Primary and Secondary Salt Welds in the Late Paleozoic Antigonish Sub-basin of Nova Scotia

by

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Abstract

The Antigonish sub-basin in the late Paleozoic Maritimes Basin stretches from the Nova Scotian Antigonish Highlands into western Cape Breton Island, Canada. The sub-basin is structural in origin and is bounded by faults that developed late in the history of the Appalachian orogen. The Late Devonian to Pennsylvanian basin-fill consists primarily of clastic sedimentary rocks with the exception of a marine succession of carbonates and evaporites, the Viséan Windsor Group. The evaporites include the halite-dominated Hartshorn Formation of the Lower Windsor Group and a Middle Windsor Salt unit (MWS) first identified by this study. Previous work located a discordant surface within the Hartshorn Formation that extends through much of the sub-basin. The surface was initially named the Antigonish Thrust, and then reinterpreted as a low-angle extensional fault, the Ainslie Detachment. The presence of salt walls in St Georges Bay and several onshore salt diapir exposures suggests that this surface is a primary salt weld, marking the expulsion of the Hartshorn Formation salt.

A combination of core, outcrop, remotely piloted aircraft photography, 3D modelling and seismic data was used to examine the sub-basin. Salt movement in the Hartshorn Formation began in the Viséan during Middle Windsor Group deposition, causing lateral thickness variations in the Middle Windsor Group. Poorly preserved salt diapirs are present around the margins of the Antigonish sub-basin and these prevented the local deposition of the Middle and Upper Windsor Group. A coastal section of outcrop at Lakevale on Cape George is interpreted to expose a primary salt weld.

Local salt expulsion from the Middle Windsor Salt began in the late Viséan during the deposition of the Hood Island Formation of the Upper Windsor Group. However, the majority of Middle Windsor Salt movement occurred later in the depositional history of the sub-basin after the deposition of Bashkirian strata (Mabou Group) that overlie the Windsor

Group. Several structures in the sub-basin that were previously mapped as faults are re-interpreted by this study as surficial expressions of MWS diapirs.

At Little Judique Harbour on Cape Breton Island, steeply dipping strata of different ages have opposing younging directions juxtaposed across a breccia zone that represents a secondary salt weld. This weld originated as a previously unrecognized salt wall with the same orientation as the offshore salt walls in St Georges Bay identified by earlier work. Lateral variations in salt expulsion rates or different initial salt thicknesses are possible reasons for the juxtaposition of strata from different units across the secondary weld.

The Antigonish sub-basin contains exposures of both primary and secondary salt welds. Salt movement has shaped the basin-fill and created numerous salt structures. The results of this thesis and other work on evaporites in the nearby Cumberland sub-basin suggest that future geological studies of the Maritimes Basin need to consider the potential impact of regional salt movement.

Preface

Chapter 1 gives an introduction to the thesis and the main objectives of this study.

Chapter 2 of this thesis was written with the intent to publish as a paper coauthored with J.W.F. Waldron in a structural geology journal. I collected the data with the aid of J.W.F. Waldron and field assistant M. Duvall. I analyzed the data with the guidance of J.W.F. Waldron and some assistance with Petrel from M. Duvall. I wrote the manuscript with edits and suggestions from J.W.F. Waldron.

Chapter 3 of this manuscript will be submitted to a structural geology journal with the intent to publish as a paper coauthored with J.W.F. Waldron. As in Chapter 2, J.W.F. Waldron and M. Duvall assisted me with data collection. J.W.F. Waldron aided in interpreting the field data. I wrote the manuscript with edits provided by J.W.F. Waldron.

Chapter 4 summarizes conclusions discussed in Chapters 2 and 3 and outlines potential directions for future work.

Acknowledgements

I would like to thank my supervisor John W. F. Waldron for giving me the opportunity to travel to a new province, study some very interesting geology, and sample some wonderful seafood chowder while there. His guidance while completing this thesis was greatly appreciated and I am always amazed by his vast wealth of geologic knowledge. Thanks also go to Michael Duvall for being a great field assistant and for guiding me through learning to use Petrel. I appreciate the support of everyone in the Structural Geology and Tectonics Group at the University of Alberta, and the time taken by my MSc committee members to review this thesis.

I would like to thank Tracy Lenfesty and Janelle Brenton at the Nova Scotia Department of Natural Resources library for helping me find obscure publications and liaising with the Department of Energy to get me some well data. Thanks go to Fraser Keppie for providing the seismic data used in my thesis. Special thanks go to Brendan Murphy at St. Francis Xavier University for taking me around one of my field sites for a preliminary visit and for letting us stay in his house during a subsequent field season. I appreciate the help of Mick O'Neill when visiting the Core Library in Stellarton, Nova Scotia. The University of New Brunswick's thin section lab did a fantastic job making several halite thin sections, and I appreciate Mark Labbe's work on the rest of my thin sections at the Thin Section Laboratory of the University of Alberta. Thank you to Mark Rowan and Katherine Giles for interesting insights and discussions during a salt tectonics field trip in Cape Breton.

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Agisoft PhotoScan was used to construct 3D outcrop models, and seismic interpretation was done in Petrel, a Schlumberger software.

I would like to thank my family, especially my parents, for their support and encouragement while completing my MSc. My houseplants are thanked for not perishing while I was away doing fieldwork and for helping relieve stress.

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Chapter 1. Introduction

This thesis examines salt movement in the Antigonish sub-basin, its impact on the basin-fill, and the resulting structures. This chapter discusses the geological setting, goals, and methods of this thesis. First, a review of the regional setting of the Maritimes Basin provides the information required to understand the purpose and main objectives of this study. An overview of salt tectonics is followed by an introduction to the Antigonish sub-basin, and a summary of the previous work on salt tectonics in this area. Procedures for several study methods are described, and this chapter concludes with a guide to the rest of the thesis.

1.1 The Maritimes Basin

The Maritimes Basin (Figure 1.1) extends through Prince Edward Island and parts of New Brunswick, Nova Scotia, Newfoundland, and the Gulf of St. Lawrence, and contains up to 12 km of upper Paleozoic strata (Gibling et al. 2009). The Late Devonian to Permian strata are primarily sedimentary but include some volcanic units (Waldron et al. 2015). There are numerous smaller depocentres within the Maritimes Basin, which are often referred to as sub-basins (e.g. St. Peter 1993, Hamblin 2001, Murphy 2001, Waldron et al. 2015). These depocentres will also be called sub-basins in this thesis to avoid confusion with the encompassing Maritimes Basin.

Sub-basins within the Maritimes Basin are isolated from each other by uplifts of igneous and metamorphic rock, and trend northeast to east (St. Peter 1993). The ages of the packages of strata, and the ages of the thickest units, vary between the sub-basins (Bradley 1982). The sub-basins and the intervening uplifts are overlain entirely or in part by upper Carboniferous to Permian strata (St. Peter 1993). Multiple structural styles of sub-basins are interpreted as products of a complex tectonic history (Gibling et al. 2009).

A thick salt unit extends across much of the Maritimes Basin (e.g. Waldron et al. 2017, Gibling et al. 2019). However, little is known about salt-related structures within the basin

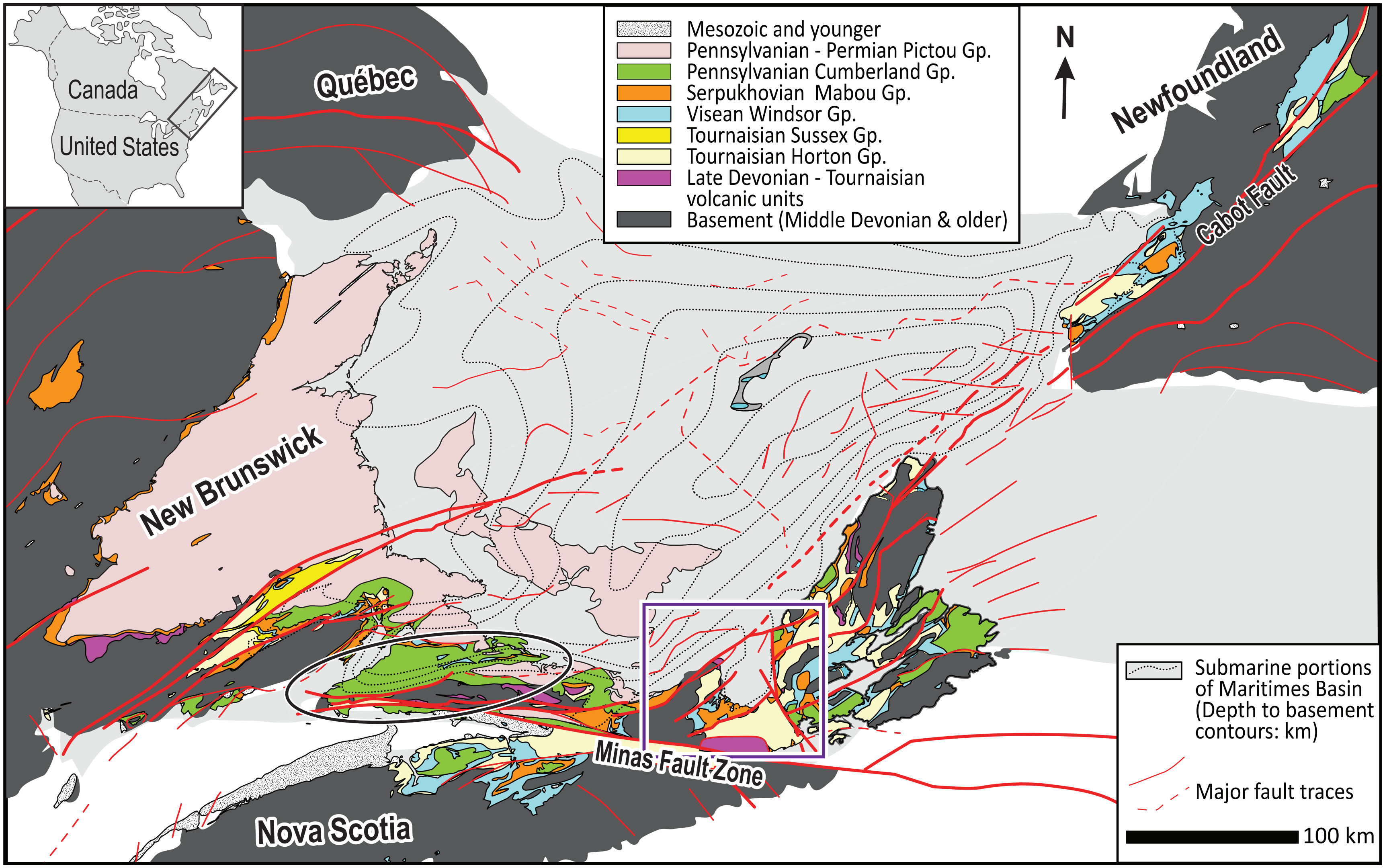


Figure 1.1. Map of the Maritimes Basin

Modified from Snyder (2018). Inset box shows the location of Figure 1.2, a map of the Antigonish sub-basin. The Cumberland sub-basin is circled in black.

(Brown 1998, Alsop et al. 2000) or the impact of syn-depositional salt movement on local sedimentation (Waldron and Rygel 2005, Waldron et al. 2013). Abundant salt diapirs extend beneath the Gulf of St. Lawrence and the Cabot Strait (Boehner 1986, Durling and Marillier 1993, Langdon and Hall 1994, Brown 1998).

1.2 Purpose and objectives of study

Existing regional mapping of the Antigonish sub-basin (Boehner and Giles 1982) minimally considers the potential impacts of salt movement on its morphology and sedimentary history. This study examines the Antigonish sub-basin (Figures 1.1 and 1.2) from a salt tectonics perspective by identifying salt structures within the sub-basin, determining the impact of syn-depositional salt movement, and constraining the timing of salt movement. A key goal is to evaluate the hypothesis that a known omission surface in the sub-basin, previously termed the Antigonish Thrust (Boehner and Giles 1982, 1993) or the Ainslie Detachment (Lynch and Giles 1995), may instead be a primary salt weld.

1.3 Salt tectonics

An overview of salt tectonics concepts and terminology is provided here due to the importance of salt tectonics to this thesis.

Early experiments (Van Tuyl 1930) found that salt deforms plastically without significant fracturing when it is under pressure or exposed to high temperatures. Additionally, salt can act as a fluid over geologic time (Hudec and Jackson 2007 and references therein). It is easier to deform a basin containing salt than a basin that does not (Hudec and Jackson 2007).

A salt layer will flow if it can overcome the resistive strength of the overlying material and the boundary friction at its margins (Hudec and Jackson 2007). Salt withdrawal, or expulsion, is where salt flows out of the layer where it was deposited and forms salt structures (e.g. Fossen 2010)(Figure 1.3). The types of structures depend in part on the

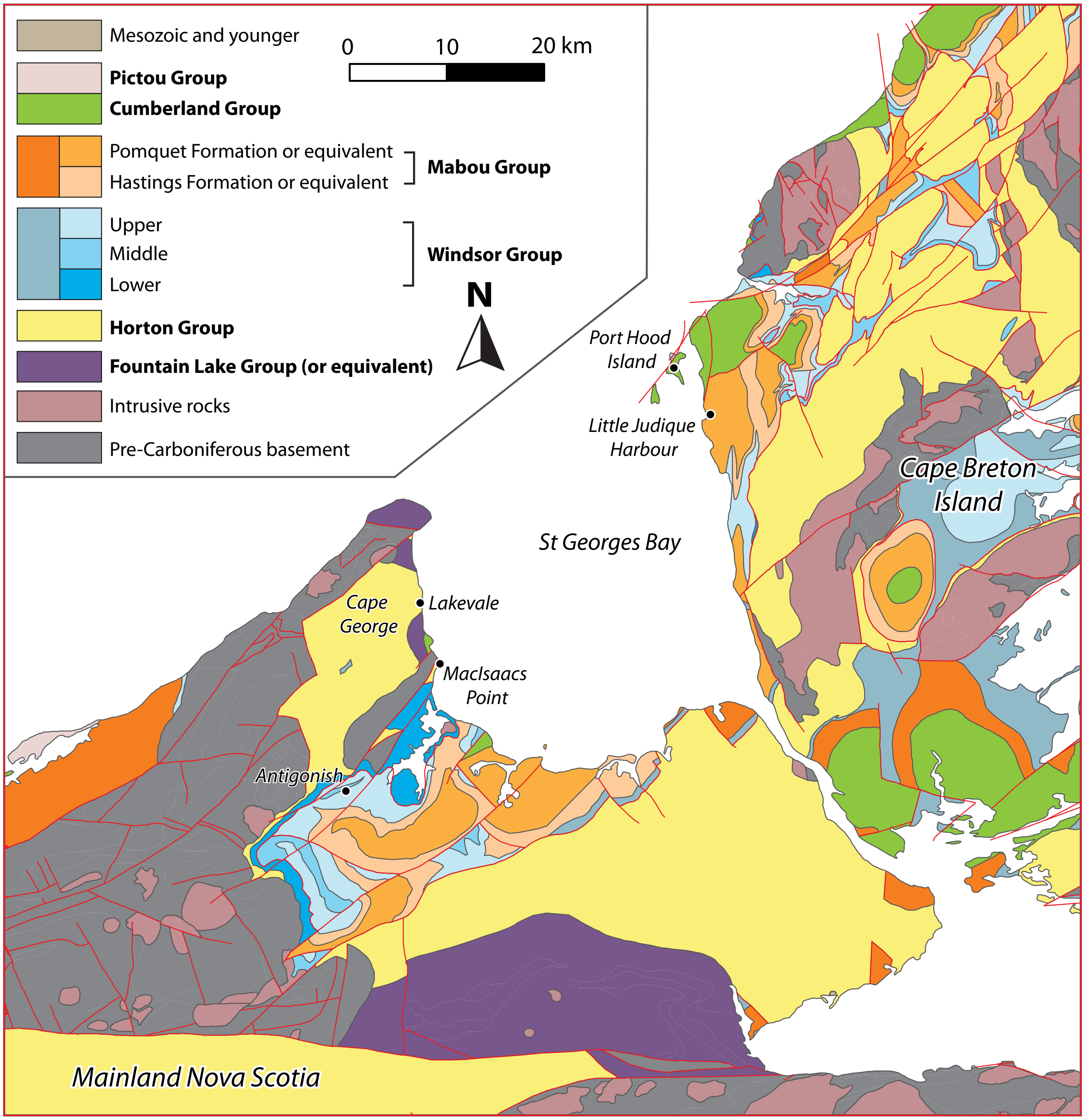


Figure 1.2. Map of the Antigonish sub-basin

Modified from Keppie (2000).

amount of salt present (e.g. Trusheim 1960, Jackson 1995 and references therein, Hudec and Jackson 2007).

1.3.1 Causes of salt movement in the subsurface

The term "diapir" was first used to describe folds with salt cores (Jackson 1995 and references therein). The term has since been expanded to include all evaporite bodies that have flowed upwards from their original location of deposition and have intruded into the overlying strata (e.g. Fossen 2010)(Figure 1.3). Passive diapirism occurs at the same time as sedimentation, while active diapirism occurs after deposition has ceased (Alsop et al. 2000). Buoyancy was initially believed to be the primary cause of diapirism (Jackson 1995), but differential loading is now thought to be the main reason for salt flow (Hudec and Jackson 2007). There are three situations where diapirs may fall instead of rise; if the salt in the source layer becomes depleted, if part of the salt flows into a different portion of the same diapir, or through collapse by dissolution (e.g. Jackson and Hudec 2017).

Three types of differential loading may cause salt flow (Hudec and Jackson 2007). These are gravitational loading, where salt moves in response to hydraulic head gradients; displacement loading, where parts of a salt body move relative to each other; and thermal loading, where heated salt expands and undergoes internal convection (Hudec and Jackson 2007). Differential erosion (Harrison 1927) and differential deposition (Bailey 1931, Rettger 1935) can also cause flow.

1.3.2 Salt structures

Salt pillows, walls and rollers are structures formed by vertical flow. Salt pillows have sub-circular bases and concordant overburden (Trusheim 1960)(Figure 1.3). Salt walls are elongated sub-vertical bodies of diapiric salt (Trusheim 1960, Jackson and Talbot 1991) (Figure 1.3). Salt rollers are asymmetric structures (Figure 1.3). The steep side of a salt

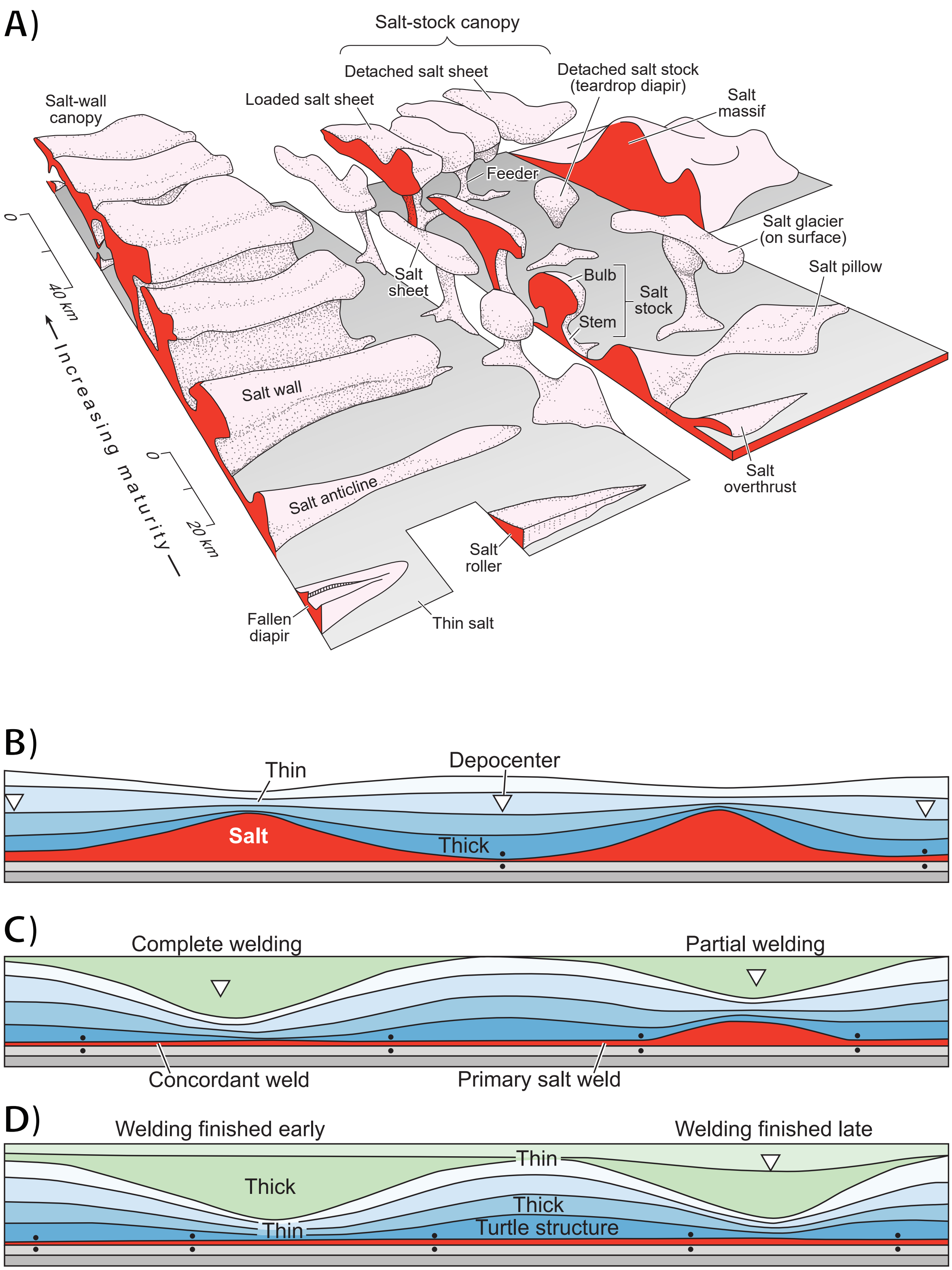


Figure 1.3. Types of salt structures

(A) Diagram of diverse salt structures from Jackson and Hudec (2017). (B-D) Turtle structure development from Jackson and Hudec (2017).

roller is bounded by a normal fault, while the shallow side is concordant with the overlying strata (Jackson and Talbot 1991).

Horizontal flow structures are broad and flat, and include salt sheets, glaciers, and canopies (e.g. Jackson and Talbot 1991, Fossen 2010)(Figure 1.3). A salt sheet is located above its source layer and extends laterally for distances several times its greatest thickness (Hudec and Jackson 2006)(Figure 1.3). The merging of horizontally flowing salt sheets, walls, or diapirs creates a salt canopy (Jackson and Talbot 1991, Hudec and Jackson 2006, 2007). Salt glaciers are considered by Hudec and Jackson (2006) to be "extrusive" salt sheets.

1.3.3 Structures formed by salt expulsion

Salt welds (Figure 1.4) form when rock units that were previously separated by a salt body come into contact after salt expulsion (Jackson 1995 and references therein). Primary salt welds form where autochthonous salt was previously present (Jackson 1995), and are typically sub-horizontal (Rowan et al. 2012). A secondary weld occurs when a diapir with near-vertical sides is expelled (Jackson 1995) (Figure 1.4). The removal of a shallowly dipping salt sheet or salt canopy forms a tertiary weld (Jackson 1995).

Numerical modelling by Wagner and Jackson (2011) demonstrated that salt flow alone is unable to completely remove a salt body. A salt layer ranging in thickness from very thin (<<1m) up to ~50 m thick will be left behind (Wagner and Jackson 2011). Other factors, such as dissolution of the remaining evaporites, need to be involved to make a complete weld with no remnant salt (Cohen and Hardy 1996, Davidson et al. 1996).

1.3.4 Salt movement and accommodation space

Increased amounts of salt withdrawal increase accommodation space. In some cases, this may lead to the formation of salt-withdrawal minibasins (Hudec et al. 2009 and references therein). Minibasins are syntectonic sedimentary basins that settle into thick

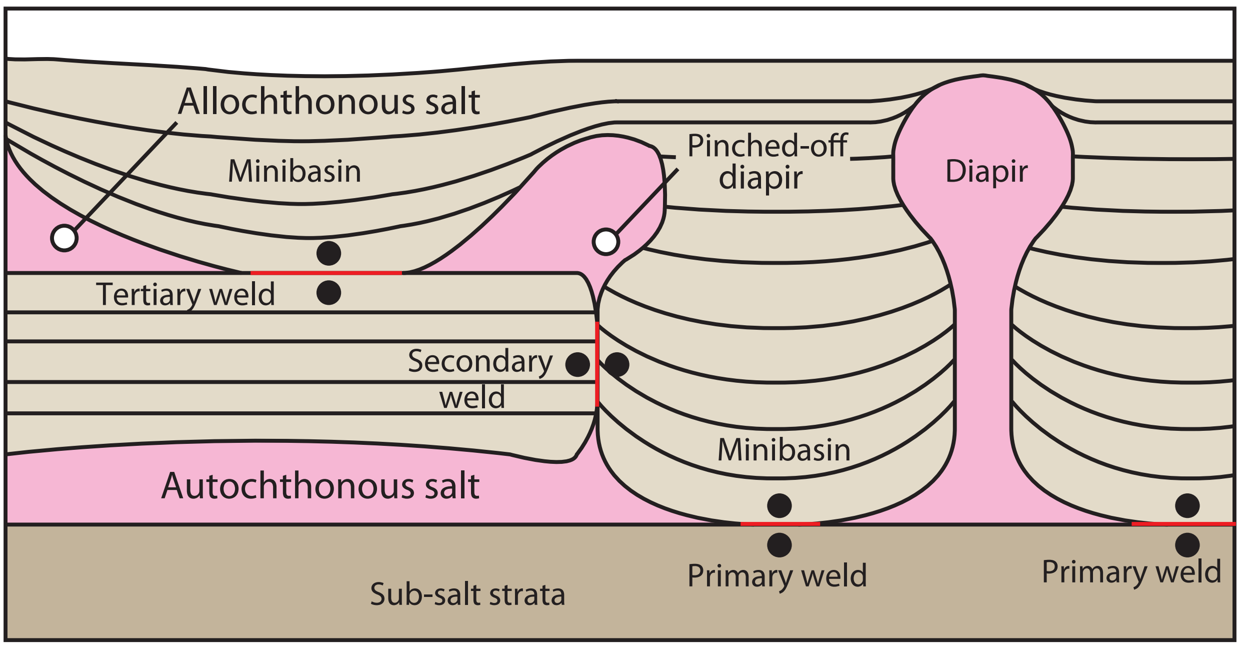


Figure 1.4. Types of salt welds

Primary, secondary and tertiary welds shown in a schematic diagram adapted from Jackson et al. (2014).

bodies of salt (Figure 1.4), and are several tens of kilometres wide and up to 8 km thick (Hudec et al. 2009 and references therein). When the contents of a minibasin become denser than the underlying salt through compaction, the salt is expelled and forms salt walls or bodies around part or all of the minibasin (Hudec et al. 2009). Changes in local diapir shape, for example through shortening, can shift the depocentre of a minibasin (Hudec et al. 2009).

Turtle structures have thick strata at the centre that thin laterally (Jackson and Talbot 1991)(Figure 1.3), and originate as depocentres flanked by salt diapirs. The salt is subsequently expelled, flattening the sides of the sedimentary package and producing a lenticular structure, often with upturned edges (Jackson and Talbot 1991)(Figure 1.3).

Salt flow, the resulting increase in accommodation space, and sedimentation can form a positive feedback loop leading to rapid deposition as the basin-fill becomes progressively denser than the salt. Dense overburden increases rates of salt flow, creating more room for deposition. The increased sedimentation increases the weight of the overburden, further escalating salt expulsion rates. This can lead to sedimentation rates of over 5 km/Myr (Hudec et al. 2009). These rates are higher than those seen in typical basins, where rapid subsidence does not occur because the asthenosphere is significantly denser and more viscous than crustal basin-fill (Hudec et al. 2009). Once a minibasin has subsided enough for its lowest unit to come into contact with the pre-salt strata, forming a primary salt weld, the minibasin becomes inactive and subsidence ceases (Barde et al. 2002).

1.4 Study area - the Antigonish sub-basin

The Carboniferous Antigonish sub-basin of northeastern mainland Nova Scotia and southwestern Cape Breton Island (Figure 1.2) is a structural sub-basin bordered by faults (Boehner and Giles 1993). The area was last mapped in 1982 by Boehner and Giles, who also published an accompanying memoir on the regional geology of the sub-basin (Boehner and Giles 1982, 1993). An angular unconformity separates sub-basin strata from the underlying igneous and metasedimentary basement (Boehner and Giles 1993). The Antigonish sub-basin and strata in southwestern Cape Breton Island and offshore under St Georges Bay have been collectively referred to as the Antigonish-Mabou sub-basin (Barss et al. 1977, Durling et al. 1995a).

Extensive Quaternary cover means that inland outcrops are mainly in streams and road cuts, and the best outcrops are along the coast (Prime 1987). Key coastal outcrops examined in this study are at Lakevale and MacIsaacs Point on Cape George, and at Little Judique Harbour on Cape Breton Island (Figure 1.2). Parts of the Antigonish sub-basin stratigraphy are not exposed and are only known from subsurface studies (Boehner and Giles 1993). Drill core was logged for this thesis to examine salt in the sub-basin. Onshore and offshore regional seismic data are available (e.g. Durling et al. 1995b, Brown 1998) and onshore seismic lines were interpreted to determine the timing of salt movement in the sub-surface.

Antigonish sub-basin strata include a basal, coarse continental siliciclastic succession, the Horton Group, the evaporite-bearing Windsor Group, and the continental siliciclastic Mabou group (Boehner and Giles 1993)(Figure 1.5). Locally these are overlain by continental siliciclastic strata of the Cumberland Group (Boehner and Giles 1993)(Figure 1.5). Boehner and Giles (1993) estimate a maximum basin-fill thickness of 5-6 km and a current maximum sub-basin depth of 3 km. Boehner and Giles (1993) attribute the discrepancy between basin-fill thickness and sub-basin depth to variable unit thicknesses upon deposition and the removal of a section by faulting along a regional omission surface at the top of a salt unit within the Windsor Group that they designated the Antigonish Thrust. This surface is re-interpreted as a detachment surface by Lynch and Giles (1995). Thomas et al. (2002) find evidence for variable directions of extension within the Antigonish sub-basin which converge towards the centre of the sub-basin, making the detachment surface interpretation less likely. In this study we re-examine this regional omission surface as a potential salt expulsion surface.

1.4.1 Group-level stratigraphy

Bell (1929, 1960) assigns the lowest Carboniferous strata of Nova Scotia to the dominantly clastic Horton Group, which is present in both Nova Scotia (e.g. Keppie 2000) and New Brunswick (e.g. New Brunswick Department of Natural Resources and Energy 2000). Equivalent rocks in Newfoundland are known as the Anguille Group (e.g. Waldron et al. 2017)(Figure 1.5). The Horton Group is Devonian to Carboniferous in age (Martel and Gibling 1996) and is composed of sandstone, mudstone and conglomerate (Bell 1960). The Horton Group is interpreted as fluvial and locally lacustrine in origin and was deposited in distal low-relief alluvial flood plains (Boehner and Giles 1993). In the Antigonish sub-basin, the Horton Group has an unconformable lower contact (Bell 1929) and an upper contact that varies between concordant and discordant (Boehner and Giles 1993).

Overlying the Horton Group is the Mississippian Windsor Group, which is present in much of the Maritimes Basin (Gibling et al. 2009), including Nova Scotia, New Brunswick, and Newfoundland, where it is known as the Codroy Group (Figure 1.5). The Windsor Group in the Antigonish sub-basin either lies with angular unconformity on the pre-Carboniferous basement or overlies the Horton Group (Boehner and Giles 1993). It variably comprises marine carbonate beds, which in many cases are fossiliferous, and interstratified mudstone, gypsum, anhydrite, halite and potash (Boehner and Giles 1993). The Windsor Group is interpreted as the only open-marine succession in the Maritimes Basin (Gibling et al. 2009). It contains numerous cycles, in which thin carbonate beds can be correlated throughout a large portion of the Maritimes Basin (Giles 1981). The Windsor Group was deposited during recurring flooding causing cyclic sedimentation of shallow marine to subtidal carbonates, supratidal calcium sulfates, and subaerial redbeds (Schenk 1969). The evaporite deposits are interpreted as having been produced during periods when low clastic sedimentation and a semi-arid climate allowed the precipitation of evaporites from a landlocked sea (Howie 1988).

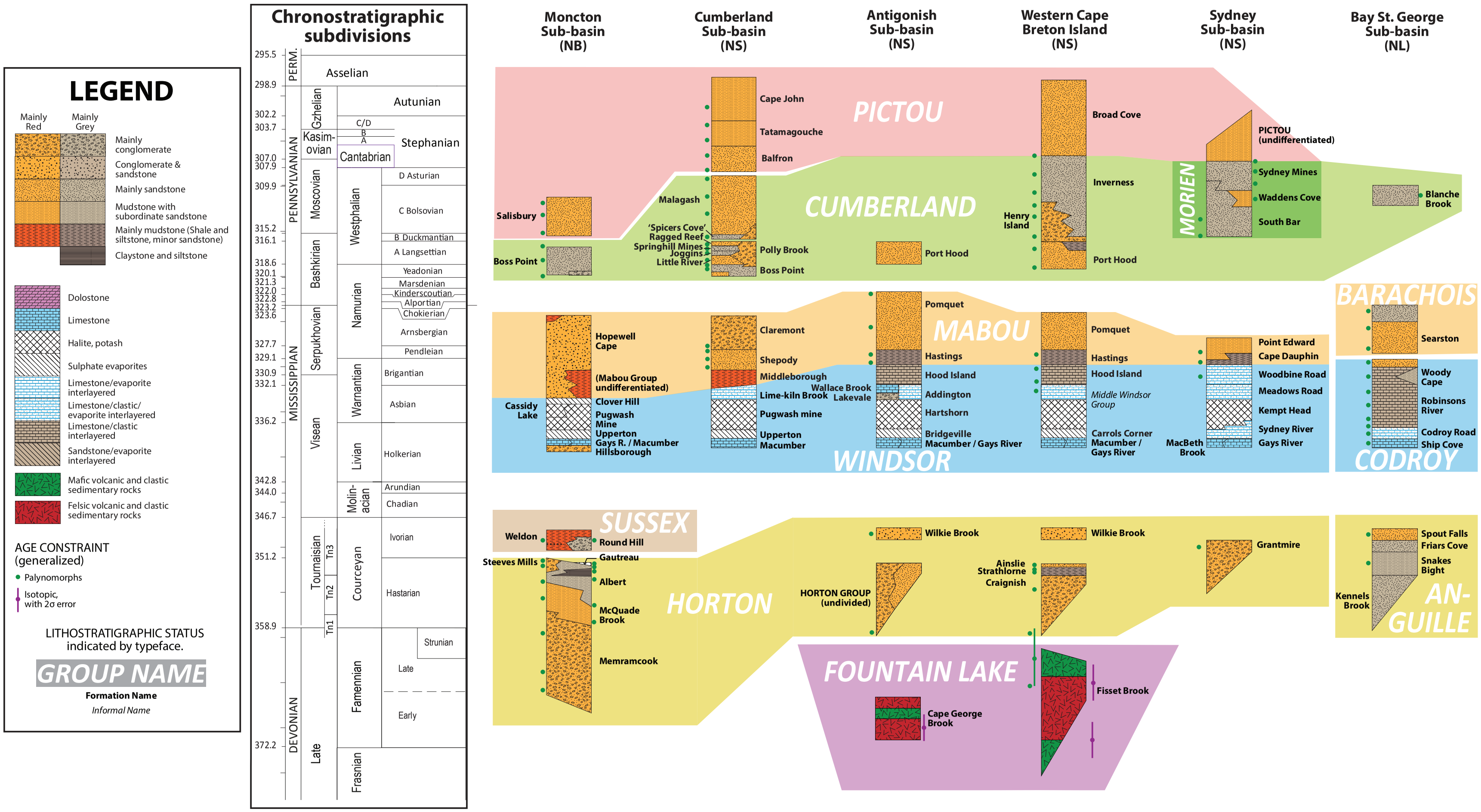


Figure 1.5. Simplified stratigraphic chart for the Maritimes Basin with legend

Modified from Waldron et al. (2017).

The Mabou Group typically conformably overlies the Windsor Group (Boehner and Giles 1993). It contains red and grey sandstone, mudstone, and shale (Belt 1965). The lower deposits of the Mabou Group primarily formed in lacustrine and marginal-lacustrine settings while the upper deposits were produced by subaerial and marginal-lacustrine environments (Hamblin 2001).

Conformably overlying the Mabou Group in the Antigonish sub-basin is the Pennsylvanian Cumberland Group (Boehner and Giles 1993). It is a clastic unit with a very limited extent in the portion of the sub-basin on mainland Nova Scotia (Boehner and Giles 1982). The Cumberland Group is primarily fluvial in origin (Ryan and Boehner 1994, St. Peter and Johnson 2009).

1.5 Previous work on salt movement in and around the Antigonish sub-basin

Brown (1998) and Alsop et al. (2000) examined salt diapirs offshore in St Georges Bay and on the coast of Cape Breton Island (Figure 1.6). They suggest that the diapirs mainly formed during the time between the Westphalian B and the Stephanian, giving the Namurian as the earliest time when the diapirs could have begun rising (Brown 1998, Alsop et al. 2000). The diapirs either formed passively, with the top of the diapir remaining near or at the surface while its base sank, or actively, with the base of the diapir remaining level while its top rose (Alsop et al. 2000).

The Cumberland sub-basin, which lies to the west of the Antigonish sub-basin (Figure 1.1), has been shaped by salt movement (Waldron and Rygel 2005, Waldron et al. 2013). The Cumberland sub-basin had a 2-3 km thick evaporite layer before expulsion began (Waldron et al. 2013). At least 1 km of subsidence in the sub-basin was controlled by salt flow (Waldron and Rygel 2005). Movement of evaporites may have even provided all of the accommodation space for the entire 1.5 km of basin-fill (Waldron and Rygel 2005). Salt expulsion was diachronous across the region and primarily vertical (Waldron et al. 2013).

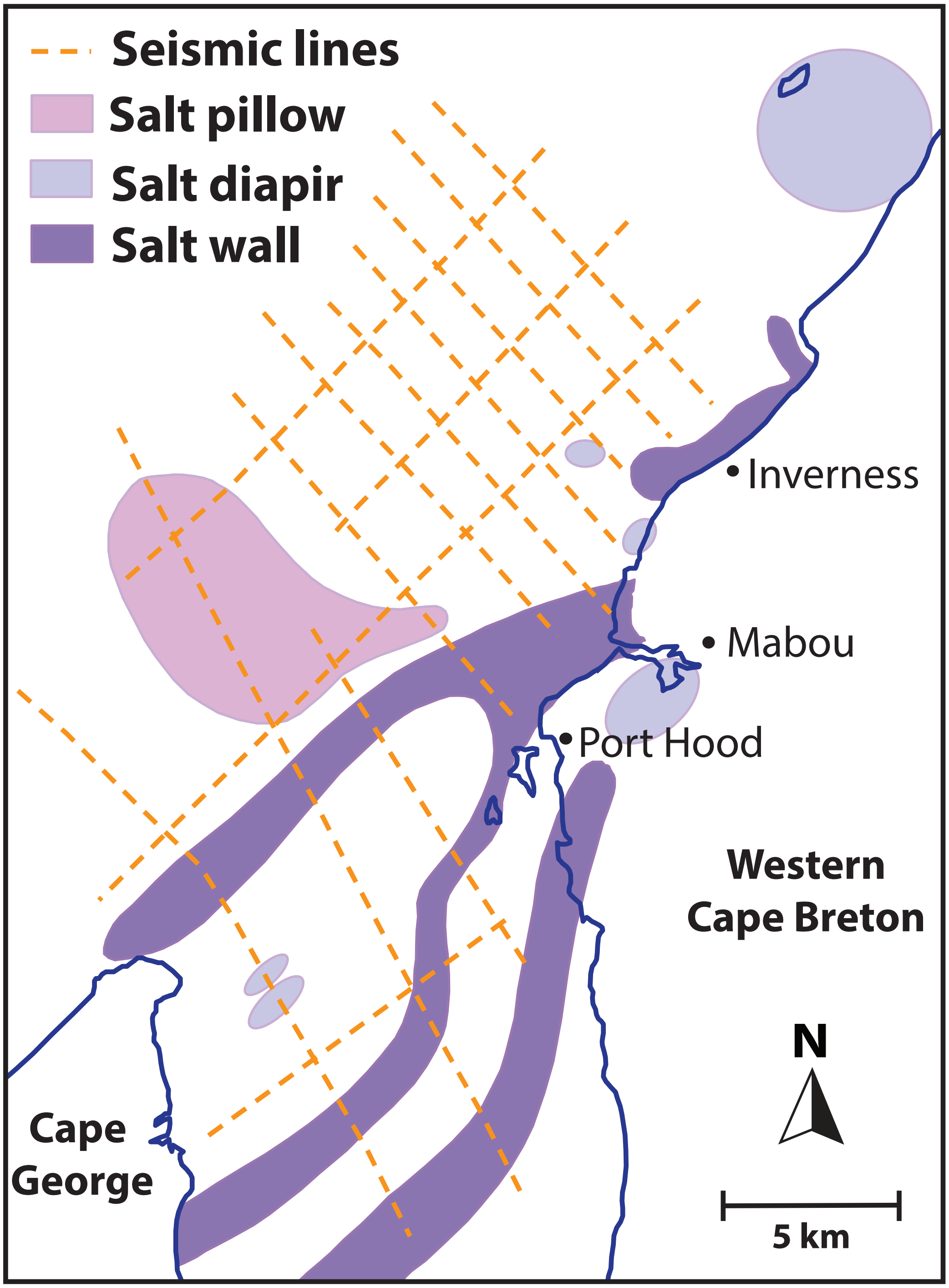


Figure 1.6. Map of interpreted salt walls beneath St Georges Bay

Modified from Brown (1998).

1.6 Methods

A week of fieldwork was completed in Nova Scotia during 2016. Three weeks of fieldwork in the Antigonish sub-basin and one week of core examination at the Nova Scotia Department of Natural Resources Core Library in Stellarton were conducted in 2017. A remotely piloted aircraft system (RPAS) or “drone” was used to photograph key outcrops. Onshore seismic data were interpreted in the seismic interpretation software Petrel.

1.6.1 Drone field methods

Photogrammetrical surveys were conducted with a DJI Inspire 1 Pro drone at coastal cliff outcrops at Lakevale and MacIsaacs Point on Cape George (Figure 1.2), and on the northern and southern ends of Little Judique Harbour on Cape Breton Island (Figure 1.2). Depending on the area of operations, either a 25 m or 50 m tape was laid out to provide a reference scale. The compass bearing of the tape was recorded. Markers were placed at each end of the tape and at other selected locations along the outcrop, and their locations were recorded with a hand-held GPS. A flat smooth section of the beach near the tape was designated as the UAV take-off and landing location. Flights lasted a maximum of 16 minutes due to battery limitations. Traverses with the UAV were completed perpendicular to the cliff, from above it, and at various angles as necessary to obtain full photographical coverage. Several hundred photographs were obtained at each location.

1.6.2 3D Modelling in Agisoft PhotoScan

High-resolution 3D models of the photogrammetrically surveyed outcrops were created using the drone photographs and Agisoft PhotoScan software. After loading the photos into Agisoft PhotoScan, undesired parts of images, such as drone hardware, were manually cropped out of the photos. Marker objects were manually located in the images and tagged in PhotoScan to aid in matching points between photographs during model building.

Once this quality control was completed, model building commenced. Agisoft PhotoScan identified points shared between drone photographs. The program located these points in three-dimensional space to create a sparse point cloud. The attached GPS location information enabled PhotoScan to georeference the sparse point cloud. Quality control was manually done on the sparse point cloud to remove spurious points. Once the sparse point cloud was satisfactory, it was used to generate a dense point cloud in PhotoScan. Undesirable points, such as those floating above the ground, were manually removed from the dense point cloud before PhotoScan generated 3D mesh surfaces from it. Extraneous surface parts were manually selected and deleted in PhotoScan from the 3D mesh surfaces. In the final step for model building, PhotoScan draped a coloured texture layer derived from the UAV photographs over the mesh surfaces to show the lithologies. The resulting models are shown in appendices A, B and E.

The generated 3D model of the outcrop was georeferenced and correctly scaled due to the GPS data embedded within the drone photographs. This allowed the measurement of unit thicknesses directly on the model. Additionally, strike and dip measurements were generated for planar surfaces in the model using a Python code written by Dr. Jeffrey Kavanaugh (University of Alberta, personal communication, October 2018). To gain these measurements, points were picked in PhotoScan along bedding planes on the models. Spatial coordinate information for the points was exported in text files that were then run through the code. The code determined the best-fit plane to the points and generated the strike and dip orientations for this plane in an exported text file.

1.6.3 Seismic reflection interpretation

Time-migrated 2-D seismic reflection data were obtained from the Nova Scotia Department of Energy as pre-stack-migrated SEG-Y files (Appendix D). The onshore data evaluated by this study consist of four lines collected by Northstar Energy Corporation in 2001 and three lines from Contact Exploration in 2002 (Figure 1.7). The seismic lines vary

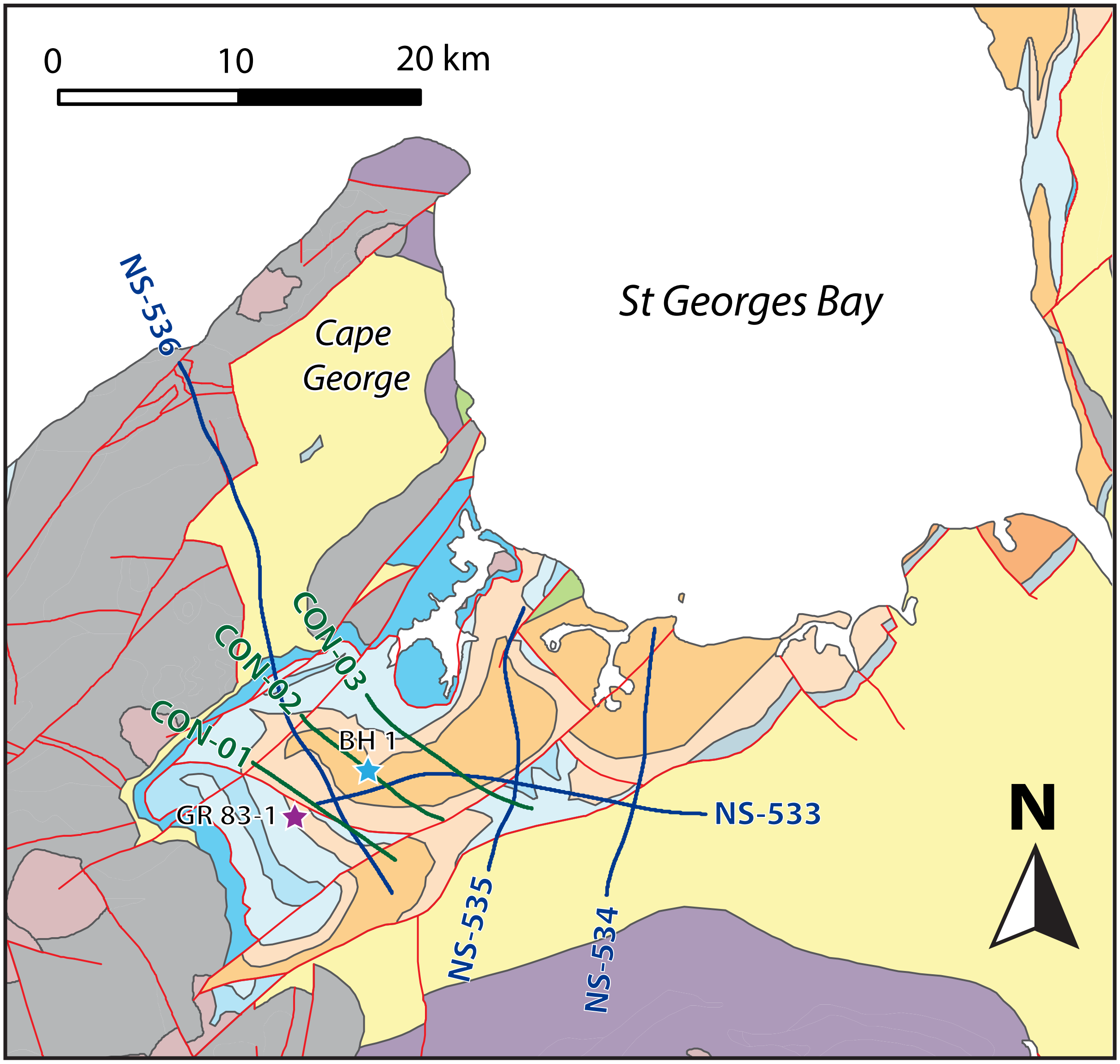


Figure 1.7. Map of Antigonish seismic line and selected drillhole locations

Seismic lines indicated in dark blue are from a 2001 Northstar Energy Corporation survey and teal lines are from a 2002 Contact Exploration survey. Stars indicate drillhole locations. See Figure 1.2 for legend.

from poor to moderate quality. No reprocessing or time-depth conversion was done for this study. The seismic lines were loaded into Petrel and adjusted to match a datum of 400 m above sea level, using the commonly-assumed seismic fill velocity of 4000 m/s.

The well Beech Hill #1 (BH 1)(Figure 1.7), drilled in 2003 by Vintage Petroleum Canada (MacDonald 2003), was tied to the seismic data using a geological report (MacDonald 2003) and sonic and density wireline logs obtained from the Nova Scotia Department of Energy. The well report for BH 1 indicated that well casing was put in to a measured depth (MD) of 487 m; therefore, the sonic and density logs above 487 m (MD) do not reflect the surrounding rock. The top portion of the sonic log was therefore removed so that it began at MD 492 m. A seismic synthetic was generated in Petrel from the density log and clipped sonic log, using a high-frequency Ricker wavelet centred at 40 Hz. The synthetic was tied to a Contact Exploration seismic line. More details on the well tie and seismic interpretation can be found in Chapter 2.

Interpretation of the seismic lines was completed in the time domain using Petrel. Formation tops in BH 1 below the well casing were picked using the well tie. Estimates of depth in time were made for horizons in BH 1 above the casing, using an average seismic velocity of 4000 m/s. These estimated picks were traced to surface and compared with boundaries on local geological maps.

Reflections can only be traced across portions of lines, particularly those within the Middle and Lower Windsor Group, making seismic interpretation challenging. To aid in interpretation, time-depth estimates for horizon tops were made for additional local drillholes (Appendix C) using written drill core logs and an assumed average seismic velocity of 4000 m/s. Tracing reflectors to surface and comparing them with geological maps allowed refinement of the estimated picks.

1.7 Thesis layout

This thesis is presented in paper format. Chapters 2 and 3 are intended for publication. These two papers examine the impact of salt movement on the Antigonish sub-basin and the resulting structures.

Chapter 2 uses outcrop, core, and seismic data to evaluate salt and salt-related structures within the portion of the Antigonish sub-basin on mainland Nova Scotia. A revised history and model for salt movement within the sub-basin is presented. A regional omission surface previously interpreted as the Antigonish Thrust (Boehner and Giles 1982, 1993) or the Ainslie Detachment (Lynch and Giles 1995) is re-interpreted as a primary salt weld.

Chapter 3 covers the region of the Antigonish sub-basin on southwestern Cape Breton Island. Structures present in coastal outcrops are examined and interpreted as representing a secondary salt weld, and the relative timing of salt movement is discussed. Logs of the coastal sections are provided in appendices G and H.

Major conclusions from this thesis are summarized in Chapter 4.

1.8 References

Alsop, G.I., Brown, J.P., Davison, I., and Gibling, M.R. 2000. The geometry of drag zones adjacent to salt diapirs. Journal of the Geological Society of London, **157**: 1019–1029.

Bailey, E.B. 1931. Salt-Plugs. Geological Magazine, **68**: 335–336.

Barde, J.-P., Chamberlain, P., Galavazi, M., Gralla, P., Harwijanto, J., Marsky, J., and van den Belt, F. 2002. Sedimentation during halokinesis: Permo-Triassic reservoirs of the Saigak field, Precaspian basin, Kazakhstan. Petroleum Geoscience, **8**: 177–187.

Barss, M.S., Grant, A.C., Sanford, B.V., and Wade, J.A. 1977. Basement structure, Eastern Canada and adjacent areas. Geological Survey of Canada, Map, scale 1:2 000 000.

Bell, W.A. 1929. Horton-Windsor District, Nova Scotia. Geological Survey of Canada, Memoir, 155.

Bell, W.A. 1960. Mississippian Horton Group of Type Windsor-Horton District Nova Scotia. Geological Survey of Canada Memoir, 314.

Belt, E.S. 1965. Stratigraphy and Paleogeography of Mabou Group and Related Middle Carboniferous Facies, Nova Scotia, Canada. Geological Society of America Bulletin, **76**: 777–802. doi:10.1130/0016-7606(1965)76[777:SAPOMG]2.0.CO;2.

Boehner, R.C. 1986. Salt and Potash Resources in Nova Scotia. Nova Scotia Department of Mines and Energy Bulletin, ME 005.

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.

Boucot, A.J., Dewey, J.F., Dineley, D.L., Fletcher, R., Fyson, W.K., Griffin, J.G., Hickox, C.J., McKerrow, W.S., and Ziegler, A.M. 1974. Geology of the Arisaig area, Antigonish County, Nova Scotia. Geological Society of America Special Paper, 139.

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

Brown, J.P. 1998. Deformation and sedimentation adjacent to Carboniferous diapiric salt structures, Nova Scotia. PhD thesis, Dalhousie University, Halifax, Canada.

Cohen, H.A., and Hardy, S. 1996. Numerical modelling of stratal architectures resulting from differential loading of a mobile substrate. Geological Society, London, Special Publications, **100**: 265–273.

Davidson, I., Alsop, I., and Blundell, D.J. 1996. Salt tectonics: Some aspects of deformation mechanics. Salt Tectonics, Geological Society Special Publication, **100**: 1–10.

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.

Durling, P., and Marillier, F. 1993. Structural elements of the Magdalen Basin, Gulf of St. Lawrence, from seismic reflection data. *In* Current Research, Current Research, Geological Survey of Canada Paper, 93–1D. pp. 147–154.

Fossen, H. 2010. Structural Geology. Cambridge University Press.

Gibling, M.R., Culshaw, N., Pascucci, V., Waldron, J.W.F., and Rygel, M.C. 2019. The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea. *In* The Sedimentary Basins of the United States and Canada, 2nd Edition, The Sedimentary Basins of the United States and Canada. *Edited by* A.D. Miall. pp. 267–314.

Gibling, M.R., Culshaw, N., Rygel, M.C., and Pascucci, V. 2009. The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea. *In* Sedimentary basins of the United States and Canada, Sedimentary basins of the United States and Canada, Sedimentary Basins of the World. *Edited by* A. Miall. pp. 211–244.

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.

Hamblin, A.P. 2001. Stratigraphy, sedimentology, tectonics, and resource potential of the lower Carboniferous Mabou Group, Nova Scotia. Geological Survey of Canada, Bulletin, 568.

Harrison, T.S. 1927. Colorado-Utah salt domes. AAPG Bulletin, **11**: 111–133.

Howie, R.D. 1988. Upper Paleozoic evaporites of southeastern Canada. Geological Survey of Canada Bulletin, 380.

Hudec, M.R., and Jackson, M.P.A. 2006. Advance of allochthonous salt sheets in passive margins and orogens. AAPG Bulletin, **90**: 1535–1564. doi:10.1306/05080605143.

Hudec, M.R., and Jackson, M.P.A. 2007. Terra infirma: Understanding salt tectonics. Earth-Science Reviews, **82**: 1–28. doi:10.1016/j.earscirev.2007.01.001.

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, M.P.A. 1995. Retrospective salt tectonics. *In* Salt tectonics: a global perspective, Salt tectonics: a global perspective, AAPG Memoir. *Edited by* M.P.A. Jackson, D.G. Roberts, and S. Snelson. [accessed 5 December 2016].

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

Jackson, M.P.A., and Talbot, C.J. 1991. A Glossary of Salt Tectonics. The University of Texas at Austin.

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.

Langdon, G.S., and Hall, J. 1994. Devonian-Carboniferous tectonics and basin deformation in the Cabot Strait area, Eastern Canada. AAPG Bulletin, **78**: 1748–1774. doi:10.1306/a25ff283-171b-11d7-8645000102c1865d.

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.

MacDonald, E. 2003. Geological Report on Beech Hill #1, Antigonish Nova Scotia. Vintage Petroleum Canada.

Martel, A.T., and Gibling, M.R. 1996. Stratigraphy and tectonic history of the Upper Devonian to lower Carboniferous Horton Bluff Formation, Nova Scotia. Atlantic Geology, **32**: 13–38.

Murphy, J.B. 2001. Geochemistry, provenance, and tectonic significance of sedimentary rocks of the Middle to Late Devonian McArras Brook and Visean Martin Road formations, Merigomish Subbasin, northern Antigonish Highlands, Nova Scotia. Atlantic Geology, **37**: 161–173.

Murray, B.C. 1955. Stratigraphy of the Horton Group in parts of Nova Scotia. PhD Thesis, Massachusetts Institute of Technology, Cambridge, USA.

New Brunswick Department of Natural Resources and Energy. 2000. Bedrock Geology of New Brunswick. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map, NR-1, scale 1: 500 000.

Prime, G.A. 1987. The Antigonish basin of Maritime Canada: A sedimentary tectonic history of a late Paleozoic fault-wedge basin. MSc thesis, Dalhousie University, Halifax, Canada.

Rettger, R.E. 1935. Experiments on soft-rock deformation. AAPG Bulletin, **19**: 271–292.

Rowan, M.G., Lawton, T.F., and Giles, K.A. 2012. Anatomy of an exposed vertical salt weld and flanking strata, La Popa Basin, Mexico. Geological Society, London, Special Publications, **363**: 33–57. doi:10.1144/SP363.3.

Ryan, R.J., and Boehner, R.C. 1994. Geology of the Cumberland Basin, Cumberland, Colchester and Pictou Counties, Nova Scotia. Nova Scotia Department of Natural Resources Memoir, 10.

Sage, N. 1954. The stratigraphy of the Windsor group in the Antigonish quadrangles and the Mahone Bay-Saint Margaret area, Nova Scotia. Nova Scotia Department of Mines and Energy Branches Memoir, 3.

Schenk, P.E. 1969. Carbonate-sulfate-redbed facies and cyclic sedimentation of the Windsorian Stage (middle Carboniferous), Maritime Provinces. Canadian Journal of Earth Sciences, **6**: 1037–1066.

St. Peter, C.J. 1993. Maritimes Basin evolution: key geologic and seismic evidence from the Moncton Subbasin of New Brunswick. Atlantic Geology, **29**: 233–270.

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, D.B., Nance, R.D., and Murphy, J.B. 2002. Deformation of the Macumber Formation, Antigonish Basin, Nova Scotia: implications for the Ainslie Detachment. Atlantic Geology, **38**: 135–144.

Trusheim, F. 1960. Mechanism of salt migration in northern Germany. AAPG Bulletin, **44**: 1519–1540.

Utting, J., Keppie, J.D., and Giles, P.S. 1989. Palynology and stratigraphy of the lower Carboniferous Horton Group, Nova Scotia. *In* Contributions to Canadian Paleontology, Contributions to Canadian Paleontology, Geological Survey of Canada, Bulletin. pp. 117–144.

Van Tuyl, F.M. 1930. Contribution to salt-dome problem. AAPG Bulletin, **14**: 1041–1047.

Wagner, B.H., and Jackson, M.P.A. 2011. Viscous flow during salt welding. Tectonophysics, **510**: 309–326. doi:10.1016/j.tecto.2011.07.012.

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. Nova Scotia Department of Energy Open File Report, 2017–02.

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.

Williams, E.P. 1974. Geology and petroleum possibilities in and around Gulf of St. Lawrence. AAPG Bulletin, **58**: 1137–1155.

Chapter 2. Primary salt weld revealed: Outcrop and subsurface observations in the late Paleozoic Antigonish sub-basin of Nova Scotia

2.1 Introduction

Salt welds are surfaces where strata that were previously separated by a body of salt have now come into contact after the salt has been removed (Jackson and Talbot 1991). The removal of a salt body required to create a salt weld may have significant impacts on a sedimentary succession, such as increasing accommodation space through the formation of minibasins, creating disconformable contacts, and juxtaposing strata with opposing younging directions (e.g. Waldron and Rygel 2005, Hudec et al. 2009). Welds are typically recognized in seismic data but their identification in core and outcrop has been limited (e.g. Giles and Lawton 1999, Rowan et al. 2012, Jackson et al. 2014).

The Maritimes Basin (Figure 2.1) is a sedimentary basin with an area of ~150 000 km^2 that developed within the Appalachian orogenic belt after the Acadian orogeny (Williams 1974). It extends through Prince Edward Island, New Brunswick, Nova Scotia, Newfoundland and beneath the Gulf of St. Lawrence (Figure 2.1) (e.g. Gibling et al. 2009). The Maritimes Basin contains up to 12 km of upper Paleozoic strata which are predominantly clastic, with the exception of a marine interval containing evaporites and carbonates, known as the Windsor Group in Nova Scotia and the Codroy Group in Newfoundland (Figure 2.2 and 2.3). Within the evaporites are halite-dominated units which in parts of the basin are known to have flowed in the subsurface, creating salt structures and affecting the overlying strata (Brown 1998, Waldron and Rygel 2005).

This study examines the structure and stratigraphy of the Antigonish sub-basin (Figure 2.4) within the Maritimes Basin. During previous mapping of the sub-basin, Boehner and Giles (1993) found major anomalies in the amount of basin-fill compared to the sub-basin depth. They attributed this to a regional omission surface which they named the Antigonish Thrust (Boehner and Giles 1993) (Figures 2.5, 2.6 and 2.7). Lynch and Giles

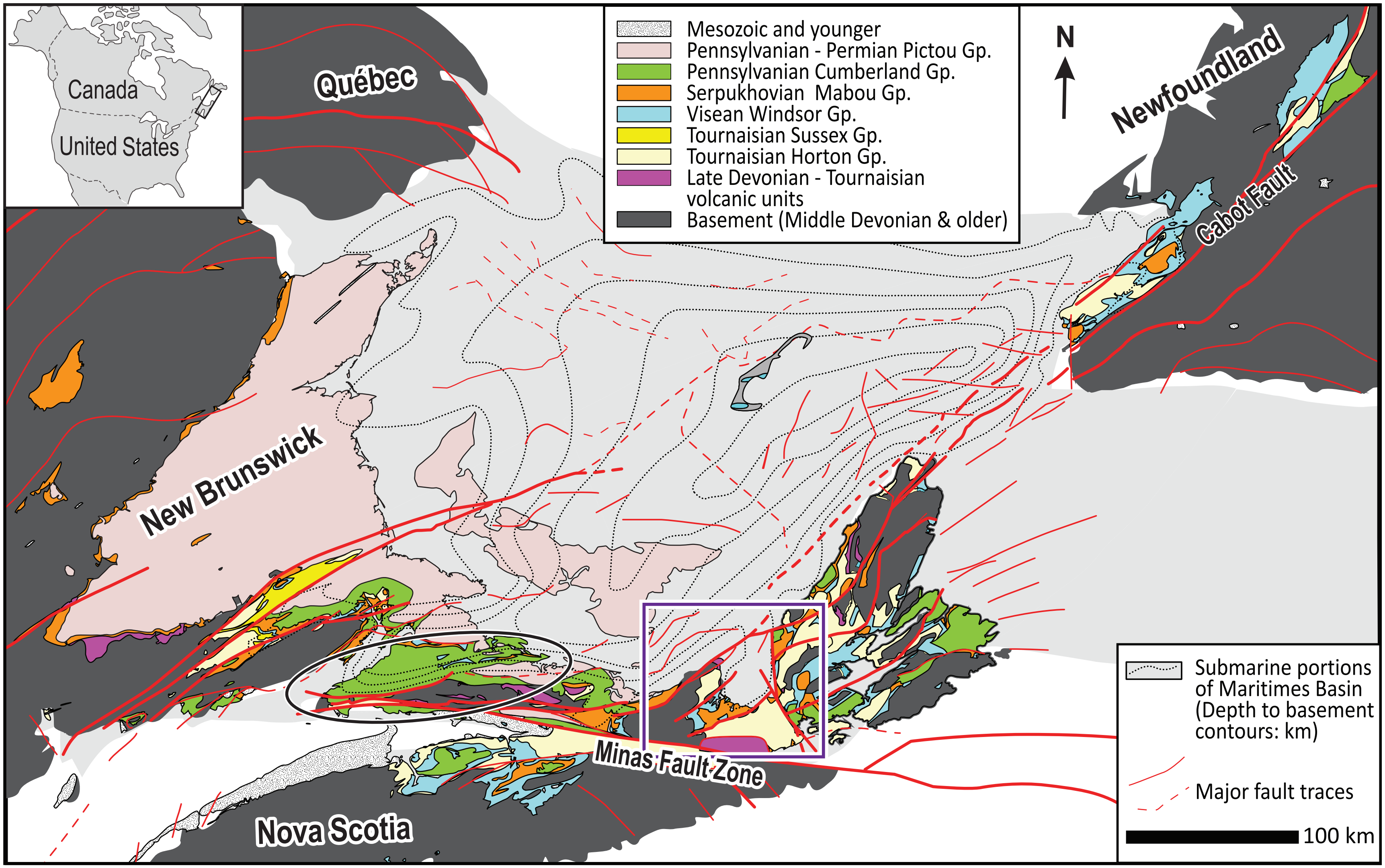


Figure 2.1. Map of the Maritimes Basin

Modified from Snyder (2018). The purple box shows the location of Figure 2.4, a map of the Antigonish sub-basin. The Cumberland sub-basin is circled in black.

(1995) later re-interpreted this surface as an extensional detachment and called it the Ainslie Detachment. In this paper, we examine the hypothesis that this regional omission surface is instead a primary salt weld.

2.2 Maritimes Basin

2.2.1 Structure

Major northeast-trending late Paleozoic faults that parallel the Appalachian Orogen are known to bound and cut through the Maritimes Basin (Figure 2.1) (e.g. Hibbard and Waldron, 2009; Waldron et al., 2015). Dextral strike-slip motion began along these faults in the Late Devonian resulting in up to ~250 km of movement (Hibbard and Waldron 2009). The Maritimes Basin was formed in a releasing step-over between faults in southern New Brunswick and similarly oriented faults in Newfoundland (e.g. Waldron et al. 2015) (Figure 2.1). A series of grabens and half-grabens were formed in which the Horton Group was deposited (e.g. Murphy et al. 2011). Nova Scotia is also cut by E-W strike-slip faults of the Minas Fault Zone (Figure 2.1), which may have originated as extensional faults within the step-over zone (Waldron et al. 2015) but were reactivated in dextral strike-slip during the Mississippian (Murphy et al. 2011).

The Maritimes Basin contains a variety of smaller depocentres historically referred to as sub-basins (e.g. St. Peter 1993, Hamblin 2001, Murphy 2001, Waldron et al. 2015) or basins (e.g. Bell 1944, Belt 1964, Gibling et al. 2009). We refer to them as sub-basins. This paper examines the Antigonish sub-basin (Figure 2.1) in northeastern Nova Scotia. Salt movement and diapirism have occurred in the subsurface beneath St Georges Bay (Figure 2.4) in the sub-basin (Brown 1998), and there are known regional omission surfaces with debated origins (e.g. Boehner and Giles 1993, Giles and Lynch 1994), making the Antigonish sub-basin an ideal study area for examining salt tectonics in the Maritimes Basin.

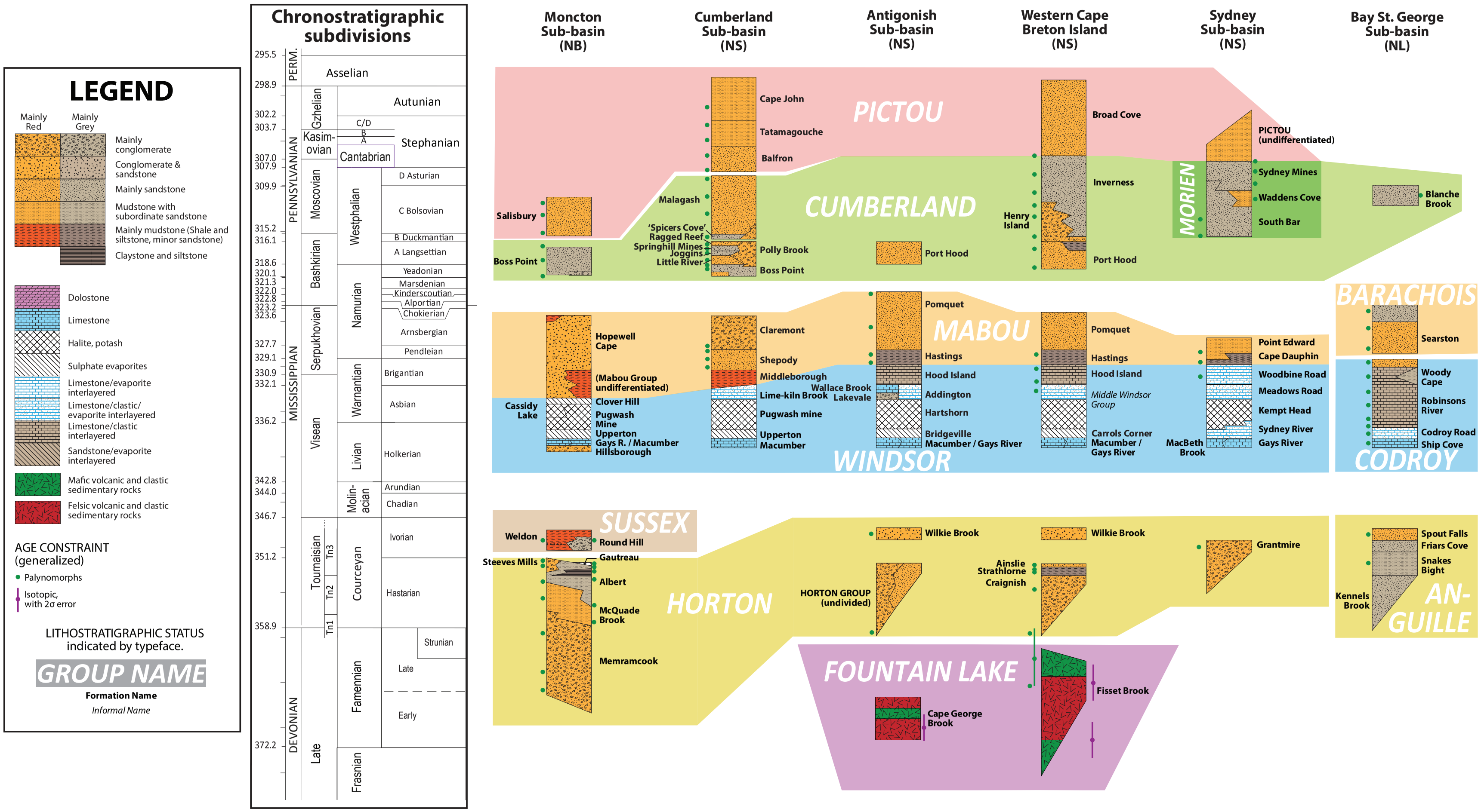


Figure 2.2. Simplified stratigraphic chart for the Maritimes Basin

Modified from Waldron et al. (2017).

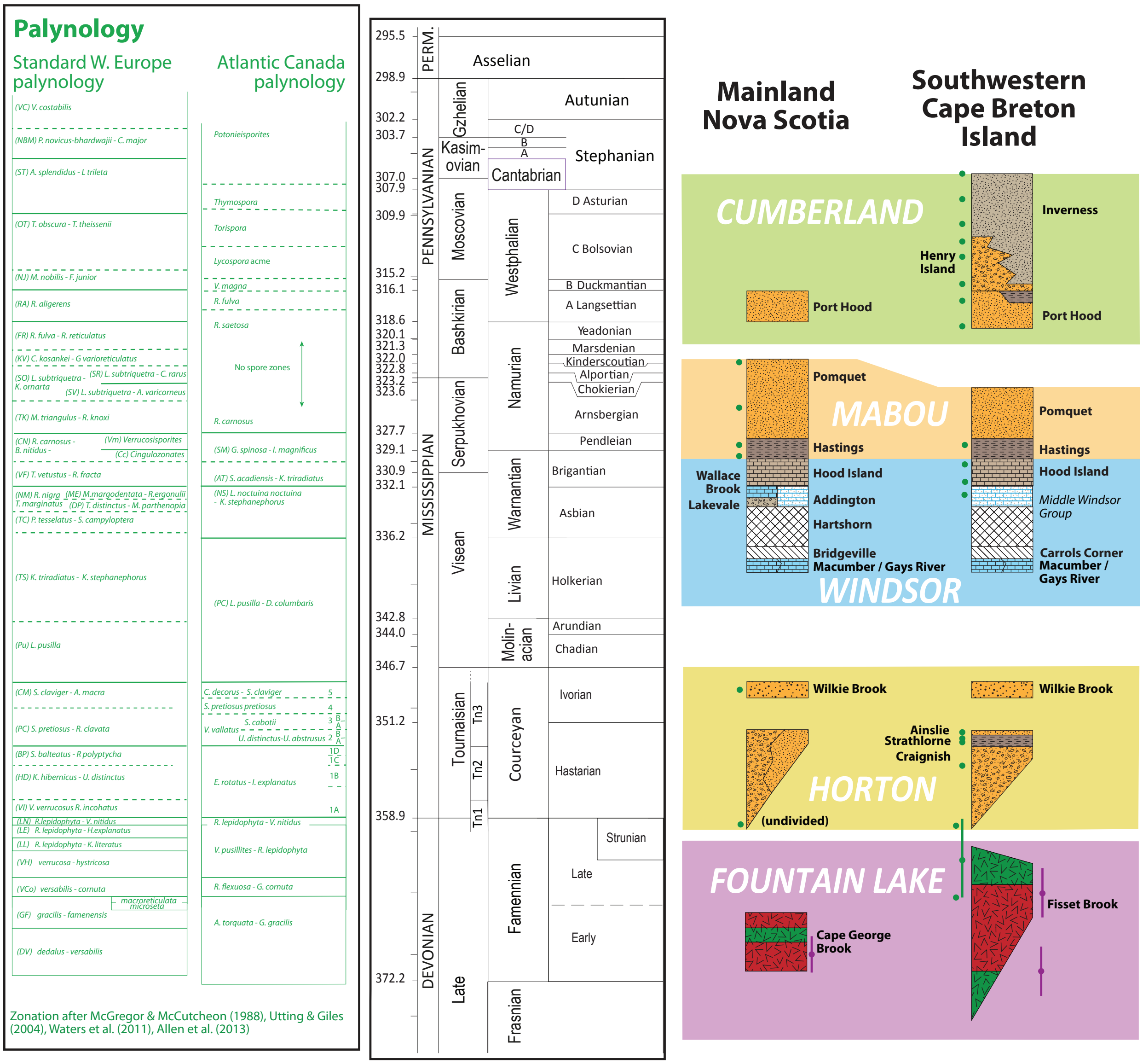


Figure 2.3. Spore zonation for the Antigonish sub-basin

Modified from Waldron et al. (2017). Symbols as Figure 2.2.

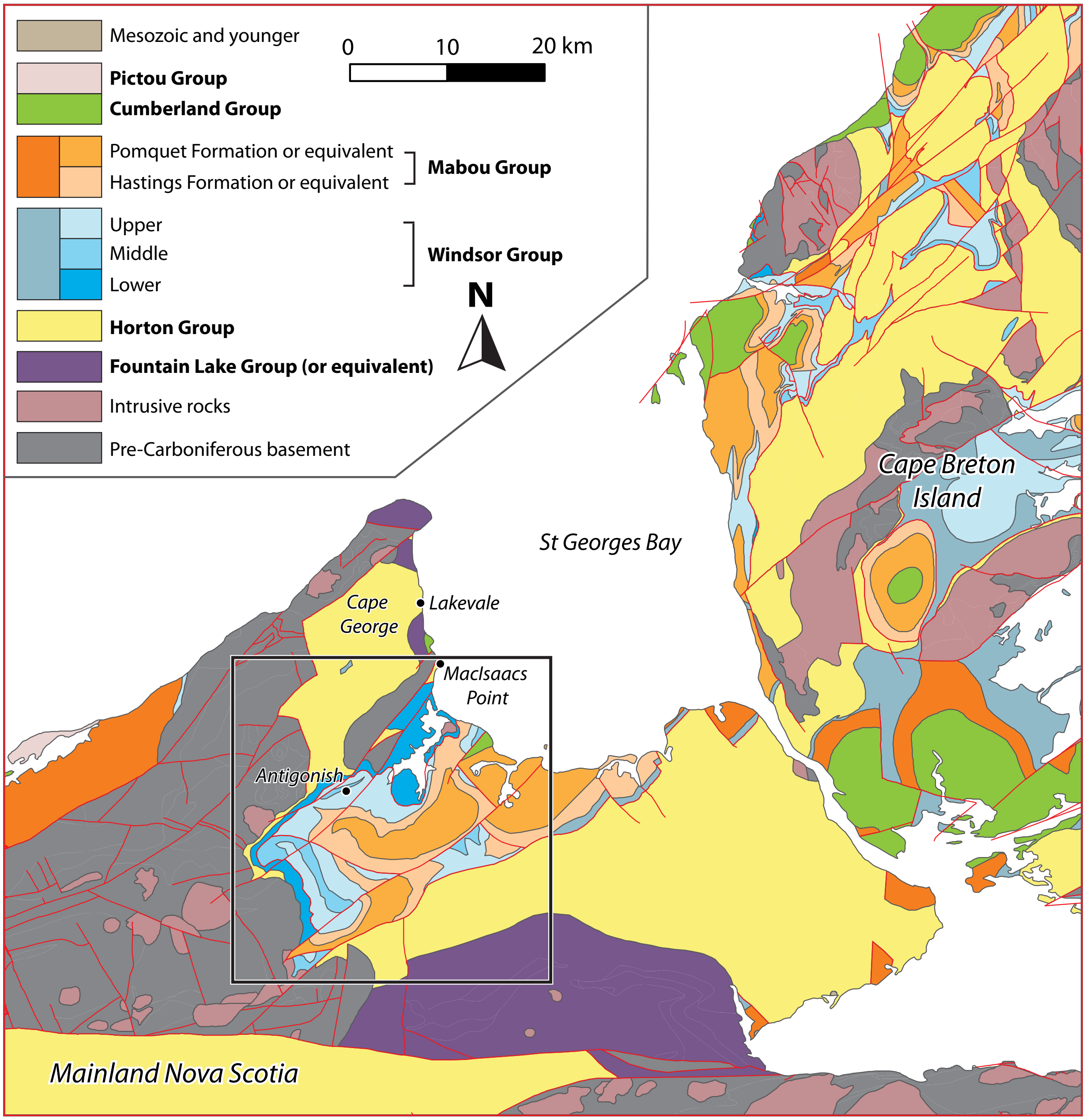


Figure 2.4. Map of the Antigonish sub-basin

Modified from Keppie (2000). The black box indicates the location of Figure 2.5.

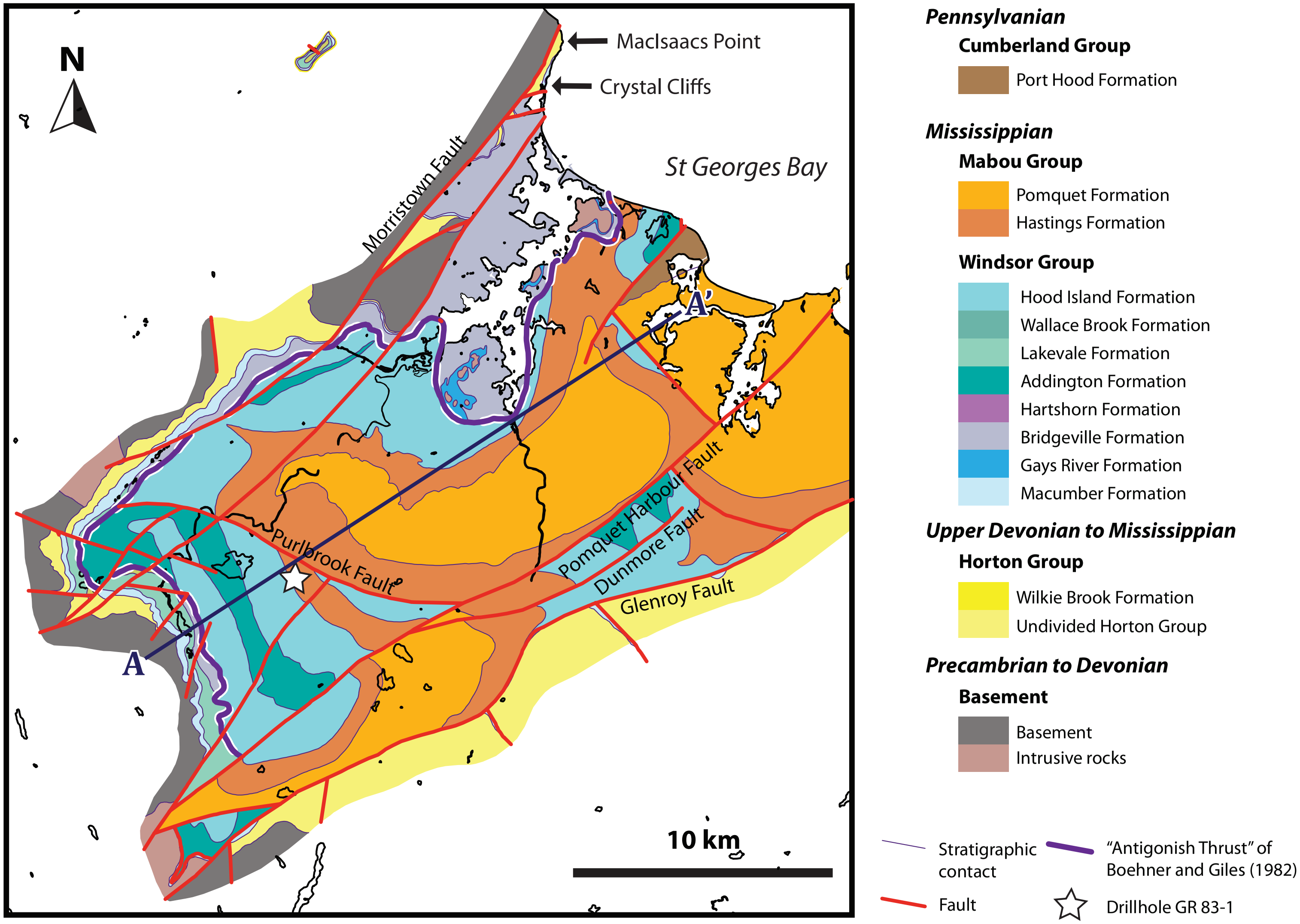


Figure 2.5. Partial map of Antigonish sub-basin

Map of the portion of the sub-basin mapped in 1982 by Boehner and Giles. A star denotes the location of core GR 83-1 which was partially logged in this study. The line of section from A to A' is shown in Figure 2.6

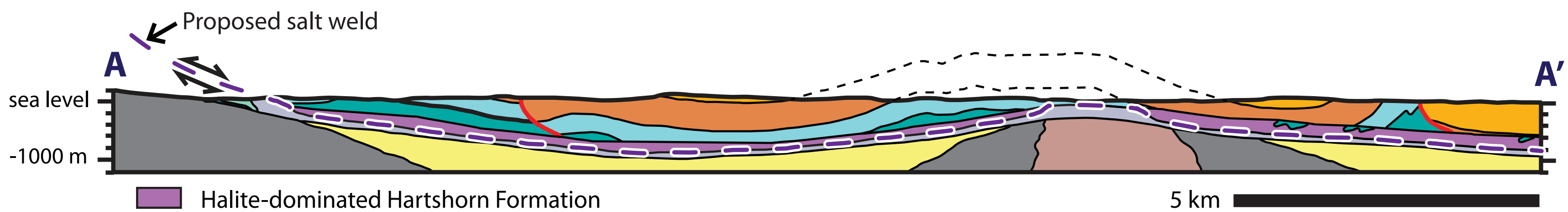


Figure 2.6. Cross section through Antigonish sub-basin

This cross section corresponds to the line of section from A to A’ in Figure 2.5. Modified from Boehner and Giles (1982).

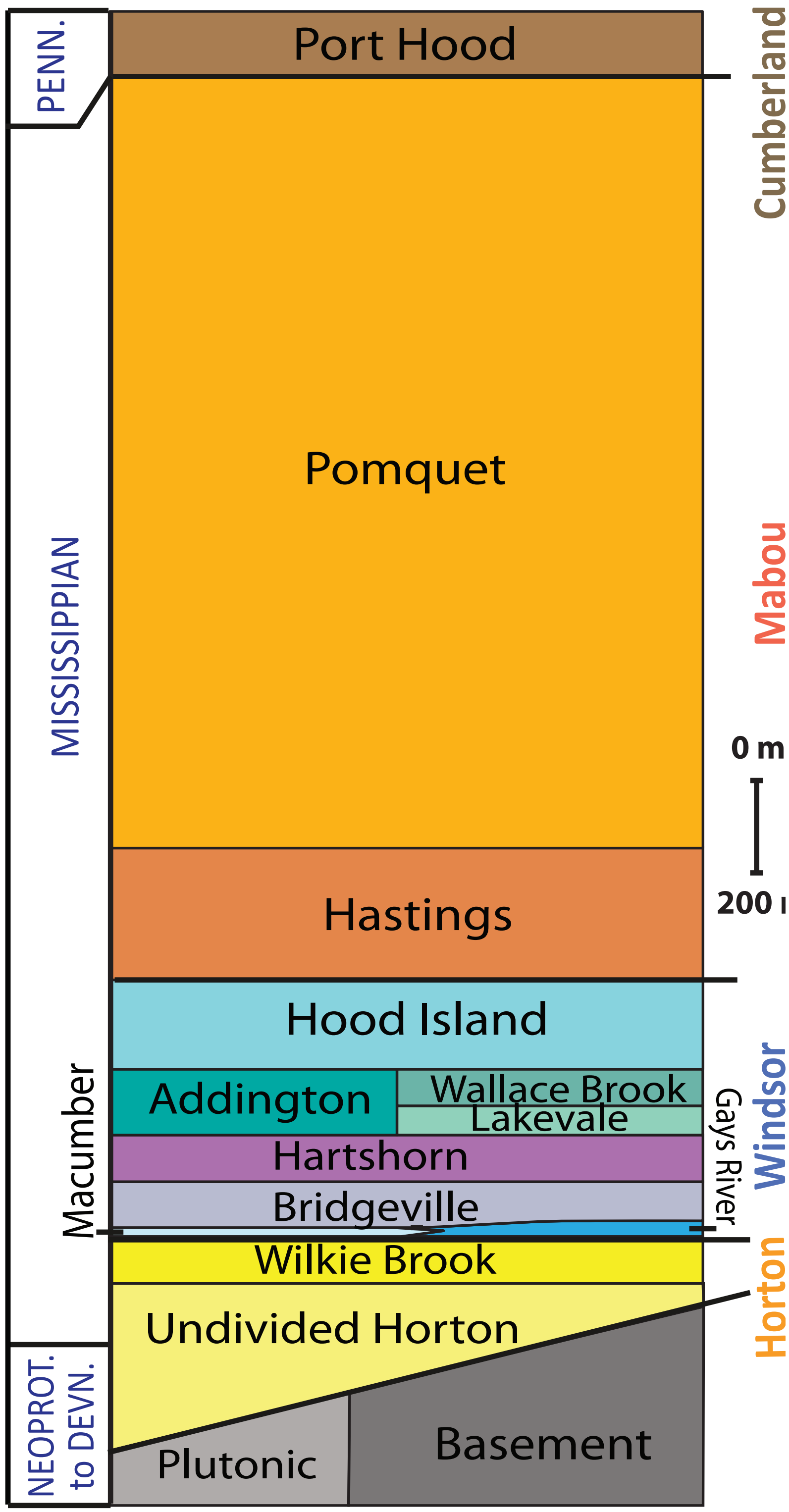


Figure 2.7. Stratigraphic chart for the Antigonish sub-basin

This stratigraphic chart is for the portion of the Antigonish sub-basin in mainland Nova Scotia. The stratigraphy for the portion of the sub-basin in Cape Breton Island is shown in Figures 2.2 and 2.3. Modified from Boehner and Giles (1993).

2.2.2 Stratigraphy

The Upper Devonian to Permian strata that fill the Maritimes Basin and its sub-basins are dominantly sedimentary but do include volcanic units (e.g. Gibling et al. 2009). The oldest unit in the basin-fill of much of the Maritimes Basin is the clastic Devonian to Tournasian Horton Group and the equivalent Anguille Group in Newfoundland (Figure 2.2) (e.g. Waldron et al. 2017). The Horton Group contains fluvial, lacustrine, and alluvial deposits (Bell 1960, Hamblin 1989, Boehner and Giles 1993, Gibling et al. 2009). In Prince Edward Island and parts of Nova Scotia, the Horton Group is underlain by the Fountain Lake Group, that includes volcanic rocks, while in New Brunswick the clastic Sussex Group unconformably overlies the Horton Group (Figure 2.2) (e.g. Gibling et al. 2009, Waldron et al. 2017).

The Viséan Windsor Group, or the equivalent Codroy Group in Newfoundland, unconformably overlies the Horton Group across most of the Maritimes Basin (Figure 2.2) (e.g. Waldron et al. 2017). It comprises cyclic carbonate, evaporite, and clastic strata (Bell 1944). Bell (1929) defined the Windsor Group and divided it into two major faunal zones, referred to as the Lower and Upper Windsor zones, and five subzones (Figure 2.8). Giles (2008) informally subdivides the Windsor Group into the Lower, Middle, and Upper Windsor subgroups using the subzones of Bell (1929) (Figure 2.8). The marine Lower Windsor includes a basal limestone overlain by a thick unit of anhydrite and/or gypsum which is in turn overlain by a halite-dominated unit (Figure 2.2) (Boehner 1986, Giles 2003, 2008). Multiple cycles of interbedded marine carbonates, siltstones, and evaporites make up the Middle Windsor Group (Boehner 1986, Giles 2008). The Upper Windsor Group is predominantly composed of non-marine clastic strata, but also contains eight or more marine carbonate units which in some cases are overlain by evaporites (Moore 1967, Boehner 1986, Giles 2008).

	MACROFAUNA			FORAMINIFERA	CONODONTS	PALYNOMORPHS	
	Zone	Subzone	Informal Subdivision	Zone	Informal Assemblage Zone	Concurrent Range Zone	
				17		*spinosa-magnificus*	Serpukovian
WINDSOR GROUP	Upper	E	Upper Windsor	16s	*Gnathodus*	*acadiensis-triradiatus*	
		D					
		C		16i			Visean
	Lower	B	Middle Windsor	15	*Clydagnathus windsorensis*	*stephanephorus*	
					Taphrognathus transatlanticus		
		A	Lower Windsor	15?/14?	*Diplognathodus*	*pusilla-columbaris*	
							Tn3

Figure 2.8. Biostratigraphic subdivisions of the Windsor Group

The macrofaunal zones and subzones are from Bell (1929), the informal Windsor Group subdivisions from Giles (2008), foraminiferal zones from Mamet (1970), informal conodont zones from Plint and von Bitter (1986), palynomorphs defined by Utting (1987) then modified by Utting and Giles (2004) and von Bitter et al. (2006). Approximate correlation to the geological timescale from Waldron et al. (2017).

The thin carbonate beds within the Middle and Upper Windsor Group were correlated across the Maritimes Basin by Giles (Giles 1981). The evaporite deposits are interpreted as having formed during periods when low clastic sedimentation and a semi-arid climate allowed the precipitation of evaporites from a landlocked sea (Howie 1988). Recurring flooding caused cyclic sedimentation of shallow marine to subtidal carbonate, supratidal calcium sulfate, and subaerial redbeds (Schenk 1969).

The Mabou Group conformably overlies the Windsor Group and contains upper Viséan to Bashkirian strata (Figure 2.2) (Gibling et al. 2009, Waldron et al. 2017). It grades from a grey lacustrine unit into a red fluvial unit laterally towards the margins of the Maritimes Basin (Belt 1965). The approximately equivalent clastic Serpukhovian to Bashkirian Barachois Group overlies the Codroy Group in Newfoundland (Figure 2.2) (e.g. Waldron et al. 2017).

A significant unconformity separates the Mississippian Mabou Group from the overlying Pennsylvanian Cumberland Group (e.g. Gibling et al. 2009). The Cumberland Group is concentrated in northern Nova Scotia and southeastern New Brunswick (St. Peter and Johnson 2009). It includes fluvial clastic strata (Ryan and Boehner 1994, St. Peter and Johnson 2009) and is notable for its coal deposits (Calder 1985). The clastic Pennsylvanian to Permian Pictou Group overlies the Cumberland Group across much of the Maritimes Basin; however, this unit is not present within the Antigonish sub-basin (Figure 2.2) (e.g. Waldron et al. 2017).

2.3 Antigonish sub-basin

2.3.1 Structure and sub-basin development

The Antigonish sub-basin (also known as the Antigonish-Mabou sub-basin: e.g. Barss et al. 1977, Durling et al. 1995), extends from northeastern mainland Nova Scotia underneath St Georges Bay and into the southwestern coast of Cape Breton Island (Figure 2.4). An angular unconformity separates the fill of the Antigonish sub-basin from the underlying igneous and metasedimentary rocks of the Neoproterozoic to Devonian basement (Boehner and Giles 1993). Within the Antigonish sub-basin, a central area (Figure 2.5) is bounded by the northeast-striking Glenroy and Morristown faults. These faults have steep dips and have been interpreted to show both strike-slip and dip-slip components of movement (Boehner and Giles 1993). Between the Glenroy and Morristown faults (Figure 2.5), thick Windsor and Mabou Group strata rest directly on basement with only thin, local intervening remnants of the Horton Group. Outside this region the Horton Group is thick and the Mabou and Windsor Group are largely absent (Figures 2.1 and 2.4). Waldron et al. (2015) suggest that before the Viséan, a horst and graben structure developed in the sub-basin; the central region between the Glenroy and Morristown faults was upthrown and the Horton Group mainly accumulated in the surrounding grabens. In Viséan to Serpukhovian time, a thick package of Windsor and Mabou Group sediments were deposited on top of the former horst, which is at present down-dropped relative to the former grabens on either side, indicating that the Glenroy and Morristown faults were inverted at some time after the deposition of the Horton Group. A similar argument is used by Murphy et al. (2011) to show that the Rawdon Block south of the Minas Fault Zone was a graben filled by Horton Group that underwent later inversion (Waldron et al. 2015). Near the end of the Tournaisian, dextral motion along the major NE-SW Appalachian-parallel fault trend in the Maritimes Basin was increasingly interrupted by motion on the E-W Minas Fault Zone (Waldron et al. 2015), which likely caused this inversion.

2.3.2 Stratigraphy of the Antigonish sub-basin

In the Antigonish sub-basin the clastic Devonian to Tournaisian Horton Group (Figure 2.7) has an unconformable lower contact with the basement (Bell 1929). Horton Group strata on Cape George (Figure 2.4) were divided into informal formations (the Right's River, South Lake Creek and Ogden Brook Formations) by Murray (1955). Benson (1970) later mapped Cape George and a region along the southern coast of St Georges Bay (Figure

2.4), breaking the Horton Group into four informal unnamed rock units by lithology. Despite these earlier attempts at subdivision, Boehner and Giles (1993) left the majority of the Horton Group undivided apart from the uppermost unit known as the Wilkie Brook Formation (Figure 2.4). Ténière et al. (2002, 2005) later mapped the Horton Group along the southern coast of St Georges Bay (Figure 2.4) and defined the Clam Harbour, Tracadie Road, Caledonia Mills, and Steep Creek Formations. The Horton Group is mostly composed of conglomerate and also contains volcanic rocks, sandstone, siltstone, shale, and a small amount of caliche limestone. The Horton Group is over 500 m thick in the Antigonish sub-basin (Boehner and Giles 1993) and is interpreted to record fluvial-lacustrine depositional environments (Bell 1960). In this study we follow Boehner and Giles (1982, 1993), leaving the group undivided except for the Wilkie Brook Formation.

Within the Antigonish sub-basin, the Wilkie Brook Formation is the youngest unit of the Horton Group (Figure 2.7) (Boehner and Giles 1993). This unit rests unconformably on the underlying units and is up to 200 m thick (Keppie et al. 1978). The Wilkie Brook Formation is interbedded conglomerate, sandstone, siltstone, shale and limestone (Keppie et al. 1978).

The Windsor Group has a lower contact that varies between concordant and discordant (Boehner and Giles 1993). Sparsely fossiliferous to unfossiliferous laminated limestone of the Macumber Formation (Schenk 1967a, 1967b) is the basal unit of the Windsor Group. Within the Antigonish sub-basin, the Macumber Formation reaches a maximum thickness of 25 m (Boehner and Giles 1993). A local facies equivalent to the Macumber Formation representing fossiliferous carbonate banks is distinguished as the Gays River Formation (Giles et al. 1979).

Conformably overlying this basal carbonate is up to 300 m of anhydrite assigned to the Bridgeville Formation, which in the shallow sub-surface has commonly been converted to gypsum (Boehner and Giles 1993). The halite-dominated Hartshorn Formation conformably overlies the Bridgeville Formation. The thickness of the halite is poorly constrained, but up to 150 m is seen in existing drillcore (Boehner and Giles 1993). The Hartshorn Formation is only present in the sub-surface, having been removed by solution near the present topographic surface (Boehner and Giles 1993). The Macumber, Bridgeville, and Hartshorn Formations make up the lower Windsor Group.

Disconformably overlying the lower Windsor Group are three units known as the Lakevale, Wallace Brook, and Addington Formations, which comprise the Middle Windsor Group, which is up to 200 m thick. Boehner and Giles (1982, 1993) designated a coastal section within the Antigonish sub-basin at Lakevale (Figure 2.4) as the type section of the Lakevale Formation. This formation and its type section are re-examined in this study. Boehner and Giles (1982, 1993) describe the formation as dominated by polymictic breccia and paraconglomerate with the majority of clasts composed of mudstone (Boehner and Giles 1982, 1993). Its highly variable thickness reaches up to 110 m (Boehner and Giles 1982, 1993). Boehner and Giles (1982) mapped the formation on the southwestern margin of the sub-basin between the Morristown and Glenroy Faults (Figure 2.4) and identified it from drillcore at Big Marsh (Figure 2.4). Gypsum and anhydrite are present in the subsurface (Boehner and Giles 1993). Giles (1980) hypothesized that the Lakevale Formation is either a siliciclastic facies equivalent to the Bridgeville or Hartshorn Formations, or a lateral facies equivalent to the Addington Formation. Boehner and Giles (1993) promote the latter hypothesis. The Addington Formation, which is poorly exposed, comprises interlayered siltstone, carbonate, and evaporites (Boehner and Giles 1993). Boehner and Giles (1993) infer the formation to have a wide distribution within the sub-basin. The Wallace Brook Formation, predominantly formed of interbedded limestone and dolostone, has a limited extent and has been interpreted to rest conformably on the Lakevale Formation (Boehner and Giles 1993). Boehner and Giles (1993) infer that the Wallace Brook Formation is a lateral facies equivalent to part of the Addington Formation.

These Middle Windsor Group units are unconformably overlain by the Hood Island Formation (Boehner and Giles 1993) that makes up the Upper Windsor Group. This unit is siltstone with interbedded cyclic carbonate, gypsum and anhydrite layers and is also variable in thickness, with an estimated maximum of around 880 m (Boehner and Giles 1993).

The Mabou Group typically conformably overlies the Windsor Group in the Antigonish sub-basin (Figure 2.7) (Boehner and Giles 1993). The basal Hastings Formation is dominated by grey shale and siltstone, and it is conformable with the overlying Pomquet Formation, which is dominated by red siltstone and sandstone (Belt 1965). Hamblin (2001) determined that the Hastings Formation mainly formed in lacustrine and marginal-lacustrine settings while the Pomquet Formation was produced by subaerial and marginal-lacustrine environments. The Mabou Group is typically up to 1000 m thick in the Maritimes Basin (Gibling et al. 2009). In the Antigonish sub-basin, the Hastings Formation alone is ~800 m thick (Boehner and Giles 1993). Belt (1965) estimated that the Pomquet Formation is 5500 m thick in the Antigonish sub-basin, based on surface mapping. Boehner and Giles (1993) incorporated data from drilling conducted after 1965 to revise this estimate to 3900 m and therefore estimated a total of 4700 m of strata in the Mabou Group. This is far more Mabou Strata than is found in the rest of Nova Scotia (e.g. Belt 1965).

The youngest basin-fill unit in the Antigonish sub-basin is the Pennsylvanian Cumberland Group, which rests conformably above the Mabou Group (Boehner and Giles 1993). It is a clastic unit with a limited extent in the sub-basin (Figure 2.5). The Cumberland Group is mostly fluvial in origin (Ryan and Boehner 1994, St. Peter and Johnson 2009).

2.3.3 Regional omission surface

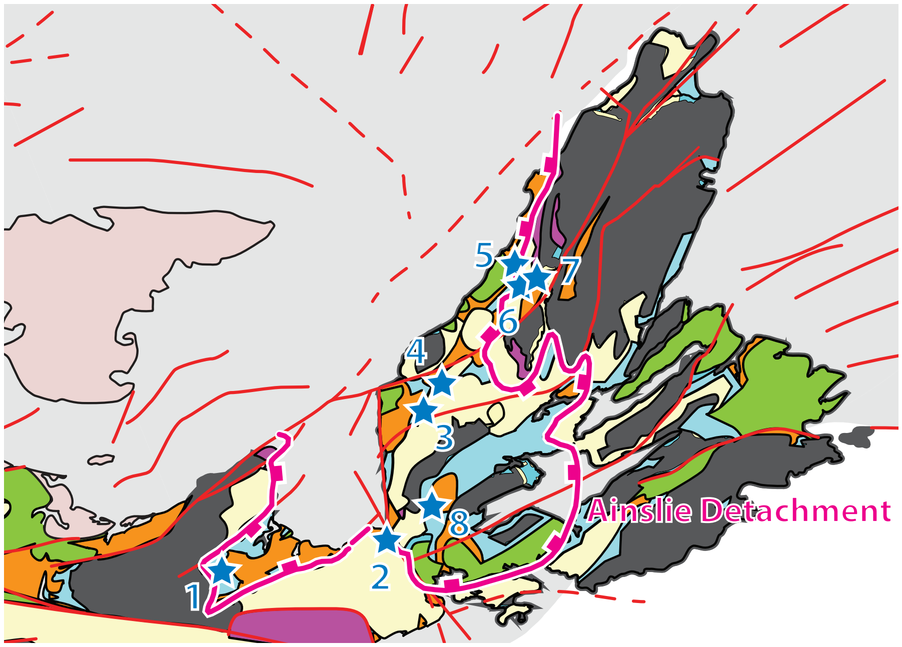
Boehner and Giles (1982) mapped an omission surface within the Windsor Group as the Antigonish Thrust (Figures 2.5 and 2.6). They placed this surface in the Lower Windsor Group at the top of the Hartshorn Formation (Figure 2.7). Boehner and Giles (1993) attributed the discrepancy between their estimated basin-fill thickness of 5-6 km and sub-basin depth of 3 km to the removal of a section by faulting along the Antigonish Thrust, and to variable unit thicknesses upon deposition. The interpretation of this surface as a thrust fault is unlikely, because the omission surface juxtaposes younger strata on top of older strata (Figure 2.6), whereas most thrust faults place older strata above younger strata (e.g. Ramsay and Huber 1983). Lynch and Giles (1995) extended this surface beneath St Georges Bay (Figure 2.4) and mapped it in western Cape Breton Island (Figure 2.9). They reinterpreted the surface as a low-angle extensional fault, which they named the Ainslie Detachment. Lynch and Giles (1995) attribute localized gaps in Windsor Group stratigraphy directly above the Macumber Formation to movement along the Ainslie Detachment. The amount of missing stratigraphy at the Ainslie Detachment varies across the Antigonish sub-basin (Figure 2.9). In some cases all of the Windsor Group formations overlying the Macumber Formation are missing, leaving the Mabou Group resting directly on the Macumber Formation (Lynch and Giles 1995). However, Thomas et al. (2002) found that the Macumber Formation immediately below the proposed detachment does not show evidence of the consistent movement in one direction expected from an extensional fault. Instead they found support for different directions of extension at different localities, which converge towards the centre of the sub-basin (Thomas et al. 2002).

2.4 Methods

2.4.1 Seismic interpretation

Time-migrated 2-D seismic reflection data collected by Northstar Energy Corporation in 2001 and by Contact Exploration in 2002 (Figure 2.10) were obtained from the Nova Scotia Department of Energy. The data were provided as pre-stack migrated S2.16-Y files and vary from poor to moderate quality. No reprocessing or time-depth conversion was conducted in this study. The data were interpreted in the time domain using Petrel seismic interpretation software. The seismic data were tied with well Beech Hill No. 1 (BH 1) (Figure 2.10) using the geological report of MacDonald (2003) and a synthetic seismogram

A)



B)

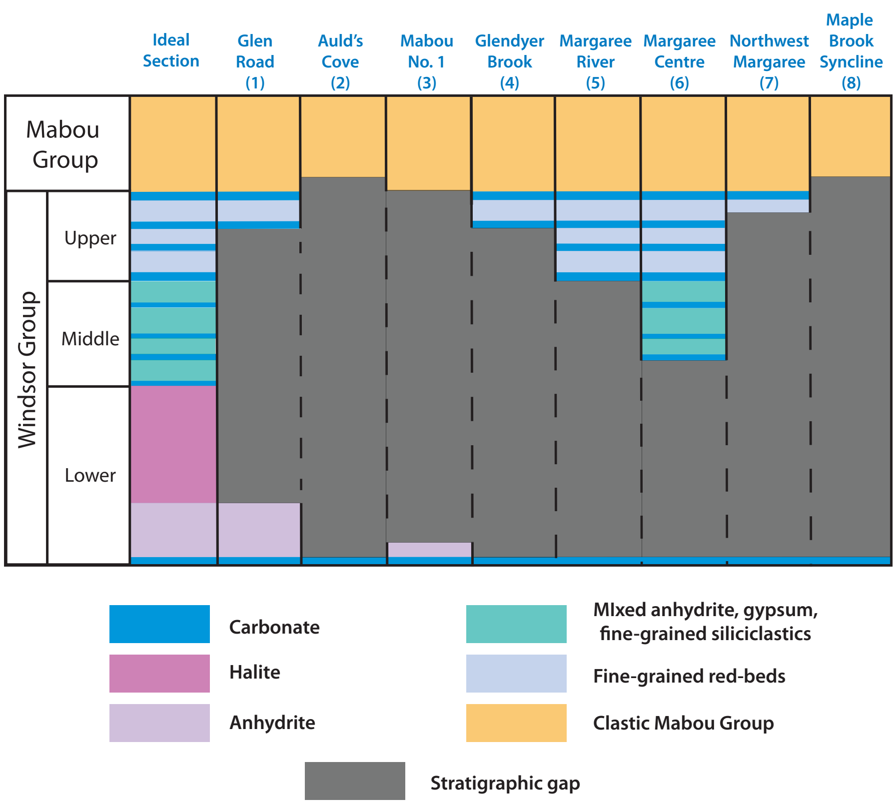


Figure 2.9. Stratigraphic gaps across the Ainslie Detachment

(A) Inset map showing approximate measured section locations from Lynch et al. (1998). Map modified from Waldron et al. (2017). (B) Measured sections of the Mabou and Windsor Group after Lynch et al. (1998) showing gaps they attribute to the Ainslie Detachment.

generated from wireline logs provided by the Nova Scotia Department of Energy (Figure 2.11). Unit tops were manually interpreted from the well where possible.

Well tops were picked in additional wells (Figure 2.10) from unpublished geological reports (Grace 1966, Amax Exploration 1974, Burton 1974, Imperial Oil Limited 1974). Where well control was not available, we assigned horizon travel-times to these tops using an average seismic velocity of 4000 m/s typical for Maritimes Basin strata (e.g. Waldron et al. 2013, Craggs et al. 2015). Additionally, reflections were traced to the surface and correlated with boundaries and outcrop locations on local geological maps. Reflections can only be traced across portions of lines, making tying them difficult. Sub-basin depth estimates were done for each onshore seismic line where a basement reflector had been picked, also using an assumed seismic velocity of 4000 m/s for the basin-fill.

2.4.2 Core observations

In 1984, the Nova Scotia Department of Mines and Energy (NSDME) drilled the vertical hole GR 83-1 (Glen Road-1) to investigate the Antigonish Thrust of Boehner and Giles (1982, 1993)(Figure 2.5). Core was collected to a depth of 846.7 m (Boehner 1984, 1993). The core is largely intact, but fractures break the core into many segments and core loss may have occurred where the ends of these segments do not interlock continuously. Boehner (1984, 1993) completed a lithological log with a 10 cm resolution (locally 5 cm) and interpreted that the Middle Windsor Group was missing.

The core interval between depths of 600.00 m and 567.00 m, which includes the halite-dominated Hartshorn Formation, was photographed and logged in detail for this study. The Macumber Formation and its contact with the underlying Horton Group, found between depths of 822.25 m and 819.25 m, were also photographed and logged. Nine samples were taken from the core and used to make sections 0.5 mm thick, which were prepared using non-polar liquids to avoid dissolution.

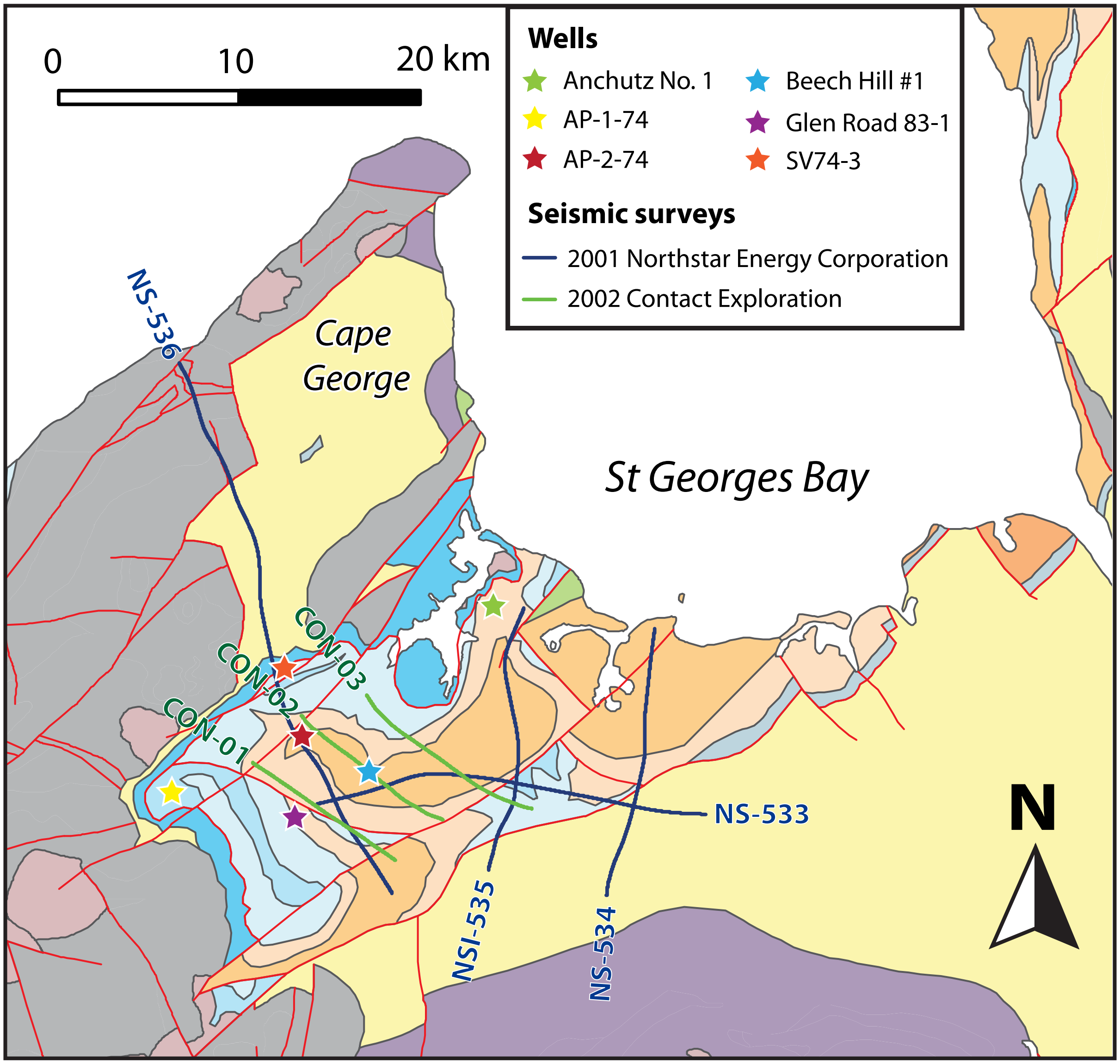


Figure 2.10. Map of Antigonish seismic line and selected well locations

Full names of drillholes and seismic lines listed in Appendices C and D.

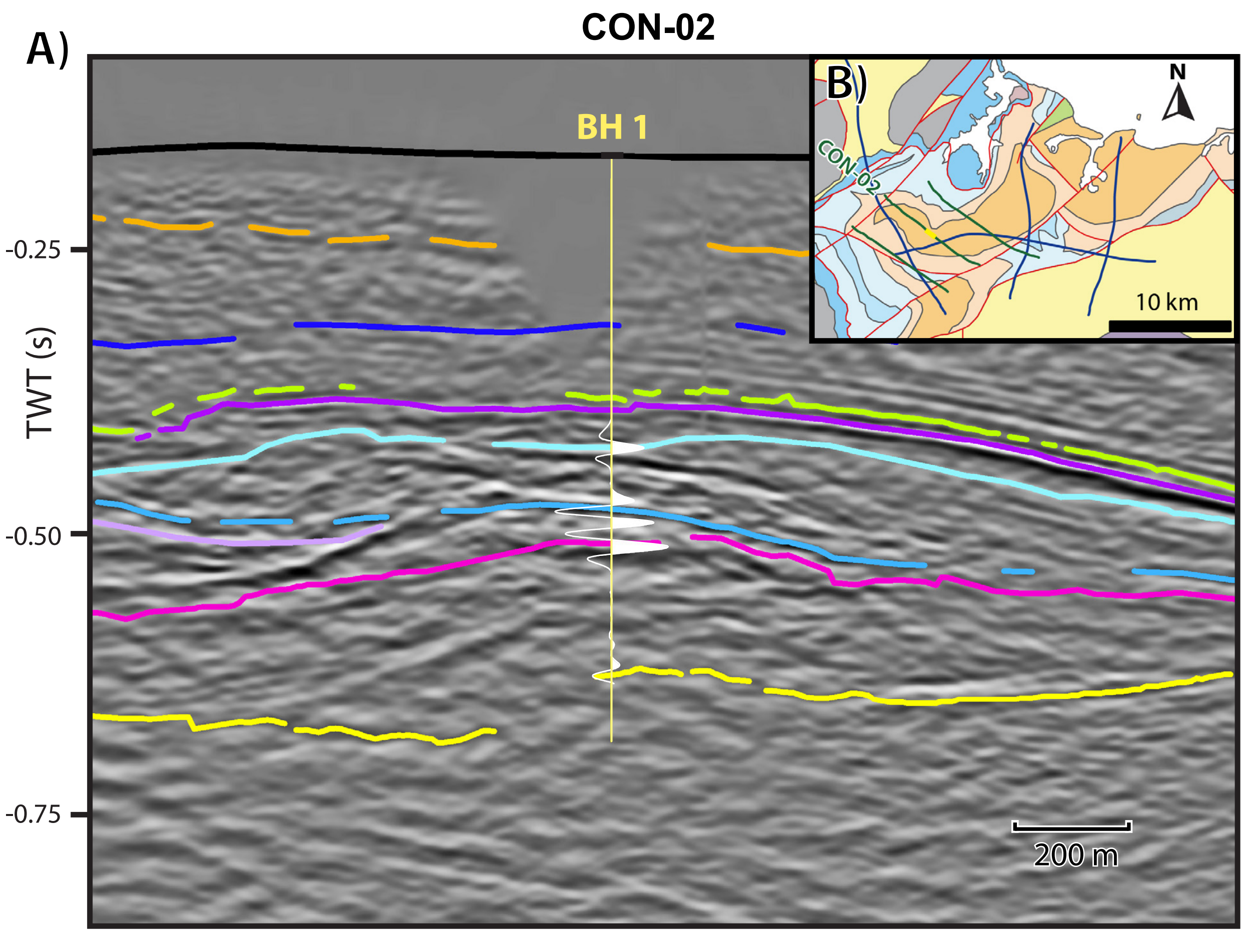


Figure 2.11. Synthetic seismogram and well tie of BH 1 on line CON-02

(A) Synthetic seismogram (peaks shown in white fill) and well tie. (B) Inset map with yellow line showing the location of the seismic line.

2.4.3 Outcrop data

Inland outcrop in the Antigonish sub-basin occurs mostly in streams and rivers, with the result that the best exposures are along the coast (e.g. Prime 1987, Boehner and Giles 1993). For this study, the map by Boehner and Giles (1982) was used to identify potential outcrop locations of their Antigonish Thrust and of other gaps in the stratigraphy. Boehner and Giles (1982) found that the majority of the Windsor Group was absent at Lakevale on the coast of St Georges Bay (Figure 2.4). Additionally, at MacIsaacs Point, also on St Georges Bay (Figure 2.4), the Macumber Formation at the base of the Windsor Group is deformed (Boehner and Giles 1993, Thomas et al. 2002), making it another location of interest for this study. At these locations, a DJI Inspire 1 Pro drone was used to conduct photogrammetrical surveys of coastal cliff outcrops. Marker objects were laid out near the outcrop and their locations were recorded by a handheld GPS receiver. Aerial drone transects were conducted to obtain photographs from directly overtop of and perpendicular to the cliffs. Additional photographs were taken at oblique angles to provide at least 60% overlap between photographs. A total of 624 photographs were taken at Lakevale and 963 at MacIsaacs Point. The drone recorded GPS locations in the metadata of each photograph. Selected photographs were printed and then used as base images to assist traditional geological mapping of these outcrops. Bedding measurements, descriptions, and samples were collected in these areas.

2.4.4 Photogrammetry

Agisoft PhotoScan software was used to create high-resolution three-dimensional (3D) models of outcrops at Lakevale and at MacIsaacs Point using the drone photographs. First, features such as drone hardware and topographic features outside the exposed study area were manually cropped out of the photos to improve image processing. Marker objects were located in the images and tagged to aid model-building. The software detected points common to multiple images and used GPS data from the photographs to locate these points in three-dimensional space, creating a sparse point cloud of 6 to 7 million points. From this, a dense point cloud of 50 to 125 million points was generated and used to construct a 3D mesh surface. Between each step, spurious points or features, such as vegetation or objects mislocated above the ground, were manually selected and deleted in PhotoScan. Finally, the software draped a texture layer over the mesh surfaces, to display the colour information from the photographs.

The GPS data from the UAV photographs allowed the 3D outcrop models to be correctly georeferenced, and for unit thicknesses to be measured directly on the models. Additionally, a code written by Jeffrey Kavanaugh (University of Alberta, personal communication, October 2018) was used to obtain strike and dip orientations for planar geologic surfaces visible in the 3D models. To do this, points were picked along bedding planes and their coordinates were exported in text files. Each text file was read by the code to find the best-fit plane and export the strike and dip orientations.

2.5 Observations

2.5.1 Seismic interpretation

Salt in the Antigonish sub-basin is restricted to the subsurface (Boehner and Giles 1993). In this study we interpret previously unpublished seismic data to examine the lateral extent and shape of salt at depth in the basin-fill. The seismic lines examined are from a central region of the sub-basin in mainland Nova Scotia (Figure 2.10).

Basement

The deepest interpreted surface in the seismic data, horizon BM, is a strong positive reflection that is sub-horizontal or shallowly dipping (Figure 2.12), above material that lacks coherent reflections. We interpret this horizon as the top of basement. The time-depth of horizon BM varies from 746 to below 1500 ms. Using these time-depths and a typical velocity of 4 km/s, we estimate the maximum sub-basin depth as 2.8 km, consistent with the sub-basin depth estimate of 3 km from Boehner and Giles (1993).

Horton Group

Reflectors between horizon BM and the next higher interpreted horizon, horizon HG, are interpreted to belong to the Horton Group. The Horton Group reflections are discontinuous, and in some cases, show gentle to moderate apparent dips distinct from the sub-horizontal reflectors within the overlying Windsor Group, suggesting an angular unconformity (e.g. line NS-535 in Figure 2.12). Based on a time-thickness up to 899 ms, the true vertical thickness of the Horton Group, which is poorly constrained in previous work in the Antigonish sub-basin (e.g. Boehner and Giles 1993), is ~1.8 km.

The top of the Horton Group is intersected by well BH 1. The synthetic seismogram (Figure 2.11) generated in Petrel for the well shows a negative reflector of moderate strength for this horizon, as a result of the decrease in acoustic impedance at the transition from the evaporites and carbonates of the Lower Windsor Group to the clastic Horton Group below. The top of the Horton Group in the well ties with seismic data at a negative reflection, horizon HG (Figure 2.13), with varying strength across the seismic lines. Reflection HG is typically sub-horizontal (Figures 2.12 and 2.13). In line NS-533, it is separated into offset segments (Figure 2.12), implying that it has been faulted. The shapes of the packages between these interpreted faults are similar to half-grabens, commonly seen in the Horton Group elsewhere (e.g. Hamblin and Rust 1989, Waldron et al. 2010).

Lower Windsor Group

BH 1 intersects the Macumber Formation and the Bridgeville Formation of the Lower Windsor Group. The Macumber Formation is only 2 m thick (MacDonald 2003) and therefore is not resolvable in seismic data. Overlying it is 274 m of anhydrite and limestone assigned to the Bridgeville Formation (MacDonald 2003). The Bridgeville Formation is in turn overlain by 83.5 m of strata dominated by shale (MacDonald 2003), which we assign to the Middle Windsor Group.

In the synthetic seismogram, the Bridgeville Formation appears as a package of low amplitude reflections with a strong positive reflection at the top. This is consistent with the positive acoustic impedance contrast expected between the anhydrite-dominated Bridgeville Formation and the overlying shale. On the seismic lines, the reflections within the Bridgeville Formation are weak and discontinuous, except in line NS-535 where the reflections show lateral transitions from strong to weak (Figure 2.12). The top of the Bridgeville Formation in BH-1 ties with a sub-horizontal strong positive reflection, horizon BF (Figure 2.13). Predicted time-depth horizons from SV74-3 (Figure 2.10)(Burton 1974) and GR83-1 were used in addition to the geological map of Boehner and Giles (1982) and the Beech Hill No. 1 well tie to interpret horizon BF across the seismic lines.

The halite-dominated Hartshorn Formation overlies the Bridgeville Formation in the Antigonish sub-basin (Boehner and Giles 1993). Several drillholes on the periphery of the seismic surveys (e.g. AN 1 and AP-1-74) intersect up to ~210 m of the Hartshorn Formation. Only 6.5 m of halite is present in GR 83-1, which is 1180 m from the nearest seismic line (Figure 2.10). No halite was recorded in the cuttings of Beech Hill No. 1 (MacDonald 2003). It is possible that a thin halite layer from the Hartshorn Formation could have been present in Beech Hill No. 1 but was dissolved by the drilling brine. The character of the seismic data indicates that a well stratified sedimentary unit (probably carbonate and clastic rock), rather than halite, lies above the Bridgeville Formation (e.g. Figures 2.12 and 2.13), with the exception of a poorly coherent lenticular package at the intersection of lines NS-533 and NS-535 (Figure 2.12), which may represent Hartshorn Formation halite. Other comparable sub-basins in the Maritimes Basin, for example the Shubenacadie sub-basin (Giles 2009), have thick salt layers so it is unusual that Hartshorn Formation is present at the Antigonish sub-basin margins but is either absent or too thin to be resolved in seismic data in the centre of the sub-basin.

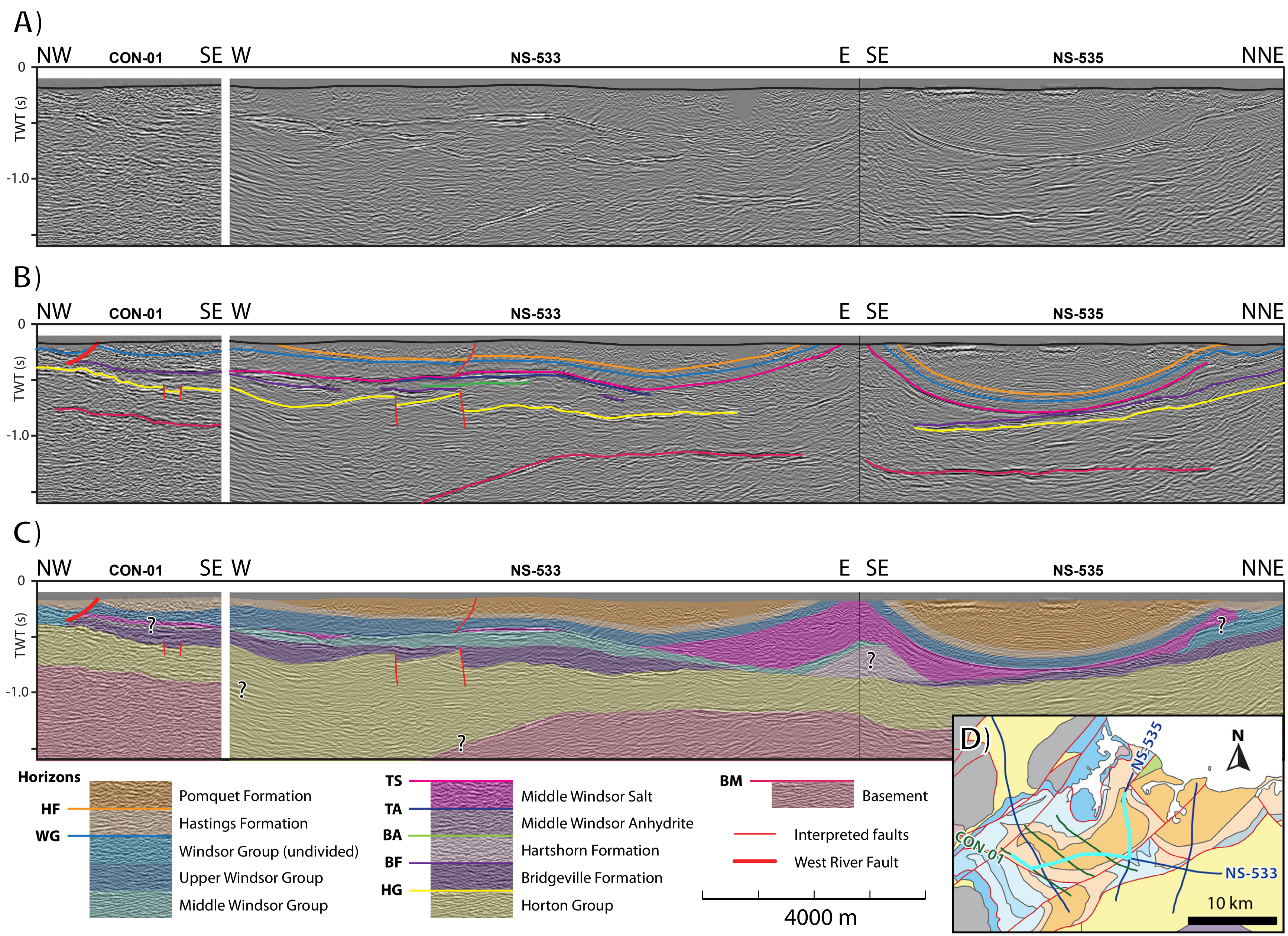

A)
NW
CON-01
SE W
NS-533
E SE
NS-535
NNE
0
TWT (s)
-1.0
B)
C)
?
D)
N
NS-535
NS-533
CON-01
10 km
Horizons
HF
WG
Pomquet Formation
Hastings Formation
Windsor Group (undivided)
Upper Windsor Group
Middle Windsor Group
TS
TA
BA
BF
HG
Middle Windsor Salt
Middle Windsor Anhydrite
Hartshorn Formation
Bridgeville Formation
Horton Group
BM
Basement
Interpreted faults
West River Fault
4000 m

Figure 2.12. Composite seismic line partial cross section through Antigonish sub-basin

(A) Uninterpreted. (B) Interpreted horizons. (C) Geology interpretation. (D) Inset map showing cross section location in bright blue.

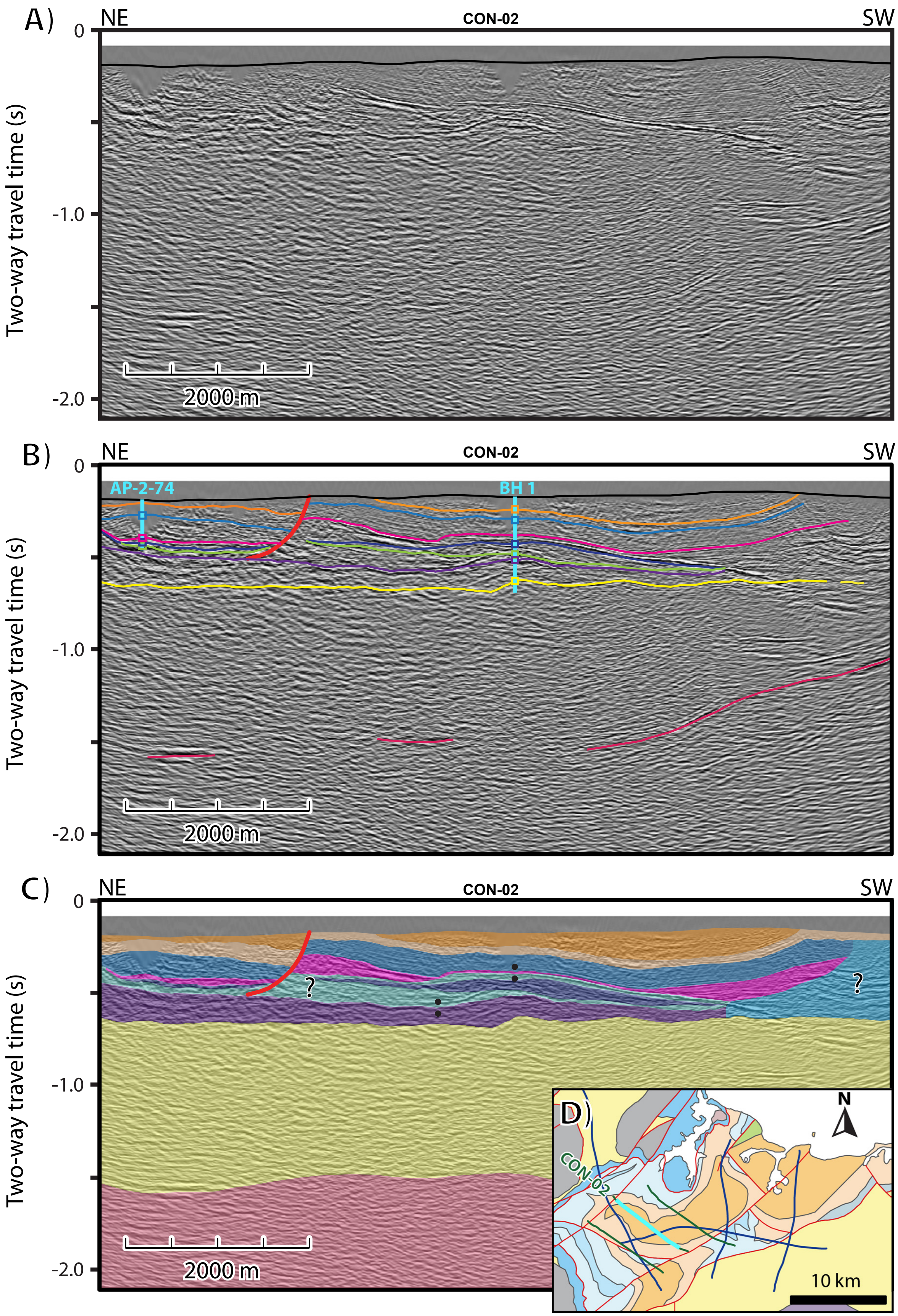

A)
NE
CON-02
SW
0
-1.0
-2.0
Two-way travel time (s)
2000 m
B)
NE
CON-02
SW
AP-2-74
BH 1
0
-1.0
-2.0
Two-way travel time (s)
2000 m
C)
NE
CON-02
SW
?
?
0
-1.0
-2.0
Two-way travel time (s)
2000 m
D)
N
CON-02
10 km

Figure 2.13. Seismic line CON-02 and well tie with BH 1

See inset map for seismic line location. (A) Uninterpreted. (B) Interpreted horizons; wells are shown as vertical yellow lines with horizon intersections in the well indicated by coloured squares. (C) Geology interpretation. (D) Inset map showing cross section location in bright blue.

Middle Windsor Group

In BH 1, 48.5 m of shale, anhydrite and limestone overlies the Bridgeville Formation (MacDonald 2003). This is in turn overlain by a 125.5 m interval dominated by anhydrite, with minor interbedded shale concentrated near the base of the unit (MacDonald 2003). MacDonald (2003) interpreted this anhydrite body as a structural repeat of the Bridgeville Formation. However, the Bridgeville Formation does not contain any shale (Boehner and Giles 1993), and is not duplicated by faulting in any other local seismic lines. This anhydrite is therefore interpreted as a Middle Windsor Group anhydrite body not previously recognized in the Antigonish sub-basin. Here, we refer to it as the Middle Windsor Anhydrite (MWA).

The Middle Windsor Group reflections are irregular and discontinuous close to the tie with Beech Hill No. 1 (Figure 2.13). This prohibits confident interpretation of the lateral extent of the MWA. In the synthetic seismogram for Beech Hill No 1., the top and base of the MWA tie with strong positive and negative reflections respectively, consistent with its high density and faster seismic velocities than the overlying and underlying shale. These reflections have been designated horizons TA and BA.

While the MWA is poorly imaged in the seismic data, drillhole and outcrop data suggest that it has a wide lateral extent in the Antigonish sub-basin. Drillhole AP-2-74 (Figure 2.10) encountered 10.8 m of anhydrite (Amax Exploration 1974), which we interpret as the thinned MWA. Additionally, Boehner and Giles (1982) mapped a layer of gypsum in outcrop overlying the Lakevale Formation near the southwest boundary of their map (close to the "A" end of the section line in Figure 2.5) as the Lower Windsor Group Bridgeville Formation. The Bridgeville Formation should overlie the Macumber Formation and not the Lakevale Formation (Boehner and Giles 1993). This leads us to reinterpret this area of gypsum as an exposure of the MWA overlying the Lakevale Formation. This map pattern, and the anhydrite seen in AP-2-74 and BH 1, suggest that the MWA may extend across a significant portion of the region between the Morristown and Glenroy faults in the Antigonish sub-basin (Figure 2.5).

The highest Middle Windsor Group unit interpreted in this study is represented by a poorly reflective interval that we interpret as a salt body, termed here the Middle Windsor Salt (MWS). The top of this salt, the strong positive reflection TS, is usually concave-upwards above a wedge of weak and irregular reflections, which are typical for salt bodies (Figures 2.12 and 2.13). The positive polarity of this reflection is consistent with the acoustic-impedance contrast expected for the boundary between the Upper Windsor Group clastics and carbonates and the MWS. Horizon TS is the most laterally continuous Middle Windsor Group reflection in the seismic lines (shown in pink on Figures 2.12 and 2.13). The top of the Middle Windsor Group is not clearly identified in the log of Beech Hill No. 1, leading us to use the top MWS salt horizon as a proxy for the top of the Middle Windsor Group. The MWS significantly varies in thickness across the sub-basin. For example, in line NS-533 it is 600 ms thick (~1.2 km, at a velocity of 4000 m/s), in the east, but it thins westward down to a single reflector near the centre of the line (Figure 2.12). The salt is typically thinnest beneath the regions with the thickest overlying Upper Windsor and Mabou Group strata.

The MWS displays several different salt structures in the seismic lines. In Contact line CON-02, the MWS thins dramatically eastward of BH 1 (Figure 2.13). We interpret the MWS to be removed at a weld on CON-02 east of BH 1, explaining why no salt was encountered in well BH1. The concave-upwards shape of horizon TS in line NS-535, with salt diapirs beneath the dipping regions of the horizon, is typical for salt-withdrawal minibasins (e.g. Jackson and Talbot 1991, Waldron and Rygel 2005, Hudec et al. 2009, Callot et al. 2016, Kergaravat et al. 2017). The overlying reflections are parallel to horizon TS rather than pinching out onto the salt diapirs. This suggests that salt movement and diapir formation in the MWS occurred after deposition of the overlying strata. Additionally, we interpret a salt roller in the MWS between AP-2-74 and BH 1 in line CON-02, which is bounded to the west by a listric fault, named here the West River Fault, which soles into the Bridgeville Formation (Figure 2.13). We have correlated the West River Fault in lines CON-01 (Figure 2.12) and NS-536. It likely extends to line CON-03, but the quality of the seismic data is too poor to resolve its position. In line CON-02, the Hastings Formation is thicker in the hanging wall of the West River Fault (Figure 2.13). We therefore interpret the West River Fault as a growth fault that occurred during the deposition of the Mabou Group.

Upper Windsor Group

Above horizon WG is a package of weak parallel reflectors. This package, representing the Upper Windsor Group, parallels the shape of the top of the MWS (Figures 2.12 and 2.13). The Upper Windsor Group has a time-thickness of around 100 ms across some seismic lines, such as in line NS-535 (Figure 2.12). One exception is line NS-534, where the time-thickness between horizons WG and TS varies between ~275 ms above a thinned region of MWS and ~90 ms above a region of incoherent reflectors in the middle of the line which we interpret as a MWS diapir. We interpret this to mean that the Hood Island Formation thins southwards onto a salt body in line NS-534.

The top of the Windsor Group cannot be picked with confidence in BH 1, because the Upper Windsor Group and Mabou Group fall within the cased portion of the well (MacDonald 2003). In the seismic data, a package of weak reflectors with varying lateral continuity overlies horizon TS. It is capped by a stronger and more laterally continuous positive reflection, horizon WG, which, when traced to surface, falls close to the top of the Windsor Group as mapped by Boehner and Giles (1982). We refer to horizon WG as the near-top-Windsor reflection.

Mabou Group

A package of weak, parallel reflections with variable lateral continuity conformably overlies horizons WG (Figures 2.12 and 2.13). The laterally continuous segments of these reflections are parallel to the underlying horizon WG and TS (Figures 2.12 and 2.13). In well BH 1, we interpret the top of the Hastings Formation, the basal unit of the Mabou Group, below the uppermost sandstone layer, at a measured depth of 145 m. This depth probably corresponds with a weak positive reflection, horizon HF, at -237 ms of two-way travel time (Figure 2.13). When traced to surface, horizon HF corresponds well with the mapped top of the Hastings Formation boundary of Boehner and Giles (1982) and therefore is interpreted as a near-top-Hastings Formation reflection.

The reflections that overlie the Hastings Formation, representing the Pomquet Formation, show large differences in character between and even within single seismic lines. For example, in line CON-01 the reflections are weak, irregular, and discontinuous. In comparison, in line NS-535 several Pomquet Formation reflections change from strong and continuous in the north to weak and less continuous in the south (Figure 2.12). The vertical thickness of the Pomquet Formation varies dramatically from line to line, ranging from absent in line CON-01, to 446 ms, or approximately 890 m, in Northstar line NS-535 (Figure 2.12). Line NS-534 contains the thickest package of strata overlying the MWS. This package is up to 650 ms thick, representing a depth of ~1.3 km. This is the maximum possible thickness for the Mabou Group in the Antigonish sub-basin, significantly less than previous estimates (e.g. Boehner and Giles 1993). However, in line NS-534 the true maximum thickness of the Mabou Group is likely ~1.1 km as we interpret a minimum of ~90 ms of Hood Island Formation (~0.18 km) to also be present above the MWS.

Reinterpreted Faults

In line NS-535, horizons TS, WG and HF all dip north away from a region of poor coherence, which we refer to as the Pomquet Harbour structure, at the mapped location (Figure 2.5) of the Pomquet Harbour Fault (Boehner and Giles 1982). South of this location the reflections in line NS-535 continue to be incoherent. The basement reflection continues below the incoherent region (Figure 2.12). Similarly, in line NS-533 horizons TS, WG and HF dip west away from the Pomquet Harbour structure. An underlying region of incoherent reflections above continuous with sub-horizontal basement is also present in line NS-533 where it intersects the structure. These observations are inconsistent with a steep fault but are common features of salt diapirs in seismic data (e.g. Jackson and Hudec 2017). Dip directions in the surficial Hastings Formation outcrops change abruptly across the Pomquet Harbour structure (Boehner and Giles 1982). Northwest of the structure the beds dip northwest, whereas southeast of the fault the beds dip southeast or south. This is consistent with the interpretation of the Pomquet Harbour structure as a salt body.

The Dunmore Fault (Boehner and Giles 1982) (Figure 2.5), which we refer to as the Dunmore structure, runs sub-parallel to the Pomquet Harbour structure. However, the Dunmore structure only shows small stratigraphic offsets and is marked by little change in dip (Boehner and Giles 1982). No reflections are resolvable where this structure intersects lines CON-01, CON-03, and NS-533. The Dunmore structure is therefore likely a part of the Pomquet Harbour salt structure.

The Purlbrook Fault (Boehner and Giles 1982), which we refer to as the Purlbrook structure, extends WNW-SSE near GR 83-1 (Figure 2.5). Reflections north of this structure are sub-horizontal and easily traced in line NS-536 (Figure 2.10). The reflectors are discontinuous and dip away from a ~1.1km wide zone to the southeast where reflections are not resolvable. In surficial outcrops, the Hastings Formation north of the structure dips north, whereas the Hood Island Formation south of the structure dips south. We interpret a salt diapir in the incoherent zone in line NS-536 at the Purlbrook Harbour structure.

2.5.2 Core

Previous logging of drillhole GR 83-1 (Figure 2.10) by Boehner (1984, 1993) found a thin layer of salt in the core and placed a regional detachment surface (the Antigonish Thrust) at the top of the salt. The thickness of this salt layer is below seismic resolution. We logged 36 m of GR 83-1 core focussing on the salt interval and adjacent strata to examine the surface and to record the physical character of the salt.

The 36 m logged in this study was divided into nine units (Figure 2.14). Unit W, the basal unit in the logged interval, is the uppermost part of the Horton Group, probably the Wilkie Brook Formation. The Macumber Formation limestone makes up unit M and the anhydrite of the Bridgeville Formation forms unit B. The overlying unit S is salt-bearing breccia of the Hartshorn formation. Units H1 through H5 correspond to the overlying Hood Island Formation.

Unit W - Horton Group

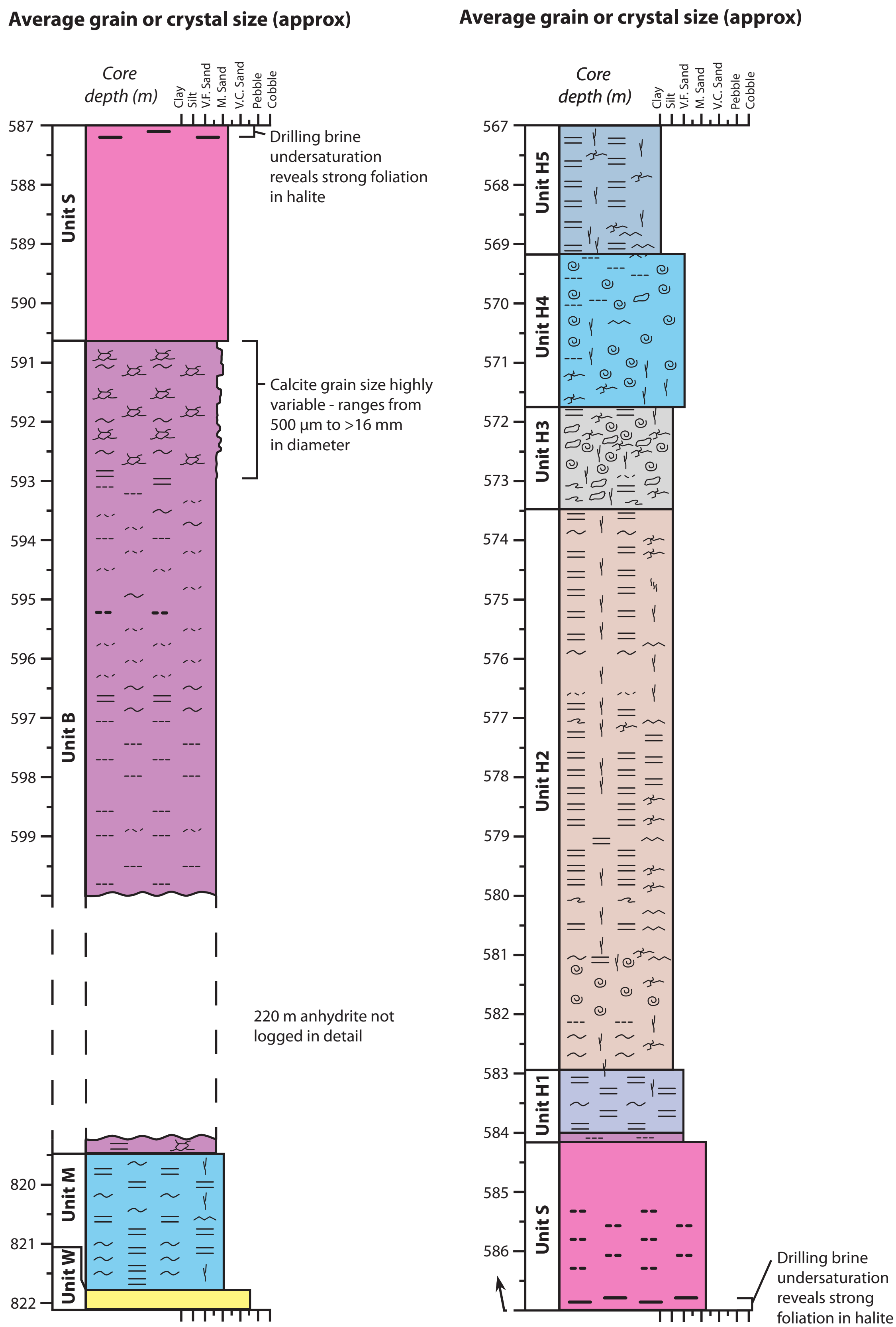
Unit W of core GR 83-1 comprises the top 0.45 m of a very poorly sorted polymictic grain-supported conglomerate unit identified as undifferentiated Horton Group by Boehner (1984, 1993) and interpreted here as Wilkie Brook Formation. The subangular clasts range from coarse sand to large pebbles (45 mm maximum diameter). The clasts are dominantly green siltstone and red plutonic rock, with minor very fine-grained metasedimentary rock. The upper contact was not visible due to core removal by previous researchers.

Unit M - Macumber Formation

The finely crystalline grey limestone of unit M was interpreted as the Macumber Formation by Boehner (1984, 1993). This unit is 2.30 m thick. The majority of the core in this unit has been removed for previous sampling, typically with only a thin slab remaining. The limestone varies between wavy and planar laminated. The laminae are dominantly light grey, with peloids concentrated along minor dark grey laminae. Previous sampling also obscured the upper contact of this unit.

Unit B - Bridgeville Formation

Unit B is calcareous anhydrite, 228.84 m thick, logged by Boehner (1984, 1993) as the Bridgeville Formation. The anhydrite is uniform in character so only the basal 23 cm and uppermost 9.36 m of the unit were described in detail. The anhydrite varies between planar or wavy laminated and mottled. In the mottled portions, agglomerates of light



Average grain or crystal size (approx)
Core depth (m)
Clay
Silt
V.F. Sand
M. Sand
V.C. Sand
Pebble
Cobble
587
588
589
590
591
592
593
594
595
596
597
598
599
820
821
822
Unit S
Unit B
Unit M
Unit W
Drilling brine undersaturation reveals strong foliation in halite
Calcite grain size highly variable - ranges from 500 µm to >16 mm in diameter
220 m anhydrite not logged in detail
Average grain or crystal size (approx)
Core depth (m)
Clay
Silt
V.F. Sand
M. Sand
V.C. Sand
Pebble
Cobble
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
Unit H5
Unit H4
Unit H3
Unit H2
Unit H1
Unit S
Drilling brine undersaturation reveals strong foliation in halite

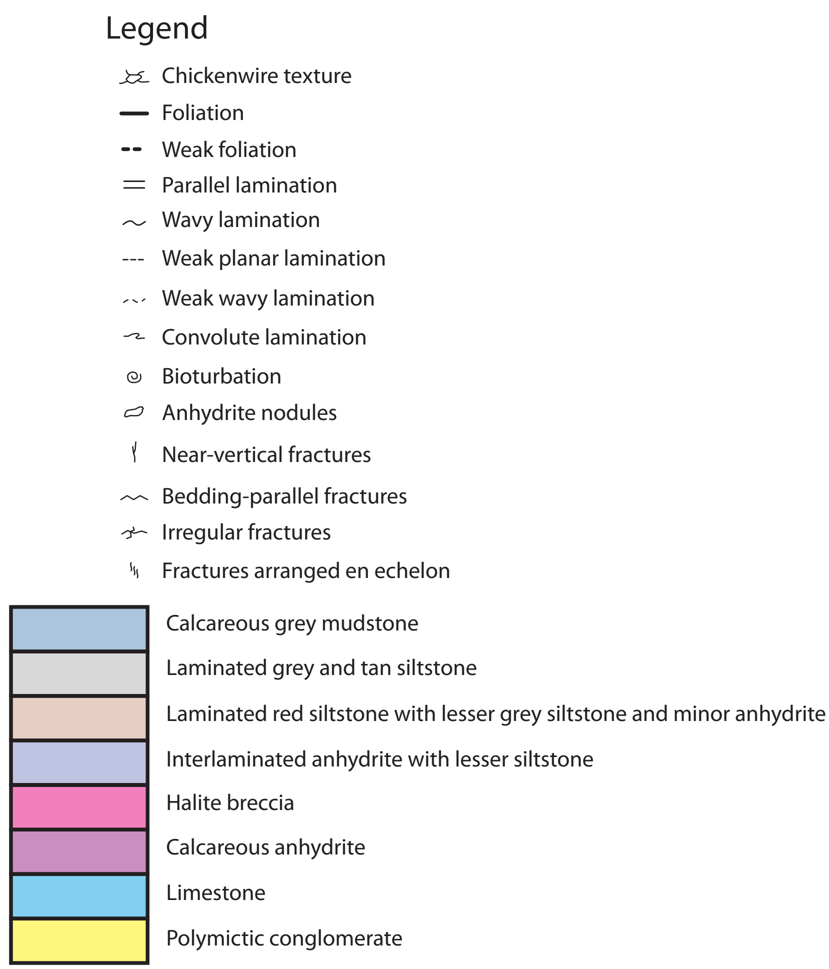


Figure 2.14. Litholog of core GR 83-1

grey anhydrite up to 15 mm in diameter are surrounded by irregular laminae of dark grey calcite.

The top 9.36 m of this unit were logged. This interval is ~70% anhydrite and ~30% calcite. In the majority of this interval, the light grey anhydrite has crystals ~63 μm in diameter while the dark grey calcite crystals are 125 to 250 μm in diameter. In the uppermost 1.5 m, calcite crystal size is highly variable, ranging from 500 μm to over 16 mm. Rare beds (≥10 cm thick) within this 1.5 m display chicken-wire texture. In a representative thin section, the crystals show weak shape-preferred orientation and common 120°-120°-120° grain boundaries, indicating that the rock has been recrystallized, probably under conditions where ions were able to diffuse to a near-equilibrium texture (e.g. Vernon 2004, Passchier and Trouw 2005).

Unit S - Hartshorn Formation

The overlying unit S consists of 3.2 m of impure halite-matrix-supported breccia of the Hartshorn Formation (Boehner 1984, 1984, 1993) (Figure 2.15). Its basal contact with the anhydrite of unit B is sharp but irregular. 10 to 60% of the core is halite, averaging about 25%. The halite is bright orange at the base of the formation and gradationally transitions into light orange-brown at the top. Crystal sizes range from 125 μm to 1 mm, averaging 250 to 500 μm. The halite supports very poorly sorted angular clasts of variably calcareous red and grey siltstone, with rare sandstone and anhydrite clasts (Figures 2.15 and 2.16). They range in size from silt particles up to 6 cm in diameter. The larger clasts typically show internal fractures with halite fill. We interpret these clasts as fragments of units that were once interbedded with the halite.

Near the middle of the unit, the core surface shows a foliation (Figure 2.16). Part of the foliated halite core is thinner than the rest of the core, indicating that the drilling brine was undersaturated. This caused selective dissolution of the salt at the core surface, revealing the foliation. This fabric is schistose and penetrative throughout the halite unit. Acicular halite crystals up to 1 cm long, visible in thin section and in breaks in the core (Figure 2.16), define a LS fabric. Abundant subrounded volumes in the halite are visible in thin section (Figure 2.16), where they occur both as irregular to subspherical bodies within halite crystals and as highly elongated shapes concentrated along grain and subgrain boundaries (Figure 2.16). These are interpreted as fluid inclusions. Their presence suggests that the halite crystals became elongated through solution and precipitation (Jackson and Hudec 2017).

Units H1 through H5 - Hood Island Formation

The rest of the core overlying the halite of unit S is interpreted as the Hood Island Formation (Boehner 1984, 1984, 1993), here subdivided into several units. Anhydrite-dominated unit H1 shows a sharp contact with the underlying Hartshorn Formation. The basal 15 cm is weakly planar laminated grey calcareous anhydrite with faint lineations, possibly slickenlines, on its lower surface. The anhydrite has an irregular, sharp upper transition that truncates laminae in the overlying interval, which is 103 cm of interlaminated dark grey anhydrite and tan siltstone. This interlaminated rock contains an estimated 30% or less of siltstone with rare discontinuous tan calcareous laminae. Discontinuous sub-vertical fractures near-parallel to the core axis are common in the upper 59 cm of this interlaminated interval. They are filled with calcite and minor halite.

The anhydrite-dominated unit H1 transitions upward into unit H2, which comprises 9.5 m of planar laminated dominantly red siltstone with lesser grey siltstone and minor anhydrite. The laminae are inclined at 80-90° to the core axis. Fractures are irregular, in some cases showing a core angle of 10° or less and in other cases parallell to bedding. The fracture widths range from hairline to 15 mm. Those near-parallel to the core axis extend up to 53 cm. Fracture fills include halite, calcite, and minor gypsum. There is no relationship between fill type and fracture orientation. Lamination displays a normal sense of offset at wider fractures.

Figure 2.15. Stitched photos of the Hartshorn Formation within GR 83-1

Photoshop has been used to minimize slight scale or lighting changes between images.

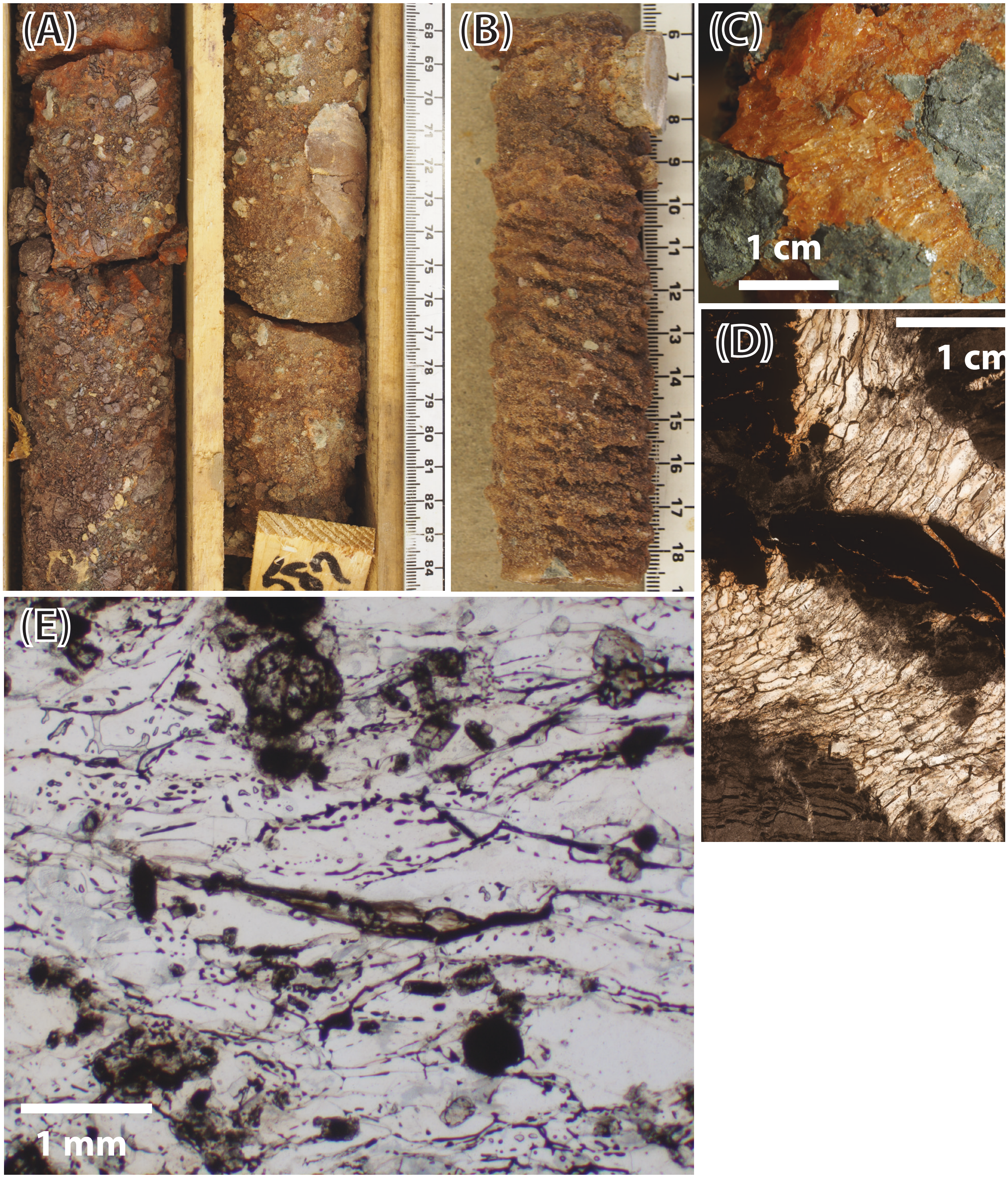


Figure 2.16. Core photographs from GR 83-1

(A) Close-up of halite breccia in core. (B) Foliated section of core. (C) Photo of end of core with elongated halite. (D) Thin section of core showing elongated crystals. (E) Close-up of thin section showing fluid inclusions, fluids along crystal boundaries

The planar laminated siltstone is in sharp contact with 1.7 m of grey and tan siltstone that forms unit H3. The basal 48 cm has convolute laminae. It contains irregular anhydrite-filled veins that in some cases connect to rare, irregularly shaped anhydrite nodules. The overlying 95 cm of grey siltstone has a mottled texture interpreted as bioturbation. Irregular anhydrite-filled fractures postdate the mottling. The uppermost 30 cm of siltstone contains abundant anhydrite nodules. A sharp contact separates the grey mottled siltstone from 30 cm of slightly calcareous tan mottled siltstone that grades into planar laminated siltstone, all with irregular calcite-filled fractures.

The calcareous siltstone has a sharp upper contact with the 2.6 m of grey to tan limestone of unit H4. The basal 35 cm are massive and very fine-grained, grading upward into medium grained mottled limestone. One irregular 2 x 7 cm anhydrite nodule was noted in the mottled limestone, unconnected to any veins. Rare weakly planar laminated intervals up to 4 cm thick occur in the mottled limestone. Fractures in the limestone are dominantly vertical and typically range from hairline to 5 mm thick with calcite fill.

The limestone has a gradational upper contact with unit H5, comprising 2.2 m of highly calcareous planar laminated grey mudstone. The grey mudstone continues to the top of the logged interval at 567.0 m below more planar laminated grey mudstone. Abundant fracturing along bedding planes indicates that the mudstone is fissile. Fractures up to 3 mm wide are filled with white calcite. Their core angles range from 10 to 40°. One white calcite vein 1.2 cm thick and 40 cm long has a core angle of 10°. At a core depth of 567.5 m another fracture and an interpreted conjugate have core angles of 30° and 40°. These conjugates have red halite fill.

2.5.3 Outcrop section at Lakevale

Since seismic data in the Antigonish sub-basin are restricted to the central portion of the sub-basin (Figure 2.10), outcrop or core data are necessary to examine salt and its remnants in the sub-basin margins. We examine a 580 m stretch of coastline at Lakevale that exposes a north-younging stratigraphic section through Mabou, Windsor, and Horton Group strata (Figures 2.17 and 2.18). Previous mapping (Boehner and Giles 1982) recorded a stratigraphic gap in the Windsor Group, which Lynch et al. (1998) mapped as the Ainslie Detachment.

Unit U – Undifferentiated Horton Group

At the south end of the stratigraphic section (Figure 2.18), over 130 m of weathered red sandstone that dips gently northwest is mapped as undifferentiated Horton Group (Boehner and Giles 1982). The oldest visible portion of this unit is >120 m of red trough-crossbedded sandstone, locally with clasts ranging up to pebbles 3 cm in diameter. The trough-crossbedding indicates that these rocks are upright. This unit grades upward into 8-10 m of pale grey sandstone. This grey sandstone contains rare lithic clasts ~1 cm in diameter. The beds, up to 1 m thick, are in some cases trough-crossbedded and massive in other cases. Moderately southwest-dipping fractures showing no visible offset extend through the Horton Group and the overlying Wilkie Brook and Macumber Formations.

Unit W - Wilkie Brook Formation

Unconformably overlying the sandstone is 1.3 m of weathered polymictic conglomerate, mapped as the Wilkie Brook Formation (Horton Group) (Boehner and Giles 1982). The unit dips north, with a sharp, erosional lower contact. The conglomerate is matrix-supported with poorly sorted subrounded to angular clasts that vary from granule to cobble size. ~30% of the clasts are brown rhyolite and ~60% of the clasts are massive green-grey very fine-grained weakly metamorphosed mudstone. The rest of the clasts are quartzose grey-green sandstone similar to, though darker in colour than, the underlying Horton Group sandstone.

Unit M1 - lower Macumber Formation

Conformably overlying the Wilkie Brook Formation is 2.4 m of planar laminated limestone that dips moderately north, marking the base of the Windsor Group. We

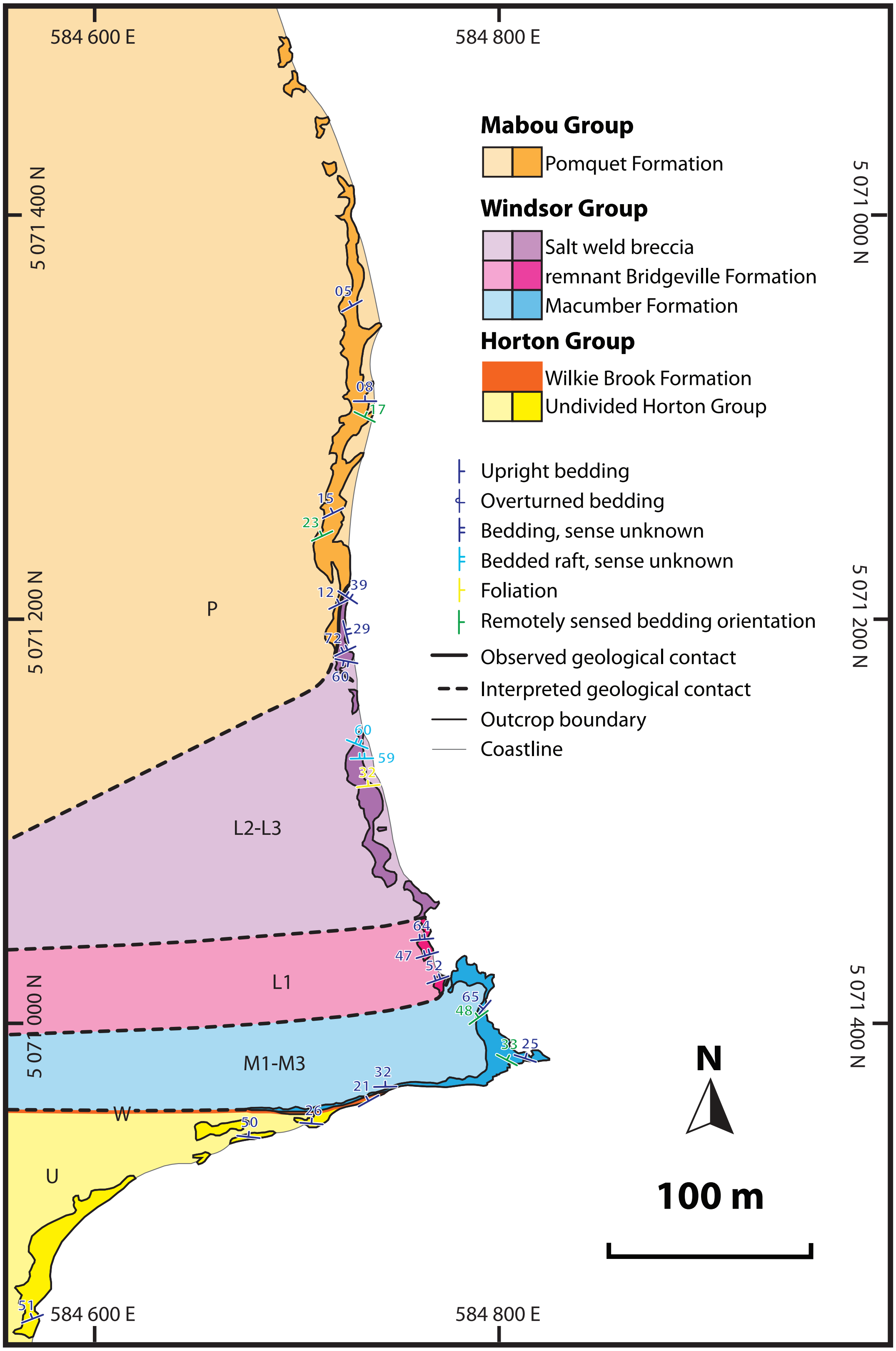


Figure 2.17. Lakevale section in map view

Constructed using orthophoto generated from 3D model in Agisoft PhotoScan (Appendix A)

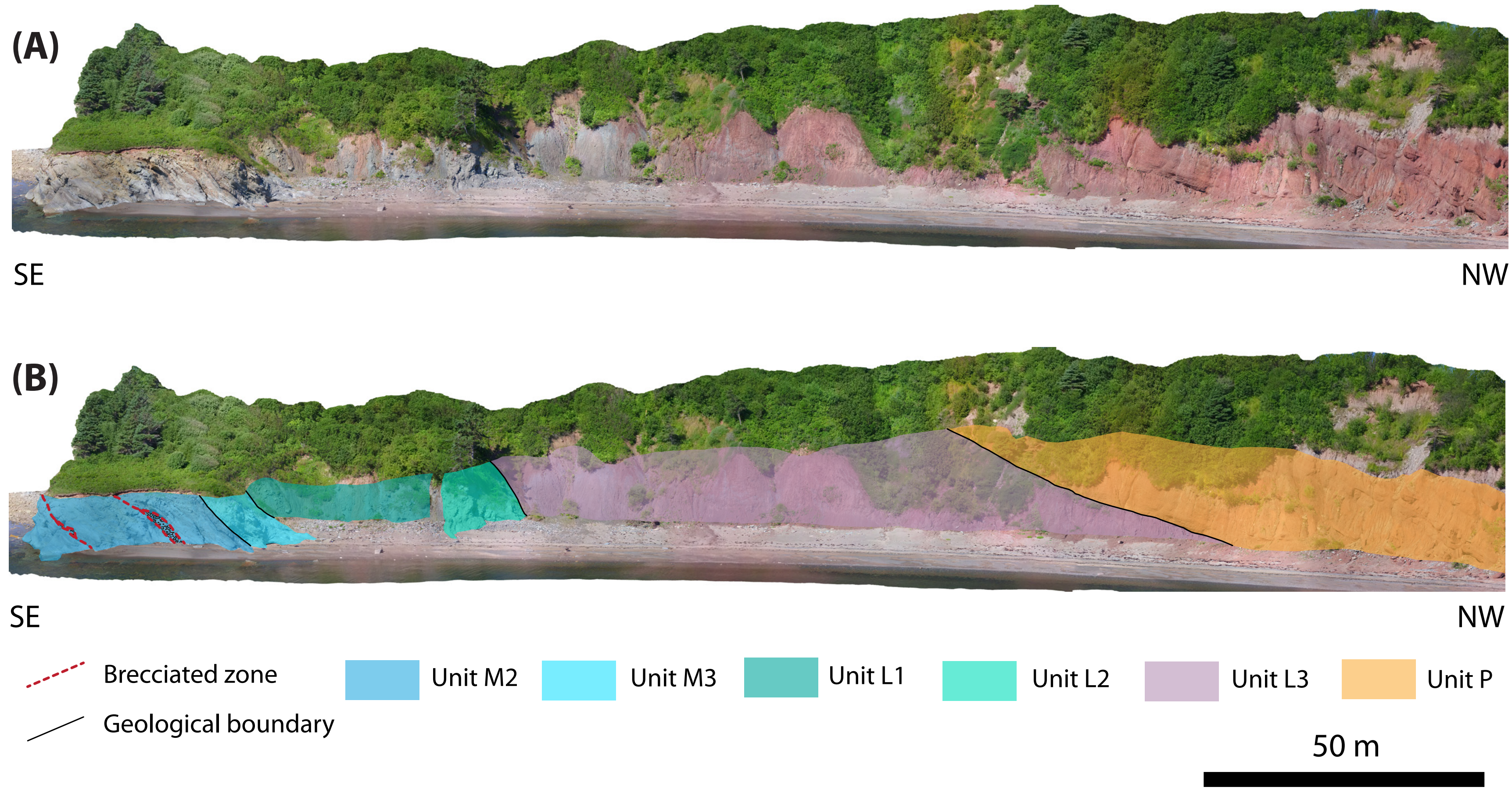


Figure 2.18. Lakevale section perpendicular to outcrop

(A) Orthophoto generated from 3D model in Agisoft PhotoScan. (B) Orthophoto with interpreted unit boundaries.

subdivide the Macumber Formation into units M1 to M3. The contact between the Wilkie Brook Formation and unit M1 is sharp. Laminae average 4 mm in thickness but range from 2 mm up to rare beds 2 cm thick. A thrust fault dipping moderately northwest offsets the base of the limestone with 1.5 m of dip separation (Figure 2.19). Minor folds occur in the hangingwall of the thrust with axial surfaces showing similar orientations to the fault plane (Figure 2.19). Several other thrusts with similar orientations and under a metre of offset extend through the planar-laminated portion of the Macumber Formation. Additionally, one thrust dips gently northeast and may be conjugate to the northwest dipping thrusts.

Unit M2 - middle Macumber Formation

Unit M2 (27.6 m thick) is laminated recrystallized limestone. The laminae in unit M2 are several millimetres thick with rare beds up to 5 cm thick. In thin section, coarser laminae with crystals ~100 μm in size alternate with laminae containing smaller crystals ~10 μm in size. In contrast to unit M1, abundant angular white polycrystalline calcite bodies, typically ~1 cm^2 in area on outcrop surfaces, occur in all but the uppermost ~3 m of the unit. The laminae in the limestone diverge toward the white calcite bodies; some laminae curve around the bodies, while others terminate at their edges (Figure 2.20). The straight sides of the calcite bodies indicate that the bodies are pseudomorphs of another mineral crystal. Some of the calcite bodies display re-entrants (Figure 2.20) implying that the replaced mineral was twinned (e.g. Bright and Ridge 1962). Their v-shaped morphology (Figure 2.20) resembles monoclinic swallow-tail twins, typical of gypsum crystals (e.g. Bright and Ridge 1962). We therefore agree with the interpretation of Boehner and Giles (1993) and Thomas et al. (2002) that these calcite bodies are pseudomorphs of gypsum. We interpret laminae that diverge around the pseudomorphs to record differential compaction, implying that the gypsum crystals were present in the limestone during early diagenesis. The crystals likely grew during deposition of the limestone, indicating that hypersaline conditions prevailed early in the deposition of the Windsor Group.

Abundant folds with wavelengths and amplitudes of 10 cm or less are prevalent in the interval from 0.1 to 4.6 m above the base of unit M2. The hinges of these folds plunge gently north (Figure 2.21). Where measurable, their axial planes are moderately northwest-inclined (Figure 2.21). From 4.6 to 27.6 m above the base of unit M2 the folds increase in size, showing wavelengths and amplitudes of ≤20 cm, but a few folds reach amplitudes up to ~0.5 m. The folds in unit M2 range from angular (Figure 2.20) to rounded with tight to gentle interlimb angles. Some have kink-like geometry (Figure 2.20). Larger folds have similar hinge orientations to the smaller underlying folds while their axial planes on average are steeply northwest-inclined (Figure 2.22). Most folds verge southeast (Figure 2.23).

The limestone layers within some of the smaller folds in unit M2 are fractured (Figure 2.20). The fractures are closed and have no fill. They are approximately perpendicular to the lamination; they bound limestone fragments up to 1.5 cm long. Individual limestone laminae and groups of laminae can be continuously traced between fragments through the folds with the result that the fold morphologies are well preserved despite the brecciation. This combination of ductile folds and brittle fracturing implies that more ductile material was interlayered with the brittle limestone during deformation. Gypsum pseudomorphs present in the underlying limestone suggest evaporites as the most likely candidates for that ductile material. We interpret that ductile evaporites were interlayered with the limestone during folding (Figure 2.24). The brittle limestone fractured during folding but the surrounding ductile evaporite layers kept the limestone fragments aligned in layers during deformation. After the folding, the evaporites were removed by solution and the limestone layers were brought into contact, producing the observed geometries (Figures 2.20 and 2.24).

A lenticular region, up to 15 cm thick, of brecciated limestone fragments occurs 7.6 m above the base of unit M2. The base of this region is bedding-parallel, while the top truncates bedding. There is a second bedding-parallel zone of brecciated fragments 21.6

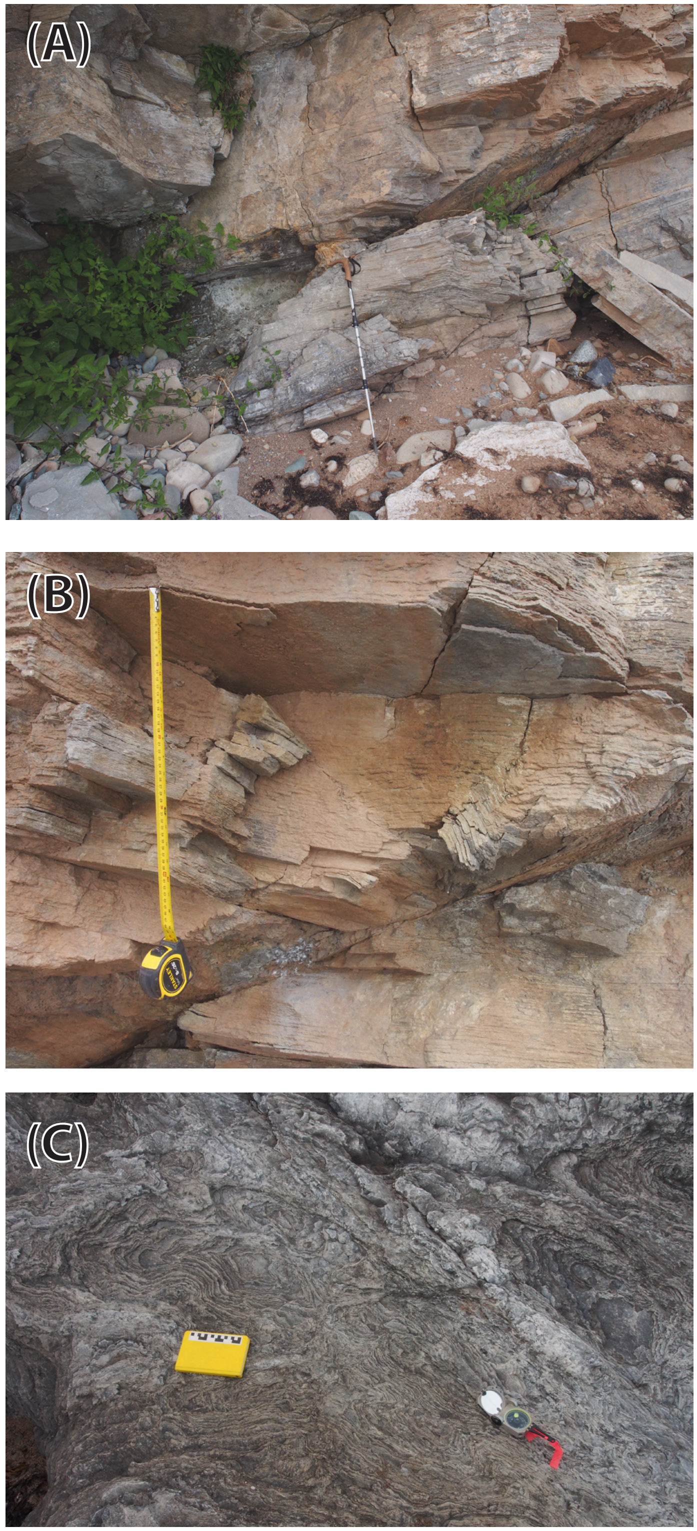


Figure 2.19. Field photographs of the Macumber Formation at Lakevale.

(A) Thrust in base of Macumber Formation, offset ~1.5 m; walking stick 1 m tall for scale. (B) Thrust fault-related folds; measuring tape 50 cm long for scale. (C) Refolded folds in the upper Macumber Formation; notebook and compass for scale.

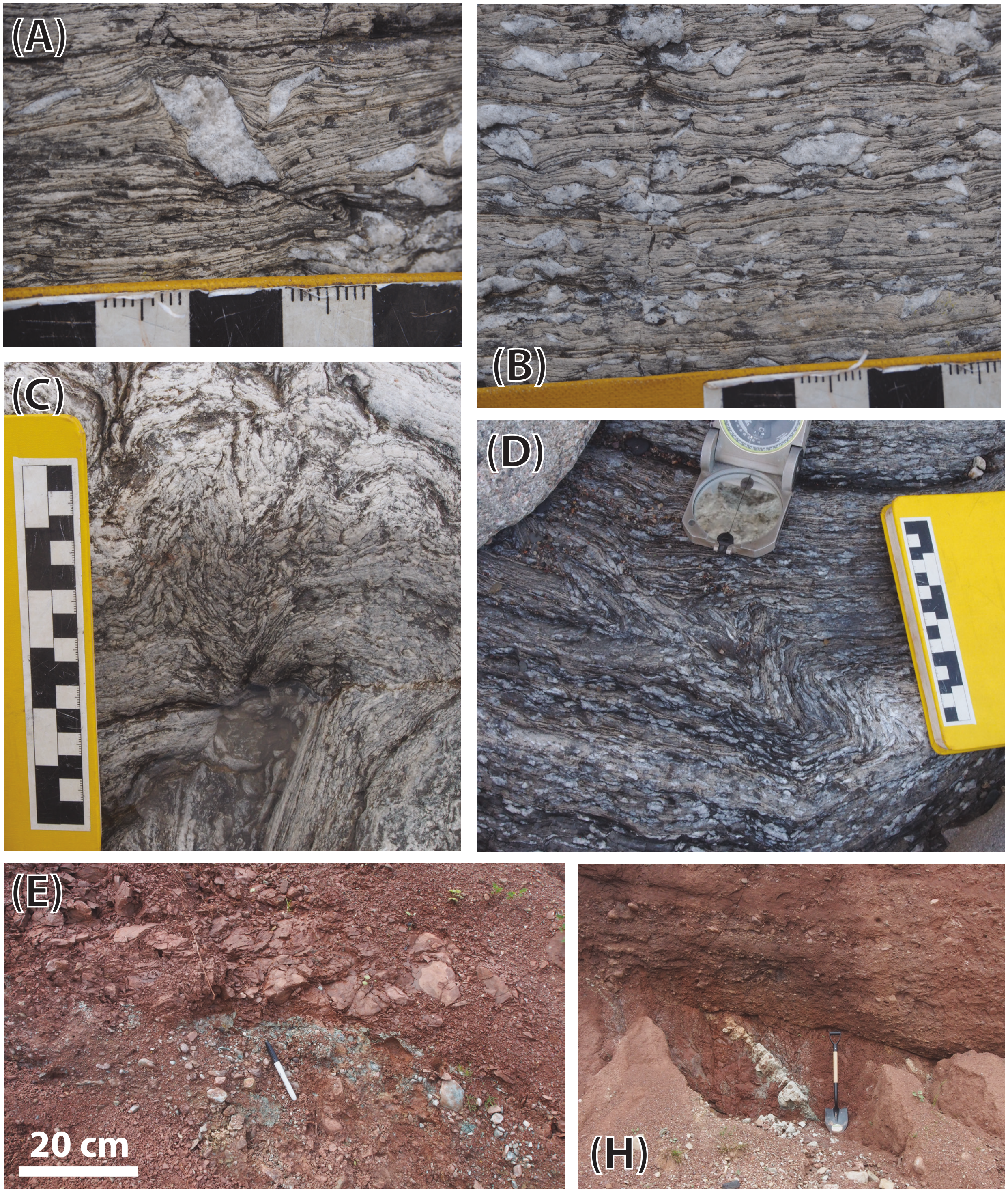


Figure 2.20. Field photographs at Lakevale.

(A, B) Gypsum pseudomorph photos showing laminae diverging away from psuedomorphs; tape on yellow notebook is in cm. (C) Angular brecciated fold in Macumber Formation; squares on notebook are centimetres. (D) Fold in Macumber Formation. (E) Siltstone breccia clasts of Unit H; pen 14 cm. (F) Angular unconformity at base of Pomquet Formation; shovel 98 cm.

m above the base of the unit. This zone is ~1 m thick but tapers to a thin horizon along strike higher in the cliff. The breccia fragments within these zones are very poorly sorted, and continuous limestone beds cannot be traced across them. These brecciated zones may represent regions where deformation was concentrated, potentially due to a locally higher proportion of evaporites.

Unit M3 - upper Macumber Formation

At the base of unit M3 is 4.7 m of brecciated planar-laminated limestone. Beds can variably be traced in aligned brecciated bedding fragments for up to several metres. The majority of the breccia fragments are oriented subparallel to the bedding of the underlying unit M2, which dips moderately north. 1.5 m of planar-laminated limestone overlies the brecciated limestone. Poorly exposed, likely open, rounded folds occur in this limestone. Hinges and axial surfaces are poorly defined, precluding measurement of their orientations. Locally a fold with a hinge plunging gently southeast folds an earlier fold with a hinge plunging gently north. This forms a type 1 fold interference pattern (Ramsay 1967) (Figure 2.19). Elsewhere, a suspected type 2 fold interference pattern is poorly exposed. The planar laminated limestone is in sharp and irregular contact with an overlying ~5 m interval of massive limestone. The upper contact of this unit is obscured.

Unit L1 - limestone and conglomerate

We subdivide the Lakevale Formation of Boehner and Giles (1993) into units L1, L2 and L3. Unit L1 overlying the Macumber Formation is a poorly exposed ~30 m section of grey limestone and conglomerate. The basal 4.5 m comprises fractured massive limestone with local planar lamination that dips moderately north. The fracturing gives the limestone a rubbly appearance. The limestone has rare siliciclastic clasts, up to granule size, of siltstone, sandstone, and possibly quartzite. In thin section it contains no clearly visible allochems, but rare regions of coarser calcite crystals suggest the past presence of allochems which have been recrystallized. The limestone grades upwards into ~2 m of

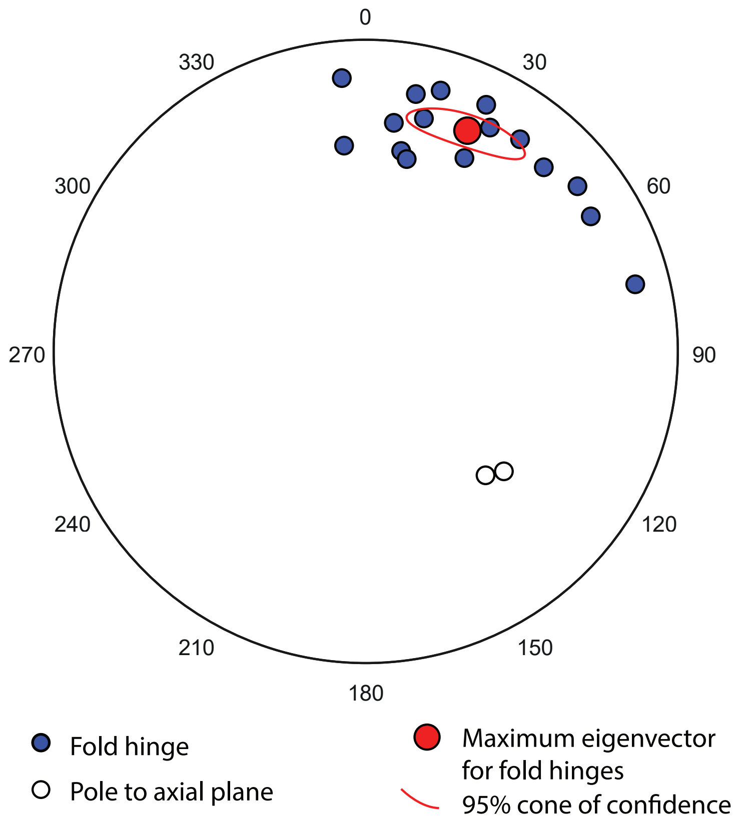


Figure 2.21. Equal area projection of small, underlying Macumber Formation folds at Lakevale

The maximum eigenvector indicates the average fold hinge orientation.

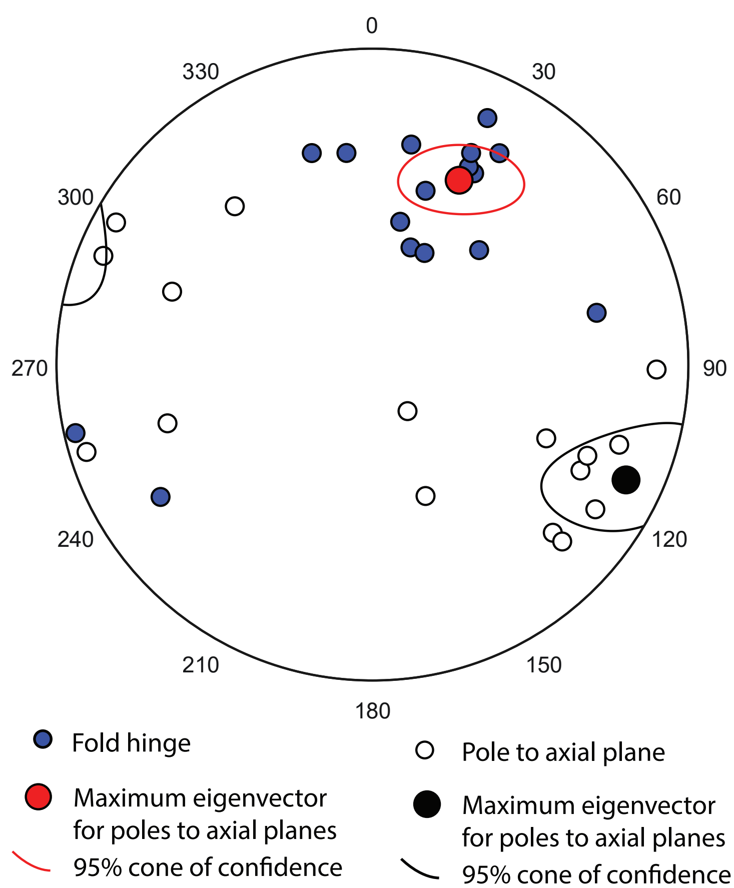


Figure 2.22. Equal area projection of larger, overlying Macumber Formation folds at Lakevale

Maximum eigenvectors represent the average orientation for each data set.

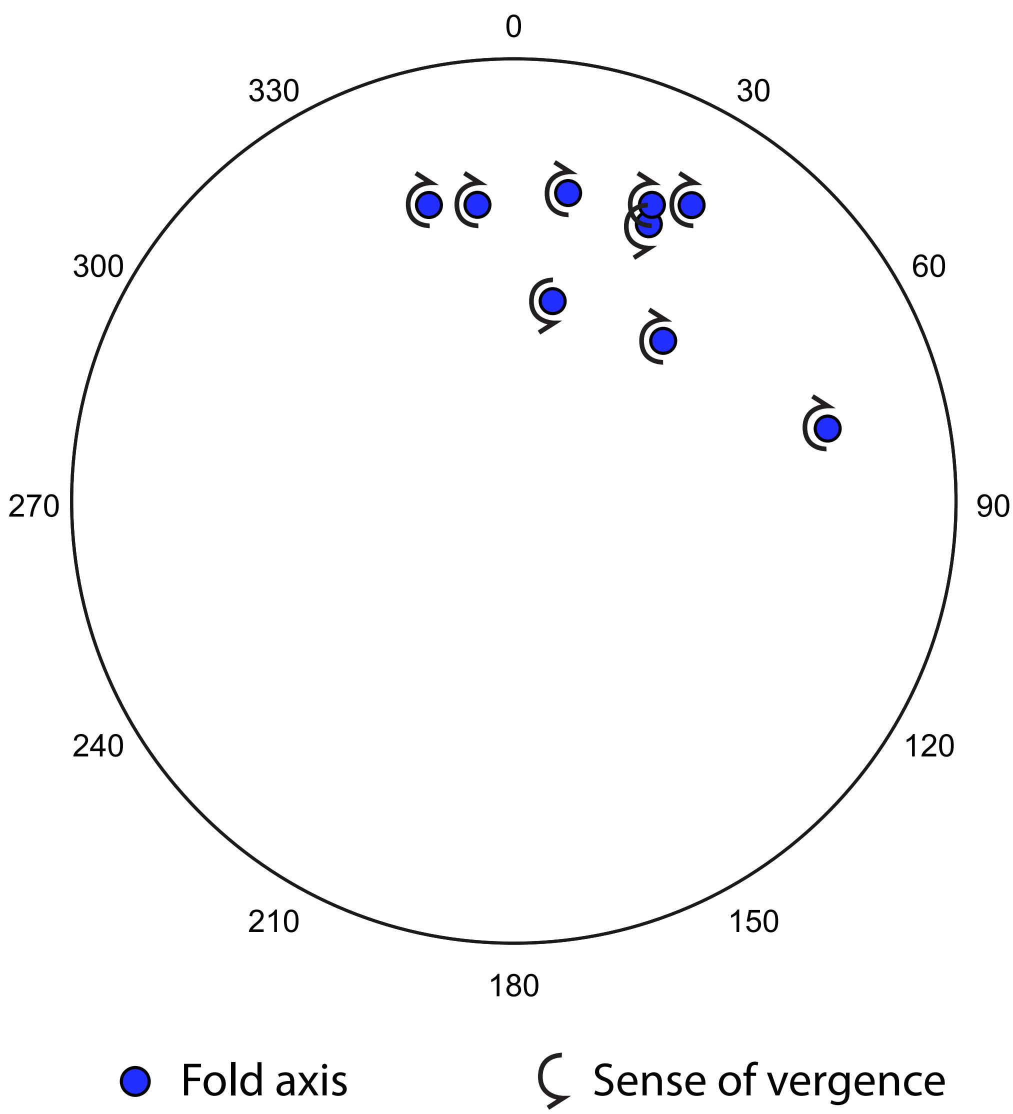


Figure 2.23. Vergence of Z and S folds at Lakevale

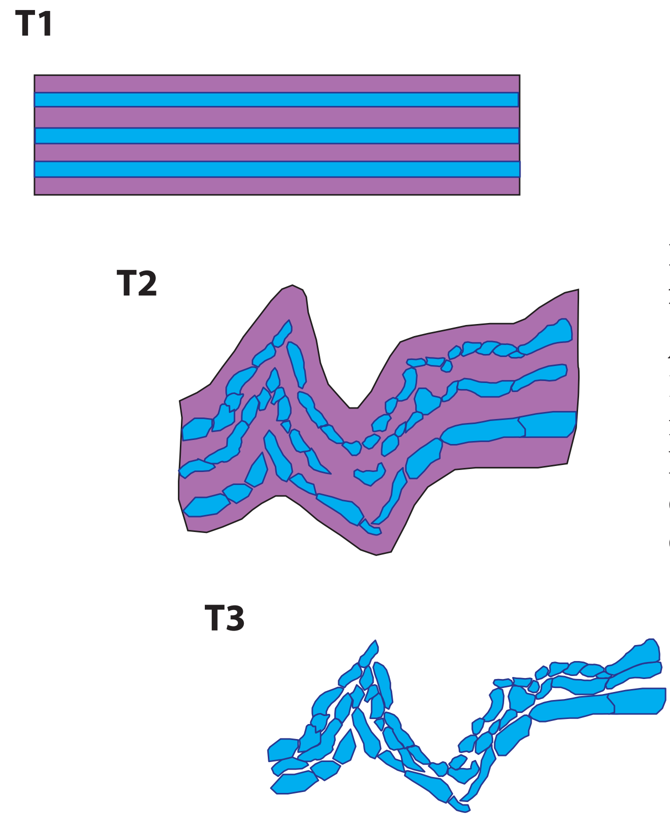


Figure 2.24. Interpretation of formation of brecciated folds

An interpretation of how the fold in Figure 2.20(C) was formed. Purple indicates evaporites and blue indicates limestone. T1 - before deformation, T2 - during deformation, T3 - post evaporite dissolution.

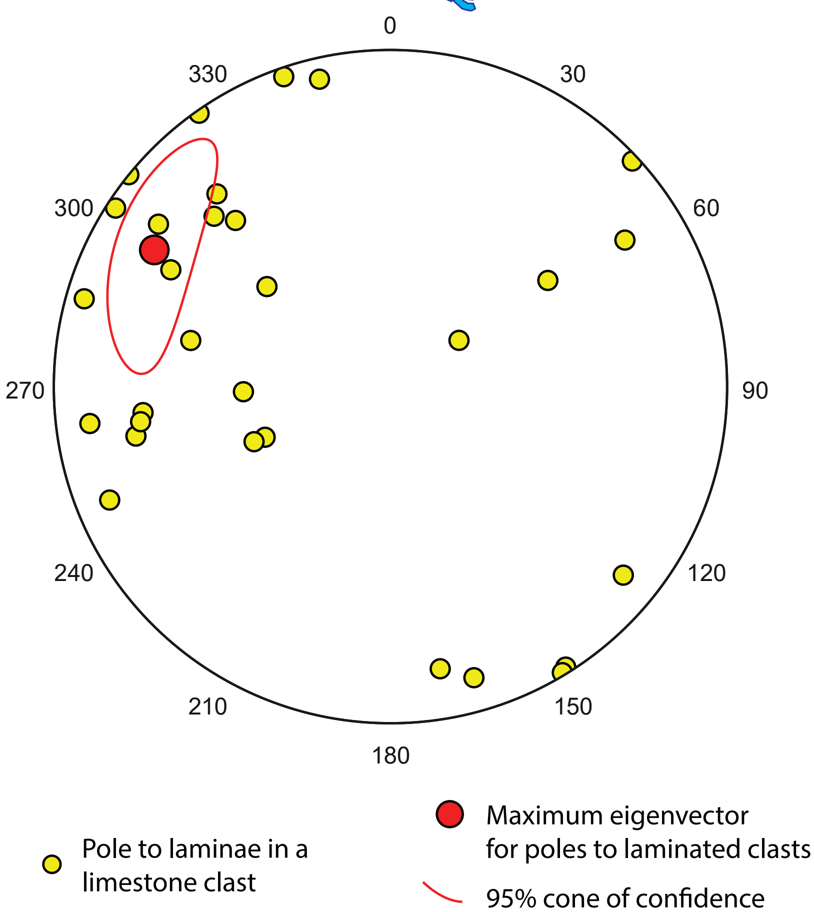


Figure 2.25. Equal area projection of clast orientations in Unit L2

The laminated limestone clasts were measured within a randomly chosen 1m^2 section of the brecciated limestone. The maximum eigenvector indicates the average pole orientation.

poorly exposed conglomerate with red sandstone clasts. The ~6 m of section to the north is obscured by Quaternary cover.

The section resumes ~12.5 m above the base of unit L1, with fractured grey limestone. The limestone has rare weak moderately north-dipping lamination at its base. ~5.8 m above the base of this limestone, minor siliciclastic clasts up to pebble-size are incorporated within the carbonate. ~9 m above the base of the limestone it grades upwards into conglomerate. The conglomerate is matrix-supported with up to pebble sized sub-rounded clasts of sandstone and siltstone with a sand sized matrix and calcareous cement. The upper contact of this unit is obscured by overburden.

Unit L2 - brecciated limestone

Overlying the rubbly limestone and conglomerate unit is 13 m of grey limestone clast-supported breccia. It contains abundant clasts of poorly sorted laminated and massive limestone up to 25 cm in diameter with an average diameter of ~4 cm. The laminated clasts appear indistinguishable from the laminated Macumber limestone lower in the section. The matrix is massive grey recrystallized limestone with the same composition as the clasts. Massive clasts can be difficult to distinguish from the matrix. The laminated limestone clasts do not show a strong preferred orientation, though the majority dip east or southeast (Figure 2.25). The upper contact of this unit is obscured by overburden.

Unit L3 – siltstone breccia

The basal ~15 m of unit L3 is composed of poorly exposed brecciated mudstone and siltstone that is dominantly grey, with minor red. The friable rubbly rock is variably calcareous. The poorly sorted breccia clasts range from medium sand to 10 cm in diameter. A weak fabric dips moderately north in the uppermost grey breccia. The incompetent breccia clasts are locally consolidated into enclaves of matrix-supported angular conglomerate with small fractured siltstone clasts and rare sandstone clasts. The conglomerate enclaves vary between matrix and clast supported.

The grey breccia is overlain by ~15 m of dominantly red fine-grained breccia at a poorly exposed irregular boundary. The boundary is gently inclined northwards. The red breccia is composed of tabular bedding-fragments predominantly of calcareous red siltstone (Figure 2.20) with rare grey siltstone and minor limestone. The fragments range up to 10 cm in maximum diameter. Minor green reduction spots up to 1.5 cm in size were observed in the red siltstone breccia. They cross clast boundaries, indicating that they post-date the brecciation. Wavy bedding in a limestone lens (1.5 m long and 0.3 m wide) dips moderately north.

Seven metres above the boundary with the underlying grey breccia, the randomly oriented bedding fragments of the red siltstone breccia transition to 4 m of oriented bedding fragments that mainly dip steeply to the north. This in turn grades upwards into 4 m of bedded siltstone at the top of the unit that moderately dips north. Unit L3 makes up the majority of the Lakevale Formation of Boehner and Giles (1982, 1993).

Unit P - Pomquet Formation

Unit P (Pomquet Formation) is angularly unconformable with the underlying siltstone of unit L3 (Figure 2.20). It consists of interbedded red conglomerate, sandstone, and siltstone paleosol. The beds dip gently northwest.

The red conglomerate layers average 2 m thick. The conglomerate is polymictic, weakly bedded, and matrix-supported. Clasts range from pebble to cobble size and include granitoid basement rock, sandstone, and rare siltstone, quartzite, and dolomite. Weakly defined 20-30 cm graded intervals occur in many conglomerate layers. Each conglomerate is overlain by a red sandstone interval, typically 40 cm thick. The sandstones variably show weak planar lamination or trough crossbedding. The trough crossbedding indicates that the Pomquet Formation is upright. Weak graded bedding rarely occurs in the sandstones. Overlying each sandstone is a poorly exposed horizon, on average 60 cm thick, consisting of highly weathered red siltstone. No root traces or soil horizons were visible in the silt but a lumpy texture and lack of stratification led us to interpret these fine-grained layers as paleosols.

These packages (paleosol over sandstone over conglomerate) were interpreted as fining-upwards sequences, with the conglomerates at the base. Six sequences were observed in the well-exposed portion of this unit. Similar red siliciclastic lithologies are present in intermittent exposures to the north.

2.5.4 MacIsaacs Point

At MacIsaacs Point, a section of coastline 620 m long exposes the upper Horton Group and the basal units of the Windsor Group (Figure 2.26). MacIsaacs Point allows further examination of the strata immediately below the regional detachment surface previously called the Antigonish Thrust (Boehner and Giles 1982, 1993) and the Ainslie Detachment (Lynch and Giles 1995).

Unit U – Undifferentiated Horton Group

The oldest stratigraphic unit at MacIsaacs Point is red trough-crossbedded medium grained arkosic sandstone with interbedded red mudstone assigned to the Horton Group. Many sandstone beds contain 5-15 cm thick pebble lags of poorly sorted sub-rounded to sub-angular clasts that range from granule to pebble sized. These lags are composed of clastic and igneous basement clasts. The Horton Group is upright, based on the crossbedding, and dips steeply east. Abundant fractures and small faults were observed throughout the sandstone. The overlying units do not display the same degree of fracturing and so most of this deformation likely predates the deposition of the younger units.

Unit W - Wilkie Brook Formation

Unconformably overlying the undifferentiated Horton Group is grey-green angular conglomerate with calcareous cement, a sandstone matrix, and clasts composed of fine to coarse feldspathic greywacke. This poorly sorted conglomerate varies from 15 to 55 cm thick. As at Lakevale, there is an angular unconformity between the Wilkie Brook Formation and the underlying red clastic undifferentiated Horton Group (Figure 2.27).

Unit M1 - lower Macumber Formation

Conformably overlying the Wilkie Brook Formation is 2.5 m of grey planar laminated limestone that dips moderately east or southeast, mapped as Macumber Formation by Boehner and Giles (1982). As at Lakevale, we have subdivided the Macumber Formation at MacIsaacs Point into three units. Unit M1 is the lowermost Macumber Formation limestone. Rare unidentifiable fossil fragments were seen in thin sections of the grey planar laminated recrystallized limestone. Rare layers show concentrations of spherical peloids up to 5 mm in diameter.

Fractures and minor faults, usually with 5 cm or less of slip and a variety of orientations, were observed in unit M1 (Figures 2.28 and 2.29). These include several east-west striking fractures and east-west minor near-vertical dominantly strike-slip faults with a component of normal movement. Several fractures instead steeply dip to the south. In some cases the fractures are filled with calcite. Two faults showed more displacement; a gently northwestern dipping thrust, and an inferred fault (Figure 2.26) with a northeast-southwest strike and dextral strike separation of about 5 m.

Sinistral tension gash sets of calcite-filled veins arranged en echelon (Figure 2.27) also occur in unit M1. Though the orientations of these sets are variable as seen in Figure 2.30, on average the sets dip steeply north, whereas individual veins within each set tend to dip steeply northwest (Figure 2.30). A few dextral vein sets striking east-west were also observed at the southernmost part of the section. The en echelon vein sets imply north-south extension and east-west shortening.

Gentle folds with wavelengths of several metres are present in the planar laminated limestone. These folds plunge gently south and are steeply inclined to the southwest (Figures 2.31 and 2.32). The orientations of the folds imply northeast-southwest

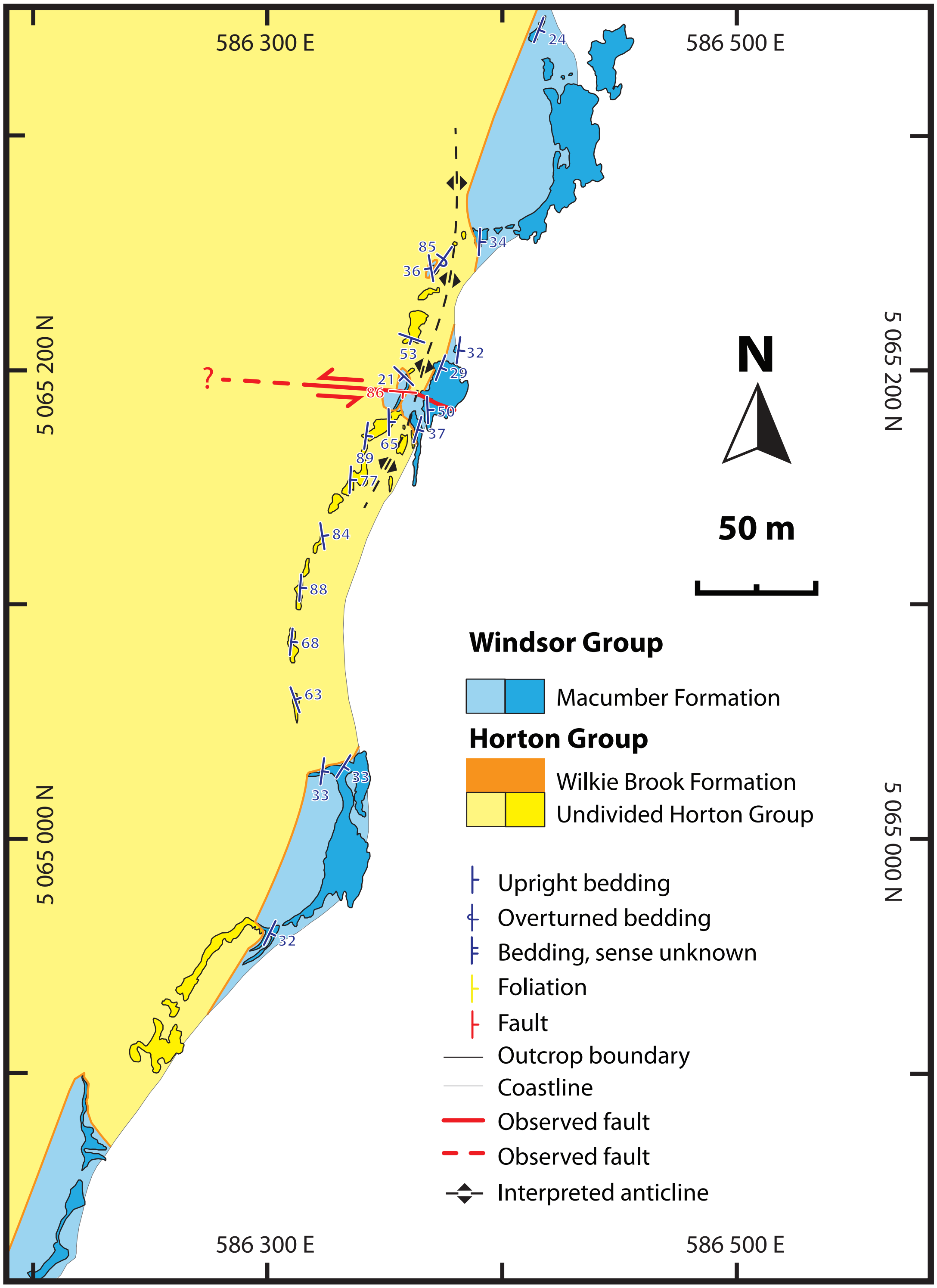


Figure 2.26. MacIsaacs Point section in map view

Map constructed on orthophoto generated from 3D model in Agisoft PhotoScan (see Appendix B).

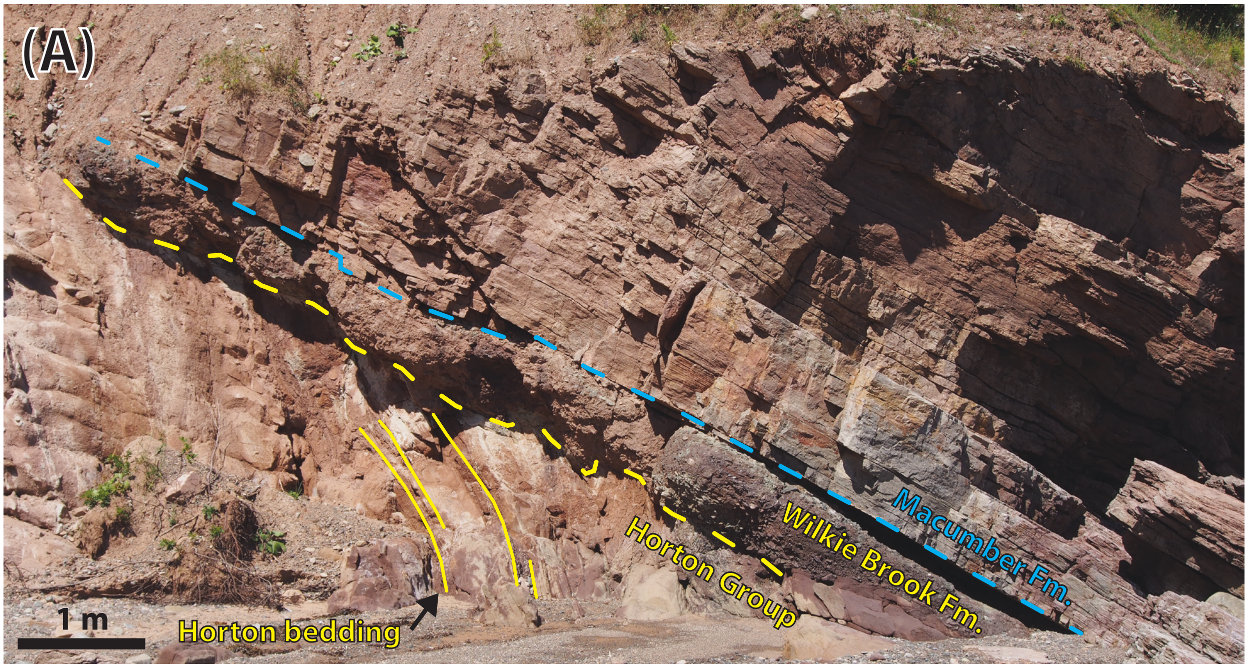
shortening. The fractures, faults, and vein sets were not folded, suggesting that they post-date the folding.

Unit M2 - middle Macumber Formation

Recumbent to upright folds are abundant in the recrystallized laminated limestone in the overlying 10-12 m of section at MacIsaacs Point, referred to as unit M2. As at Lakevale their morphologies are diverse, with interlimb angles ranging from open to tight. Their sizes vary from the centimetre scale to rare folds with wavelengths over a metre in size, somewhat smaller than the folds at Lakevale. The majority of the folds are moderately inclined to the southwest as seen in Figure 2.31, while their fold hinges are sub-horizontal to gently south-plunging. The down-plunge sense of vergence in asymmetric folds is dominantly eastward (Figure 2.32). Several of the folds display morphologies like those observed at Lakevale, where angular fragments of limestone mark the traces of smoothly curving folds (Figure 2.27). Evaporites are interpreted to have been interlayered with the limestone layers during deformation and were subsequently removed by solution.

Unit M3 - upper Macumber Formation

The 37 m of limestone of unit M3 contains a gradual transition from the top of the laminated, folded limestone of unit M2 into breccia of poorly sorted angular laminated and non-laminated clasts ranging from 4 mm to 20 cm in diameter. In some places this transition is gradual and in other places along-strike it is sharp. The limestone is recrystallized with irregular crystal boundaries showing evidence of pressure solution. In thin section, minor quartz grains are seen within the limestone. The top of the formation is not exposed here. The breccia of unit M3 at MacIsaacs Point appears very similar to the brecciated limestone of unit L2 at Lakevale.



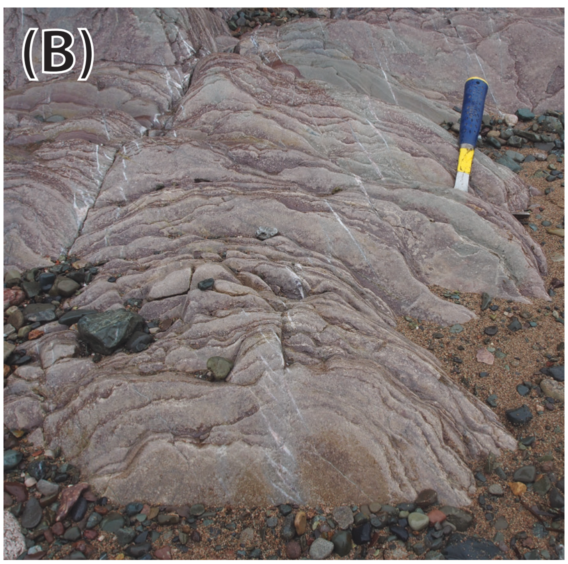
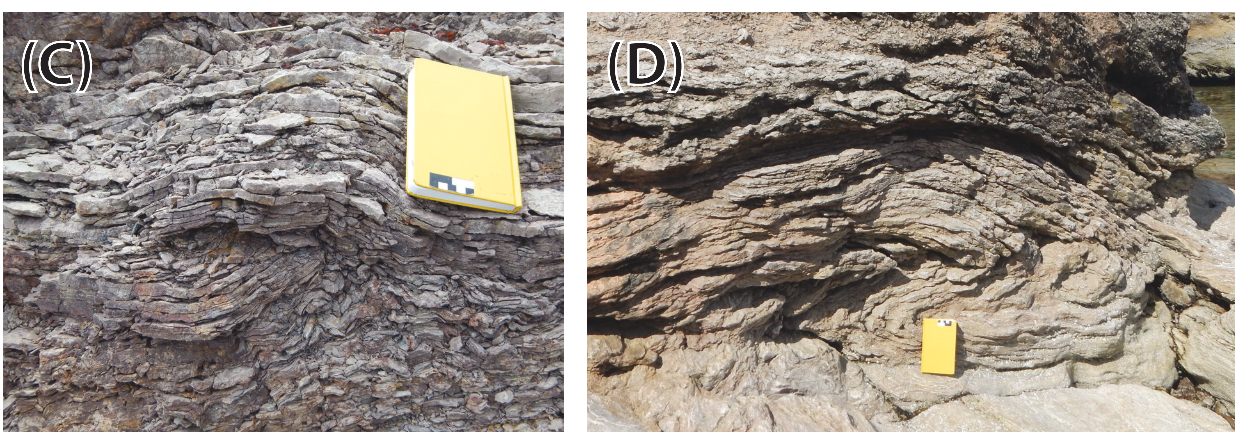


Figure 2.27. Field photographs at MacIsaacs Point.

(A) Angular unconformity between the Horton Group and the Wilkie Brook and Macumber Formations. Photo taken while looking ~north. (B) En echelon veins in Macumber Formation; hammer for scale. (C, D) Brecciated folds in Macumber Formation limestone; notebook for scale.



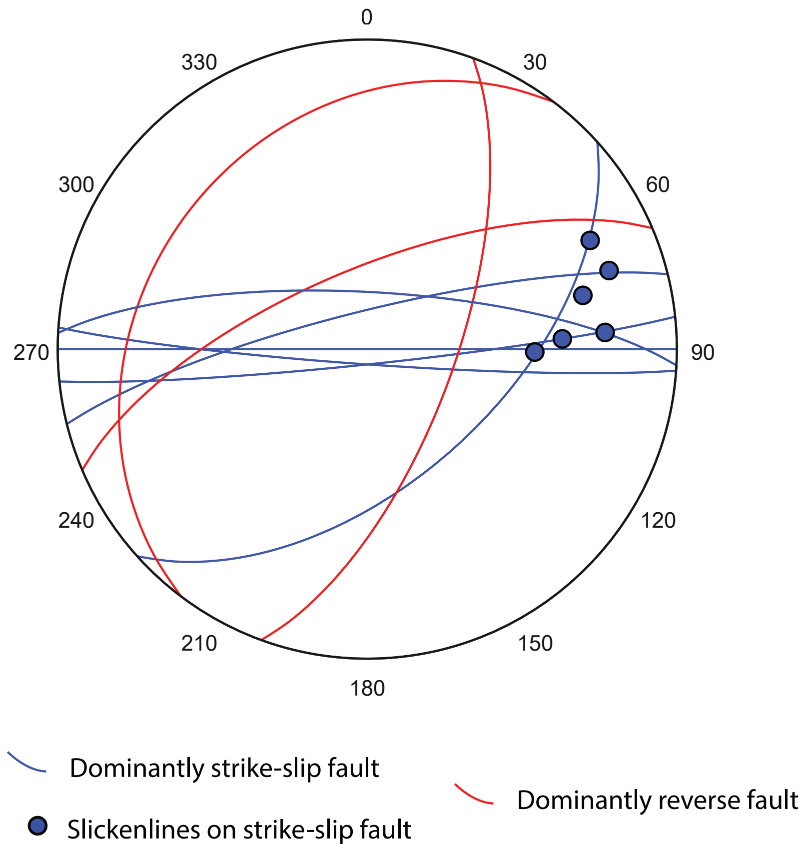


Figure 2.28. Orientations of faults in the Lower Macumber Formation at MacIsaacs Point

Slickenlines did not occur on the reverse faults.

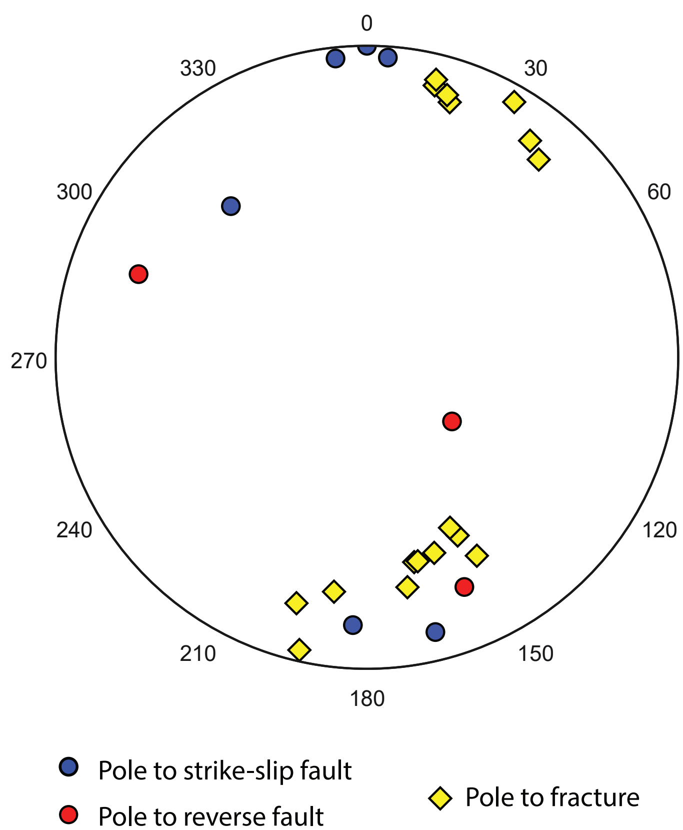


Figure 2.29. Orientations of fractures in the Lower Macumber Formation at MacIsaacs Point

Poles to the fault planes in Figure 2.28 are included in this figure for comparison with the fracture orientations.

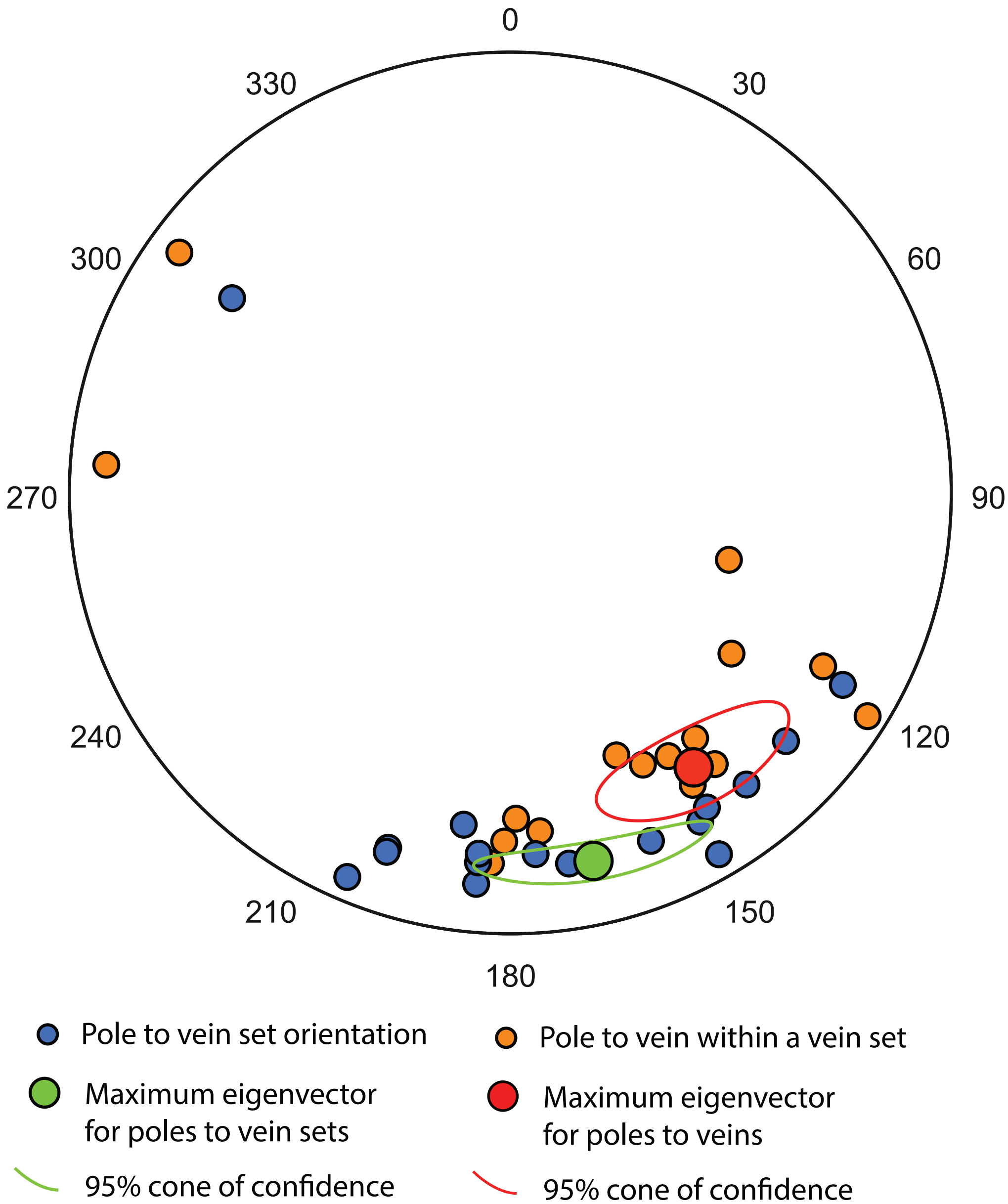


Figure 2.30. Tension gash vein set and fibre orientations at MacIsaacs Point

Maximum eigenvectors indicate average orientations for the each dataset.

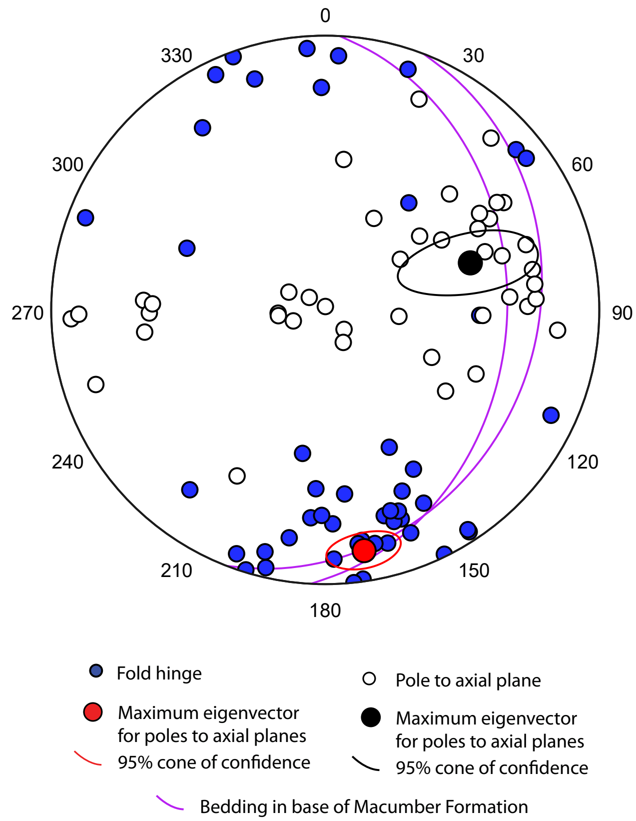


Figure 2.31. Equal area projection of folds in the Macumber Formation at MacIsaacs Point

Maximum eigenvectors show average orientations for the data sets.

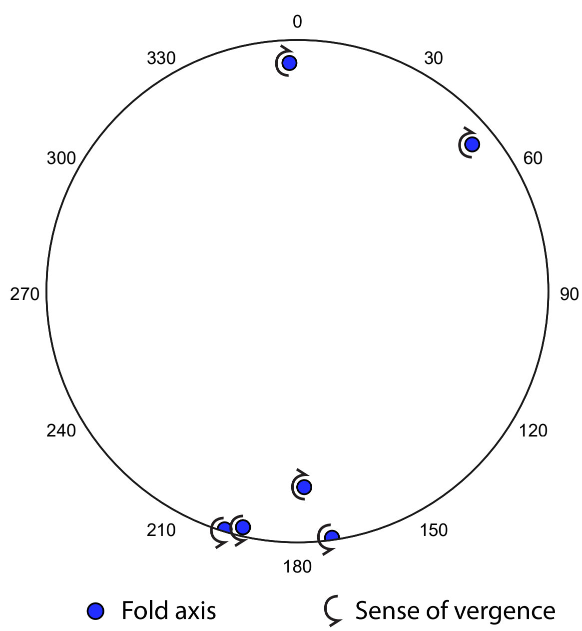


Figure 2.32. Vergence of Z and S folds at MacIsaacs Point

2.6 Discussion and interpretation

2.6.1 Sub-basin history

Macumber Formation: distribution of structures

Thrusts at Lakevale extend down into the underlying Wilkie Brook Formation and Horton Group but do not continue up into the middle Macumber Formation, implying either that the folds and tension gashes formed prior to middle Macumber Formation deposition, or that deformation was accommodated by bed-parallel motion in the overlying evaporite units.

The Macumber Formation becomes progressively more deformed from the basal planar laminated limestone to the breccia at the top of the formation. We interpret the cause of the upwards-increasing-deformation as drag from movement of the overlying Bridgeville Formation anhydrite and Hartshorn Formation halite (Figure 2.7). However, studies in evaporite basins elsewhere suggest that typically there is little or no deformation in the strata on the sides and bases of salt bodies from drag caused by the salt unless the surrounding strata are very weak (e.g. Rowan et al. 2003, Schultz-Ela 2003). Observations of the Macumber formation, especially the brecciated folds (Figures 2.20 and 2.27) suggest that deformation was facilitated by the presence of evaporite layers interlayered in the Macumber Formation limestone. Interlayered evaporites would have weakened the Macumber Formation, enabling deformation to occur in response to low stresses transmitted from overlying moving units.

Lower Windsor Group evaporites

Although the Lower Windsor Group evaporites are typically thick across the Maritimes Basin, they are discontinuous in the Antigonish sub-basin. The Bridgeville Formation is present in most sections, though notably absent, along with much of the overlying stratigraphy of the Windsor Group, at Lakevale. We suspect that the carbonate-dominated unit L1 at Lakevale represents the remnants of the Bridgeville Formation after removal of sulfate by solution. The Bridgeville Formation in core GR 83-1 contains abundant calcite, and thin limestone beds are interlayered with the anhydrite of this formation throughout the Antigonish sub-basin (Boehner and Giles 1993). If the anhydrite were removed from the Bridgeville Formation (unit B) of core GR-1, leaving the calcareous component, the result would be similar to unit L1 at Lakevale. Therefore, we interpret unit L1 as remnants of the anhydrite-dominated Bridgeville Formation.

Thick sections of Hartshorn Formation salt recorded by drilling are concentrated at sub-basin margins, where seismic data are most difficult to interpret or do not exist. Our observations of this horizon in drillhole GR 83-1 show only 3.2 m of highly deformed salt, suggesting that the majority of the Hartshorn Formation was expelled at this location. A thicker possible body of Hartshorn salt is interpreted on seismic line CON-01 (Figure 2.12). The presence of the Hartshorn Formation in salt diapirs around the sub-basin margins and its absence in the middle of the sub-basin suggests that salt moved away from the centre of the sub-basin and accumulated in basin-marginal diapirs, forming a salt weld across the centre of the sub-basin. We therefore interpret the omission surface previously known as the Antigonish Thrust or the Ainslie Detachment as a primary salt weld.

The Lower Windsor salt in GR 83-1 contains abundant silt fragments of mudstone layers that were originally interbedded with salt. No salt remains in equivalent outcrop sections because of solution, but structureless siltstone breccia is common. Based on our observations in core, we interpret this siltstone breccia lithology as residue of evaporite layers from which the halite has been removed by solution during exhumation. The deformed limestone lithology at the base of the siltstone breccia may have been a raft within the diapir. Alternatively, this unit, together with remnants of stratified Windsor Group at the top of the siltstone breccia, may represent the middle or upper Windsor Group.

The substantial thickness (~45 m) of the siltstone breccia at Lakevale shows that a significantly thicker salt body once existed here. This body may have prevented the deposition of much of the Middle and Upper Windsor Group, which explains the stratigraphic gap between unit L3 and the overlying Mabou Group (unit P).

Features of the Middle Windsor Group

Intact Middle Windsor Group is absent in the outcrop sections described here. However, in seismic data we identify a variety of salt structures within the Middle Windsor Group, indicating the presence of substantial Middle Windsor salt (MWS). The MWS is concentrated in diapiric structures clearly displayed on seismic profiles (e.g. Figures 2.13 and 2.12). Many of these structures are observed in the centre of the sub-basin, suggesting that movement in the MWS occurred from the sub-basin margins to the centre of the sub-basin. These salt structures roughly follow "faults" mapped by Boehner and Giles (1982), who did not have the benefit of seismic data. Bedding orientations show many areas of divergent younging directions, which are more easily explained by diapirism than by fault movement.

The MWS is thinnest beneath the thickest regions of overlying strata. We interpret these areas as salt-withdrawal minibasins, the MWS having been expelled from beneath the overlying Upper Windsor Group and Mabou Group. Line NS-535 shows an excellent example of a salt-withdrawal minibasin (Figure 2.12). We interpret the significant thickness variations in the Mabou Group to be caused by differences in accommodation resulting from salt movement. Areas where salt moved away gained accommodation space, while areas where salt formed diapirs are characterized by thinned Mabou Group.

In many areas, however, the MWS is absent and represented only by a weld (Figures 2.12 and 2.13), such as in well BH 1 where the position of the MWS is recorded only by carbonate and sulfate fragments in the well cuttings. Therefore, the MWS is discontinuously welded across the Antigonish sub-basin.

Late Windsor Group and Mabou Group History

The Hood Island Formation is substantially more laterally continuous than the Middle Windsor Group, suggesting that it was deposited in a layer above the MWS. Divergent reflectors in line NS-534 show that accommodation of Hood Island Formation locally varied above the MWS, meaning that movement of the MWS started in the east during deposition of the Upper Windsor Group. However, most of the overlying Upper Windsor Group and Mabou Group is represented by parallel reflections deformed so that they are concave-upwards between diapirs, demonstrating that the majority of MWS movement post-dated deposition of the Pomquet Formation.

Timing of salt movement

The timing of Lower Windsor Group salt expulsion is uncertain. However, seismic line NS-533 shows a lenticular, convex-up body of Middle Windsor strata that indicates localized accommodation during its deposition. We therefore interpret this body as a turtle structure, which records a minibasin that developed as Lower Windsor salt was expelled during deposition of the Middle Windsor Group. Additionally, the overlying Upper Windsor Group and Mabou Group reflectors are typically parallel, showing that they were deposited upon a flat surface. Therefore, salt expulsion from the Lower Windsor Group was occurring during deposition of the Middle Windsor Group, and concluded prior to the deposition of the Hood Island Formation. It is likely that Lakevale represents an area of diapiric accumulation of Lower Windsor Salt (now represented only by siltstone breccia of unit L3, attributed to the Lakevale Formation). This salt body largely prevented accumulation of the Middle and Upper Windsor Group, accounting for the stratigraphic omission formerly explained by the Ainslie Detachment hypothesis. Subsequent collapse of this salt diapir, a process common in salt provinces on passive margins (Vendeville and Jackson 1992), juxtaposed the younger Mabou Group strata on diapir remnants previously mapped as Lakevale Formation.

The timing of movement of Middle Windsor Salt (MWS) is potentially indicated by thickness variations in the overlying strata of the Upper Windsor and Mabou Groups. The most recent estimate of the thickness of the Mabou Group in the Antigonish sub-basin prior to this study was 3900 m (Boehner and Giles 1993). This is unusually thick for a sub-basin in the Maritimes Basin. We initially hypothesized that salt expulsion increased the accommodation space, enabling this extreme thickness of the Mabou Group. However, in seismic data the Upper Windsor Group shows only localized thickness variations, mainly in the eastern Antigonish sub-basin, and the majority of the Upper Windsor and Mabou strata are parallel. The Upper Windsor Group is typically ~200 m thick, while we interpret the Mabou Group to have a maximum thickness of ~1100 m, which is consistent with the typical 1000 m of Mabou Group found in the Maritimes Basin (Gibling et al. 2009). This, together with the typical uniform lateral thicknesses of the overlying Upper Windsor Group and Hastings Formation, suggest that salt expulsion did not create large amounts of accommodation space for deposition of the Upper Windsor or Mabou Group strata, but that significant salt movement post-dated the Mabou Group, as in the western part of the Cumberland sub-basin (Waldron and Rygel 2005, Waldron et al. 2013).

Direction of salt movement

Thrust faults at Lakevale, NW-dipping tension gashes at MacIsaacs Point, and folds at both locations indicate east-west shortening in the lower Macumber Formation, confirming the inferences of Thomas (2002). At both locations, our fold measurements from the middle Macumber Formation indicate vergence to the east and southeast respectively. Neither the predominance of contractional structures, nor the west-over-east sense of vergence, is consistent with the Ainslie Detachment hypothesis, which would predict SE-over-NW motion and a predominance of extension in this region (Lynch et al. 1998). A more likely hypothesis is that deformation of the Macumber Formation resulted from a history of halokinesis in overlying and interbedded evaporites.

To deform the Macumber Formation, any drag from Hartshorn or MWS salt movement would first have to significantly deform the anhydrite of the Bridgeville Formation. No Bridgeville Formation anhydrite is found at Lakevale or MacIsaacs Point. However, a coastal outcrop section at Crystal Cliffs (Figure 2.5), 900 m southwest along the coast from the southern end of the MacIsaacs Point section, includes ~20 m of the Bridgeville Formation (Boehner 1980). The Macumber Formation at Crystal Cliffs shows the same upwards-progressing deformation (Boehner 1980) present at MacIsaacs Point and Lakevale. However, the anhydrite of the Bridgeville Formation shows minimal deformation and is not folded (Boehner 1980) and the thick section of Bridgeville Formation anhydrite in drillhole GR 83-1 does not show evidence for deformation apart from recrystallization. This lack of deformation in the Bridgeville Formation suggests that if salt movement was the cause for the deformation of the Macumber Formation, the entire Bridgeville Formation must have slid as one layer.

Movement in the Hartshorn Formation is unlikely to have deformed the Macumber Formation. We interpret the Hartshorn Formation halite to have moved from the centre of the sub-basin towards its margins. Fold data from outcrops of the Macumber Formation and seismic data for the MWS show evidence of salt movement towards the centre of the sub-basin. Therefore, MWS movement was probably responsible for Macumber Formation deformation.

Sub-basin history

We use our conclusions on salt movement within the Antigonish sub-basin to present the following model for the history of deposition and salt movement within the sub-basin.

1. A horst developed between Morristown and Glenroy faults and the Horton Group was mainly deposited in lows on either side of the horst
2. The Lower Windsor Group was deposited, probably across most of the Antigonish sub-basin.

3. Salt expulsion in the Hartshorn Formation began within the centre of the sub-basin during the deposition of the Middle Windsor Group.

4. The Hartshorn Formation formed a primary weld in the centre of the sub-basin and diapirs around the margins. These diapirs locally prevented Middle Windsor Group deposition.

5. The Middle Windsor Salt (MWS) was deposited as a layer across the centre of the sub-basin.

6. The deposition of the Upper Windsor Group began. At the same time, expulsion of the MWS initiated in the eastern portion of the sub-basin.

7. Expulsion of the MWS continued in the east but the rest of the salt remained relatively immobile as the Upper Windsor Group and the Mabou Group were deposited.

8. Movement of MWS occurred across the sub-basin, forming structures such as diapirs and welds. Basin-margin diapirs of Hartshorn salt collapsed; as the salt thinned to near-zero thickness in basin-margin areas, interlayered limestone and gypsum in the Macumber formation were deformed, producing folds, thrusts, and other fractures.

9. Inversion of the Morristown and Glenroy faults occurred. Between these faults, the former horst representing the central Antigonish sub-basin became a graben, preserving the Windsor Group. The presence of thin Cumberland Group on both sides of these faults suggests that inversion occurred prior to or during deposition of this unit in the Bashkirian.

There is no direct evidence for the relative timing of stages 8 and 9. However, by analogy with the western Cumberland sub-basin, where dextral transpression along the Minas Fault zone prompted salt expulsion, it is likely that these two processes were related, and that stages 8 and 9 were concurrent.

2.6.2 Regional implications

Existing maps in the Maritimes Basin where the presence of salt is known should be examined from a salt tectonics perspective, and future mapping should take the potential for salt movement and the resulting structures into consideration. Salt movement has significantly influenced the geometries within the Antigonish sub-basin and has likely had similar impacts on other regions within the encompassing Maritimes Basin. Local stratigraphic gaps in units of Middle Windsor Group age or younger may record locations where the presence of a salt body prevented deposition, such as is hypothesized to have occurred at Lakevale. Structures interpreted as faults may be salt structures. Regional omission surfaces may be salt welds. The Ainslie Detachment (Lynch and Giles 1995) is shown to be a primary salt weld across the portion of the Antigonish sub-basin within mainland Nova Scotia. The portion of this surface in Cape Breton Island should be re-examined as a likely continuation of this primary salt weld.

The Antigonish sub-basin contains two different salt units that have formed salt welds, diapirs, and other structures. Other regions within the Maritimes Basin with some degree of known salt in the Middle Windsor Group, such as the Shubenacadie and Sydney sub-basins and the Northumberland Strait (Boehner and Giles, 1993; Figure 8), have the potential for halokinesis along two different horizons, and therefore potentially complex salt tectonics histories. Other areas of the Maritimes Basin that instead have only one thick known salt horizon with a poorly constrained younger age, such as the Cumberland sub-basin (e.g. Waldron et al. 2013), may represent regions where the MWS was deposited directly on top of the lateral equivalent of the Hartshorn Formation. Waldron et al. (2013) estimate that the original thickness of the salt unit within the Cumberland sub-basin was

~2-3 km before diapirism initiated. If this unit is composed of salt from two different periods, that would help explain why it was so thick.

2.7 Conclusions

Previous authors have struggled with the unique stratigraphic and tectonic features of the Antigonish sub-basin. A regional omission surface in the Lower Windsor Group was first mapped as the Antigonish Thrust by Boehner and Giles (1982), and later as the Ainslie Detachment by Lynch and Giles (1995). The stratigraphic gap mapped in the Windsor Group at Lakevale (Boehner and Giles 1982) was reinterpreted as part of this detachment. However, the orientations of minor structures associated with this surface were shown to be inconsistent with the Ainslie Detachment model by Thomas (2002). Boehner and Giles (1982) interpreted steep faults cutting the basin-fill; however, dip directions in upper Windsor and Mabou Group strata change 180° across several of these structures. These features are challenging to explain through typical tectonic processes of faulting but are common features of salt expulsion structures such as salt welds and salt diapirs.

Evidence for salt movement is recorded in core, in outcrop, and in seismic data. Movement occurred along two salt horizons; the Lower Windsor Hartshorn Formation and the previously unrecognized Middle Windsor Salt. Salt movement within the Hartshorn Formation occurred during the deposition of the Middle Windsor Group and concluded prior to the deposition of the Upper Windsor Hood Island Formation. The Middle Windsor Salt was immobile and sub-horizontal during the deposition of the Hood Island Formation and Mabou Group with the exception of the eastern part of the sub-basin where Middle Windsor Salt expulsion occurred during the deposition of the Hood Island Formation and Mabou Group. The majority of salt-related structures observed in onshore seismic data in the sub-basin originate from the Middle Windsor Salt rather than the Hartshorn Formation.

We reinterpret the regional omission surface previously referred to as the Antigonish Thrust (Boehner and Giles 1982, 1993) or the Ainslie Detachment (Lynch and Giles 1995) as a primary salt weld. This weld extends across the sub-basin and is exposed in outcrop at Lakevale. Primary welds are rarely exposed in outcrop, and we believe this study contains the first detailed outcrop examination of a primary weld in Canada. Several other structures, previously mapped as faults in the Antigonish sub-basin, are seen in seismic profiles to instead be salt structures.

2.8 References

Amax Exploration. 1974. Diamond Drill Record, Hole No. AP-2-74. Unpublished diamond drill record. Available from https://novascotia.ca/natr/meb/data/ar/11E/AR_ME_11E08D_40-B-19_01_431684.pdf [accessed 26 April 2019].

Barss, M.S., Grant, A.C., Sanford, B.V., and Wade, J.A. 1977. Basement structure, Eastern Canada and adjacent areas. Geological Survey of Canada, Map, scale 1:2 000 000.

Bell, W.A. 1929. Horton-Windsor District, Nova Scotia. Geological Survey of Canada, Memoir, 155.

Bell, W.A. 1944. Carboniferous rocks and fossil floras of northern Nova Scotia. Geological Survey of Canada, Memoir, 238.

Bell, W.A. 1960. Mississippian Horton Group of Type Windsor-Horton District Nova Scotia. Geological Survey of Canada Memoir, 314.

Belt, E.S. 1964. Revision of Nova Scotia Middle Carboniferous units. American Journal of Science, **262**: 653–673.

Belt, E.S. 1965. Stratigraphy and Paleogeography of Mabou Group and Related Middle Carboniferous Facies, Nova Scotia, Canada. Geological Society of America Bulletin, **76**: 777–802. doi:10.1130/0016-7606(1965)76[777:SAPOMG]2.0.CO;2.

Benson, D.G. 1970. Notes to accompany geological maps of Antigonish and Cape George map-areas, Nova Scotia. Geological Survey of Canada, Paper, 70–8.

Boehner, R.C. 1980. Note on revised stratigraphy of the Lower Carboniferous Windsor Group, Crystal Cliffs section, Antigonish county, Nova Scotia. Mineral Resources Division, Report of Activities 1979,: 137–145.

Boehner, R.C. 1984. Stratigraphic drillhole NSDME Glen Road 83-1, western part of the Antigonish Basin, Antigonish County, Nova Scotia. *In* Mines and Minerals Branch, Report of Activities 1984, Mines and Minerals Branch, Report of Activities 1984, Nova Scotia Department of Mines and Energy, Report 84-1. pp. 125–132.

Boehner, R.C. 1986. Salt and Potash Resources in Nova Scotia. Nova Scotia Department of Mines and Energy Bulletin, ME 005.

Boehner, R.C. 1993. Diamond-drill Core Log of Nova Scotia Department of Natural Resources Drillhole GR83-1, Glen Road, Antigonish County, Nova Scotia. Open-File Report, ME 1993-008.

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.

Bright, J.E., and Ridge, M.J. 1962. Twinned crystals of precipitated gypsum. Mineralogical Magazine, **33**: 347–348.

Brown, J.P. 1998. Deformation and sedimentation adjacent to Carboniferous diapiric salt structures, Nova Scotia. PhD thesis, Dalhousie University, Halifax, Canada.

Burton, W. 1974. SV74-3 Diamond Drill Record. Unpublished diamond drill record.

Calder, J.H. 1985. Coal in Nova Scotia. Information Series ME 008.

Callot, J.-P., Salel, J.-F., Letouzey, J., Daniel, J.-M., and Ringenbach, J.-C. 2016. Three-dimensional evolution of salt-controlled minibasins: Interactions, folding and megaflap development. AAPG Bulletin, **100**: 1419–1442. doi:10.1306/03101614087.

Craggs, S., Keighley, D., Waldron, J.W.F., and Park, A.F. 2015. Salt tectonics in an intracontinental transform setting: Cumberland and Sackville basins, southern New Brunswick, Canada. Basin Research, **29**: 266–283.

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

Gibling, M.R., Culshaw, N., Rygel, M.C., and Pascucci, V. 2009. The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea. *In* Sedimentary basins of the United States and Canada, Sedimentary basins of the United States and Canada, Sedimentary Basins of the World. *Edited by* A. Miall. pp. 211–244.

Giles, K.A., and Lawton, T.F. 1999. Attributes and evolution of an exhumed salt weld, La Popa basin, northeastern Mexico. Geology, **27**: 323–326.

Giles, P.S. 1980. Windsor Group Stratigraphy and paleogeography: Project activities 1979-80. *In* Mineral Resources Division, Report of Activities 1979, Mineral Resources Division, Report of Activities 1979, Nova Scotia Department of Mines and Energy, Report 80-1. pp. 205–209.

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. 2008. Windsor Group (Late Mississippian) stratigraphy, Magdalen Islands, Quebec: a rare eastern Canadian record of late Viséan basaltic volcanism. Atlantic Geology, **44**: 167 – 185.

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., Boehner, R.C., and Ryan, R.J. 1979. Carbonate banks of the Gays River Formation in central Nova Scotia. Nova Scotia Department of Mines, Paper 79-7.

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, Eastern Canada and National and General Programs, Geological Survey of Canada Current Research. pp. 89–94.

Grace, K.A. 1966. Report on Antigonish Basin Nova Scotia; Kennco Explorations, (Canada) Limited. Unpublished diamond drill record.

Hamblin, A.P. 1989. Sedimentology, Tectonic Control, and Resource Potential of the Upper Devonian – Lower Carboniferous Horton Group, Cape Breton Island, Nova Scotia. PhD thesis, University of Ottawa, Ottawa, Canada.

Hamblin, A.P. 2001. Stratigraphy, sedimentology, tectonics, and resource potential of the lower Carboniferous Mabou Group, Nova Scotia. Geological Survey of Canada, Bulletin, 568.

Hamblin, A.P., and Rust, B.R. 1989. Tectono-sedimentary analysis of alternate-polarity half-graben basin-fill successions: Late Devonian-Early Carboniferous Horton Group, Cape Breton Island, Nova Scotia. Basin Research, **2**: 239–255. doi:10.1111/j.1365-2117.1989.tb00038.x.

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.

Howie, R.D. 1988. Upper Paleozoic evaporites of southeastern Canada. Geological Survey of Canada Bulletin, 380.

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.

Imperial Oil Limited. 1974. Summary Report on Diamond Drilling at Pomquet - Captain's Pond, Antigonish Co. Nova Scotia. Unpublished diamond drill record.

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.

Jackson, M.P.A., and Talbot, C.J. 1991. A Glossary of Salt Tectonics. The University of Texas at Austin.

Keppie, J.D., Giles, P.S., and Boehner, R.C. 1978. Some Middle Devonian to lower Carboniferous rocks of Cape George, Nova Scotia. Nova Scotia Department of Mines, Paper 78-4.

Kergaravat, C., Ribes, C., Callot, J.-P., and Ringenbach, J.-C. 2017. Tectono-stratigraphic evolution of salt-controlled minibasins in a fold and thrust belt, the Oligo-Miocene central Sivas Basin. Journal of Structural Geology, **102**: 75–97. doi:10.1016/j.jsg.2017.07.007.

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.

MacDonald, E. 2003. Geological Report on Beech Hill #1, Antigonish Nova Scotia. Vintage Petroleum Canada.

Moore, R.G. 1967. Lithostratigraphic units in the upper part of the Windsor Group, Minas Sub-basin, Nova Scotia. *In* Collected papers on geology of the Atlantic Region, Collected papers on geology of the Atlantic Region, Geological Association of Canada, Special Paper. *Edited by* E.R.W. Neale and H. Williams. pp. 245–266.

Murphy, J.B. 2001. Geochemistry, provenance, and tectonic significance of sedimentary rocks of the Middle to Late Devonian McArras Brook and Visean Martin Road formations, Merigomish Subbasin, northern Antigonish Highlands, Nova Scotia. Atlantic Geology, **37**: 161–173.

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.

Murray, B.C. 1955. Stratigraphy of the Horton Group in parts of Nova Scotia. PhD Thesis, Massachusetts Institute of Technology, Cambridge, USA.

Passchier, C.W., and Trouw, R.A.J. 2005. Microtectonics.

Prime, G.A. 1987. The Antigonish basin of Maritime Canada: A sedimentary tectonic history of a late Paleozoic fault-wedge basin. MSc thesis, Dalhousie University, Halifax, Canada.

Ramsay, J.G. 1967. Folding and Fracturing of Rocks. McGraw Hill, San Francisco.

Ramsay, J.G., and Huber, M.I. 1983. The Techniques of Modern Structural Geology. Volume 2: Folds and fractures. Academic Press, London.

Rowan, M.G., Lawton, T.F., and Giles, K.A. 2012. Anatomy of an exposed vertical salt weld and flanking strata, La Popa Basin, Mexico. Geological Society, London, Special Publications, **363**: 33–57. doi:10.1144/SP363.3.

Rowan, M.G., Lawton, T.F., Giles, K.A., and Ratliff, R.A. 2003. Near-salt deformation in La Popa basin, Mexico, and the northern Gulf of Mexico: A general model for passive diapirism. AAPG bulletin, **87**: 733–756.

Ryan, R.J., and Boehner, R.C. 1994. Geology of the Cumberland Basin, Cumberland, Colchester and Pictou Counties, Nova Scotia. Nova Scotia Department of Natural Resources Memoir, 10.

Schenk, P.E. 1967a. 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. 1967b. The significance of algal stromatolites to paleo-environmental and chronostratigraphic interpretations of the Windsorian Stage (Mississippian), Maritime Provinces. *In* Collected Papers on Geology of the Atlantic Region, Collected Papers on Geology of the Atlantic Region, Geological Association of Canada Special Paper, 4.

Schenk, P.E. 1969. Carbonate-sulfate-redbed facies and cyclic sedimentation of the Windsorian Stage (middle Carboniferous), Maritime Provinces. Canadian Journal of Earth Sciences, **6**: 1037–1066.

Schultz-Ela, D.D. 2003. Origin of drag folds bordering salt diapirs. AAPG Bulletin, **87**: 757–780. doi:10.1306/12200201093.

St. Peter, C.J. 1993. Maritimes Basin evolution: key geologic and seismic evidence from the Moncton Subbasin of New Brunswick. Atlantic Geology, **29**: 233–270.

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.

Ténière, P., Giles, P.S., Naylor, R.D., and MacDonald, D.R. 2002. Stratigraphy of the Horton Group, Guysborough and Antigonish counties. *In* Minerals and Energy Branch Report of Activities, Minerals and Energy Branch Report of Activities, Nova Scotia Department of Natural Resources, Report, ME 2002-001. pp. 129–139.

Ténière, P.J., Barr, S.M., and White, C.E. 2005. Stratigraphy and structure of the Horton Group, Lochaber-Mulgrave area, northern mainland Nova Scotia. Atlantic Geology, **41**: 41–52.

Thomas, D.B., Nance, R.D., and Murphy, J.B. 2002. Deformation of the Macumber Formation, Antigonish Basin, Nova Scotia: implications for the Ainslie Detachment. Atlantic Geology, **38**: 135–144.

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

Vernon, R.H. 2004. A Practical Guide to Rock Microstructure. Cambridge University Press.

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. Nova Scotia Department of Energy Open File Report, 2017–02.

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.

Williams, E.P. 1974. Geology and petroleum possibilities in and around Gulf of St. Lawrence. AAPG Bulletin, **58**: 1137–1155.

Chapter 3. A secondary salt weld revealed: Outcrop and subsurface observations in the Maritimes Basin of Nova Scotia

3.1 Introduction

When strata once separated by a body of salt are brought into contact after the expulsion of the salt, the resulting surface between the units is known as a salt weld (Jackson and Talbot 1991). Welds are known as primary welds if the salt was autochthonous, and secondary if the salt was a steep-sided diapir (Jackson and Talbot 1991) (Figures 3.1 and 3.2).

The Maritimes Basin (Figure 3.3) formed after the Acadian Orogeny in the Appalachian Orogen (Williams 1974). It encompasses a variety of smaller depocentres, also known as sub-basins, over a total area of approximately 150 000 km^2 (Williams 1974) across Prince Edward Island, Nova Scotia, New Brunswick, Newfoundland, and below the Gulf of St. Lawrence (e.g. Gibling et al. 2009) (Figure 3.3). The strata within the Maritimes Basin are late Paleozoic in age and are up to 12 km thick (e.g. Gibling et al. 2009). Most of the basin-fill is clastic. The marine Windsor Group of Viséan age, containing carbonates and evaporites, is the main non-clastic unit of the basin-fill. In this study we examine several structures, previously described as faults, which are here re-interpreted as secondary salt welds.

3.2 Maritimes Basin

3.2.1 Structure

The Maritimes Basin formed during a tectonically active period near the end of the formation of the supercontinent Pangea (e.g. Gibling et al. 2019). During the Late Devonian up to ~250 km of dextral strike-slip movement occurred along the major faults (Hibbard and Waldron 2009), creating accommodation space for the Maritimes Basin in a releasing step-over (e.g. Waldron et al. 2015). Abundant steep faults cut through the basin and

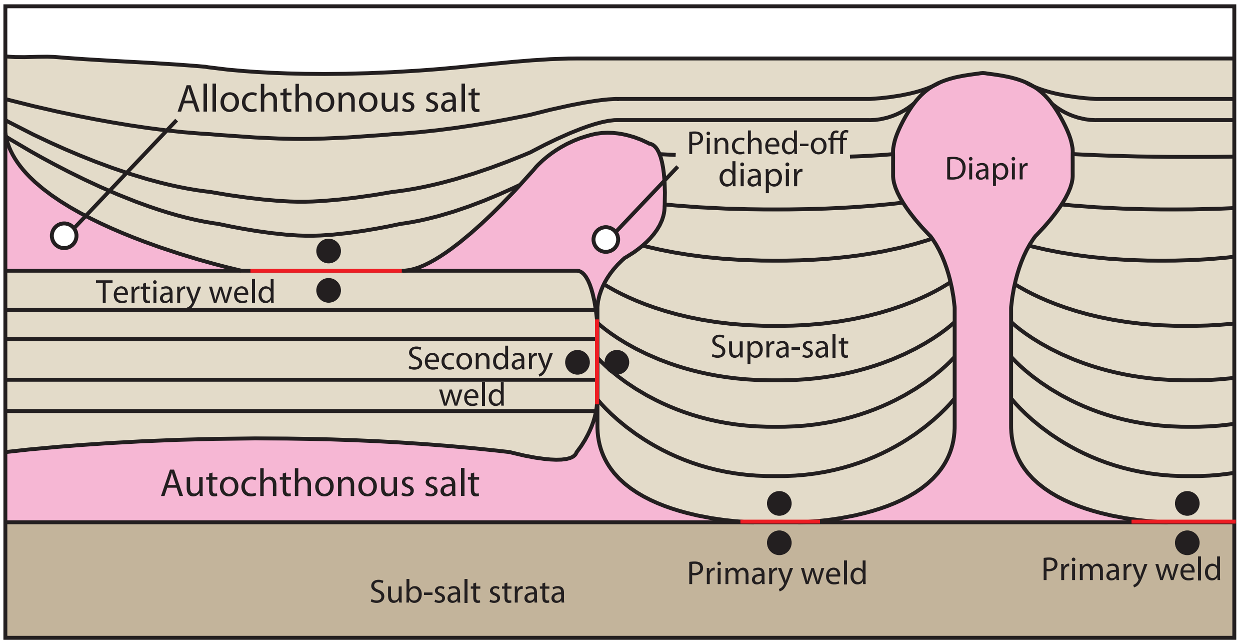


Figure 3.1. Types of salt welds

Schematic diagram of primary, secondary and tertiary welds adapted from Jackson et al. (2014).

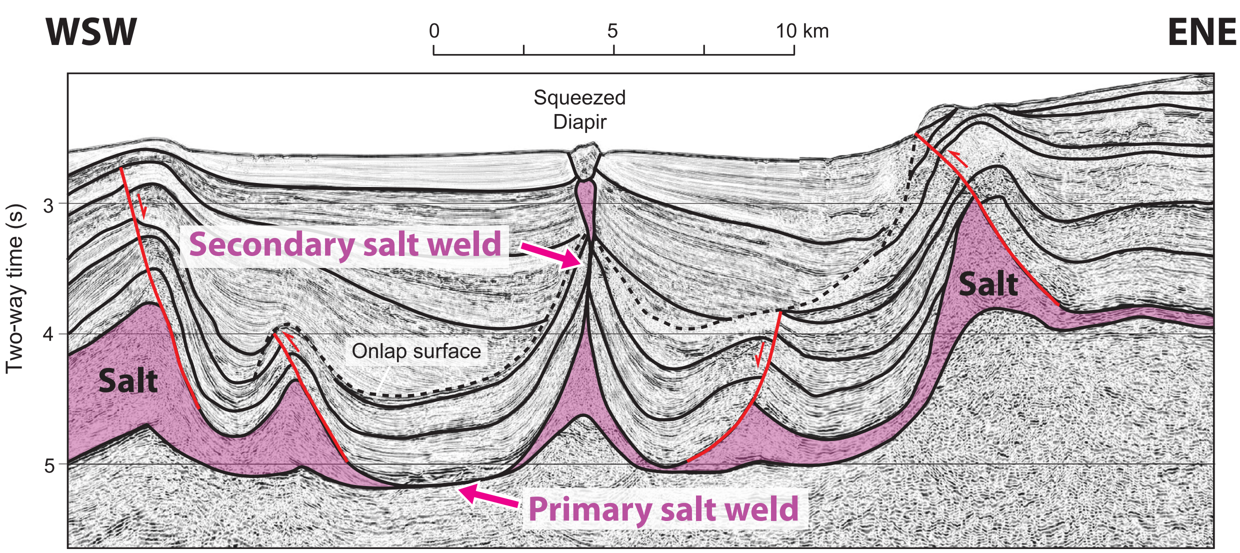


Figure 3.2. Salt welds in seismic data

Primary and secondary welds in a seismic line from Angola, modified from Hudec and Jackson (2004).

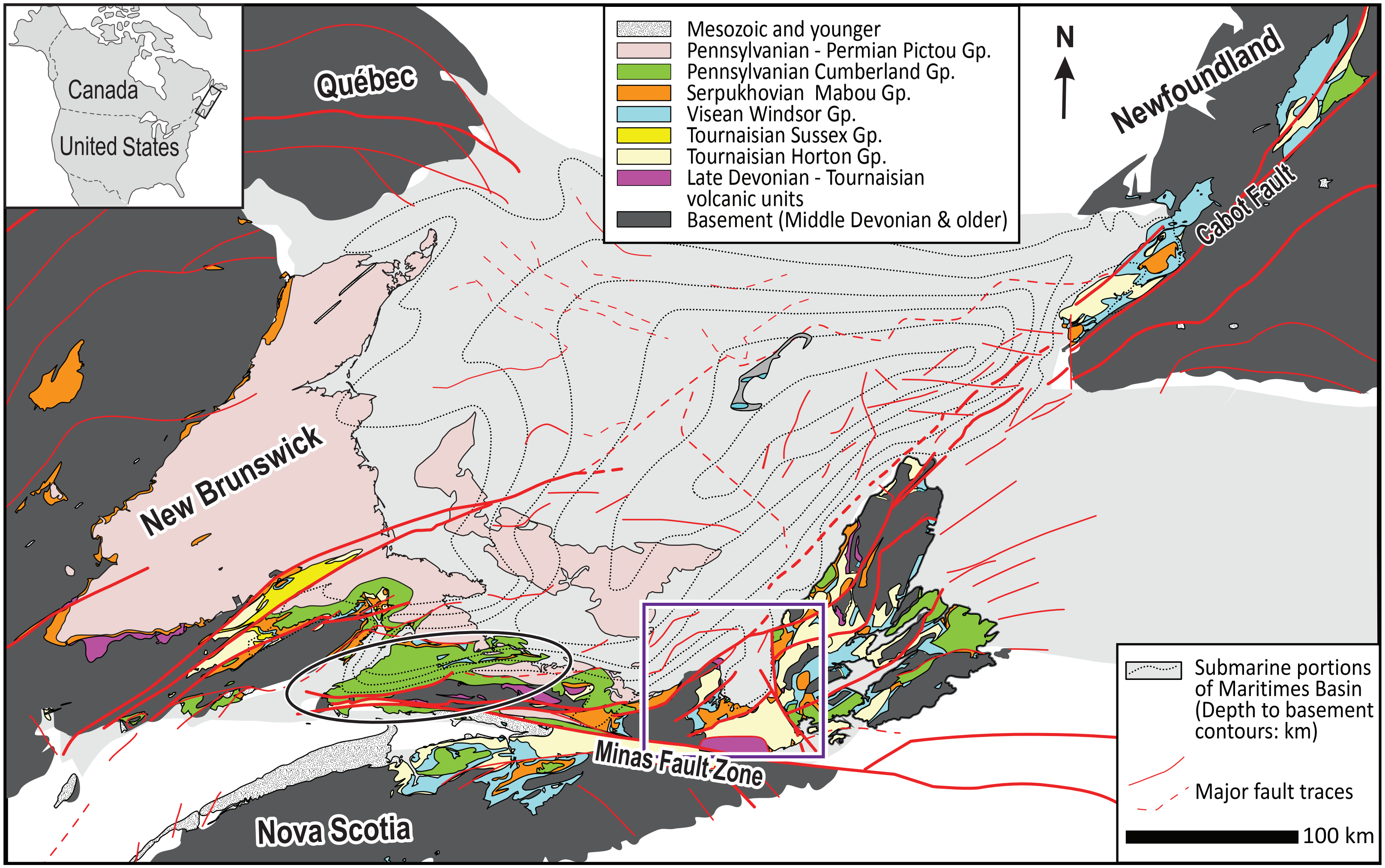


Figure 3.3. Map of the Maritimes Basin

Inset box shows the location of Figure 3.5, a map of the Antigonish sub-basin. Modified from Waldron et al. (2015).

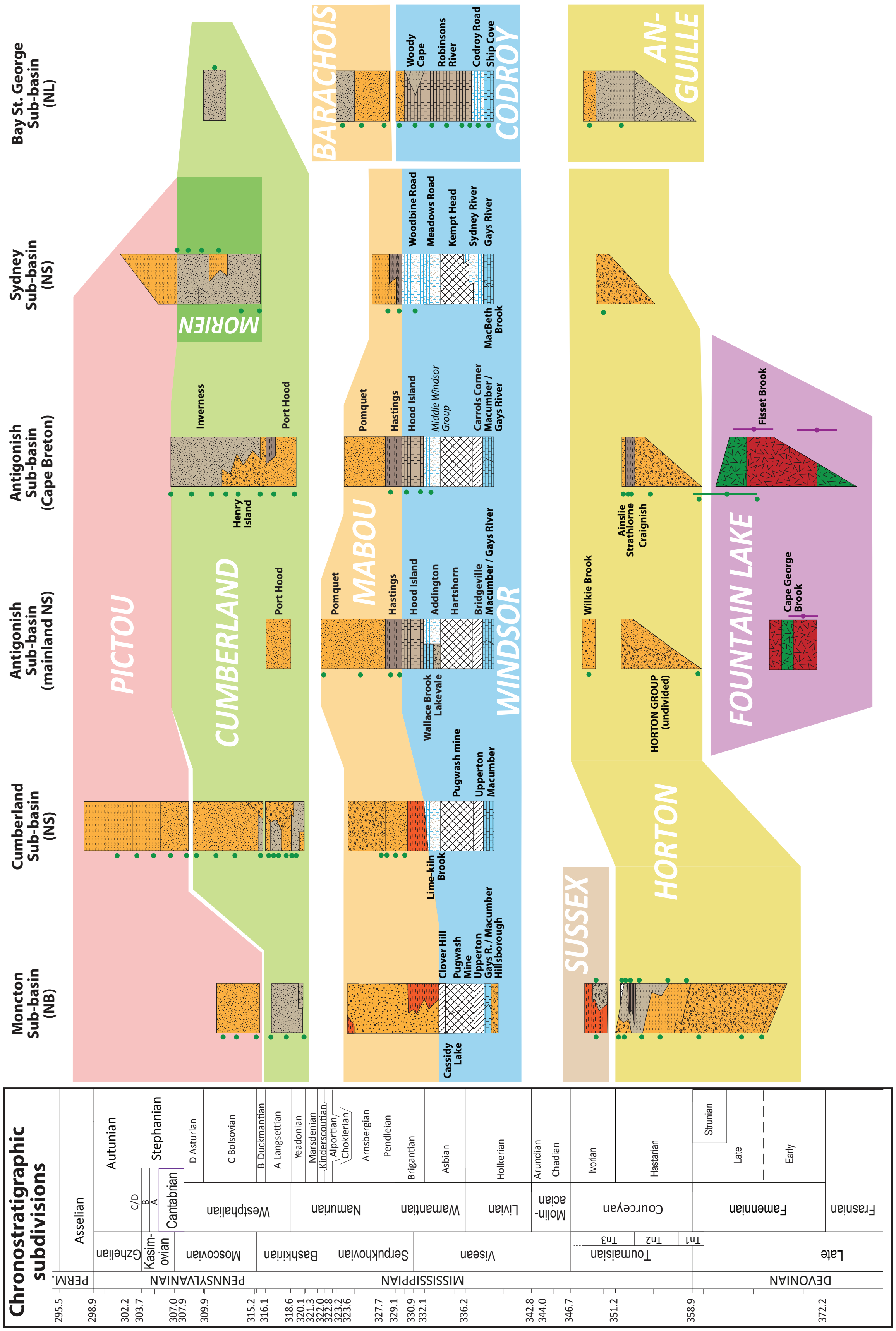
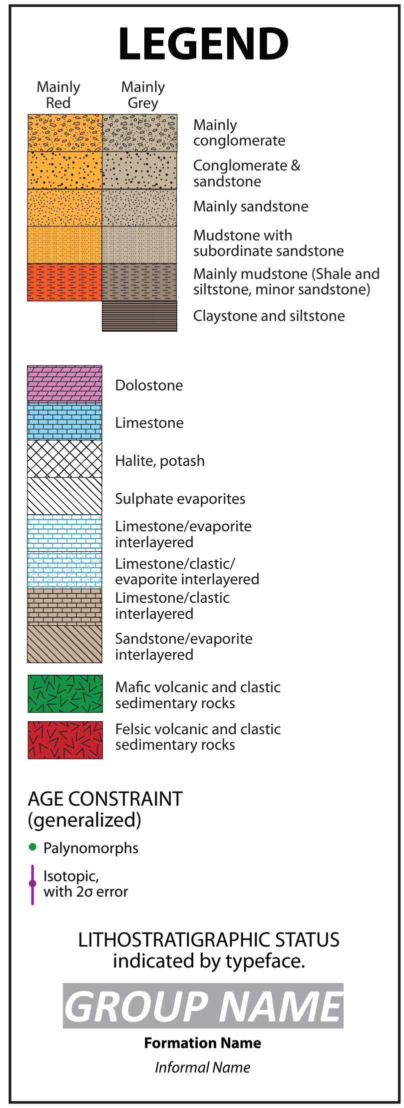

Chronostratigraphic subdivisions
Moncton Sub-basin (NB)
Cumberland Sub-basin (NS)
Antigonish Sub-basin (mainland NS)
Antigonish Sub-basin (Cape Breton)
Sydney Sub-basin (NS)
Bay St. George Sub-basin (NL)
PICTOU
CUMBERLAND
MORIEN
MABOU
WINDSOR
BARACHOIS
CODROY
SUSSEX
HORTON
FOUNTAIN LAKE
AN-GUILLE
Inverness
Port Hood
Henry Island
Pomquet
Hastings
Hood Island
Addington
Hartshorn
Bridgeville
Macumber / Gays River
Middle Windsor Group
Carrols Corner
Macumber / Gays River
Woodbine Road
Meadows Road
Kempt Head
Sydney River
Gays River
MacBeth Brook
Woody Cape
Robinsons River
Codroy Road
Ship Cove
Cassidy Lake
Clover Hill
Pugwash Mine
Upperton
Gays R. / Macumber
Hillsborough
Lime-kiln Brook
Pugwash mine
Upperton
Macumber
Wallace Brook
Lakevale
Wilkie Brook
Ainslie
Strathlorne
Craignish
HORTON GROUP (undivided)
Cape George Brook
Fisset Brook
PERM.
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
Asselian
Gzhelian
Kasim-ovian
Moscovian
Bashkirian
Serpukhovian
Viséan
Tournaisian
Late
Autunian
Stephanian
C/D
B
A
Cantabrian
Westphalian
Namurian
Warnantian
Livian
Molin-acian
Courceyan
Famennian
Frasnian
Tn3
Tn2
Tn1
D Asturian
C Bolsovian
B Duckmantian
A Langsettian
Yeadonian
Marsdenian
Kinderscoutian
Alportian
Chokierian
Arnsbergian
Pendleian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Ivorian
Hastarian
Strunian
Late
Early
295.5
298.9
302.2
303.7
307.0
307.9
309.9
315.2
316.1
318.6
320.1
321.3
322.0
322.8
323.2
323.6
327.7
329.1
330.9
332.1
336.2
342.8
344.0
346.7
351.2
358.9
372.2

Figure 3.4. Simplified stratigraphic chart for the Maritimes Basin

Modified from Waldron et al. (2017). Legend on facing page.



bound many of the sub-basins within it (e.g. Hibbard and Waldron 2009, Waldron et al. 2015, Gibling et al. 2019). The sub-basins within the Maritimes Basin vary in style and in basin-fill (St. Peter 1993).

3.2.2 Stratigraphy

Group-level stratigraphy extends across the sub-basins of the Maritimes Basin (Figure 3.4). The late Devonian to Tournaisian clastic Horton Group is the basal unit in most areas, although volcanic units occur at the base of some sub-basins. It is unconformably overlain by the carbonates and evaporites of the Viséan Windsor Group (e.g. Waldron et al. 2017). The Viséan to Serpukhovian clastic Mabou Group conformably overlies the Windsor Group and is unconformably overlain by the Bashkirian to Kasimovian Cumberland Group (e.g. Waldron et al. 2017). The youngest basin-fill unit is the Kasimovian to Asselian clastic Pictou Group that is variably conformable to unconformable with the older units (e.g. Waldron et al. 2017).

3.3 Antigonish sub-basin

3.3.1 Structure

The Antigonish sub-basin is one of the many sub-basins within the Maritimes Basin. It extends from the Antigonish region of Mainland Nova Scotia underneath St Georges Bay into southwestern Cape Breton Island (Figure 3.5). The central part of the sub-basin is bounded by the Morristown and Glenroy faults in mainland Nova Scotia, the Hollow Fault Zone offshore beneath St Georges Bay, and by the Judique Fault in Cape Breton Island (e.g. Boehner and Giles 1993, Thomas et al. 2002)(Figure 3.5). In mainland Nova Scotia, a horst is interpreted to have developed between the Morristown and Glenroy Faults (Figure 3.5) prior to the Viséan, with the surrounding grabens accumulating Horton Group strata (Waldron et al. 2015). A thick succession of Mabou Group and Windsor Group rock was deposited on the former horst during the Viséan to the Serpukhovian (Waldron et al.

2015). Inversion preserved this region between the two faults, creating the present-day map pattern (Figure 3.5), in which the former horst (with thin Horton Group) is down-dropped between blocks on which the Horton Group is much thicker. The Morristown Fault is interpreted to die out to the northeast, offshore beneath St Georges Bay (Durling et al. 1995)(Figure 3.6). The part of the Antigonish sub-basin underneath St Georges Bay and in Cape Breton Island is interpreted to have formed as a half graben along the Judique Fault (Thomas 1999)(Figure 3.6), in a similar fashion to other sub-basins further north along the western coast of Cape Breton Island (Hamblin and Rust 1989). The focus of this study is the Antigonish sub-basin in Cape Breton Island.

3.3.2 Stratigraphy

The oldest unit present is the Devonian to Carboniferous Horton Group (e.g. Boehner and Giles 1993, Giles et al. 1997). It has an unconformable lower contact (Bell 1929) and an upper contact that varies between concordant and discordant (Boehner and Giles 1993). On Cape Breton Island, the Horton Group is subdivided from bottom to top into the Creignish, Strathlorne, and Ainslie Formations (Giles et al. 1997). The basal Creignish Formation is dominated by coarse sandstone and conglomerate, the Strathlorne Formation by shale and siltstone, and the Ainslie Formation by sequences that grade from fine to coarse clastic strata (Murray 1955, Giles et al. 1997). Murray (1955) defined the Ainslie Formation as overlying the Strathlorne Formation. However, in some areas of Cape Breton Island the Ainslie and Strathlorne Formations are not separated. A rare complete section through the Horton Group exposed along Southwest Mabou River (Figure 3.5) serves as the type section for the Creignish, Strathlorne and Aislie Formations (Murray 1955). In this section the Horton Group has an estimated total thickness of 2400 m. The Horton Group is interpreted to represent a variety of fluvial-lacustrine depositional environments (Hamblin 2001).

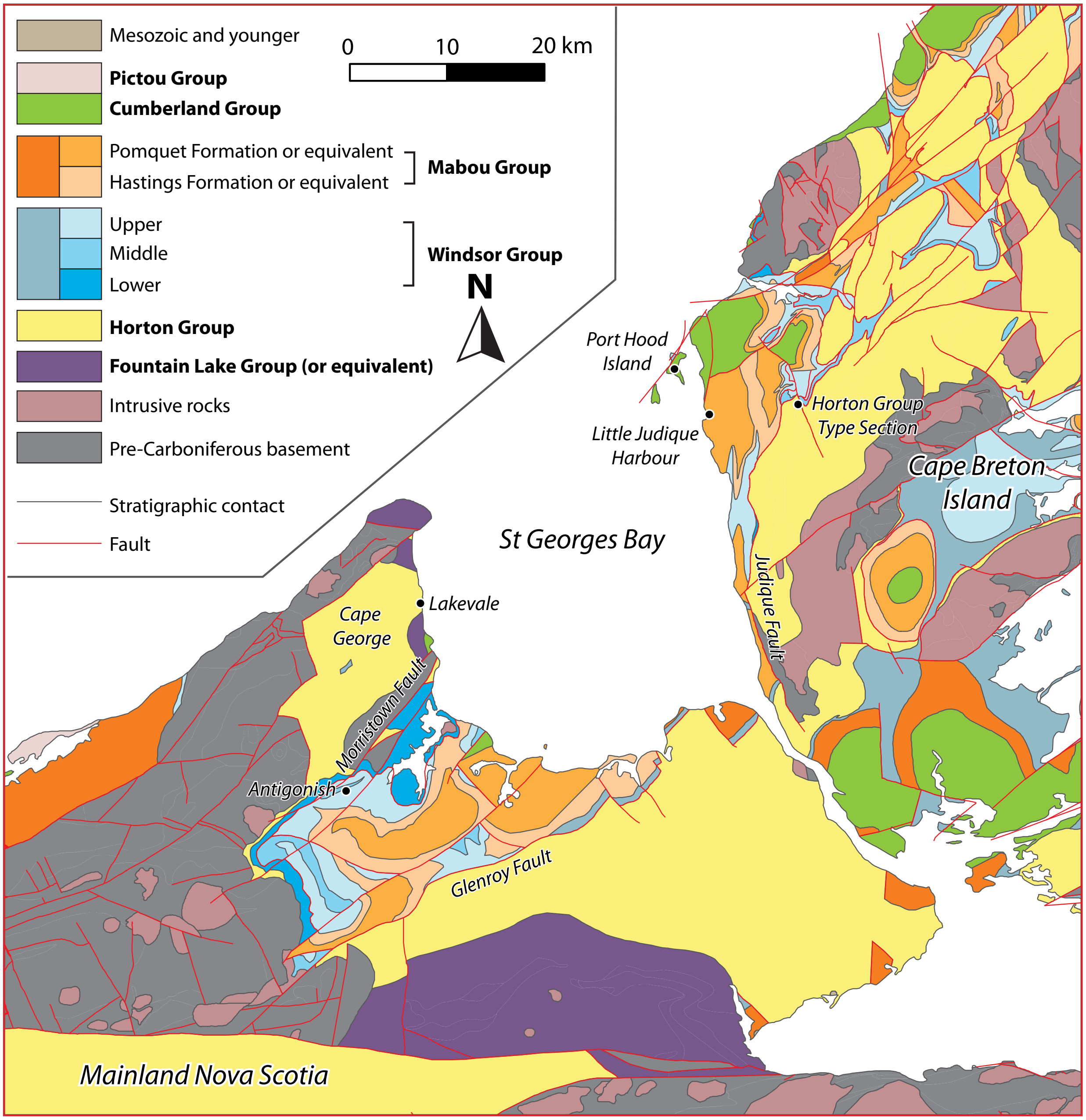


Figure 3.5. Map of the Antigonish sub-basin

Modified from Keppie (2000).

Overlying the Horton Group is the Viséan Windsor Group. The lower contact of the Windsor Group is disconformable or locally an angular unconformity (Giles et al. 1997). The basal Macumber Formation, dominated by laminated limestone, is the only formally defined unit in the Lower Windsor Group of this region (Giles et al. 1997)(Figure 3.4). In western Cape Breton the Macumber Formation is up to ~20 m thick (Giles et al. 1997). Overlying the Macumber Formation is a gypsum unit (anhydrite in the subsurface), locally named the Bridgeville Formation, estimated to be up to 400 m thick (Giles et al. 1997). In the subsurface a halite unit overlies the anhydrite (Giles et al. 1997). Brown (1998) estimates that beneath St Georges Bay this halite was initially a minimum of 540 m thick prior to diapirism. This estimate was obtained from a 2D area balancing restoration on an offshore seismic line, with the assumption that all the Windsor Group salt has flowed into the diapirs imaged in the seismic line (Brown 1998). Diapirs imaged in seismic data from St. Georges Bay are typically 0.9 to 1.5 km high (Alsop et al. 2000). The Middle Windsor Group is interbedded limestone, gypsum, siltstone and sandstone, with halite in the subsurface (Giles et al. 1997). No units have been formally defined in the Middle Windsor Group of western Cape Breton Island (Giles et al. 1997)(Figure 3.4). The Hood Island Formation makes up the Upper Windsor Group of southwestern Cape Breton Island (Giles et al. 1997)(Figure 3.4). It consists of interbedded siltstone, carbonates, gypsum, and anhydrite (Boehner and Giles 1993). In its type section on Port Hood Island the Hood Island Formation is 442 m thick (Boehner and Giles 1993). Many of the limestone units within the Hood Island Formation can be correlated throughout a large portion of the Maritimes Basin (Giles 1981a).

The Serpukhovian Mabou Group typically conformably overlies the Windsor Group (e.g. Gibling et al. 2009)(Figure 3.4). This unit includes red and grey sandstone, mudstone, and shale (Belt 1965). Within the Antigonish sub-basin the Mabou Group is subdivided into the Hastings and Pomquet Formations (e.g. Boehner and Giles 1993, Giles et al. 1997) (Figure 3.4). The Hastings Formation is dominated by grey shale and siltstone with minor limestone (e.g. Belt 1965, Giles et al. 1997). The conformably overlying Pomquet Formation is dominated by red siltstone and sandstone (e.g. Belt 1965, Giles et al. 1997). The Mabou Group is up to ~1000 m thick in southwestern Cape Breton Island (Howie and Barss 1975). The Hastings Formation mainly formed in lacustrine and marginal-lacustrine settings while the Pomquet Formation was produced by subaerial and marginal-lacustrine environments (Hamblin 2001).

The Pennsylvanian clastic Cumberland Group is disconformable with the underlying Mabou Group (e.g. Boehner and Giles 1993, Giles et al. 1997)(Figure 3.4). The Cumberland Group is primarily fluvial (Ryan and Boehner 1994). It is divided into the Port Hood and the Henry Island Formations (Giles et al. 1997, White and Boehner 2008). The lower Port Hood Formation, called the Margaree Member, is dominated by thick, stacked trough-crossbedded sandstones which are interbedded with shale and siltstone (Keighley and Pickerill 1996, Giles et al. 1997). The upper Colindale member comprises thick mudstone units with interbedded coal seams, and thin sandstone beds (Keighley and Pickerill 1996). The Margaree Member may be over 2000 m thick and the Colindale Member over 700 m thick (Giles et al. 1997). The overlying Henry Island Formation consists of sandstone, locally approaching conglomerate, with interbedded shale, siltstone, and minor coal (Giles et al. 1997). The minimum estimated thickness of the Henry Island Formation is 650 m (Giles et al. 1997).

3.3.3 Regional salt movement

Salt movement has been recognized in the Maritimes Basin and the Antigonish sub-basin for decades (Howie 1988 and references therein). Durling et al. (1995) examined shallow offshore seismic data in St Georges Bay (Figures 3.6 and 3.7) and interpreted salt-cored structures as "faulted anticlines". In these structures, strata steepen and, in some cases, thin towards the salt body at the core of the structure (Figure 3.7). Later, Brown (1998) mapped onshore diapir exposures and interpreted salt structures in offshore seismic lines

(Figure 3.8) and interpreted primary salt welds in the Windsor Group beneath St Georges Bay. The locations and orientations of the salt walls identified by Brown (1998) are similar to structures that Durling et al. (1995) interpreted as “faulted anticlines” (Figures 3.8 and 3.6).

Salt structures were interpreted by Waldron and Rygel (2005) in seismic data from the Cumberland sub-basin, which lies to the west of the Antigonish sub-basin (Figure 3.3). Waldron et al. (2013) theorize that the sub-basin initially had 2-3 km of evaporite deposits before expulsion began. The expulsion of evaporites below localized areas of rapid deposition allowed the formation of minibasins in parts of the Cumberland basin through subsidence of the sediment overlying the evaporites (Waldron and Rygel 2005, Waldron et al. 2013). Waldron and Rygel (2005) attribute the excellent preservation of near-vertical lycopsid fossils in the Joggins Fossil Cliffs, a UNESCO World Heritage Site within the Cumberland sub-basin, to rapid subsidence resulting from salt expulsion.

In Chapter 2, we interpret a regional omission surface within the Windsor Group of the Antigonish sub-basin as a primary salt weld. This surface was interpreted first as a thrust, known as the Antigonish Thrust (Boehner and Giles 1982, 1993), and then as an extensional fault named the Ainslie Detachment (Lynch and Giles 1995). We identify an additional horizon of salt expulsion in the sub-basin; a Middle Windsor salt unit, referred to as the Middle Windsor Salt (MWS), that forms diapirs imaged by local seismic data. We also determine that several structures previously mapped as faults by Boehner and Giles (1982) are instead surficial expressions of underlying MWS diapirs.

3.4 Methods

3.4.1 Outcrop data

Coastal outcrops provide the best geological exposures in southwestern Cape Breton. Previous mapping at Little Judique Harbour (Figure 3.5)(Giles et al. 1997) shows steeply

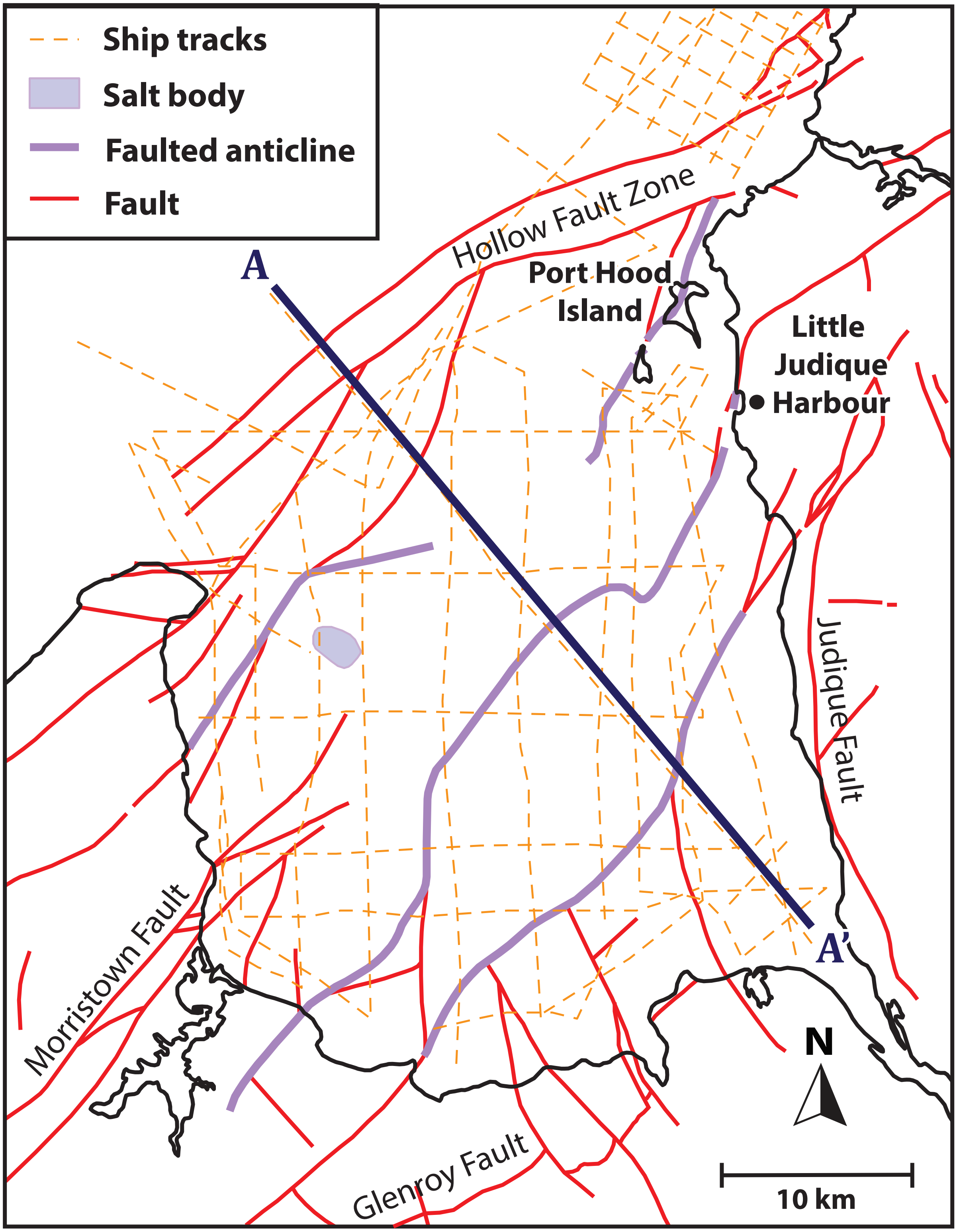


Figure 3.6. Map of interpreted "faulted anticlines" beneath St Georges Bay

Modified from Durling (1995). We interpret the "faulted anticlines" as secondary salt welds. The cross section from A to A' is shown in Figure 3.7.

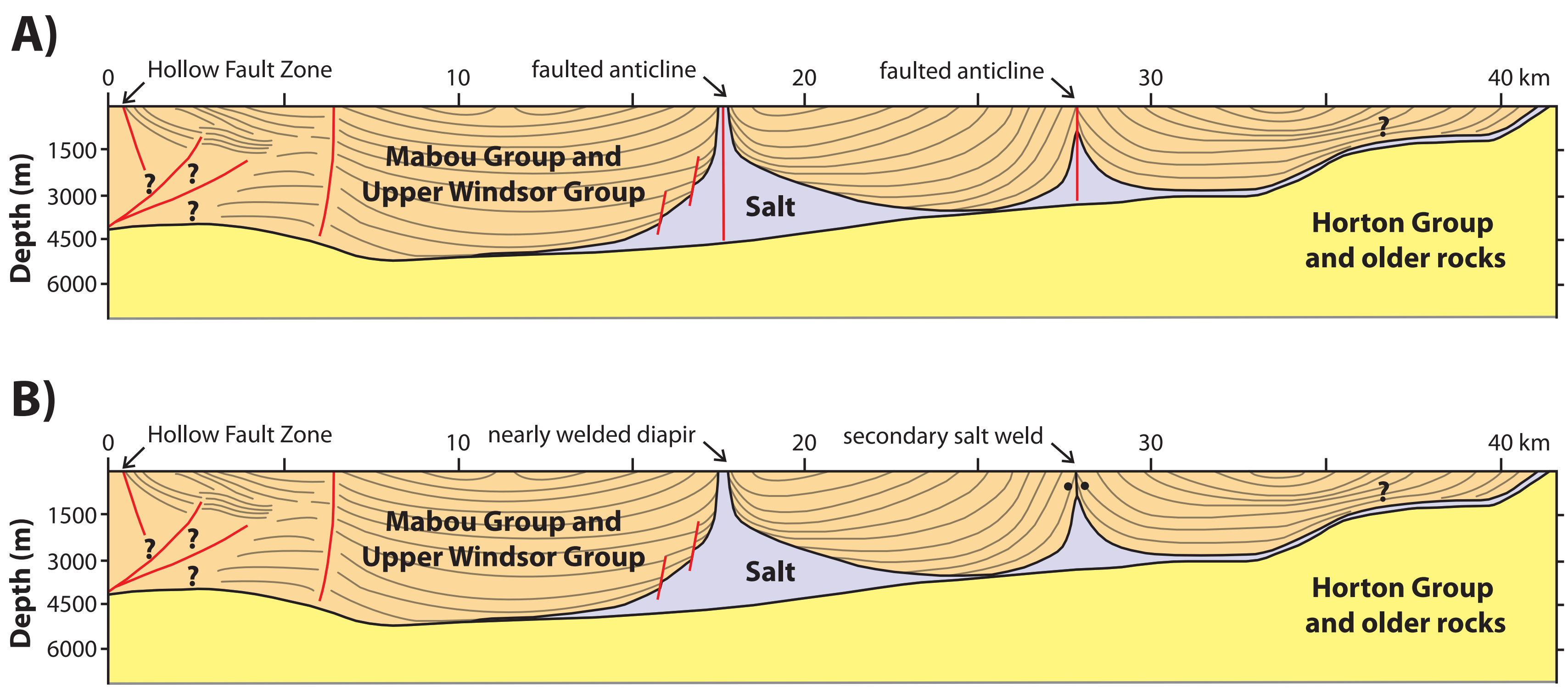


Figure 3.7. Cross section interpretation through "faulted anticlines" beneath St Georges Bay

Modified from Durling (1995). See Figure 3.6 for location of cross section. A) Interpretation from Durling. B) A salt tectonics interpretation of these structures.

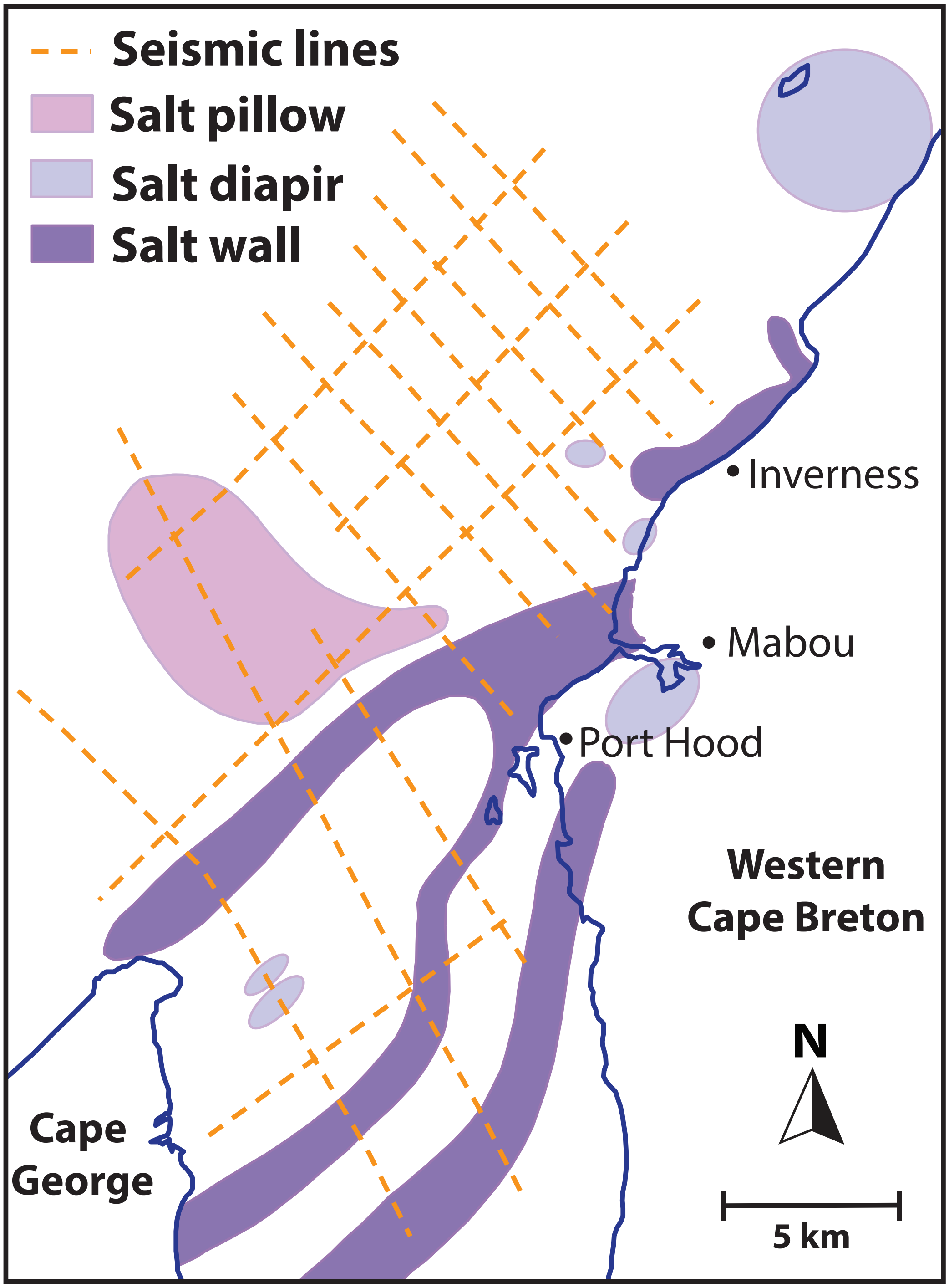


Figure 3.8. Map of interpreted salt walls beneath St Georges Bay

Modified from Brown (1998).

dipping strata with opposing younging directions on either side of a north-south striking fault. We examined outcrop at the northern (NLJH - Figure 3.10) and southern (SLJH - Figure 3.11) ends of Little Judique Harbour, which are separated by a gap in exposure.

A DJI Inspire 1 Pro Unmanned Aerial Vehicle (UAV) was used to conduct photogrammetric surveys of coastal cliff rock outcrops at northern and southern Little Judique Harbour (NLJH and SLJH respectively). A 50 m tape with markers at each end was laid out in each area of interest. Additional markers were spaced along the outcrop. Approximate marker locations were recorded with a handheld GPS unit. Aerial transects were conducted with the drone to gain photos from directly overtop of and perpendicular to the cliffs, and at a variety of angles so as to obtain at least 60% overlap between photographs. 439 photographs were taken at the northern end of Little Judique Harbour and 138 at the southern end. Selections of these photographs were used to assist with traditional geological mapping of the Little Judique Harbour outcrops.

3.4.2 Photogrammetry

Images were imported into Agisoft PhotoScan Professional software to create high-resolution 3D models of the outcrops (Appendices E and F). To create these models, images were first manually cropped to remove drone hardware and the coastline and ocean outside the area of study. Marker objects were manually located and tagged. This assisted the program in correctly matching points between photographs during image processing. PhotoScan then created a sparse point cloud by locating points common to multiple photographs, oriented in 3D space by using GPS data from the drone. The sparse point clouds contained 1 to 2 million points. PhotoScan generated dense point clouds of 21 to 39 million points from the sparse point clouds. 3D mesh surfaces were created from the dense point clouds and then a texture layer generated from the imagery was projected onto the mesh surfaces.

The 3D outcrop models generated in PhotoScan are correctly scaled and georeferenced. This allows unit thicknesses to be measured on the models. Orientations of geologic structures were also extracted from the models by picking points along planes, exporting text files with the point locations, and then running the text files through a Python code written by Dr. J. Kavanaugh (University of Alberta, personal communication, Oct 2018) to find best-fit planes through the sets of points.

3.5 Observations

Pomquet Formation

The easternmost unit at Little Judique Harbour is the Pomquet Formation of the Mabou Group (Figures 3.10 and 3.11). The Pomquet Formation is mainly siltstone and lesser sandstone that is variably calcareous. Rare limestone beds are also observed. The unit is dominantly red with subordinate grey portions. The grey strata are concentrated at the base of the formation. Many sandstone beds display ripples or crossbedding. The crossbeds indicate that the Pomquet Formation is upright and dips steeply east (Figure 3.10). Halite casts (Figure 3.12) were observed on the bottom of the sandstone bed at the base of the formation and in many pieces of float near the middle of the Hastings Formation. We interpret the basal contact of the Pomquet Formation as conformable, consistent with mapping by Giles et al. (1997).

Continuous outcrop extends 160 m at NLJH (Appendix G), whereas only one outcrop occurs at SLJH (Appendix F). Giles et al. (1997) mapped several additional outcrops of Pomquet Formation to the east and west. These may now be hidden by erosion, deposition of beach sediment, or slumping of overburden.

Hastings Formation

The underlying Hastings Formation contains siltstone and lesser mudstone that is locally slightly calcareous. The siltstone is grey with lesser red intervals, while the mudstone is

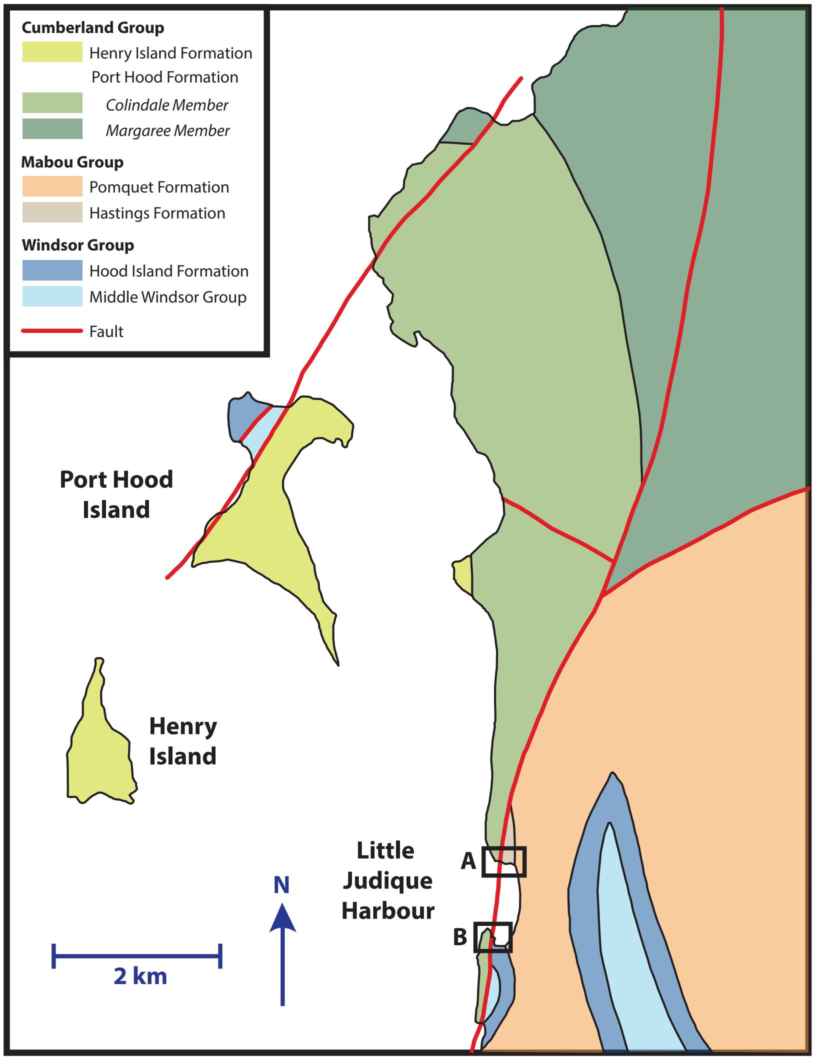


Figure 3.9. Geological map of Little Judique Harbour and Port Hood Island based on previous mapping

Modified from Giles et al. (1997) and Brown (1998). Boxes A and B show the locations of Figures 3.10 and 3.11 respectively.

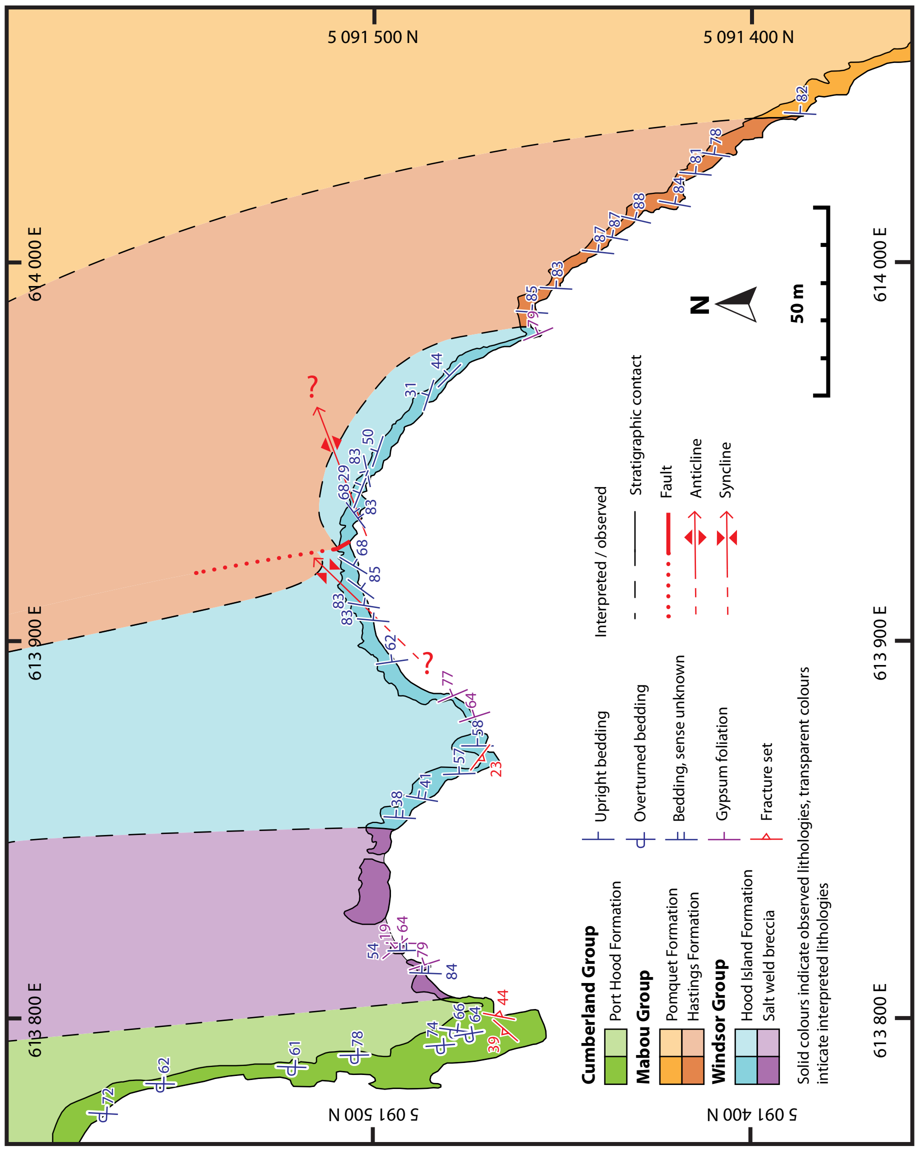


Figure 3.10. Geological map of northern Little Judique Harbour (NLJH)

The base image is a map-view orthophoto of a 3D model constructed in PhotoScan (see Appendix E). More detailed shore section shown in Appendix G.

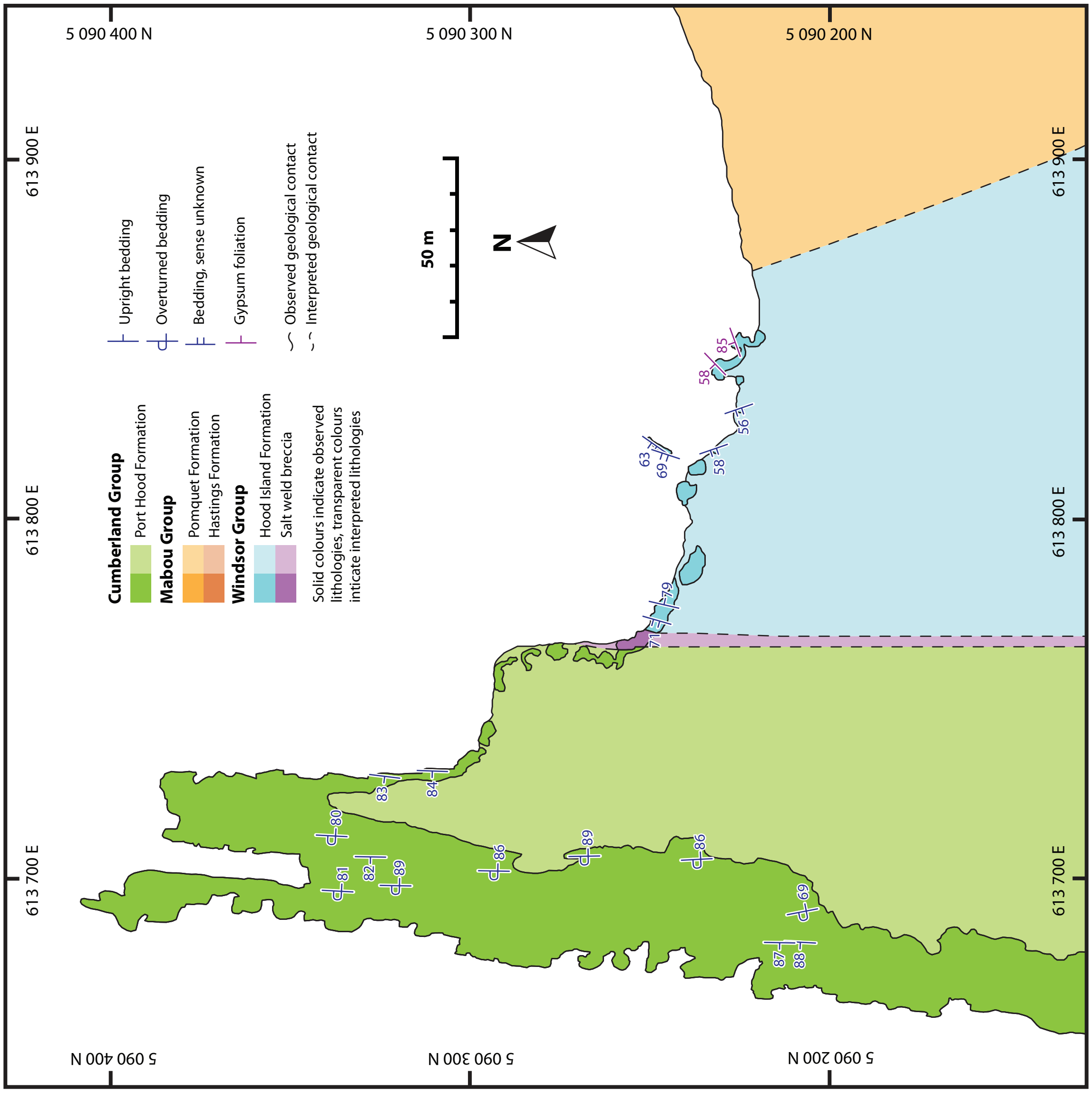


Figure 3.11. Geological map of southern Little Judique Harbour (SLJH)

The base image is a map-view orthophoto of a 3D model constructed in PhotoScan (see Appendix F). More detailed shore section shown in Appendix H.

mainly red. The strata are nearly vertical (Figure 3.10). Near the middle of the formation a 2 m thick sandstone bed shows ripples and mudcracks indicating that this unit youngs eastwards. Graded beds, 5-8 cm thick, were observed. The base of the Hastings Formation appears conformable with the top of the underlying Windsor Group. However, 15 m above the base of the formation is a poorly exposed zone of fractured siltstone 3 m wide. This may indicate a bedding-parallel deformation zone.

We mapped ~60 m of Hastings Formation at NLJH (Appendix G). Giles et al. (1997) included an interval of calcareous shale and gypsum which we interpret as underlying Hood Island Formation. At SLJH there is a significant gap in outcrop between the Pomquet Formation and the Hood Island Formation (Figure 3.11 and Appendix H). Based on spacing between former outcrops recorded by Giles et al. (1997), there could be up to 80 m of concealed Hastings Formation at SLJH.

Hood Island Formation

The Hood Island Formation (Upper Windsor Group) underlies the Hastings Formation at NLJH. The formation is dominated by locally calcareous red and grey siltstone and mudstone. These fine-grained clastic strata vary from massive to laminated, and the majority are poorly exposed due to cover by slipped rubble. Locally the mudstone and siltstone are brecciated into rubble of randomly oriented clasts. The formation contains rare carbonate intervals, including ~10 m of dolomite near the western edge of the formation in NLJH. Intervals of gypsum, typically represented by white slipped blocks up to 4 m in diameter, are included in the formation (Figure 3.12). In NLJH a foliated black gypsum layer 3 m thick occurs at the easternmost edge of the formation.

Bedding orientations are variable in the Hood Island Formation (Figures 3.10 and 3.11). Climbing ripples in a siltstone bed at NLJH (Figure 3.12) and rare cross lamination in mudstone at SLJH indicate that this unit youngs eastwards. In NLJH the easternmost part

Figure 3.12. Field Photographs from Northern Little Judique Harbour

A) Halite casts from the Pomquet Formation. Blocks on scale bar are in cm. B) Ripples showing that the Hood Island Formation youngs to the east. Hammer head for scale, photo taken looking ~north. C) Slipped white gypsum. D) Brecciated siltstone. Hammer for scale E) Port Hood Formation crossbedding indicating the unit is overturned. Walking stick is 1 m long, photo taken looking ~north. F) Fossil tree bits in Port Hood Formation. Blocks on scale bar are in cm.

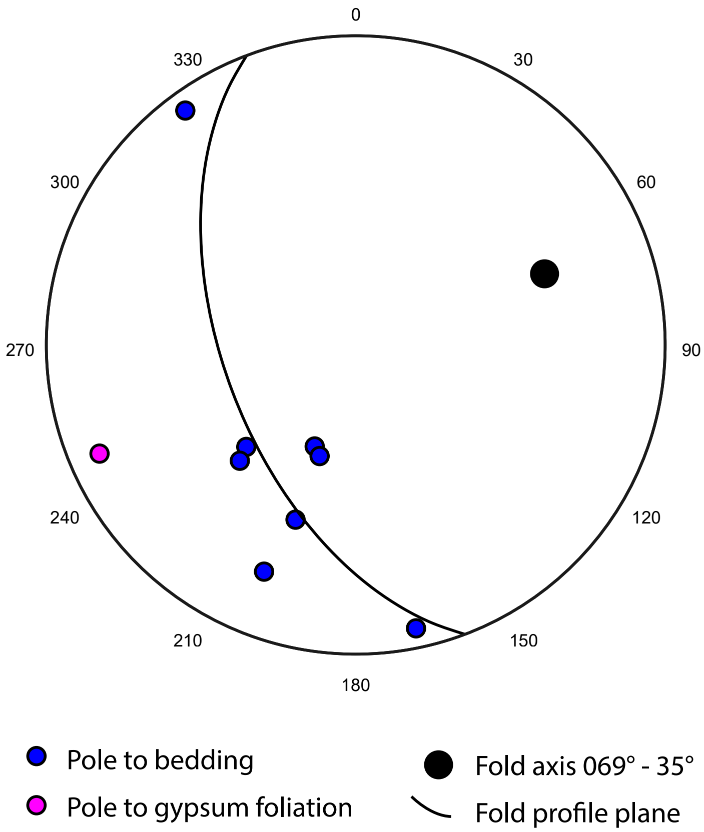


Figure 3.13. Equal area projection of Hood Island Formation bedding and foliations in eastern anticline

Bedding and foliations plotted are from Hood Island Formation measurements taken to the east of the interpreted fault in Figure 3.10. Only bedding poles were used to find the fold axis.

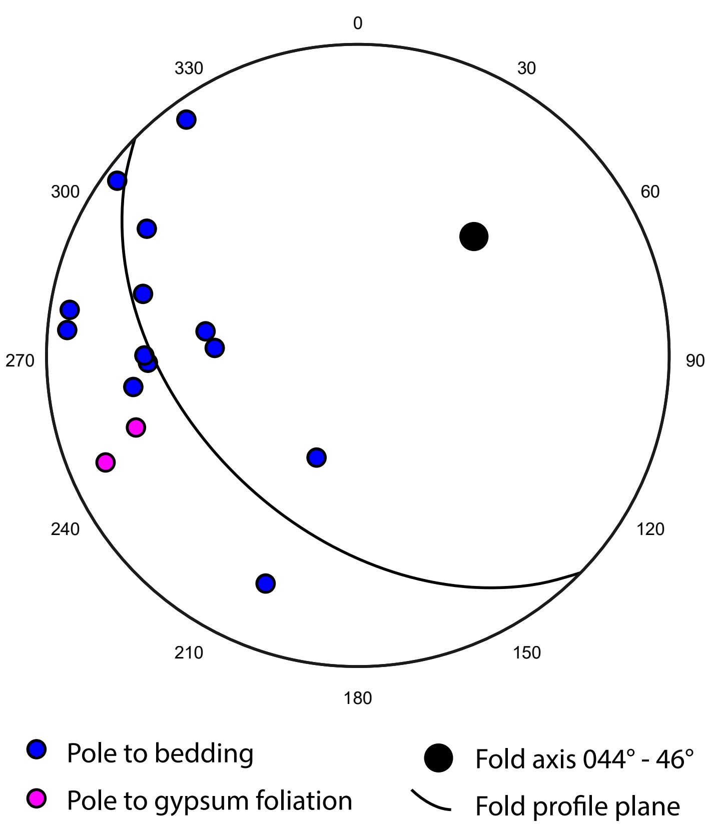


Figure 3.14. Equal area projection of Hood Island Formation bedding and foliations in western syncline

Bedding and foliations plotted are from Hood Island Formation measurements taken to the west of the interpreted fault in Figure 3.10. Only bedding poles were used to find the fold axis.

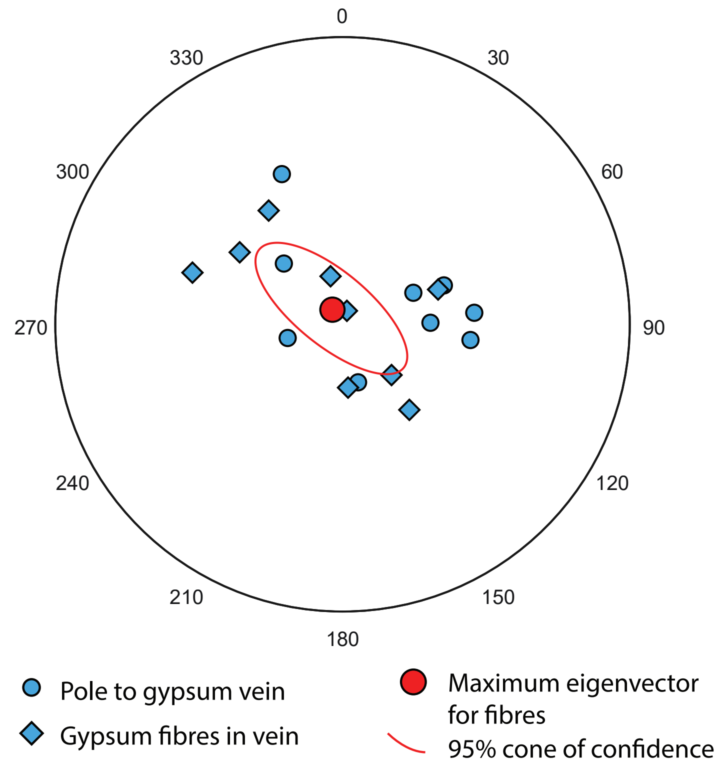


Figure 3.15. Equal area projection of fibrous gypsum veins in the Hood Island Formation at NLJH

Poles to veins are represented by circles, and fibre orientations are shown by diamonds.

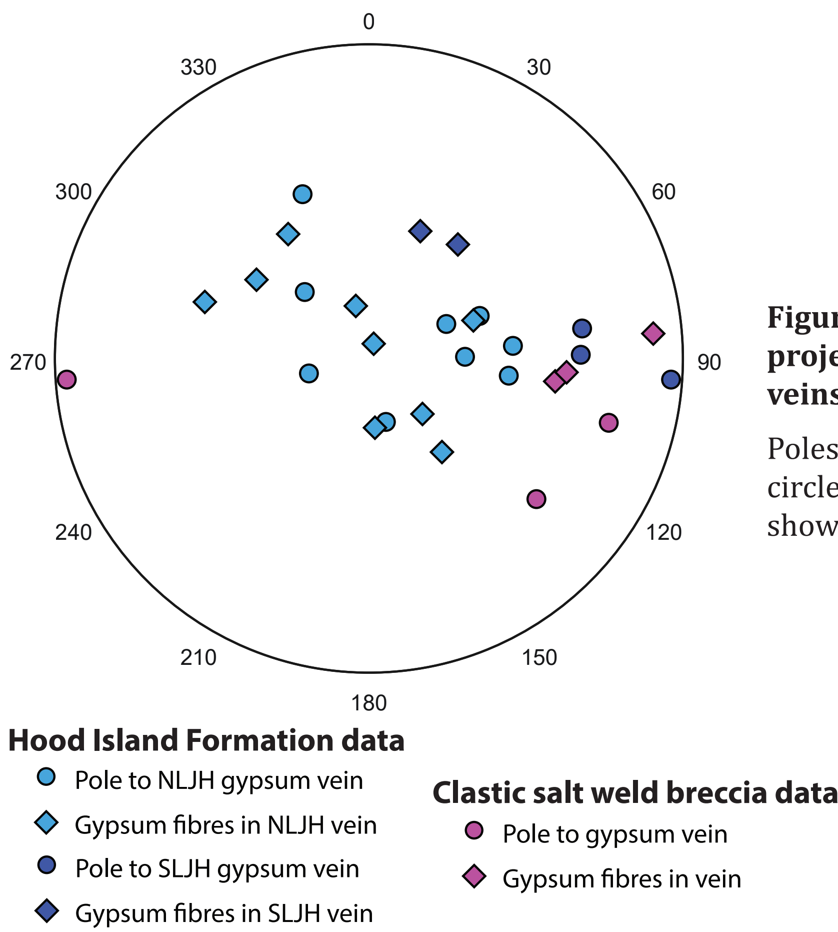
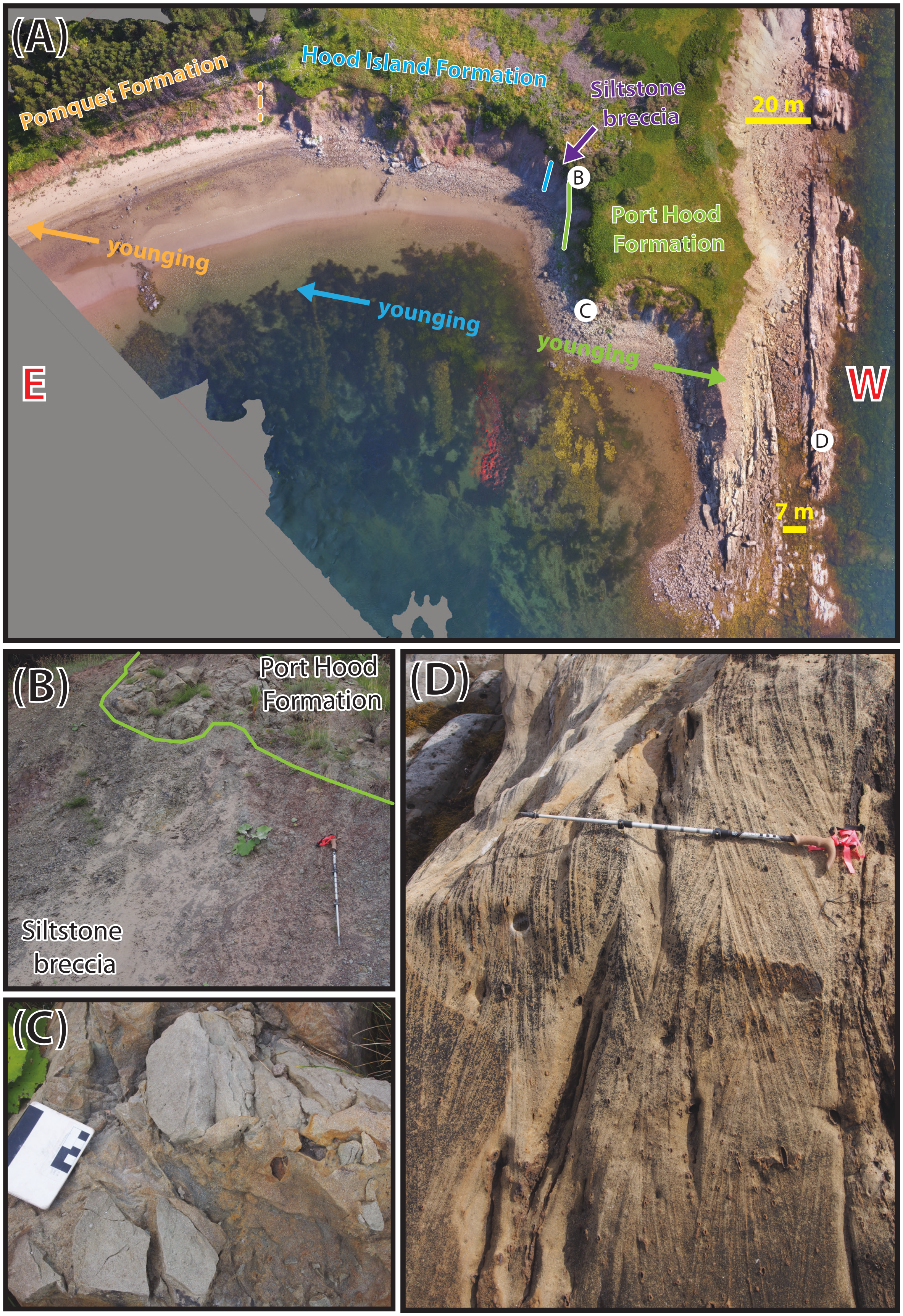


Figure 3.16. Equal area projection of all fibrous gypsum veins at Little Judique Harbour

Poles to veins are represented by circles, and fibre orientations are shown by diamonds.



(A)
Pomquet Formation
Hood Island Formation
Siltstone breccia
B
Port Hood Formation
20 m
younging
younging
C
younging
E
W
D
7 m
(B)
Port Hood Formation
Siltstone breccia
(C)
(D)

Figure 3.17. 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.

of the unit dips moderately northeast and suggests a northeast-plunging anticline (Figures 3.10 and 3.13). The western part of the unit dips moderately east and implies a northeast-plunging syncline (Figures 3.10 and 3.14). Between these two regions is a poorly exposed zone of randomly oriented breccia 13 m wide that we interpret as a fault between the anticline and syncline (Figure 3.10). In SLJH the bedding dips moderately to steeply west (Figure 3.11). We estimate a total structural thickness of 135 m of Hood Island Formation at NLJH (Figure 3.10).

Common discontinuous white to pink fibrous gypsum veins were observed in the siltstone and rarely in the gypsum of the Hood Island Formation at NLJH. The veins dip shallowly southwest where intact (Figure 3.15). The average fibre orientation is vertical, indicating a strong vertical component to the extension that formed them (Figure 3.15). The relationship of the veins and fibres ranges from perpendicular to oblique; there is no consistent sense of obliquity. This suggests locally variable shear directions during vein formation. The dominantly vertical direction of extension of these fibres may indicate that the interpreted fault through the Hood Island Formation (Figure 3.10) had dominantly vertical slip, if the fault occurred at the same time as the fibrous gypsum veins formed.

The dolomite at NLJH is cut by fractures dipping gently southwest. The similar orientations of the gypsum veins in the siltstone and the fractures in the dolomite suggest that they share an origin. In SLJH the siltstone breccia near the top of the formation is cut by subvertical fibrous gypsum veins that dip steeply west (Figure 3.16). Fibres in the veins plunge moderately northwest, oblique to the planes of the veins (Figure 3.16), suggesting west-side-up shear followed by horizontal extension.

Fine-grained Clastic Breccia

West of the Hood Island Formation is a zone dominated by brecciated red and grey mudstone and siltstone (Figures 3.10, 3.11, 3.12 and 3.17). In NLJH this zone is ~50 m wide, whereas it is only 5 m wide at SLJH. The clasts average 1-2 cm in size but are very poorly sorted. They are locally calcareous. No way up indicators were found in this zone at either NLJH or SLJH.

The middle part of this zone in NLJH currently comprises incompetent silt grains, with rare clasts of siltstone several centimetres in diameter. Large pieces of fibrous gypsum veins in this silt suggest that initially this outcrop was a competent lithology, likely a breccia of siltstone fragments, in which gypsum veins were formed. This implies that a later stage of deformation broke the veins apart and reduced the clast size of the rock to silt.

Siltstone clasts in a more competent region of siltstone breccia immediately west of the incompetent silt have similar orientations, suggesting bedding that dips moderately to steeply east (Figure 3.10). Two intervals of foliated gypsum, up to 1 m thick, are present within this siltstone breccia (Appendix G). Fibrous gypsum veins locally crosscut the siltstone breccia, indicating that they formed after the brecciation. Additionally, several slumped pieces of fibrous gypsum veins occur within the highly weathered middle portion of this zone. Where intact, the veins steeply dip west with fibres plunging gently east (Figure 3.16). Within the foliated gypsum, the veins are sub-parallel to the foliation.

Port Hood Formation

The westernmost unit at Little Judique Harbour is the Port Hood Formation of the Cumberland Group (Giles et al. 1997). This formation is composed of alternating units 10-30 m thick dominated by sandstone and siltstone. Trough crossbedding in the sandstones in the north and the south shows that the Port Hood Formation youngs to the west. The base of the Port Hood Formation overlies the siltstone breccia in both NLJH and SLJH.

The tan sandstone units are strongly trough-crossbedded except for the easternmost one. The crossbeds show that this steeply dipping to near-vertical formation youngs west, varying between upright and overturned (Figures 3.10 and 3.11). Some sandstone units are calcareous. Rare pebble lenses up to 1 m thick with clasts up to 15 cm in diameter, averaging 2 cm in diameter, are found in the western sandstone units. The lenses contain dominantly siderite clasts with minor sandstone and limestone clasts. The lenses also typically contain coal fragments, including rare fossil tree pieces over 1 m long and 15 cm wide (Figure 3.12).

The red, grey and tan siltstone-dominated units are highly weathered compared to the sandstone units, and are poorly exposed. These units also contain minor thin intervals of very fine-grained sandstone, limestone, shale, mudstone, and coal. Rare sandstone beds with climbing ripples indicate that the siltstone units young west. Rare bivalves occur in limestone float. Rare rod-shaped siderite concretions were observed in the siltstone units, and we interpret that they were the source of the siderite clasts in lenses within the sandstone units. In SLJH one of the siltstone units changes thickness from 21 to 7 m over an along-strike distance of 125 m (Figure 3.12), suggesting a lateral change in accommodation.

The basal sandstone locally displays weak crossbedding and is capped by a 50 cm thick limestone bed at NLJH. At SLJH this sandstone has rare convolute lamination and limestone clasts. In both locations the basal sandstone is heavily fractured. At NLJH it has two dominant fracture orientations that dip moderately east and northwest respectively (Figure 3.10). At SLJH this sandstone is highly but unsystematically fractured. Additionally, at SLJH angular light grey sandstone clasts occur in a matrix of massive tan sandstone at the base of the lowermost sandstone unit (Figure 3.17). The clasts are more weathering resistant than the matrix. Together with the colour difference, this suggests that the two episodes of cementation occurred at different times. The absence of laminae in the matrix implies that it was likely liquidized during emplacement around the clasts (Berra and Felletti 2011, Snyder and Waldron 2016). This suggests that the light grey sandstone was deposited, partially cemented, then was deformed and brecciated, and finally was fully cemented. The base of the Port Hood Formation therefore contains a synsedimentary sandstone breccia, which was in turn broken up by the fractures that cut through the entire sandstone unit.

3.6 Discussion and interpretation

We interpret the structure running north-south through Little Judique Harbour (Figure 3.18) as a secondary salt weld (the Little Judique Weld), based on: (i) outcrop-scale sedimentary and structural evidence for salt movement; (ii) the overall mapped geometry of the units; and (iii) the relationship to offshore salt-related structures described by Durling et al. (1995) and Brown (1998).

3.6.1 Field evidence for halokinesis

The past presence of evaporites at Little Judique Harbour, and possible modern presence of evaporites in the subsurface, is suggested by halite casts in the base of the Pomquet Formation and by gypsum in the Hood Island Formation and the fine-grained clastic breccia unit. Much of the breccia observed at NLJH and SLJH (Figures 3.12 and 3.17) closely resembles the siltstone breccia at Lakevale (Figure 3.5) interpreted in Chapter 2 to represent a primary salt weld. The clastic breccia unit at NLJH and SLJH therefore probably represents remnants of clastic interbeds in salt that was expelled and/or dissolved.

We suggest that the Port Hood Formation was locally deposited on top of moving salt. A significant along-strike thickness change occurs in the upper siltstone unit in the Port Hood Formation at SLJH (Figure 3.17). This amount of localized lateral thickness variation in a siltstone unit implies highly variable accommodation. The most likely cause of increased accommodation would be laterally variable salt movement in the subsurface beneath the Port Hood Formation. Locally, higher rates of salt expulsion beneath a particular area would create a greater amount of accommodation, while lower rates of salt expulsion in other areas along-strike would restrict the accommodation space available for the siltstone.

We therefore interpret that the salt was moving during the deposition of the Cumberland Group.

Additionally, evidence from deformation in the base of the Port Hood Formation suggests deposition on top of moving salt. In SLJH the base of the Port Hood Formation comprises a synsedimentary sandstone breccia. This synsedimentary breccia is in turn fractured by a later stage of deformation that impacted the entire basal sandstone unit. Fractures strike sub-parallel to the structure through Little Judique Harbour. Significant fracturing occurred in this sandstone, while the overlying strata show minimal fracturing. We suggest that the basal sandstone unit was deposited and lithified during a period of minimal and/or laterally consistent salt movement. Then, a significant increase in salt movement beneath the sandstone, likely creating laterally variable amounts of accommodation space, caused the fracturing of the entire sandstone. A substantial reduction in the amount of fracturing in the rest of the formation overlying the basal sandstone suggests that salt movement was relatively slow and constant during the deposition of the rest of the Cumberland Group.

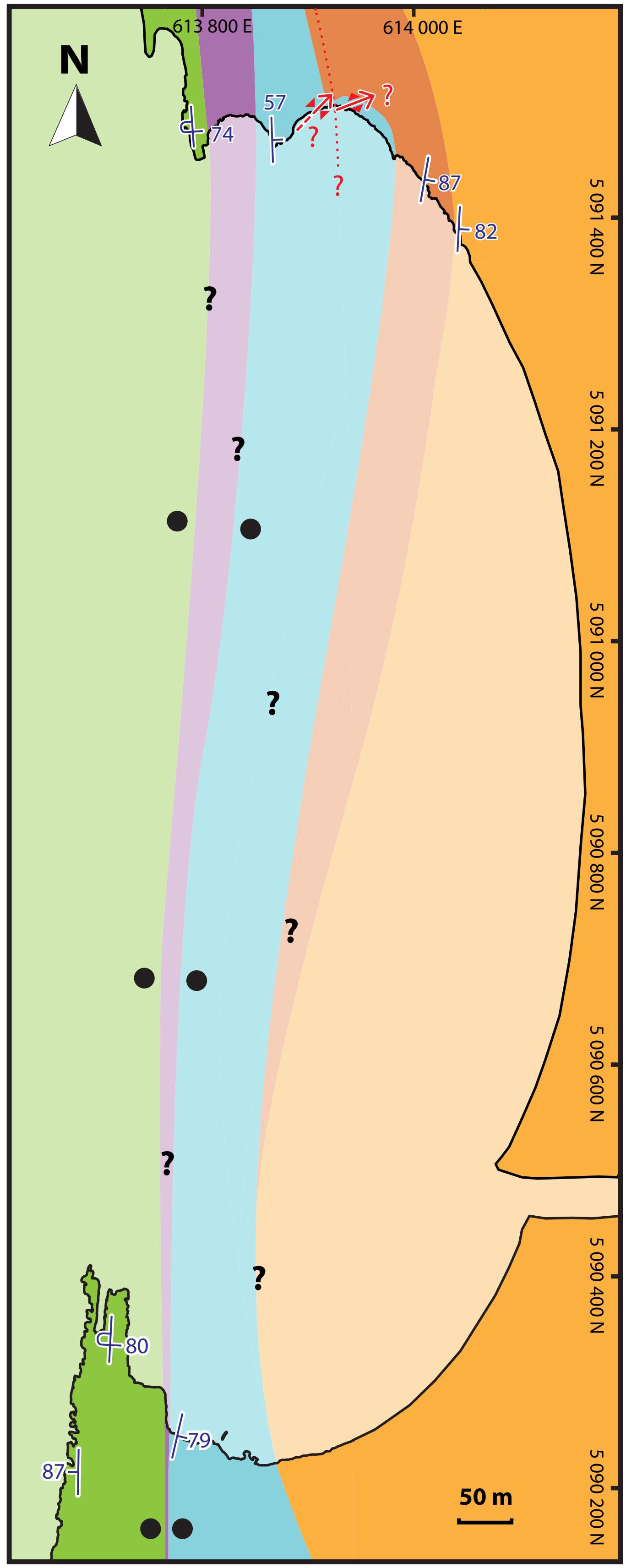
The fibrous gypsum veins that locally crosscut the clastic breccia and the Hood Island Formation likely formed prior to the deposition of the veinless Port Hood Formation. Fibre orientations within the veins are variable but in NLJH dominantly suggest vertical extension, consistent with subsidence as a result of underlying salt expulsion. At SLJH the fibres imply west-side-up shear and then horizontal extension, likely from the narrowing of the diapir that once occupied the space between the Hood Island Formation and the Port Hood Formation.

3.6.2 Mapped geometry

Giles et al. (1997) mapped the structure separating steep east-younging and west-younging strata as a fault of unknown type and displacement (Figure 3.9). A more likely interpretation is that this structure is a secondary salt weld. Secondary salt welds

Figure 3.18. Geological Map of Little Judique Harbour

Coastline reconstructed using an NRCAN shapefile and Google Earth. Made using Figures 3.10 and 3.11.



commonly separate steeply dipping sections with opposing younging directions (Jackson and Talbot 1991), the exact geometry that occurs at Little Judique Harbour. Thick salt is not a known component of the Hood Island Formation (the portion of the Windsor Group exposed at Little Judique Harbour), suggesting that the salt body/bodies responsible for the weld originated from lower in the Windsor Group; likely either from the Hartshorn Formation or the Middle Windsor Salt unit identified in Chapter 2.

The presence of strata of different ages in contact across a secondary weld (Bashkirian Port Hood Formation against the Viséan Upper Windsor Group) is likely the result of differential accommodation during salt movement. The lack of Cumberland Group strata on the eastern side of the weld suggests that insufficient salt expulsion occurred there to preserve the Cumberland Group. This could be due to the western, basinward side of the weld having initially had a thicker deposit of salt, resulting in more space created by salt expulsion. Alternatively, the western side of the structure could have had a greater rate of salt expulsion than the eastern side. The La Popa secondary salt weld in the La Popa Basin in northeastern Mexico similarly juxtaposes strata of different ages; Giles and Lawton (1999) interpret the La Popa Weld to have developed above a normal fault that created space for a thicker salt deposit above the hanging wall.

3.6.3 Relationship to structures offshore

We re-interpret the “faulted anticlines” of Durling et al. (1995) as near-surface secondary welds of salt walls identified at depth by Brown (1998) (Figure 3.8). Durling et al. (1995) interpreted Upper Windsor and Mabou Group strata beneath St Georges Bay to thin and steepen onto sub-vertical salt walls that bound local depocentres (Figure 3.7). This morphology implies that the thickest strata at the centre of the depocentres accumulated in deposition space enhanced by the movement of salt outwards and up into the bounding sub-vertical salt walls. We interpret these depocentres as salt-withdrawal minibasins (Jackson and Talbot 1991). The minibasins are up to 4500 m deep, suggesting that they have subsided into salt that had an original thickness much greater than the 540 m postulated by Brown (1998). Re-examination of the other shallow seismic lines in St Georges Bay studied by Durling et al. (1995) should be completed to place greater constraints on the original thickness of this salt.

3.6.4 Regional implications

Brown (1998) interpreted diapirism in St Georges Bay to have occurred from the Serpukhovian until after the Westphalian (Brown, 1998). Our results are largely consistent with his interpretation, showing that salt moved during the deposition of the Serpukhovian Hastings Formation and Westphalian Port Hood Formation. We propose that salt movement at Little Judique Harbour may have initiated in the late Viséan during the deposition of the upper Hood Island Formation.

The laterally variable thicknesses of the Upper Windsor and Mabou Group strata within the minibasins in St Georges Bay (Figure 3.7) show that salt expulsion was occurring during their deposition. One of these salt walls connects with the secondary salt weld through Little Judique Harbour. It is likely that the salt was being expelled at Little Judique Harbour during Hood Island Formation (Upper Windsor Group) and Mabou Group deposition.

In Chapter 2 we found that salt movement and welding in the Hartshorn Formation finished prior to the deposition of the Hood Island Formation, whereas the MWS was moving during the deposition of the Hood Island Formation and the Mabou Group. Therefore, the secondary weld at Little Judique Harbour likely represents expulsion from the MWS. Sedimentary and structural evidence at Little Judique Harbour indicates halokinesis throughout the deposition of the exposed Cumberland Group. This suggests that movement of the MWS continued until at least the Bashkirian.

3.7 Conclusions

A salt wall once ran north-south through Little Judique Harbour. The salt has since been expelled to form a secondary salt weld, which is visible in outcrop at the northern and southern ends of the harbour (Figure 3.18). Salt movement occurred at inconsistent rates laterally and temporally throughout the deposition of the Port Hood Formation, and likely during the deposition of the Upper Windsor Hood Island Formation and Mabou Group. Differences in salt expulsion rates and/or initial thicknesses of salt on either side of the salt wall led to strata of different units being juxtaposed across the weld, with westward-younging Cumberland Group on the western side of the weld and eastern-younging Hood Island Formation on the eastern side of the weld (Figure 3.18). The salt that formed the weld was likely from the MWS that was identified in Chapter 2.

The Antigonish sub-basin contains outcrops of both secondary and primary welds, with the potential for more to be discovered. Salt welds have rarely been described in outcrop and detailed studies have been performed only on the La Popa Weld in Mexico (e.g. Giles and Lawton 1999). The Antigonish sub-basin is an excellent location for further study of salt welds as abundant salt diapirs are known in the subsurface.

Salt movement has been occurring throughout the Antigonish sub-basin since the deposition of the Lower Windsor Group. It may even be ongoing today if sufficient salt remains in the sub-surface. This salt movement controlled the geometries of strata in all regions of the Antigonish sub-basin: in Cape Breton Island, beneath St Georges Bay, and within mainland Nova Scotia (as discussed in the previous chapter).

3.8 References

Alsop, G.I., Brown, J.P., Davison, I., and Gibling, M.R. 2000. The geometry of drag zones adjacent to salt diapirs. Journal of the Geological Society of London, **157**: 1019–1029.

Bell, W.A. 1929. Horton-Windsor District, Nova Scotia. Geological Survey of Canada, Memoir, 155.

Belt, E.S. 1965. Stratigraphy and Paleogeography of Mabou Group and Related Middle Carboniferous Facies, Nova Scotia, Canada. Geological Society of America Bulletin, **76**: 777–802. doi:10.1130/0016-7606(1965)76[777:SAPOMG]2.0.CO;2.

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.

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

Brown, J.P. 1998. Deformation and sedimentation adjacent to Carboniferous diapiric salt structures, Nova Scotia. PhD thesis, Dalhousie University, Halifax, Canada.

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

Gibling, M.R., Culshaw, N., Pascucci, V., Waldron, J.W.F., and Rygel, M.C. 2019. The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea. *In* The Sedimentary Basins of the United States and Canada, 2nd Edition, The Sedimentary Basins of the United States and Canada. *Edited by* A.D. Miall. pp. 267–314.

Gibling, M.R., Culshaw, N., Rygel, M.C., and Pascucci, V. 2009. The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea. *In* Sedimentary basins of the United States and Canada, Sedimentary basins of the United States and Canada, Sedimentary Basins of the World. *Edited by* A. Miall. pp. 211–244.

Giles, K.A., and Lawton, T.F. 1999. Attributes and evolution of an exhumed salt weld, La Popa basin, northeastern Mexico. Geology, **27**: 323–326.

Giles, P.S. 1981a. 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. 1981b. The Windsor Group of the Mahone Bay Area, Nova Scotia. Nova Scotia Department of Mines and Energy, Paper 81-3.

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.

Hamblin, A.P. 2001. Stratigraphy, sedimentology, tectonics, and resource potential of the lower Carboniferous Mabou Group, Nova Scotia. Geological Survey of Canada, Bulletin, 568.

Hamblin, A.P., and Rust, B.R. 1989. Tectono-sedimentary analysis of alternate-polarity half-graben basin-fill successions: Late Devonian-Early Carboniferous Horton Group, Cape Breton Island, Nova Scotia. Basin Research, **2**: 239–255. doi:10.1111/j.1365-2117.1989.tb00038.x.

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.

Howie, R.D. 1988. Upper Paleozoic evaporites of southeastern Canada. Geological Survey of Canada Bulletin, 380.

Howie, R.D., and Barss, M.S. 1975. Upper Paleozoic rocks of the Atlantic provinces, Gulf of St. Lawrence, and adjacent continental shelf. *In* Offshore geology of eastern Canada, Volume 2 - Regional Geology, Offshore geology of eastern Canada, Volume 2 - Regional Geology, Geological Survey of Canada, Paper. *Edited by* W.J.M. Van Der Linden and J.A. Wade. pp. 35–50.

Jackson, M.P.A., and Talbot, C.J. 1991. A Glossary of Salt Tectonics. The University of Texas at Austin.

Keighley, D.G., and Pickerill, R.K. 1996. The evolution of fluvial systems in the Port Hood Formation (Upper Carboniferous), western Cape Breton Island, eastern Canada. Sedimentary Geology, **106**: 97–144.

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.

McBride, B.C., Weimer, P., and Rowan, M.G. 1998. The effect of allochthonous salt on the petroleum systems of northern Green Canyon and Ewing Bank (offshore Louisiana), northern Gulf of Mexico. AAPG bulletin, **82**: 1083–1112.

Mello, U.T., Anderson, R.N., and Karner, G.D. 1994. Salt restrains maturation in subsalt plays. Oil & Gas Journal, **92**: 101–102, 104–107.

Murray, B.C. 1955. Stratigraphy of the Horton Group in parts of Nova Scotia. PhD Thesis, Massachusetts Institute of Technology, Cambridge, USA.

Ryan, R.J., and Boehner, R.C. 1994. Geology of the Cumberland Basin, Cumberland, Colchester and Pictou Counties, Nova Scotia. Nova Scotia Department of Natural Resources Memoir, 10.

Schenk, P.E. 1969. Carbonate-sulfate-redbed facies and cyclic sedimentation of the Windsorian Stage (middle Carboniferous), Maritime Provinces. Canadian Journal of Earth Sciences, **6**: 1037–1066.

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.

St. Peter, C.J. 1993. Maritimes Basin evolution: key geologic and seismic evidence from the Moncton Subbasin of New Brunswick. Atlantic Geology, **29**: 233–270.

Thomas, D.B. 1999. Structural evolution of the Antigonish Basin, Nova Scotia, Canada. MSc thesis, College of Arts and Sciences of Ohio University, Columbus, USA.

Thomas, D.B., Nance, R.D., and Murphy, J.B. 2002. Deformation of the Macumber Formation, Antigonish Basin, Nova Scotia: implications for the Ainslie Detachment. Atlantic Geology, **38**: 135–144.

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. Nova Scotia Department of Energy Open File Report, 2017–02.

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.

White, C.E., and Boehner, R.C. 2008. Bedrock Geology Map of the Whycogomagh Area, NTS Sheet 11F/14, Inverness County, Nova Scotia. Nova Scotia Department of Natural Resources Open File Map, ME 2008-1, scale 1:50,000.

Williams, E.P. 1974. Geology and petroleum possibilities in and around Gulf of St. Lawrence. AAPG Bulletin, **58**: 1137–1155.

Chapter 4. Conclusions

The Paleozoic Antigonish sub-basin of Nova Scotia, Canada records a complex history of salt movement and the resulting deformation of the basin-fill. Salt movement occurred in the Hartshorn Formation of the Lower Windsor Group and in a younger halite unit named the Middle Windsor Salt (MWS). The majority of salt-related structures observed in seismic data from the Antigonish sub-basin are from MWS movement. Initiation of this salt movement was diachronous across the sub-basin.

Salt expulsion began in the Antigonish sub-basin during the Viséan as the Middle Windsor Group was deposited on top of the Hartshorn Formation. The salt moved outwards, collecting in diapirs around the sub-basin margins, and the Hartshorn Formation became welded in the centre. The diapirs prevented local deposition of the Middle and Upper Windsor Group. The MWS was deposited as a sub-horizontal layer across the sub-basin after movement in the underlying Hartshorn Formation concluded. Local expulsion of the MWS began during deposition of the Upper Windsor Group; however, the majority of the movement occurred after the Upper Windsor Group and Mabou Group were deposited. The MWS locally forms primary salt welds.

Several structures that were previously interpreted as faults are re-interpreted as salt welds. The regional omission surface at the top of the Hartshorn Formation that was named the Antigonish Thrust (Boehner and Giles 1982, 1993) and later the Ainslie Detachment (Lynch and Giles 1995) is a sub-basin wide primary weld, exposed at Lakevale (Figure 4.1). The presence of salt prevented the local deposition of Windsor Group strata, explaining the variable stratigraphic gaps identified by Lynch et al. (1998) (Figure 4.2), and the missing Windsor Group stratigraphy at Lakevale (Figure 4.1). Several “faults” in the central portion of the sub-basin between the Morristown and Glenroy faults are salt diapirs. A secondary salt weld is exposed at the northern and southern ends of Little Judique

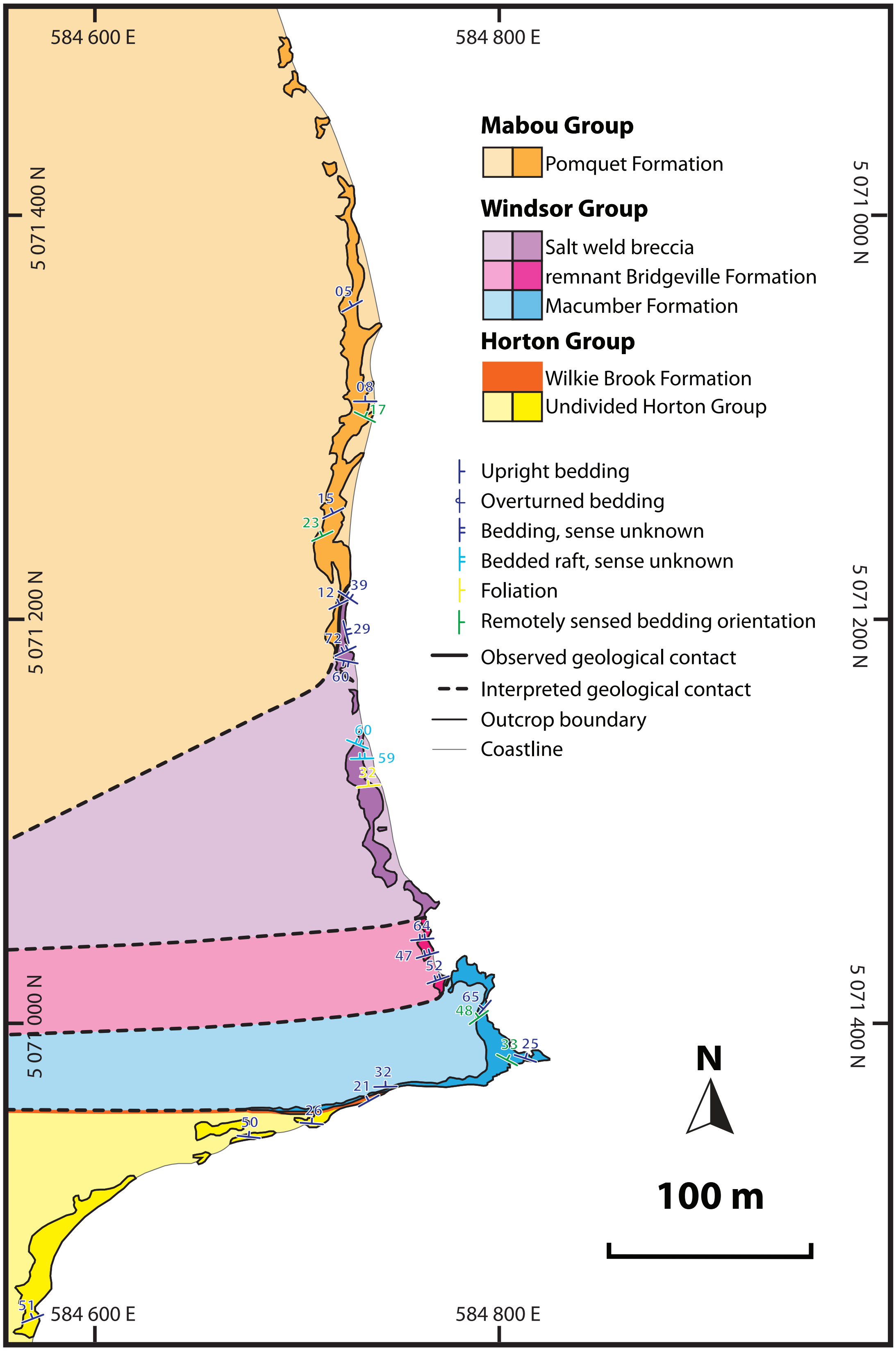


Figure 4.1. Lakevale section in map view

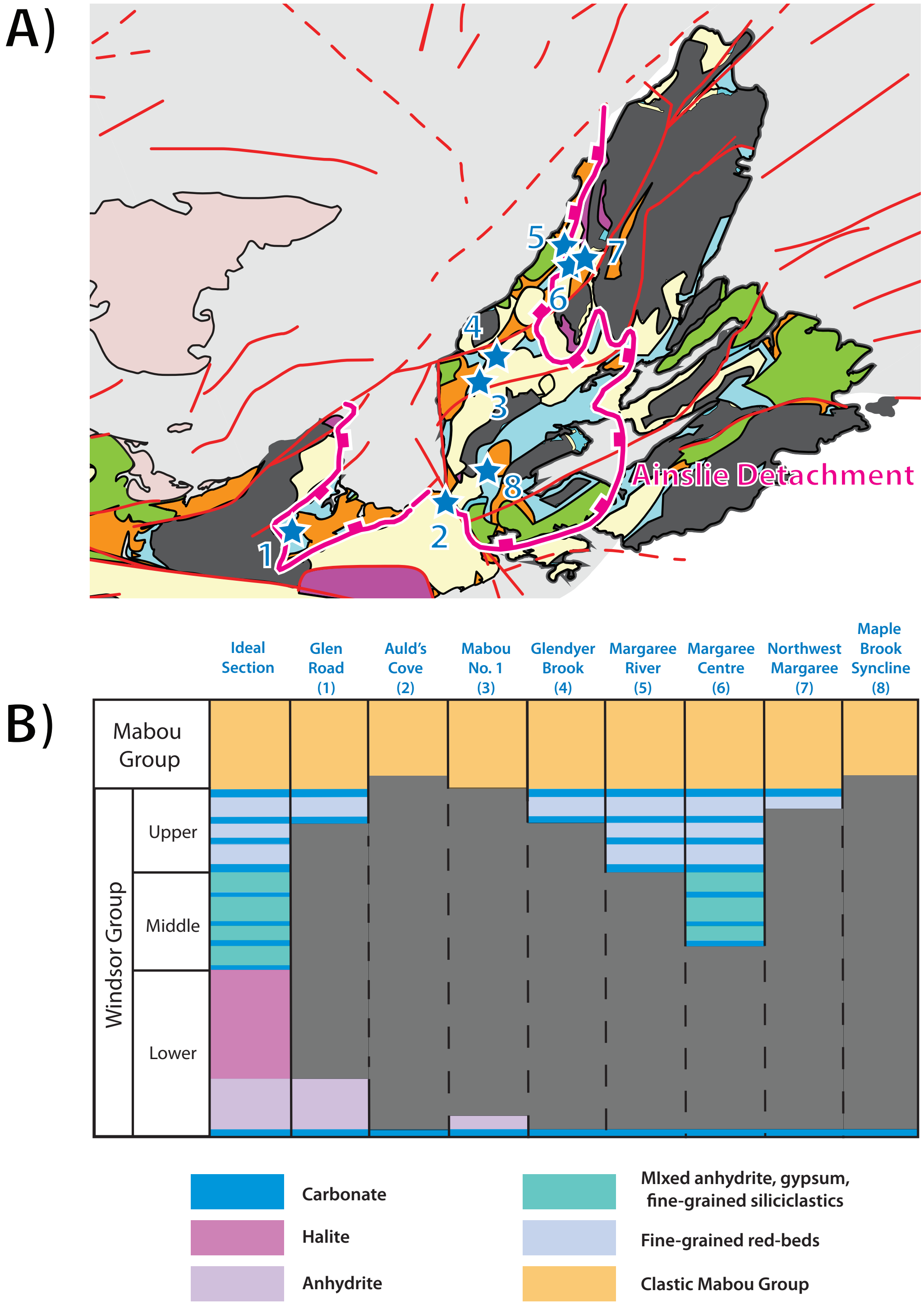


Figure 4.2. Stratigraphic gaps across the Ainslie Detachment

(A) Inset map showing approximate measured section locations from Lynch et al. (1998). Map modified from Waldron et al. (2017). (B) Measured sections of the Mabou and Windsor Group from Lynch et al. (1998) showing gaps they attribute to the Ainslie Detachment.

Harbour (Figure 4.3). Salt movement here began during the Viséan and continued until after the Serpukhovian, indicating that expulsion of the MWS formed this secondary weld.

The Antigonish sub-basin should be remapped with consideration of the impact of salt tectonics. Outcrops of the “Ainslie Detachment” in Cape Breton (Lynch et al. 1998) should be re-examined to see if they represent the exposure of a primary weld in outcrop and can provide evidence of the timing of salt movement from the Hartshorn Formation. Structures mapped as faults that have associated unusual stratigraphic relationships or gaps should be re-examined as potential salt structures. A prime candidate is the structure running northeast-southwest through Port Hood Island (Giles et al. 1997)(Figure 4.4) as it separates strata of opposing younging directions and has a similar orientation to the secondary salt weld at Little Judique Harbour. Seismic data and drillcore should be examined to determine if the MWS continues from mainland Nova Scotia into southwestern Cape Breton Island, and is responsible for the diapirs studied by Brown (1998) and the weld at Little Judique Harbour. Additionally the possibility of more salt walls or welds in the sub-surface of the island with a northeast-southwest orientation should be considered, as this study shows that one of the salt walls interpreted by Brown (1998) continues onshore as a secondary salt weld.

Salt-related research in the Maritimes Basin has focused on locating salt rather than considering salt movement and its impact on stratigraphy. This study on the Antigonish sub-basin and recent work on the nearby Cumberland sub-basin (Waldron and Rygel 2005, Waldron et al. 2013) show that salt movement has significantly affected portions of the Maritimes Basin. The potential for salt movement in other regions of the Basin is high and should be evaluated in future research.

References

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.

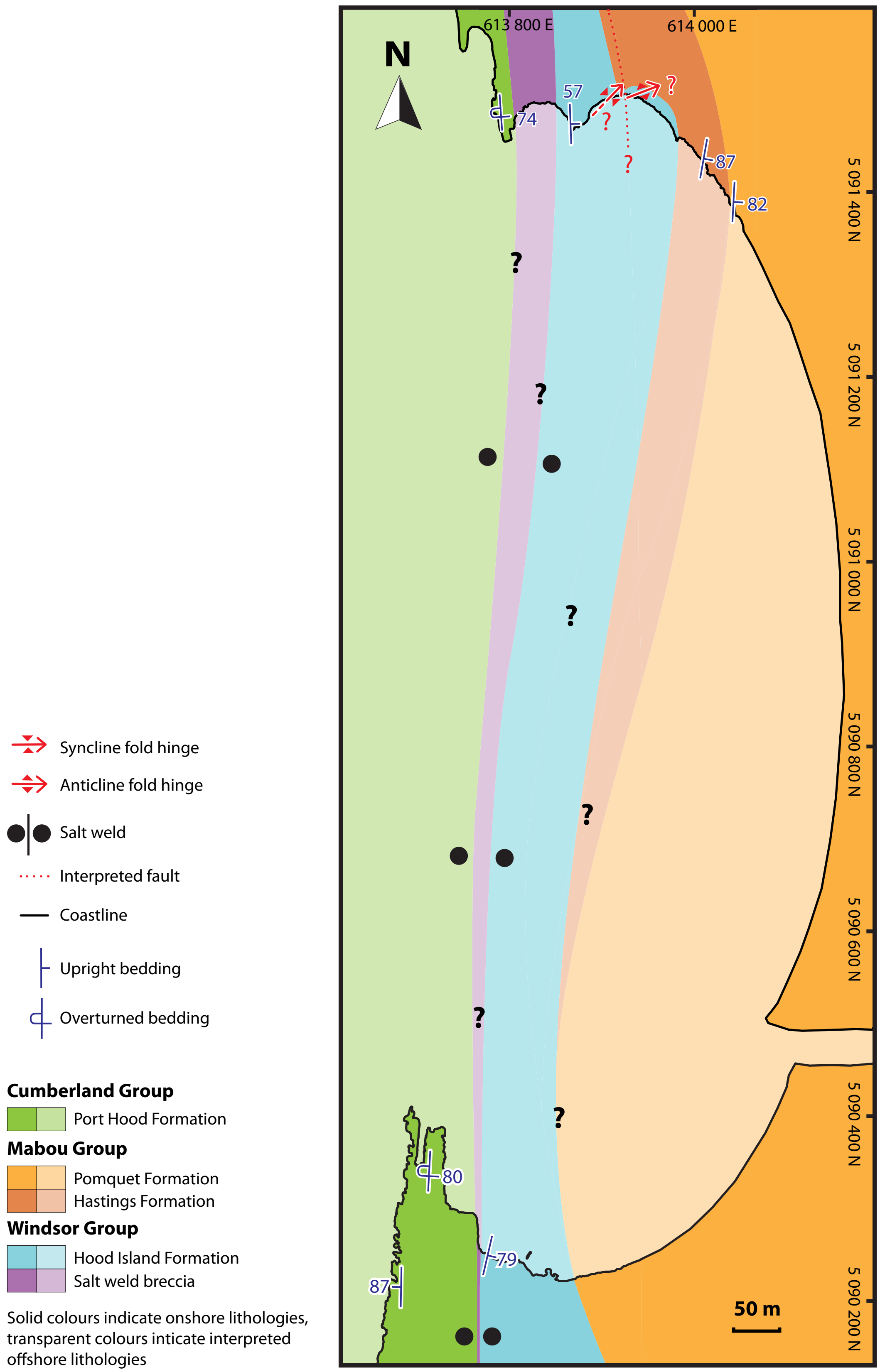


Figure 4.3. Geological Map of Little Judique Harbour

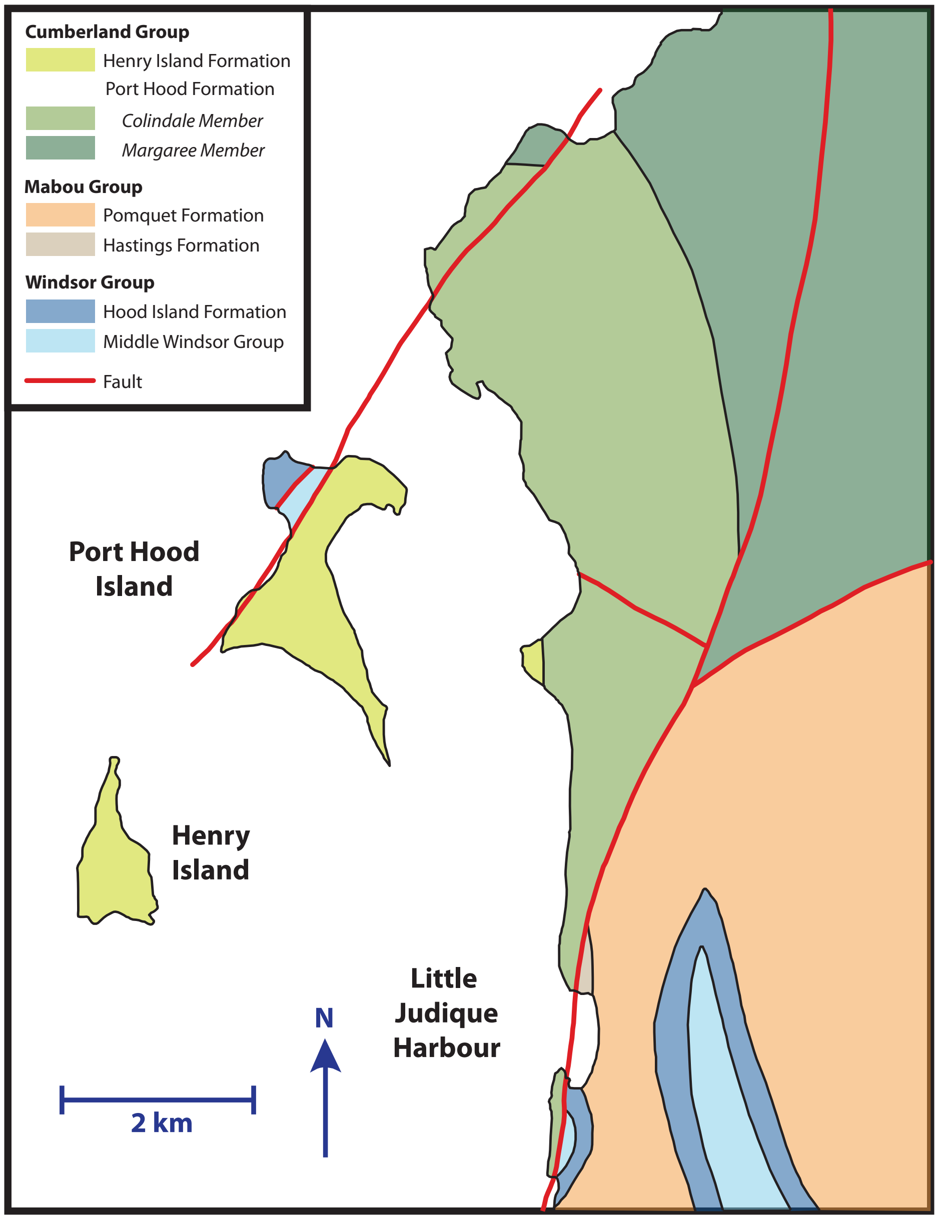


Figure 4.4. Geological map of Little Judique Harbour and Port Hood Island based on previous mapping

Modified from Giles et al. (1997) and Brown (1998).

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.

Brown, J.P. 1998. Deformation and sedimentation adjacent to Carboniferous diapiric salt structures, Nova Scotia. PhD thesis, Dalhousie University, Halifax, Canada.

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.

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.

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.

Bibliography

Alsop, G.I., Brown, J.P., Davison, I., and Gibling, M.R. 2000. The geometry of drag zones adjacent to salt diapirs. Journal of the Geological Society of London, **157**: 1019–1029.

Amax Exploration. 1974. Diamond Drill Record, Hole No. AP-2-74. Unpublished diamond drill record. Available from https://novascotia.ca/natr/meb/data/ar/11E/AR_ME_11E08D_40-B-19_01_431684.pdf [accessed 26 April 2019].

Bailey, E.B. 1931. Salt-Plugs. Geological Magazine, **68**: 335–336.

Barde, J.-P., Chamberlain, P., Galavazi, M., Gralla, P., Harwijanto, J., Marsky, J., and van den Belt, F. 2002. Sedimentation during halokinesis: Permo-Triassic reservoirs of the Saigak field, Precaspian basin, Kazakhstan. Petroleum Geoscience, **8**: 177–187.

Barss, M.S., Grant, A.C., Sanford, B.V., and Wade, J.A. 1977. Basement structure, Eastern Canada and adjacent areas. Geological Survey of Canada, Map, scale 1:2 000 000.

Bell, W.A. 1929. Horton-Windsor District, Nova Scotia. Geological Survey of Canada, Memoir, 155.

Bell, W.A. 1944. Carboniferous rocks and fossil floras of northern Nova Scotia. Geological Survey of Canada, Memoir, 238.

Bell, W.A. 1960. Mississippian Horton Group of Type Windsor-Horton District Nova Scotia. Geological Survey of Canada Memoir, 314.

Belt, E.S. 1964. Revision of Nova Scotia Middle Carboniferous units. American Journal of Science, **262**: 653–673.

Belt, E.S. 1965. Stratigraphy and Paleogeography of Mabou Group and Related Middle Carboniferous Facies, Nova Scotia, Canada. Geological Society of America Bulletin, **76**: 777–802. doi:10.1130/0016-7606(1965)76[777:SAPOMG]2.0.CO;2.

Benson, D.G. 1970. Notes to accompany geological maps of Antigonish and Cape George map-areas, Nova Scotia. Geological Survey of Canada, Paper, 70–8.

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. 1980. Note on revised stratigraphy of the Lower Carboniferous Windsor Group, Crystal Cliffs section, Antigonish county, Nova Scotia. Mineral Resources Division, Report of Activities 1979,: 137–145.

Boehner, R.C. 1984. Stratigraphic drillhole NSDME Glen Road 83-1, western part of the Antigonish Basin, Antigonish County, Nova Scotia. *In* Mines and Minerals Branch, Report of Activities 1984, Mines and Minerals Branch, Report of Activities 1984, Nova Scotia Department of Mines and Energy, Report 84-1. pp. 125–132.

Boehner, R.C. 1986. Salt and Potash Resources in Nova Scotia. Nova Scotia Department of Mines and Energy Bulletin, ME 005.

Boehner, R.C. 1993. Diamond-drill Core Log of Nova Scotia Department of Natural Resources Drillhole GR83-1, Glen Road, Antigonish County, Nova Scotia. Open-File Report, ME 1993-008.

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.

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

Bright, J.E., and Ridge, M.J. 1962. Twinned crystals of precipitated gypsum. Mineralogical Magazine, **33**: 347–348.

Brown, J.P. 1998. Deformation and sedimentation adjacent to Carboniferous diapiric salt structures, Nova Scotia. PhD thesis, Dalhousie University, Halifax, Canada.

Burton, W. 1974. SV74-3 Diamond Drill Record. Unpublished diamond drill record.

Calder, J.H. 1985. Coal in Nova Scotia. Information Series ME 008.

Callot, J.-P., Salel, J.-F., Letouzey, J., Daniel, J.-M., and Ringenbach, J.-C. 2016. Three-dimensional evolution of salt-controlled minibasins: Interactions, folding and megaflap development. AAPG Bulletin, **100**: 1419–1442. doi:10.1306/03101614087.

Cohen, H.A., and Hardy, S. 1996. Numerical modelling of stratal architectures resulting from differential loading of a mobile substrate. Geological Society, London, Special Publications, **100**: 265–273.

Craggs, S., Keighley, D., Waldron, J.W.F., and Park, A.F. 2015. Salt tectonics in an intracontinental transform setting: Cumberland and Sackville basins, southern New Brunswick, Canada. Basin Research, **29**: 266–283.

Davidson, I., Alsop, I., and Blundell, D.J. 1996. Salt tectonics: Some aspects of deformation mechanics. Salt Tectonics, Geological Society Special Publication, **100**: 1–10.

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.

Durling, P., and Marillier, F. 1993. Structural elements of the Magdalen Basin, Gulf of St. Lawrence, from seismic reflection data. *In* Current Research, Current Research, Geological Survey of Canada Paper, 93–1D. pp. 147–154.

Fossen, H. 2010. Structural Geology. Cambridge University Press.

Gibling, M.R., Culshaw, N., Pascucci, V., Waldron, J.W.F., and Rygel, M.C. 2019. The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of

Pangea. *In* The Sedimentary Basins of the United States and Canada, 2nd Edition, The Sedimentary Basins of the United States and Canada. *Edited by* A.D. Miall. pp. 267–314.

Gibling, M.R., Culshaw, N., Rygel, M.C., and Pascucci, V. 2009. The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea. *In* Sedimentary basins of the United States and Canada, Sedimentary basins of the United States and Canada, Sedimentary Basins of the World. *Edited by* A. Miall. pp. 211–244.

Giles, K.A., and Lawton, T.F. 1999. Attributes and evolution of an exhumed salt weld, La Popa basin, northeastern Mexico. Geology, **27**: 323–326.

Giles, P.S. 1980. Windsor Group Stratigraphy and paleogeography: Project activities 1979-80. *In* Mineral Resources Division, Report of Activities 1979, Mineral Resources Division, Report of Activities 1979, Nova Scotia Department of Mines and Energy, Report 80-1. pp. 205–209.

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. 2008. Windsor Group (Late Mississippian) stratigraphy, Magdalen Islands, Quebec: a rare eastern Canadian record of late Viséan basaltic volcanism. Atlantic Geology, **44**: 167 – 185.

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., Boehner, R.C., and Ryan, R.J. 1979. Carbonate banks of the Gays River Formation in central Nova Scotia. Nova Scotia Department of Mines, Paper 79-7.

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, Eastern Canada and National and General Programs, Geological Survey of Canada Current Research. pp. 89–94.

Grace, K.A. 1966. Report on Antigonish Basin Nova Scotia; Kennco Explorations, (Canada) Limited. Unpublished diamond drill record.

Hamblin, A.P. 1989. Sedimentology, Tectonic Control, and Resource Potential of the Upper Devonian – Lower Carboniferous Horton Group, Cape Breton Island, Nova Scotia. PhD thesis, University of Ottawa, Ottawa, Canada.

Hamblin, A.P. 2001. Stratigraphy, sedimentology, tectonics, and resource potential of the lower Carboniferous Mabou Group, Nova Scotia. Geological Survey of Canada, Bulletin, 568.

Hamblin, A.P., and Rust, B.R. 1989. Tectono-sedimentary analysis of alternate-polarity half-graben basin-fill successions: Late Devonian-Early Carboniferous Horton Group, Cape Breton Island, Nova Scotia. Basin Research, **2**: 239–255. doi:10.1111/j.1365-2117.1989.tb00038.x.

Harrison, T.S. 1927. Colorado-Utah salt domes. AAPG Bulletin, **11**: 111–133.

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.

Howie, R.D. 1988. Upper Paleozoic evaporites of southeastern Canada. Geological Survey of Canada Bulletin, 380.

Howie, R.D., and Barss, M.S. 1975. Upper Paleozoic rocks of the Atlantic provinces, Gulf of St. Lawrence, and adjacent continental shelf. *In* Offshore geology of eastern Canada, Volume 2 - Regional Geology, Offshore geology of eastern Canada, Volume 2 - Regional Geology, Geological Survey of Canada, Paper. *Edited by* W.J.M. Van Der Linden and J.A. Wade. pp. 35–50.

Hudec, M.R., and Jackson, M.P.A. 2006. Advance of allochthonous salt sheets in passive margins and orogens. AAPG Bulletin, **90**: 1535–1564. doi:10.1306/05080605143.

Hudec, M.R., and Jackson, M.P.A. 2007. Terra infirma: Understanding salt tectonics. Earth-Science Reviews, **82**: 1–28. doi:10.1016/j.earscirev.2007.01.001.

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.

Imperial Oil Limited. 1974. Summary Report on Diamond Drilling at Pomquet - Captain's Pond, Antigonish Co. Nova Scotia. Unpublished diamond drill record.

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. 1995. Retrospective salt tectonics. *In* Salt tectonics: a global perspective, Salt tectonics: a global perspective, AAPG Memoir. *Edited by* M.P.A. Jackson, D.G. Roberts, and S. Snelson. [accessed 5 December 2016].

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

Jackson, M.P.A., and Talbot, C.J. 1991. A Glossary of Salt Tectonics. The University of Texas at Austin.

Keighley, D.G., and Pickerill, R.K. 1996. The evolution of fluvial systems in the Port Hood Formation (Upper Carboniferous), western Cape Breton Island, eastern Canada. Sedimentary Geology, **106**: 97–144.

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.

Keppie, J.D., Giles, P.S., and Boehner, R.C. 1978. Some Middle Devonian to lower Carboniferous rocks of Cape George, Nova Scotia. Nova Scotia Department of Mines, Paper 78-4.

Kergaravat, C., Ribes, C., Callot, J.-P., and Ringenbach, J.-C. 2017. Tectono-stratigraphic evolution of salt-controlled minibasins in a fold and thrust belt, the Oligo-Miocene central Sivas Basin. Journal of Structural Geology, **102**: 75–97. doi:10.1016/j.jsg.2017.07.007.

Langdon, G.S., and Hall, J. 1994. Devonian-Carboniferous tectonics and basin deformation in the Cabot Strait area, Eastern Canada. AAPG Bulletin, **78**: 1748–1774. doi:10.1306/a25ff283-171b-11d7-8645000102c1865d.

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.

MacDonald, E. 2003. Geological Report on Beech Hill #1, Antigonish Nova Scotia. Vintage Petroleum Canada.

Martel, A.T., and Gibling, M.R. 1996. Stratigraphy and tectonic history of the Upper Devonian to lower Carboniferous Horton Bluff Formation, Nova Scotia. Atlantic Geology, **32**: 13–38.

Moore, R.G. 1967. Lithostratigraphic units in the upper part of the Windsor Group, Minas Sub-basin, Nova Scotia. *In* Collected papers on geology of the Atlantic Region, Collected papers on geology of the Atlantic Region, Geological Association of Canada, Special Paper. *Edited by* E.R.W. Neale and H. Williams. pp. 245–266.

Murphy, J.B. 2001. Geochemistry, provenance, and tectonic significance of sedimentary rocks of the Middle to Late Devonian McArras Brook and Visean Martin Road formations, Merigomish Subbasin, northern Antigonish Highlands, Nova Scotia. Atlantic Geology, **37**: 161–173.

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.

Murray, B.C. 1955. Stratigraphy of the Horton Group in parts of Nova Scotia. PhD Thesis, Massachusetts Institute of Technology, Cambridge, USA.

New Brunswick Department of Natural Resources and Energy. 2000. Bedrock Geology of New Brunswick. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Map, NR-1, scale 1: 500 000.

Norman, G.W.H. 1935. Lake Ainslie map-area, N.S. Geological Survey of Canada, Memoir 177.

Passchier, C.W., and Trouw, R.A.J. 2005. Microtectonics.

Prime, G.A. 1987. The Antigonish basin of Maritime Canada: A sedimentary tectonic history of a late Paleozoic fault-wedge basin. MSc thesis, Dalhousie University, Halifax, Canada.

Ramsay, J.G. 1967. Folding and Fracturing of Rocks. McGraw Hill, San Francisco.

Ramsay, J.G., and Huber, M.I. 1983. The Techniques of Modern Structural Geology. Volume 2: Folds and fractures. Academic Press, London.

Rettger, R.E. 1935. Experiments on soft-rock deformation. AAPG Bulletin, **19**: 271–292.

Rowan, M.G., Lawton, T.F., and Giles, K.A. 2012. Anatomy of an exposed vertical salt weld and flanking strata, La Popa Basin, Mexico. Geological Society, London, Special Publications, **363**: 33–57. doi:10.1144/SP363.3.

Rowan, M.G., Lawton, T.F., Giles, K.A., and Ratliff, R.A. 2003. Near-salt deformation in La Popa basin, Mexico, and the northern Gulf of Mexico: A general model for passive diapirism. AAPG bulletin, **87**: 733–756.

Ryan, R.J., and Boehner, R.C. 1994. Geology of the Cumberland Basin, Cumberland, Colchester and Pictou Counties, Nova Scotia. Nova Scotia Department of Natural Resources Memoir, 10.

Schenk, P.E. 1967a. 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. 1967b. The significance of algal stromatolites to paleo-environmental and chronostratigraphic interpretations of the Windsorian Stage (Mississippian), Maritime Provinces. *In* Collected Papers on Geology of the Atlantic Region, Collected Papers on Geology of the Atlantic Region, Geological Association of Canada Special Paper, 4.

Schenk, P.E. 1969. Carbonate-sulfate-redbed facies and cyclic sedimentation of the Windsorian Stage (middle Carboniferous), Maritime Provinces. Canadian Journal of Earth Sciences, **6**: 1037–1066.

Schultz-Ela, D.D. 2003. Origin of drag folds bordering salt diapirs. AAPG Bulletin, **87**: 757–780. doi:10.1306/12200201093.

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.

St. Peter, C.J. 1993. Maritimes Basin evolution: key geologic and seismic evidence from the Moncton Subbasin of New Brunswick. Atlantic Geology, **29**: 233–270.

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.

Ténière, P., Giles, P.S., Naylor, R.D., and MacDonald, D.R. 2002. Stratigraphy of the Horton Group, Guysborough and Antigonish counties. *In* Minerals and Energy Branch Report of Activities, Minerals and Energy Branch Report of Activities, Nova Scotia Department of Natural Resources, Report, ME 2002-001. pp. 129–139.

Ténière, P.J., Barr, S.M., and White, C.E. 2005. Stratigraphy and structure of the Horton Group, Lochaber-Mulgrave area, northern mainland Nova Scotia. Atlantic Geology, **41**: 41–52.

Thomas, D.B. 1999. Structural evolution of the Antigonish Basin, Nova Scotia, Canada. MSc thesis, College of Arts and Sciences of Ohio University, Columbus, USA.

Thomas, D.B., Nance, R.D., and Murphy, J.B. 2002. Deformation of the Macumber Formation, Antigonish Basin, Nova Scotia: implications for the Ainslie Detachment. Atlantic Geology, **38**: 135–144.

Trusheim, F. 1960. Mechanism of salt migration in northern Germany. AAPG Bulletin, **44**: 1519–1540.

Van Tuyl, F.M. 1930. Contribution to salt-dome problem. AAPG Bulletin, **14**: 1041–1047.

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

Vernon, R.H. 2004. A Practical Guide to Rock Microstructure. Cambridge University Press.

Wagner, B.H., and Jackson, M.P.A. 2011. Viscous flow during salt welding. Tectonophysics, **510**: 309–326. doi:10.1016/j.tecto.2011.07.012.

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. Nova Scotia Department of Energy Open File Report, 2017–02.

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.

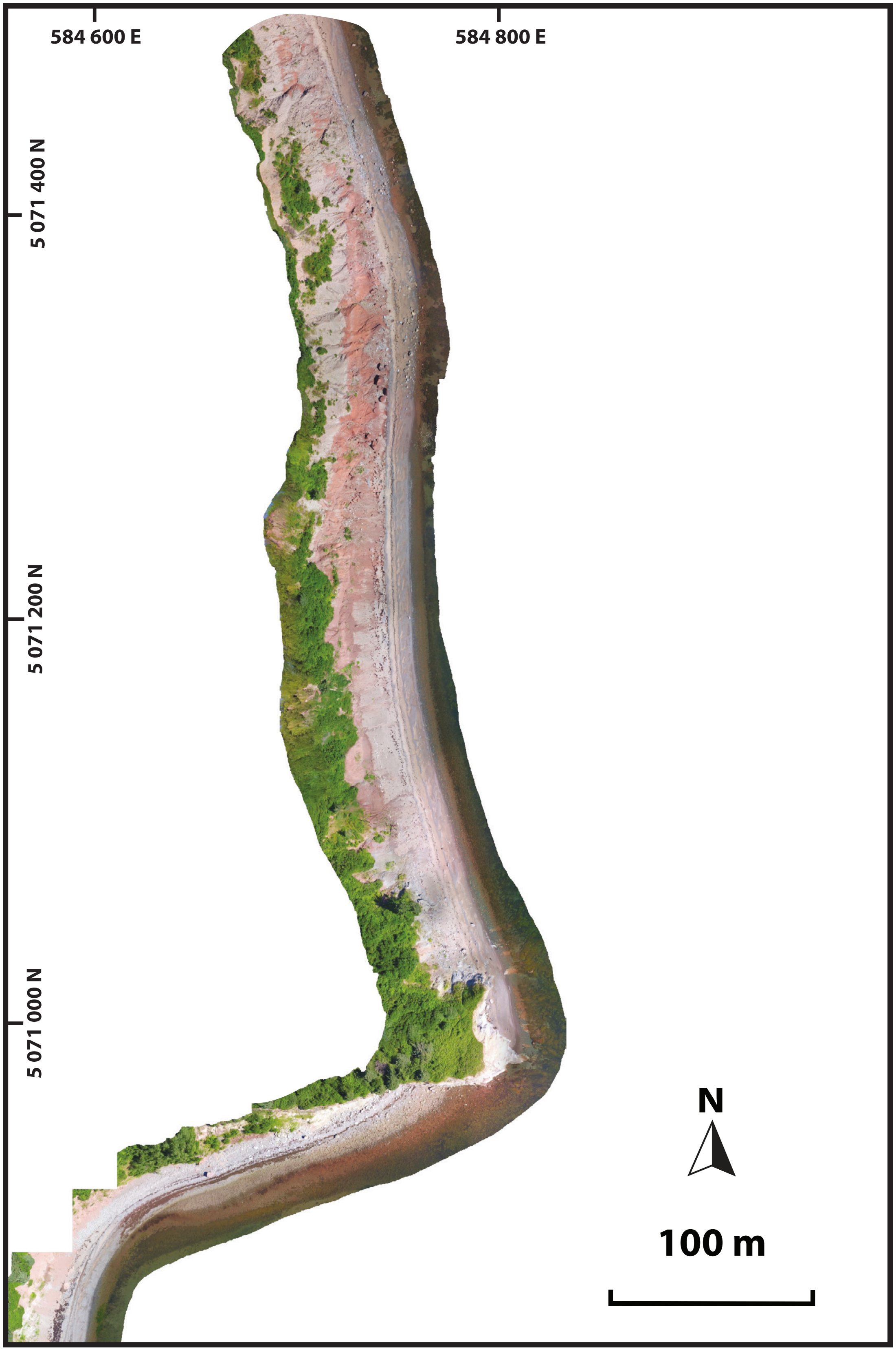
Waldron, J.W.F., and Rygel, M.C. 2005. Role of evaporite withdrawal in the preservation of a unique coal-bearing succession: Pennsylvanian Joggins Formation, Nova Scotia. Geology, **33**: 337–340.

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.

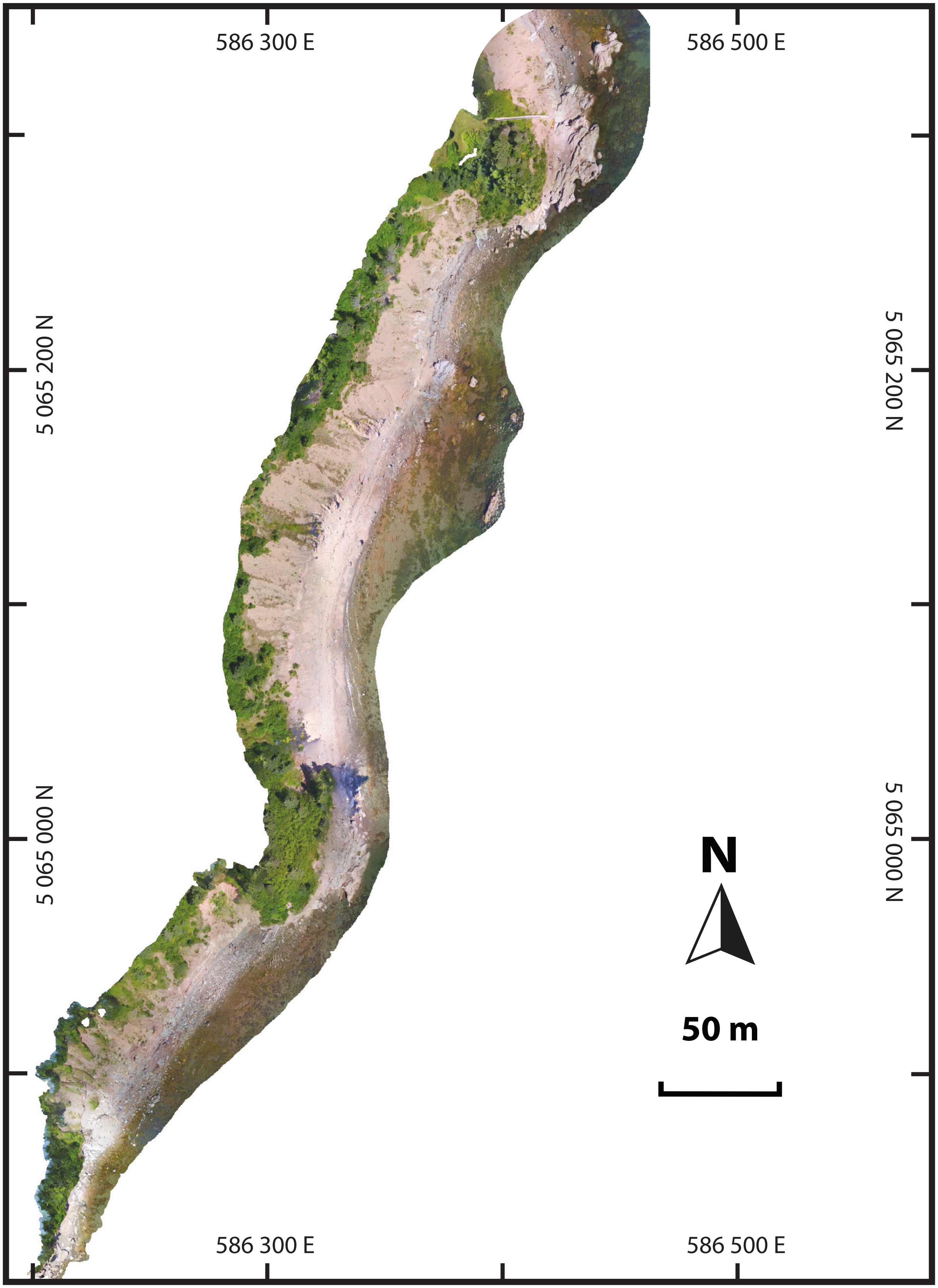
White, C.E., and Boehner, R.C. 2008. Bedrock Geology Map of the Whycogomagh Area, NTS Sheet 11F/14, Inverness County, Nova Scotia. Nova Scotia Department of Natural Resources Open File Map, ME 2008-1, scale 1:50,000.

Williams, E.P. 1974. Geology and petroleum possibilities in and around Gulf of St. Lawrence. AAPG Bulletin, **58**: 1137–1155.

Appendix A: Orthophoto of Lakevale



Appendix B: Orthophoto of MacIsaacs Point



Appendix C: List of full well names used in study

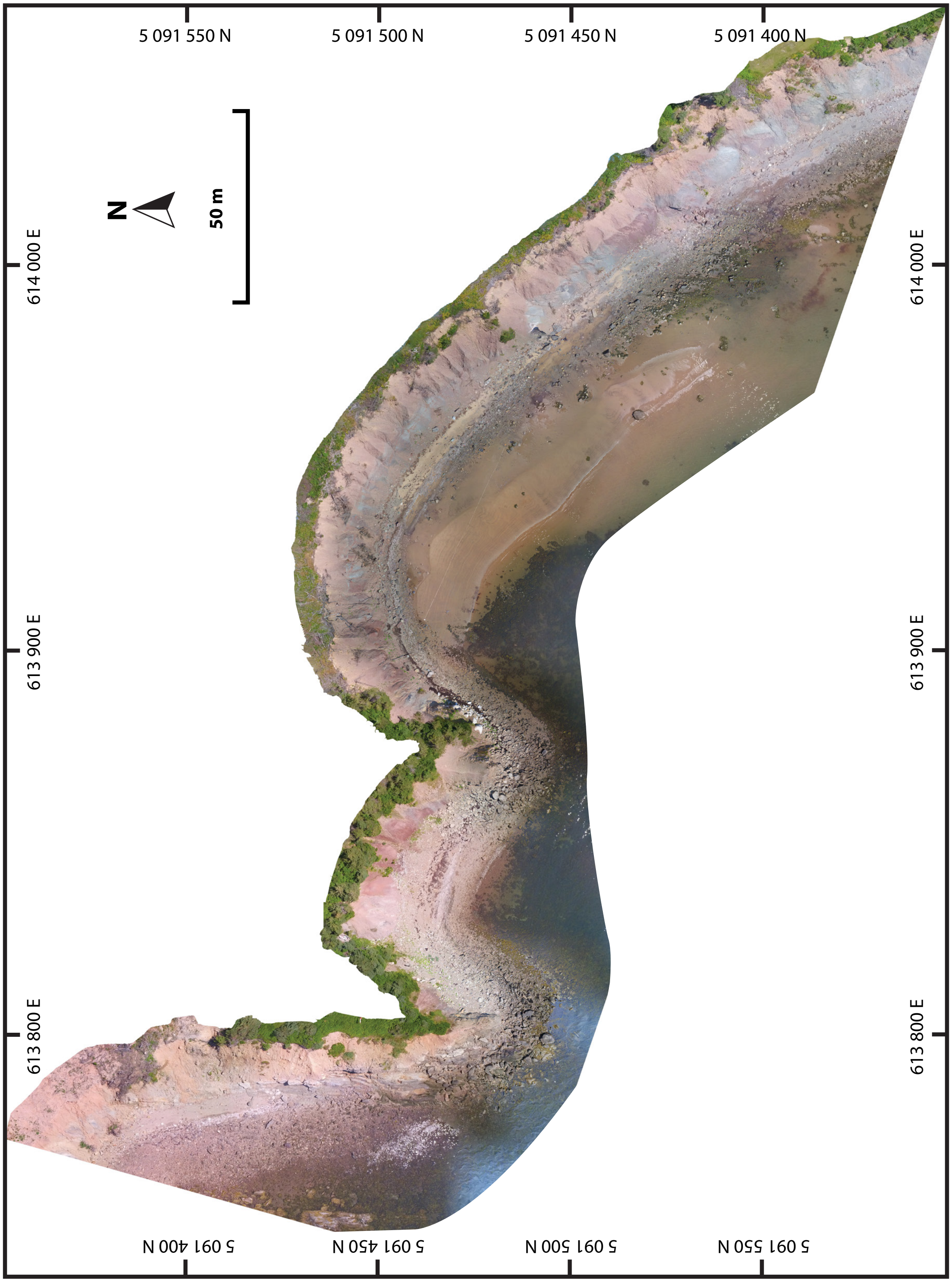
Abbreviation used in text	Full well name
AN 1	Brador Anchutz Hole No. 1
AP-1-74	AP-1-74
AP-2-74	AP-2-74
BH 1	Beech Hill #1
GR 83-1	Glen Road 83-1
SV74-3	SV74-3

Appendix D: List of full seismic names from SEG-Y files

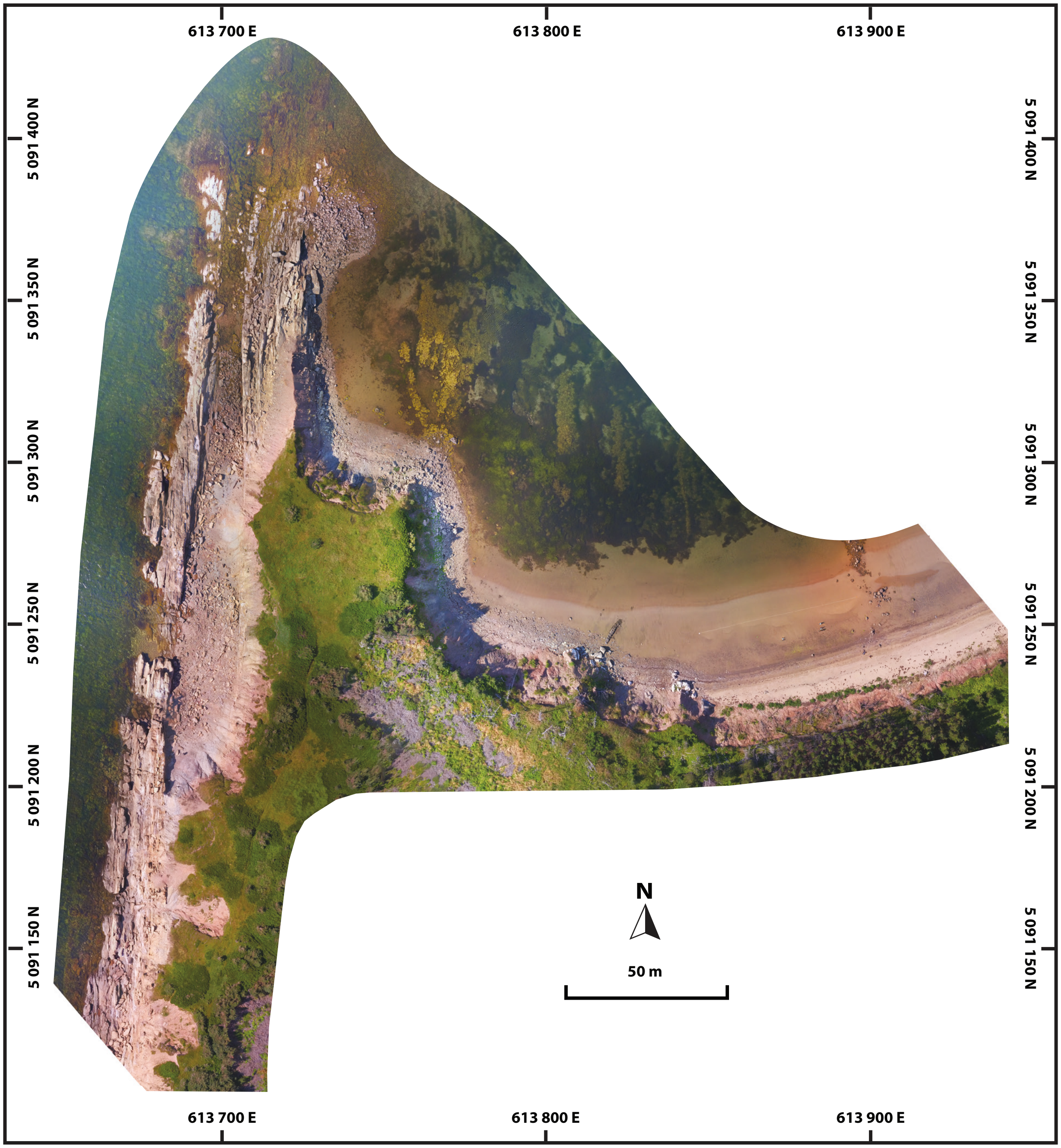
Northstar Energy lines (2001)	
Abbreviation used in study	**Full line name**
NS-533	NS01-ANTI-533_PSTM
NS-534	NS01-ANTI-534_PSTM
NS-535	NS01-ANTI-535_PSTM
NS-536	NS01-ANTI-536_PSTM

Contact Exploration lines (2002)	
Abbreviation used in study	**Full line name**
CON-01	CON02-ANTI-01_PSTM
CON-02	CON02-ANTI-02_PSTM
CON-03	CON02-ANTI-03_PSTM

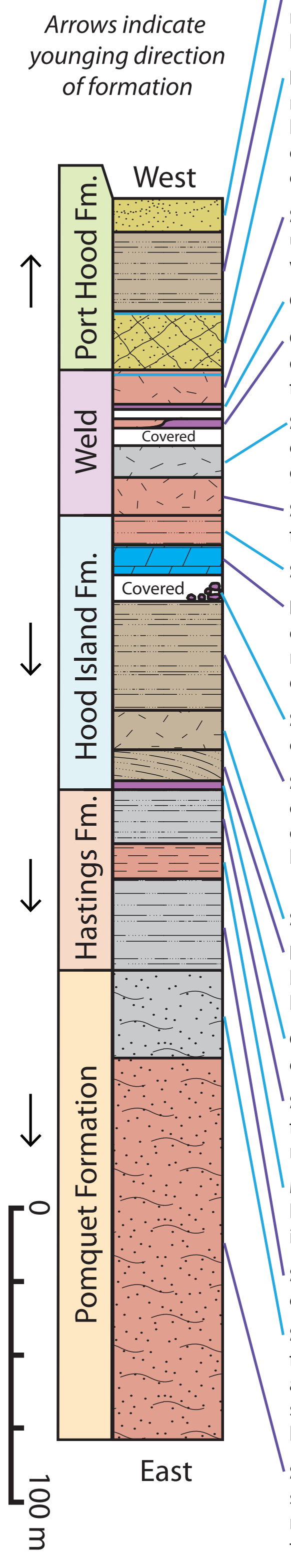
Appendix E: Orthophoto of northern Little Judique Harbour



Appendix F: Orthophoto of southern Little Judique Harbour



Appendix G: Northern Little Judique Harbour shore section



Crossbedded sandstone - top is underwater; tan coloured; bedsets range from 10 cm to 1 m thick; trough crossbeds show youngs to west and is overturned; rare conglomerate beds up to 1 m thick with clasts of siderite and coal fragments, including rare tree fragments > 1 m long; rare siltstone beds 1 to 20 cm thick

Clay and siltstone - very weathered; grey, red and brown; rare sandstone beds up to 1.3 m m thick and rare limestone beds up to 35 cm thick; ripples in one of the sandstone beds indicate unit is overturned; lumpy texture likely from smectite interacting with rain; several organic-rich dark grey intervals ≤1 m thick

Fractured sandstone - tan; heavily fractured with two main fracture orientations - dip moderately east or moderately northwest; typically massive with rare weak trough crossbedding, showing unit is overturned; limestone bed ~50 cm thick at top of unit; whole unit grades from strongly calcareous at base to weakly calcareous at top; rare pebble lenses ≤50 cm thick with clasts ≤11 cm in diameter (2 cm on average), clasts composed mainly of siderite with minor limestone and sandstone

Siltstone breccia - red with minor grey (redox spots); clasts typically ≤several cm in diameter; typically unstructured but locally discontinous area have possible bedding; several pieces of limestone close by the western edge of this unit suggest a bed

Gypsum - white; foliated; has fibrous gypsum veins up to 1 cm thick, veins are near-parallel to the foliation

Gypsum and siltstone - white gypsum and grey siltstone; gypsum is foliated and has dark brown rosettes, discontinous gypsum veins, and siltstone clasts; foliation in gypsum is folded; siltstone also cut by white fibrous gypsum veins; siltstone is breciated but locally bedded

Silty rubble - mixed red and grey; very weathered; contains randomly oriented fragments of siltstone and gypsum in matrix of silt, gypsum fragments are up to 2 m by 10 cm in size; slumped fragments of fibrous gypsum veins suggest the lithology may have once been cut by veins

Silt - red; very weathered mound of clay and silt with lumpy texture; minor randomly oriented siltstone fragments averaging 1-2 cm in diameter

Siltstone - red with rare grey redox spots; largely slumped, the intact portions show bedding

Dolomite - grey; fractured into pieces ~0.5 m diameter on average; weakly laminated near base but otherwise massive; contians ooids and shells, shells are concentrated along a ~20 cm thick layer near the base of the dolomite, bivalves suggest this dolomite youngs eastwards; one bedding surface has eggcarton-like texture - algal mat?

Slipped gypsum - white; foliated; blocks up to ~2 m in diameter; some blocks shows a partially developed chicken wire texture, some have dark brown gypsum porphyroblasts 1.5 cm by 0.5 cm

Siltstone - grey and red; local competent rafts and beds under silty rubble; grey siltstone is locally calcareous; climbing ripples in a siltstone bed show this unit youngs east; unit cut by discontinous fibrous gypsum veins, fibre and veins orientations are not consistent, likely due to slumping; one 0.5 m sandstone bed present with several thrust faults that steeply dip south with 7-20 cm dip separation

Siltstone rubble - grey and red; coherent bedding very rare; cut partial slumped fibrous gypsum veins

Folded siltstone - red and grey; very weathered and fragmented; bedding gently folded; in some cases beds are laminated; dark grey siltstone is calcarous; orange gypsum nodules observed in one red siltstone bed; unit cut by fibrous gypsum veins, fibres dominantly vertical suggesting vertical extension

Gypsum - black; foliated; contians thin white gypsum veins sub-parallel to the foliation; has 1-4 cm diameter black gypsum rosettes

Siltstone - grey with minor red; planar laminated with rare wavy lamination; top of unit has 3 m interval of fractured and distorted bedding - shear zone?; one 60 cm thick fining upwards sequence observed in middle of unit, sequence goes from very fine sand at base to siltstone at top

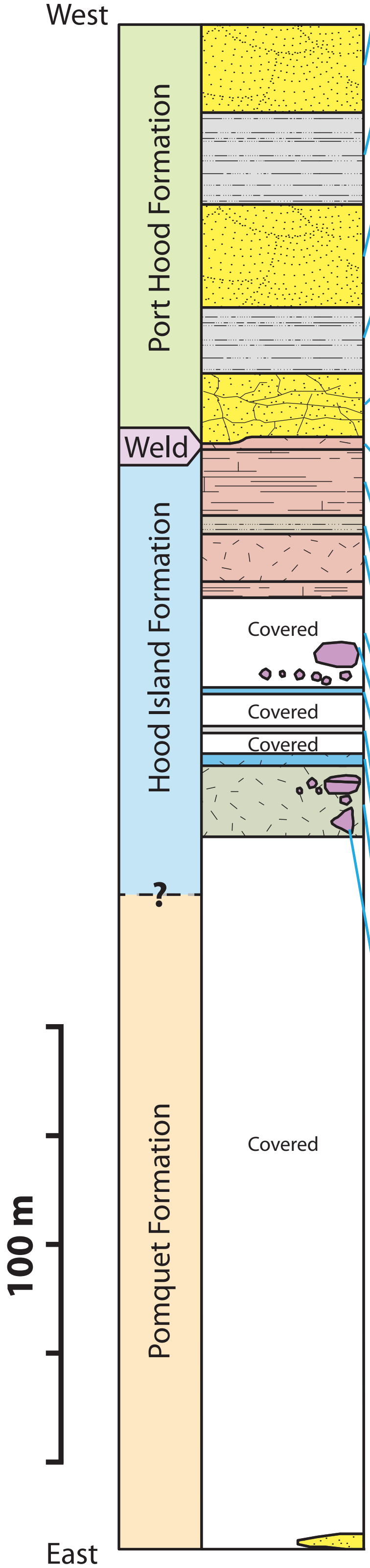
Mudstone - red with minor grey; weathered so is very crumbly; mudstone varies from massive to well laminated; rare very fine grained sandstone beds; typically weakly calcareous with rare very calcareous intervals, ripples and mudcracks in 2 m thick sandstone bed near top of unit, ripples show unit youngs east

Siltstone - grey with lesser red; fissile; minor calcareous intervals; middle ~third of unit is made up of 5-8 cm thick fining upwards sequences that grade from rippled very fine sandstone to mudstone

Siltstone and sandstone - grey with lesser red; siltstone is fissile and variably calcareous; abundant very fine grained sandstone beds ~20 cm thick; sandstone typically has calcareous cement; many sandstones are rippled or trough cross-bedded, crossbedding shows unit youngs east; rare convolute lamination in sandstones; ~60 cm thick grey fissile limestone exposed in beach at top of unit, another ~20 cm thick limestone in beach ~25 m from the top of the unit; halite casts found at base of unit and in nearby float

Siltstone and sandstone - red with minor grey; interbedded very fine to fine grained sandstone and siltstone, dominantly siltstone; some sandstone beds are planar laminated, some have climbing ripples, ripples show this unit youngs east; minor locally calcareous regions; sandstone beds typically 10-30 cm thick; often have 20 cm - 1 m thick siltstone intervals between the sandstone beds

Appendix H: Southern Little Judique Harbour shore section



Crossbedded sandstone - top is underwater; beds up to ~2.5 m thick; trough crossbeds show youngs to west; fine-grained, well-sorted; rare flutes and siderite lags observed in base of unit, siderite clasts may have originated from underlying siltstone unit; reverse fault locally extends base of unit by several cm

Shale and siltstone - thickness varies along-strike from 21 to 7 m; minor limestone and sandstone in beds up to 30 cm thick; bivalves observes in limsetone float; climbing ripples seen in siltstone beds near base of unit; rare siderite concretions

Crossbedded sandstone - beds up to ~2.5 m thick; trough crossbeds show youngs to west; fine-grained, well-sorted; calcarous cement; conjugate faults with up to 1 cm of dip separation make horst and grabens in top of unit; near top of unit are several fossilized wood pieces up to ~1m long; abundant siderite clasts in channel lag at base of unit

Very fine grained clastics - poorly exposed interbedded bituminous shale, mudstone, very fine sandstone, with minor paleosol (?) and coal; thin climbing rippled sandstone at top of unit, the immediately underlying ~3.5 m of coal and coaly shale, some boundinaging of beds in middle of unit

Fractured massive sandstone - irregularly fractured; most of outcrop appears to be displaced; rare convolute lamination; granule-sized limestone and organic clasts, top of unit has 1.5 m grey shale overlain by 1 m calcareous conglomerate then 30 cm sandstone

Brecciated mudstone - slipped red, green and grey mudstone breccia; three limestone pieces ~30 cm thick suggest a bed in the breccia, no other evidence of bedding in breccia; separates bedded strata younging west from bedded strata younging east

Mudstone - slipped; typically thinly to very thinly bedded; rare thin carbonate beds and laminae; possible poory exposed synform at top of unit; crossbeds show youngs east

Siltstone - red; massive

Mudstone - sheared; red; massive

Mudstone - very slipped; red and green mottled; distinct beds and indistinct laminae

Gypsum blocks - slipped; white; up to ~4 m in diameter

Limestone -discontinuous layer in cliff, interpreted to connect with segment exposed in beach; dark brown; poikolitic with limestone ooids surrounded by dolomite crystals

Shale - small poor outcrop; red; bedded; possibly sheared

Brecciated limestone - varies between laminated and thinly bedded; generally blocks dip gently southeast; cut by subvertical fibrous gypsum veins that dip west

Brecciated mudstone and limestone - locally foliated; cut by fibrous gypsum veins that dip west

Gypsum blocks - slipped; white; up to ~4 m in diameter, some show foliation, easternmost gypsum is likely intact and has a near-vertical pressure solution cleavage that dips north along its eastern surface where it is in contact with the limestone and mudstone breccia

Crossbeded sandstone - thickly bedded; medium grained; outcrops exposed in beach at low tide; cross beds show youngs to east