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FIELD TRIP GUIDEBOOK – A2

Geology, Groundwater and Wines of the Annapolis Valley

Leaders: Denise Brushett, David E. Brown, Nicole LeRoux, Mitch Maracle, Gavin Kennedy, and Barret Kurylyk

GEOLOGICAL ASSOCIATION OF CANADA / ASSOCIATION GÉOLOGIQUE DU CANADA

MINERALOGICAL ASSOCIATION OF CANADA / ASSOCIATION MINÉRALOGIQUE DU CANADA

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ATLANTIC GEOSCIENCE SOCIETY

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Cover photo: *Benjamin Bridge Vineyards, view looking northeast over the Gaspereau Valley*

LAND ACKNOWLEDGEMENT

We would like to begin by acknowledging that the land on which we live, work, and play is Mi'kma'ki, the unceded traditional territory of Mi'kmaq and L'nuk peoples, who have inhabited this place for more than 11,000 years. This territory is covered by the "Treaty of Peace and Friendship" which Mi'kmaq, Wolastoqiyik (Maliseet) and Passamaquoddy Peoples first signed with the British Crown in 1725. The treaties did not deal with surrender of lands and resources but in fact recognized Mi'kmaq and Wolastoqiyik (Maliseet) title and established the rules for what was to be an ongoing relationship between nations. The Region of Mi'kma'ki encompasses all of what we now call Nova Scotia, Cape Breton, PEI, New Brunswick and the Gaspé Peninsula of Quebec, and parts of Maine and Massachusetts.

ACKNOWLEDGEMENTS

The authors are grateful to numerous vineyard operators and staff for making site visits possible and for their insightful discussions on their vineyards and their connections to the local geology; these include Domaine de Grand-Pré, Mercator Vineyards, Lucketts Vineyards, Mercator Vineyards, Ellslea Vineyards, L'Acadie Vineyards, Benjamin Bridge Winery, Blomidon Estates Winery, and Millstone Harvest Brewhouse (Sea Level Brewing). The Skylit Solar Power team are thanked for providing outcrop access (Field Stop 6). We would also like to acknowledge sponsorship from the Nova Scotia Department of Natural Resources and Renewables – Geological Survey Division as well as photo contributions provided by Bruce Ewart (L'Acadie Vineyards) and Arthur and Julia Fox of the Hikers' Movement.

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SAFETY INFORMATION

General Information

The Geological Association of Canada (GAC®) and the Mineralogical Association of Canada (MAC) recognize that their field trips may involve hazards to the leaders and participants. It is the policy of the GAC® and the MAC to provide for the safety of participants during field trips, and to take every precaution, reasonable in the circumstances, to ensure that field trips are run with due regard for the safety of leaders and participants.

Field Trip Leaders are responsible for: insisting on adherence to the provisions of the GAC®/MAC Safety Policy and Program on the field trip; planning for all aspects of field trip safety; identifying and providing for mitigation of hazards; ensuring that the trip has an appropriately trained person responsible for first aid and that participants are accompanied at all times while in the field; ensuring that participants have and know how to use any required PPE; taking action to minimize any unsafe action or condition while the trip is in progress; and implementing emergency procedures in case of an incident.

Field trip participants are responsible for: acting in a manner that is safe for themselves and their co-participants; following the safety instructions of the field trip leaders during the trip; using PPE when necessary; and informing the field trip leader of any matters of which they have knowledge that may affect their health and safety or that of co-participants.

Participants should be prepared for a wide range of temperatures and conditions, typical of Nova Scotia in May and especially at field stops in coastal areas. Please take suitable clothing including layers, rain wear, gloves, warm hat in case of cold, wet weather as well as sunscreen and sun protection.

Specific Hazards

While most of the field stops will be at vineyards, several field stops will be at other geological sites of interest, on or adjacent to roads or parking lots, and one stop at a coastal locality.

Coastal localities present several specific hazards and participants must behave appropriately for the safety of all. Access to the coastal section will require a short hike along a beach (~ 500 m), in some cases over rough, stony, or muddy and wet terrain and including saltwater pools, seaweed, and mud. It may also be possible to cross small brooks and uneven rock surfaces on the beach. There is a possibility that participants will get their feet wet. Waterproof sturdy footwear is recommended for this site.

The timing of the coastal field stop was planned taking the local tide levels into consideration. Field trip leaders will provide more information regarding the local tide at that stop. Participants must keep a safe distance from the ocean and be aware of the magnitude and reach of ocean waves. Participants should stay on dry sections of outcrops that lack any seaweed or algal deposits and stay well back from the ocean's edge. Remember that wave-washed surfaces may be slippery and treacherous and avoid any area where there is a risk of falling. The cliffs along the coastal section are extremely dangerous, and participants must stay clear of the cliff edges at all times, stay with the field trip group, and follow safety instructions from field trip leaders. Most of the coastal section is actively eroding, and participants must be aware of the constant danger of falling debris.

Several field stops are located on or adjacent to roads or parking lots. At these stops, participants should make sure to stay off the roads, and pay careful attention to traffic, which may be distracted by the field trip group. Roadcut outcrops hazards from loose material and should be treated with the same caution as coastal cliffs; be extremely careful and avoid hammering or removing material beneath any overhanging surfaces. The hammering of rock outcrops is generally unnecessary and represents a significant flying debris hazard. Participants are asked to inform the leaders if they have a reason to collect a sample and make sure that it is done so safely and with regard for others.

Other Hazards

Lyme disease is a bacterial infection transmitted to humans and pets by a bite from a Black-legged tick but not all ticks carry the bacteria. The Black-legged tick has been found in all areas of Nova Scotia and are common throughout the area of this field trip. The tick that carries the bacteria can only transmit Lyme Disease after it has filled itself with blood, which takes at least 24 hours. In most cases, the first symptom of Lyme disease is a rash near the tick bite that may look like a bull's eye target. The bite is often painless, so you may not even know that you have been bitten. The rash usually appears 7 to 10 days after the bite, but ranging from 3 to 30 days. Antibiotics are used to treat Lyme disease. Early treatment almost always results in full recovery.

Cover as much of your skin as possible when walking in areas where ticks are found and use insect or tick repellent. Wear enclosed footwear, tuck your shirt into your pants, and tuck your pants into your socks. Light-coloured clothing with a tight weave allows ticks to be more easily seen. Check yourself after walking in grassy or wooded areas. Inspect all parts of the skin, including arm pits, groin, and scalp. Remove ticks as soon as you find them using a tick removal tool or tweezers to carefully grasp the tick as close to the skin as possible. Gently and slowly pull the tick straight out without jerking, twisting or squeezing it. Disinfect the site to prevent other infections.

OVERVIEW

This one-day field trip explores the local geology, soil characteristics, groundwater characteristics, and of course the wines of the southern Nova Scotia terroir of the eastern Annapolis Valley, one of Canada's emerging wine regions! Here distinctive Nova Scotia mesoclimates, proximity to the moderating influences of the Bay of Fundy and Atlantic Ocean, and landscapes and soils shaped by multiple glaciations create a complex interplay of climate, soil, geology, and groundwater that influence the character and quality of grapes, thus creating a unique terroir. We will also explore the importance of groundwater resources to the vitality of the Town of Wolfville and Fundy area and the vulnerability of these resources to the effects of climate change.

At the time of preparation of this guidebook there are at least 13 vineyards in the Annapolis Valley wine region. The field trip route includes several stops to local vineyards and related sites of geologic interest to sample the wines and learn about the geology and local terroir (**Figure 1**). Vineyards were selected to showcase a wide diversity of geological settings. Field trip leaders and vintners will present a short presentation on their particular expertise and current research. Transportation and on-board guide is being provided by the Magic Winery Bus.

ITINERARY

8:30 am - Depart Halifax Convention Centre

10:00 am - Grand Pre Look-Off (field stop 1)

10:30 am - Domaine de Grand Pré (2)

11:30 am - L'Acadie Vineyards & lunch (3, 4)

12:30 pm - Benjamin Bridge Winery (5)

1:30 pm - Outcrop: White Rock (6.)

2:00 pm - Outcrop - Kingsport Beach (7)

3:00 pm - Blomidon Estates Winery (8)

4:00 pm - Millstone Harvest Brewhouse (9)

4:40 pm - Depart Wolfville for Halifax

6:00 pm - Arrive Halifax Convention Centre

An abbreviated 'Story Map' version of the field trip guide can be accessed by scanning this QR Code (https://storymaps.arcgis.com/stories/ecb1b6c6e23e4371982e8ad03a10d243

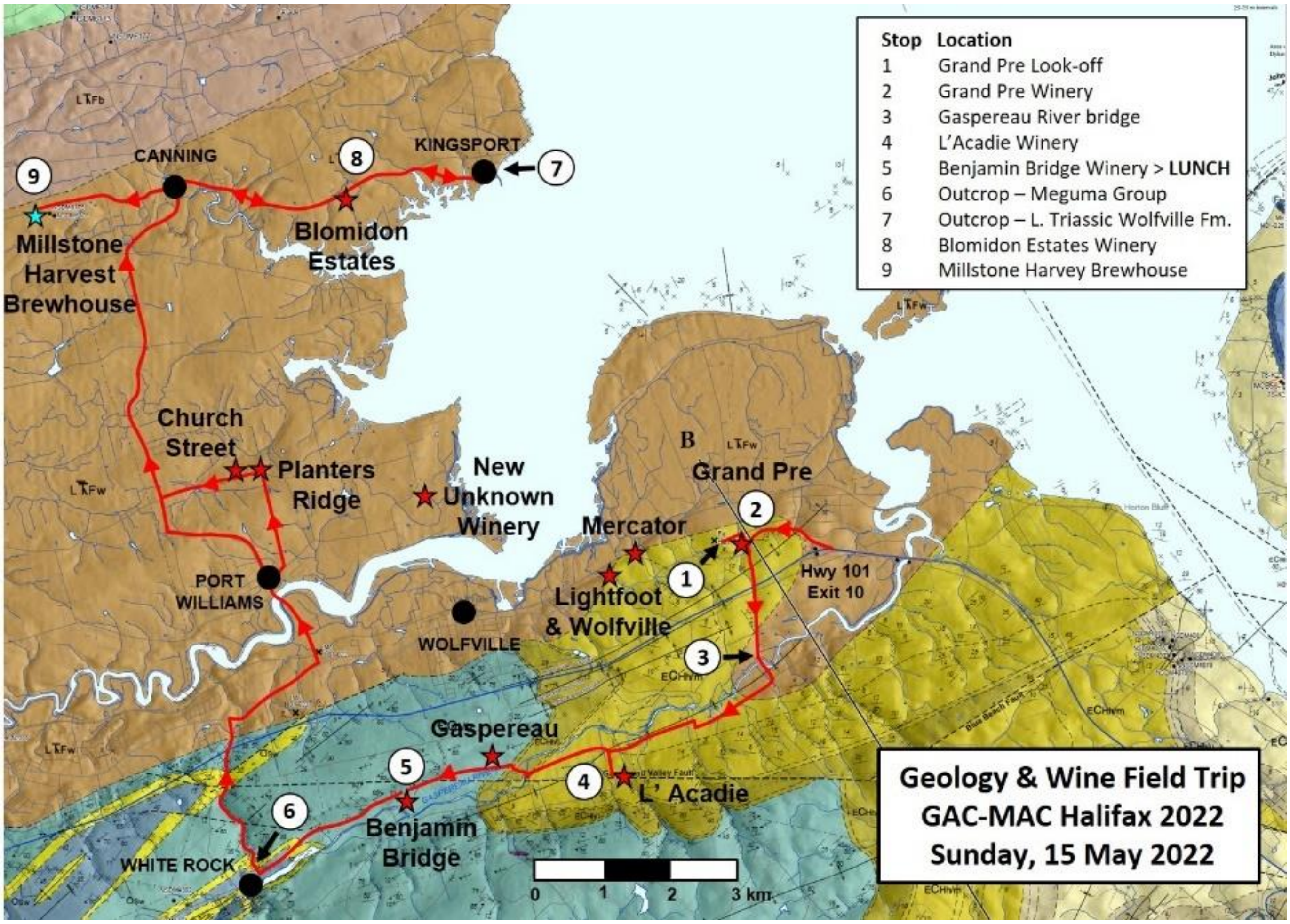

Figure 1: *Itinerary and location of field trip stops. The geological base map is modified after Moore et. al., 2000. Legend:* ***LTFb*** *(light brown) = Triassic Blomidon Formation,* ***LTFw*** *(medium brown) = Triassic Wolfville Formation,* ***ECHh/m*** *(yellow-green) = Mississippian Horton Bluff Formation,* ***LSK*** *(blue) = Silurian Kentville Formation,* ***OSw*** *(yellow) = White Rock Formation,* ***COMh*** *(blue-green) = Cambro-Ordovician Halifax Group.*

INTRODUCTION

Nova Scotia was one of the first regions in North America to grow grapes for wine. Acadian settlers started growing grapes starting in the early 1600s in the Annapolis Valley and La Have River areas. It wasn't until the early 1980s, however, that wine-grape related research and commercial cultivation started in Nova Scotia. Since then, Nova Scotia has rapidly emerged as a wine region with wines based on varietals and hybrids expressing a unique style that reflects our unique terroir. The complex interplay of climate, soil, geology, and groundwater influences the character and quality of grapes in the region. In particular, the Annapolis Valley, an important agricultural area of Nova Scotia, has emerged as a focus for grape growing and wine production in the province.

Photo courtesy of Bruce Ewert, L'Acadie Vineyards

In recognition of its unique setting and terroir, the Winery Association of Nova Scotia (WANS) in 2011 created an appellation of origin for a white wine blend produced in the province. The Tidal Bay appellation identifies wines produced from specified grape varietals under strictly defined processes and grown in Nova Scotia. To be given the right to this appellation, submitted wines are adjudicated by a panel of experts to be "fresh, crisp, dryish, still, white with a bright, 'signature Nova Scotia' aromatic component". On this trip participants will be given the opportunity to sample these wines from several wineries representing different geographic and geological settings and taste the differences!

Terroir can be a simple concept or a very complex one. Translated from French, the term succinctly means "soil" (Haynes, 2018). However, the actual relation to the concept with viticulture is quite complex. Terroir can be broken down into five naturally contributing factors: meteorological, physiographic, pedological, geological, and viticultural (Hamblin, 2018; Haynes, 2000). All of these dynamically interact to impact grape growth. The following definitions are provided verbatim from *Geology and Wine 1: Concept of Terroir and the Role of Geology by Simon J. Haynes, 2018*:

Meteorological – temperature maxima and minima, hours of sunlight, wind conditions, and rainfall

Physiographic – type of landform, elevation, slope aspect and gradient, and slope drainage

Pedological – composition and porosity of overlying soils, soil mineralogy and chemistry, soil grain size and texture, and clay mineralogy

Geological – geology of the subsoil and the geochemistry, petrology and texture of individual strata, surface water and ground water flow rates and chemistry

Viticultural – Trellising method, row spacing, grape-bunch thinning and allowable production, fertilizing, mechanical addition of soils or rock material, systematic tile-draining, and irrigation.

The Eastern Annapolis Valley wine growing area includes the Grand Pré National Historic Site situated along the Minas Basin. Grand Pré (Great Marsh) was designated as Canada's first rural historic district of national significance in 1995, and later designated as a UNESCO World Heritage Site in 2012. This site was once the epicentre of Acadian culture and is now a memorial to their 'great upheaval', where they were deported from Nova Scotia between the years 1755 and 1763. Across the Minas Basin is the new Cliffs of Fundy UNESCO Global Geopark.

The Annapolis Valley area is home to several Mi'kmaq First Nations, the founding people of Nova Scotia, including Annapolis Valley First Nation and Glooscap First Nation. For the Mi'kmaq aboriginal people, today's Grand Pré was known as Setnog or Chdnouk, which means 'extending out into the sea' (Landscape of Grand Pré, 2022). According to Mi'kmaq traditions, the legendary figure Kluscap (Glooscap), who is responsible for the creation of many landscape features throughout Mi'kmak'i, kept watch over his people from his lodge on Cape Blomidon (Fig. 1). The Mi'kmaq lived off the natural resources of the Minas Basin area when it was a fresh-water lake. Around 3000 to 4000 years ago, it is believed that there was a breach in a large gravel barrier located near Cape Split that allowed seawater from the Bay of Fundy to flood the lake and transform it into the Minas Basin (Landscape of Grand Pré, 2022; Shaw et al., 2010).

PHYSIOGRAPHY

The Annapolis valley forms part of the Appalachian physiographic region and is bounded by the south-facing slopes of North Mountain and the north-facing slopes of South Mountain (Roland, 1982). South Mountain is underlain by Paleozoic metasedimentary and granitoid rocks. North Mountain, comprising Triassic-Jurassic basalt, is a cuesta typically with a sharp scree slope facing the Valley and a gently dipping slope facing the Bay of Fundy. The shelter provided by the North and South mountains allow the Valley to have earlier spring and hot summers, making it one of Nova Scotia's most productive agricultural and viticultural areas.

The Annapolis Valley is underlain by red fluvial sandstones of the Triassic Wolfville Formation, and by the conformably overlying fluvial and lacustrine mudstones of the Blomidon Formation. The Valley generally has a flat to gently undulating topography and is drained by two main rivers, the Annapolis and Cornwallis rivers. The Annapolis River flows southwest to the Annapolis Basin and the Cornwallis River flows northeast to the Minas Basin. The high tides of the Bay of Fundy affect both basins and have formed extensive areas of tidal salt marsh. Most of this marshland, which is now protected from tidal flooding by a system of dykes, is used for agriculture (described in more detail in the Hydrogeology research section).

CLIMATE

“While the landscape, geology, and soil strongly interact to influence a vine’s balance of nutrients and water, it is the climate that is critical because it is this that limits where wine grapes can be grown at both global and local scales”

Gregory V. Jones. The Climate Component of Terroir published in Element

Vineyards located in northern latitudes, such as the Annapolis Valley, obtain less direct sunlight, however, during the growing season receive longer daylight hours (Meinert and Busacca, 2000). The region also benefits from the moderating effect of the Atlantic Ocean, Bay of Fundy, Minas Basin, and Annapolis Basin, all of which moderate potential extreme temperatures. These bodies of water act as heat sinks, re-radiating heat during colder evenings in the valley and extending the growing season. Additionally, they reflect sunlight, increasing sunlight exposure of the vineyards (Hamblin, 2018).

Topography plays a major role in the climate for the Annapolis Valley creating a uniquely temperate to semi-humid climate ideal for agriculture and viticulture in Nova Scotia (Rivard et al., 2012). These bounding landforms shelter the valley from the colder Atlantic winds. The Annapolis Valley has the highest average temperature in Nova Scotia, with a historical annual average air temperature of 6.9°C compared to the provincial historical average of 6.4°C (Rivard et al., 2010). The Annapolis Valley receives the second lowest amount of annual precipitation in all of Nova Scotia (1181 mm), compared to the provincial average of 1352 mm; with the winter months being the wettest and the late summer and fall period being the driest (Climate Change Nova Scotia, 2014; Environment and Natural Resources, 2021; Rivard et al., 2010). The ideal amount of precipitation for grape cultivation is approximately 700 mm annually, with most of the precipitation occurring in the spring and dry conditions prevailing in the summer and fall (Hamblin, 2018). The Annapolis Valley receives about 605 mm of precipitation over the spring and summer months alone (30-year mean) with a projected annual increase in precipitation over the next century (Hamblin, 2018; Climate Change Nova Scotia, 2014). The Valley therefore tends to be wetter than ideal conditions for grape cultivation.

Degree days are used in agriculture to quantify and measure productive growing temperatures. Standard degree days are the amount of time a region experiences air temperatures above 10°C. The Annapolis Valley vineyards were found to have an average of 984 to 1007 growing degree days (above 10°C) between 2004 - 2008, which is lower compared to Canada’s other winery regions, Niagara, Ontario, and Okanagan, British Columbia, which have an average of 1471 and 1181 growing degree days respectively (Lewis, 2018).

Climate change will alter current and future grape growing regions. Many traditional growing regions are harvesting earlier, changing the flavour profiles of their wine and climate change is threatening in-situ grape varieties. However, marginal growing regions are now suitable for wine grape cultivation, and grapes can now be grown commercially further than 50° latitude (Nicholas, 2015; Hamblin, 2018). The Annapolis Valley will benefit from rising temperatures allowing additional warm climate grape varietals to be grown, however, wetter than ideal conditions will need to be managed. Sea level may also reduce the area available for cultivation for those existing vineyards that extend to the coastal interface. Opportunities and risks with respect to the impacts of climate change on the sector were recently explored as part of the AgriRisk pilot project (Robicheau et al., 2018; Nova Scotia Federation of Agriculture, 2018).

GEOLOGY

"In this totality of elements, geology dictates the overall landscape, rock type, the landform, the exposure, soil, subsoil, and drainage. The climate invites distribution of the vine, the selection of the variety, and its cultivation by man."

James E. Wilson

"Terroir – The Role of Geology, Climate, and Culture in the Making of French Wine"

Geological Setting

The story of Nova Scotia's geological evolution – and in a broader sense that of the Northeastern Appalachians – is one of amalgamation of disparate crustal blocks from far-flung locations, and later break-up and separation through rifting. This has resulted in a complex mosaic of various geologic terranes separated by faults that formed in different geologic settings. They were later buried under a blanket of sediments, and following 175 million years of erosion, the exposed remnants of these basement rocks now define upland regions. Thus, this interplay of tectonics, erosion and sedimentation has, over the vast expanse of time, created the varied terrain of highlands and lowlands, shorelines, shelfs and basins existing today.

The following is a very broad overview of the complex processes that created Atlantic Canada and specifically Nova Scotia over geologic time. Emphasis is made to those successions that have a direct relevance to sites visited on this field trip: Silurian-Devonian Rockville Notch Group, Mississippian Horton Group, and Triassic-Jurassic Fundy Group. The following summary draws upon the excellent publication "The Last Billion Years" (Atlantic Geoscience Society, 2001).

Bedrock Geology

Neoproterozoic Era to Late Devonian Period (~750 to ~375 Mya)

About 750 million years ago, during the Neoproterozoic Era, two continents – Laurentia and Gondwana were created through the rifting of the supercontinent Rodina. Each were composed of an amalgam of large chunks of continental crust, micro-continents, and island arcs separated by major faults and subduction zones. Over the following 60 million years, this rift basin broadened through seafloor spreading and within it formed the Iapetus Ocean. In the Lower Cambrian, plate tectonic motion initiated the closing of the ancient Iapetus Ocean through an extended period of collision, accretion, and consolidation of various geologic terranes on the eastern margin of North America. In the Atlantic region, this collision involved Laurentia (North America) and fragments from Gondwana (Northwest Africa and Western Europe), with seafloor spreading from ocean ridges driving these fragments towards the Laurentian margin. Following Gondwana's initial collision, it moved away from Laurentia creating the Rheic Ocean that similarly directed isolated island arc complexes and continental

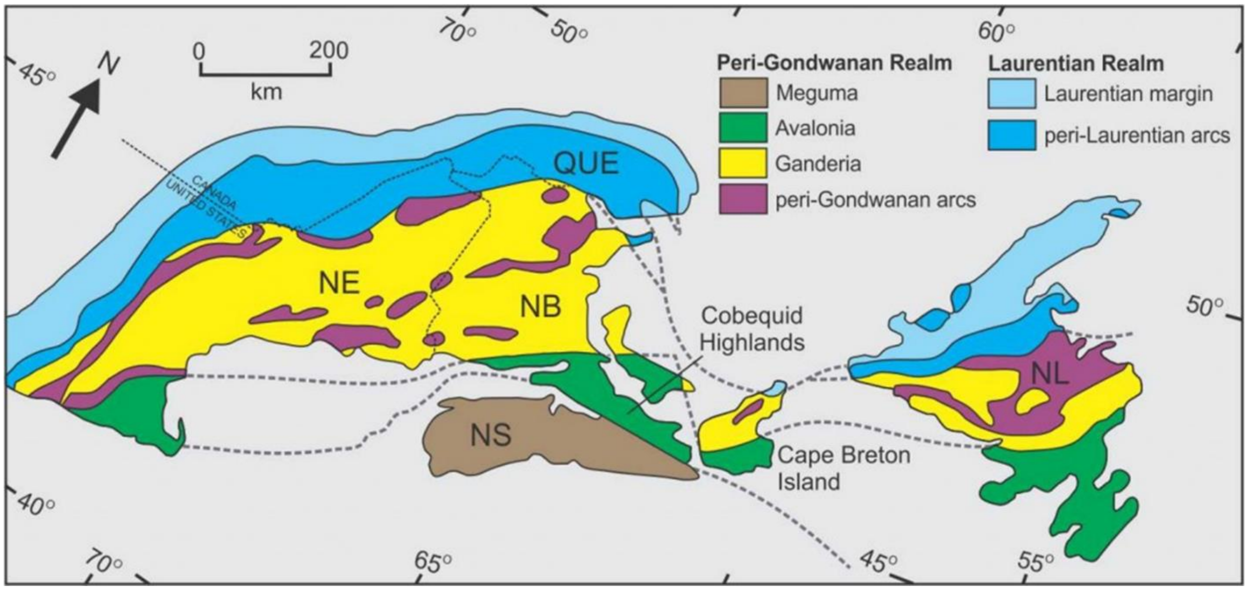

Figure 2. *Geological terranes of the Northeastern Appalachians, Atlantic Canada. After Hibbard et al., 2006.*

fragments towards Laurentia. As these terranes collided, each underwent tectonism, structural deformation, plutonism, metamorphism, and metallogenesis unique to each terrane and bounded by major faults. **Figure 2** illustrates the current distribution of these terranes in Atlantic Canada.

Middle Cambrian to Middle Devonian Periods (~513 to ~385 Mya)

The Early Cambrian to Early Devonian Meguma terrane makes up the southern half of Nova Scotia and is the most outboard of all Appalachian terranes. It was deposited as a thick succession of deep-water sandstones and shales, and following an erosional event, deposition of shallower water shelf sandstones, shales and bimodal volcanics. During the Early to Middle Devonian, the Meguma collided with several Avalon composite terranes along the eastern North American margin. Its sediments were subjected to compressional deformation in the form of harmonic folding and related faulting and creation of a series of northeast-southwest trending anticlines and synclines. Meguma rocks were then intruded by large granitic plutons. This regional metamorphism altered the succession to varying metamorphic grades.
This approximately 11 to 13 km thick stratigraphic and magmatic succession is known as Meguma Terrane, and is subdivided into three groups. In ascending order these are the Goldenville, Halifax and Rockville Notch groups and within each a number of subordinate formations and members are defined (White, 2007; White et al., 2007) **(Figure 3).** The following is a brief summary of these three groups based on the descriptions by White and Barr (2012, 2012a), Pothier et al. (2015), and White et al. (2018).

The Goldenville is dominated by thick, massive bedded metasandstones, metasiltstones and slates. The rocks were deposited as sand-rich turbidite fans and channel complexes in an upper to middle slope in a deep-water basin along a continental margin. The Halifax Group sediments are dominantly fine-grained metasiltstones and slates that were originally deposited as deep-water shales and siltstones in turbidite fan complexes on a continental rise to upper slope and outer shelf setting. The Rockville Notch Group is the thinnest of the three groups and rests on the angular unconformity above the Halifax Group. Its siliciclastic and minor carbonate sediments, and felsic and mafic volcanic rocks, record deposition in a much shallower water setting, interpreted as a prograding continental shelf, with sediments representing shelf storm to nearshore deposits.

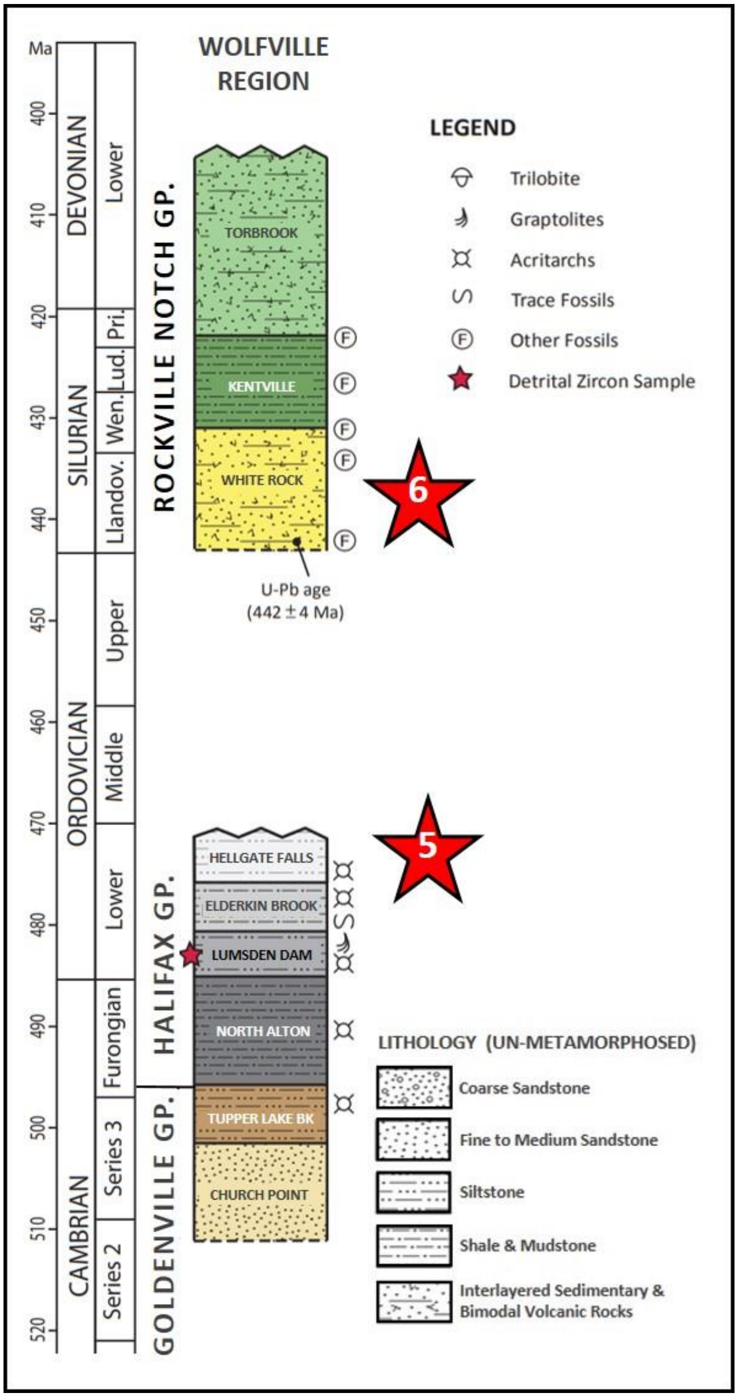

Figure 3. *Stratigraphy of the Meguma terrane in the Wolfville region, Central Nova Scotia. Modified after Pothier et al. (2015). The stratigraphic position of field trip Stop 5 (Benjamin Bridge Winery) and Stop 6 (outcrop at White Rock) are indicated by the red stars.*

Late Devonian to Middle Triassic Periods (~385 to ~240 Mya)

By the mid-Devonian, Atlantic Canada consisted of an amalgamation of several different peri-Gondwanan crustal fragments, assembled during the Late Precambrian to middle Paleozoic, through the closing of the Iapetus and Rheic oceans and the creation of the supercontinent Pangea. Each terrane is separated from adjacent ones by deep crustal faults, has its own unique geological history, and forms the bedrock upon which later sedimentary rocks were deposited. Following terrane assembly, the region underwent several stages of tectonism from the Late Devonian to Early Permian, and Middle Triassic to Early Jurassic. The sedimentary succession of the Maritimes and Fundy basins respectively record these events and was greatly influenced by the new tectonic elements (Appalachian Mountains), paleolatitudinal position (equatorial), and ongoing tectonism (transpression, extension and salt deformation).

The Horton Group is the oldest unit in the thick Carboniferous-Permian succession in the Maritimes Basin **(Figure 4).** Martel (1990), and Martel and Gibling (1996) defined five depositional stages within the Horton Group, four of which are members of the basal Horton Bluff Formation, and the fifth the overlying Cheverie Formation **(Figures 4 and 5).** The overall trend observed in the Horton is one of a gradual but persistent infilling of the basin in a tropical (equatorial) continental setting. The Horton in the Minas Basin area was deposited in a large north-dipping half graben basin bounded by the Cobequid-Glooscap (Minas) fault system to the north. In the western and southern part of the basin it is well exposed along the Avon River and in coastal sections.

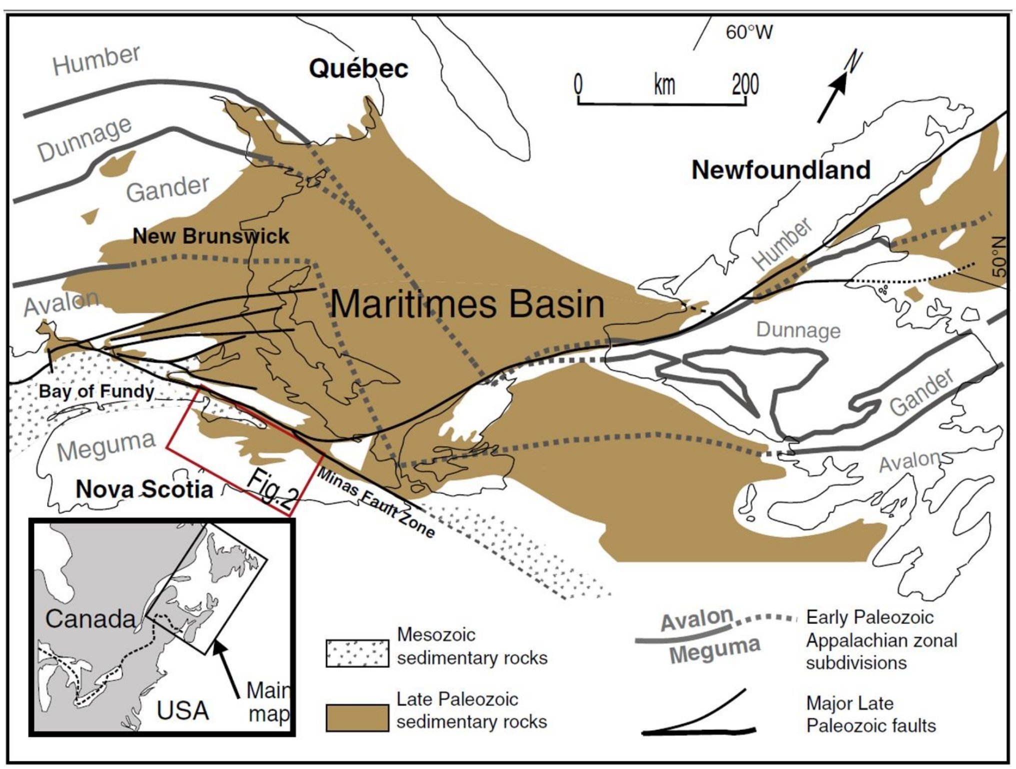

Figure 4. *Distribution of Carboniferous-Permian sediments in Eastern Canada and their distribution over underlying Appalachian accretionary terranes (Snyder and Waldron, 2016). Note the presence of major transpressional faults that define the terrane boundaries. The red box covers the area of the Windsor-Kennetcook-Shubenacadie-Musquodoboit basins, and easternmost Annapolis Valley.*

The observed cyclicity in the Horton Bluff Formation's lacustrine sequences is characteristic of these rocks and was probably influenced both by climate (precipitation >> evaporation) and basin subsidence. Based on the classification of lake systems by Carroll and Bohacs (1999) the Horton succession represents a water lake system that fluctuated subtly between being overfilled to slightly balanced–filled.

Conformably overlying the Horton Bluff Formation is a thick sequence of sandstones, conglomerates, and mudstones of the Cheverie Formation. The Cheverie records the basin's response to uplift along its margins, with the source area dominated by material shed from the Middle Devonian South Mountain Batholith to the southwest (Gibling et al., 2008). Proximal to the basement, the Cheverie is very coarse-grained, conglomeritic and highly arkosic, with abundant feldspar clasts (Conrod, 1987). It transitions into very coarse planar to cross bedded quartz-rich fluvial sandstones and associated muddy overbank deposits. The lacustrine sequences represent deposition in a hydrologically-open fresh water lake system that fluctuated subtly between being overfilled to slightly balanced-filled (Bohacs et al., 2002).

During the Early Mississippian, there were incursions of marine water into the rift basins. Transgressive basal carbonates were formed within these restricted basins and were then overlain by fluvial sandstone (Macumber Formation over Cheverie Formation). Increasing volumes of marine waters in this hyper-arid setting resulted in hypersaline conditions and the deposition of thick deposits of gypsum, halite and related evaporites (Lower Windsor Group). Over time, the salinity of the marine incursions decreased and resulted in a repetitive succession of shallowing upwards cycles of shallow marine limestones, minor evaporites, and fluvial-alluvial siliciclastics (Upper Windsor Group). The driver of this cyclicity was orbitally-forced (eccentricity) expansion and contraction of major continental ice sheets in the southern hemisphere of Gondwana (Giles, 2009). The basins then transitioned back to continental siliciclastic alluvial-fluvial-lacustrine sedimentation (Mabou Group), followed in the Pennsylvanian by regional transpression and later thick sequences of fluvial-lacustrine sediments with abundant coals (Cumberland Group) within which the famous Joggins succession – a UNESCO World Heritage Site – is located.

Compressional tectonism resumed reflecting the final adjustments to Pangea (Variscan Orogeny) and subsequent erosion of older rocks. By the late Pennsylvanian, the Maritimes Basin had moved north of the paleo-equator into the arid climate belt with the deposition of fluvial and eolian sediments of the Pictou Group (Early Permian). From then to Middle Triassic, this now-central Pangean region underwent a period of stasis with little deposition and limited erosion for a period of about 50 Ma.

Middle Triassic to Pleistocene Period (~240 to 2.58 Mya)

After tens of millions of years of quiescence, in the Middle Triassic the Pangean supercontinent became tectonically active. This process initiated the break-up of Pangea and formation of the proto-Atlantic Ocean, with the Atlantic still expanding to this day. In Nova Scotia, geological evidence of this event are recorded in fluvial redbed strata on the north shore of Minas Basin. Its location adjacent to the deep crustal Cobequid-Glooscap fault system – that defines the

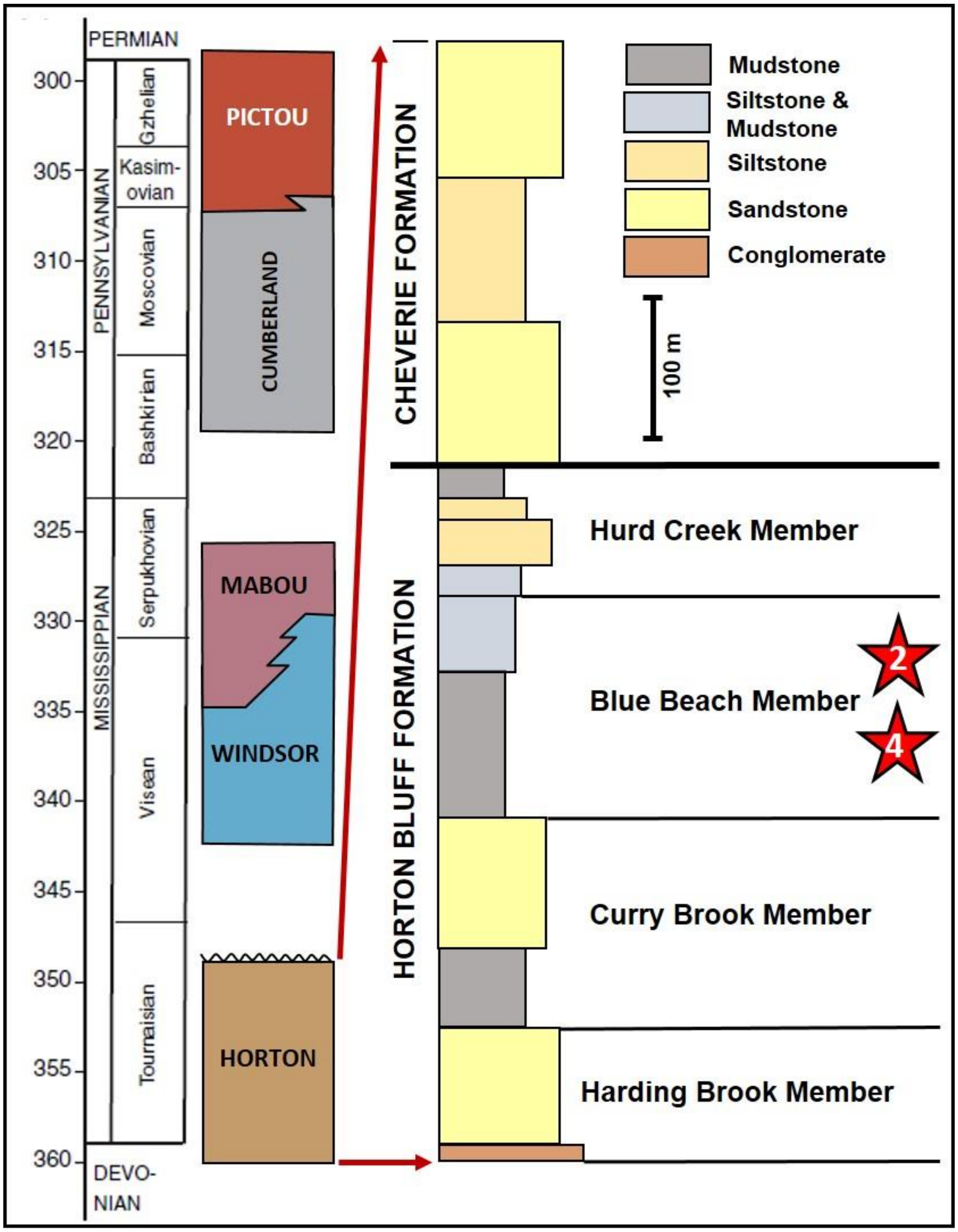

Figure 5. *Stratigraphy of the Horton Group in the Windsor and Kennetcook subbasins, central Nova Scotia (Snyder & Waldron, 2016). Horton Group stratigraphy is from Martel and Gibling (1996). The siltstones, mudstones and shales of the Blue Beach Member compose the bedrock of the Domaine de Grand Pre (Stop 2) and L'Acadie (Stop 4) wineries with their relative stratigraphic positions shown as red stars.*

boundary between the Meguma and Avalon terranes – resulted in the succession being tilted and faulted as the Meguma Group strata began to move slowly to the east in relation to the Avalon strata moving to the north. Nova Scotia was now in an extensional tectonic regime.

At the beginning of the Late Triassic, the rifting process accelerated, with thermal uplift of the Appalachian region from Nova Scotia to the U.S. Carolinas. Pre-existing thrust faults and ramps formed during the Permian Variscan Orogeny were reactivated but now in an extensional setting and created rift basins. Most of these basins are half grabens, though some, such as the Fundy, Minas, and Chignecto basins, have been variously influenced by major strike-slip faults. Each basin exhibits a trend in which its long axis is parallel to the main bounding fault, into which thousands of metres of continental sediments and basic volcanic rocks were deposited over a period of about 45 My (Olsen, 1997). The basins of the Fundy Rift System represent the largest (~14,000 sq. km), northernmost exposed remnant of Triassic-Jurassic synrift sedimentation along the east coast of North America and northwest Africa.

In the Minas Basin area, four formations are exposed in coastal cliff sections, and much less commonly in stream and road cuts, especially along its north shore (**Figure 6).** On the south side of the basin, alluvial and fluvial sandstones and conglomerates of the basal Wolfville Formation are well exposed but limited to headlands and to the east its lateral extent away from the shore can be measured in the tens of meters. This side of the basin is the ramp/hinge margin and as such in a number of cases the base of the formation is spectacularly exposed in angular unconformity with near-vertical bedded Early Carboniferous Horton Group lacustrine strata. This is the rift onset unconformity and represents the start of the rifting process.

In the Cape Blomidon area near Wolfville, playa-lacustrine mudstones and siltstones of the conformable and younger Blomidon Formation are well exposed at its type area and capped (and preserved) by hard tholeiitic basalts of the North Mountain Formation. In the eastern Annapolis Valley (west of the Avon River) the strata are very close to horizontal with generally an unconformity with near-vertical bedded Early Carboniferous Horton Group lacustrine strata. This is the rift onset unconformity and represents the start of the rifting process. In the eastern Annapolis Valley (west of the Avon River) the strata are very close to horizontal, with generally a gentle 4 to 5 degree dip to the northwest (Moore et al., 2000). At its western end at Rossway (St. Mary's Bay / Digby area) area, the dips are up to 15 degrees (White et al., 2012).

Capping the Blomidon are extrusive tholeiitic basalts of the North Mountain Formation. This continuous succession of lava flows was sourced from fissure-type eruptions and are about 300 m thick at onshore locations. Offshore, the NMF is about 1000 m thick in the basin depocentre southeast of Grand Manan Island in the western part of the Bay of Fundy (Wade et al., 1996). At Scots Bay (located north of the Annapolis Valley on the Fundy shore), a thin (9 m) interval of lacustrine sandstones and limestones is present (Scots Bay Member). These sediments were deposited in depressions on the top of the last cooling basalts flows and are of earliest Jurassic age. The Scots Bay's coeval equivalent on the north shore of Minas Basin is the McCoy Brook Formation. Its lacustrine, alluvial, fluvial and eolian siliciclastic strata are over 230 m thick (Tanner, 1996) and offshore at least 3000 m in the basin depocentre (Wade et al., 1996).

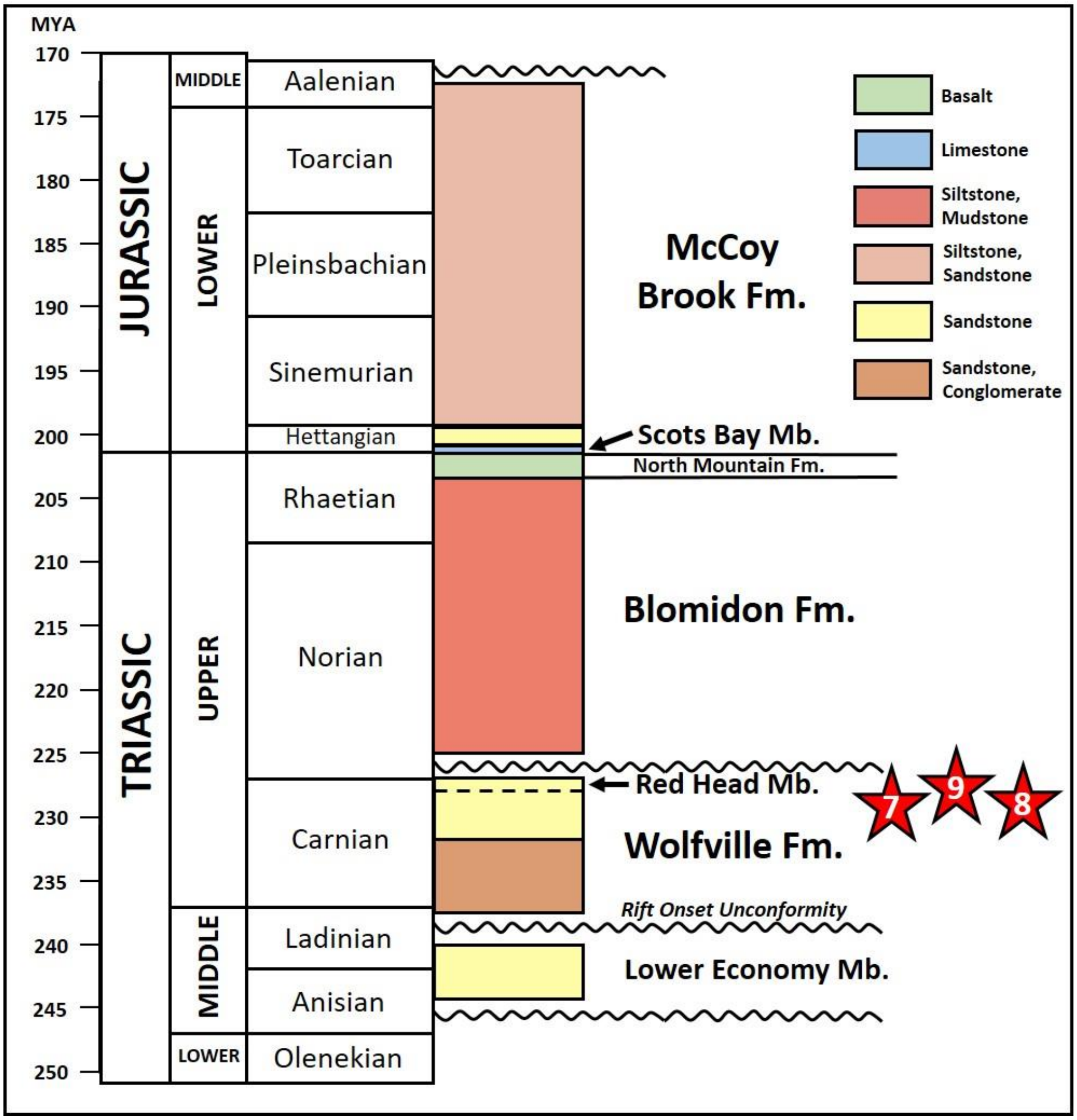

Figure 6. *Stratigraphy of the Fundy Group, Bay of Fundy and Minas Basin region (onshore and offshore). Modified after Sues and Olsen (2015). The fluvial sandstones of the upper Wolfville Fm. are observed at Kingsport (Stop 7) and compose the bedrock of the Blomidon Estates winery (Stop 8) and Millhouse Harvest Brewhouse (Stop 9). The red stars show the relative stratigraphic position of the Stops.*

SURFICIAL GEOLOGY

The surficial geology and geomorphology of the Annapolis Valley, like much of Canada, are the product of multiple glacial advances and retreats throughout the Quaternary, the latest being the Wisconsinan Glaciation, 70,000 – 11,000 years ago (*e.g.*, Stea et al., 2011). In Maritime Canada, a series of local ice centers and divides developed during the Wisconsinan, referred to as the Appalachian Glacier Complex; a summary of which is provided in **Figure 7.** These glaciations produced a wide variety of surficial deposits which form the parent materials for most soils in Nova Scotia. The upper surface of these deposits has been altered by pedogenic (soil-forming) processes during the Holocene to form the modern soils that sustain agriculture and viticulture. Surficial deposits also influence the rate of runoff and erosion, geometry of water courses, and the amount of near- surface aquifer replenishment. Glacial erosion and deposition of Quaternary glacial sediments and non-glacial deposits mantle the scoured bedrock surface to varying depths forming the modern landscape. While these deposits may directly reflect the underlying bedrock geology, they are more likely to have been transported some distance from their source, resulting in Quaternary deposits that may have characteristics and compositions that differ from the local bedrock, or be a mixture of local and regional influences.

Glacial Dynamics

The oldest ice movement to have influenced the Annapolis Valley region is the southeast-flowing Caledonia phase (~75 ka – 40 ka?) likely originating from an ice centre in central New Brunswick and crossing and eroding highlands areas in Maritime Canada, including the Caledonia Highlands of New Brunswick (Stea, 2004). The majority of drumlins in Nova Scotia were formed during this ice flow and subsequently modified by the subsequent south to southwestward ice flow advance, the Escuminac Phase (MIS 2; 25-20 ka) associated with the Late Wisconsinan glacial maximum. At its maximum, this ice flow reached the edge of the continental shelf (Stea et al. 2011; Shaw et al., 2006). A reddish till (Lawrencetown till) was deposited during this ice movement, its distinctive reddish colour results from the entrainment of material from the local red Triassic Fundy Group and partly from the Carboniferous redbeds of New Brunswick, Prince Edward Island and Magdalen Shelf, (Stea, 2004; Stea et al., 2011).

As ice thinned rapidly due to continued ice streaming into marine channels offshore Atlantic Canada, an ice divide (Scotian Ice Divide) formed over much of the province changing ice flow patterns dramatically such that there was northerly ice flow in northern Nova Scotia and south to southwestward ice flow in southern Nova Scotia (Scotian Phase; 20-17 ka; Stea, 2004; Stea et al., 2011). South Mountain Batholith-derived erratics and till clasts have been identified on North Mountain indicating northwestward ice flow in the Valley; NW-trending striations and oriented landforms are also present (Rivard et al., 2010).

Residual ice persisted on South Mountain and highland areas in the ensuing Chignecto Phase (15.9 – 14.7 ka). Several of these small ice caps (remnants of Scotian phase ice) readvanced as a result of continued calving and drawdown of the Scotian Ice Divide (Stea et al., 2011; Stea and Finck, 2001). Ice from the Antigonish and Cobequid Highlands flowed into the southern lowlands of the Minas Basin-Annapolis Valley where it produced west-trending streamlined glacial landforms which terminated in the middle of the valley, most likely near Margaretsville, where ice-contact deposits related to westward-flowing ice are in contact with an outwash delta (Rivard et al., 2010; Stea et al., 2011).

A prolonged period of climatic warming followed during which most ice melted and there was a rapid fall in sea level. Proglacial lakes formed, likely from being dammed by remaining ice, to at least 80 m above sea level (ASL) in the central and eastern part of the valley, where it is marked by a shoreline along the southern flank of North Mountain, while the western part of the valley was still isostatically depressed and underwent marine inundation such that it was connected to the Bay of Fundy via Digby Neck (Rivard et al., 2010; Stea, 2004; Stea et al., 2011). Radiocarbon dates on glaciomarine deltas, minimum dates on lake sediments and buried organic horizons in northern Nova Scotia imply that the final retreat of ice after 15 ka was slow or interrupted by several stillstands and possible re-advances (Stea and Mott, 1998).

At ~ 10.8 ka climate cooled abruptly (Collins Pond phase - Younger Dryas), during which small glaciers developed or readvanced over the span of several hundred years. One of these was an ice cap originating from near PEI, which advanced southward over northern Nova Scotia. At this time, the relative sea level lowstand was -30 to -60 m ASL and as ice readvanced a series of proglacial lakes were blocked along the southern and western edge of the Minas Basin. Evidence for this advance is preserved at several sites as glacial and fluvial sediments overlying organic beds (Stea and Mott, 2005). By ~10 ka Nova Scotia was ice free (Stea et al., 2011). After the Younger Dryas, climate warmed and sea level rose to modern day levels. This rise in sea level combined with the tidal range of the Bay of Fundy led to the inundation of lowland areas, including those along the major rivers draining the valley.

Surficial deposit types

The distribution of Quaternary glacial and other surficial deposits present in the Annapolis Valley are shown in **Figure 8**. Deposits of varying thicknesses consist of till, ice-contact glaciofluvial sands and gravels, glaciomarine and/or glaciolacustrine clays and intertidal sediments. Surficial deposits are generally thinner in the upland areas (generally < 1 m) and thicker in the valley where some depressions in bedrock have been infilled by glacial and postglacial sediments reaching thicknesses of up to 60 m (Paradis et al., 2006; Rivard et al., 2010). Throughout the valley, bedrock depressions have been infilled by glaciofluvial sand and gravel deposits. These deposits host surficial aquifers that supply industrial, commercial, agricultural and municipal water uses, including the Town of Wolfville and Kentville (Rivard et al. 2010, Kennedy, 2014). The middle and eastern portion of the Valley are generally covered by glaciofluvial ice proximal/ice contact sandy sediments. Ice contact deposits are also present along secondary depressions near the Minas Basin and in many of the tributary valleys along South Mountain, and also scattered along North Mountain. Sediments are generally sandier and better sorted in the centre of the valley, whereas gravel and boulders are more widespread along the flanks of South Mountain.

Kames and other ice-contact deposits are closely associated with eskers, forming complex and sometimes large and continuous glaciofluvial ridges in the eastern part of the Valley. An extensive outwash plain occupies much of the central part of the valley. Outwash sediments typically consist of well-stratified and cross-bedded fine to coarse sand. Till deposits occur throughout the valley as a thin veneer (< 0.5 m) and also as thicker till blankets and drumlins which typically have an upper sandier facies and a compact basal clay-rich till. Till deposits generally have a silty sand matrix and their composition reflects the underlying bedrock lithology and different ice flow phases. Till deposits along the slopes of North Mountain and in the bottom of the valley generally have a silty sand matrix and are sandier over South Mountain granitic rocks.

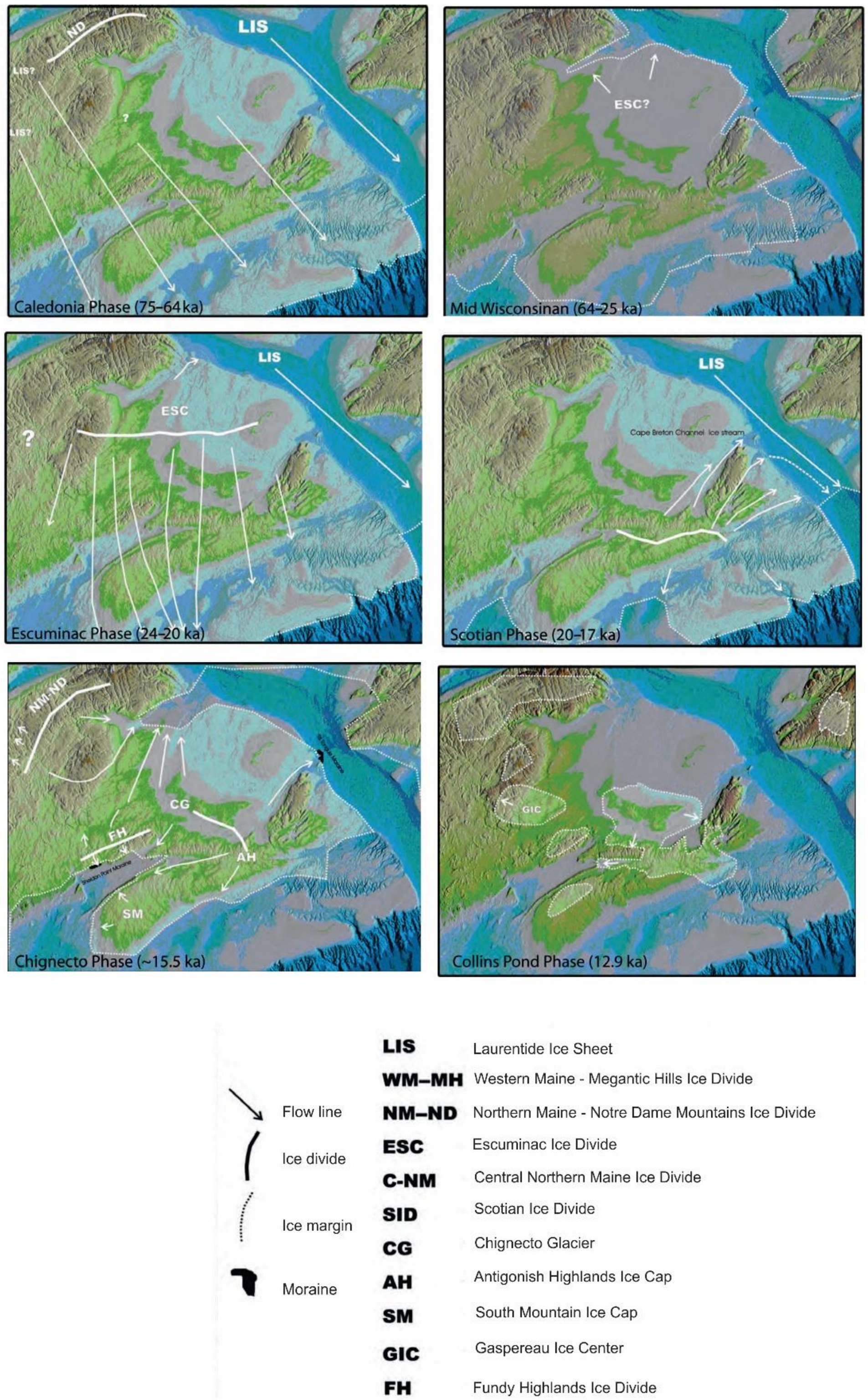

Figure 7. *A summary of the evolution of the Appalachian Glacier Complex from the Caledonian (MIS 3-4) to the Late Wisconsinan (MIS 2) in Maritime Canada (modified from Stea et al., 2011).*

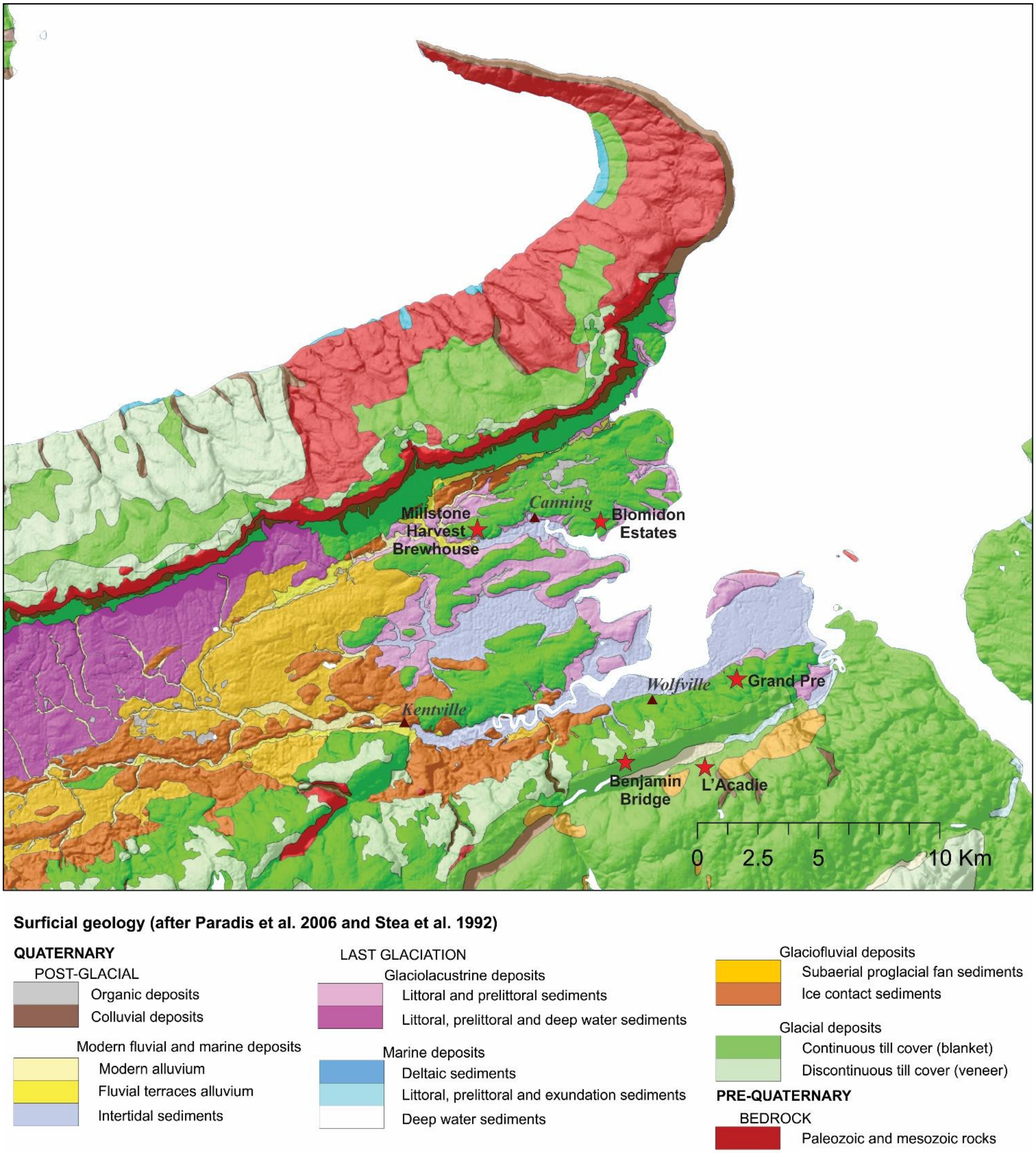

Figure 8. *Surficial geology of the Annapolis Valley region (modified from Paradis et al., 2006 and Stea et al., 1992). Red stars identify the four wineries to be visited on this trip.*

SOILS

There are a wide variety of soil types in the Annapolis Valley owing to both the complex bedrock geology and glacial history of the region. Most of the soils suitable for viticulture are the product of reworking and weathering of till produced from multiple glacial movements during the Quaternary. For other soils, the parent material, which determines the texture and mineral content of the soil, comes from other surficial deposits, including colluvial, outwash, glaciolacustrine and tidal deposits (Holmstrom et al., 1989).


Soil testpit at L'Acadie Vineyards. Photo courtesy of L'Acadie Vineyards.

The primary soil series present in the Annapolis valley region are shown in **Figure 10**; they include the Kentville, Falmouth, Middleton, Nictaux, Pelton, Queens, Torbrook, Woodsville, and Wolfville soils (Harlow and Whiteside, 1943; Cann et al., 1965; MacDougall *et al.*, 1969; Bowen, 1982, and Holmstrom *et al.*, 1989). Each soil series has developed from the same kind of parent material and possess the same texture, structure, colour, drainage and soil horizon characteristics.

Wolfville soils are the predominant type found in Wolfville, Grand-Pre and most of the northern part of the Gaspereau Valley. Wolfville soils are dark reddish brown with a medium to heavy loamy texture. They are typically moderately to well drained except when saturated for prolonged periods. These soils are primarily developed from dark reddish brown sandy clay loam till derived primarily from local bedrock lithologies (dominantly shale and slate) and often found on drumlins and terrains with undulated to rolling topography. Hantsport soils, closely associated with Wolfville soils, are another group of heavy-textured soils developed from clay till and strongly influenced by Devonian argillaceous sandstone, shale and slate. These soils are poorly drained and generally have a compact soil profile.

Middleton and Pelton soils primarily occur along the slopes of North Mountain, where the surficial geology is a mix of till and colluvial deposits (predominantly basalt). Middleton soils are developed from a dark reddish brown clay loam till. Pelton soils are developed from the red shales and siltstones of the Late Triassic Blomidon Formation.

Queens soils, the dominant soil type in the Avon River Valley, are developed from a reddish-brown clay loam till derived from red shales and mudstones and to a lesser extent, red or brown sandstone of the Horton Group or Windsor Group depending on the location.

Nictaux and Kentville soils occur along the Annapolis Valley floor. Nictaux soils are derived from post-glacial outwash primarily composed of stratified coarse sand and gravel whereas Kentville soils are derived from reddish-brown to dark-red sandy loam till with input from the Wolfville Formation and often show evidence of water reworking (Holmstrom et al., 1989).

In a recent terroir study of the Nova Scotia wine growing region (Grallert and Laytte, 2017) most of the analyzed soils from the Annapolis Valley were described as principally sandy soils with important levels of organic matter, a low to high soil acidity and a generalized potassium deficiency. Medium to high compaction was observed in many soil profiles – this typically occurs in a 30 – 40 cm thick horizon where a more impermeable clayey till is encountered. These findings have implications for enhancing soil aeration, improving mineralization of the organic matter and preventing soil compaction.

An important soil characteristic for wine grapes is soil cation exchange capacity (CEC), the ability of soils to store and exchange cations (nutrients). Most of the mineral nutrients that grapevines need to grow are cations, the most important of these include: calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), sodium (Na^{+}), hydrogen (H^{+}), ammonium (NH^{4+}), and aluminum (Al^{3+}; Maltman, 2018). Clay minerals and organic matter in soils are negatively charged and therefore able to attract and exchange cations. Soil CEC is controlled by soil texture, clay mineralogy, concentration of organic matter in the soil and soil pH (acidic soils tend to have high concentration of aluminum atoms that are easily attracted by charged molecules, which prevents cation exchange with other atoms relevant for wine grapes nutrition (Saxton, 2002)). The higher the CEC, the more cationic nutrients the soils can retain and make available to grapes. Soils with very low CEC are less able to retain enough nutrients for grapes to grow whereas soils with very high CEC result in elevated vigour, which increases the grape skin/juice ratio and lowers the quality of the grape (Wright, 2007).

Albuquerque (2007) examined the geological influence on CEC of soils in several vineyards in southern Nova Scotia to determine their influence on the vigour of various grape varieties. The Annapolis Valley showed high local variance in CEC that was attributed to complex bedrock and surficial geology. The LaHave River Valley showed high variance due to differences between vineyards on thin local till overlying metasedimentary bedrock and vineyards developed on drumlins with more regional sources. Ongoing studies at Acadia University are focused on advancing our understanding of how soil chemistry impacts grape vine vigor and how projected climate change in Maritime Canada (at the northern limit of grape vine viability) will influence soils and nutrient transfer.

HYDROGEOLOGY

The main bedrock aquifers of the Annapolis Valley are found in the Late Triassic Fundy Group's Wolfville and Blomidon formations (**Figures 1 and 5**). These formations are composed of sandstones and conglomerates (Wolfville Formation) and siltstone and shale (Blomidon Formation) in different proportions, forming layered and discontinuous aquifer/aquitard sequences (Rivard et al., 2010). These aquifers, especially Wolfville Formation aquifers, tend to host many of the high-capacity groundwater supplies used in the valley (CBCL Limited, 2009). Groundwater quality from these aquifers is generally very good, although elevated concentrations of nitrate and geogenic contaminants, such as arsenic, uranium, and manganese have been detected in some groundwater supplies (Kennedy and Drage, 2020).

Wolfville and Blomidon Formation aquifers are often confined, and flow is driven by topographic gradients from the surrounding North or South Mountain slopes towards the centre of the valley, ultimately discharging to the Cornwallis and Annapolis Valley river systems that flow towards the Bay of Fundy. Groundwater recharge, adjusted for low permeability tills and artesian conditions, has been estimated to range from 115 to 224 mm in the Annapolis Valley aquifers (Rivard et al., 2010).

In comparison, Horton Group aquifers (**Figures 1 and 4**) tend to have lower yields due to the higher percentage of thick shale and siltstone units. Windsor Group aquifers (**Figure 1**), located to the southeast of the Annapolis Valley, also have a high percentage of shales, in addition to limestone and gypsum units which can make them unsuitable as a source of drinking water due to the presence of high sulfates, hardness and dissolved solids in groundwater. Aquifers composed of other rock types offer variable yields depending on fracturing and jointing. These include the tholeiitic basalts of the latest Triassic North Mountain Formation, granites and related felsic intrusives of the middle Devonian South Mountain series, and metasedimentary siliciclastics of the Cambro-Ordovician Meguma Supergroup (Rock Notch and Halifax groups; **Figures 1 and 3**).

As noted in the 'Surficial Geology' section, Quaternary sediments overlying the region consist mostly of tills, but ice-contact glaciofluvial sands and gravels of various thickness are found along the valley floor (**Figure 8**) and host some of the province's largest and most productive surficial aquifers (Kennedy, 2014). These aquifers tend to have very good water quality and are utilized to supply municipal water to several municipalities, including the communities of Greenwood, New Minas, Kentville and Wolfville.

The heterogeneity evident across the region with respect to bedrock and surficial geology contributes to the observed variability in terms of groundwater quality and quantity associated with the region's vineyards, and therefore to the flavour profile of the wines themselves (**Figure 9**). Most vineyards in the region rely on water wells in bedrock aquifers to supply water for winemaking, equipment washing and domestic water requirements for on-site facilities (*e.g.,* restaurants and tasting rooms), and do not typically require well water supplies for frost control or irrigation. At some vineyards, well water is treated to amend the water and remove metals and other undesirable geogenic contaminants.

HYDROGEOLOGY RESEARCH ALONG THE BAY OF FUNDY

Acadians, who settled in the Annapolis Valley in the 17th century, used barriers known as dykes to reclaim land from the sea and thus increase available land for farming. Aboiteaux (wooden box channels and one-way flapper vanes) were constructed at the base of the dykes to drain the dykelands at low tides, resulting in some of the highest quality farmland in the Maritimes, but also altering the dynamics and distribution of sediments in the Bay of Fundy. Following the deportation of Acadians in the 1750s, New England Planters settled in the Grand Pre region and adopted the Acadian dykeland technology. Nova Scotia currently has 241 kilometers of dykes protecting 17,400 hectares with increasingly diverse land uses (Sherren et al., 2016). In many areas, however, dykes may no longer offer adequate protection due to climate change effects such as rising sea levels, increasing tidal amplitude, and increased storm surges.

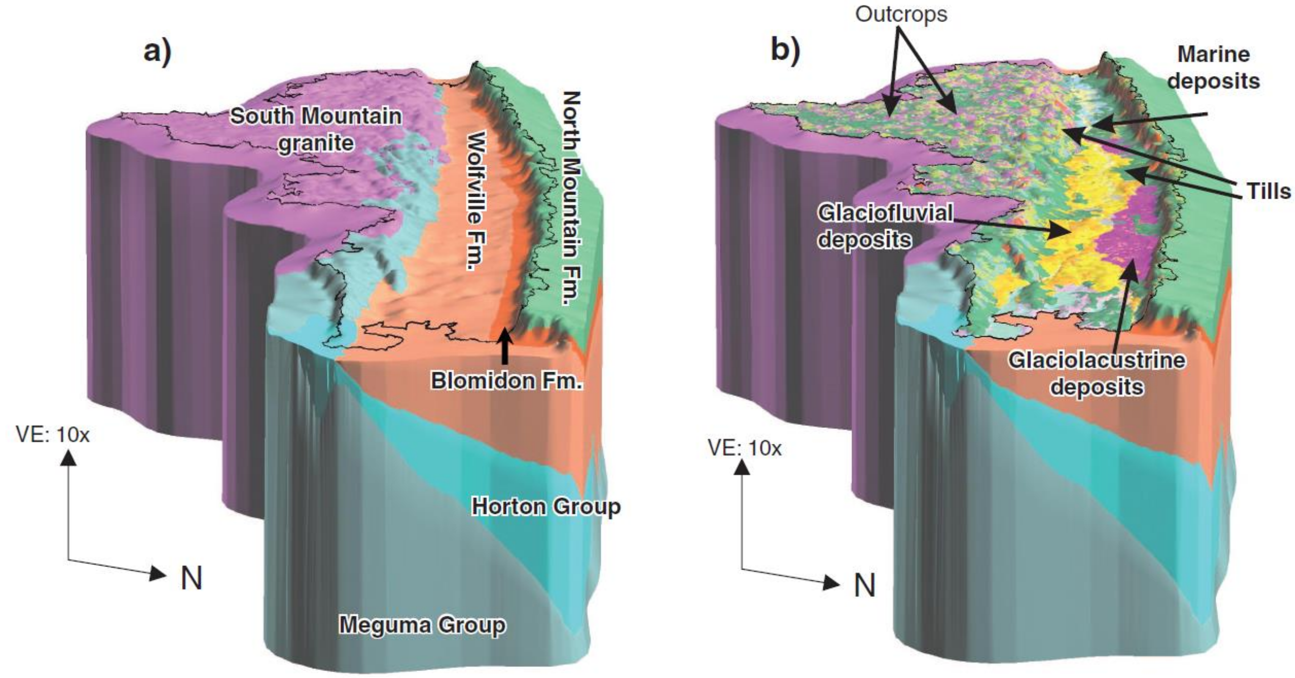

***Figure 9**. Geological models of the Annapolis Valley looking west for a) simplified bedrock geology, and b) simplified surficial sediments (from Rivard et al., 2010).*

Saltwater intrusion, the landward migration of saline water into formerly freshwater zones of coastal aquifers, is one of the most severe global threats to coastal groundwater resources. This process can arise due to both anthropogenic and natural causes and can occur over timescales ranging from hours to millennia. The influence that macro- to mega-tidal conditions exert on saltwater intrusion dynamics is a largely unstudied forcing that is highly relevant to changing coastal groundwater systems. Groundwater flow dynamics in coastal environments are highly complex due to many factors, such as tide and wave influences and density-dependent flow, that constantly alter the magnitude and direction of flow. In conjunction with these natural conditions, ocean-aquifer interactions are strongly influenced by anthropogenic activities along coastal areas that rely on dykes to protect their resources and infrastructure.

Climate change and concomitant sea-level rise is increasingly stressing the dykeland dimensions (coastal squeeze) and threatening coastal groundwater and surface water resources. While the *surface* effects of dyke overtopping have received considerable attention, the *subsurface* effects are largely unexplored. Two study sites (**Figure 10**) have been selected to monitor coastal change and ocean-groundwater interactions to assess the vulnerability to saltwater intrusion in these dykelands with the end goal of informing provincial decisions on dykeland management techniques.

The town of Wolfville (**Figure 11**) is an ideal location for a coastal groundwater observatory as the town relies entirely on groundwater resources and is bordered by several kilometers of dykes that protect crucial infrastructure and agricultural crops from the mega-tidal conditions in the Minas Basin. To investigate the potential for saltwater intrusion above, through, or under the dykes, a series of deep and shallow monitoring wells were installed and instrumented, and paired hydrodynamic monitoring (wave buoy and tidal station) in the basin was initiated to monitor wave dynamics and deeper aquifer-ocean interactions. Preliminary results suggest that the mega-tides exert strong controls on the groundwater flow dynamics and thus the potential for saltwater intrusion. These data will be used to calibrate and/or drive a numerical model (HydroGeoSphere) to simulate the impacts of climate change projections (changing sea levels and precipitation) and develop practical water resources engineering solutions to emerging saltwater intrusion threats.

Similar research is ongoing near Truro, another agricultural hub that has been heavily dyked for the past three centuries and is susceptible to rising sea levels and coastal flooding. This research has far-reaching implications as coastal groundwater resources around the world face increasing risk of overland flooding in the face of rising seas and intensifying storms. Data collection and numerical modeling results from both monitoring locations will provide critical information for Nova Scotia Department of Agriculture on prioritizing provincial investments for dykeland areas that are more vulnerable to climate change or where cost-effective mitigation strategies are possible.

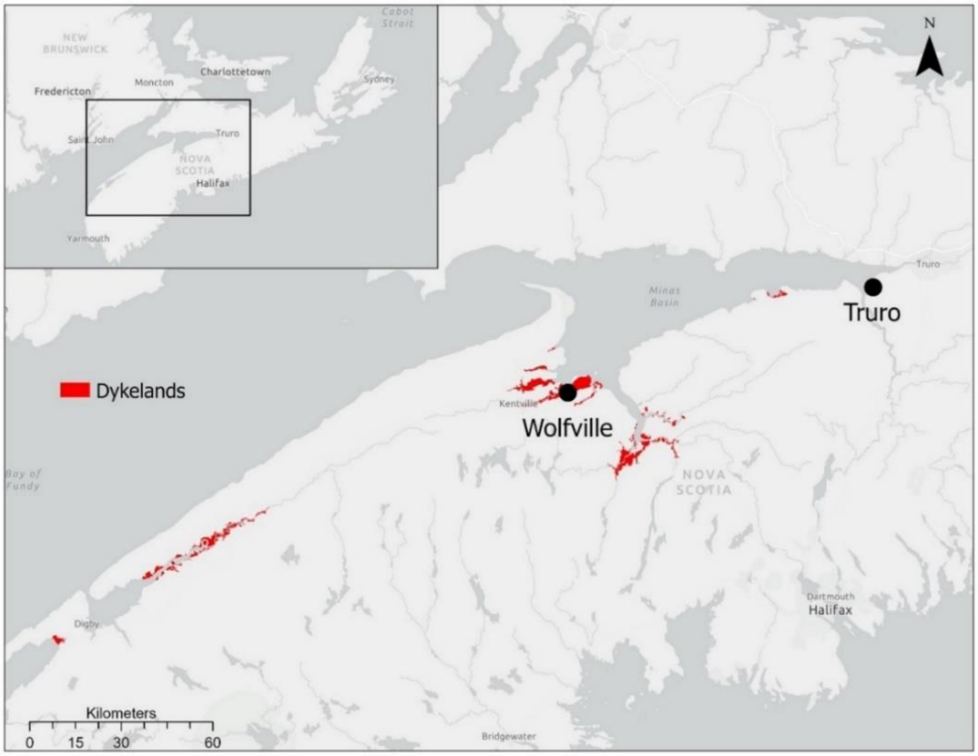

Figure 10. *Wolfville and Truro dykeland study sites in the province of Nova Scotia.*

Figure 11. *Wolfville dykeland study site. Sewage treatment plant settling ponds are shown on the left and the Minas Basin on the right. Photo taken looking west on October 14th, 2021.*

FIELD STOP DESCRIPTIONS

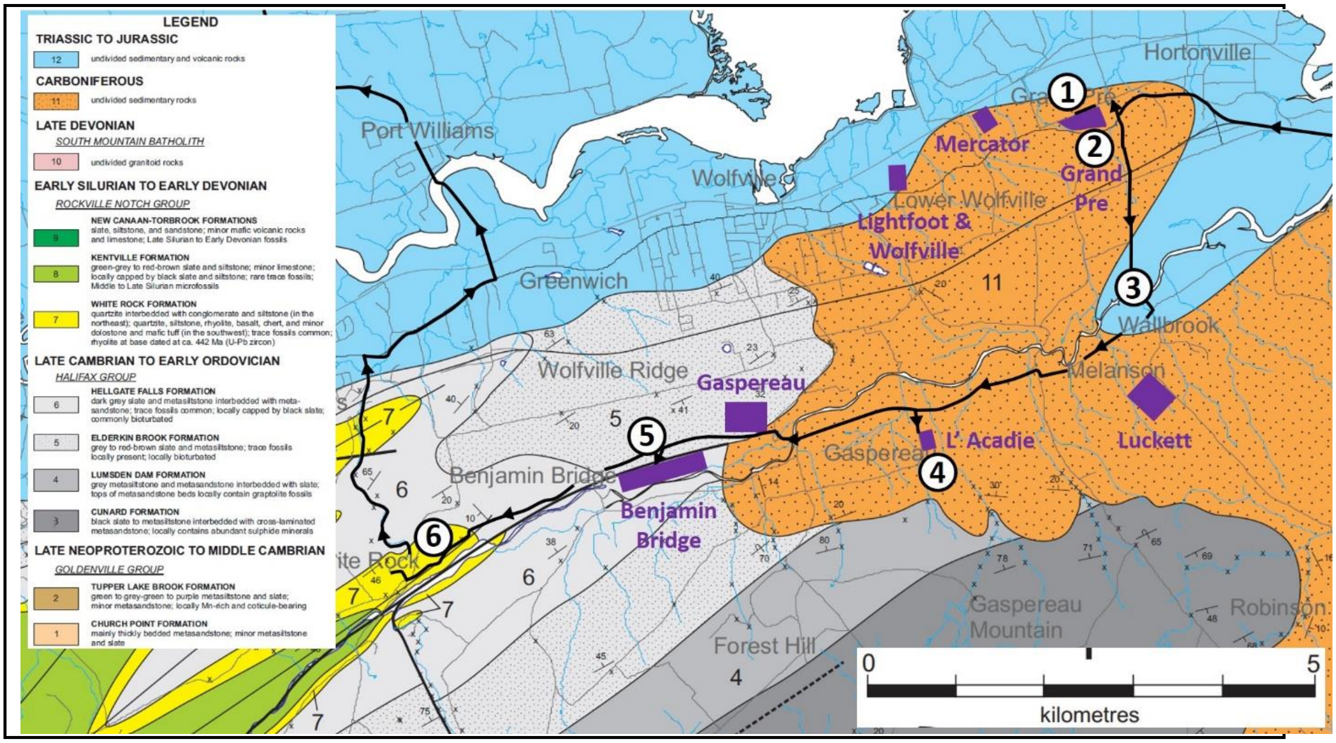

Figure 12. *Geological base map for field trip stops 1 to 6. The violet polygons are a simplistic approximation of the location and area of the respective wineries' vineyards (modified after White et al., 2017).*

STOP 1: View Site – The Landscape of Grand Pré View Park

Address: Old Post Road, Grand Pré, NS
Coordinates (parking lot): 45°6'11.29"N / 64°18'42.47"W

This stop provides a vantage of the UNESCO Grand-Pré National Historic Site and dykelands along the Cornwallis River. From this site we can see where the Cornwallis River meets the Minas Basin, and across the valley floor we can see the Blomidon look-off site on North Mountain. The hill we are standing on is composed of Early Mississippian siltstones and shales (Horton Bluff Formation). From the base of this hill and to the north the near-flat valley floor is underlain by soft Triassic sandstones and conglomerates (Wolfville Formation). Further distant is the northeast-southwest trending North Mountain that is defined and capped by hard basalts (North Mountain Formation), and its southeast-facing slopes composed of soft mudstones of the Blomidon Formation. Cape Blomidon is prominent from this site as are field trip Stops 7 and 8.

To the west of our location is the Dalhousie research site described in the previous section (Nicole LeRoux will present an overview of her research at this field stop) and across the Minas Basin is the UNESCO Cliffs of Fundy Geopark.

The UNESCO Grand Pré National Historic Site represents a cultural landscape showcasing the first European settlement and adaptation to the North American Atlantic Coast. Here is an outstanding example of the 17th century Acadian diaspora and their development of agricultural practices and land reclamation of the intertidal zone using the *aboiteau wooden sluice* and dyke building techniques that promoted the development of Grand Pré and Hortonville settlements. First established in the 1680's the Acadians developed these systems to reclaim agricultural land from tidal marshes producing some of the most fertile soils in Nova Scotia. The dykeland landscape hosts archaeological settlement remains that are a testimony to the Acadian pioneering culture creating their own territory. After the Acadian expulsion beginning in 1755, these land reclamation techniques were later maintained by successors including New England Planters, English, and Scottish descendants.

The Cliffs of Fundy UNESCO Geopark, one of five geoparks in Canada, is located on the northern shore of the Minas Basin, extending 165 km from Cape Chignecto to Lower Truro. Encompassing the stunning Bay of Fundy shoreline are cliffs, tidal estuaries, beaches, waterfalls, and lighthouses. Geologically, the Cliffs of Fundy display evidence of the supercontinent Pangea's formation 300 million years ago and its subsequent breaking apart 100 million years later with outcrops of the Central Atlantic Magmatic Province (CAMP), the largest outpouring of lava in Earth's history. The shorelines also host Early Jurassic vertebrate fossils and more. Further inland running parallel to the shore is the Cobequid-Chedabucto Fault system that greatly influenced the topographic history of the Geopark and Nova Scotia as a whole.

STOP 2: Winery – Domaine de Grand-Pré

Address: 11611 Evangeline Trail, Grand-Pré, NS B0P 1M0
Webpage: https://grandprewines.com/
Established: 2000 (1979 as Grand-Pré Wines)

"Through grape growing and winemaking, Domaine de Grand Pré has added diversity and depth to the style of wine made in Nova Scotia."

Domaine de Grand-Pre is the oldest farm winery in Atlantic Canada. Like many wineries in the Annapolis Valley, it is positioned on south-sloping hillsides of the Wolfville Ridge which provide good wind and frost protection, as well as more daylight hours when the sun is low in the sky. Domaine Grand-Pré and several other nearby wineries are situated on drumlins comprising Wolfville soils derived from Lawrencetown Till. Here, the Lawrencetown Till provides thick surficial cover and a wide mixture of source material.

The rocks underlying the vineyards of Domaine de Grand Pré are siltstones, mudstones and shales of the Early Mississippian age Blue Beach Member of the Horton Bluff Formation; these can influence the composition of soil in the area where the thick surficial cover is thinner **(Figures 5 and 9).** Though not exposed, outcrops in nearby stream cuttings indicate the rocks dip gently to the north-northeast between 8 to 12 degrees. Most of the strata are composed of very soft shales and mudstones and thus easily eroded and covered by soil. Fragments of the harder siltstone and rare limestones may be seen in the vineyard and indeed larger slabs can occasionally be found, some of which preserve tetrapod footprints. The Blue Beach Member sediments represent deposition in a very large lake system that was possibly connected to a distant ocean, and record deep water to shoreline beach and marsh environments. This formation is exposed spectacularly in a long continuous outcrop in the cliffs along the west bank of the Avon River about 12 km east of the winery **(Figures 1, 14 and 15).**

Several drilled wells have been constructed at this site ranging in depth from 60 to 150 m, intercepting fractured shale and siltstone aquifers of the underlying Horton Bluff Formation aquifer with low to moderate well yields indicated. Groundwater chemistry from the Horton Group aquifers is generally acceptable, however well water quality may be associated with elevated concentrations of total dissolved solids, hardness and trace metals and require water treatment.

Figure 15. *A typical shallowing-upward (regressive) lacustrine cycle of the Blue Beach Member, Horton Bluff Formation at Blue Beach. This approximately 4.5 m thick interval records the transition from a deep water lake at the base (dark grey shales) to a lake margin marsh at the top (buff-coloured siltstone). In-situ tree and amphibian trackways – plus rare tetrapod and fish fossils – are found in the later lithology.*

STOP 3: View Site – Gaspereau Valley and River

Location: Bridge over the Gaspereau River, Grand-Pré Road, Wallbrook, NS
Coordinates: 45° 5'6.06"N / 64°18'8.40"W

From this location one is afforded an excellent view of the Gaspereau River valley and its main topographic/geological elements. It is about 20 km long and in plan view the valley is a long narrow tapering triangle with the base its mouth on the Minas Basin. It is bounded to the north by the Wolfville Ridge and the south an extension of the South Mountain. At this vantage point it is tidally influenced that extends up to the hamlet of Gaspereau.

STOP 4: Winery – l’Acadie Vineyards

Address: 10 Slayter Road, Gaspereau, RR1, Wolfville, NS B4P 2R1
Website: https://www.lacadievineyards.ca/
Established: 2004

“The warm rocky mineral-rich soil of an ancient sea-bed. Northwest-facing slopes for excellent drainage. Crisp, dry and rich organic, vegan wines from traditional methods.”

L’Acadie Vineyards is distinctive from others in the Annapolis Valley for its location on the northwest-facing slopes of the Gaspereau Valley. The soils on these slopes (Torbrook soils) are primarily well-drained gravel-rich sandy loams that are believed to impart a complex and mineral flavour to wines **(Figure 10).** These soils are mainly developed from stratified sandy and cobbly gravel ice-contact glaciofluvial sediments that occur as terraces along the valley flanks.

Figure 16. *Portion of the rock pile collected by vintner Bruce Ewert. These cobbles and boulders are representative of the lithologies from the various rock units in the eastern Annapolis Valley and Gaspereau Valley.*

L’Acadie Vineyards’ bedrock geology is the same as that at the Domaine de Grand Pré: siltstones, mudstones and shales of the Early Mississippian age Blue Beach Member of the Horton Bluff Formation (**Figures 4, 14 and 15)**. These are exposed in the bank and bed of Duncanson Brook on the edge of the property (White, 2019) though are not accessible safely during periods of high discharge. The beds dip 15 degrees to the north and occupy the southern flank of a shallow syncline that plunges gently to the northeast with its nose two kilometers to the southwest. Underlying the Horton Bluff are older rocks of the Halifax Group that reflect this synclinal architecture and thus most probably reflect the original bedrock topography in Early Mississippian time.

Visitors to the winery are fortunate that owner Bruce Ewert has collected cobbles and boulders from his property and piled them behind his building (**Figure 16).** In addition to Blue Beach siltstones are rocks from many of the geological units in the region, these include older Halifax Group slates, phyllites and quartzites and White Rock Formation quartzites, and younger Cheverie Formation porous quartz sandstones, North Mountain Formation basalts, and other lithologies.

This winery obtains a groundwater supply from a deep bedrock water well (>100 m) installed in the underlying fractured slate bedrock aquifer (Halifax Group – Elderkin Brook Formation). Halifax Group aquifers are associated with low to moderate well yields and acceptable groundwater quality, though water treatment may be required to remove hardness and trace metals.

STOP 5: Winery – Benjamin Bridge Winery

Address: 1966 White Rock Road, Wolfville, NS B4P 2R1
Website: https://benjaminbridge.com/
Established: 1999

"Over two short decades, Benjamin Bridge has distinguished itself as Canada's premier sparkling wine house."

The Benjamin Bridge winery and vineyards occupy the steep south-facing slopes of Wolfville Ridge near the terminus of the Gaspereau River valley. In contrast to the gravel-rich sandy soils on the northwest-facing slopes, relatively fertile silty to clayey loams (Wolfville soils) derived from Lawrencetown till occur here and dominate the south-facing slopes of the Gaspereau River Valley.

Figure 17. *Steeply-dipping and high fractures and sheared slates and metasiltstones of the Elderkin Brook Formation exposed in the excavation along the slope of the Wolfville Ridge approximately one kilometer from the Benjamin Bridge Winery.*

The bedrock for the ridge and south highlands are those of the Cambro-Ordovician age Halifax Group. This group's lithologies are variable, but is all cases are metamorphosed and are dominated by slates, phyllites, and quartzites (metasiltstones and metasandstones). They are highly deformed through folding and subordinate faulting. Bedrock mapping by White (2019) (simplified version in **Figure 14**) shows a long northeast-southwest trending fault (presumably strike-slip) that defines the course of the Gaspereau River from its headwaters to the hamlet of Gasperau. This fault approximates the axes of similarly orientated series of anticlines and synclines of Halifax and Rockville Notch group rocks. The highway above the vineyards parallels the fault's trace that is a few tens of metres down the slope.

The vineyard's covered bedrock is composed of grey metasiltstones and metasandstones interbedded with slates Halifax Group's Hellgate Falls Formation. They are exposed in the riverbank of the Black River 3 km southwest of the winery. Here they are in fault contact with the underlying Elderkin Brook Formation's grey and red-brown slates and metasiltstones. This formation is also exposed at Black River and its conformable contact with the Hellgate Falls visible. The Elderkin Brook rocks are very well exposed in a large excavation about a kilometer northeast of the Benjamin Bridge winery. This project was undertaken to explore the potential of creating storage caverns for wine storage and maturation. However, as is obvious (**Figure**

17) their high inclination (~80 degrees to the south) and extremely fractured nature would suggest their unsuitability for this purpose.

STOP 6: Outcrop – White Rock Formation

Location: Deep Hollow Road, White Rock, NS. Access (with permission) from the Skylit Solar Power property on White Rock Road.
Coordinates: 45° 3'13.87"N / 64°24'39.78"W

This site beautifully exposes highly fractured and deformed quartzites of the Silurian White Rock Formation. This unit is the basal formation of the Rockville Notch Group (**Figures 14 and 18**). They were deposited on a prograding continental rise to shelf/slope complex and represent deep water sedimentation in a turbidite fan complex (White et al., 2018). It is conformably overlain by slates of the Kentville Formation, and it in turn by slates, sandstones and minor limestones and volcanic rocks of the Torbrook Formation. The contact between the White Rock, and older Hellgate Falls Formation (Halifax Group) slates, phyllites and metasiltstones, is unconformable with an estimated time gap of about 35 million years.

Angular phyllite boulders from the older Halifax Group rocks are also present and are either sourced from the erosion of the overlying basal till regolith or brought in by human hands. Nevertheless, they are useful examples of rocks from this older geological unit whose outcrops we will unfortunately not be visiting on this trip.

Figure 18. *Heavily fractured thick-bedded White Rock Formation metaquartzites viewed to the north. Note that this exposure shows deformation in the form of a gentle syncline with its axis projecting to the northeast parallel to the strike of the Wolfville Ridge.*

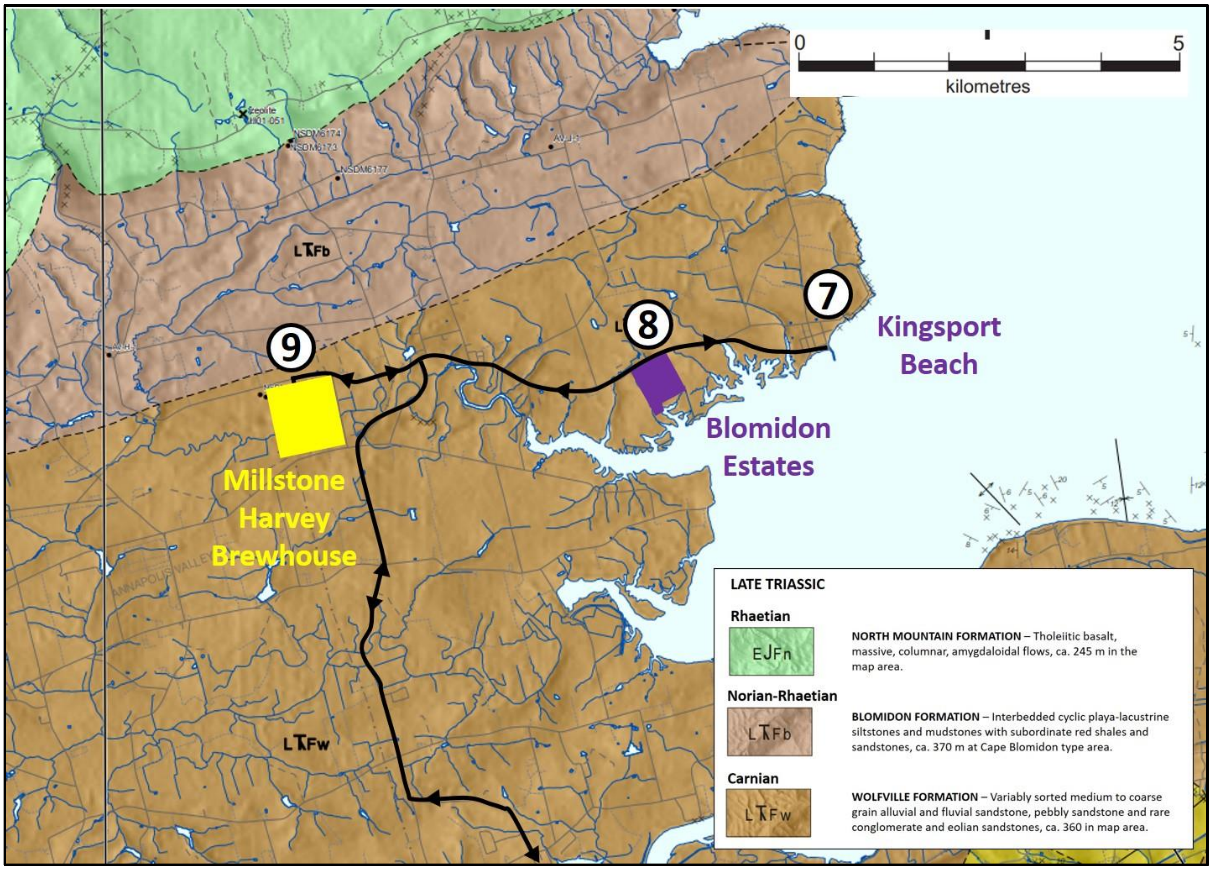

Figure 19. *Geological base map for field trip stops 7 to 9. The violet and yellow polygons are a simplistic approximation of the location and area of the respective wineries' vineyards and brewhouse crop fields, respectively (modified after Moore et al., 2000).*

STOP 7: Outcrop – Late Triassic Wolfville Fm.

Location: Kingsport Beach, Kingsport, NS
Coordinates (wharf parking lot): 45° 9'33.81"N / 64°21'33.49"W. Outcrops are visible north along the shore/beach.

The Upper Wolfville Formation exposed here represents the basal 30 m of this 230 m thick unit. It records a gradual fining upward succession of stacked braided river sandstone cycles that show a gradually increasing proportion of fine grain fluvial abandonment (overbank) and playa siltstones and mudstone, and eolian sandstones through time (Leleu and Hartley, 2010; **Figure 5).**

At this locality, the rocks are well exposed in the vertical (sea cliffs) and horizontal (wave-cut platform) dimensions as they are nearly horizontal with a gentle 2 to 3 degree dip to the northwest. They represent a succession of stacked, multi-storied fining-upward fluvial channel cycles in a braided river depositional setting. These fluvial deposits are high energy systems with a great capacity for sediment transport and erosion. The water flow rates are highly

Figure 20. *Wolfville Formation exposed at Medford Beach. The top of this exposure is about 20 m below the formation's conformable contact with playa-lacustrine siltstones and mudstones of the overlying Blomidon Formation.*

variable given that the region was semi-arid belt and underwent seasonal flooding through monsoonal precipitation. The sedimentary packages are thus separated / bounded by erosional scour surfaces.

On the intertidal beach terrace can be seen low-relief channel bars, mega-dune remnants, and lateral accretion surfaces, the latter recording oblique accretion developed along bar-margins. These features are essentially the depositional surface that last saw the light of day about 218 million years ago **(Figure 21 A and B).**

The sediments at this site are dominantly sandstone composed of quartz, feldspars and lithic fragments. They are medium to coarse-grained, moderately sorted, occasionally pebbly, and exhibit planar and trough stratified bedding. The pebbles represent bedload and suspended load fluvial deposits within a braided channel system. At the top of these sandstone cycles can sometimes be preserved silty sandstones, and rarer clay beds. The former are composed of silt to medium grained sand with rare pebbles representing suspended load deposits in a lower energy flow regime. The latter clay intervals reflect low energy suspended load sediments deposited in scour surface. The dynamic depositional setting results in a low preservation potential for these sediments.

An obvious feature of these rocks is that they are moderately lithified with silica and carbonate cements. They erode relatively easily and this accounts for the armouring of the cliff sections with harder rocks such as the North Mountain Formation basalts. Here they are observed to be fine grained extrusive thoeliites from the central or lower parts of the lava flows. In the beach sandstones can be found rounded pebbles and cobbles of amygdaloidal basalts representing the upper 'frothier' part of the flows with subsequent growth of various zeolite minerals during its cooling phases and the circulation of hot element-rich groundwater brines.

Figure 21. A) *Low angle cross-stratified channel bedforms near the base of a fluvial fining upwards cycle. View is to the northeast, with the measured paleocurrent direction to the north-northwest (mean = 329°; Leleu and Hartley, 2010). Note the white quartz, grey quartzite, and brownish siltstone pebbles in the modern tidal sediments, these being liberated from the Triassic sandstones through erosion.* ***B)*** *Base of a fluvial channel. The underlying silty and muddy red sandstone has been scoured and eroded by the overlying channel cycle. Note the presence of the pebbles and coarse grain sand in a small wedge-shaped depression. The clasts are imbricated and dip to the left indicating the flow direction was from the right to the left.*

STOP 8: Blomidon Estate Winery

Address: 10318 Highway 221, Canning, NS B0P 1H0
Website: https://blomidonwine.ca/
Established: 2007 (1998 as Habitant Vineyards and 2002 as Blomidon Ridge Estates Vineyards)

"Our beautiful seaside setting offers a unique location for viticulture, as well as a scenic stopping point for our many visitors."

Blomidon Estate Winery occurs on the shores of the Minas Basin. The moderating influences of the waters of the basin provide unique climatic conditions for this winery. The soils (Kentville series) are mainly developed from till, largely sourced from The Wolfville Formation and in places show evidence of water reworking.

Underlying the winery's vineyard are the near horizontal pebbly sandstones of the Upper Wolfville Formation. Though not visible here, they are on strike with the well exposed in vertical and plan view as seen our previous Stop 7 at Kingsport Beach (**Figures 20 and 21**).

Blomidon Estate Winery obtains a groundwater supply from a 47 m deep drilled well intercepting a fractured sandstone and shale aquifer. Wolfville Formation aquifers are associated with moderate to high well yields and very good water quality, though water treatment may be required to remove hardness, total dissolved solids and trace metals.

Figure 22. View of Upper Wolfville Formation fluvial sandstones. Their moderate level of induration permits easy wave and tidal erosion. Note that the transition between the sandstone and overlying soil horizon is hard to discern and appears transitional. Photo courtesy Arthur Fox / HikersMovement.com (All rights reserved).

STOP 9: Brewery – Millstone Harvest Brewhouse (Sea Level Brewing)

Address: 9146 Highway 221, Canning, NS B0P 1H0
Website: https://www.sealevelbrewing.com/
Established: 2007

"We strive to produce an approachable taste to quality, micro brewed craft beers and ciders, providing distinguished characteristics and unique flavours to each truly handcrafted recipe."

Millstone Harvest Brewhouse is Nova Scotia's first Estate Brewery, with all of their malting barley, some hops and other fruits inputs grown onsite.

Looking north from the brewery parking lot towards North Mountain ridge, one can observe a gradual increase in the valley's elevation that steepens towards the ridge capped by harder basalts. The rocks over this intermediate interval are the playa-lacustrine siltstones and mudstones of the Late Triassic Blomidon Formation. These sediments conformably overly Wolfville Formation sandstones with the contact about 200 m north of and paralleling the highway. The Wolfville rocks underlay the brewery's fields are those at the top of the formation being mostly horizontally-bedded sandstones with more significant beds of softer overbank and crevasse-splay mudstones and siltstones. These rocks – and the contact with the Blomidon Formation – are well exposed at Medford Beach about 8 km northeast of Stop 9 (**Figures 20 and 21**).

Figure 23. *Aerial view of the Millstone Harvest Brewhouse looking southeast. The fields surrounding the complex are underlain by sandstones of the uppermost Wolfville Formation that also composes the northeast-southwest trending low ridge in the background.*

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