known as the "Red Rocks". To the north and west are intensely fragmented, folded and cleaved grey shale, phyllite, and sandstone of the Carboniferous Horton Group (Nutttby Formation) in the core zone of the Cobequid Fault.

WA-1 Mesozoic Cobequid fault trace

The Mesozoic trace of the Cobequid fault is marked by the abrupt edge of the "Red Rocks". Several small faults within the Triassic sandstone strike parallel to the inferred main fault. The slip direction is difficult to determine directly, but several of the small faults show sinistral strike separation and small Riedel fractures, both consistent with sinistral slip. Sinistral transtension is also consistent with what we know of the oblique rifting process that opened the Bay of Fundy. The folding of the Triassic rocks seen in the satellite imagery is probably fault-bend ("rollover") faulting associated with this late extensional motion.

Figure 35. Trace of Cobequid fault at W. Advocate (©Google and sources shown in image).



WA-2 Paleozoic Core Zone

The Paleozoic fault is marked by a core zone that is at least 200 m wide, in which bedding cannot be traced in fractured, fragmented, and cleaved rocks of the Horton Group (Nuttby Formation). Donohoe and Wallace (1982) also recorded gypsum in the fault zone. In places, the fault rocks have been reworked into glacial till, further complicating the geometry.

Walk NW to the large projecting block of sandstone at

- 356523 5023721

Major slickensides show striations and offsets of bedding which, taken together, indicate dextral strike slip. This is confirmed by rare slickenfibre sheets. Despite the high degree of brittle deformation, parts of the sandstone block are intact enough to show ripple cross-lamination, showing that the block is right-way-up.

Several hundred metres farther west, the cliff shows a transition into a broad damage zone, in which folds trending NE-SW were mapped by Donohoe and Wallace (1982), oblique to the Cobequid fault itself (which strikes ENE-WSW), also indicating dextral shear. The mapped geometry of the fault suggests that the damage zone is at least a kilometre wide.

If time permits, walk NW to see more complete exposure of sheared and folded Horton Group.

Fundy Geological Museum (FG)

Drive 51 km 0:47
Head SE on W Advocate Rd. Turn right on NS-209 eastbound. Continue 45.6 km and turn right on NS-2 (signs for Parrsboro / Truro. In Parrsboro turn right onto Two Island Road and park at Fundy Geological Museum.

- 396367 5028177

The Fundy Geological Museum was founded following the discovery of dinosaur fossils at Wasson's Bluff in the late 20th century. The Museum has a range of exhibits on the local geology. The museum is well worth a visit, but because of the tight schedule and timing of tides, this stop will be treated as a "backup" option in case of access or weather problems with other sites.

Clarke Head (CH)

Drive 0:06
Turn right and continue along Two Island Road to Glooscap Park Campground. Park at the picnic area near the road to the beach.

- 400540 5026181

Dangerous cliffs. Wear a hard had if approaching cliffs and do not stand under overhangs. Section is tidal with pinch-points at both ends: Do not venture onto the section except on a falling tide, and leave the section 3 hours before high tide. Low Tide Five Islands 2022 May 13 17:18. No washrooms after leaving campground.

Clarke Head (Figure 36, Figure 37) has long been known for its spectacular block-in-matrix rocks, or "bimrocks" which have typically been described as "megabreccia". However, a number of the contained blocks are somewhat rounded, so the best name

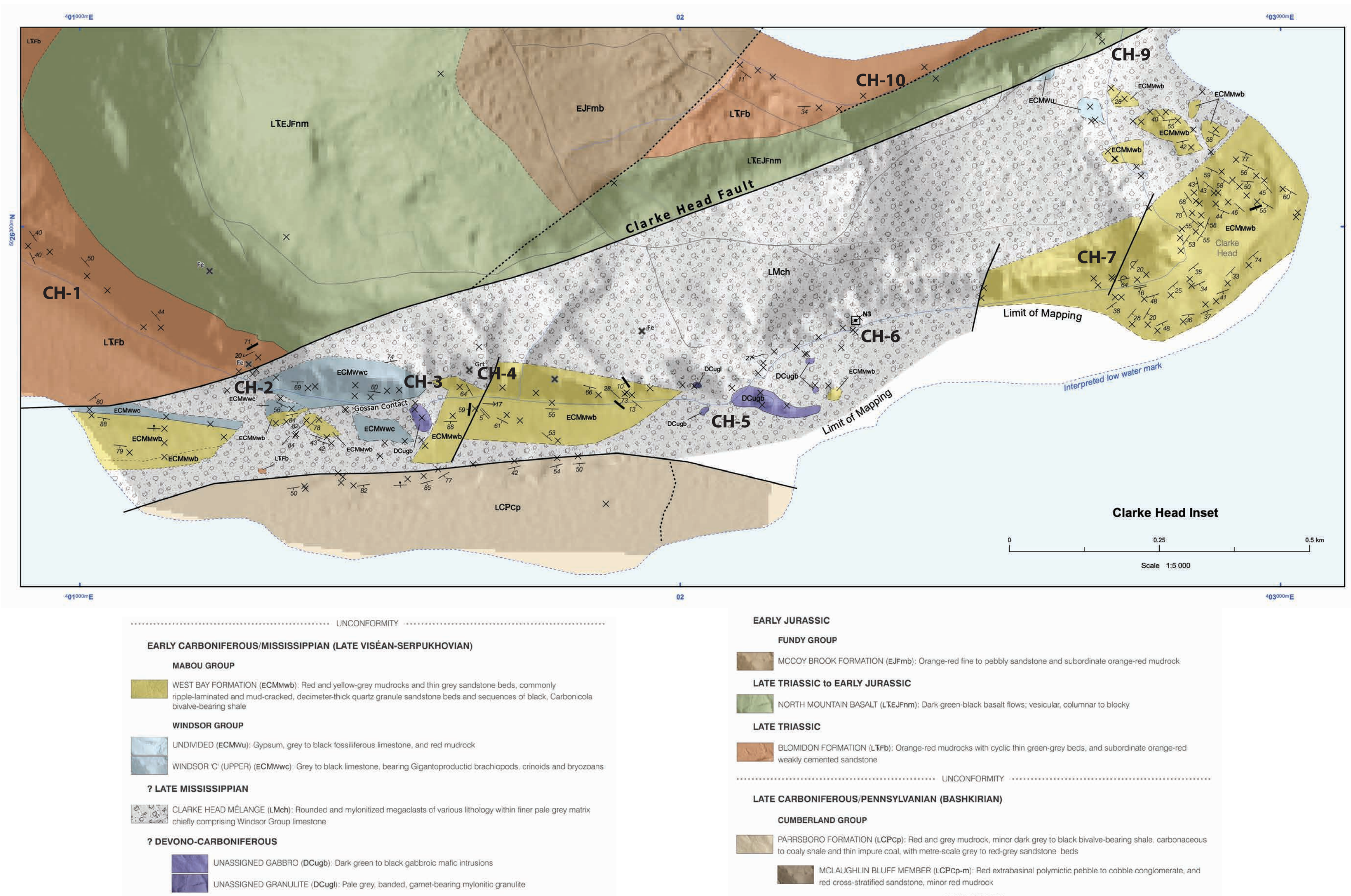


Figure 36. Map of Clarke Head after Calder et al. (2019).

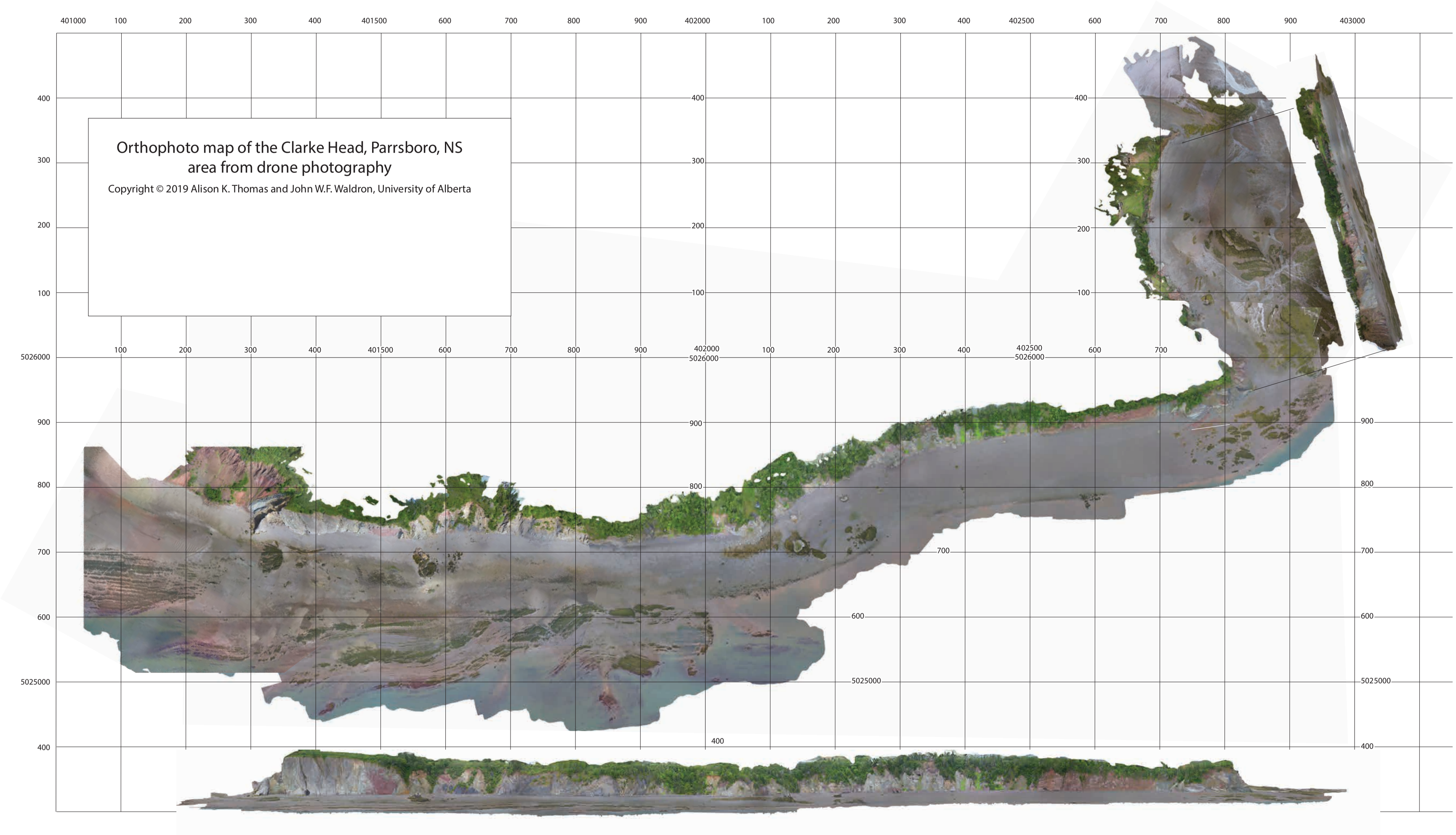


Figure 37. Orthographic projections of 3D model of Clarke Head built from drone photographs. (unpublished Agisoft PhotoScan model by A.K. Thomas and J.W.F. Waldron).

for these fragmental rocks is unclear. They satisfy most of the proposed criteria for designation as "mélange" - a mappable unit containing exotic blocks supported in a finer matrix - and this is perhaps the best word to describe them. Clarke Head lies on a fault strand that lies south of the main Cobequid fault, but may connect eastward with another strand of the MFZ, either the Portapique or the Gerrish Mountain fault. All these faults were active in the Mesozoic, in addition to their major Carboniferous activity. There is evidence from multiple sources that evaporites played a role in the emplacement of the mélange and the alteration of the blocks within it. The Clarke Head mélange can therefore be interpreted as a salt wall that developed along the MFZ during mid-Carboniferous deformation.

The following account is taken, in part, from an earlier field guide (Waldron et al. 2005), and especially to sections prepared by Joe White and Ellie MacInnes.

CH-1: Triassic Blomidon and Jurassic North Mountain formations

About 200 m east of the beach access, Triassic Blomidon Formation (Fundy Group) sandstones and siltstones are exposed in the cliff, dipping shallowly northeast. Deposition of the Mesozoic units occurred during transtensional rifting of Pangea that formed the Fundy-Minas basins. The dominant deformation features at this location are micro- and meso-scale high-angle normal faults presumably associated with Mesozoic extension.

CH-2: Carboniferous-Triassic contact

At the first sharp bend in the cliff face, there are several striking stratigraphic and structural features. The Blomidon Formation sandstones are overlain at the top of the cliff by North Mountain Formation basalt, part of the Central Atlantic Magmatic Province, or CAMP, that records the onset of rift volcanism. Volcanic rocks are most extensively exposed on the south and east sides of Minas Basin and the Bay of Fundy respectively, consistent with asymmetric rifting. The sandstone-basalt contact exhibits distinct colour variations as a result of contact metamorphism of the sediments.

These rift-sequence rocks are in steep fault contact with deformed upper Windsor Group limestone (Figure 36). Gouge and breccia produce a dramatic colour contrast at the contact zone between the Triassic and the Carboniferous. The dominant mode of deformation within the relatively homogenous body of limestone is through fracturing and veining including tension-gash arrays. However, the limestone is also folded and kinked. Productid brachiopods occur within the limestone. There is dispute as to whether the limestone unit is upright or overturned.

CH-3: Brecciated Windsor Group

Rounding the headland and continuing east, the Windsor Group limestone terminates. To the south, the mélange contains blocks of shale, limestone, dolostone, mafic and felsic igneous rocks and gneiss supported by a light grey-green fragmental matrix. Along the base of the bluff is a distinctive band of dirty-orange limestone breccia or "gossan" about 2 m wide which parallels the bedding in the cliff and is composed of limestone fragments in a limonitic limey matrix. This breccia may represent a bedding-parallel fault separating the Windsor Group from more diverse mélange.

CH-4: Mabou Group

To the east are steeply dipping Carboniferous Mabou Group (West Bay Formation) strata that extend for ~225 m. The beds are medium-grey, evenly-bedded, pervasively fractured fine-grained sandstones, shales and siltstones. Upright bedding surfaces form the face of the bluff and terminate in fault contact with the main mass of the mélange which is continuously exposed along the shore and cliff for the next 600 m eastward.

CH-5: Mélange Zone

At this point a boulder field which has a high proportion of igneous and metamorphic rocks (igneous rocks, marble, granulite gneiss) extends for 100 m. The source of many of these boulders is the cliff immediately above. Standing in the intertidal zone, at the east end of the boulder field, is a 25 m high stack of igneous rocks including scapolite- and analcime-rich syenite intruded into gabbro and diorite interpreted to represent a fragment of the widespread Late Devonian to Tournaisian intrusive suite of the found elsewhere in the Cobequids (Pe-Piper et al. 2019). However, only at Clarke Head are these rocks found to be so pervasively mineralized. The presence of scapolite, together with Cl-rich hastingsite, is interpreted by Pe-Piper et al to record extreme Na- and Cl-rich metasomatism. Scapolite replacement of K-feldspar in the syenite led to the release of potassium, contributing to the development of secondary biotite in the more mafic rocks (Pe-Piper et al. 2019).

The granulite gneiss boulders (cpx-opx-plag-gnt) are the deepest-level rocks contained within the Minas Fault Zone. These exotic blocks are indicative of the complex and long-lived history of this terrane boundary (see CH-6).

CH-6: Clarke Head Mélange

Igneous, sedimentary and metamorphic basement rock fragments are found within the mélange, ranging in size from tens of metres down to centimetres, supported within a matrix consisting of finer grained, quartzose, clayey (illite and chlorite), carbonate and gypsum. Satin spar gypsum veins cross-cut blocks and matrix, while pyrite and large gypsum crystals are distributed throughout the matrix.

Time constraints on the tectonic history of the mélange (Gibbons et al. 1996) are strongly dependent on records within the granulite gneiss block. Granulite-grade mylonites within the mélange exhibit Devonian metamorphic zircon ages (369 Ma: U-Pb zircon). This date is interpreted as the time of deep seated ductile shearing within the Minas fault system and is coeval with the initiation of widespread continental clastic sedimentation that produced the Horton Group.

Subsequent mid-crustal brittle deformation is recorded by hastingsitic amphibole veins (ca. 335 ± 3 Ma: $^{40}Ar/^{39}Ar$) which cut the mylonitic granulite fabric. These amphibole veins are the most Cl-rich amphiboles yet reported, comparable to hydrothermal systems such as the Salton Sea, California. This early Carboniferous age may correspond (Yeo and Gao 1987) to the establishment of fluvial conditions during Serpukhovian time as expressed by the Mabou Group.

A post-Mabou (Serpukhovian) age for the mélange forming event is inferred from the abundance of Windsor limestones and evaporites and Mabou clastics within the mélange.

Return by same route to vehicles

The following additional stops are included here in case time permits, or for the benefit of extended future excursions.

CH-7: Mabou Group

Continuing east towards the headland, the mélange is seen enclose multiple blocks of Mabou Group (West Bay Formation) at the southeast corner of the Clarke Head peninsula. The beds are overturned to the northwest and display mudcrack casts and sole markings.

CH-8: Mélange continued

Across the east end of the peninsula, there is a 300 m zone of mélange that is an along-strike of the mélange exposed at CH-6. Absence of outcrop on the surface precludes confirmation that the mélange zone is continuous, but it is nevertheless anticipated. Higher in the cliff are red and grey-green, slightly calcareous siltstone and sandstone about 4 thick. This unit has been interpreted to rest unconformably on the mélange, but it could also be a large slab included within it or even thrust upon it.

CH-9: North Mountain Basalt

The mélange unit is in fault contact here with North Mountain Basalt which displays columnar structure in a subhorizontal attitude. The alteration zone between the columns contains large sheets of asbestiform anthophyllite.

CH-10: Basal contact of basalt

Around the northeast corner of the peninsula, the North Mountain Basalt is in turn juxtaposed with Mesozoic sedimentary rocks. We interpret this contact as the primary base of the lava on underlying Triassic Blomidon Formation (Calder et al. 2019), and not as a fault against the younger McCoy Brook Formation (Jurassic), as appeared on earlier maps.

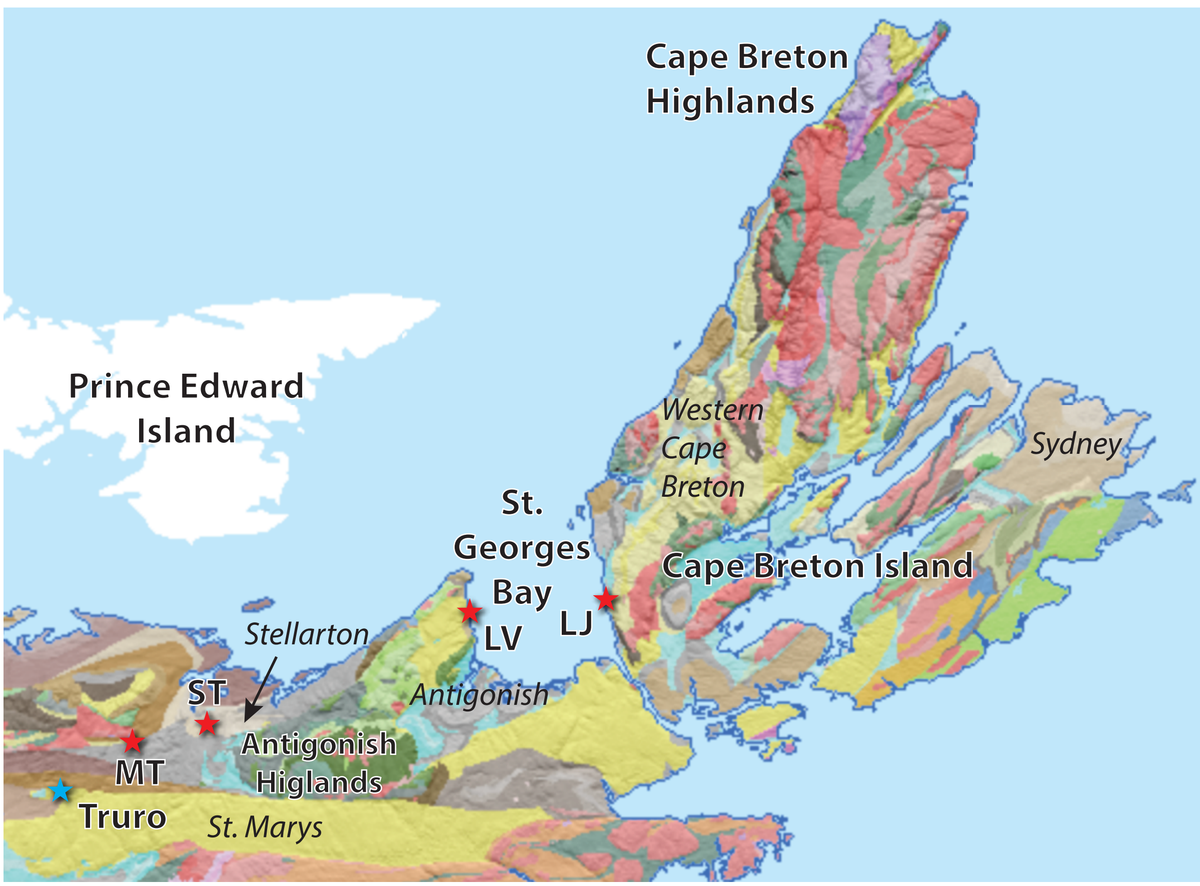
Looking across the bay towards the northeast, we see the Mesozoic red beds and basalts at Wasson's Bluff. This is an exciting palaeontological site famous for the discovery of extensive bone beds of "miniature" early dinosaurs. In the Fundy Geological Museum there is an exhibit on their recent work at Wasson's Bluff.

At the headland there appears to be an outsize human figure leaning against the rocks. Mik'maq tradition tells that this is the figure of the legendary figure Glooscap. At Clarke Head, he is looking out towards the islands in the basin (appropriately named Two Islands and Five Islands) which he created by throwing sod at a beaver. Glooscap then threw jewels which explains why this area is so rich in minerals!

Overnight Truro

Drive 98 km 1:20
Return along Two Island Road to NS-2 and turn right. Washroom available at Fundy Geological Museum or in Parrsboro cafés. Follow NS-2 68 km. Turn right onto NS-2 /NS-4 eastbound (signs for Masstown/Truro).
In 2.8 km at the roundabout take 2nd exit onto NS-104 Trans-Canada Highway.
Continue 12.1 km then take exit 15 to NS-102 toward Truro/Halifax.
Continue 2.0 km; then take exit 14 NS-2 toward Truro / Bible Hill. At the roundabout take the first exit and continue into Truro as on day 1

Figure 38. Stellarton to Cape Breton Island location map. Source (Keppie 2000), with full legend, at: https://novascotia.ca/natr/meb/download/dp043.asp



DAY 3: STELLARTON TO CAPE BRETON ISLAND

Introduction to the day

Day 3 will pursue the twin topics of strike-slip deformation and salt tectonics eastward along the Minas Fault Zone to Cape Breton Island. East of Truro the Minas Fault Zone extends along the southern margin of the Cobequid Highlands. The most conspicuous mapped lineament is the Cobequid Fault itself, which separates well indurated basement rocks of the Cobequids from softer, late Carboniferous to Triassic rocks to the south.

East of the eastern extremity of the Cobequids is a region in which Avalonian basement rocks are unexposed; sedimentary of Carboniferous age extend from the Minas Fault Zone northward as far as the Northumberland Strait, and beyond beneath the Gulf of St. Lawrence and Prince Edward Island. Farther east, Avalonian basement reappears in the Antigonish Highlands. The area between the Cobequid and Antigonish Highlands, occupied by sedimentary rocks of the Maritimes Basin, is known as the Stellarton Gap.

The Minas Fault Zone splays into the Stellarton Gap. A deep basin, the Stellarton sub-basin, filled with Pennsylvanian Cumberland Group (Stellarton Formation), joins the Cobequid fault to the Hollow Fault, which runs along the NW margin of the Antigonish Highlands (Figure 39). The Stellarton Basin is interpreted as a transtensional basin, occupying a pull-apart structure developed at a releasing bend on the Cobequid-Hollow system. The basin is filled with about 3 km of Pennsylvanian sediments, mainly of early Moscovian (Bolsovian, Westphalian C) age, including the entire Pictou coalfield. The Foord seam, up to 13 m thick, is reputed to be the thickest coal seam in eastern North America.

Because of its history of coal mining and exploration, the subsurface structure of the Stellarton Basin is exceptionally well documented. The map and cross sections (Figure 40) show an extensional basin overprinted at its northwest edge by a positive flower structure, representing late-stage shortening. Based on variations in the thickness of its fill, the basin is interpreted to have subsided asymmetrically (Figure 41). Subsequent (latest Carboniferous or Permian?) interaction with irregularities in the MFZ associated with the east edge of the Antigonish Highlands was probably responsible for the overprinted compressional structures.

The Stellarton core library is the main repository of subsurface core in NS. Apart from the Pugwash salt mine, this is currently the only place to see the halite evaporites that underlie many parts of the Maritimes Basin. There, we hope to have a chance to see evaporite core from several sub-basins of the Maritimes Basin.

From Stellarton we will travel east, crossing the Antigonish Highlands into the Antigonish sub-basin, which is really continuous with Maritimes Basin rocks beneath St. Georges Bay and exposed on its eastern shore, on Cape Breton Island. The last stops will be at locations interpreted as faults in the past, but interpreted by us as salt welds marking the expulsion of Windsor evaporites.

Figure 39. Geological map of the Stellarton Gap

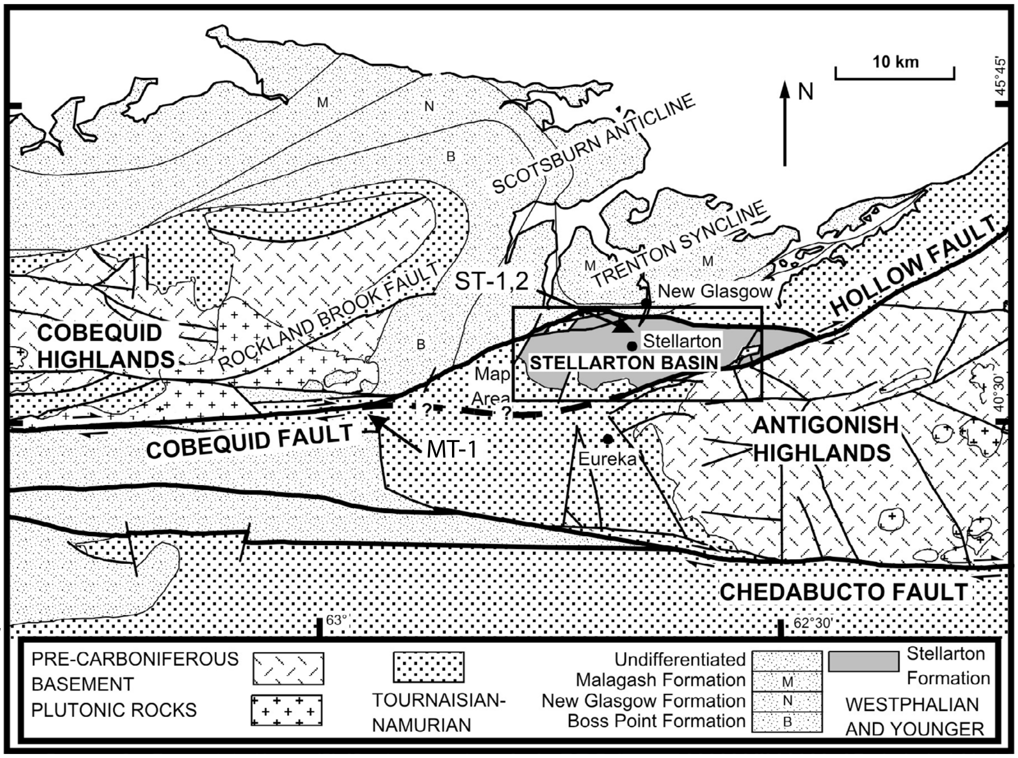


Figure 41. Models for the development of the Stellarton sub-basin

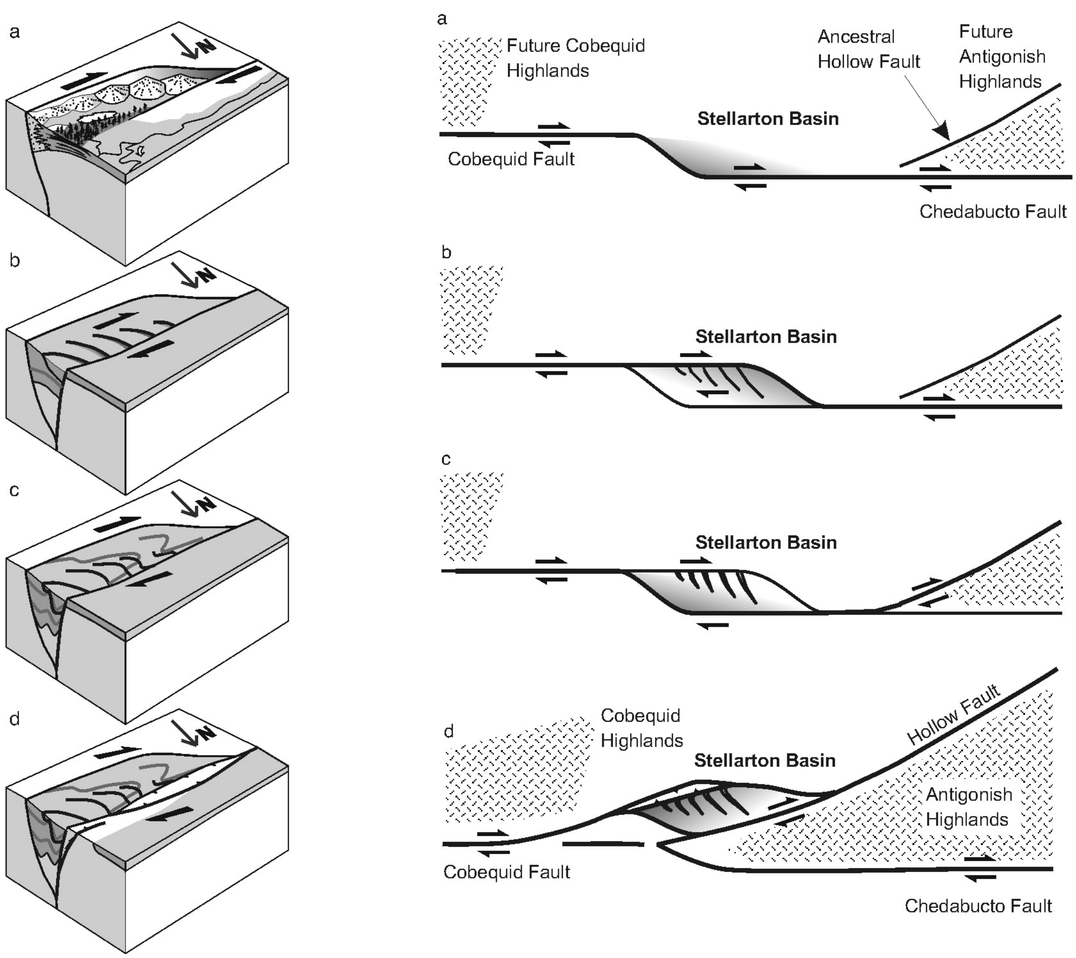
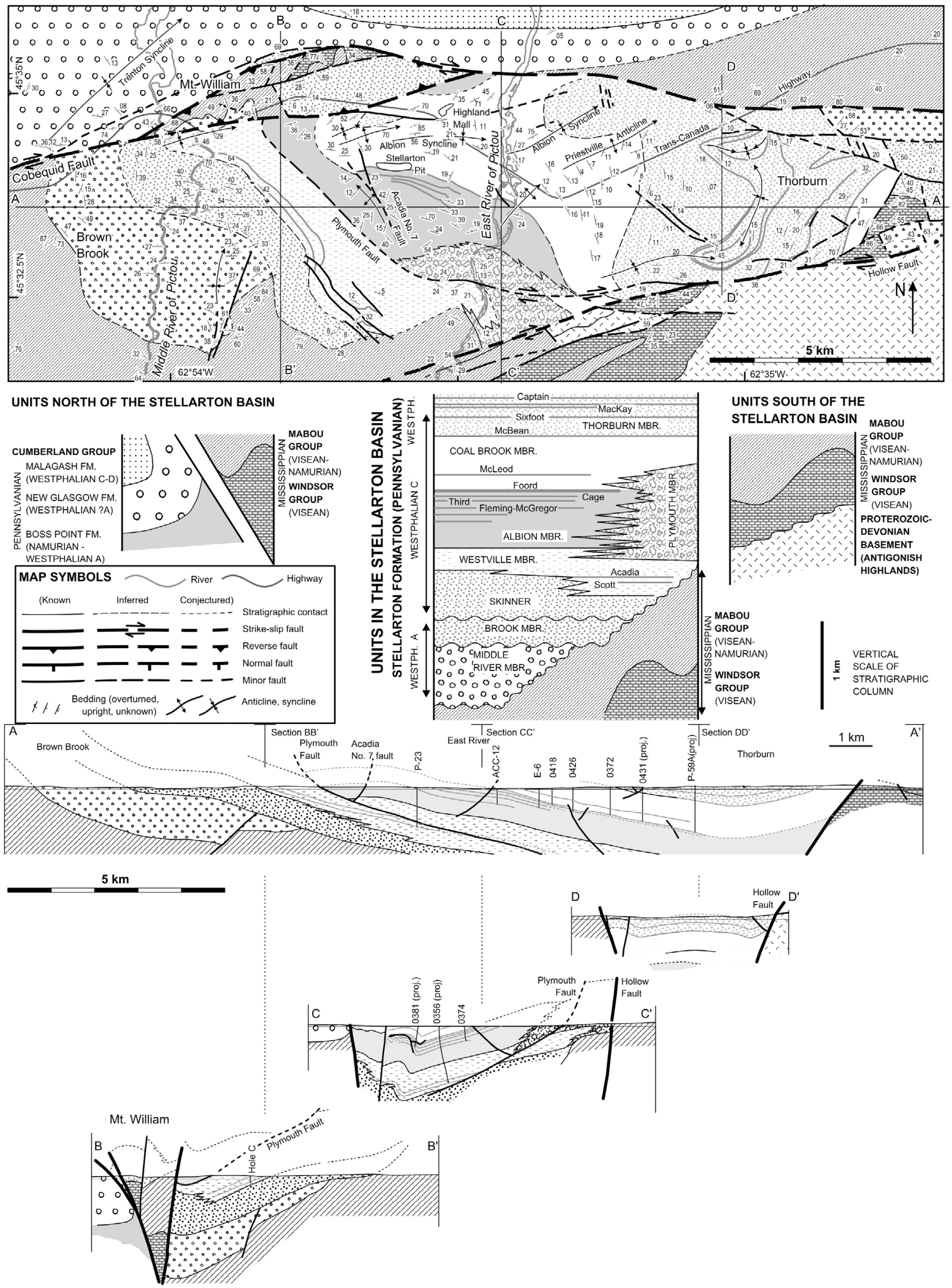


Figure 40. Map and cross-sections of the Stellarton sub-basin



Mount Thom (MT)

MT-1 Mount Thom: Former salt wall (?) in Minas Fault Zone

Drive 33 km 0:31
Head east on Horseshoe Crescent. Turn left onto Cumming Dr. Turn right onto College Rd.
In 1.3 km Turn left onto Johnson Ave then turn right onto Pictou Rd / NS-4 E
In 4.2 km Take the Trans-Canada Hwy / NS-104 ramp to New Glasgow / Cape Breton
In 15.2 km Take exit 18A toward NS-4 / Mt. Thom; turn left onto Pictou Rd E, then right onto Pictou Rd / NS-4 E (signs for NS-4 E / Mt Thom)
In 8.2 km Turn right onto Mt Thom Rd; then in 950 m Turn left onto Cove Rd. Park at N end of road cut.

- 502554 5039879

Caution: although this road carries little traffic, occasional fast truck traffic uses the road. Trucks tend to travel fast under the bridge. Keep off the roadbed and keep eyes and ears open for traffic at this locality. No washrooms.

At Mount Thom a broad zone of breccia is developed within Mabou Group rocks (Namurian) and is exposed in a road cut beneath the Trans-Canada Highway. The breccia zone apparently cuts Mabou Group both to the north and south. Although it was interpreted in an earlier field guide as a southern splay of the main Cobequid fault, it more likely represents a diapiric salt wall, though probably ultimately triggered by motion on the Cobequid fault to the north.

The zone includes highly folded and brecciated lithologies of the Mabou Group. In addition, just north of the highway bridge, there are mudrocks that appear only weakly deformed. In places these contain cubic casts of a mineral that has since dissolved, possibly halite. These mudrocks are tentatively interpreted as a residue resulting from the solution of evaporites that were formerly present in the brecciated zone.

Field stops in the Stellarton area (ST)

ST-1 Stellarton Core Library (SL)

Drive 0:23
Head north on Cove Rd and turn right onto Mt Thom Rd
In 950 m turn right onto NS-4 E. In 7.3 km turn right , then left to merge onto Trans-Canada Hwy NS-104.
In 17 km Take exit 23 to MacGregor Ave. Continue 2.6 km.
Turn right onto Beaufort St. Turn right onto Acheron Ct and park at end. A washroom is available at the Core Library.

- 524573 5045003

Wear approved safety equipment and follow instructions from core library staff. Those handling core are required to wear steel-toed boots. Do not attempt to move core boxes. Be aware of and keep clear of forklift and other machinery.

The Nova Scotia government core library stores subsurface core from all over the province. Much of our knowledge of the more soluble evaporites (rock salt, potash) in the Maritimes Basin comes from subsurface core. At the Stellarton core library we will have the opportunity to view core from evaporite-bearing Windsor Group in both relatively undeformed and highly deformed parts of the Maritimes Basin.

Figure 42. Logs of core, middle and upper Windsor Group from various parts of the Maritimes Basin (Giles 2009).

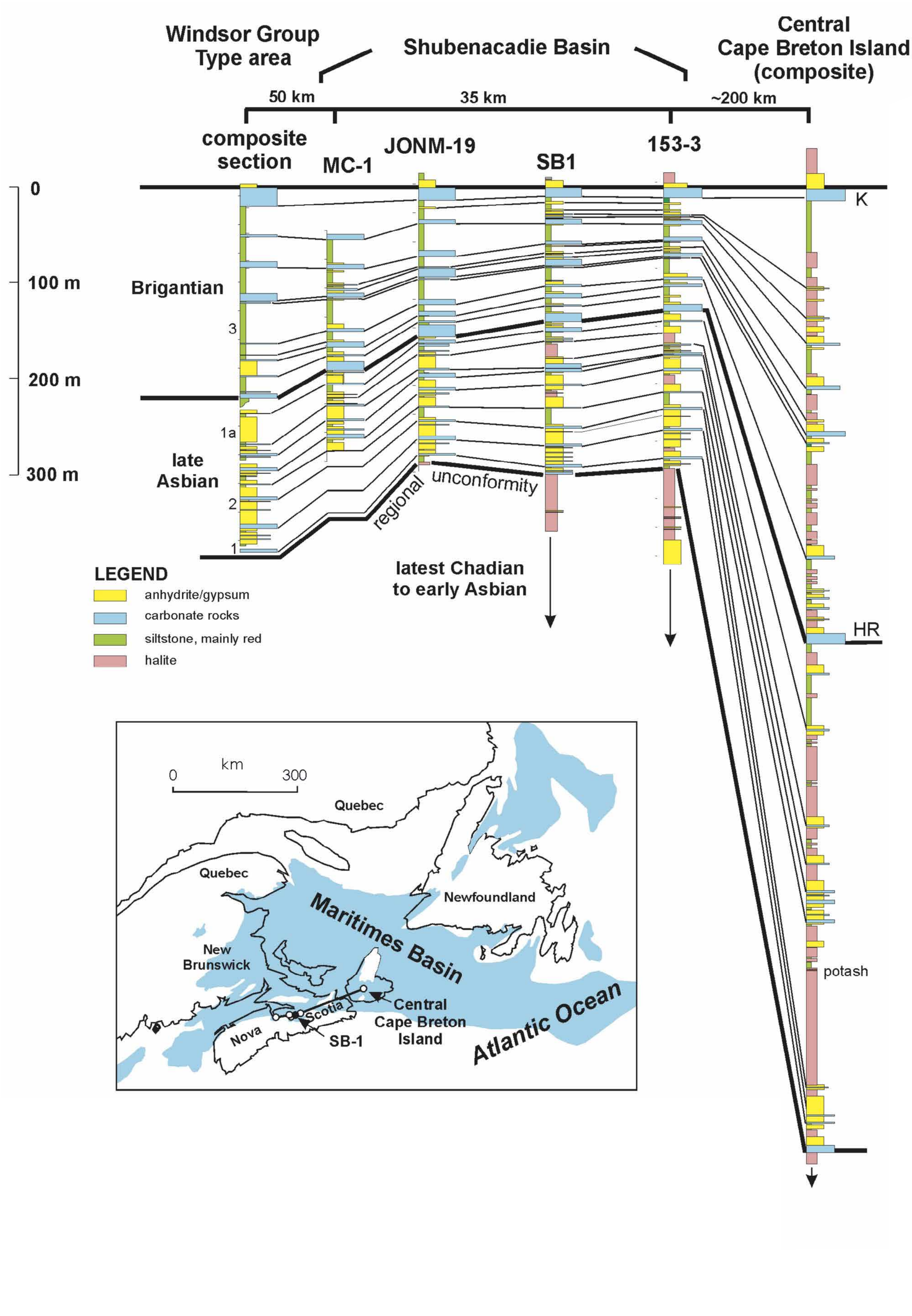
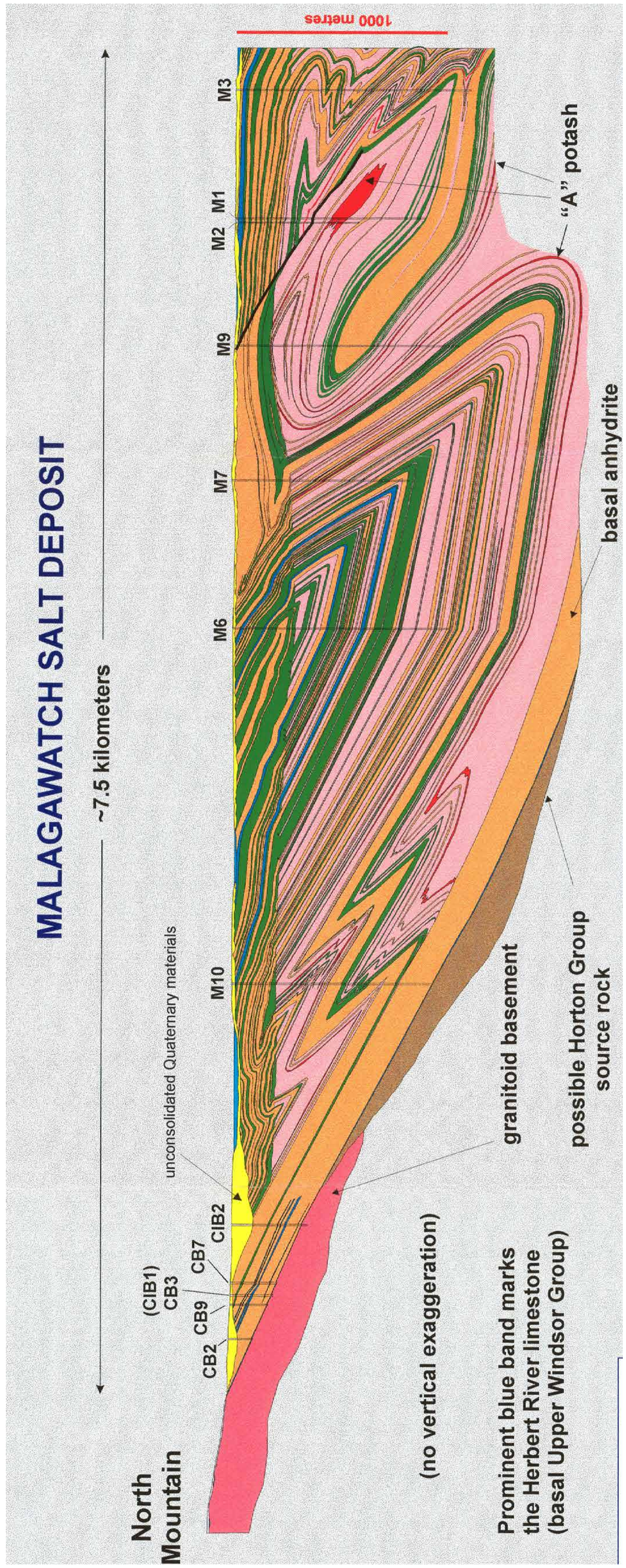


Figure 43. Core from drillhole LR-1 in Antigonish sub-basin, passing through interpreted primary salt weld (Thomas 2019).

Figure 44. Interpreted cross-section through highly deformed evaporite-bearing succession at Malagawatch, showing effect of near-surface evaporite dissolution (Giles 2003).



ST-2 Stellarton Walmart (SW)

Drive 4.4 km (0:08)
Return to MacGregor Ave. Continue north 2.5 km. Turn right onto Westville Rd/NS-4 E. In 600 m turn left into Highland Mall parking lot. Drive to outcrop behind Walmart. Public washrooms inside the main Highland Mall.

- 525831 5047514

Commercial access road for store deliveries. Be aware of trucks and other vehicles. Do not obstruct access.

This series of outcrops is representative of a block separated from the main section of basin fill by the Bridge Fault, but lying south of the Fletcher fault. The Bridge Fault lies immediately south, passing through Exit 23 where you may have turned off the Trans-Canada Highway. The rocks in this slice can be tentatively correlated with those to the south of the Bridge Fault in the main part of the basin. To the north of this location, a historic mine, known as the Haliburton pit, was sunk into a south-dipping seam identified as the Foord, which marks the top of the Albion Member. The section in these outcrops is probably therefore correlative with the Coal Brook Member of the Stellarton Formation.

Lithologically, the rocks are shale and sandstone, locally with abundant fossil wood and fish scales, indicating fresh-water, lacustrine to fluvial environments. The overall structure is a series of folds plunging very gently NNE. These are cut by faults that strike NNW-SSE, most of which are extensional, but which show a variety of mineral fibre orientations that are consistent with a combination of dip-slip and strike-slip motion (present-day orientation).

Figure 45. Outcrop at Highland Mall, Stellarton.

Lakevale (LV)

Drive 84 km, 1:10.
Turn right onto Westville Rd/NS-4 W; then turn left to merge onto Trans-Canada Hwy / NS-104 E toward Antigonish/Cape Breton. In 56.1 km take the off ramp (exit 32) to NS-7 and Antigonish. (One of several exits to Antigonish.) At the first roundabout, take the 4th exit onto NS-7; At the second roundabout, take the 1st exit onto NS-7 E.
Continue onto West St/NS-4 E (signs for NS-4 E/NS-245/NS-337). Continue straight onto Main St/NS-4 E. Washrooms in gas stations and cafés on Main St. In 1.1 km continue onto Bay St/NS-337 N. Continue 23 km to civic address 4663 NS-337.

- 584313 5071653

With permission from property owners access the coast at.

- 584595 5071634

Seek permission before crossing private land. Cliffed tidal coast. Be aware of falling rocks and do not stand under overhangs. Rocks are slippery when wet. The headland towards the south end of the traverse is only passable around low tide. Low tide 2022 May 14 15:01 at Ballantynes Cove. No washrooms.

The section at Lakevale is typical of sections that have major stratigraphic omissions in the Windsor Group, interpreted by Lynch et al. (1998) as resulting from horizontal motion at a major omission surface termed the Ainslie detachment (Figure 7). We suggest a reinterpretation (Figure 12) in which sections lacking middle and/or upper Windsor stratigraphy represent the locations of early-formed rising diapiric walls of lower Windsor salt, which blocked the deposition of middle and/or upper Windsor sediments. One such location is at Lakevale on the west coast of St. George's Bay.

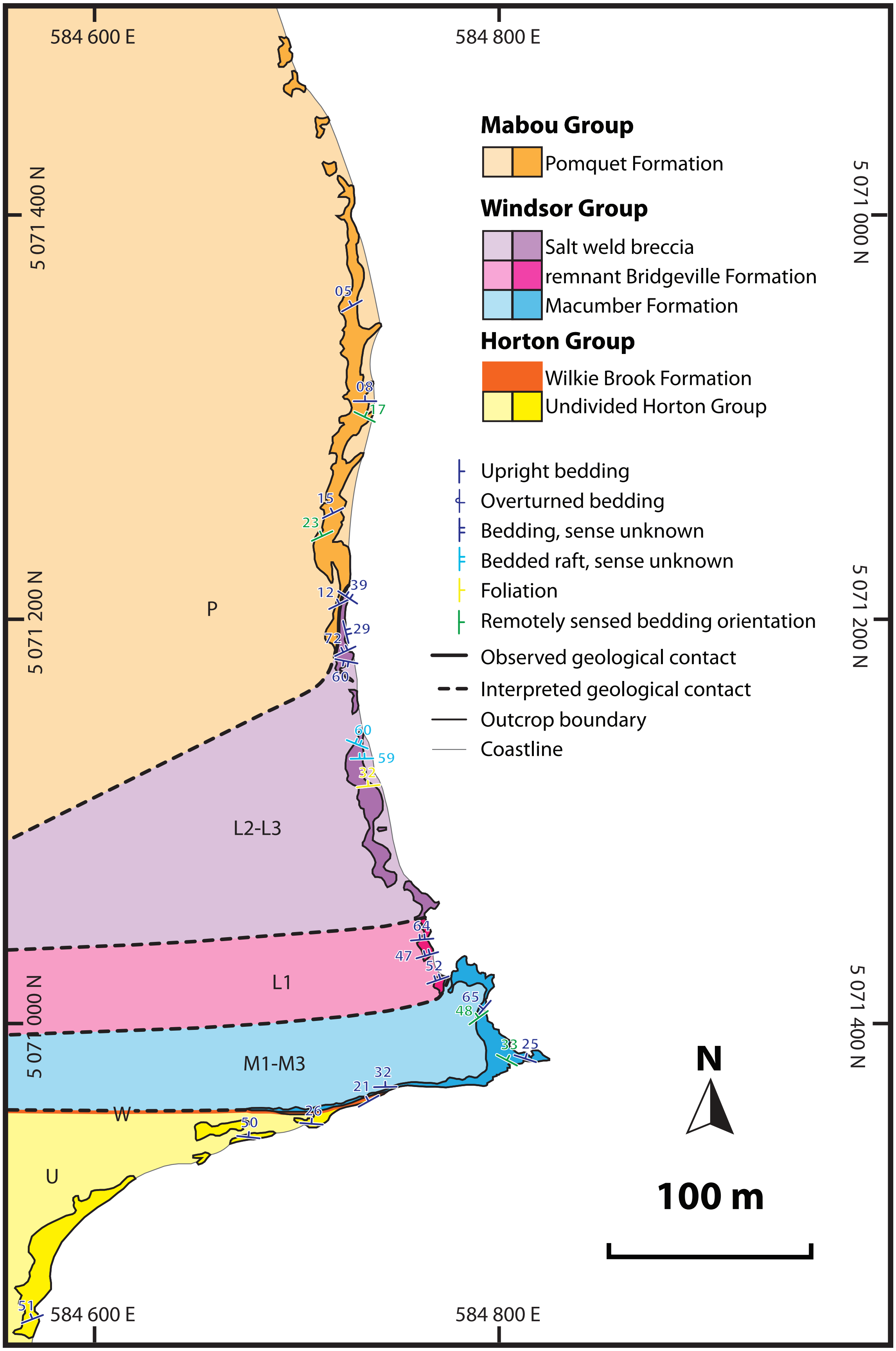
LV-1: Mabou Group - Pomquet Formation

The upper part of the section is represented by redbeds - a sandstone and shale succession with well developed fining-upward cycles, a classic indicator of channelized fluvial flow (Unit P in Figure 47). At the base of the succession, it rests with angular unconformity upon brecciated, somewhat disorganized red and green siltstone with minor limestone of the Windsor Group, which has here been mapped as Lakevale Formation.

LV-2: Lakevale "Formation"

The Lakevale "Formation" is represented by a variety of fragmental rocks (Figure 47 Unit L1-3) ranging from almost purely siltstone, to largely limestone. Though sedimentary origins as debris flows have been proposed, the fragmental siltstones have a striking resemblance to the appearance of cores through deformed impure Windsor evaporites (Figure 43); if these deformed evaporite sections are imagined in their state after evaporite dissolution, they appear almost identical to the siltstone breccias seen in outcrop at Lakevale and other locations. We therefore interpret the thin succession of fragmental rocks at Lakevale as the residue of an evaporite diapir, probably derived from the lower Windsor salt, that blocked deposition of the middle and upper Windsor Groups. The diapir then subsided as a result of Serpukhovian extension, or alternatively was dissolved, allowing deposition of the Mabou Group in the resulting accommodation space.

Figure 46. Geological map of the Lakevale section (Thomas 2019)



LV-3: Macumber Formation

The lowest part of the Windsor succession at Lakevale consists of faulted and locally folded laminated limestone of the Macumber Formation (Figure 47 Unit M1-3). Large lenticular to angular megacrysts within the Macumber Formation probably represent pseudomorphs of primary gypsum crystals that were deposited within the Macumber during the transition from shallow-marine carbonate to evaporite sedimentation.

The folds in the Macumber Formation at Lakevale are heavily fractured approximately perpendicular to the lamination of the limestone. Despite this, the fold geometries are well preserved and layers are traceable within the folds. This unusual combination of brittle fracturing and ductile folds is proposed to have resulted from the interlayering of evaporites with the limestone during deformation, the evaporites having been removed post-deformation, bringing the previously-separated limestone layers together (Thomas 2019).

LV-4: Horton Group

If the tide permits, it may be possible to round the headland at the south end of the section and see the underlying Horton Group. At the base of the Macumber limestone a thin band of conglomerate represents the Wilkie Brook Formation, a unit lithostratigraphically assigned to uppermost Horton Group that may have marked, in sequence stratigraphy terms, the beginning of the first cycle of Windsor deposition. It rests unconformably on sandstone and shale of the main Horton Group succession. Trough-crossbedding in the sandstone in the southernmost visible portion of the Horton Group indicates that this unit is upright.

Figure 47. Drone-photography 3D model of the Lakevale outcrops, showing the main units. A: uninterpreted. B: interpreted (Thomas 2019).

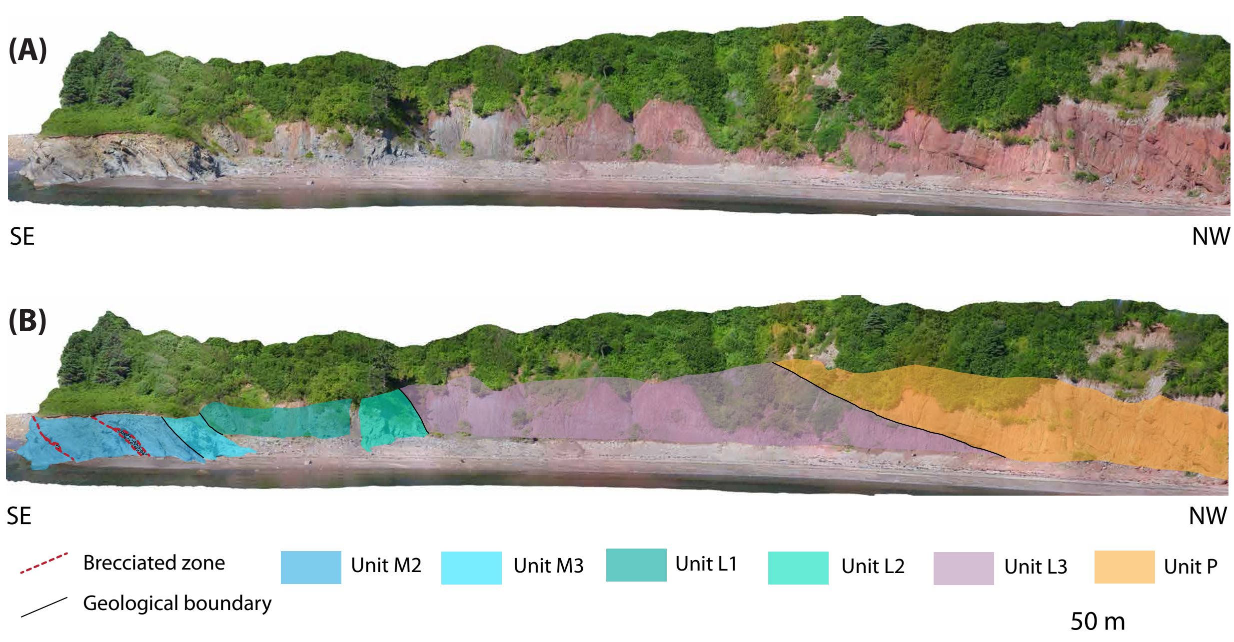
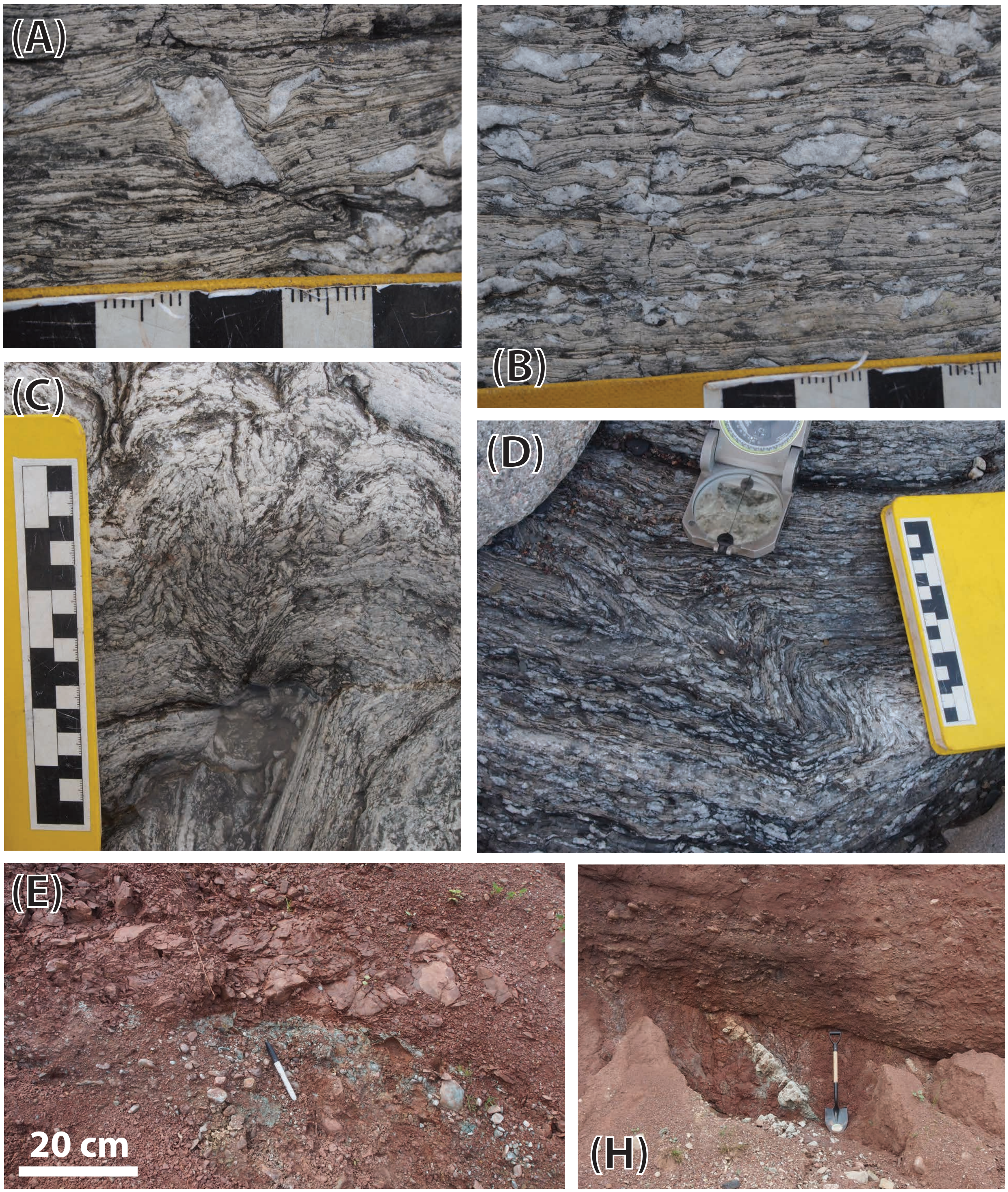


Figure 48. Outcrop features at Lakevale. (A, B) Gypsum pseudomorph photos showing laminae diverging away from pseudomorphs; scale in centimetres. (C) Angular brecciated fold in Macumber Formation; scale in centimetres. (D) Fold in Macumber Formation. (E) Siltstone breccia clasts of Unit L3; pen 14 cm. (F) Angular unconformity at base of Pomquet Formation; shovel 98 cm (Thomas 2019).



Little Judique Harbour (LJ)

Drive 1:24
Head southwest on NS-337. In 23.4 km turn left onto S River Rd / NS-4 E
In 1.4 km Turn right onto Beech Hill Rd.
At the first roundabout, take the 2nd exit and stay on Beech Hill Rd. At the second roundabout, take the 2nd exit to Cape Breton and merge onto Trans-Canada Hwy/NS-104 E. Washrooms available at gas stations and cafés on the approach to the Canso Causeway.
After 49 km cross the Canso Causeway onto Cape Breton Island.
At the roundabout immediately after the causeway take the 3rd exit onto NS-19 N Ceilidh Trail toward Inverness. Washrooms are available at the tourist centre on the roundabout.
After 30.9 km turn left onto Shore Road and follow Shore Road for 8.0 km until you are level with the Little Judique Harbour Wharf near a small sign for Little Judique Harbour. Turn left on Lower Shore Rd. and park at the wharf out of the way of any fishing operations or vehicles. Walk southwest along the beach until you hit outcrop, then keep going along the outcrop until you can go no further northwest along the shoreline.

- 613680 5090280

Low tide Port Hood 15:05

The presence of salt in southwestern Cape Breton has historically been known from coastal outcrops where diapirs have been mapped (e.g., Brown, 1998) at areas such as Port Hood Island, Finlay Point, and Broad Cove. Salt walls have also been identified beneath St Georges Bay on seismic data (Brown, 1998). One of these salt walls can be traced to shore at Little Judique Harbour. Previous mapping at Little Judique Harbour by Giles et al. (1997) interpreted a north-south striking fault through the harbour, with steeply dipping strata of opposing younging directions on either side of the fault surface. We interpret (Thomas 2019) this surface as a secondary salt weld (Figure 49 to Figure 51), a surface where rocks were once separated by a steep-sided diapir that has since been removed, bringing the rocks into contact with each other. Salt welds are often observed on seismic profiles but rarely seen in outcrop. This secondary salt weld is exposed at both the north and the south ends of Little Judique Harbour (Figure 51). We will begin at the southern exposure (Figure 52A) and move on to the northern exposure (time permitting).

LJ-1: Trough-crossbedded sandstone

- 613694 5090344

The Port Hood Formation of the Cumberland Group comprises the westernmost unit at LJ. Alternating 10-30 m thick units of sandstone and siltstone make up this formation, with beautiful trough crossbeds (Figure 52D) indicating that this unit youngs west. The beds are near-vertical and vary from upright to overturned. The western sandstone units contain rare pebble lenses of dominantly siderite clasts, minor sandstone and limestone clasts, and coal fragments. Rare fossil tree fragments over 1 m long and 15 cm wide are found in the lenses.

The westernmost siltstone unit is recessive due to being preferentially eroded. By walking along strike down the unit, or observing drone photography from above, it is apparent that this unit thins from 21 to 7 m over an along-strike distance of 125 m (Figure 50), implying a lateral change in accommodation space during the siltstone unit's deposition.

As you walk towards the next stop, observe how the sandstone becomes more brecciated towards the base of the unit.

LJ-2: Brecciated sandstone

- 613766 5090278

Here, the basal sandstone unit of the Port Hood Formation locally displays weak crossbedding, rare convolute lamination and limestone clasts. The sandstone is heavily but unsystematically fractured. At the base of the lowermost sandstone unit, there are light grey sandstone clasts in a matrix of massive tan sandstone, with the clasts more resistant to weathering than the matrix (Figure 52C). The colour and weathering contrasts between the two sandstones imply that there were two episodes of cementation at different times. A lack of laminae in the matrix suggests that the matrix was likely liquidized during emplacement around the clasts (Berra and Felletti 2011, Snyder and Waldron 2016). Therefore, the light grey sandstone was deposited, partially cemented, then was deformed and brecciated, and finally was fully cemented. This created a sandstone breccia at the base of the Port Hood Formation, the lowermost sandstone having been later fractured together with the rest of the sandstone unit.

The brecciation of the basal sandstone unit, the synsedimentary breccia in the lowermost part of the basal sandstone unit, and the along-strike thickness change of the siltstone unit at the previous stop are interpreted as implying that the Port Hood Formation at LJH was deposited on top of moving salt.

LJ-3: Siltstone breccia

- 613775 5090243

West of the Port Hood Formation is a 5 m wide zone of brecciated red and grey mudstone and siltstone (Figure 52B). The very poorly sorted clasts average 1-2 cm in size and are locally calcareous. No way-up indicators are present.

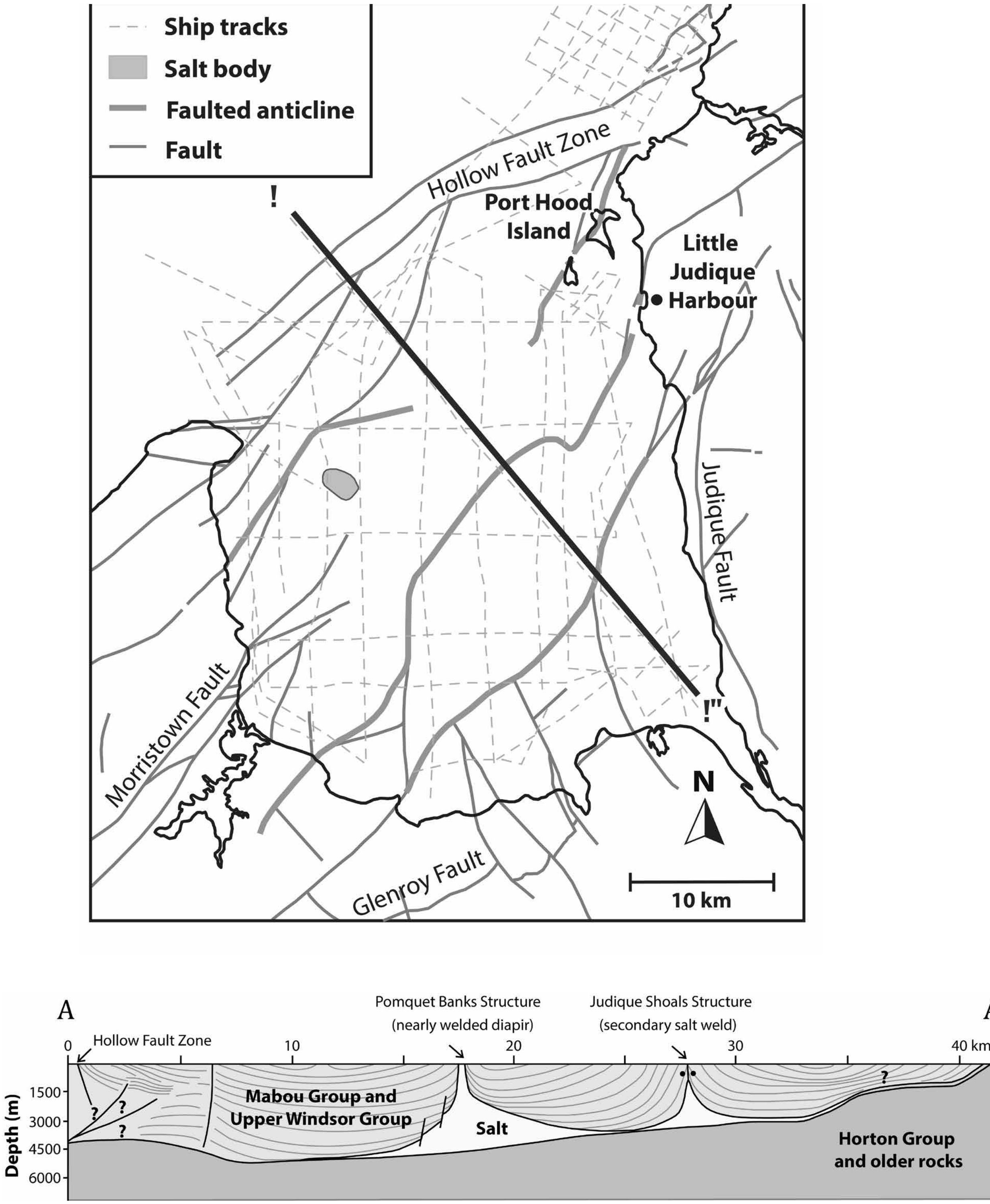
This zone is interpreted as a salt-solution residue: clasts represent fine-grained clastic rocks that were once hosted within salt and were left behind after the salt was removed.

LJ-3: Upper Windsor Group

- 613794 5090241

On the eastern side of the siltstone breccia is the Hood Island Formation from the Upper Windsor Group. The outcrop is poorly exposed due to cover by slipped rubble. The formation is made up of locally calcareous red and grey siltstone and mudstone, ranging from massive to laminated. Intervals of gypsum, usually white slipped blocks up to 4 m in diameter, are also included in the Hood Island Formation. In some areas, the fine-grained clastics are brecciated into a rubble with randomly oriented clasts. Rare cross lamination in mudstone shows that this unit youngs eastwards, with bedding dipping moderately to steeply west (opposite to the Port Hood Island Formation).

Figure 49. Map and cross-section of St. Georges Bay (Durling et al. 1995b), showing named faulted anticlines reinterpreted by Thomas (2019).



The siltstone breccia near the top of the formation is cut by subvertical fibrous gypsum veins that dip steeply west. Fibres in the veins plunge moderately northwest, oblique to the planes of the veins, suggesting west-side-up shear followed by horizontal extension.

Note: previous mapping by Giles et al. (1997) suggests that there could be up to 80 m of concealed Hastings Formation at the southern end of Little Judique Harbour. However, in recent years the formation has not been visible at the southern part of the harbour.

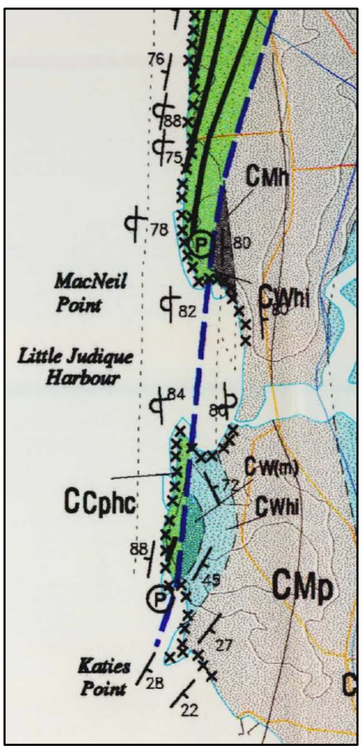


Figure 50. Map of Little Judique and Port Hood area after Giles et al. (1997).

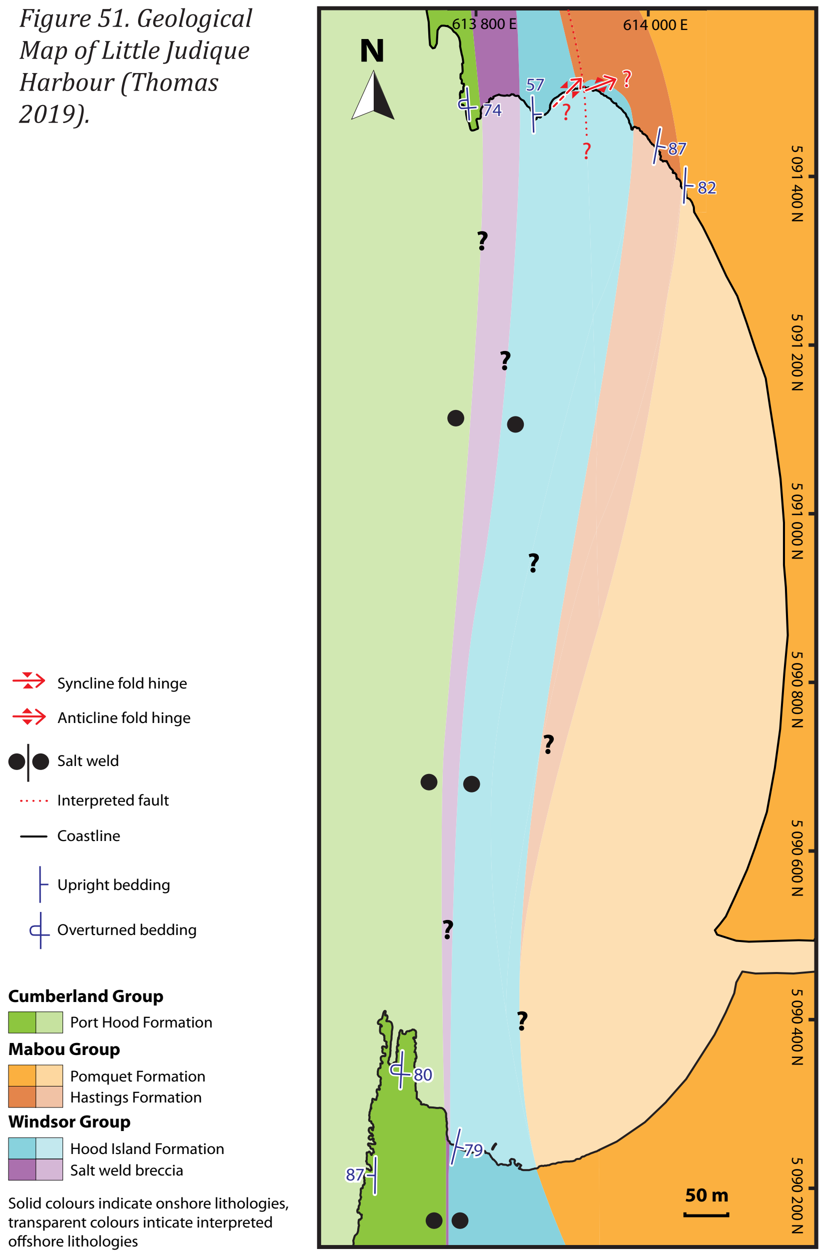
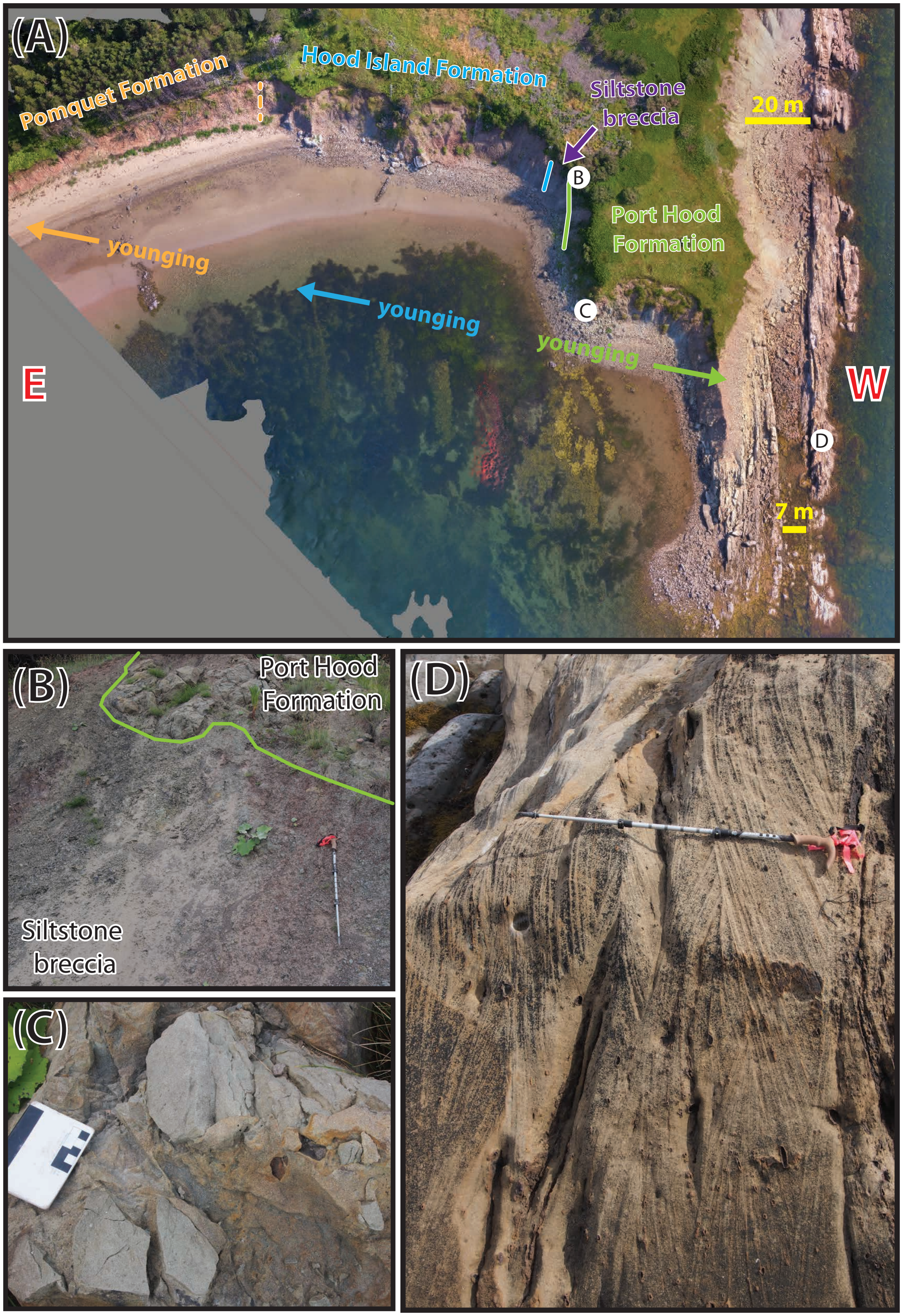


Figure 51. Geological Map of Little Judique Harbour (Thomas 2019).

Figure 52. Field Photographs from Southern Little Judique Harbour. A) Orthophoto of 3D model showing along-strike thickness changes in the Port Hood Formation, showing locations of parts B - D. B) Siltstone breccia and base of Port Hood Formation. Walking stick is 1 m long. C) Synsedimentary sandstone breccia at the base of the Port Hood Formation. Grain size chart for scale. D) Crossbedding in Port Hood Formation indicating that the unit youngs westward. Walking stick is 1 m long, photo taken looking ~south (Thomas 2019).



Return to Halifax

Drive 312 km (3:20)
Head southeast on Murphys Pond Rd toward Main St.
In 450 m turn right onto Main St.
In 2.3 km: Turn right onto NS-19 S toward Port Hawkesbury.
In 44.3 km: At the roundabout, take the 1st exit onto Trans-Canada Hwy/NS-104 heading to Canso Causeway/ Antigonish. (Washrooms available in tourist information centre at roundabout and at several cafés and gas stations just west of the causeway.)
In 167 km: Take exit 15 for NS-102 S toward Truro/Halifax.
In another 74.1 km Keep left at the fork to continue on NS-118, follow signs for NS-107/NS-111/Dartmouth/ Halifax via bridges.
In 17 km Turn left onto Victoria Rd/Victoria Rd Ext/NS-322 S.
In 600 m Turn right onto Nantucket Ave and continue onto Angus L. Macdonald Bridge.
Toll bridge

Turn right onto the ramp to Barrington Street and continue to downtown Halifax.

REFERENCES

Allen, M.B., Macdonald, D.I., Xun, Z., Vincent, S.J., and Brouet-Menzies, C. 1998. Transtensional deformation in the evolution of the Bohai Basin, northern China. Geological Society, London, Special Publications, **135**: 215–229.

Anderson, E.M. 1905. The dynamics of faulting. Transactions of the Edinburgh Geological Society, **8**: 387–402.

Anderson, E.M. 1951. The dynamics of faulting and dike formation with application to Britain. 2nd Edition, Edinburgh. Oliver and Boyd.

Belt, E.S. 1968. Post-Acadian rifts and related facies, eastern Canada. *In* Studies of Appalachian Geology, Northern and Maritime. *Edited by* E. Zen, W.S. White, and J.A. Hadley. Wiley Interscience, New York. pp. 95–113.

Belt, E.S. 1969. Newfoundland Carboniferous stratigraphy and its relation to the Maritimes and Ireland. *In* North Atlantic Geology and Continental Drift, American Association of Petroleum Geologists Memoir. *Edited by* M. Kay. pp. 734–753.

Berra, F., and Felletti, F. 2011. Syndepositional tectonics recorded by soft-sediment deformation and liquefaction structures (continental Lower Permian sediments, Southern Alps, Northern Italy): Stratigraphic significance. Sedimentary Geology, **235**: 249–263. doi:10.1016/j.sedgeo.2010.08.006.

Boehner, R.C., and Giles, P.S. 1982. Geological Map of the Antigonish Basin. Nova Scotia Department of Mines and Energy Map, 82-2, scale 1:50 000.

Boehner, R.C., and Giles, P.S. 1993. Geology of the Antigonish Basin, Antigonish County, Nova Scotia. Nova Scotia Department of Natural Resources, Mines and Energy Branches, Memoir, 8.

Boehner, R.C., and Prime, G. 1993. Geology of the Loch Lomond Basin and Glengarry Half Graben, Richmond and Cape Breton Counties, Cape Breton Island, Nova Scotia. Nova Scotia Department of Natural Resources Memoir, ME 009.

Bradley, D.C. 1982. Subsidence in late Paleozoic basins in the northern Appalachians. Tectonics, **1**: 107–123.

Calder, J.H., Waldron, J.W.F., Naylor, R.D., Adams, K., Fedak, T., and MacHattie, T.G. 2019. Geology of the Parrsboro Shore, Black Rock to Moose River, Cumberland County, Nova Scotia. Nova Scotia Department of Energy and Mines Open File Map, ME 2019-001, scale 1:25000.

Carter, D.C. 1990. Geology of the Canadian Salt Company Limited Pugwash Mine. Nova Scotia Department of Mines and Energy Map, 90-3, scale 1:1500.

Dewey, J.F., Holdsworth, R.E., and Strachan, R.A. 1998. Transpression and transtension zones. *In* Continental Transpressional and Transtensional Tectonics, Geological Society of London Special Publication, 135. *Edited by* J.F. Dewey, R.E. Holdsworth, and R.A. Strachan. pp. 1–14.

Donohoe, H.V., and Wallace, P.I. 1982. Geological map of the Cobequid Highlands, Nova Scotia. Nova Scotia Department of Mines and Energy Map, 82-09, scale 1:50,000. 82-09.

Durling, P., Harvey, P., and Howells, K. 1995a. Geophysical evidence for thrust faulting in the Carboniferous Antigonish-Mabou Subbasin, Nova Scotia. Atlantic Geology, **31**: 183–196.

Durling, P., Howells, K., and Harvey, P. 1995b. The near-surface geology of St. Georges Bay, Nova Scotia: implications for the Hollow Fault. Canadian Journal of Earth Sciences, **32**: 603–613.

Fossen, H., Tikoff, B., and Teyssier, C.T. 1994. Strain modelling of transpressional and transtensional deformation. Norsk Geologisk Tidsskrift, **74**: 134–145.

Gibling, M.R., Culshaw, N., Pascucci, V., Waldron, J.W.F., and Rygel, M.C. 2019. Chapter 6 - The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction During the Paleozoic Assembly of Pangea. *In* The Sedimentary Basins of the United States and Canada, 2nd edition. Elsevier. pp. 267–314.

Giles, P.S. 1981. Major Transgressive-Regressive Cycles in Middle to Late Visean Rocks of Nova Scotia. Nova Scotia Department of Mines and Energy Branch, Paper 81-2.

Giles, P.S. 2003. Stratigraphy and structure of the Malagawatch salt deposit - Windsor Group, central Cape Breton Island, Nova Scotia. Geological Survey of Canada, Open File, 1531.

Giles, P.S. 2009. Orbital forcing and Mississippian sea level change: time series analysis of marine flooding events in the Viséan Windsor Group of eastern Canada and implications for Gondwana glaciation. Bulletin of Canadian Petroleum Geology, **57**: 449–470.

Giles, P.S., and Boehner, R.C. 1982a. Geological Map of the Shubenacadie and Musquodoboit Basins, central Nova Scotia. Nova Scotia Department of Mines and Energy, Map, scale 1:50 000.

Giles, P.S., and Boehner, R.C. 1982b. Subdivision and regional correlation of strata of the Upper WIndsor Group, Cape Breton Island and Central Nova Scotia. *In* Mineral Resources Division, Report of Activities 1981, Nova Scotia Department of Mines and Energy, Report 82-1. pp. 69–78.

Giles, P.S., Hein, F.J., and Allen, T.L. 1997. Bedrock geology of Port Hood-Lake Ainslie (11K04, 11K03, 11F13), Cape Breton Island, Nova Scotia. scale 1:50 000. Geological Survey of Canada Open File 3253.

Giles, P.S., and Lynch, G. 1994. Stratigraphic omission across the Ainslie Detachment in east-central Nova Scotia. *In* Eastern Canada and National and General Programs, Geological Survey of Canada Current Research. pp. 89–94.

Hibbard, J., and Waldron, J.W.F. 2009. Truncation and translation of Appalachian promontories: Mid-Paleozoic strike-slip tectonics and basin initiation. Geology, **37**: 487–490. doi:10.1130/G25614A.1.

Hudec, M.R., Jackson, M.P.A., and Schultz-Ela, D.D. 2009. The paradox of minibasin subsidence into salt: Clues to the evolution of crustal basins. Geological Society of America Bulletin, **121**: 201–221.

Jackson, C.A.-L., Rodriguez, C.R., Rotevatn, A., and Bell, R.E. 2014. Geological and geophysical expression of a primary salt weld: An example from the Santos Basin, Brazil. Interpretation, **2**: SM77–SM89. doi:10.1190/INT-2014-0066.1.

Jackson, M.P.A., and Hudec, M.R. 2017. Salt Tectonics. Cambridge University Press.

Johnston, S.K. 1999. Structural Geology of the Horton and Windsor Groups, Cheverie, Nova Scotia. B.Sc. Honours Thesis, Saint Mary's University, Halifax, Nova Scotia.

Jutras, P., MacRae, R.A., and Utting, J. 2007. Viséan tectonostratigraphy and basin architecture beneath the Pennsylvanian New Brunswick Platform of eastern Canada. Bulletin of Canadian Petroleum Geology, **55**: 217–236.

Keppie, J.D. 1982. Tectonic Map of the Province of Nova Scotia [1:500 000] [with Lineament Map Insert 1:1 000 000]. Nova Scotia Department of Mines and Energy Map, ME 1982-011.

Keppie, J.D. 2000. Geological Map of the Province of Nova Scotia. Nova Scotia Department of Natural Resources, Map, ME 2000-1, scale 1:500 000.

Kontak, D., Ansdell, K., and Douglas, A. 2000. Zn-Pb mineralization associated with a mafic dyke at Cheverie, Hants County, Nova Scotia: implications for Carboniferous metallogeny. Atlantic Geology, **36**: 7–26.

Lavoie, D., and Sangster, A.L. 1995. Origins and timing of basal Windsor carbonate breccias, Nova Scotia. *In* Current Research, Geological Survey of Canada Paper. pp. 79–88.

Lavoie, D., Sangster, D.F., Savard, M.M., and Fallara, F. 1995. Multiple Breccia Events in the lower part of the Carboniferous Windsor Group, Nova Scotia. Atlantic Geology, **31**: 197–207.

Lynch, G., and Giles, P.S. 1995. The Ainslie Detachment: a regional flat-lying extensional fault in the Carboniferous evaporitic Maritimes Basin of Nova Scotia. Canadian Journal of Earth Sciences, **33**: 169–181.

Lynch, G., Keller, J.V.A., and Giles, P.S. 1998. Influence of the Ainslie Detachment on the stratigraphy of the Maritimes Basin and mineralization in the Windsor Group of Northern Nova Scotia, Canada. Economic Geology, **93**: 703–718.

Martel, A.T. 1987. Seismic stratigraphy and hydrocarbon potential of the strike-slip Sackville Sub-basin, New Brunswick. *In* Sedimentary basins and basin-forming mechanisms, Atlantic Geoscience Society Special Publication, 5. *Edited by* C. Beaumont and A.J. Tankard. Atlantic Geoscience Society, Halifax. pp. 319–334.

Martel, A.T., and Gibling, M.R. 1993. Clastic dykes of the Devono-Carboniferous Horton Bluff Formation, Nova Scotia: storm-related structures in shallow lakes. Sedimentary Geology, **87**: 103–119.

McCutcheon, S.R., and Robinson, P.T. 1987. Geological constraints on the genesis of the Maritimes Basin, Atlantic Canada. *In* Sedimentary Basins and Basin-Forming Mechanism, Canadian Society of Petroleum Geologists, Memoir, 12. *Edited by* C. Beaumont and A.J. Tankard. pp. 287–297.

Moore, R.G., and Ferguson, S.A. 1986. Geological map of the Windsor area, Nova Scotia [NTS 21A16 north and 21H01 south]. Nova Scotia Department of Natural Resources, Mineral Resources Branch, Map, ME 1986-2.

Moore, R.G., Ferguson, S.A., Boehner, R.C., and Kennedy, C.M. 2000. Preliminary Geological Map of the Wolfville/Windsor Area, Hants and Kings Counties, Nova Scotia [21H/01 and parts of 21A/16C and D]. Nova Scotia Department of Natural Resources, Open File Map, ME 2000-3.

Murphy, J.B., Waldron, J.W.F., Kontak, D., Pe-Piper, G., and Piper, D.J.W. 2011. Minas Fault Zone: Late Paleozoic history of an intra-continental orogenic transform fault in the Canadian Appalachians. Journal of Structural Geology, **33**: 312–328.

Nance, R.D. 1987. Dextral transpression and late Carboniferous sedimentation in the Fundy coastal zone of southern New Brunswick. *In* Sedimentary Basins and Basin-Forming Mechanisms, Canadian Society of Petroleum Geologists, Memoir. *Edited by* C. Beaumont and A.J. Tankard. pp. 363–377.

Pe-Piper, G., Piper, D.J.W., McFarlane, C.R.M., Sangster, C., Zhang, Y., and Boucher, B. 2018. Petrology, chronology and sequence of vein systems: Systematic magmatic and hydrothermal history of a major intracontinental shear zone, Canadian Appalachians. Lithos, **304–307**: 298–310. doi:10.1016/j.lithos.2018.02.016.

Pe-Piper, G., Piper, D.J.W., and Nagle, J. 2019. Scapolite and analcime: Monitors of magmatic fluid metasomatism in a major shear zone. Chemical Geology, **522**: 208–222. doi:10.1016/j.chemgeo.2019.05.014.

Plint, A.G., and Van de Poll, H.W. 1984. Structural and sedimentary history of the Quaco Head area, southern New Brunswick. Canadian Journal of Earth Sciences, **21**: 753–761.

Reynolds, L.A., Barr, S.M., White, C.E., and Ténière, P.J. 2004. 40Ar/39Ar dating in the Lochaber–Mulgrave area, northern mainland Nova Scotia: implications for timing of regional metamorphism and sediment provenance in the Late Devonian – Early Carboniferous Horton Group. Canadian Journal of Earth Sciences, **41**: 987–996.

Rouby, D., Raillard, S., Guillocheau, F., Bouroullec, R., and Nalpas, T. 2002. Kinematics of a growth fault/raft system on the West African margin using 3-D restoration. Journal of Structural Geology, **24**: 783–796. doi:10.1016/S0191-8141(01)00108-0.

Ryan, R.J., Boehner, R.C., and Calder, J.H. 1991. Lithostratigraphic revision of the Upper Carboniferous to Lower Permian strata in the Cumberland Basin, Nova Scotia and the regional implications for the Maritimes Basin in Atlantic Canada. Bulletin of Canadian Petroleum Geology, **39**: 289–314.

Ryan, R.J., Boehner, R.C., and Deal, A.J. 1990. Cumberland Basin geology map, Oxford and Pugwash, Cumberland County, Nova Scotia [11E12 and 11E13]. Nova Scotia Department of Natural Resources, Mines and Energy Branch, Map, 1990-13, scale 1:50,000.

Rygel, M.C., and Shipley, B.C. 2005. “Such a section as never was put together before”: Logan, Dawson, Lyell, and mid-Nineteenth-Century measurements of the Pennsylvanian Joggins section of Nova Scotia. Atlantic Geology, **41**: 87–102.

Sanderson, D.J., and Marchini, W.R.D. 1984. Transpression. Journal of Structural Geology, **6**: 449–458.

Schenk, P.E. 1967. The Macumber Formation of the Maritime Provinces, Canada - A Mississippian Analogue to Recent Strand-Line Carbonates of the Persian Gulf. Journal of Sedimentary Research, **37**.

Schenk, P.E., Von Bitter, P.H., and Matsumoto, R. 1994. Deep-basin/deep-water carbonate-evaporite deposition of a saline giant; Loch Macumber (Visean), Atlantic Canada. Carbonates and Evaporites, **9**: 187–210.

Snyder, M.E., and Waldron, J.W.F. 2016. Unusual soft-sediment deformation structures in the Maritimes Basin, Canada: Possible seismic origin. Sedimentary Geology, **344**: 145–159.

Snyder, M.E., and Waldron, J.W.F. 2021. Deformation of soft sediments and evaporites in a tectonically active basin: Bay St. George sub-basin, Newfoundland, Canada. Atlantic Geology, **57**: 275–304. doi:10.4138/atlgeol.2021.013.

St. Peter, C.J., and Johnson, S.C. 2009. Stratigraphy and structural history of the late Paleozoic Maritimes Basin in southeastern New Brunswick, Canada. New Brunswick Department of Natural Resources, Memoir, 3.

Thomas, A.K. 2019. Primary and Secondary Salt Welds in the Late Paleozoic Antigonish Sub-basin of Nova Scotia. M.Sc. thesis, University of Alberta, Edmonton, AB, Canada.

Thomas, W.A. 1977. Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin. American Journal of Science, **277**: 1233–1278.

Vendeville, B.C., and Jackson, M.P.A. 1992a. The fall of diapirs during thin-skinned extension. Marine and Petroleum Geology, **9**: 354–371.

Vendeville, B.C., and Jackson, M.P.A. 1992b. The rise of diapirs during thin-skinned extension. Marine and Petroleum Geology, **9**: 331–353.

Von Bitter, P.H., Scott, S.D., and Schenk, P.E. 1992. Chemosynthesis; an alternate hypothesis for Carboniferous biotas in bryozoan/microbial mounds, Newfoundland. Palaios, **7**: 466–484.

Waldron, J.W.F. 2004. Anatomy and evolution of a pull-apart basin, Stellarton, Nova Scotia. Geological Society of America Bulletin, **116**: 109–127.

Waldron, J.W.F., Barr, S.M., Park, A.F., White, C.E., and Hibbard, J.P. 2015. Late Paleozoic strike-slip faults in Maritime Canada and their role in the reconfiguration of the northern Appalachian orogen. Tectonics, **34**: 1661–1684. doi:10.1002/2015TC003882.

Waldron, J.W.F., Giles, P.S., and Thomas, A.K. 2017. Correlation chart for late Devonian to Permian stratified rocks of the Maritimes Basin, Atlantic Canada. *In* Nova Scotia Department of Energy and Mines Open File. Available from https://energy.novascotia.ca/sites/default/files/files/NSDOE%20Open%20 File%20Report%202017-02%20-%20Supporting%20Notes(2).pdf.

Waldron, J.W.F., Roselli, C., and Johnston, S.K. 2007. Transpressional structures on a Late Paleozoic intracontinental transform fault, Canadian Appalachians. *In* Tectonics of Strike-Slip Restraining and Releasing Bends in Continental and Oceanic Settings, Geological Society of London Special Publication. *Edited by* W.D. Cunningham and P. Mann. pp. 367–385.

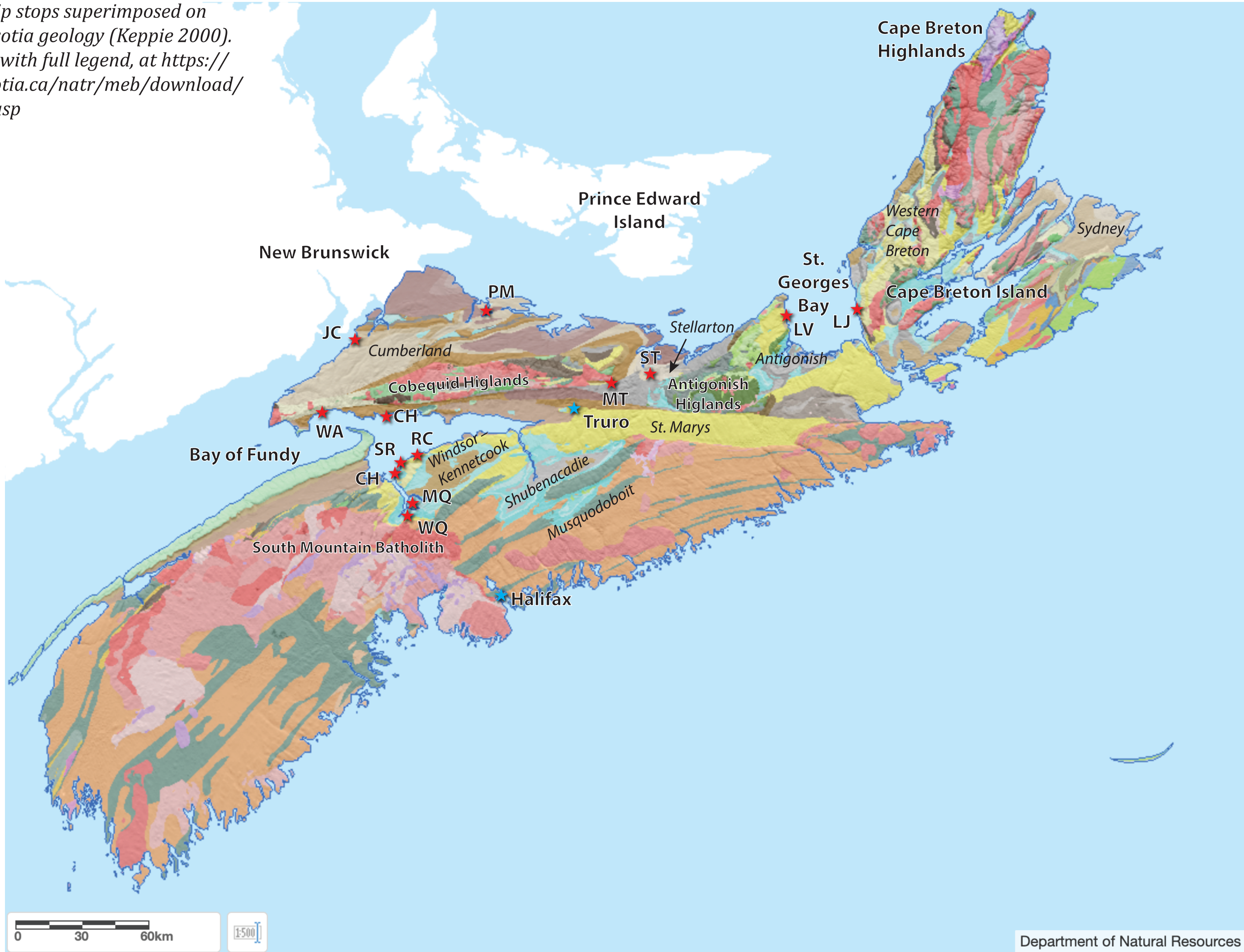
Waldron, J.W.F., Roselli, C.G., Utting, J., and Johnston, S.K. 2010. Kennetcook thrust system: Late Paleozoic transpression near the southern margin of the Maritimes Basin, Nova Scotia. Canadian Journal of Earth Sciences, **47**: 137–159.

Waldron, J.W.F., and Rygel, M.C. 2005. Role of evaporite withdrawal in the preservation of a unique coal-bearing succession: Pennsylvanian Joggins Formation, Nova Scotia. Geology, **33**: 337–340.

Waldron, J.W.F., Rygel, M.C., Gibling, M.R., and Calder, J.H. 2013. Evaporite tectonics and the late Paleozoic stratigraphic development of the Cumberland basin, Appalachians of Atlantic Canada. Geological Society of America Bulletin, **125**: 945–960. doi:10.1130/B30718.1.

Waldron, J.W.F., White, J.C., MacInnes, E., and Roselli, C.G. 2005. Field Trip B7: Transpression and transtension along a continental transform fault: Minas Fault Zone, Nova Scotia. Geological Association of Canada, Mineralogical Associatoin of Canada, Canadian Society of Petroleum Geologists and Canadian Society of Soil Sciences Annual Meeting Field Guides. Atlantic Geoscience Society, Halifax, N.S.

Yeo, G.M., and Gao, R.-. X. 1987. Stellarton graben: an upper Carboniferous pull-apart basin in northern Nova Scotia. *In* Sedimentary basins and basin-forming mechanisms, Canadian Society of Petroleum Geologists Memoir, 12. *Edited by* C. Beaumont and A.J. Tankard. pp. 299–309.



Field trip stops superimposed on Nova Scotia geology (Keppie 2000). Source, with full legend, at https://novascotia.ca/natr/meb/download/dp043.asp

Simplified stratigraphic table for the Maritimes Basin.