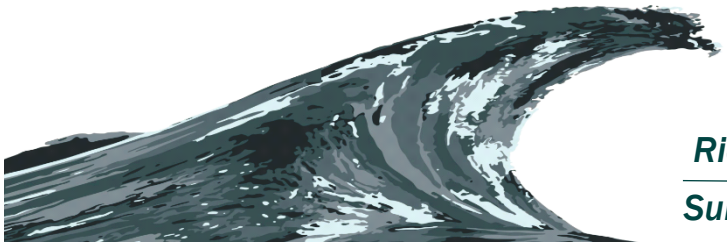

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FIELD TRIP GUIDEBOOK – B3

Telling the Story of the Cliffs of Fundy UNESCO Global Geopark, Nova Scotia: Linking Geoheritage, Indigenous Heritage and Culture

Leaders: Caleb Grant, John Calder, David Piper, Georgia Pe-Piper, and Louise Leslie

GEOLOGICAL ASSOCIATION OF CANADA
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Geological Association of Canada – Mineralogical Association of Canada –

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Canadian Society of Petroleum Geologists Joint Annual Meeting

Halifax, May 2022

Field Trip B3

Telling the Story of the Cliffs of Fundy UNESCO Global Geopark, Nova Scotia: Linking Geoheritage, Indigenous Heritage and Culture

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Cliffs of Fundy Geopark

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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.

The Cliffs of Fundy UNESCO Global Geopark acknowledges its position within Mi'kma'ki; the unceded and ancestral territory of the Mi'kmaq and L'nuk peoples.

The Geopark looks to honour and educate residents and visitors on the importance of this land, the history of its people and promote equity, equality, and prosperity for all.

Safety Information

Code of Conduct

The Cliffs of Fundy UNESCO Global Geopark and the Geological Association of Canada (GAC®) aim to provide all participants of GAC®-related events with a positive, safe, and harassment-free environment in which diverse participants may learn, discuss, and network in an atmosphere of mutual respect, regardless of race, ethnicity, gender or gender identity, gender expression, sexual orientation, country of origin, age, disability, physical appearance, body size, religion, or culture. We recognize the responsibility to create and maintain that diverse environment for the benefit of all and to be active in promoting meaningful participation of individuals from all underrepresented groups and minorities.

If you experience or witness any form of unsafe or unacceptable behavior, please consult the Field Trip Safety Officer (Caleb Grant), a field trip leader, or an LOC volunteer.

Terrane and Weather

Participants should have adequate footwear and protection against both wet and cold, including a hat, gloves, and boots. Adequate clothing is important if you are involved in an accident or if you are unexpectedly required to spend an extensive period of time outdoors. Spring weather in Nova Scotia is unpredictable and can change from sunny and warm, to rain, wet snow, and high winds with little notice.

Tides

The most important safety concern throughout the Geopark is the tides. The rising tide can flood parts of some tidal flats and sand bars faster than you can run. The rising tide may block your access route around a headland, creating a “pinch point”. Many coves are completely flooded at high tide, with no escape route up the steep cliffs.

A general rule of thumb is to plan to return to your vehicle two hours before high tide, three hours before if you have passed headlands that will be cut off earlier. In most cases this means you are venturing out on a falling tide.

In windy/stormy weather, the tides can reach estimated high tide levels 2.5 hours ahead of schedule. Also, high tides in the Minas Basin are delayed from tides in areas like Halifax. To make sure you know the tide time for the area you are exploring, please visit https://wla.iwls.azure.cloud.dfo-mpo.gc.ca/.

Coastal Erosion

With the highest tides in the world, comes some of the highest rates of coastal erosion in the world. This erosion and deterioration of the coastal cliffs can be dangerous to navigate as rocky material can collapse without warning! A general rule of thumb when hiking in the Cliffs of Fundy is to keep back from the cliff bottom one school bus length (~10 meters)!

When on a cliff-top trail, do not approach the very edge of the cliff. It may have overhanging soil and vegetation that could give way under your weight. Never attempt to go down a steep cliff from the top!

Cell Reception

Be aware that cell reception can be very poor, or non-existent, in many areas of the Geopark, especially near steep cliffs along the coast or in narrow river valleys. Make sure there is someone who knows your planned route for the day and when you are expected to return.

Historic Mining

Be aware that many of the areas within the Geopark have been mined historically. When exploring areas such as Cape d'Or and Horseshoe Cove, be aware of abandoned mine shafts and adits. Use caution around these features as they are often unmarked and can be deep and/or unsupported.

Wildlife

The Geopark is home to a diverse group of plants and animals. Respecting the habitats and maintaining adequate distance from wildlife helps to protect visitors and the many species that call this area home. It is important to know how to act if encountering species such as coyotes, moose, or bears. Many stinging insects, including bees and wasps also live within the Geopark, do not approach or disturb insect nests. Another prominent insect of note in the Geopark are Ticks: tiny insects that can bite and attach themselves to travelers walking through the forest, maintained trails, tall grass, fields and other natural environments. Protect yourself by covering up exposed skin when outside and

make sure to do daily self-checks when you get home. If you find an attached tick, follow the public health Agency of Canada's guidelines for prompt removal of the insect.

Also be cautious when interacting with unfamiliar plants on trails. Many species of mushrooms and other plants are poisonous and/or can cause severe irritation if eaten or touched.

Abstract

The recently designated Cliffs of Fundy UNESCO Global Geopark stretches for 165 km along the northern shore of the Minas Basin, in the Bay of Fundy, from Lower Truro to Apple River. The Geopark extends across the long-lived Minas Fault Zone that experienced major strike-slip displacement and mineralization during the Late Paleozoic assembly of Pangea. The fault zone was reactivated in the Mesozoic as the bounding fault of the Fundy Rift Basin, the fill of which includes the North Mountain Basalt, part of the Central Atlantic Magmatic Province (CAMP) related to the opening of the Atlantic Ocean. The spectacular coastal landscapes provide high quality outcrops illustrating the geological history. The Minas Basin has the highest tidal range in the world, and glimpses of the tidal amplification in the Holocene are recorded in oral histories of the Mi'kmaw people, the original stewards of this landscape. Late glacial outwash terraces provided the hunting grounds for the earliest peoples in the area more than 11,000 years ago, and fertile tidal marshes were later dyked for fertile farmland by Acadian and later settlers.

The three-day field trip will demonstrate the interpretive storyline of internationally significant geological features and expose participants to the many aspects of Indigenous and colonial heritage. We will visit some of the readily accessible Geosites, demonstrating the history of the Minas Fault Zone at West Advocate and East Bay as well as the Mesozoic sedimentation and magmatism at Cape d'Or, Partridge Island and Five Islands. Both Cape d'Or and Partridge Island hold even greater significance as sites of Mi'kmaw heritage and archeology. The Geopark endorses the concept of Two-Eyed Seeing where Indigenous understanding and western scientific practice coexist with equal

respect. The tour will show how the landscapes and seascapes evolved and how they influenced the cultural, shipbuilding, mining and agricultural heritage of the area. We will discuss the challenges of interpreting the complex geological history of the Geopark and designing accessible material for public education. We will also consider the UNESCO educational objectives, in terms of sustainable development of mineral and energy resources and the geohazards created by climate change and rising sea level.

Introduction

UNESCO Global Geoparks

UNESCO Global Geoparks are an important designation that formalizes the link between humanity and the Earth – rooted in the geology of a region but exploring the many ways that the natural environment and human culture have developed in relation to geology. Global Geoparks respect Indigenous storylines and interpretations of the landscape in equal standing with western scientific interpretation; the Indigenous concept of Two-Eyed Seeing. Global Geoparks are not just geological parks; therefore, the inherent challenge for geoscientists is to translate the story of the Earth and its relevance to the broader public. We will explore these opportunities and challenges during this field trip.

The seed that would eventually grow philosophically into both geoheritage and geoparks was planted in 1991 at Digne les Bains, France, with the Déclaration Internationale des Droits de la Mémoire de la Terre (Declaration of the Rights of the Memory of the Earth) (ProGeo, 1991; https://www.geosoc.fr/declaration-des-droits-de-la-memoire-de-la-terre.html; translation http://www.progeo.ngo/downloads/DIGNE_DECLARATION.pdf). Geoheritage was tangibly recognized with the establishment of European Geoparks in 2000, joining with China in 2004 to become the Global Geoparks Network. In 2015, Global Geoparks became an official programme of UNESCO. As of January, 2022, UNESCO Global Geoparks number 177 in 46 countries worldwide (https://en.unesco.org/global-geoparks/list). Differences between

UNESCO World Heritage Sites and UNESCO Global Geoparks are explored by McKeever and Narbonne (2021).

A Short History of the Cliffs of Fundy UNESCO Global Geopark

The possibility of a Global Geopark including part of the "Parrsboro Shore" was long advocated by various members of the Atlantic Geoscience Society, in particular by Graham Williams and Garth Demont, especially following the inscription of the Joggins Fossil Cliffs UNESCO World Heritage Site in 2008. Identification of the potential for a Global Geopark on the northern shore of the Minas Basin grew from the identification of geoheritage sites in Nova Scotia by the Nova Scotia Geological Survey (NSGS; Calder, 2014; Calder and Poole, 2017). The geological and GIS staff of the NSGS continued to provide important support throughout the development of the Aspiring Geopark as part of its Geoheritage program.

Whereas Global Geoparks strive to be developed in a "bottom up" model by the community, the first group to be consulted were the Elders Advisory Council of the Mi'kmaq, who felt that such a designation would be consistent with their deep sense of belonging to, and respect for, this region of Mi'kma'ki. Meetings ensued in rural communities across the region, during which strong support was voiced for pursuit of a Global Geopark. The board of the Cumberland Geological Society, and in particular Dr. Tim Fedak, then of the Fundy Geological Museum, played an important early role in supporting the work of a steering committee formed in 2015 to begin work as an Aspiring Geopark. The two municipalities of Cumberland and Colchester Counties threw their material support behind the Aspiring Geopark from the beginning, and work to develop the application to

UNESCO received further support from the provincial and federal governments via the Atlantic Canada Opportunities Agency. From the onset, equal partnership with the Confederacy of Mainland Mi'kmaq has been central to the Cliffs of Fundy (Calder and Gloade, 2016), which is a storied and sacred part of Mi'kma'ki and very much central to the legends of the legendary Mi'kmaw figure Kluskap (https://www.mikmaweydebert.ca/ancestors-live-here/). A fully independent, incorporated, not-for-profit society and governing body for the Geopark was in place for the evaluation of the Aspiring Geopark in 2019 by the Global Geoparks Network on behalf of UNESCO. The Cliffs of Fundy was officially accorded the status of a UNESCO Global Geopark in July, 2020.

Storytelling in the Cliffs of Fundy Geopark

As mentioned above, UNESCO Global Geoparks are landscapes of international significance, that link an area's geological heritage with the natural, cultural, and intangible heritage to define the region's unique geoheritage. The Cliffs of Fundy Geopark has three pillars that define our identity:

- The highest tides in the world
- High quality outcrops that tell the story of the assembly and subsequent separation of the supercontinent Pangea
- Mi'kma'ki, the land of Kluskap. The ancestral home of the Mi'kmaw people.

These three pillars define the Geopark as not only internationally significant, but globally unique. Bringing these elements together to create engaging and accessible interpretive materials for visitors, or interested persons, of any background is a driving goal of the Cliffs of Fundy, and all UNESCO Global Geoparks.

General Geologic Timeline of the Cliffs of Fundy Geopark

Preface

The “General Geologic Timeline of the Cliffs of Fundy Geopark” has been abridged and lightly edited from a forthcoming book "*The Story in the Rocks of the Cliffs of Fundy*" by David J.W. Piper and Georgia Pe-Piper (2022); all rights are retained by the authors. We also recommend *The Last Billion Years* and *Island at the Centre of the World* (Atlantic Geoscience Society, 2001; Calder, 2018) as accounts of regional geology aimed at a more general readership.

Building Blocks: The Appalachian History of the Geopark, the Lost Continent of Avalonia

The old Precambrian rocks of the Cobequid Highlands, in the northern part of the Geopark, were once at the northern edge of the great southern continent, Gondwana (Pollock et al., 2012), comprising the ancestral landmasses of South America, Africa, Antarctica, India and Australia. Most of the rocks formed as ocean subducted beneath the edge of Gondwana, and the resulting island arc rifted away from the main continent, some 600 million years ago (Ma) in latest Precambrian time. This suite of rocks form what is now the Avalon terrane of the Appalachian orogen, which includes correlative rocks in southern New Brunswick, the Antigonish Highlands, southern Cape Breton Island and the Avalon Peninsula

of Newfoundland. Within the Cobequid Highlands, three main blocks of Avalon terrane rocks show rather different geological histories and are today separated by major east-west (E-W) faults (Figure 1). These blocks arrived somewhere close to their present relative positions some time before 360 Ma, but their earlier relative history is unknown. From northwest to southeast (NW to SE), these blocks are known as the Jeffers Block, the Bass River Block and the Mount Ephraim Block.

The Jeffers Block extends along the entire Cobequid Highlands west of Economy and continues eastwards along the northern half of the highlands. It consists of deep-water sedimentary rocks derived from arc volcanoes and lesser flows of basalt, andesite and rhyolite, probably from submarine eruptions. All these rocks are weakly metamorphosed and contain no fossils; one rhyolite was dated at 630 Ma (Murphy et al., 1997). They are intruded in the west by small plutons of diorite and granodiorite, of which the Jeffers Brook Pluton is best recognized.

The Bass River Block, from Bass River to Kemptown (Figure 1), consists principally of plutonic igneous rocks. These consist principally of black and white granodiorite, with lesser gabbro and red granite (White et al., 2022) with ages ranging from 640–585 Ma[7].

The Mount Ephraim Block is located in the southeast of the Cobequid Highlands, beyond the eastern boundary of the Geopark. It includes gabbro and granite dating from 765–735 Ma (MacHattie et al. 2019) that is deformed in places to gneiss. Small intrusions of granite and gabbro are of Ordovician age (482–480 Ma).

Evidence from global reconstructions of tectonic plates and biogeography suggests that rocks of the Avalon terrane split away from Gondwana towards the

end of the Cambrian period (ca. 490 Ma) by the spreading of the Rheic Ocean (Figure 2; Cocks and Torsvik, 2002; Nance et al., 2010; van Staal and Barr, 2012; van Staal et al., 2021), forming a “microcontinent” called Avalonia. It was similar in size to the modern West Pacific Ocean microcontinents like New Zealand and Japan. Continued opening of the Rheic Ocean and closure by subduction of the Iapetus Ocean caused the Avalonia microcontinent to collide with southern edge of Laurentia in the latest Silurian (ca. 420 Ma; Waldron et al., 1996). Laurentia was a large, low latitude continent built around the Canadian Shield (Kroner et al., 2021). The inner (northern) part of the Appalachian Mountains had already accreted to Laurentia by this time.

Glints of Pangea: Docking of Meguma

Another microcontinent had a rather similar history to Avalonia. The Megumia microcontinent today comprises the Meguma terrane in the southern part of Nova Scotia, which also underlies Georges Bank, the Scotian Shelf and the southern Grand Banks of Newfoundland. Megumia also originated from the northern margin of Gondwana (Waldron et al., 2009), and like Avalonia, it drifted northward as the Rheic Ocean widened (White et al., 2018). The thick sedimentary rocks of the Meguma terrane were pervasively folded and metamorphosed in the later part of the Early Devonian (395–388 Ma; Hicks et al., 1999). In the Middle Devonian (Keppie and Krogh, 1999; Carruzzo et al., 2003), the Meguma terrane was intruded by voluminous granites, including the South Mountain Batholith (Figure 3). This magmatism was related to northward subduction of the Rheic Ocean (Figure 4).

How can we know the time when the Meguma terrane came together ("docked") with the Avalon terrane? In the Silurian and Early Devonian (444–394 Ma), marine sedimentary rocks of the Meguma terrane in the Annapolis Valley have different sediment types and fossil faunas from marine and coastal rocks of similar age in the Avalon terrane that are well exposed at Arisaig (Pollock et al., 2012). This and other evidence suggest that the Meguma and Avalon terranes at that time were geographically and geologically distinct.

There was a fundamental change in the style of sedimentation in the Geopark between the Early and Late Devonian. The Silurian to Early Devonian marine to coastal sedimentary rocks were deposited regionally over a span of at least 100 km of the Cobequid Highlands, with the most complete section in the Geopark found in an inaccessible area of the Portapique River. In contrast, later Devonian and Early Carboniferous sedimentary rocks of the Murphy Brook Formation, Fountain Lake Group, and Horton Group show rapid changes in sediment type and thickness, with common occurrence of conglomerate and lacustrine deposits (Figure 3). Such observations suggest deposition in small terrestrial basins with coarse-grained detritus shed from a mountainous terrain. Since the end of the Devonian period (358 Ma), it is certain that the Meguma terrane was located adjacent to the Avalon terrane in Nova Scotia. Sandstones of the Horton Group in the Cliffs of Fundy Geopark, and also in the St Mary's Basin east of Truro, contain conglomerates. Some of the conglomerate pebbles are typical Meguma terrane granites, from the south; others are Avalon terrane rhyolites and granites from the north (Murphy and Rice, 1998; Murphy, 2000; Piper and Pe-Piper, 2021). The oldest rocks of the Horton Group date from the very end of the Devonian period, at 359 Ma (Martel et al., 1993; Myrow et al., 2014).

The Carboniferous Period: Sedimentary History of the Appalachians

Paleozoic sedimentary successions within the Geopark span the Late Devonian to Late Carboniferous; younger Mesozoic successions date to the Late Triassic and Early Jurassic periods. Sedimentation in the Paleozoic occurred within the large Maritimes basin, centered on what is today the southern Gulf of St. Lawrence. On the south side of the Minas Basin, opposite the Geopark, a much more complete record of sedimentation in the Early Carboniferous is preserved in the Kennetcook Basin (Waldron et al., 2010) and similar sedimentary successions are found throughout Atlantic Canada. The following description from these more complete sedimentary records paint the picture of the changing depositional environments in what is now Atlantic Canada, through the Devonian and Carboniferous time periods.

Throughout the Carboniferous, glacial icecaps developed at high southern latitudes in the ancient continent of Gondwana. The advance and retreat of these polar ice sheets was determined by variations in the Earth's axis and orbit around the Sun (Giles, 2009), that led to fluctuations in sea level similar to those of the Quaternary ice ages. Studies of the paleomagnetic history of eastern North America show that the Cliffs of Fundy Geopark was situated at low latitudes in the southern hemisphere and gradually drifted northwards through the Carboniferous (Figure 5). The Geopark thus passed through the arid zone around the Tropic of Capricorn in the Early Carboniferous, into the equatorial zone in the later Carboniferous, and later into the northern hemisphere arid zone by the Permian (Figure 4; Calder, 1998; Gibling et al., 2008). In the Kennetcook Basin (Gibling et al., 2008; Waldron et al., 2010), the latest Devonian to Early

Carboniferous Horton Group is of very variable thickness to a maximum of 2.5 km (this section can also been seen in the cliff face within Cape Chignecto Provincial Park in West Advocate). It consists of conglomerates, sandstones and dark shales deposited on alluvial fans, in river systems and in lakes, respectively. These sediments accumulated in an asymmetric basin, bounded to the north by the Kirkhill and Rockland Brook faults within the Geopark and to the south by a gentler slope towards the South Mountain Batholith. There was tectonic disruption and uplift along these faults prior to deposition of the overlying Windsor Group, which is at least one kilometer thick. A marine limestone at the base of the group is overlain by thick evaporite deposits of gypsum/anhydrite. The middle Windsor Group consists of alternating evaporite deposits including rock salt, limestones and sandstones (Giles, 2009; MacNeil et al., 2018). The upper Windsor Group has thick terrestrial red siltstones and a few thin limestone beds that can be traced regionally, representing marine incursions at high stands of sea level. It is unknown how continuous the sedimentation of the Windsor Group was and there may have been large depositional gaps. The overlying Mabou Group is made up of around one km total thickness of lacustrine, desert playa and river floodplain deposits (Hamblin, 2001).

Faulted sections of Horton, Windsor and Mabou group rocks are present in the Geopark. Horton Group rocks crop out between the Cobequid Fault and the Kirkhill–Rockland Brook faults, which formed the bounding fault of the Horton Basin. Some of these Horton Group rocks are intruded by granite or gabbro and most are “cooked”, rendering fossil spores in a condition that prevents determination of their relative age through palynology. Additionally, diagnostic macro plant fossils have yet to be discovered in these strata, which are folded and deformed near the Cobequid Fault (e.g. West Advocate Geosite). Most of the

Horton Group sandstones, siltstones and shales in the Geopark can be compared with rocks in the Kennetcook Basin in their sedimentary structures and geochemistry (Piper and Pe-Piper, 2021), and were deposited as erosional detritus from the Meguma terrane. Conglomerates with granite and rhyolite pebbles close to the Kirkhill–Rockland Brook faults are rather different. They represent alluvial fans at the southern edge of the Cobequid Highlands. Conglomerates of likely similar age overlie the Fountain Lake volcanic rocks in Spicer Cove and siltstones and sandstones interbed with and overlie Fountain Lake basalts in the eastern Cobequid Highlands (Dessureau et al., 2000; Dunning et al., 2002). Windsor Group limestones are distinctive, but are restricted to only a few isolated localities. Some of these were quarried for lime in the past, such as in Upper Economy and on the coast at Brookville. The best exposure of Windsor Group limestones crop out at the Clarke Head within a complex mélange. The Mabou Group is represented by the West Bay formation in the Parrsboro area, with exceptional outcrops of predominantly lacustrine sedimentary rocks at the East Bay Geosite and also at Crane Point. The East Bay succession represents a transition to terrestrial conditions subsequent to the ultimate withdrawal of the Windsor sea.

The Cobequid and Kirkhill–Rockland Brook faults show evidence for prolonged movement throughout the Early Carboniferous (Piper and Pe-Piper, 2021). Part of this evidence is represented by the deformation that took place during emplacement of gabbro and granite. Some recrystallized minerals in faults, such as secondary biotite, monazite and allanite, can be dated directly by Ar-Ar or U-Pb methods. Where the Kirkhill and Rockland Brook faults cut gabbro, recrystallized amphibole and mica minerals give Ar-Ar ages that correspond to the gap in sedimentation and angular unconformities at basin margins elsewhere

in the Maritimes Basin between the upper Horton and lower Windsor groups (Figure 3).

The Dynamic Geopark: Faulting and Regional Scale Movement in Active Orogenic Belts

The accumulated evidence paints a picture of a very dynamic landscape in the Early Carboniferous of the Geopark. This evidence includes analysis of structures along faults, in veins, and in the granites and gabbros, chronology from radiometric dating and fossils, and the record of accumulated sediment. Blocks of the rising mountains in the Cobequid Highlands were at times jostled into new positions, followed by periods of relative quiescence. Regionally, in the Mid-Late Devonian, a large SW–NE strike-slip fault system extended the length of the Appalachian mountain chain in the USA, with up to 250 km dextral slip. This fault system bounded the western margin of the Magdalen Basin, corresponding approximately to the modern Gulf of St Lawrence (Figure 6). Motion on this fault system was transferred in a distributed manner to a parallel dextral strike-slip fault system on the east side of the Magdalen Basin, along the west coast of Cape Breton Island (Dunning et al., 2002), along the Cabot Fault of western Newfoundland, and into either East Greenland or Scotland (Hibbard and Waldron, 2009; Waldron et al., 2015). It seems probable that this eastern fault system continued southwestward through the middle of the Meguma terrane, where it localized the intrusion of the South Mountain Batholith around 380 Ma and continued to deform the hot batholith (Benn et al., 1997, 1999). By about 355 Ma, the batholith had cooled sufficiently that the granites around the fault effectively welded the fault and the Meguma terrane acted as a rigid block. The continuing

SW–NE dextral slip on the eastern fault, driven by larger scale plate motions, was taken up along the Hollow Fault and the Rockland Brook Fault, with a more WSW–ENE direction (Figure 6). By this time, Horton rifting and extension had already begun along the old Meguma-Avalon suture, south of the bounding Kirkhill–Rockland Brook series of faults. Initial sinistral slip on these faults in the Late Devonian gave way to dextral slip in the Early Carboniferous (Figure 3). Times of enhanced fault slip resulted in uplift of the basin margin and of the Highlands. This uplift was driven by the bend in the fault system at the eastern end of the Cobequid Highlands, where the ENE –trending Rockland Brook Fault passes into the NE trending Hollow Fault (Figure 6). At times of tectonic quiescence, the ongoing subsidence of the Early Carboniferous basins predominated and allowed the accumulation of sediment however, regions of the Maritimes Basin were only intermittently connected to the sea. The connection to the Rheic Ocean south of the Meguma terrane was tenuous, and frequently interrupted by fault-controlled uplift. Under more humid conditions, lakes developed in the Horton and Mabou groups, whereas salt, gypsum and desert muds accumulated in the more arid Windsor Group. Influx of sea water is marked by limestones and evaporitic rock salt and gypsum/anhydrite in the Windsor Group and some brackish water microfossils (Tibert and Scott, 1999) in the Horton Group.

Data from the entire Appalachian region allows us to imagine the setting of the Geopark in a plate tectonic context, informed by modern analogues (Figure 4). The Rheic Ocean, separating the Meguma terrane from the main Gondwana continent, was subducted beneath the Meguma terrane at least in the Early to Middle Devonian. The South Mountain Batholith and its satellite plutons are typical intrusive rocks found above subduction zones, where an ocean subducts

beneath a continent, forming a volcanic arc with most of the magma trapped in mid-crustal magma chambers. Such magma is produced by partial melting of the mantle above the subducting slab that is triggered by the dehydration of the subducted ocean crust at a depth of around 100 km. Behind the volcanic arc, in a back-arc position, studies of modern analogues show that the lithosphere (crust plus rigid part of the mantle) is thinned, and heat flow is high. This high thermal gradient and upwelling of asthenosphere (more plastic part of the mantle) leads to partial melting of the mantle to give basaltic magma, most of which accumulates at the base of the crust. That granitic magma may mix with other granitic magma produced as lower to middle crust is partially melted by the heat from the basaltic magma (Papoutsa et al., 2016). Where there are strike-slip faults that take up the relative motion of colliding plates, such as within the Geopark, they also provide pathways for magma to rise to upper crustal levels.

Closure of the Rheic Ocean and the Formation of Pangea: Late Carboniferous Tectonic Activity

From the Middle Devonian and throughout the Early Carboniferous, the dominant active strike-slip faults in Nova Scotia (Benn et al., 1997) were aligned SW–NE, part of a more extensive set of faults extending from the Appalachians in the southeastern USA to Greenland and western Europe (Hibbard and Waldron, 2009). E– W trending faults, parallel to the Meguma-Avalon contact bounded some Early Carboniferous rift basins (Murphy and Rice, 1998), but show little evidence for major strike-slip motion at this time. All this changed in the Mid Carboniferous. A series of E–W strike slip faults were initiated along the Minas Fault Zone, cutting and deforming Early Carboniferous and older rocks (Waldron

et al., 2005)and uplifting the Cobequid Highlands. After a gap of ten million years, fluvial conglomerates, sandstones, and shales were again deposited along the margins of the Cobequid Highlands, forming the Boss Point Formation to the north and the Parrsboro Formation to the south. The age of these formations is based on the fossil plants and spores that they contain. We surmise that during the ten-million-year gap in sedimentation both the Cobequid Highlands and the old Early Carboniferous basins to the north and south were raised into mountains and became areas of erosion. Regionally, this gap in sedimentation has been correlated with a major lowering of sea level, due to extensive southern polar glaciation, resulting in enhanced erosion by rivers (Gibling et al., 2008). In the Cumberland Basin, NE flowing rivers deposited thick flood plain and deltaic deposits, while streams flowing off the Cobequid Highlands deposited alluvial fans; between these two systems, forested swamps accumulated thick peat that hardened to become coal deposits mined at Joggins and Springhill. The dominant plants in the "coal swamps" were lycopsid trees distantly related to modern club mosses, of *Lepidodendron* and *Sigillaria* rising unbranched to over 40 m high. The roots, stumps and foliage of these trees are preserved at the Joggins Fossil Cliffs UNESCO World Heritage Site, where fossil remains of amphibians and the earliest known reptiles are found within the once hollow tree stumps (Lyell and Dawson, 1853; Calder, 2017).

One prominent E–W strike-slip fault is the Cobequid Fault within the Geopark. This fault is a few kilometers south of the master faults that were active in the latest Devonian and earliest Carboniferous, such as the Rockland Brook and Kirkhill faults. These faults were already "stitched" by the crystallization of granite-gabbro plutons, which strengthened the brittle upper crust. The new Cobequid Fault cut its own path through weaker sedimentary rocks at the

northern margin of the Kennetcook Basin (Piper and Pe-Piper, 2021). The internal structure of the Cobequid Fault, at an original depth of several kilometers below the ground surface, is now exposed along the coast of Greville Bay at the Brookville Rock Geosite. A highly stretched internal zone, 100 m wide, is flanked by a marginal zone of similar width, both made up principally of strongly deformed Horton Group shales with abundant quartz veins. Blocks of exotic rocks in fault contact include Jeffers Group metasedimentary rocks, Fountain Lake Group rhyolite, Windsor Group limestone and Parrsboro Formation sandstone and siltstone, the last being less deformed suggesting that much of the fault movement was older than the deposition of the Late Carboniferous (Bashkirian) Parrsboro strata (Waldron et al., 2005). The main deformation of the fault post-dates deposition of the Horton Group and may have begun before deposition of the Windsor Group. However, the scale of the fault zone suggests that its main deformation resulted from the development of the Minas Fault Zone. The amount of dextral slip along the Cobequid Fault at this time is at least tens of kilometers.

The onset of E–W faulting along the Minas Fault Zone had widespread effects throughout the Geopark. The re-activated Cobequid Fault at Moose River moved the southern part of the West Moose River granite westward to an unknown location and thrust Fountain Lake volcanic rocks over the Horton Group. Widespread fractures in the granite and adjacent Horton Group on the Lynn Road were filled with veins of magnetite and iron carbonates, followed by later but lesser titania, barite and rare-earth element minerals[10] (Pe-Piper et al., 2018).

Towards the end of the Carboniferous and into the Permian, the climate became increasingly dry as the globe warmed. The Pictou Group rocks in the

Cumberland Basin and Prince Edward Island followed a similar course to the northeast flowing river system of the Cumberland Basin, but the river deposits were from wet-season floods. During the dry season the sediments dried out beneath the tropical Sun and unstable minerals oxidized to give a brick-red colour to both sandstones and shales. These “red beds” contain excellent records of tetrapod (reptile and amphibian) footprints at Brule and on Prince Edward Island.

All of this deformation in the Late Carboniferous took place as Africa was sliding westward past Nova Scotia, driving the dextral strike-slip movement not only on the Minas Fault Zone, but also on faults as far north as the Gaspé Peninsula (Jutras et al., 2003) including the Percé UNESCO Global Geopark. The collision with Africa culminated in the Permian with the uplift and westward thrusting of the US Appalachians south of New York. This final collision in the earliest Permian is represented in the Carboniferous Maritimes Basin by a cessation of deposition, some uplift, and local deposition of desert sands (Gibling et al., 2008). At that time, the Cliffs of Fundy Geopark was located near the equator in the middle of the supercontinent Pangea, 2000 kilometers from the nearest part of the Panthalassia Ocean, in the Appalachian Mountains (Figure 2; Calder, 2018).

Last Days of Pangea: Triassic-Jurassic Mass Extinction and the Extrusion of CAMP Basalts

The Triassic and Early Jurassic rocks of the Geopark, in particular basalts of the North Mountain Formation, provide a record of the break-up of Pangea, as northwest Africa rifted apart from Atlantic Canada. In Nova Scotia, Triassic rift basin formation likely started about 230 Ma. The large Fundy Rift Basin, mostly in

the area now covered by the present-day Bay of Fundy, is one of a series of sedimentary basins along the eastern margin of North America (Figure 7). The Fundy Basin is bounded on its northern side by a reactivated Carboniferous fault, the Chignecto Fault, extending along the southern coast of New Brunswick (Figure 7). In the east, the Fundy Basin is bounded by the old Minas Fault Zone, last active in the Late Carboniferous, which was reactivated again in the Triassic. The motion on this bounding fault, represented within the Geopark by the Portapique Fault within the Geopark, was largely vertical but with a sinistral component of slip. Farther east, the Minas Fault Zone forms the northern bounding fault of the Orpheus Graben, south of Cape Breton Island. Likely at the same time, rift basins also developed on the outer part of what is now the Scotian Shelf, but their geometry and deposits, some of them oil and gas-bearing, are known only from seismic reflection profiles and petroleum exploration wells. The Triassic rocks of the Geopark are represented by three formations (Figure 8): the Wolfville Formation (Donohoe and Wallace, 1980; Leleu and Hartley, 2010; Sues and Olsen, 2015) dominantly of red sandstone and lesser conglomerate; the Blomidon Formation dominantly of red mudstone with lesser sandstone; and the North Mountain Basalt Formation. Dinosaur-bearing Lower Jurassic sedimentary rocks overlying the North Mountain Basalt are known as the McCoy Brook Formation. The Triassic sedimentary rocks are very broken up by faults within the Geopark, and are better known from less faulted sections on the southern coast of Minas Basin, between Burntcoat Head and Medford Beach (Leleu and Hartley, 2010).

These sedimentary formations of Triassic–Jurassic age in the Fundy Basin are separated by regional unconformities, particularly clear at the edges of the basin. As in the Early Carboniferous, these unconformities may represent

extended gaps in sediment deposition, giving an incomplete record of geological history. The unconformities seem to correspond to times of uplift at basin margins and renewed supply of coarse-grained sediment. Studies of paleomagnetism in other Triassic basins along the eastern USA show that the Fundy Basin moved northward through the Triassic, from 15°N at the time of the Wolfville Formation to 25°N at the time of the North Mountain Basalt (Figure 5; Olsen and Et-Touhami, 2008). Being located in the middle of the Pangea supercontinent at these latitudes resulted in desert conditions, somewhat similar to those in the American Southwest, with seasonal tropical rainfall in the Wolfville Formation, but more arid conditions thereafter.

The Late Triassic Wolfville Formation (Sues and Olsen, 2015) is several hundred meters thick regionally and consists mostly of red-brown sandstones, some conglomerate, and some siltstone deposited from rivers. In the Geopark, a thinner development of the formation, some 100 m thick (Sues and Olsen, 2015), is well exposed in the cliffs at the Carrs Brook Geosite. It consists principally of red and brown sandstones with trough cross bedding deposited from river channels; minor brown siltstones and two horizons of orange, cross-bedded, wind-deposited sandstone dunes (Olsen, 1997; Withjack et al., 2009). However, the formation thickens greatly to the southwest beneath the Bay of Fundy, reaching ~3 km thick near Grand Manan Island (Wade et al., 1996).

The type section of the Blomidon Formation underlies North Mountain Basalt at Cape Blomidon, directly south across the Minas Basin from Parrsboro. There, it consists of some 300 m of red mudstones overlying red sandstones that rest unconformably on the Wolfville Formation (Sues and Olsen, 2015).

Within the Geopark, more than 50 m of the lower Blomidon Formation, called the Red Head Member is exposed in coastal cliffs in several areas. At the

Red Head Geosite, at the eastern end of the Five Islands Provincial Park, the sandstones include a 33 m thick section of wind-blown sand dunes with spectacular crossbedding (Olsen and Et-Touhami, 2008; Sues and Olsen, 2015) and minor interbedded river-deposited sandstones. Barchan dunes formed and were sculpted by NE winds, analogous to the NE trade winds of today's world that blow Saharan dust to the Caribbean and, in the past, blew ships of early explorers across the Atlantic Ocean.

The prominent middle unit of the Blomidon Formation, called the White Water Member (Sues and Olsen, 2015), is up to 300 m thick and is exposed in the cliffs immediately west of the Red Head Geosite, from which it is separated by a fault (Olsen and Et-Touhami, 2008). The rocks of this unit consist of meter-scale cycles of alternating red sandstone and mudstone (Figure 9), with the amount of sandstone progressively decreasing up-section (Olsen and Et-Touhami, 2008). The Blomidon Formation accumulated on the floor of ephemeral desert lakes within a rift valley, with sandstones representing the deposits of occasional sheet floods on the distal parts of alluvial fans, and the muds representing lake deposits. Evaporation of the lakes precipitated halite (NaCl), now preserved as casts of cubic halite crystals, and crystals and nodules of gypsum ($CaSO_4.2H_2O$). Distinctive wispy centimeter scale irregular patches of sand (Olsen and Et-Touhami, 2008) are interpreted to be formed by saline brines on the original sediment surface. Some of the irregular bedding deformation in the Blomidon Formation mudstones are interpreted to be caused by dissolution of precipitated salt resulting in the collapse of overlying strata, although some fracturing is related to later fault movement such as at the Red Head Geosite. The meter-scale sediment cycles record changes in climate from more arid to more humid on scales of tens of thousands of years (Olsen, 1997). Farther seaward, beneath the

modern Scotian Shelf, red mudstones similar to those of the Blomidon Formation interbed with halite deposits up to two kilometers thick. The bromine content of those halite deposits indicates a marine origin, implying that the opening rift between Nova Scotia and Morocco was linked to the Tethys Ocean some 2000 km to the east.

The upper unit of the Blomidon Formation, called the Partridge Island Member, is only a few meters thick. East of the Old Wife Geosite, it forms a distinctive light green-grey horizon high in the cliffs immediately underlying the North Mountain Basalt.

The cliffs of the North Mountain Basalt at Cape d'Or, Partridge Island, Wasson Bluff, Five Islands, and many other locales (Figures 7, 10) are some of the most iconic features of the Geopark. Looking across the Bay of Fundy from the central and western parts of the Geopark affords vistas of Cape Blomidon, Cape Split and the continuation of North Mountain Basalt extending 200 km southwestward along the southern shore of the Bay of Fundy. Seismic reflection profiles, used for petroleum exploration, show that the basalt underlies the entire main Bay of Fundy (Figure 7; Wade et al., 1996; Withjack et al., 2010). Basalt also outcrops on Grand Manan Island and Isle Haute and was identified in two wild-cat petroleum wells off the south coast of New Brunswick (Figure 7; Pe-Piper et al., 1992). Total thickness of basalt in places exceeds 400 m. A section of interpreted North Mountain basalt greater than 1000 m thick was recognized in seismic profiles off the coast of Grand Manan Island (Wade et al., 1996). Geological mapping shows that the same three units of basalt can be traced along the entire length of North Mountain.

The lower and upper units comprise single flows up to 150 m thick; the middle unit in any locality has between 3 and 16 thinner flows that are typically

10–20 m thick (Kontak, 2008). Individual flows are defined by a fine-grained base and top, where the basalt lava was rapidly cooled, and a coarser-grained interior, where cooling was slower and crystals of feldspar and pyroxene crystallized. Commonly, the top of a flow is reddened, representing the development of a soil horizon before being covered by a subsequent flow. Particularly in the middle unit, bubbles and pipes of gas were frozen into the basalt as vesicles. Many of these vesicles were later filled by silica and zeolite minerals. The thick upper and lower units show prominent vertical columnar jointing, formed by contraction of the basalt as it cooled from its eruption temperature of at least 1000 °C. The lower flow yielded a U/Pb zircon age of 201.5 Ma (Blackburn et al., 2013).

The upper flow unit is thin or absent within the Geopark and along much of the eastern part of North Mountain (Greenough et al., 1989; Kontak, 2008; Olsen and Et-Touhami, 2008). In the Geopark, the lower unit shows characteristic columnar jointing, for example, at the Old Wife, on the Five Islands, and at Wasson Bluff, Partridge Island, Cape Sharp and Cape d'Or (Greenough et al., 1989) and is overlain by thin flows of the middle unit, well exposed at Wasson Bluff (Greenough et al., 1989; Kontak, 2008; Olsen and Et-Touhami, 2008). Thin sections of the upper flow unit crop out at Wasson Bluff and McKay Head. The lava units of the North Mountain Basalt can be compared with modern lavas in Iceland and Hawaii, and ancient lava piles such as the Columbia River basalts and the Deccan Traps of India (Kontak, 2008). The upper and lower flow units of the North Mountain Basalt were not emplaced as single catastrophic 150 m high lava flows. Rather, a relatively thin initial flow, extending hundreds of kilometers, cooled at its base and top. Subsequently, new lava was episodically emplaced into the still molten interior of the flow, which was inflated vertically. This resulted in complexities in cooling patterns revealed by columnar jointing. The

middle flow unit comprises several single smaller flows of so-called pahoehoe lava, of irregular thickness and with a ropy surface texture. The extent of individual flows cannot be determined in the field but is likely of the order of tens of kilometers.

The earliest Jurassic McCoy Brook Formation (Tanner, 1996) overlies the North Mountain Basalt. It consists of red-brown sandstone and mudstone, with minor conglomerate. Eolian sandstones of the McCoy Brook Formation at the Wasson Bluff Geosite yield examples of early dinosaurs, the largest of which are prosauropods. The Wasson Bluff Geosite is a designated Special Place and, like the rest of Nova Scotia, is protected from fossil retrieval except under a Heritage Research Permit issued by the Nova Scotia Museum. In the type section, 800 m west of McKay Head, the formation is some 180 m thick and consists principally of desert lake mudstones and distal alluvial fan sandstones, with some gypsum nodules, similar to the Blomidon Formation underlying the North Mountain Basalt. The formation is also well exposed on the west-facing cliff at Five Islands Provincial Park, where it can be viewed along the beach leading to the Old Wife Geosite.

Locally, where the contact with the underlying basalt is exposed, lake deposits are preserved at the base of the McCoy Brook Formation. These rocks are known as the Scots Bay Member, named for a section of limestones and silica deposits overlying the middle unit of the North Mountain Basalt at Scots Bay, southeast of Cape Split on the south side of the Bay of Fundy. Fossils include fragments of charophytes (green algae), fish bones, ostracods, gastropods (snails), and clam shrimps. Hot springs on the floor of the lake precipitated silica as banded agate and chalcedony.

In the cliff section between the Old Wife and Red Head Geosites, SE dipping faults with SE-directed slickenlines (slip marks) offset at the base of the North Mountain Basalt and are interpreted as normal faults related to the extension of the Fundy Basin. They appear to have developed after the deposition of the Blomidon Formation (Withjack et al., 2009). Abundant agate and zeolite minerals found in the North Mountain Basalt were precipitated from hot water circulating through fractures and pores in the basalt in a convection system, driven by heat associated with the basaltic magma deeper in the crust. Banded agate and sequential precipitation of different types of zeolites indicate a process changing through time, as a result of variation in the properties of the circulating hot water (dissolved chemical species, temperature, oxidation state, acidity). Porous vesicles and pipes in the middle unit host large numbers of zeolites, but zeolites are also common in faults and fractures, including the prominent SE-dipping faults cutting the basalt.

There are differences in the abundance of particular zeolites between the Geopark and the southern coastline of the Bay of Fundy (Pe-Piper and Horton, 1996), where the circulating water was hotter and more saline than in the basalts of the Geopark (Pe-Piper and Miller, 2002). Studies of the succession of minerals filling veins and vugs show that the first mineral to precipitate is commonly the green mica celadonite, followed by copper, iron oxide and varieties of quartz (Pe-Piper, 2000). Amethyst is best developed in the southwestern part of North Mountain. Native copper was mined at Cape d'Or by the Mi'kmaq prior to contact with colonial people, and was traded far and wide across eastern North America (Hanley et al., 2022). Deposits of both iron oxide (Digby area, Economy Mountain) and copper (Margaretsville, Cape d'Or) continue to have been mined in the Nineteenth and early Twentieth Centuries (Figure 11).

The North Mountain Basalt makes up a small part of a regional set of basalt flows and dykes that extend from France and Spain through the regions bordering the Atlantic Ocean as far south as Brazil and Bolivia (Figure 12) known as the Central Atlantic Magmatic Province or CAMP. This volcanic activity lasted for one-two million years around the Triassic to Jurassic boundary (~200 Ma). Recent research places the minimum aerial extent of CAMP magmatism at 10 million km^2 (Denyszyn et al., 2018, Marzoli 2018). CAMP is the most expansive so-called Large Igneous Province (LIP) ever discovered, and one of the largest by erupted volume.

Some questions about the nature of CAMP persist. Were the basalt flows formerly much more extensive and removed by erosion, or were flows topographically restricted to basins and the CAMP magmatic products mostly trapped in the crust as dykes, sills and laccoliths? Where were the feeders that sourced the very low viscosity basalt flows? In the case of the North Mountain Basalt, there is evidence that the upper flow unit thins towards the faulted basin margin on the north side of the Fundy Basin. The flow direction of basalt on the south side of the Fundy Basin is to the south or southwest (Figure 7; Kontak, 2008). The basalt flows accumulated in a half graben, with major bounding faults in the north, but there is also circumstantial evidence for a faulted southeastern margin immediately prior to basalt eruption (Olsen and Schlische, 1990; Olsen and Et-Touhami, 2008; Kettanah et al., 2014). The extent of pre-basalt faulting within the Fundy Rift Basin, and hence the detailed topography of the basin, is unknown, as is the role of topography in steering the direction of lava flows. The source of the basalt flows is from a fissure eruption, either in the middle of the Bay of Fundy, or more likely from the Lepreau River and associated dykes in southwestern New Brunswick (Figure 7; Kontak, 2008; Davies et al., 2017;

McHone et al., 2022). On the Scotian Shelf and Grand Banks, the sparse distribution of basalt in the Triassic-Jurassic basins also suggests that basalt flows were limited in extent (Pe-Piper and Piper, 1999). Nevertheless, even if basalt flows were restricted to basins, the volume of lava erupted in the CAMP eruptions is likely greater than a million cubic kilometers. In a broad sense, major flood basalt events, associated with the rifting apart of continents and the initiation of new oceans, commonly are synchronous with major global extinction events. The release of large amounts of volcanic gasses, particularly carbon and sulfur dioxides, together with fine volcanic ash, may have a catastrophic impact on global climate and ocean acidification. Volcanic ash may also blanket the land surface, destroying land animal habitat and vegetation. The fossil pollen and spores in the 1.2 m thick upper unit of the Blomidon Formation at Partridge Island have been intensely investigated and debated (Whiteside et al., 2007; Cirilli et al., 2009), as to where the boundary between the Triassic and Jurassic periods lies and what changes took place across that boundary. This is not some esoteric academic debate, but centers on questions concerning the magnitude and causes of extinctions at the Triassic-Jurassic boundary. This boundary marks the third largest mass extinction event in the last half billion years of Earth history, with the extinction of approximately 30% of marine genera (particularly corals and ammonites) and a major turnover of terrestrial vertebrates, sporomorphs and megaflora (Davies et al., 2017). There is general agreement that the Earth experienced significant environmental perturbations during the latest Triassic including at the Triassic-Jurassic boundary. But this is where the agreement ends, and many questions remain. Was there rapid sea level rise or widespread anoxia in the oceans, due to the particularities of morphology and circulation in the ocean basins? Was the change triggered by the impact of an

extraterrestrial bolide? Was the extinction a consequence of the outpouring of basalt in the CAMP, releasing carbon dioxide, sulfur dioxide and volcanic ash resulting in a global environmental crisis? The microscopic fossils of plant spores within the uppermost part of the Blomidon Formation change abruptly at about 20 cm below the base of the basalt. This level is known as the end-Triassic extinction (ETE, Figure 13). A similar horizon is better represented in the Newark Basin (Figure 12), where it is dominated by very high percentages of fern spores, which are a hardy pioneer vegetation.

Precise dating of basalts and related intrusions shows that the oldest basalt in the Argana Basin of Morocco, originally juxtaposed with Nova Scotia before the opening of the Atlantic Ocean, is older than the ETE. The North Mountain Basalt is estimated to be 3,000 years younger than the ETE and the Orange Mountain Basalt in the Newark Basin is 14,000 years younger (Blackburn et al., 2013). There is clear evidence, from marine rocks across the Triassic-Jurassic boundary, linking high carbon dioxide levels to the timing of the CAMP volcanism (Cirilli et al., 2009; Whiteside et al., 2010). In addition, carbon dioxide levels in the atmosphere can be extrapolated from carbonate concretions in soils. In the Newark Basin there are three discrete periods of basalt eruption, with the oldest of similar age to the North Mountain Basalt and the youngest half a million years later (Figure 13). Following each eruptive phase, the measurements from soil concretions show an increase in atmospheric carbon dioxide, followed by a gradual decline. The general consensus is that there were environmental stresses in the latest Triassic, perhaps exacerbated by bolide impacts. At the end of the Triassic, the CAMP volcanic eruptions released vast amounts of volcanic gasses that triggered rapid environmental change in the oceans, including ocean

acidification (Greene et al., 2012) and global warming in a 3–4°C increase in mean atmospheric temperature (McElwain et al., 1999).

Jurassic sedimentary rocks exposed on land in Atlantic Canada are restricted to small outcrops of McCoy Brook Formation in and around the central part of the Geopark. However, an approximately two kilometer thick package of inferred Jurassic strata overlies the North Mountain Basalt in the central part of the Bay of Fundy. Based on the character of reflections in seismic reflection profiles, the lower one km may be mostly lake deposits, whereas upper strata may include more river deposits (Wade et al., 1996; Withjack et al., 2010). At the same time as these sediments accumulated in the Fundy Basin, rifting, extension and subsidence accelerated on the Scotian Shelf and ocean crust of the central Atlantic Ocean started to form around 190 Ma (Sibuet et al., 2012). By 165 Ma there is evidence of river sand passing through the Fundy Basin and into the developing Atlantic Ocean off SW Nova Scotia (Nagle et al., 2021). Although Nova Scotia was still in desert latitudes at this time, the river flowed from the wetter climate in the Canadian Shield to the north (Blowick et al., 2021).

Further breakup of pieces of Pangea continued for 150 million years after the formation of the Fundy Rift and the massive outpouring of basalt around 200 Ma. Throughout the Jurassic, the opening Atlantic Ocean extended only as far north as the southwestern margin of the Grand Banks of Newfoundland. At this time, Iberia (Spain and Portugal) was a continuation of southern Newfoundland and Ireland was joined to northern Newfoundland and southern Labrador. North of Nova Scotia and Morocco, there was no North Atlantic Ocean. Continuous land or shallow continental shelves extended from Scotland through Greenland to Labrador and Baffin Island.

Throughout the Cretaceous (145–66 Ma), this northern vestige of Pangea began to rift apart. Like a sticky zipper, first one segment of the rift and then the next would open up, eventually allowing seafloor spreading to build new ocean crust. The first to open was the seaway between Iberia and the Grand Banks. Starting in the Late Jurassic, around 150 Ma, the continental crust was stretched from its previous thickness of around 30 kilometers to as little as two kilometers east of the Grand Banks, a process known as hyperextension (Pérez-Gussinyé, 2013). To the north, southern Labrador and Ireland had not yet started to split apart (Figure 14). The geometry of the hyperextension required that Nova Scotia and southern Newfoundland move westward, relative to northern Newfoundland and the Gulf of St Lawrence, to accommodate the elongation of the hyperextended crust. This motion lasted throughout the Early Cretaceous and was taken up (or accommodated) by mostly horizontal slip on some of the old Late Devonian–Early Carboniferous NE–SW trending faults and also on the E–W faults of the Minas Fault Zone. The most compelling evidence of this Cretaceous faulting is the presence of small fault-bounded basins along several NE–SW trending faults throughout Nova Scotia. These basins contain gravels and sands transported by rivers and clays deposited in lakes, swamps and flood plains. The deposits, known as the Chaswood Formation, are rarely more than 200 m thick and have been explored by many borehole investigations and, in a few pits, mined for silica sand and kaolin clay. The age of the Chaswood Formation is known from fossil plants, largely preserved as charcoal from forest fires (Scott and Stea, 2002), and from plant spores: the age ranges throughout the Early Cretaceous (Falcon-Lang et al., 2007). Geophysical imaging of the deposits show that the oldest layers are folded and, in places, cut by the bounding fault (Gobeil et al., 2006), whereas the uppermost layers are flat lying (Figure 15). A small deposit of

Chaswood Formation overlies Triassic rocks at Belmont, in the eastern part of the Geopark. Boreholes show that the sandy deposit is less than 20 m thick and is overlain by 5–10 m of glacial till (Pe-Piper et al., 2004).

Offshore southern Cape Breton Island, in the Orpheus Graben, geophysical imaging and exploratory petroleum wells show a very similar succession to that in the Chaswood basins of central Nova Scotia, overlain by 0.7 km of Late Cretaceous and Early Cenozoic shales and chalks (Figure 15B; Pe-Piper and Piper, 2004), suggesting little active erosion of the continent. The “cooking” of lignite in Chaswood Formation basins of central Nova Scotia suggests that they were also buried beneath 0.5–1.0 km of younger sediment (Hacquebard, 1984; Pe-Piper and Piper, 2012) and we can suppose that similar sedimentation took place in the Geopark. A similar blanket of sediment is inferred to have overlain the landscape of Nova Scotia but has been removed by erosion during the past 40 million years. Comparable thicknesses of sediment were deposited over the same period in the offshore Scotian Basin. In the Geopark, the Triassic basalt flows and underlying sedimentary rocks were deformed by younger faulting, for example offsetting the North Mountain Basalt against the Jurassic McCoy Brook Formation north of the Old Wife Geosite (Donohoe and Wallace, 1985; Withjack et al., 2010). Detailed studies of the structure of such faults show that they formed at small offsets along E–W faults experiencing predominantly horizontal slip and reactivated older NE–SW faults that formed at the time of the basalt eruptions (Olsen and Et-Touhami, 2008). The basalt that forms Economy Mountain (crossed by Highway 2) is offset across the Gerrish Mountain fault by three kilometers to the east, outcropping north of Lower Economy (Figure 16).

One of the most stunning views in the Geopark is that from atop the viewing platform at the Partridge Island Geosite and trail, looking westward to

Blomidon, Cape Split and Cape d'Or, forming the basaltic northern rim of a large-scale syncline (or downward fold) beneath the Bay of Fundy. The basalt on the south side of the fold forms the North Mountain along the entire length of the Annapolis Valley (Figure 7). The underlying Triassic red mudstones and sandstones are also folded into this syncline. Geophysical imaging of the rocks beneath the Bay of Fundy shows in places at least two kilometers of interpreted Jurassic sediments overlying the North Mountain Basalt (Wade et al., 1996). At the margins of the syncline, where basalt outcrops today, this two kilometer thickness of interpreted Jurassic sedimentary rocks has been removed by erosion. Evidence from petroleum wells from the southwest part of the offshore Scotian Basin, seaward of the Bay of Fundy, indicate erosion started at the beginning of the Cretaceous. Distinctive Jurassic microfossils are abundant in the Early Cretaceous limestones in the Bonnet P-23 well (Weston et al., 2012). More generally, there is widespread evidence for uplift and erosion in the nearshore part of the Scotian Basin just above the base of the Cretaceous (Weston et al. 2012; Nagle et al., 2021), probably indicating a regional change in plate movements. The major syncline within the Bay of Fundy is mirrored on a small scale by the syncline north of the Gerrish Mountain Fault (Figure 16). Both synclines are the result of horizontal slip on the regional Minas Fault Zone. The westward motion of southern Nova Scotia relative to New Brunswick closed up the Fundy Basin, restoring some of the original Triassic extension which had been accompanied by eastward motion of southern Nova Scotia. As a result of fault movements in the Early Cretaceous that folded and uplifted the Fundy Basin, there is virtually no record of the geological history of the Geopark for nearly a hundred million years prior to the geologically-recent Ice Ages. We can only make educated guesses as to what happened over this long stretch of

geological time, principally from evidence in the offshore Scotian Basin. At about 100 Ma, the Sable River that had drained from Labrador to the Scotian Basin throughout the Early Cretaceous was diverted westward, flowing down the St Lawrence Valley (Blowick et al., 2021) and the Orpheus Graben record suggests little active erosion of the continent in the Late Cretaceous and Early Cenozoic. The presence of highland plateaus that become gradually lower towards the Atlantic Ocean (1.2 km in Gaspé, 0.8 km in northern New Brunswick, 0.36 km in the Cobequid Highlands, and 0.28 km in South Mountain, sloping to sea level on the Atlantic Coast of Nova Scotia; King, 1972; Grant, 1989) has been widely interpreted as a tilted coastal plain dating from this time, with deep weathering of bedrock areas. About 30 Ma, in the Middle Oligocene, there was renewed uplift in Nova Scotia and probably in southeastern Canada generally (Pe-Piper and Piper, 2004). Sandy river deltas, built out across the Scotian Shelf throughout the Miocene and Pliocene, imply uplift and erosion of the adjacent continent. This mostly 0.5–1.0 km blanket of younger sediments was stripped off the continent and bedrock was eroded from highland areas such as the Cobequid Highlands. The old coastal plain was uplifted to form the prominent flat-topped highland areas of Atlantic Canada, most clearly seen in the Cape Breton Highlands National Park, but also represented by the flat top of the Cobequid Highlands.

Then came the Glaciers

Only 25 thousand years ago (ka), all of Nova Scotia was covered by an ice sheet, in places up to a kilometer thick (Dyke et al., 2002; Lambeck et al., 2017), which extended all the way to the edge of the continental shelf (Figure 17). During this time of maximum ice advance in the last glaciation, water that had

evaporated globally from the oceans was trapped on land as snow and ice, so that sea level was some 110 m below its present level. During these glacial periods, sea water evaporates most rapidly in equatorial regions, and falls back to both the land and sea as rain, or snow at high latitudes. Thus, a greater proportion of the evaporated water becomes trapped on land as snow and ice.

In the Geopark, this glacial event is represented by the characteristically red-brown silty Eatonville Till. It is present as a relatively thin blanket (2-10 m thick) overlying most of the elevated areas throughout the Geopark. Morainal ridges, 2-8 km in length are found at the western boundary of the Geopark. East of Parrsboro, the Eatonville Till is characterized by numerous areas of southwest to southeast trending drumlins, striae and structural ridges. The Eatonville Till is also present as a stony till in lowland areas in the vicinity of Diligent River adjacent to outwash plain deposits and also over a large area west of Debert.

The initial retreat of the ice sheet in Nova Scotia, from its maximum position at 25,000 years ago in the last glaciation (Stea, 2004), is a story of rising sea level. 22,000 years ago, as glaciers retreated in various parts of the world, sea level began to gradually rise, (Figures 18, 19) causing the margins of the Nova Scotia ice sheet to float and break off as icebergs. By about 18,500 years ago (King, 1996)., ice flowing out through the Northeast Channel (Figure 17) retreated to the northern edge of Georges Bank. In the east, ice retreated well back up the Laurentian Channel and up the deep channel between western Cape Breton Island and the Magdalen Islands. This ice retreat led to a reorganization of ice flow directions, as it flowed downhill to the north into the newly opened seaways. Ice in southern mainland Nova Scotia was cut off from the main body to the north, resulting is an almost complete reversal of ice flow directions from southeastward to northwards across the central and eastern Cobequid Highlands

(Stea and Finck, 1988; Stea and Mott, 2005). Late stony tills in the Cobequid Highlands east of Parrsboro (Stea and Finck, 1984) have directional indicators showing northward flow (Stea and Finck, 1984). The age of this northward flow is not well constrained within the Geopark, but regionally has been dated between 21,000 and 18,000 years ago (Figure 19).

A continued phase of glacial retreat marked by high sea levels caused ice to retreat to the edge of the Cobequid Highlands. The weight of the thick ice had depressed the Earth's crust sufficiently that when the rising sea flushed out the glacial ice in the upper Bay of Fundy, even though globally sea level was more than 60 m below its present level, the present coastal areas were flooded by the advancing sea. The calving ice as the sea rapidly ingressed into the Bay of Fundy is marked by marine mollusk shells from Spencer's Island with estimated ages from 17,000 to 14,400 years ago (Stea and Wightman, 1987), as well as the oldest marine mollusks along the Fundy coasts of Maine and New Brunswick which date from about 16,000 years ago (Stea, 2004). Ages of ice-margin marine mollusks are difficult to determine precisely because of uncertainty as to the age of the carbon in the ambient water (Forman and Polyak 1997; Rayburn et al. 2006). This time interval corresponds to a period of rapid retreat of ice in marine areas of eastern Canada, known as Heinrich event 1 (Stanford et al., 2011). Marine events are also represented by the formation of raised beaches at the Squally Point Geosite, at 37 m above present sea level; and another raised beach at Advocate Harbour at 32 m above present sea level (Figure 18; Wightman, 1976; Stea et al., 1985).

Further east along the north shore of Minas Basin, meltwater flowed from the ice margin at the edge of the Cobequid Highlands carrying mostly sand and gravel eroded by the ice from the Cobequid Highlands and deposited a series of

deltas. The nearly flat tops of extensive deltas are clearly visible in the landscape around Diligent River and the town of Parrsboro. A smaller delta built out seaward at the Five Islands Lighthouse Park Geosite, where dipping foreset beds that are capped by flat-lying topset beds of the delta are exposed in the coastal cliff (Figure 20). Other deltas are found at Economy, Bass River and Portapique communities situated along the north shore of the Minas Basin. The elevation of the deltas above present sea level decreases eastward (Figure 20), interpreted as indicating that the deltas formed immediately following the establishment of marine conditions, as ice retreated eastward up the Minas Basin (Wightman, 1980; Stea et al., 1985).

As the ice margins retreated north into the Cobequid Highlands, large blocks of ice separated from the glacier and became trapped in glaciofluvial outwash sediments, subsequently forming kettle lakes. Two of the larger kettle lakes are Leake Lake on the Parrsboro delta and Little Dyke Lake, in Glenholme. Radiocarbon dating of organic matter near the base of a sediment core from the Leake Lake Geosite suggests that ice had melted and lake sediment was able to accumulate since 16,100 years ago (Stea and Wightman, 1987; Stea and Mott, 1998). At Little Dyke Lake sediment accumulation is estimated to have begun 15,000 years ago (Stea and Mott, 1998). These ages suggest that ice retreated progressively eastward up Minas Basin, with the edge of the ice sheet retreating to the southern edge of the Cobequid Highlands. Glaciofluvial deposits, present as kettle lakes and holes (a kettle lake without water), adjacent to kames and eskers, are common in river valleys throughout the Geopark.

The Parrsboro delta is one of the larger deltas that formed along the north shore of the Minas Basin. Shortly after ice had retreated up the Parrsboro Gap, formation of terraces commenced. Four terrace sets were formed by the braided

meltwater streams crisscrossing and eroding the surface of the delta as the land rebounded due to the absence of the weight of the glacier and the sea level falling. The two lower terraces have similar soil development, whereas the upper two levels have a thicker soil horizon (20 cm or more). This suggests there was a hiatus, or waning in the rate of rebound occurring, after the first two terrace levels were formed, which was then followed by another pulse of uplifting during the downcutting of the lower terraces. Unfortunately, the sands and gravels of the delta topsets do not normally contain datable material that could be used to track the timing of their construction. Their overall age is bracketed imprecisely between 17,000 and 14,000 from mollusk shells in the bottomset muds of the Spencer's Island delta and by dates from the bottom of kettle lakes (Figure 18).

During the latter part of terrace development on the deltas, there was a small ice readvance that extended south into the Cobequid Highlands, confined within the Parrsboro Gap, and deposited a cross-valley moraine that dammed the valley, forming Gilbert Lake. The moraine cut off the flow of meltwater to the Minas Basin and created a drainage divide (Figure 21 inset) with Gilbert Lake draining north into the Hebert River. A distinct stony till in the northern part of the Chignecto Peninsula, referred to as the Shulie Lake Till, is believed to have formed during this brief cooling event. This readvance is younger than Leake Lake (16.1 ka) and older than the deepest lake sediment in Gilbert Lake (13.4 ka) and may compare with a readvance in southern New Brunswick imprecisely dated at about 15 to 16 ka (Nicks, 1988; Stea and Mott, 1998). Shulie Lake till (locally mapped as Cobequid Till) can also be found in an extensive area in the Cobequid Highlands north of Five Islands and Portapique.

It is during the cold Younger Dryas period that there is the first evidence for humans populating Nova Scotia, believed to be ancestors to the Mi'kmaq. The

famous fire pits at the Debert archeological site are located in a sandy deposit from small rivers draining a residual ice cap in the Cobequid Highlands (Stea et al., 1985). These sands locally overlie lake deposits that in turn rest on an old soil horizon inferred to be from the 14–13 thousand year old Allerød warm period (Rosenmeier et al., 2012). Radiocarbon dates are from charcoal, probably spruce, from fire pits apparently used to heat and crack knappable stone for implements (Rosenmeier et al., 2012) and appear to range from the late part of the 14-13 thousand year old Allerød warm period and the beginning of the much colder Younger Dryas.

The World's Highest Tides

The evolution of the marine realm in the Geopark has been driven principally by changes in sea level. Globally, sea level rose some 50 m between the end of the Younger Dryas and the Middle Holocene at 6,500 years ago. However, to fully understand the history of sea level, it is useful to go back to the time when the Geopark was completely covered by ice, 20 thousand years ago (Figure 19). The weight of the ice depressed the Earth's surface by at least 150 m, so that as the rising sea flooded in, it eroded a wave-cut coastal platform. As the ice retreated the Earth's surface rebounded, with 75 m of uplift taking place in the first five thousand years (https://oceanservice.noaa.gov/facts/glacial-adjustment.html). Sea level rise, until recently, has been largely due to subsidence of the forebulge at the margin of the Ice Age ice sheets and to a lesser extent the loading effects of rising ocean levels.

Behind the village of Advocate is a gravelly raised beach deposit, at 32 meters above present sea level, which was excavated for gravel and

subsequently used as a dump. The vertical distance between the beach crest and the low tide limit recognized from sedimentary structures is 3.4 meters. The beach would have been exposed to storm waves and storm surge, so the beach crest was probably above the normal spring high tide level. The mean tidal range estimated from the beach is 2–2.5 meters, much less than the range of more than four meters today at Advocate.

Georges Bank, an outer shelf bank at the entrance to the Bay of Fundy, was connected to Cape Cod and Long Island during the Younger Dryas (Shaw et al., 2002) and was home to large mammals including walruses, mastodons, and giant sloths, the bones of which are sometimes recovered in fishing trawls (Whitmore et al., 1967). The bank was progressively flooded by the rising sea, and completely flooded at about 7,000 years ago, allowing the Atlantic Ocean tides to enter the Gulf of Maine and Bay of Fundy. From that time on, sea level has continued to rise (Figure 18; Vacchi et al., 2018). At the same time, observations on markers for both high and low tide levels in marshes, and computer modelling of the interaction between tides and the deepening water of the Bay of Fundy system, show that tidal range has been steadily rising (Figure 22). The Bay of Fundy has the largest recorded tides on Earth, 16.3 m at Burntcoat Head opposite Economy Point (O'Reilly et al., 2005; Gordon et al., 2014). The tides are actually waves, the largest water waves on our planet (https://ocean.si.edu/planetocean/tidescurrents/currents-waves-and-tides). The passage of these waves causes the sea to rise and fall along the shore all around the world. The tide is produced by the gravitational pull of the Moon, and to a lesser extent the Sun. The Moon's gravity has the stronger pull on the side of Earth that is closest to it, so the ocean bulges on that side. On the opposite side of the Earth, the gravitational pull of the Moon is least, and centrifugal force due

to the Moon and Earth orbiting around one another pulls the ocean out. As the Earth rotates, the bulges in water level (high tides) stay in line with the Moon while the surface of the Earth moves underneath it. During one day, when there is a complete rotation of the Earth, any particular place will pass through both bulges (or high tides), and the intervening low tide conditions. The Earth rotates in 24 hours but needs an extra 50 minutes to catch up with the orbiting Moon. Thus high and low tide are approximately an hour later each day. The blocking effects of land influence the details of the tide in the open ocean. The open ocean tide has a range of about one meter, but frictional interaction of the wave that is the tide with the bottom leads to an increase in height of the wave on shallow continental shelves. In the same way, open ocean swell waves increase in height as they approach a beach, as surfers well know. In the Bay of Fundy, the tide behaves as a symmetrical standing wave, but in the shallow waters of Cobequid Bay it transforms to an asymmetric progressive wave, which breaks as a tidal bore in the Salmon and Shubenacadie river estuaries (Amos and Long, 1980).

The height of the tide depends on the relative position of the Moon and Sun. When the Moon and Sun are on opposite sides of the Earth, at the time of the full Moon, or when they are aligned on the same side of the Earth, at the time of the new Moon, then their gravitation effects combine to produce a spring tide, which is higher than normal. When the gravitational pull of the Sun corresponds to the position of the low tide created by the Moon, then a neap tide is produced, which is lower than usual. The smallest neap tide is roughly 7.4 days after the largest spring tide. Note that spring tides have nothing to do with the spring season. There are longer period variations in tidal height due to the elliptical orbit of the Moon, which brings it closer (perigee) to the Earth with a stronger gravitational pull, resulting in a larger perigean tide every 27.6 days. In the Bay of

Fundy, the perigee/apogee tidal height variation exceeds the spring/neap variation. Changes in the orbit of the Moon relative to the Earth's equator take place on an 18.6 year cycle and this lunar nodal cycle produces particularly high tides when the Moon's orbit is farthest from the equator and the Moon is highest in the sky. In addition, the Earth has an elliptical orbit around the Sun and there are longer period fluctuations in orbital patterns. When the Earth is closest to the Sun, the tides are enhanced. Each of these various factors can be thought of as having its own periodicity, its own beat. Sometimes the various factors are additive, combining to produce a particularly high tide. At other times, different beats work against each other and the tidal range is small.

So why are the tides of the Bay of Fundy so high? It is because the natural resonance period of the Gulf of Maine–Bay of Fundy system is about 13 hours, similar to the period of the main component of the tide in the open Atlantic Ocean. Children sitting in a bathtub soon learn that rocking back and forth creates a large wave in the tub, which is even more exciting when it sloshes on the floor. That wave has a natural period dependent on the length of the tub and the depth of the water. In the Bay of Fundy, the wave known as the tide is pushed every 12.42 hours by the oceanic tide at the edge of Georges Bank. As the wave moves up the Bay of Fundy, friction causes it to become slower moving and higher. Approximately 110 billion tonnes of water flow in and out of the Bay of Fundy twice daily (once per tidal cycle)! This volume is considerably greater than the cumulative total daily discharge of all the freshwater rivers in the world (Dai and Trenberth, 2002). The main Bay of Fundy is connected to Minas Basin by Minas Channel (15 km wide) and Minas Passage, which is only 4.5 km wide between the Parrsboro shore and Cape Split (Figure 22). The rising water creates strong flood tide currents in these constricted waters. In Minas Passage alone,

the average current speeds are 12 km/h with the transport of approximately million cubic meters of water per second, almost as much as the combined discharge of all the rivers of the world (Dai and Trenberth, 2002). Maximum measured speed in Minas Passage is 18 km/h (Mulligan et al., 2019), capable of suspending gravel in the water column (de Leeuw et al., 2020). The highest tidal range is between Economy Point and Burntcoat Head (Figure 23), with the range decreasing again in the shallow Cobequid Bay.

Classical barrier beaches are developed between headlands on the more exposed coastlines of the western part of the Geopark, at Spicer Cove, Eatonville, Advocate Harbour, Spencer's Island and Greville Bay (Figure 23). Barrier beaches accumulate sand and gravel derived either from offshore or from adjacent headlands, and if sediment supply is plentiful will build higher and wider. They commonly trap behind them low brackish marshes or ponds that may be connected to the sea by a tidal channel through the beach. The net direction of alongshore drift of beach sediment is quite clear in Greville Bay, where the mouths of the Greville and Fox rivers have been diverted eastward behind the barrier beach. In cases such as Advocate Harbour, parts of the coastline have been further protected by building dykes. As sea level and/or tidal range rise, barrier beaches tend to migrate landwards. This may take place gradually, as sand and gravel are washed over the beach crest by storm waves; or catastrophically, where a storm largely destroys a barrier beach and sand and gravel are washed inland, where a new beach develops. Such processes have been well documented on the Atlantic Coast of Nova Scotia but are only inferred within the western Geopark.

Within the Minas Basin, however, there is evidence of the catastrophic destruction of a barrier beach as sea level rose thousands of years ago (Shaw et

al., 2010). An important series of samples at Evangeline Beach (on the south side of Minas Basin, opposite Two Islands) includes a bed of large American Oysters (Bleakney and Davis, 1983), indicating subtidal conditions at 1.5 m above lowest low water (LLW), that were dated 3615–3750 ^{14}C years BP (calibrated age 3251–3855 BP). The oysters were in growth position and were killed by rapid burial in silt. Oysters, as filter feeders, do not thrive in the muddy waters of Minas Basin today. Furthermore, in the intertidal zone off Evangeline Beach, a drowned forest of white pine, birch and hemlock trees ~1.8 m above present LLW level range in age from 3675 to 4455 ^{14}C years BP. Intertidal ribbed mussels at a similar elevation to the oysters were dated at 3310 and 3800 ^{14}C years BP. The trees were supratidal, the ribbed mussels intertidal and the Oysters were subtidal; all are of much the same age, yet they indicate a tidal range of < 0.7 m. The best estimate of the calibrated age of the siltation event that killed the oysters is 3400 BP. After that time, dates from salt marshes (which represent the upper 25% of the tidal range) show a gradual increase in the elevation of high tides in Minas Basin, whereas in the last thousand years dates from Great Piddock Clams that live at extreme low water show little change in low tidal level (Figure 45). We can thus infer that tidal range has increased from 1–2 meters at 3400 BP to the present values of more than 10 meters (Figure 22). It appears as though the Minas Basin before 3400 BP was a clean, brackish lake, similar to the Bras d'Or Lakes today. Looking at the magnificent sweep of gravelly barrier beaches at Advocate Harbour, Greville Bay and Scots Bay (Figure 46), it is not difficult to imagine a barrier beach across Minas Passage, before the Passage was scoured to its present depths by increased tidal range. Such a barrier beach could have migrated eastward as sea level rose during the Early Holocene (Figure 18), fed by coastal erosion of the deglacial gravel terraces, as is still taking place today in

Greville Bay. Exactly where the barrier beach was located is not known: presumably at a narrow pinch point, such as between Partridge Island and Blomidon or between Cape Sharp and Cape Split. Barrier beaches of comparable size are known in other areas of plentiful deglacial gravel, for example the 12 km long, 50 m thick Flat Island spit south of Stephenville in western Newfoundland. The presence of a small tidal range and brackish water fauna at Evangeline Beach shows that the proposed barrier beach was breached by a small tidal channel allowing some exchange with the Bay of Fundy (Shaw et al., 2010).

Such barrier beaches migrate landward as sea level rises. Large storms may break through a barrier beach and redistribute the gravel to build a new beach farther inland. Breaching of the barrier beach in Minas Passage would have allowed the tides of the upper Bay of Fundy to course through Minas Passage and flood Minas Basin twice a day. The tidal currents in Minas Channel and Passage would erode proglacial muds, similar to those at Spencer's Island, from the sea floor. The estimated volume of mud removed from the scours that are up to 170 m deep, together with known rates of cliff erosion in Minas Basin, are equivalent to the estimated volume of tidal flat deposits accumulated in the past 3400 years (Wilson et al., 2017). Seismic reflection profiles show that the Holocene of Cobequid Bay is clearly divided into two units. The upper unit, younger than 3400 BP, has 10–15 m thick sand bars with inclined stratification, overlying a lower unit that is more acoustically transparent and has reflector geometry suggesting a wave-dominated estuary (Dalrymple and Zaitlin, 1994).

The breaching of the Minas Passage barrier beach would have been a major environmental disaster. The fertile shores of the Minas Lake were replaced by the murky, red seawater we see today. The event is recorded in Mi'kmaw oral history. In this story, Kluskap's troublesome adversary, Giant Beaver, built a dam

from Cape Blomidon to Advocate Harbour (https://www.mikmaweydebert.ca/ancestors-live-here/advocate-harbour/). This caused problems for many of the animals, who turned to Kluskap to help. Kluskap enlisted the support of Whale to break up the dam by smashing his tail.

So how has the Minas Basin evolved since this environmental disaster 3400 years ago? An increased tidal range has resulted in seawater flooding previously forested coastline, such as at Highland Village (Grant, 1985). Higher sea levels exacerbated coastal erosion, especially in gravelly outwash and soft Triassic bedrock. Slack water around high tide allowed mud to settle out on tidal flats, and growth of marsh vegetation stabilized the upper tidal flats, producing fringing marshes in Cobequid Bay and estuaries, sequestering carbon in the organic-rich sediments. In deeper intertidal zones, strong tidal currents sculpted sand bars and dunes, visible at low tide from the Little Dyke viewpoint. Sea level rise continues as a result of three processes: regional subsidence or uplift resulting from glacioisostatic effects (minor), increase in tidal range (~0.3 mm per year) and global sea level rise due to melting of glacier ice and thermal expansion of the ocean (currently 3–4 mm per year; https://royalsociety.org/topicspolicy/projects/climatechange-evidence-causes/question-14/).

Field trip Stops

DAY 1

1.1: Fundy Discovery Site – Introduction to tides and the tidal bore

Traveling north on Highway 102, take exit 14 in Truro and cross under the highway overpass on Highway 236. Turn right approximately 200 m from the highway overpass to access the Fundy Discovery site in Lower Truro. The Fundy Discovery site is located on the flood plain of the Salmon River at the head of the Minas Basin. From the parking lot at the Fundy Discovery Site, walk along the Cobequid Trail built on top of the dykes that bound Salmon River.

The Earth's tides are great waves formed by the gravitational pull of our Moon and (to a lesser degree) Sun. The pendulum-like resonance of the tidal periodicity in the uniquely shaped Bay of Fundy creates the phenomenon of the World's highest tides. But, here at the head of the bay along various tidal rivers, there is another phenomenon that is unique to areas of the world with high tidal range, a tidal bore. A tidal bore is a tumbling wavefront that moves upstream against the seaward flow of a river as the rising tidal water flows into the river channel and overwhelms the normal flow. Many of the rivers around the Bay of Fundy display observable tidal bores, with some of the most notable standing waves observed near the head of the bay in the Shubenacadie River.

Geopark Storylines

- The tidal bore is a phenomenon that perplexes many people because the normal flow of the river appears to reverse directions and to top it off there are waves that travel upstream against the current.
- At slack water at high tide, mud settles out on high tidal flats where it is stabilized by vegetation. In a natural system, this deposition of mud keeps track with rising sea level. Where marshes have been reclaimed by building dykes, this natural process is halted and as sea level rises the dykes are at risk of rupture.
- The big box store shopping district of Truro was built on undeveloped land on the Salmon River flood plain and is susceptible to both river flooding and storm surge. In the Bay of Fundy, 1-2 m of storm surge on top of a perigean high tide can cause disastrous coastal flooding, most famously in the 1869 Saxby Gale.

1.2: Upper Bay Estuaries – Development of salt marshes and estuaries at the interplay of fresh and salt water systems

On Highway 2 at Glenholme, about 500 m south of the junction with Highway 4, where the main road bends right at the church, drive south on Little Dyke Road. This road crosses the broad outwash plain of the Folly and Debert rivers, constructed by fluvioglacial outwash gravels at 15–14 ka. These gravels are visible in numerous active and abandoned pits over the next 2 km and consist of topset deposits of the Saints Rest Member deposited from braided rivers. At Glenholme and for the first few hundred metres down Little Dyke Road, the modern Folly River is visible, with a highly meandering course enclosed by dykes.

At the T-junction ~2 km down Little Dyke Road, turn left to go to the coast. At low tide, to the southwest there is a view of the Great Village sand bar, the largest of the sand bars in outer Cobequid Bay. These bars have been constructed by tidal currents in the past 3.4 ka, since the breaching of the barrier beach in Minas Passage, when Minas Basin changed from a tranquil brackish lake to a muddy tidal sea. The sand bars are typically 10 m thick and built by flood tidal flows channelled along the north and south margins of the Bay, spilling over the bars and with the main ebb current down the middle of the Bay (Figure 24). The currents produce large scale cross bedding where the main bar progrades into a swatchway. The sand bars are ornamented with smaller sand dunes – larger features known as sandwaves that average a meter high with a 40 m wavelength, and smaller meter-scale features termed 3D megaripples.

Looking eastward along the coastline, mixed mud-sand tidal flats begin to rim the shoreline of our viewpoint and, 2 km further, continuous salt marsh is developed near the high tide mark. To the west of our viewpoint, the shoreline is more erosional. The high tide level has risen several metres since 3.4 ka and continues to rise. As a result, the coastline to the west is retreating and narrow aggrading tidal flats overlie tree stumps dated at 1780 and 2080 ^{14}C years BP in Highland Village. The rising sea level also created estuaries along the main river valleys, which have aggraded and are filled with high salt marsh, flooded only at spring high tides or during storm surges. We will drive past fine examples at Portapique River, Little Bass River and Economy River. At the Bass River of Five Islands, dead spruce trees indicate recent salt intrusion as a result of rising sea level.

Then drive north on the western loop of Little Dyke Road, past Little Dyke Lake and Millen Farm and back to Highway 2. Little Dyke Lake is a kettle lake with

basal sediment dated at about 15 ka, recording the time that the ice sheet retreated from this area back to the Cobequid Highlands.

Geopark Storylines and Challenges

- How to deal with world-class marine features (e.g. the sand bars) that pose a safety threat to visitors?
- Opportunity to discuss resource extraction and reclamation – importance of gravel to even an ecological society.
- Little Dyke Lake is a key dated point in the deglaciation of the region and helps to illustrate the glacial retreat in the Geopark area didn't happen at a single time.
- Enclosure of dykelands; fertile Triassic lowlands.
- Evolution of Cobequid Bay estuaries: ports for mining products in the 19th century, but shipbuilding was more common farther west.

1.3: The Old Wife formation and the cliffs of Five Islands Provincial Park – Last Days of Pangea

This N–S cliff section provides good outcrops of the lower Jurassic McCoy Brook Formation and the top of the North Mountain Basalt (Figure 25). At the Old Wife sea stack, North Mountain Basalt is deformed across Early Cretaceous sinistral strike-slip faults. The view to the east of the Old Wife shows Triassic North Mountain Basalt overlying Blomidon Formation.

Access to the Old Wife and beyond is very dependant on the tide. The best strategy is to walk to the farthest point along the coast and to examine the geology on the return walk. The most critical pinch point is just south of the McCoy Brook–North Mountain contact.

Stop 1.3.1

The view to the east from the Old Wife shows the East Ferry Member of the North Mountain Basalt overlying thin Partridge Island Member of the Blomidon Formation, overlying thick White Water Member in the lower part of the cliff. In the distance is the headland of Red Head, formed of eolian cross-bedded sandstones, 33 m thick, of the Red Head Member. Eolian sandstones occur at several horizons within the Wolfville and lower Blomidon formations. Their style of cross bedding indicates an origin in barchan dunes, sculpted by NE trade winds and migrating southwestward down the Fundy Basin. Through the Triassic, the Fundy Basin migrated from 8°N to 25°N and so was within the desert climatic belt around the Tropic of Cancer.

Note the cooling columns within the basalt of the East Ferry Member (Kontak, 2008). Elsewhere, this unit is up to 150 m thick and grew in thickness by repeated injection of new magma and inflation of the flow. It can be recognized over the entire Fundy Basin and was probably sourced from the Point Lepreau dyke (Figure 7). Palynology of the overlying Scots Bay Member south of Cape Split shows that the North Mountain Basalt is of Late Triassic age. The base of the East Ferry Member at the top of the cliff is offset by SE-dipping normal faults with SE-directed slickenlines that do not appear to have been active during Blomidon Formation deposition. Such faulting is seen more accessibly at Wasson Bluff. It suggests that basalt extrusion was synchronous with a new phase of accelerated extension in the Fundy Basin.

The underlying thin Partridge Island Member consists of grey and black mudstones that weather a distinctive white colour. This unit is thermally metamorphosed here, but the equivalent rocks at Partridge Island (stop 3-1)

show palynological records that can be correlated to the better-known section in the Newark Basin where the “End-Triassic Extinction” (ETE in Figure 13) is marked by a horizon in which opportunistic ferns are dominant. The combination of precise U-Pb dating of zircons and Milankovitch cyclostratigraphy suggests that the ETE was immediately preceded by eruption of basalt in the Argana Basin of Morocco, whereas the East Ferry Member was 3,000 years younger and the first basalt in the Newark Basin was 15,000 years younger. Major basalt eruptions in the Newark Basin were followed by abrupt increases in atmospheric CO_2 (as proxied by isotopic composition of pedogenic carbonate concretions) that gradually declined to background levels (Figure 13). The ETE was the third largest mass extinction event in the last half billion years of Earth history, with the extinction of some 30% of marine genera (particularly corals and ammonites) and on land a major turnover in vertebrates, sporomorphs and megaflora. There is a growing consensus that the extinction was provoked by release of volcanogenic CO_2 and perhaps Hg on land, where there was a 3–4 °C rise in temperature, and resultant ocean acidification.

The main cliff section consists of red mudstones and lesser sandstones of the White Water Member. This section shows metre-scale cyclicity (Figure 9) of sandstones passing up into mudstones, with some gypsum and pseudomorphed halite crusts and sand “patches” in the mudstones. This section is synchronous with the kilometer-thick Argo Salt Formation in the Scotian Basin and is interpreted to represent ephemeral sheet floods and playa lakes. The sediment cyclicity records changes in climate from more arid to more humid on scales of tens of thousands of years.

The adjacent south-facing cliff viewed from the Old Wife is bounded by two major faults on its west and east sides. Between these two faults, the jointed

basalt is folded in a monocline. To the west there is a fine view of the Five Islands, which are fault bound blocks of basalt overlying Blomidon Formation to the south (Figure 16).

The major faults are part of an Early Cretaceous dextral strike-slip system driven by the hyperextension of the Newfoundland Basin, 1500 km to the east (Figure 14). This faulting principally reactivated E-W faults of the Minas Fault Zone, but in places such as the Old Wife transferred motion through the SE-dipping faults that were originally active at the time of the North Mountain Basalt (Figure 35). This faulting led to the inversion of the Fundy Basin and the creation and deformation of lower Cretaceous Chaswood Formation basins (Figure 15).

Stop 1.3.2.

The contact of the basalt with the overlying McCoy Brook Formation sedimentary rocks can be studied in the small cove north of the Old Wife tidal pinch point (Figure 26). This is a faulted stratigraphic contact, with horizontal slickenlines on faults that lack zeolites. There appears to be a gradational succession from vesicular basalt with zeolites upward into a polymict basalt breccia, a polymict cobble conglomerate and finally a red siltstone with basalt clasts, all highly disrupted by faulting. Similar transitions largely unaffected by Cretaceous faulting can be seen at Wasson Bluff.

Stop 1.3.3.

Immediately north of the cove is a large rotational landslide. This is one style of coastal retreat, which in the McCoy Brook Formation here is at an average rate of at least 0.5 m/yr.

Stop 1.3.4.

North of the landslide, subhorizontal channel sandstones outcrop at the base of the cliff. In this area, small scale toppling of undercut sandstone blocks represents another style of cliff erosion.

Stop 1.3.5.

Farther north, siltstones with thin bedded sandstones overlie the channel sandstones. Higher in the cliff, rather stony Eatonville till is overlain by well sorted fluvioglacial outwash gravels of the Five Islands Formation.

Geopark storylines

- The basalt flows at this Geosite are part of a very extensive area of volcanic activity associated with the initial breakup of Pangea, extending from western Europe to Brazil.
- The dark shales immediately beneath the basalt preserve a record of a major extinction of terrestrial plants. At the same time, there was also extinction of many terrestrial animals and some 30% of marine life. The extinction event eliminated competitors of the dinosaurs, giving them the ecological and evolutionary freedom to dominate the terrestrial world for the next 135 million years. These global changes were not just the result of loss of habitat due to the lava flows and volcanic ash. The lava eruptions put large amounts of CO_2 into the atmosphere, leading to a 3–4°C rise in temperature and related ocean acidification led to the extinction of much marine life. We face similar challenges today, except that the CO_2 comes from fossil fuels, not volcanic eruptions.

- Continents and the plates below them move around as a result of plate tectonics. The Geopark was at a latitude of about 25°N at this time, the latitude of the Sahara Desert today. The rocks that have accumulated reflect those desert conditions.
- We can see some of the ways in which cliffs retreat in the Geopark. Average cliff retreat exceeds 0.5 m/year and will be exacerbated by sea level rise due to global warming. This cliff erosion threatens transportation routes (Highway 2 in Economy; Two Island Road near Parrsboro) and rising sea level threatens communities such as Advocate Harbour.

1.4: Leake Lake – Kettle Lake formation and glacial history

A short walk along a gentle pathway behind the Sunshine Inn takes us to Leake Lake, a favourite swimming hole of the local community. Leake Lake is a kettle lake situated on the western boundary near the apex of the Parrsboro outwash fan delta, which marks the former ice margin at the southern edge of the Parrsboro Gap (Figure 21). Kettle lakes are usually formed by the melting out of large ice blocks that have separated from the glacier as it retreats. The bathymetry of Leake Lake shows steep symmetrical contours to a depth of over 12 meters, indicative of the kettle lake origin. The origin of the term 'kettle lake' is based on the fact that their morphology mimics the shape of a kettle that's been inverted! Another kettle lake of comparable size and also formed in the Parrsboro delta is MacAloneys Lake (formerly Pleasant Lake) located about one kilometer east of Leake Lake.

A basal age of Lake Leake is estimated at 13.3 ^{14}C ka (ca. 16 ka in calibrated years, Figure 19) based on gytta (a mud formed from partial decay of peat, commonly found at the bottom of eutrophic lakes).

Geopark Storylines

- Not just any lakes! Kettle lakes are much more interesting than just any old lake! In the Geopark, these glacially formed lakes shed light on the glacial history of the area, particularly, when the glaciers started to melt and retreat.

DAY 2

2.1: Kames north of Spence Road

About five kilometers north, along Highway 2, from the town of Parrsboro is our first stop along the roadside. At this stop is an excellent viewpoint of the "basket of eggs topography", presenting textbook examples of kames. These hills were formed from large holes in the glacier where meltwater and the sediments they carried accumulated and then formed mounds of stratified drift as the ice melted. To our south and at the top of the hill along Highway 2 is a choke point, marking a former ice wedge where the kames end and the outwash plain starts.

The well drained nature of glaciofluvial sediments and low nutrient level of the soil on this kame-dominated topography make for ideal conditions for the wild low-bush blueberries that this area of Nova Scotia is well known for. These wild, low-bush blueberries are Nova Scotia's Provincial berry, and are known best in Oxford, NS (the blueberry capital of Canada). Many farmers in the Geopark grow Blueberries that have helped Oxford achieve this prestigious title. These blueberries are harvested every other year. Thus, a common practice is for the growers to split their fields into two so that each year they harvest approximately the same amount. Notice one of the kames where you can see the divide between the two harvest seasons.

2.2: Recessional Moraine along Lakeland Road, on south shore of Gilbert Lake

Our next stop along Lakeland Road, just a few kilometers north of Stop 2.1, is the location of a cross-valley recessional moraine. The moraine is interpreted as an end-moraine of a readvance of an ice cap north of the Parrsboro Gap. An

AMS radiocarbon date of 11.3 ^{14}C ka (ca. 13 ka calibrated), obtained from an Alnus twig in basal organics, establishes a minimum age for the moraine. This suggests that glaciers persisted in this northern area predating the Younger Dryas event and therefore likely relates to the Older Dryas cooling event associated with the end stages of the last glaciation, associated with the Shulie Lake Till.

This readvance resulted in a drainage divide essentially cutting off the meltwater supply to the Parrsboro outwash fan delta to the south and the establishment of Gilbert Lake which now drains north into the Hebert River. As you walk along Lakeland Rd notice the differences on either side of the road. Looking to the north, the slope is steep and it is some distance down to the south shore of Gilbert Lake. In contrast, on the south side of the road, there is no steep slope but rather the rolling hills. These are a continuation of the basket of eggs topography we observed at the Stop 2.1.

2.3: Terraces along Prospect Road

Making our way south to the outwash fan delta on the outskirts of Parrsboro, is the location of our next stop. It is the largest of the deltas formed along the north shore of the Minas Basin, extending some six kilometers in width and length. At this stop you will notice two prominent terrace levels. These are the two higher level terraces (shown as T0 and T1 in Figure 21 inset). The two lower-level terraces are not visible at this location.

This delta formed in front of a glacier that sat in the Parrsboro valley to the north. Soon after the glacier retreated, the land rebounded causing glacier meltwater streams to cut into the delta forming the terrace levels. The two lower terraces have similar soil development; whereas the upper two levels have a

thicker soil horizon (20 centimeters or more). This suggests that there was a hiatus, or waning in the rate of rebound, occurring after the first two terrace levels were formed which was then followed by another pulse of uplifting during the downcutting of the lower terraces.

Geopark Storylines

- Connection of these glacial sediments to the bountiful growth of Wild Blueberries that define the area and provide blueberries for Oxford, NS, the blueberry capital of Canada.
- Links to the various landforms in the area that might seem "out of place" and connecting them to the way that ice moved, flowed, and bulldozed this area over thousands of years.

2.4: Coastal drive from Parrsboro to Advocate Harbour – Brief introduction to Cobequid Highland geology along the "Mini Cabot Trail"

Leaving Parrsboro, the road snakes along the trace of the Minas Fault Zone, at the base of steep cliffs that define the Cobequid Highlands along the Fundy Shore. So far in the field trip, delegates have enjoyed outcrops of Triassic and Jurassic strata, remnants of last days of Pangea and the End-Triassic Extinction marked by voluminous CAMP magmatism. We have also seen younger Quaternary deposits, deposited as glaciers ravaged the Appalachians and shaped the landscape we know today. But, as we drive through the village of Port Greville, we cross the Cobequid Fault and begin to ascend into what is affectionately called the "Mini Cabot Trail". The dramatic change in landscape results as we drive out in the resistant Late Devonian to Carboniferous rocks of the Horton Group that have been deformed by movement along the Cobequid Fault. This

striking landscape creates some of the most dramatic views of the Bay of Fundy and Spencer's Island as we travel through the communities of Brookville and Fraserville. However, as we drive into the community of Spencer's Island and on to Advocate Harbour, we cross back over the Cobequid Fault and return to the flat lying landscaped typical of the younger Triassic and Jurassic strata.

Geopark Storylines

- Sometimes a road trip is a great geology lesson. When you drive into different bedrock units, the landscape commonly changes! The hard rocks of the Cobequid Highlands are very resistant to weathering and erosion so they remain the high ground even after the incursion of such extensive glacial ice! The more exciting the drive, generally the harder the rocks are underfoot!

2.5: Cape Chignecto – Crossing the Cobequid Fault and exploring deformation in Horton Group sediments

On your left (to the east) are the outcrops known as Red Rocks. These are red sandstones, with a few pebbles, from the middle of the Triassic desert succession and an age of about 225 Ma. The trough cross bedding was created by sand dunes on the channel floor of a west-flowing ephemeral river channel. The pebbles are of vein quartz; heavy minerals elsewhere in Triassic sandstones suggest a predominant source from the Meguma terrane (Kettanah et al., 2014).

Walking westward along the beach, there is a hundred-meter gap in bedrock outcrop, presumably with a large fault which can be located on the foreshore along strike from the small brook.

For the next two kilometers along the beach, the shoreline crosses a belt of Horton Group rocks showing lithologies similar to those in the Kennetcook sub-basin. This belt extends eastward to Parrsboro and consists of folded, faulted and fractured rocks seen at the Wharton and Ward Falls Geosites. In the east, the belt lies between the Cobequid and Kirkhill faults, but in the west it is bounded to the north by the Rapid Brook facies of the Horton Group, comprising locally sourced alluvial fan conglomerate and sandstone. At the eastern end of the outcrops at West Advocate Beach, the Horton Group is highly deformed and difficult to interpret. It is worth the effort to walk a couple of hundred meters down the beach to see more informative outcrops.

At the small headland at 45.352267, -64.831800, massive sandstone is cut by abundant quartz veins, in turn cut by narrow veins rich in hematite. Walk past the large landslide in the cliff and about 100 m before McGahey Brook is a small headland at 45.354033, -64.841200. On the west side of this headland, quartz veins cut foliated silty shale (Figure 4A of Pe-Piper et al., 2018). The quartz veins contain some chlorite and rare monazite, dated at 339±4 Ma (equivalent to the middle Windsor Group). The field observations indicate deformation during the Early Carboniferous, prior to the onset of the Minas Fault Zone at 327 Ma, followed by veins of hematite, magnetite or siderite-ankerite.

The precise history of the Cobequid Fault at West Advocate awaits further investigation. The Kirkhill Fault (Figure 10b) was the master fault localizing the Cape Chignecto pluton, based on magma mixing textures and distribution of mylonite. It acted as the basin-bounding fault during deposition of the Horton Group, shedding coarse-grained alluvial fan sediments of the Rapid Brook facies. But by the time of Windsor Group deposition, deformation of the Horton Group had begun along the new Cobequid Fault, formed as the granite pluton cooled

and behaved in a rigid manner. Further deformation took place with the onset of the Minas Fault Zone, demonstrated by the deformation of lower Carboniferous rocks at the Brookville Rock Geosite (Waldron et al., 2005) and the widespread occurrence of hematite and ankerite-siderite veins in the Horton Group belt (Pe-Piper et al., 2018). In the Triassic, various Paleozoic faults were reactivated as basin-margin faults, notably the Portapique Fault. The Red Rocks provide no evidence for proximity to a basin-bounding fault. On the other hand, the continuation of structures offshore, imaged by seismic-reflection profiling, shows that Early Cretaceous dextral slip on the Cobequid Fault played an important role in the inversion of the Fundy Basin (Withjack et al., 2010; Blowick et al., 2020).

Geopark Storylines

- Looking at the textbook examples of brittle-ductile faulting and folding in the cliffs at West Advocate, this is a tremendous place to really dig into the scale of deformation with anyone visiting. It doesn't take a scientist to realize that those rocks are messed up! And, this is what happens underground when continents slide past one another, producing earthquakes.
- To go along with faulting and folding, West Advocate is an awesome spot to talk about variable competency and hardness in different rock types. The sandstones hold together and crack vs the shaley layers that bend and twist and almost seem to flow between the more rigid layers.

2.6: Cape d'Or – Mining for Millenia in the Continental Flood Basalts of the Central Atlantic Magmatic Province

Driving back to Parrsboro from Advocate Harbour on Highway 209, turn right onto Back St which is 1.5 km past the Advocate Rite Stop/Irving Gas Station. Follow Back St for 1.2 km before turning right onto the Cape d'Or Rd. Follow the Cape d'Or Rd for approximately 5.4 km until you reach a parking lot on the right hand side of the gated roadway down to the Lighthouse.

Walk to the lighthouse and turn right. Visitors are treated to breathtaking views of some of the most dramatic cliffs in the Geopark, as well as extreme tidal currents, colloquially known as the "Dory Rips". The cliffs at Cape d'Or are made up of the basal flows of the North Mountain Basalt, termed the East Ferry Member by Kontak (2008). The East Ferry Member is typically massive basalt that variably displays columnar jointing (Kontak, 2008). Like other exposures of columnar jointing in the East Ferry Member throughout the Geopark, columnar joint patterns are contorted by multiple basaltic magma injections during cooling.

Southwest of the Cape d'Or lighthouse, visitors can walk out along the surface of these basalt flows. Here several zeolite minerals have been recognized in vesicular basalts and in faults and joints (Pe-Piper and Miller, 2002). Recognized zeolite minerals include abundant analcime and natrolite, common mesolite and stilbite, and rare thomsonite, chabazite, laumonite, and heulandite (Pe-Piper and Miller, 2002).

The most significant aspect of Cape D'Or's geoheritage, however, may be the mining of copper by the Mi'kmaq pre-contact with European settlers (Hanley et al., 2022). Cape D'Or copper was traded widely across eastern North America centuries before its "discovery" by Samuel de Champlain and mining at the close of the Nineteenth and beginning of the Twentieth Centuries.

Adits of Nineteenth and early Twentieth Century Copper Mines

Open copper mine adits are visible at Horseshoe Cove, adjacent Cape d'Or to the east. A mining community, now long gone, thrived here until the 1920s.

The Dory Rips at Cape d'Or

The "Dory Rips" offshore from Cape d'Or develop about an hour before high tide. They consist of breaking standing waves and have been described as due to the "collision" of two currents. Normally such standing waves develop in thin, high velocity flows, such as a sheet flow during heavy rain in a sloping paved parking lot. The water depth here is at least 40 m, so the waves are not the result of a current interacting with the seafloor. We suggest that they result from a thin W-flowing coastal eddy in Greville Bay that flows over the denser (slightly colder and probably more saline) east-flowing flood tide current, as illustrated in Figure 16A of Shaw et al. (2012). It is a challenge of seamanship to collect data on water salinity and temperature that would shed more light on this process.

Geopark Storylines

- This was an area that has been mined for native copper and knappable material tracing back before settlers or even European explorers ever crossed the Atlantic. Recent research by the Nova Scotia Museum and geoscientists at Saint Mary's University (Hanley et al., 2022) have established by the unique geochemical signature of Cape d'Or copper that it was extracted by the Mi'kmaq and traded widely across eastern North America, underscoring the international significance of the Geopark and the link between geology and cultural history.

- This is a great locale to discuss the power of the tides and the immense volume of water moving through the Minas Passage as well as the threat that rising sea level poses to many coastal communities living at or below high water level.
- This is also a tremendous location to give people a visual representation of the volume of basalt extruded. Cape d'Or showcases 100 m of basalt but, in many places beneath the Bay of Fundy the thickness of North Mountain Basalt is estimated at 400 m+ and locally as much as 1000 m+ southeast of Grand Manan Island (Wade et al., 1996).
- As at Little Dyke, this site raises the question of how to deal with potential submarine Geosites. The paired sand and gravel banks on either side of Cape d'Or and the Late Holocene scouring of Minas Channel are both world-class features that can be illustrated by multibeam bathymetry maps (Figure 27) but not directly seen by visitors. They are an integral component of Pillar 1, the tides.

DAY 3

Stops 3.1-3.3 will all be accessed from the Partridge Island Road or the Ottawa House Museum (approximately four kilometers south of the town of Parrsboro on the Whitehall Road)

3.1: East Bay

A short walk northwest along the beach from the end of the Partridge Island Road, visitors are greeted by the West Bay formation in the Mabou Group. The East Bay section is located on the eastern shore of West Bay, and the formation, as yet informal, has long been called the West Bay formation.

The strata of the West Bay formation exposed at East Bay, standing near vertically, offer exceptional exposures of sedimentary structures and fossils, in particular ichnofossils. The section has long been explored by paleontologists, and in particular for fossils of tetrapod footprints. The section was visited regularly by local collector and expert Eldon George and his mentor and colleague Donald Baird of Princeton University. East Bay was included in the 1970 field trip of the International Geological Congress (Carroll et al., 1972). In the latter Twentieth and early 21st C, the site was monitored regularly by Ken Adams, Curator of the Fundy Geological Museum, at the time.

The East Bay section is the proposed type section for the West Bay formation of Late Viséan-Early Namurian (Serpukhovian) age on the basis of palynology (fossil spores), estimated to be 330–327 Ma (Waldron et al., 2017; Dolby, reported in Calder et al., 2019). The formation also crops out to the east at Crane Point, at McLaughlin Bluff, and within the complex Clarke Head mélange

(Calder et al., 2019). The West Bay formation is assigned to the Mabou Group, a largely terrestrial transition from the older and largely marine Windsor Group of Mississippian (Viséan) age. The westernmost strata at East Bay are folded at their contact with the overlying polymictic cobble conglomerates of the McLaughlin Bluff member of the Parrsboro formation (Calder et al., 2019). The contact is poorly exposed but represents a possible angular unconformity (JWF Waldron, pers comm) or fault contact between the West Bay formation and younger Parrsboro formation.

The strata at East Bay include poorly sorted conglomeratic sandstone characterized by quartz granules, interpreted as having been deposited as ephemeral sheetwash by poorly constrained streams, presumably from neighbouring uplands. Putative halite casts may be observed on occasion.

The predominant lithology is thinly bedded red and ochre coloured mudstone and grey sandstone beds, the latter characterized by ripple marks in trains, and by dessication ('mud') cracks. These beds are interpreted as having been deposited at shallow playa lake margins. The rippled sandstone beds commonly exhibit fossil footprints of tetrapods that traversed the sand and mud flats. The commonly deep impression of footprints suggests that the tetrapods walked the flats soon after or prior to subaerial exposure, perhaps drawn by availability of water and food sources.

Beds of black, organic-rich shales and siltstone are rich in the small bivalve *Carbonicola* sp. In contrast to the rippled beds with tetrapod ichnofossils, these beds represent deeper water lacustrine conditions, possibly initiated by sudden tectonic movement or by cyclical more humid conditions. Recently discovered fossil fish are currently being studied by Dr. Hillary Maddin, Carleton University.

In summary, the East Bay strata represent a basin margin playa lake environment in a paleotropical to paleoequatorial latitude of the assembling continental landmass of Pangea.

Geopark Storylines Summary

Sir Charles Lyell, considered by many to be the founder of modern geology, spoke of working on the celebrated rocks of the Joggins, now a UNESCO World Heritage Site, as “reading a chapter of the Big Volume”. East Bay may represent a short chapter of Earth history’s “Big Volume”, but they stand exposed much like pages of a book, open for you to read. The story that they tell transports us to tropical Pangea 330 million years ago, to the edge of a playa lake, fed by brief torrential rains and possibly by springs along the Minas fault system. This lake must have been much like an oasis at this time of heat and arid climate, attracting large amphibians to feed (and breed), the first reptiles having yet to make their appearance.

A famous tenet or saying of Lyell was that “the present is the key to the past”, meaning that you can interpret much of Earth’s history by observing conditions, environments and events in our world today. Lyell would have been thrilled then by the sedimentary rocks of East Bay, with their vast ripple-marked surfaces with footprints, looking for all the world like modern day sand flats.

3.2: Partridge Island (West Side)

Partridge Island is a resistant basalt island connected to the mainland by a double tombolo – two barrier beaches that enclose a marshy lagoon. The detailed history of these beaches and lagoon have, to the best of our knowledge, never been investigated by boreholes. We can therefore only speculate on the

origin of this large gravel deposit. Several lines of evidence point to the possibility of an Early to Middle Holocene barrier beach in Minas Passage, impounding a fertile brackish lake in the present Minas Basin, similar to the Bras d'Or Lakes in Cape Breton Island. This barrier beach was breached at about 3.4 ka, leading to Minas Basin becoming part of the Bay of Fundy tidal system (Shaw et al., 2010). Re-organization of the breached gravel beach presumably nourished the Partridge Island tombolo and allowed it to aggrade as high tide level rose 6-8 m in the Late Holocene. Oral histories record that Partridge Island was only connected to land by the gravelly bars after the historic Saxby Gale of 1869 however, another possibility, based on historic maps prior to the Saxby Gale, depicts pre-existing tombolos (T. Fedak and K. Adams, pers. comm.).

Park along the gravel spit connecting Partridge Island with the mainland and proceed to the west face of the island. Throughout the warmer parts of the year, when walking southwest along the beach, notice the towering wooden poles and nets rising from the beach. Weir fishing is an ancient style of fishing in the Bay of Fundy, which has been practiced by the Mi'kmaq for thousands of years (Bernard et al., 2015). The unique shape of the fishing weir uses the inward flow of the rising tide to direct fish into the trap and keep them there until low tide when fishermen can harvest the catch. The height of the poles and netting, ensures that fish will not simply swim over the net as these traditional traps are completely submerged at high tide. Historic paintings illustrate that a weir has long existed at this site.

On the west side of the island, heading toward the fishing weir, is an excellent outcrop of the uppermost unit of the Blomidon Formation and the overlying North Mountain Basalt (Fowell and Traverse, 1995). Here, unlike at the Old Wife Geosite, the contact between the Blomidon Formation and North

Mountain Basalt is easily accessible and extensive study has revealed that the End-Triassic Extinction (ETE), marking one of the great mass extinctions in Earth History (Whiteside et al., 2007; Cirilli et al., 2009; Davies et al., 2017) is located just below the basal flows of the North Mountain Basalt, in a 1.5 m thick section of cyclical red, gray, and black clastic rocks, named the Partridge Island Member of the Blomidon Formation (Fowell and Traverse, 1995; Olsen et al., 2002a, 2003, 2005;). Does this mean that the North Mountain Basalt had nothing to do with the ETE? More discussion will follow on the outcrop.

Geopark Storylines

- This locale is a fantastic site to follow up on the storytelling from Five Islands Provincial Park. This opens up the discussion that sometimes the most breathtaking views are not the best places to conduct research because the steepest cliffs are not always accessible for sampling and field work. Recognizing correlative units in various places help geologists fill in the blanks on maps and recognize the original extent and relationships of rock units.

3.3: Partridge Island (East Side)– Two-Eyed Seeing in the Cliffs of Fundy Geopark

The land within the Geopark is Mi'kma'ki, home of the legendary figure Kluskap, whose incredible feats shaped the iconic seascapes of the Cliffs of Fundy. Several legends are set along the Parrsboro shore that overlooks Partridge Island. These rich legends, that steep the land with a deep cultural heritage, are recorded in the oral traditions of the Mi'kmaw people. These oral traditions span generations and millennia, transcending simple storytelling, and encoding ecological and traditional knowledge.

Partridge Island is one of the most spectacular viewscapes within the Cliffs of Fundy Geopark. Looking from the Ottawa House Museum, visitors can have a panoramic view across the Minas Channel to Cape Blomidon, which bounds the Annapolis Valley. This place is sacred in oral histories of the Mi'kmaw people and many stories reference Partridge Island. This place is rich in natural materials such as flint and other knappable stones precipitated from siliceous fluids in vugs and fractures of the North Mountain Basalt (Pe-Piper, 2000), utilized for making tools by the Mi'kmaq (Mi'kmawey Debert, 2014). Other natural materials such as sections of columnar basalt and hematite were also collected for ceremonial use (Mi'kmawey Debert, 2014). These minerals can be found along the east-facing beach connecting Partridge Island to the shore as well as along the base of the basalt cliffs that define the island. The plentiful natural resources that the Mi'kmaq collected from the island earned it the name Wa'so'q, meaning "heaven" in the Mi'kmaw language (https://www.mikmaweydebert.ca/ancestors-live-here/partridge-island/wasoq/).

The east-facing beach connecting Wa'so'q to the mainland is home to another natural wonder. If viewed approximately two hours before high tide, the water along the shore bubbles vigorously. The Mi'kmaq call this phenomenon "Grandmother's Cooking Pot" as it is said that Kluskap's grandmother made her camp here at Partridge Island (Mi'kmawey Debert, 2014). Science explains this phenomenon as the action of the giant tides of the Bay of Fundy pressing trapped air out of pore space in the underlying beach and interpreted vesicular basalt (https://www.mikmaweydebert.ca/ancestors-live-here/partridge-island/kkijinu-wtuoml-grandmothers-cooking-pot/).

Geopark Storylines

- Partridge Island is a terrific site to expand on the topic of Two-Eyed Seeing and the opportunity for collaborative storytelling within a Geopark.

3.4 Five Islands Lighthouse Park (Time Dependent)

Driving from Parrsboro to Truro on Highway 2. Turn right on Broderick Ln in Lower Five Islands (approximately 21 km east of Parrsboro). Drive down Broderick Ln 600 m and park on the parking lot on the right-hand side of the road marked with Municipal Park signage.

Before you is one of the most iconic viewscapes in the Geopark. The Five Islands: Moose, Diamond, Long, Egg, and Pinnacle (labelled from left to right as you view them from the park, or East to West) have long been associated with Two-Eyed Seeing in the Cliffs of Fundy Geopark. The reputation of the Five Islands is preceded only by the legend of their formation! Mi'kmaw oral histories tell the story of Kluskap who, in an attempt to drive away Beaver, hurled 5 sods of earth into the bay, and these became the 5 islands you see before you (https://www.mikmaweydebert.ca/ancestors-live-here/five-islands/).

Another interpretation of the breathtaking scene before you, told by geologists, sees the Five Islands as a single basalt ridge that have been offset by splays along the Gerrish Mountain Fault (Figure 16).

The grassy lawn of the Lighthouse Park also records the glacial history of outwash deltas being deposited as glaciers retreated from the Cobequid Highlands. Walking from the lighthouse to the beach, proceed west and observe the dipping sedimentary beds exposed in the cliff. These are the foreset beds of a prograding delta that is capped by flat-lying topset bed at the cliff top (Figure 20).

Figures

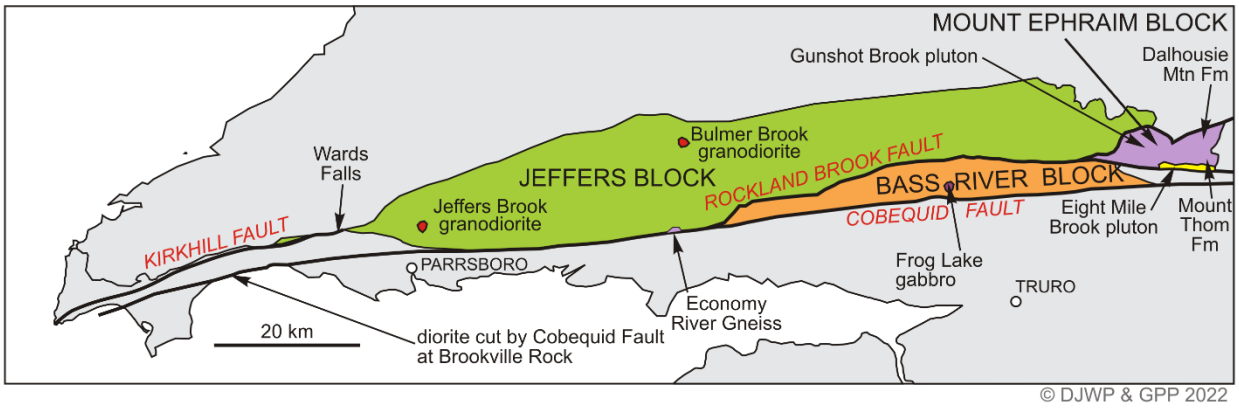

Figure 1: Blocks and place names of the Neoproterozoic basement of the Cobequid Highlands. Modified from White et al. (2022).

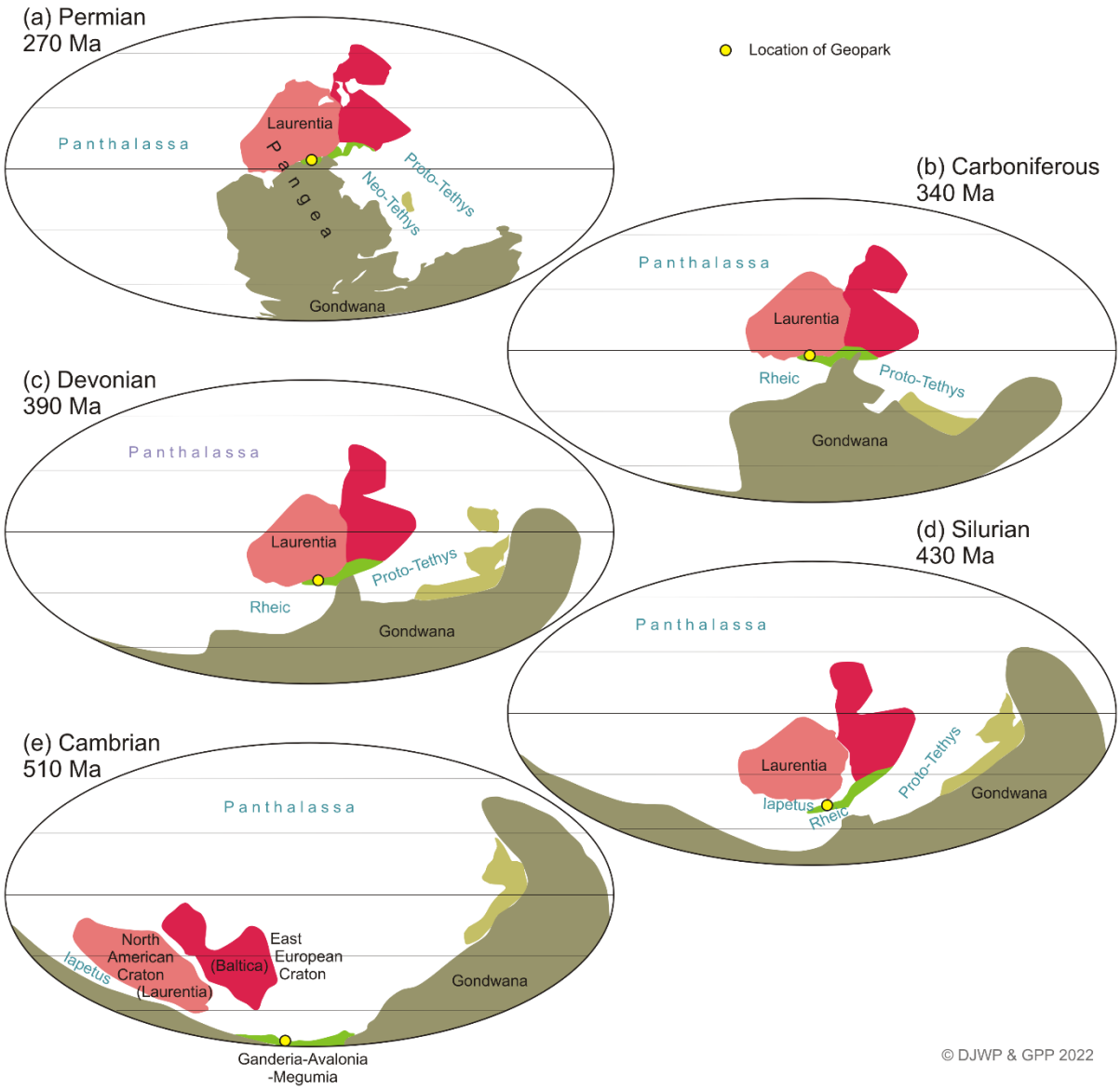

Figure 2: Series of plate tectonic reconstructions showing the movement of the Geopark during the assembly of Pangea (Kroner et al., 2021).

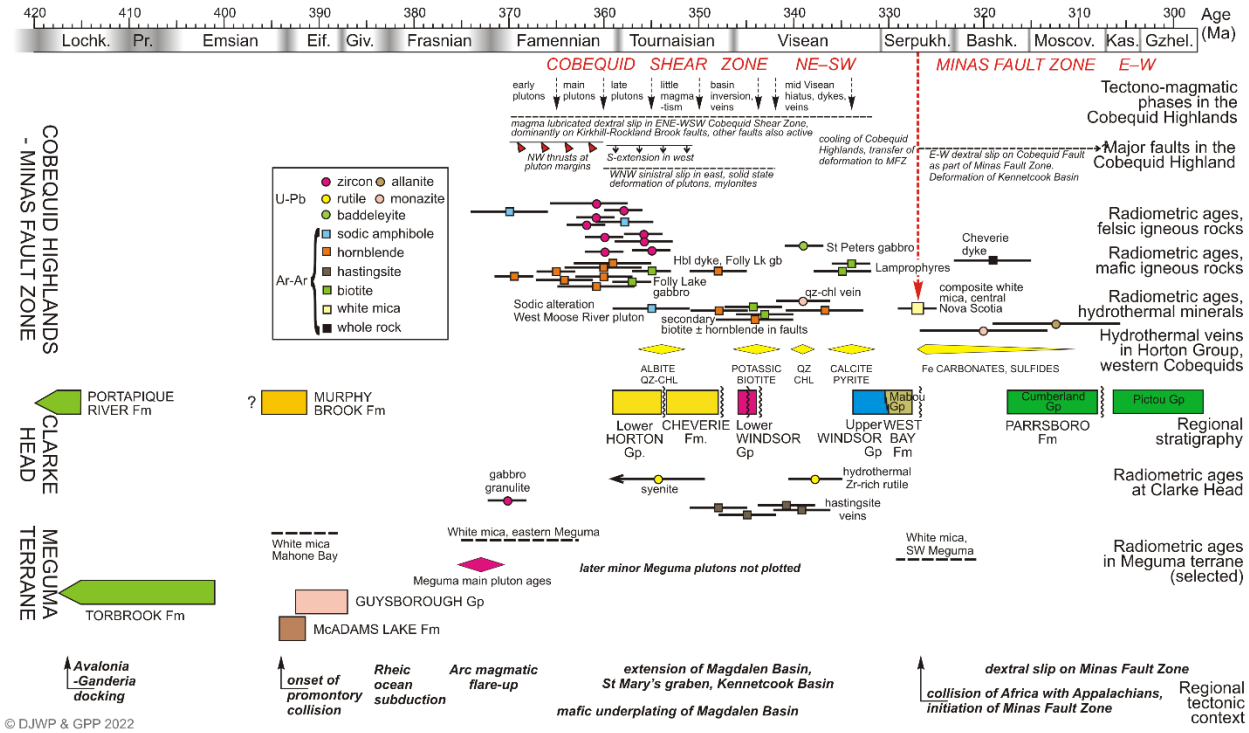

Figure 3: Timeline for docking of the Meguma and Avalon terranes and subsequent Carboniferous evolution of the Geopark.

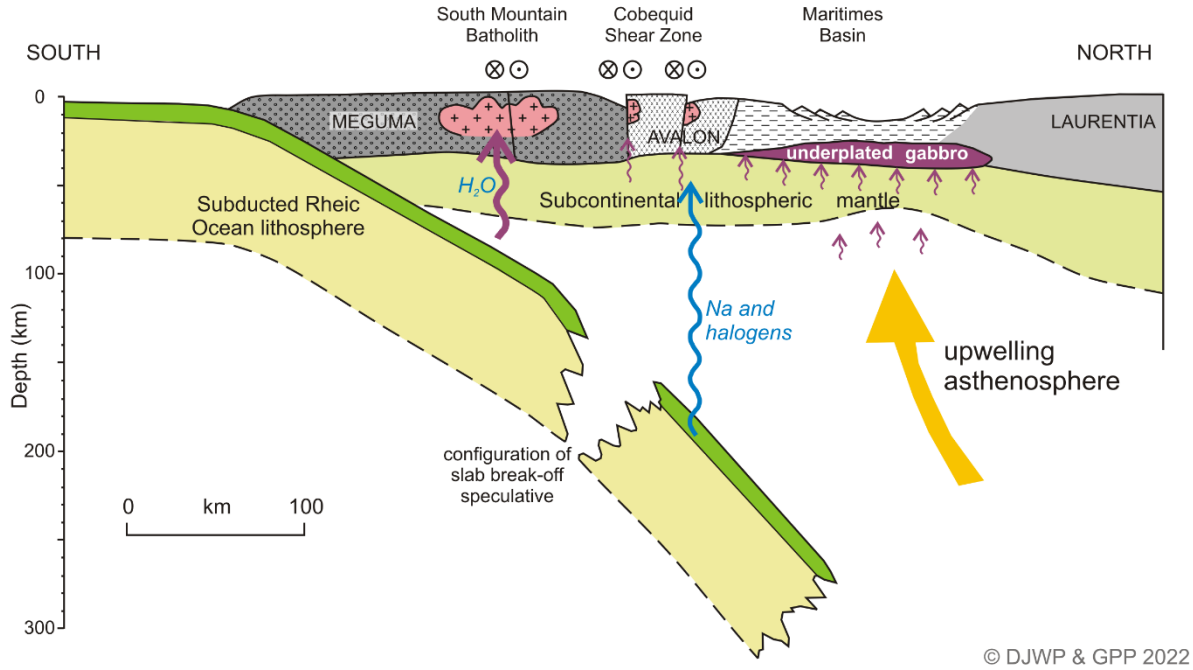

Figure 4: Plate tectonic cross section showing the Geopark at the beginning of the Carboniferous.

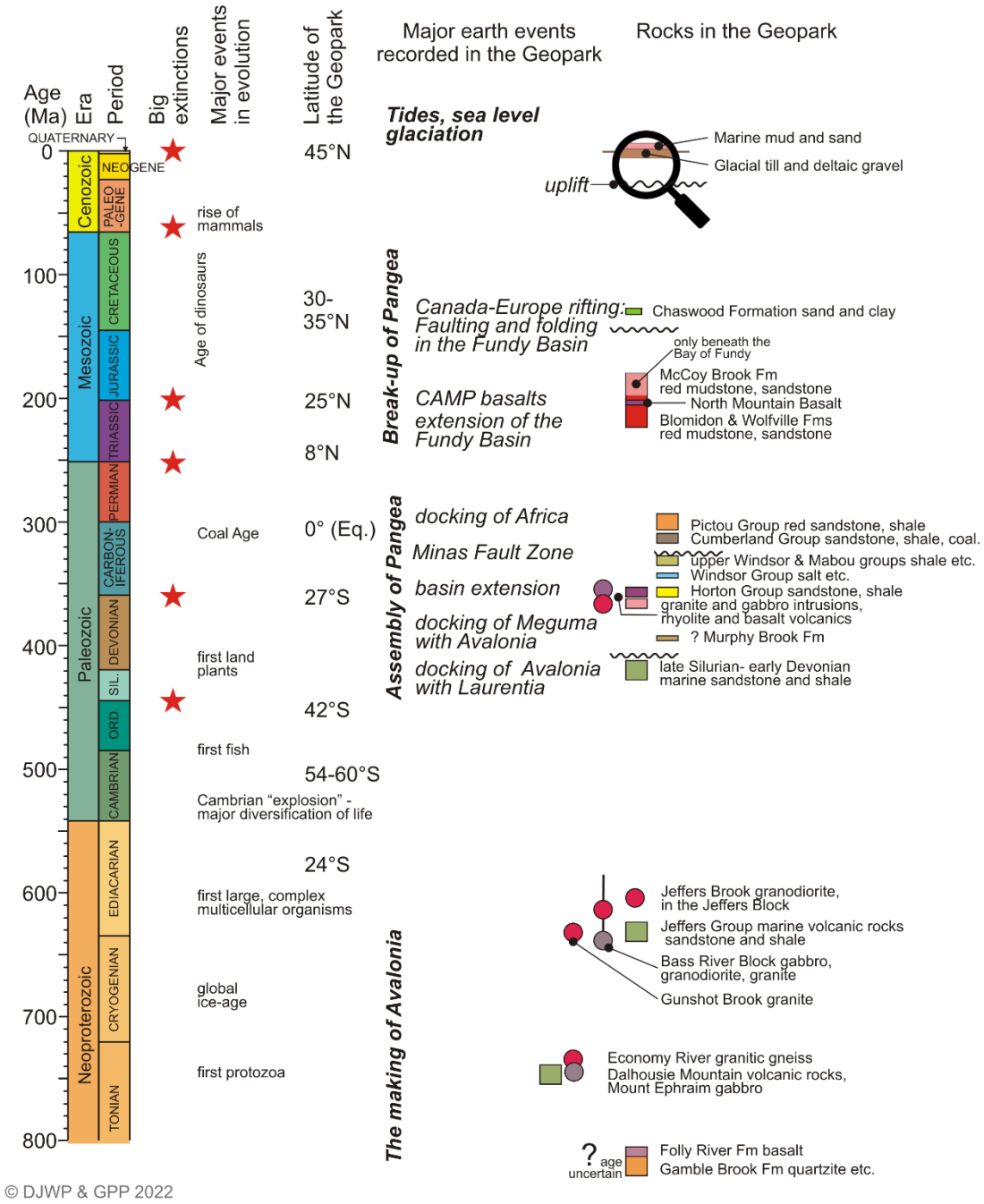

Figure 5: Timeline of the Cliffs of Fundy Geopark.

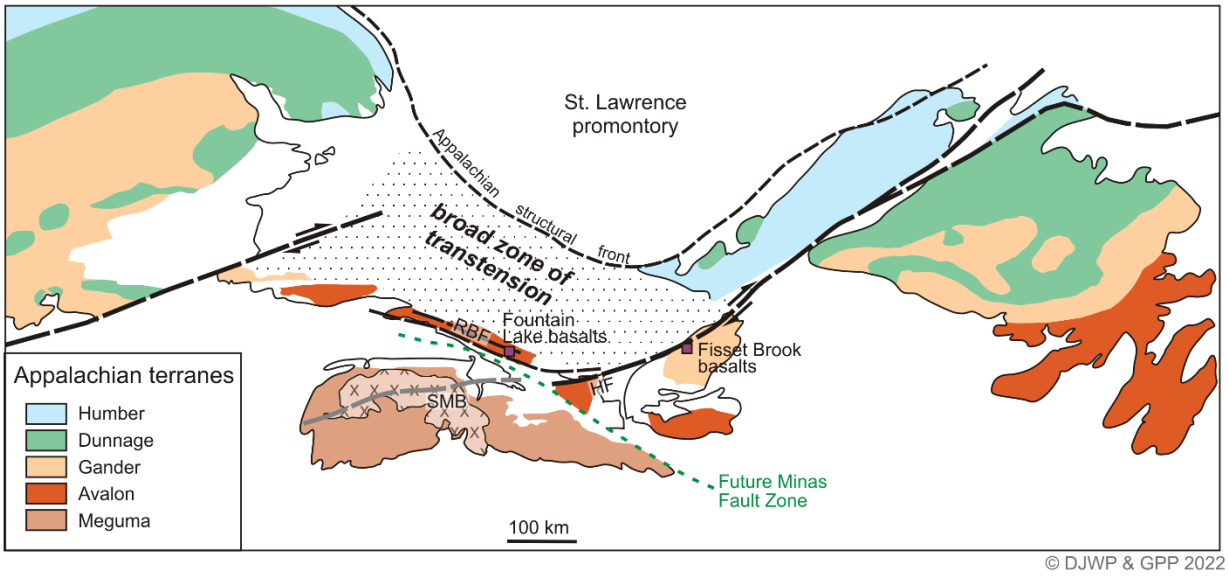

Figure 6: Relationship of the Geopark faults to regional faults in the Late Devonian--Early Carboniferous. HF = Hollow Fault; RBF = Rockland Brook Fault; SMB = South Mountain Batholith.

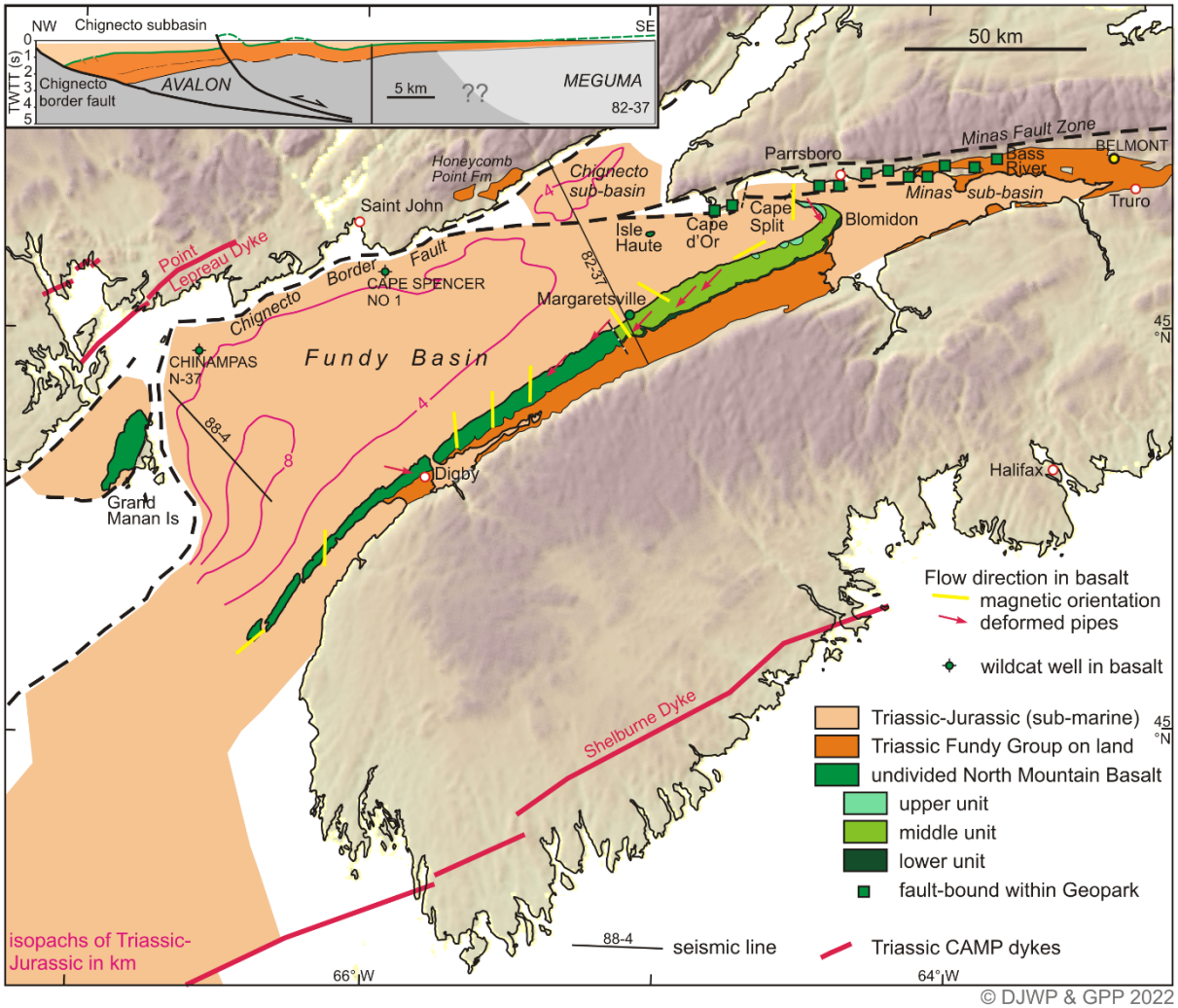

Figure 7: Map of the Fundy Basin with Triassic dykes and North Mountain Basalt. Inset shows cross section of the Bay of Fundy showing basement rocks, basin bounding fault, and Triassic–Jurassic rocks (Wade et al., 1996; Withjack et al., 2009).

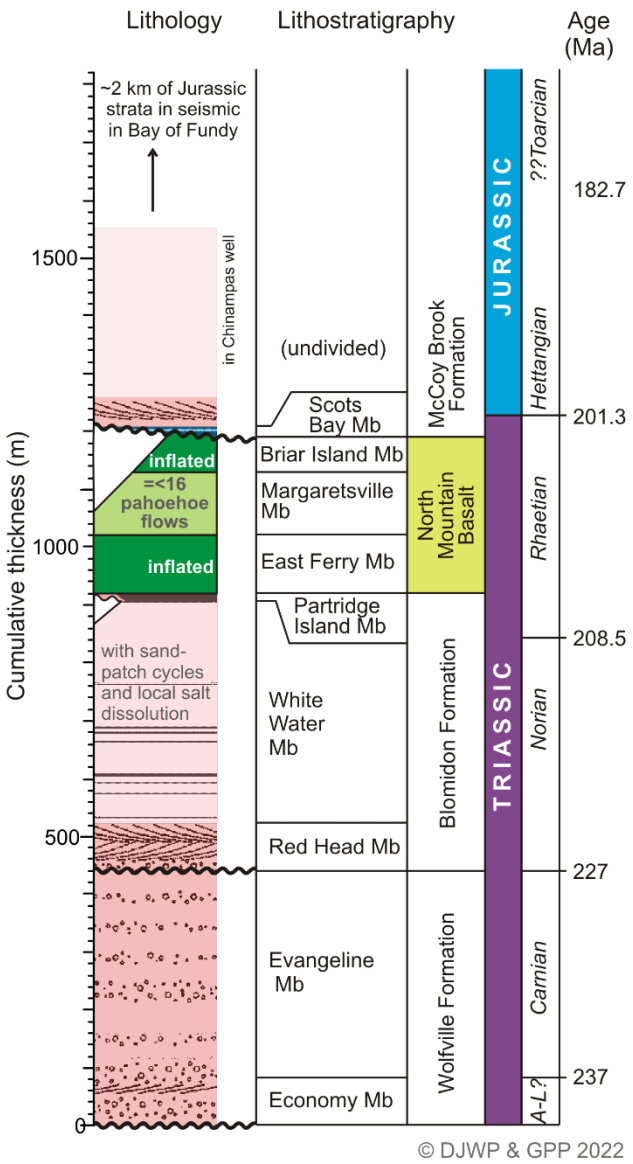

Figure 8: Lithologic column and timeline for the rocks of the Fundy Basin (Sues and Olsen, 2015).

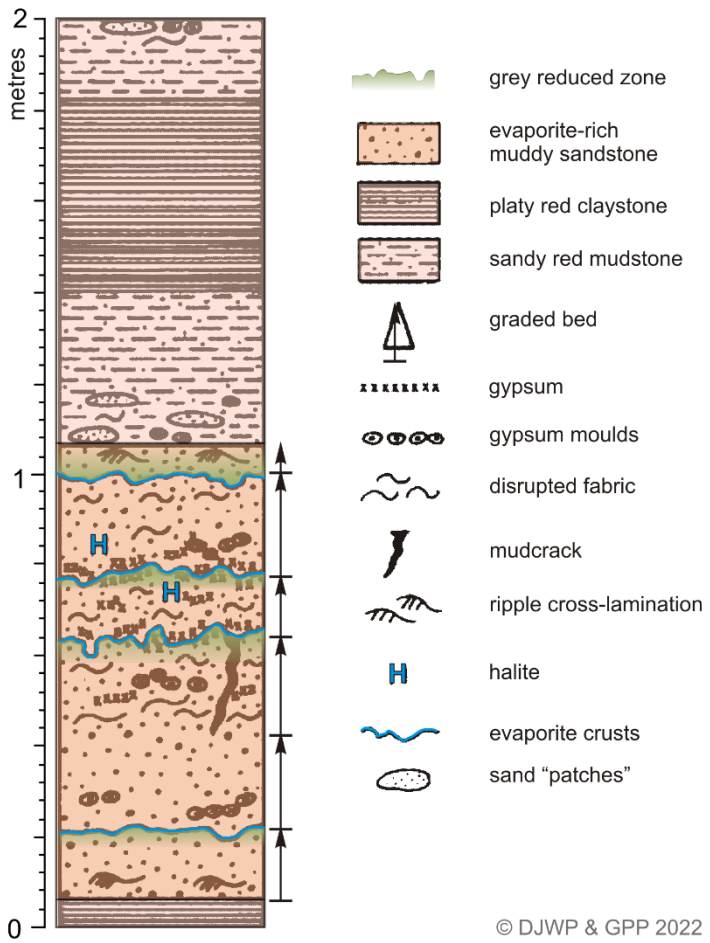

Figure 9: Schematic representation of depositional cycle in the Blomidon Formation at the Red Head Geosite (Mertz and Hubert, 1990).

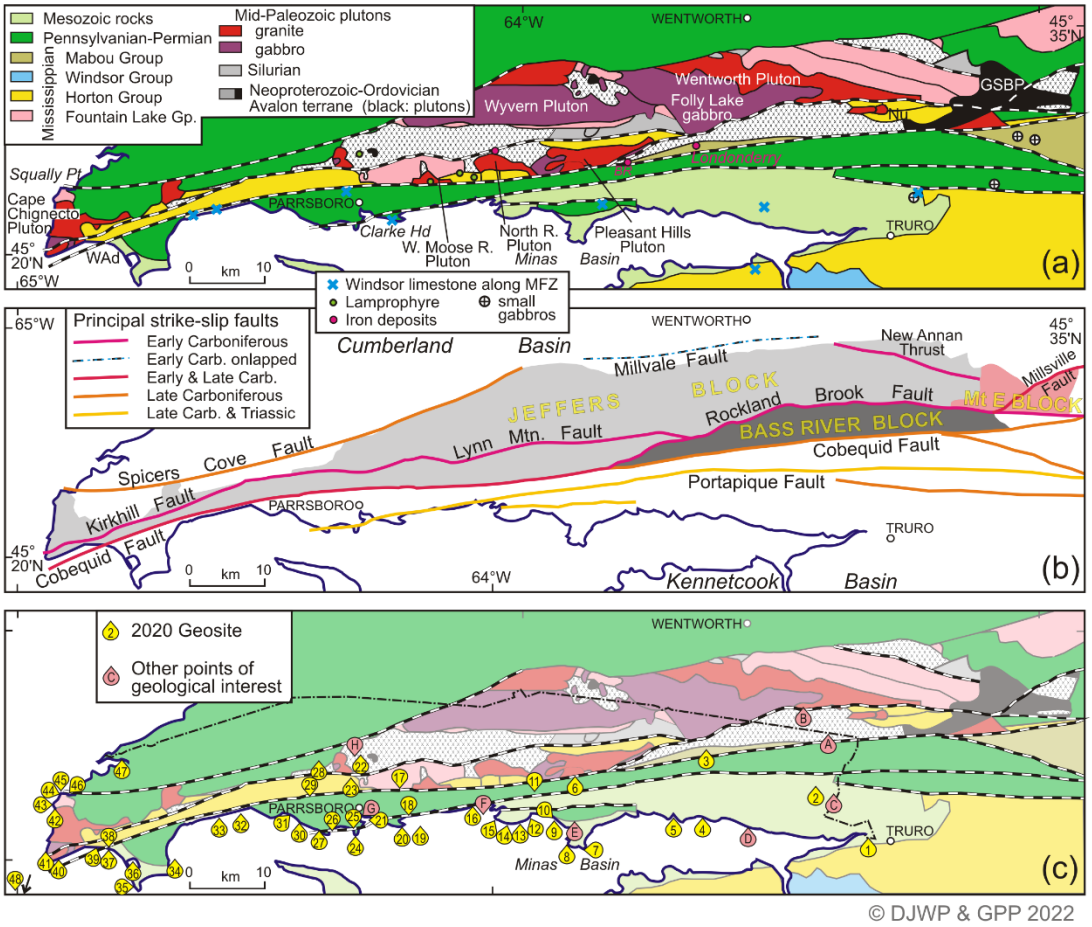

Figure 10: (a) Simplified geological map of the Cliffs of Fundy UNESCO Geopark and its environs. (b) The principal blocks of Avalonian basement and the timing of major faults. (c) Geopark boundary and location of the 2020 Geosites. GSBP = Gunshot Brook pluton; Nu = Nuttby; Wad = West Advocate

GEOSITES: 1 Fundy Discovery Site; 2 Mi'kma'wi Debert Interpretive Trail; 3 Londonderry Iron Mines; 4 Highland Village drowned peat; 5 Upper Bay Estuaries; 6 Economy Falls Keno'mi; 7 Economy Point Keno'mi; 8 Thomas Cove and Brick Kilns; 9 Carrs Brook; 10 Drowned Forest at Carrs Brook; 11 Gerrish Valley; 12 Soley Cove Flowerpot; 13 Soley Cove Seacaves; 14 Red Head; 15 Old Wife; 16 Five Islands Lighthouse Park Nankl Mniku'l; 17 Hidden Falls; 18 Wasson Bluff; 19 The Brothers; 20 Clarke Head; 21 Parrsboro Harbour; 22 Jeffers Falls; 23 Leake Lake; 24 Partridge Island Plawejue'katik or Wa'soq Wktaqamiku'jk; 25 East Bay; 26 West Bay; 27 FORCE Center; 28 Ward Falls; 29 Wharton Fault; 30 Rams Head; 31 Diligent River Harbour; 32 Age of Sail; 33 Brookville Rock; 34 Spencer's Island Wtuoml; 35 Cape D'Or-Horseshoe Cove L'mu'juiktuk; 36 Advocate Harbour Atuonjek; 37 Red Rocks; 38 West Advocate Atuonjek; 39 McGahey Brook; 40 Refugee Cove; 41 Bald Rock Cove; 42 Eatonville Loop, Anderson Cove Lookoff; 43 Seal Cove; 44 Three Sisters; 45 Squally Point; 46 Spicer Cove; 47 Apple River; 48 Isle Haute Makusetki.

OTHER POINTS OF GEOLOGICAL INTEREST: A: Frog Lake quarry; B: Rockland Brook Fault mylonite; C: Belmont Cretaceous sand; D: Little Dyke Lake and viewpoint; E: Economy Welcome Center; F: The islands of Five Islands; G: Fundy Geological Museum; H: Lakelands.

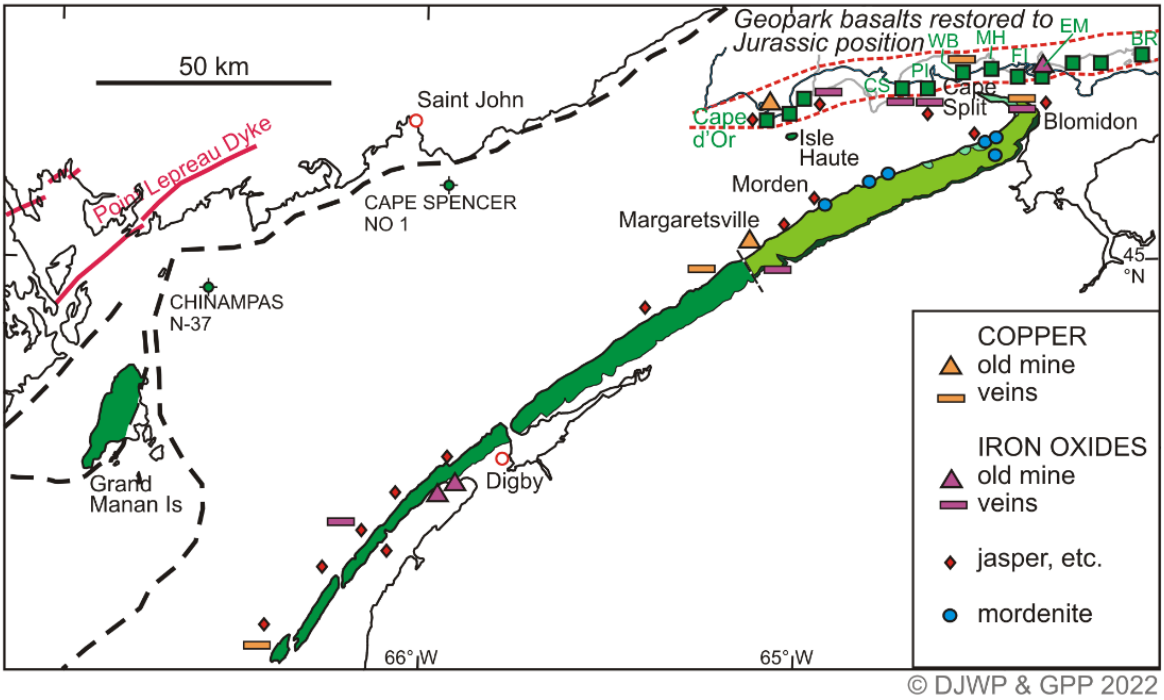

Figure 11: Map of North Mountain Basalt showing distribution of distinctive vein minerals. CS = Cape Sharpe; PI = Partridge Island; WB = Wasson Bluff; MH = McKay Head; FI = Five Islands; EM = Economy Mountain; BR = Bass River.

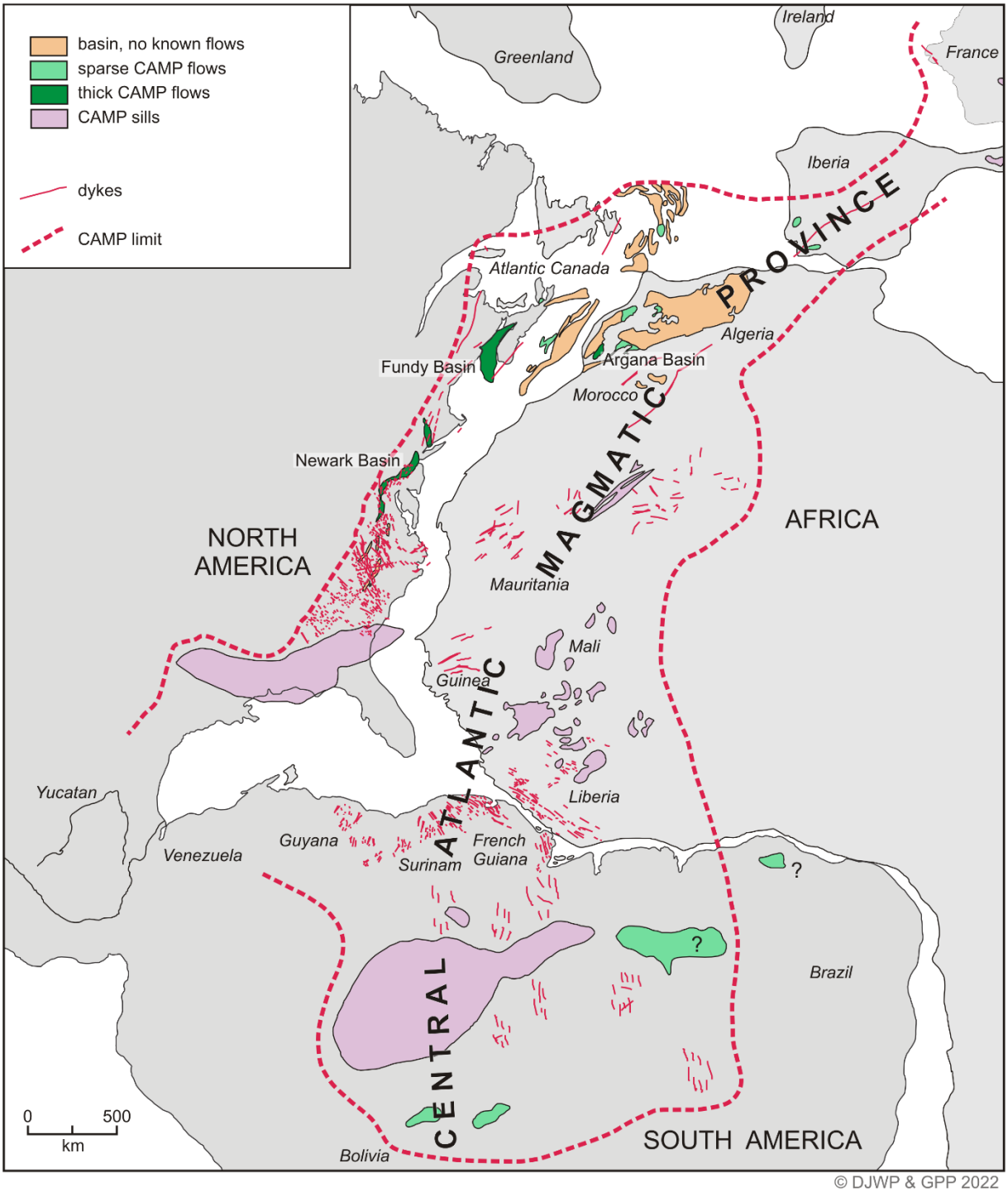

Figure 12: The extent of CAMP magmatism and Triassic basins on the eastern North American margin. Base map is an approximate continental reconstruction before the breakup of Pangea. (Largely from Marzoli et al. 2018).

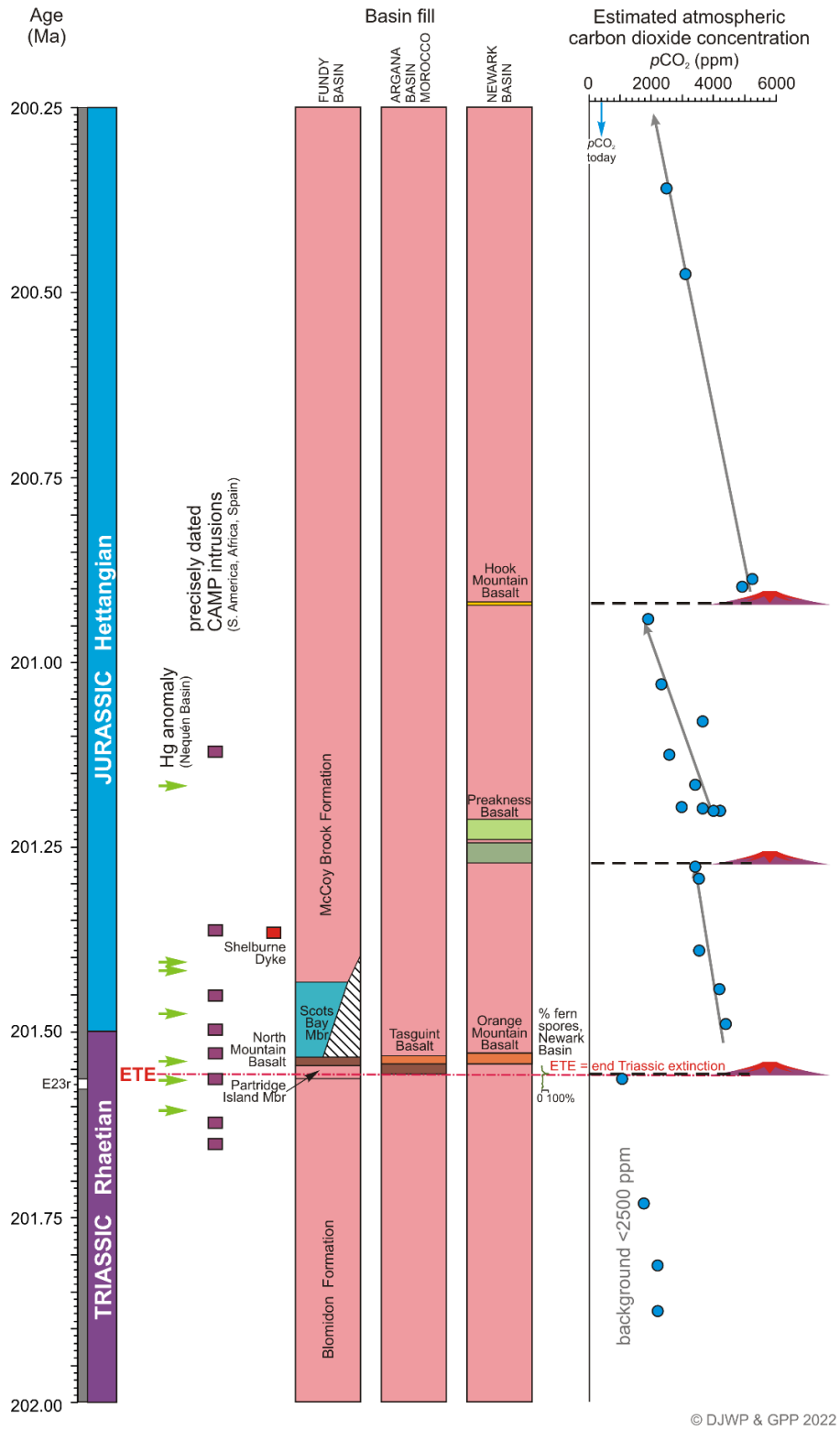

Figure 13: Stratigraphic setting of basalts in Newark Basin, Morocco and Fundy Basin and environmental change at the Triassic-Jurassic transition. Compiled from Schaller et al. (2011); Blackburn et al. (2013) and Ruhl et al. (2020).

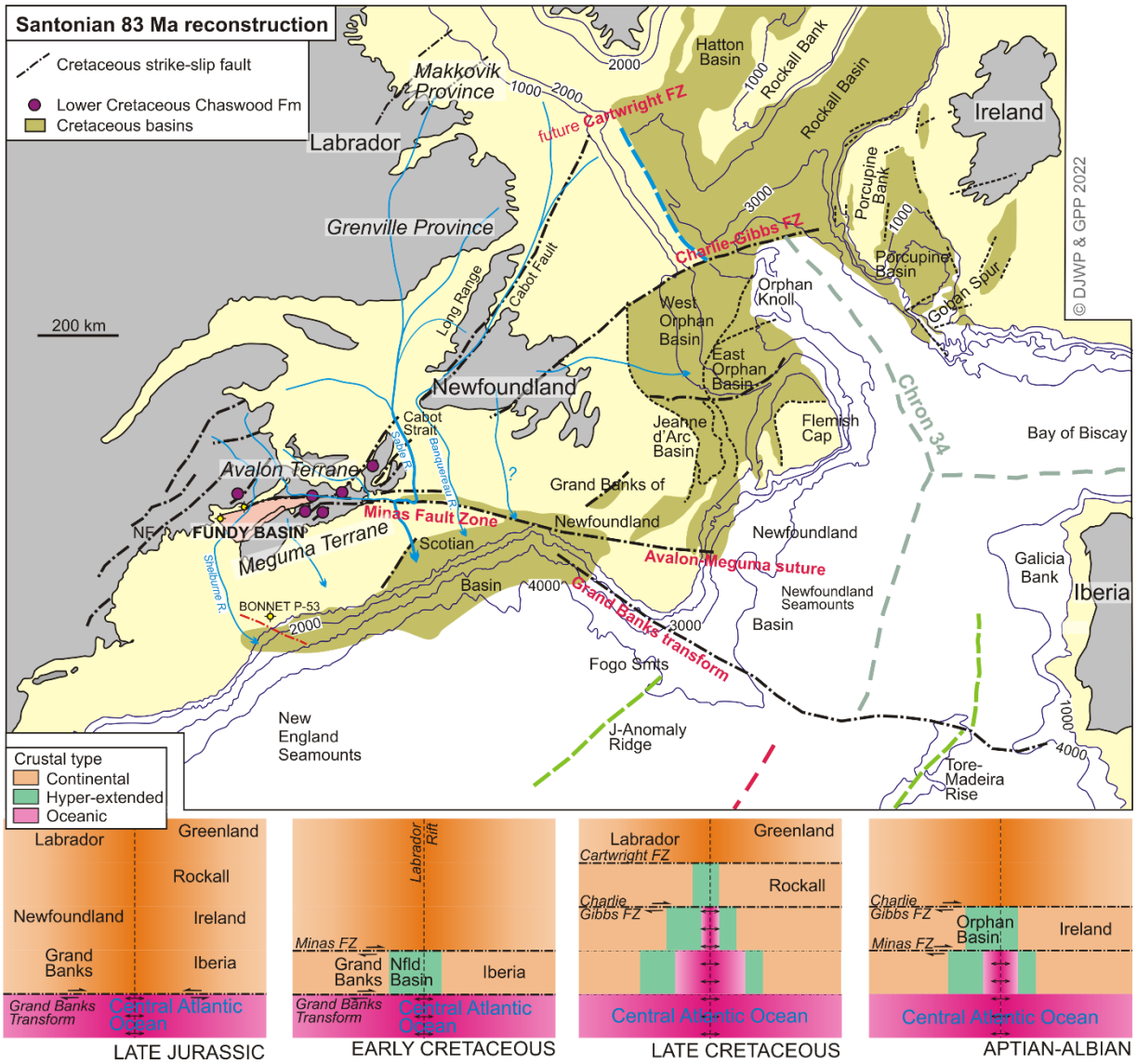

Figure 14: Cartoon illustrating hyperextension between Iberia and Newfoundland and the consequences from the Chaswood Formation and the Bay of Fundy.

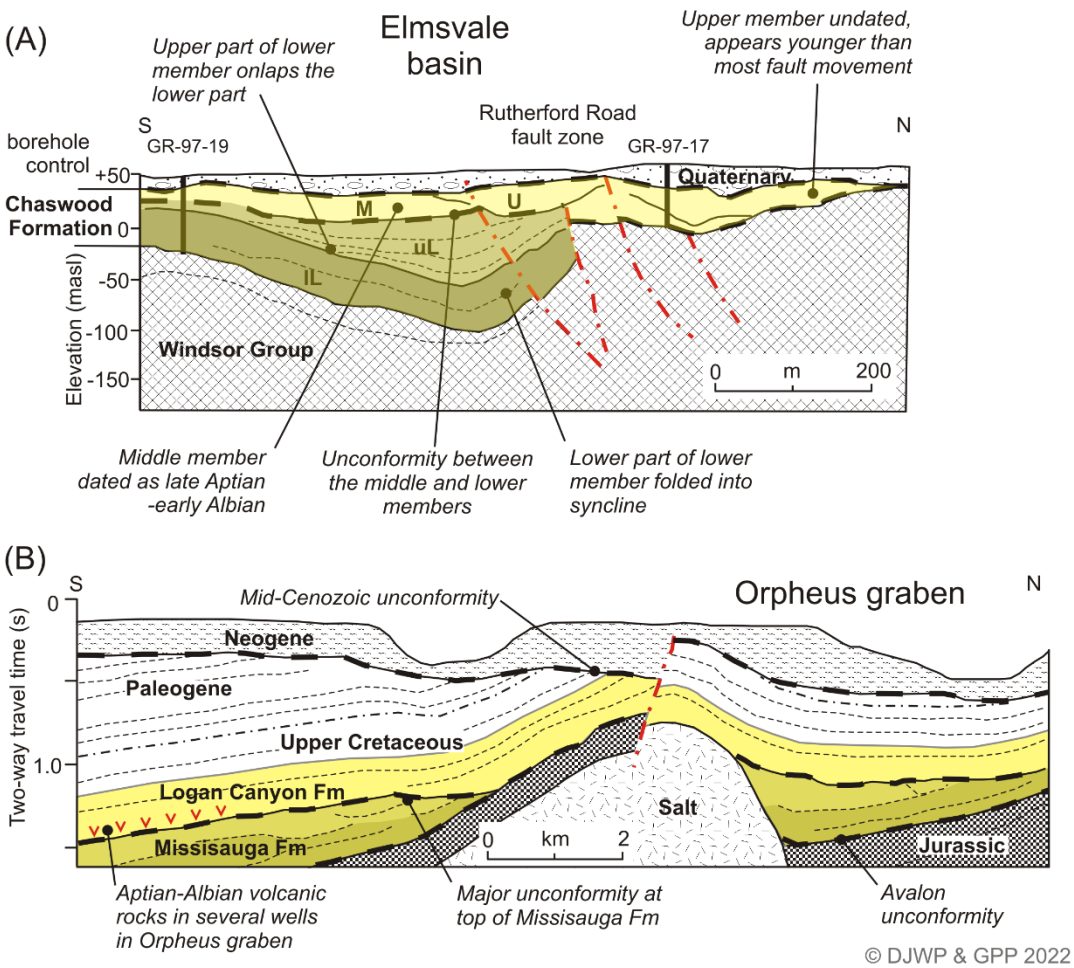

Figure 15: (A) Seismic section across the Chaswood Formation showing borehole control and deformation of the lower part of the formation. (B) Seismic section across the Orpheus Graben showing analogy to the Chaswood basins. Modified from Pe-Piper and Piper (2004).

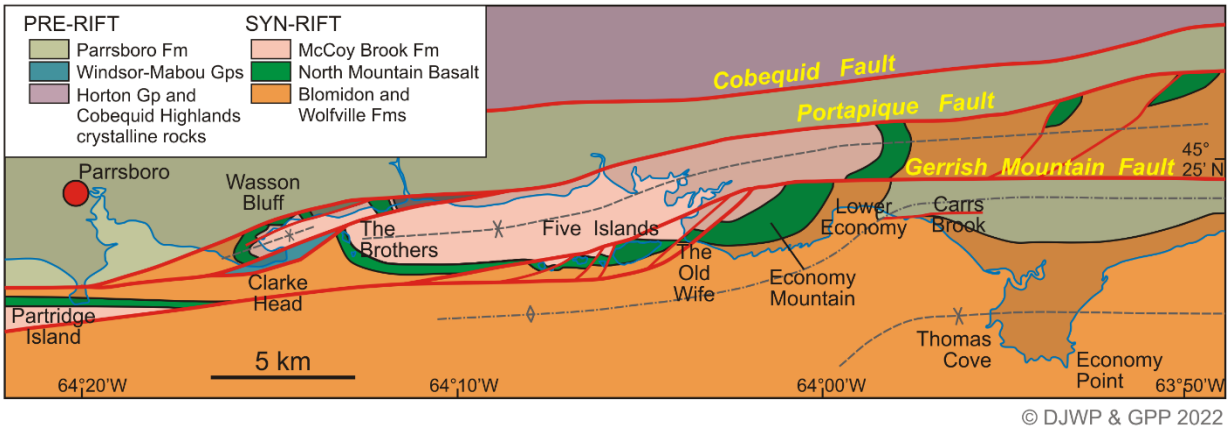

Figure 16: Sketch map of Triassic–Jurassic rocks from Economy Mountain to Partridge Island showing evidence for Cretaceous faulting along the Gerrish Mountain Fault (Withjack et al., 2010).

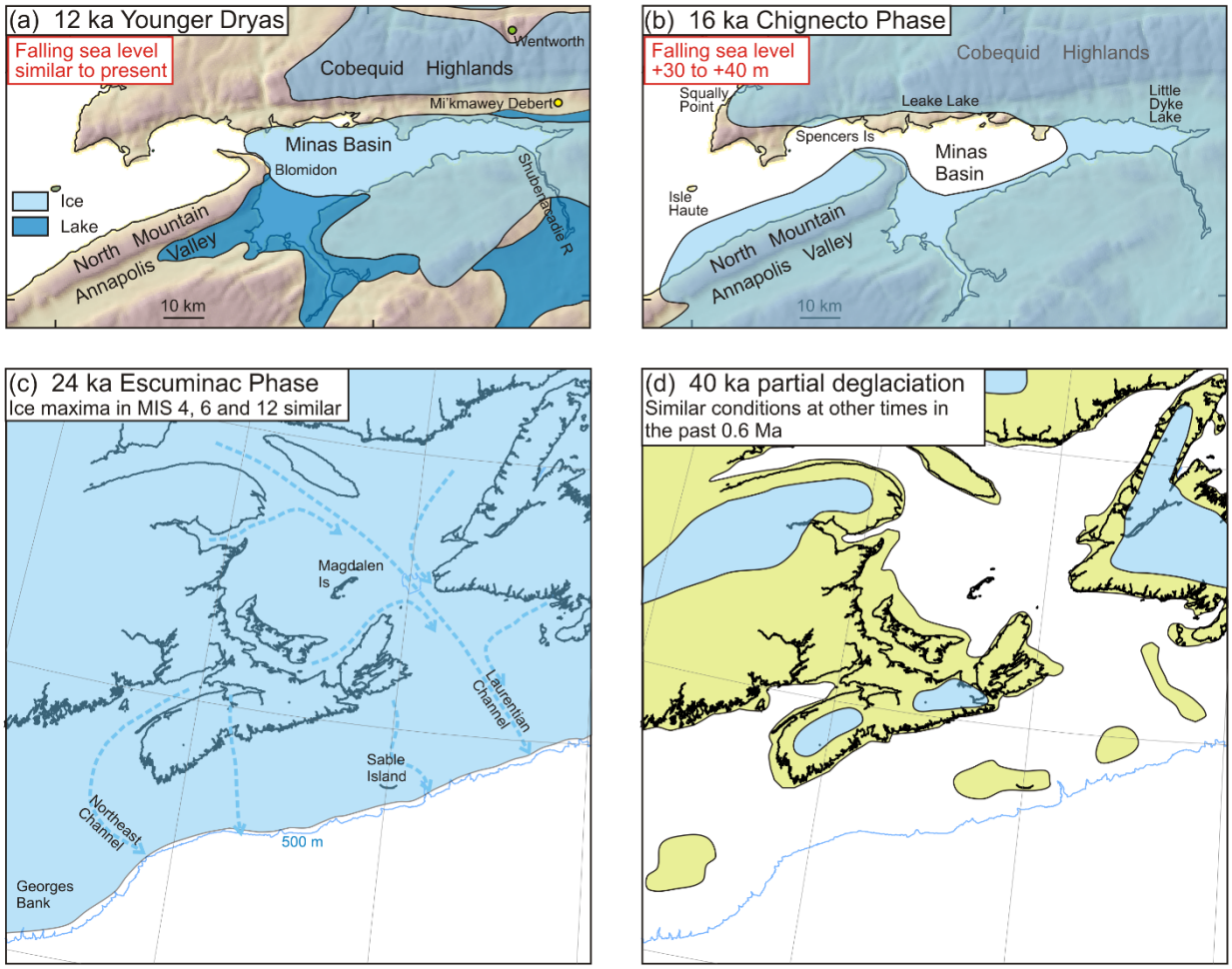

Figure 17: Changes in glacial conditions through time. (a) Ice extent in the Younger Dryas around the Geopark. (b) Ice conditions at 16 ka marking the beginning of deglaciation of the Geopark. (c) The most recent ice maximum at 24 ka. There were similar conditions in MIS 4, 6 and 12. (d) Speculative ice extent at 40 ka, when mastodons roamed the Maritime Provinces.

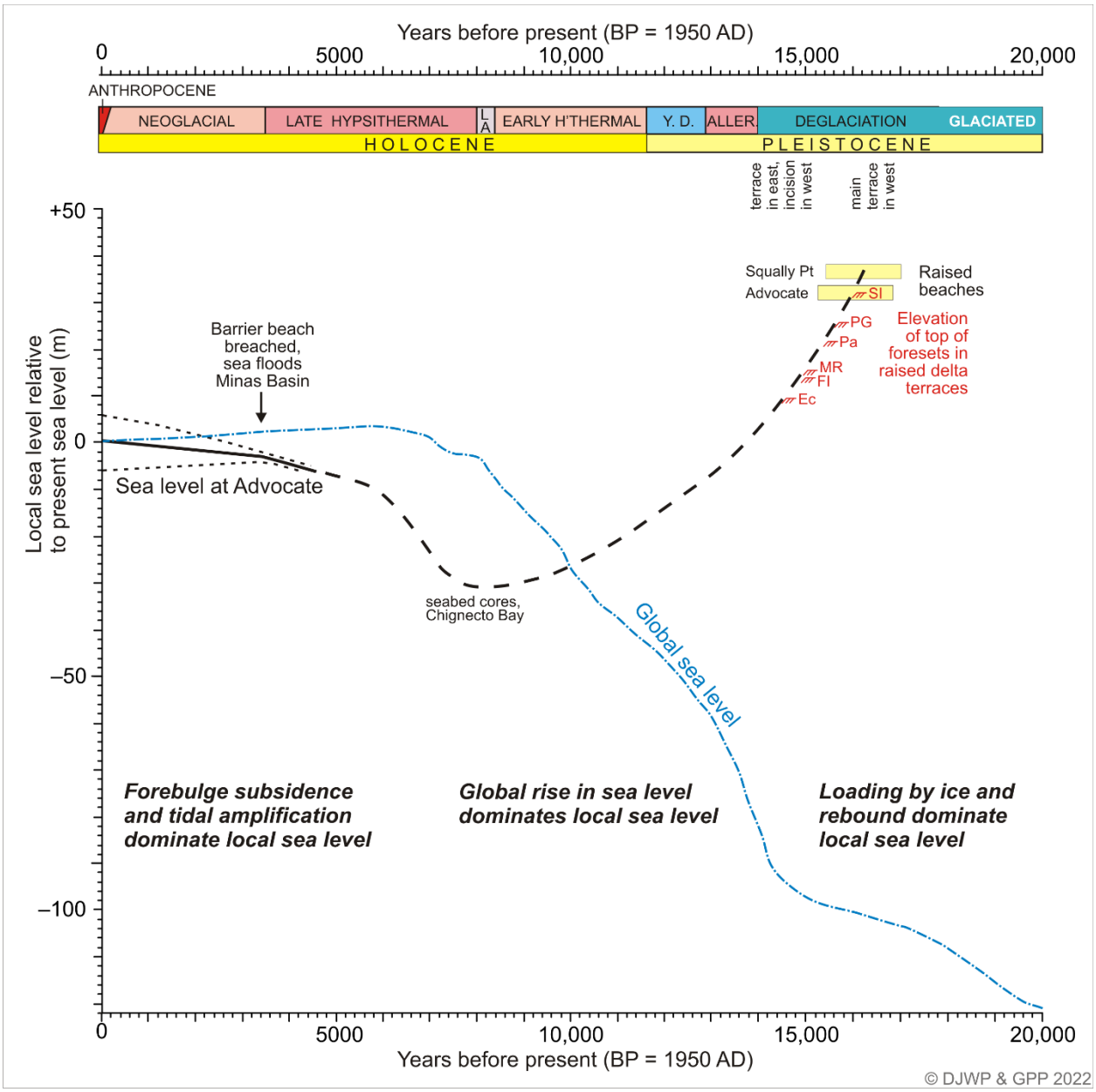

Figure 18: Timeline of sea level change in the Holocene and deglacial period. Based principally on data from Shaw et al. (2010) and Amos and Zaitlin (1984). Elevation of raised terraces from Wightman (1980). Global eustatic curve from Lewis et al. (2013).

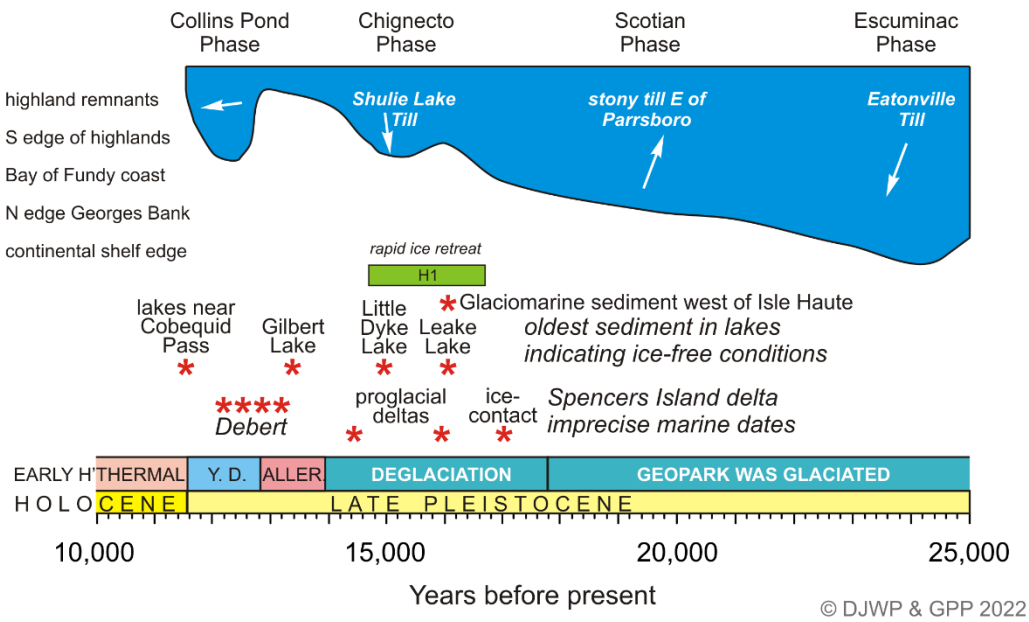

Figure 19: Timeline of deglaciation in the Cliffs of Fundy Geopark. All radiocarbon dates are calibrated.

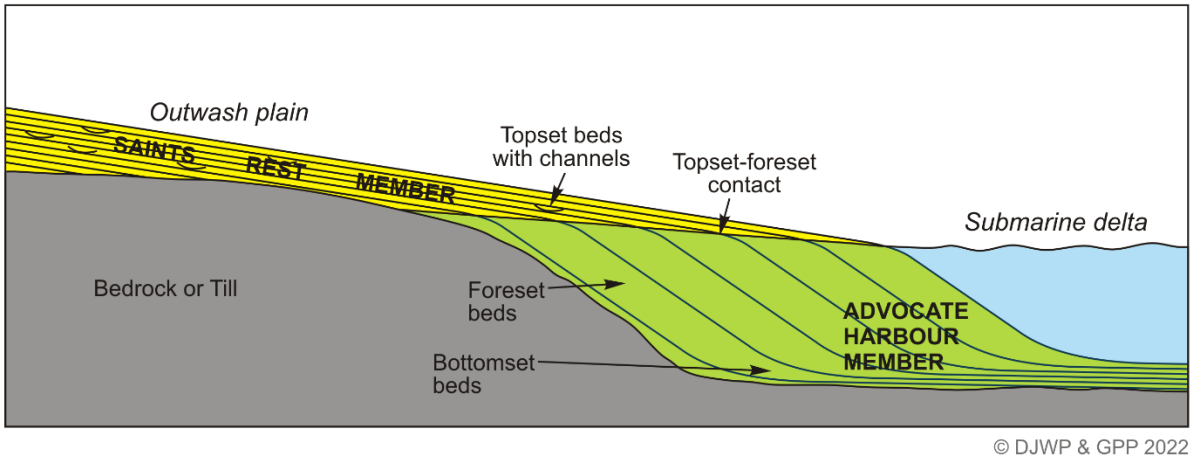

Figure 20: Schematic diagram of the formation of delta foresets and topsets. Modified from Stea et al. (1985).

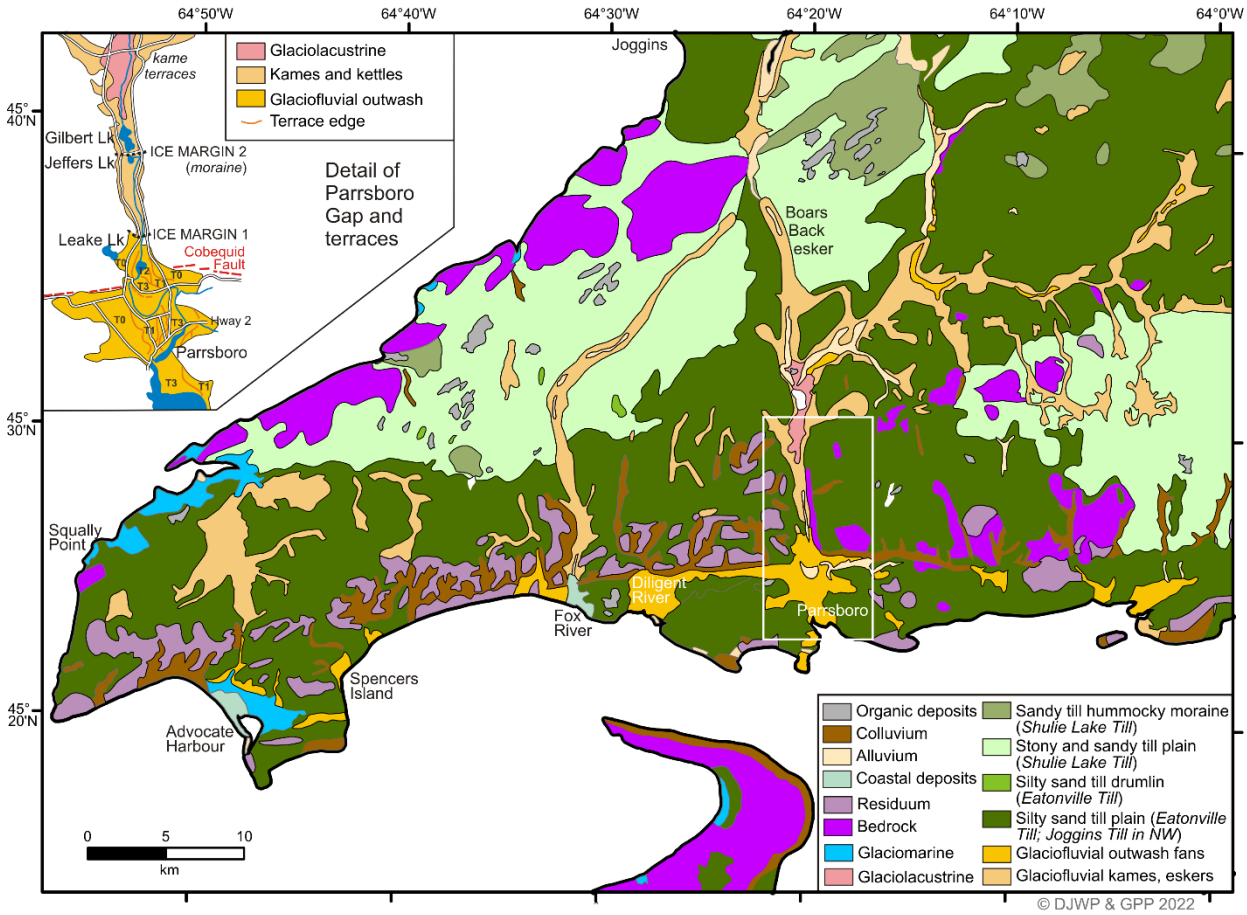

Figure 21: Summary map of glacial deposits in the western Cobequid Highlands (Stea et al., 1985). Inset shows details of the Parrsboro Gap and terraces (Grant, 1985).

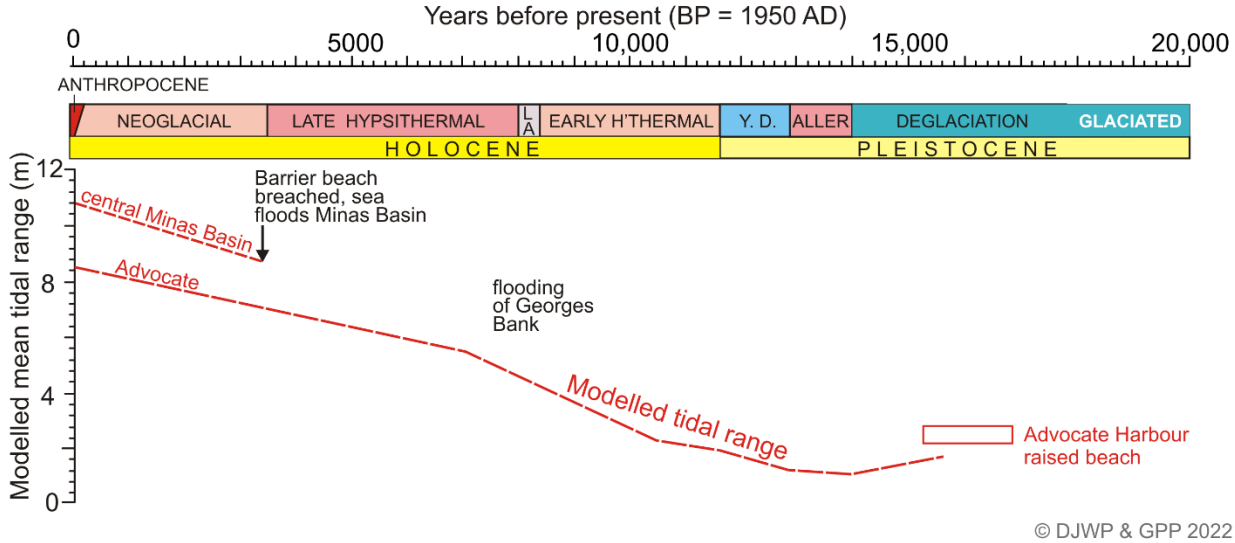

Figure 22: Timeline of tidal amplification in the Geopark. LA = Lake Agassiz event; Y.D. = Younger Dryas; ALLER = Allerød warm period.

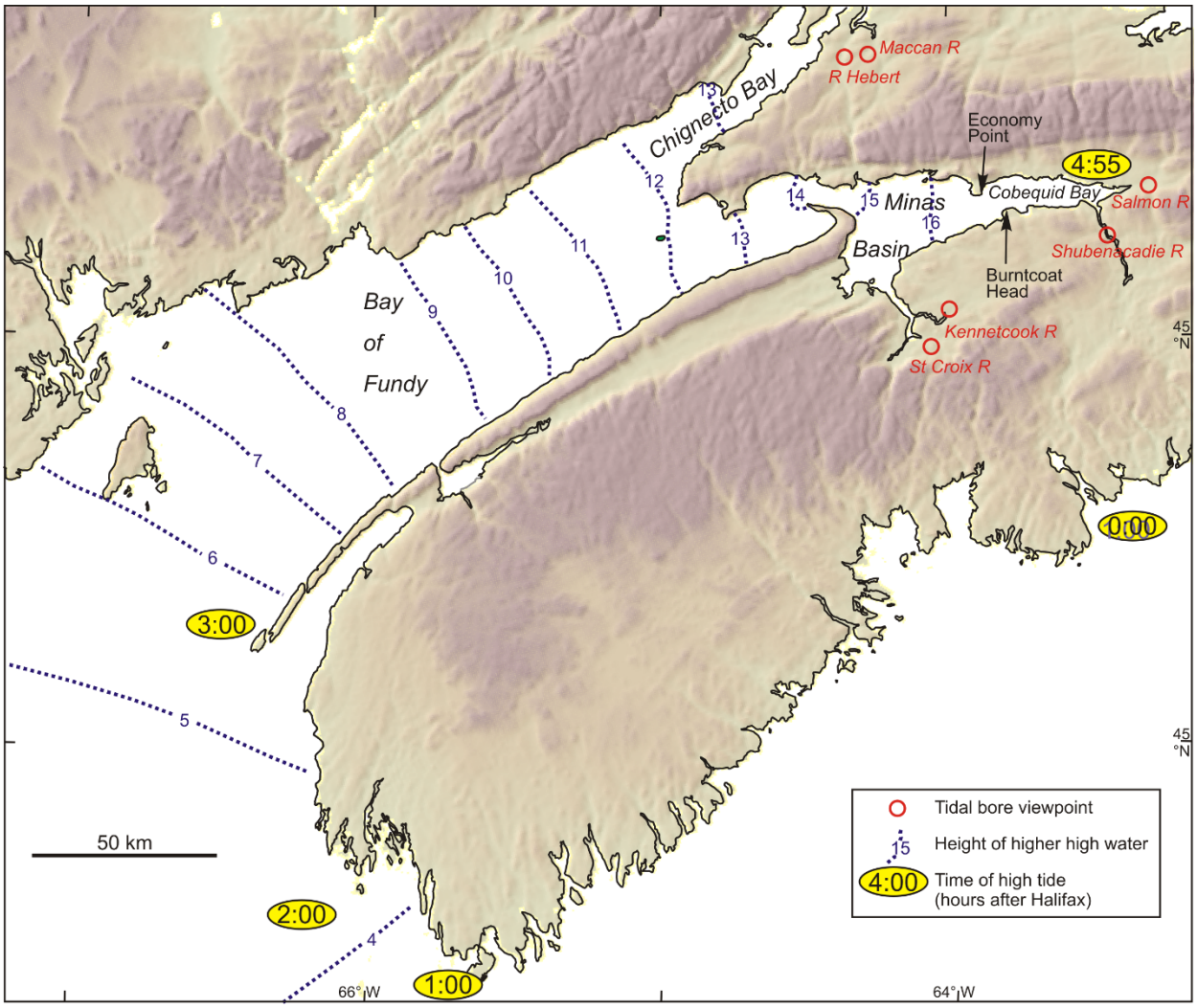

Figure 23: Time and range of spring high tide in the Atlantic Ocean – Bay of Fundy system (Davies and Browne, 1996).

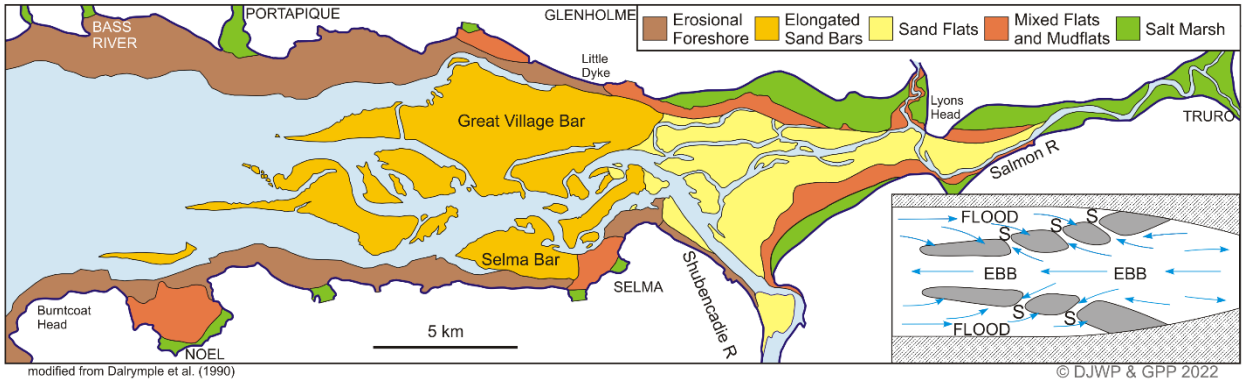

Figure 24: Holocene sediment types in Cobequid Bay (Dalrymple et al., 1990). Inset shows flood and ebb currents and their relationship to swatchways (S).

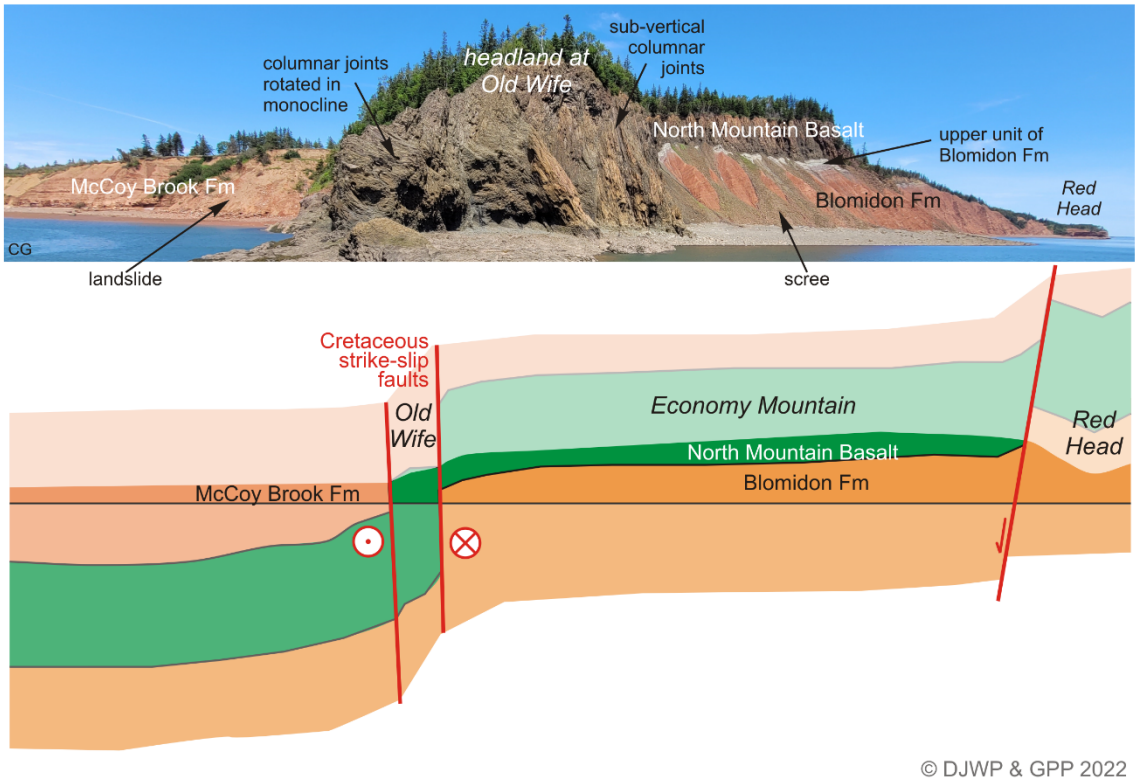

Figure 25: Cretaceous faults cutting North Mountain Basalt overlying Blomidon Formation at Five Islands Provincial Park.

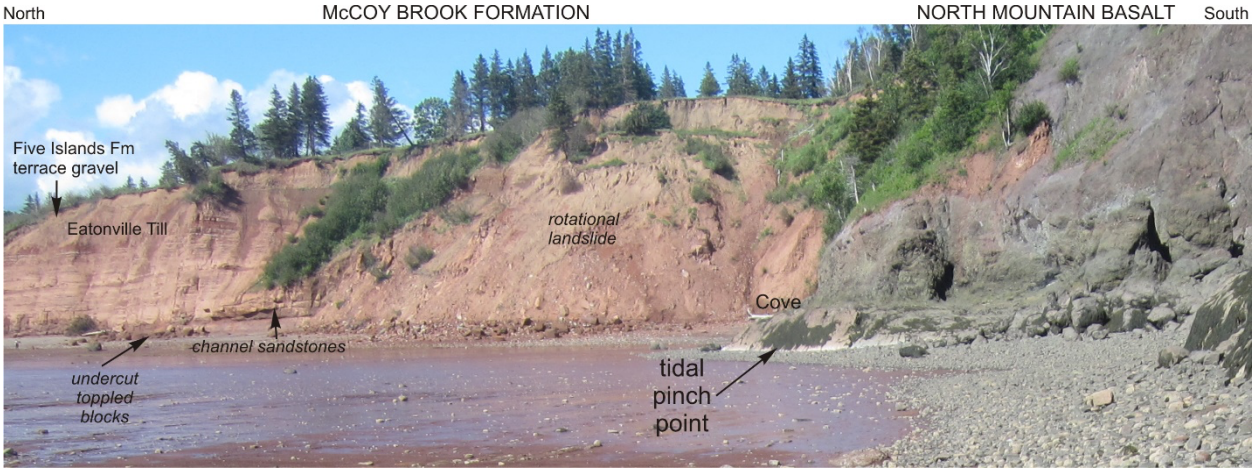

Figure 26: Faulted Contact between McCoy Brook Formation and North Mountain Basalt, north of the Old Wife.

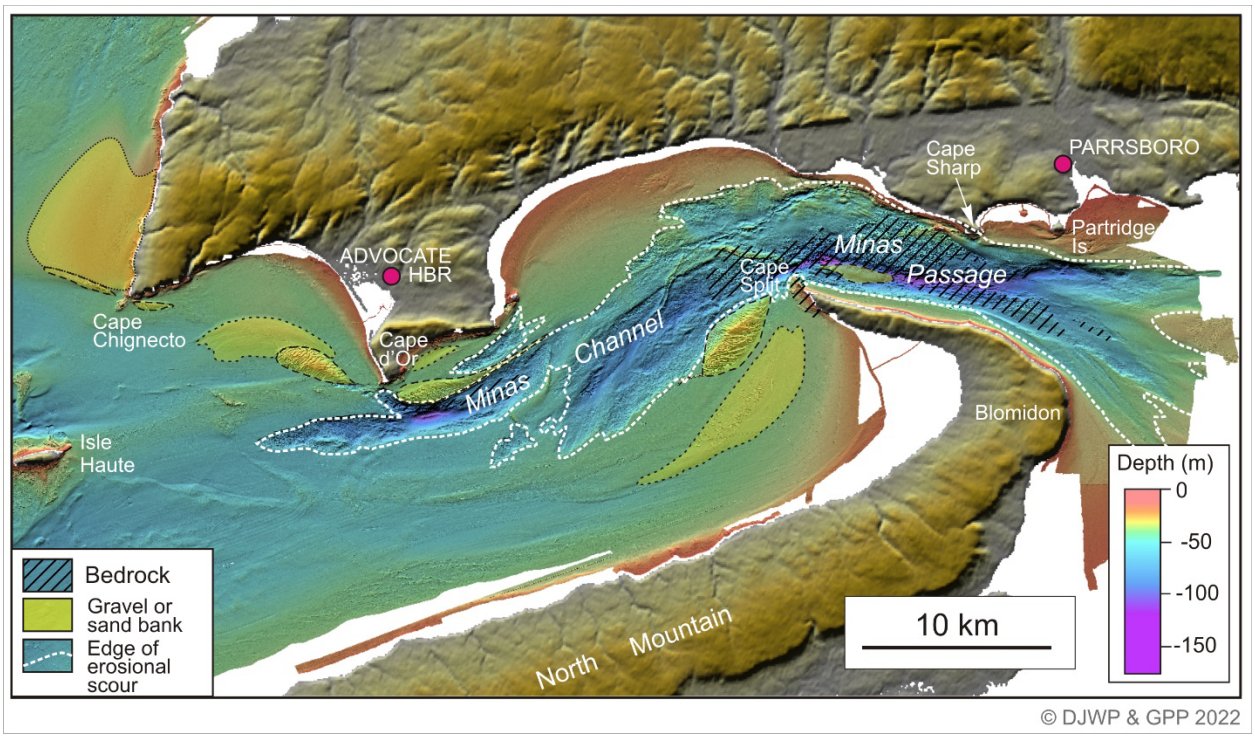

Figure 27: Map of scour features and banks in Minas Channel and Minas Passage (from Shaw et al., 2012). White patches are marine areas lacking multibeam bathymetry data.

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