GAC-MAC-IAH-CNC-CSPG

JOINT ANNUAL MEETING 2022

HALIFAX,

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VIRTUAL FIELD TRIP

THE CALEDONIAN HIGHLANDS, AVALONIA IN SOUTHERN NEW BRUNSWICK

GEOLOGICAL COMPARISONS AND CORRELATIONS AMONG CRUSTAL BLOCKS OF EASTERN NORTH AMERICA, NORTHWEST AFRICA, AND WESTERN EUROPE

MAY 19–23, 2022

Susan C. Johnson and Adrian F. Park

New Brunswick Department of Natural Resources and Energy Development

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ABSTRACT

The province of New Brunswick lies within the Canadian Appalachians, the northeastern North American segment of the Caledonian-Appalachian mountain chain. The northeastern Appalachians were built during several successive Paleozoic accretionary orogenic events collectively known as the Appalachian Orogeny. This long-lived accretionary orogen began in the Early Ordovician and culminated with the Middle to Late Permian amalgamation of the supercontinent Pangea. The Caledonian Highlands in coastal southeastern New Brunswick are part of Avalonia, a peri-Gondwanan or Baltica-derived microcontinent typified by Cryogenian (700-670 Ma) and Ediacaran (640-565 Ma) continental margin arc magmatism and an overlying latest Ediacaran to Early Ordovician marine clastic sedimentary cover, commonly referred to as the Avalonian cover sequence. Avalonia also locally preserves evidence for an older Tonian passive margin and early arc event that resulted in collision and ophiolite emplacement prior to the development of the later Cryogenian and Ediacaran arcs.

On this field trip to the Caledonian Highlands, we will examine the Cryogenian and Ediacaran metavolcanic, metasedimentary, and plutonic rocks, and overlying early Paleozoic rocks of the Avalonian cover sequence, along with younger Carboniferous and Triassic continental clastic rocks. On the trip you will see panoramic views of the Bay of Fundy along the Fundy Trail Parkway, beginning just outside of the small coastal community of St. Martins and winding its way through coastal wilderness, eventually linking up with Fundy National Park. St. Martins and the Fundy Trail Parkway are part of Stonehammer Geopark, the first North American member of the Global Geoparks Network, an organization assisted by UNESCO.

INTRODUCTION AND TECTONIC OVERVIEW

The geodynamic setting of the Early to Late Paleozoic Appalachian orogen has been compared to that of the modern-day western and southwestern Pacific Ocean (van Staal et al. 1998). The Appalachians are an accretionary orogen comprised of various oceanic terranes, arcs and back-arc basins, and microcontinental fragments that were sequentially accreted to the margin of eastern North America during the closing of the Iapetus and Rheic oceans (van Staal et al. 1998; Nance et al. 2010; Hibbard et al. 2010). Consequently, the tectonic history of the orogen is complex, and involves several orogenic cycles (van Staal et al. 1998; Zagorevski et al. 2007; van Staal and Barr 2012).

The northeastern Appalachians are fundamentally divided into either peri-Laurentian or peri-Gondwanan elements that are further divided into major tectonostratigraphic zones (Fig. 1) that represent various paleogeographic settings, marginal to and, within the Iapetus and Rheic oceans. The Humber zone includes Grenville basement (the eastern continental margin of Laurentia) and associated passive margin sedimentary rocks. Outboard of the Laurentian margin is the Notre Dame zone, which includes the Dashwoods terrane, a small peri-Laurentian microcontinent preserved only in Newfoundland (Waldron and van Staal 2001) and its associated Early Paleozoic active margins. The Notre Dame and Exploits subzones are separated by the Iapetan suture, marking the boundary between the Laurentian and Gondwanan realms. The Notre Dame and Exploits subzones (collectively referred to as the Dunnage zone) both preserve remnants of Early Paleozoic arcs, back-arc basins, and oceanic tracts associated with the Laurentian and Gondwanan margins of Iapetus, respectively. The outboard terranes of Ganderia, Avalonia and Meguma, represent Gondwanan - and/or Baltica - derived microcontinents that were accreted to the North American margin during the Salinic, Acadian, and Neo-Acadian orogenies, respectively (van Staal and Barr 2012), and references therein. The events leading up to and including the final closing of the Rheic Ocean outboard of the Meguma terrane are part of the Alleghanian orogeny (Hatcher 2002; Nance et al. 2010), which in New Brunswick only affected the southern coastal areas (Rast and Grant 1973; Nance 1985).

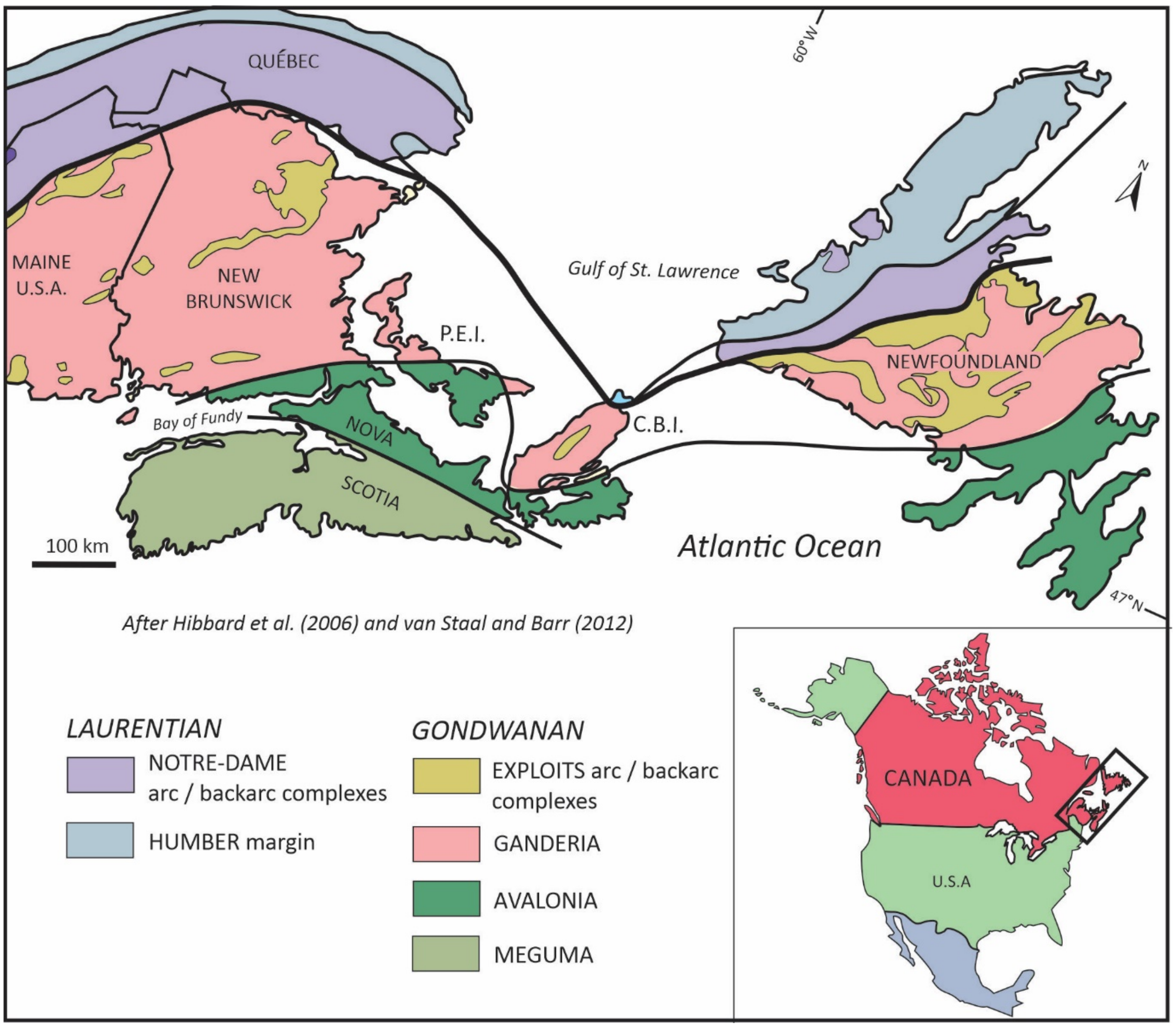

Figure 1. Lithotectonic subdivisions of the northeastern Appalachians in Atlantic Canada. After Hibbard et al. (2006). C.B.I. – Cape Breton Island; P.E.I – Prince Edward Island

In New Brunswick, rocks of Neoproterozoic age are found in four fault - bounded “terranes” or belts, all of which are in the southern part of the province (Fig. 2). These belts include, from southwest to northeast, Grand Manan, New River, Brookville, and Caledonia (Fyffe et al. 2011). The latter is the only belt widely considered to be part of Avalonia (Barr et al. 1994, 2020; van Staal et al. 2021a, b and references therein). This is based in part on the presence of the classic Avalonian cover sequence (Cambrian to Early Ordovician rocks of the Saint John Group), one of the defining elements of Avalonia (Landing 1996; Landing et al. 2022). Most workers consider the Neoproterozoic rocks on Grand Manan and in the Brookville and New River belts to represent the trailing margin of Ganderia (e.g. van Staal and Barr 2012; van Staal et al. 2021b), although many questions remain. Some of the issues were explored by Barr et al. (2014) and are briefly discussed below.

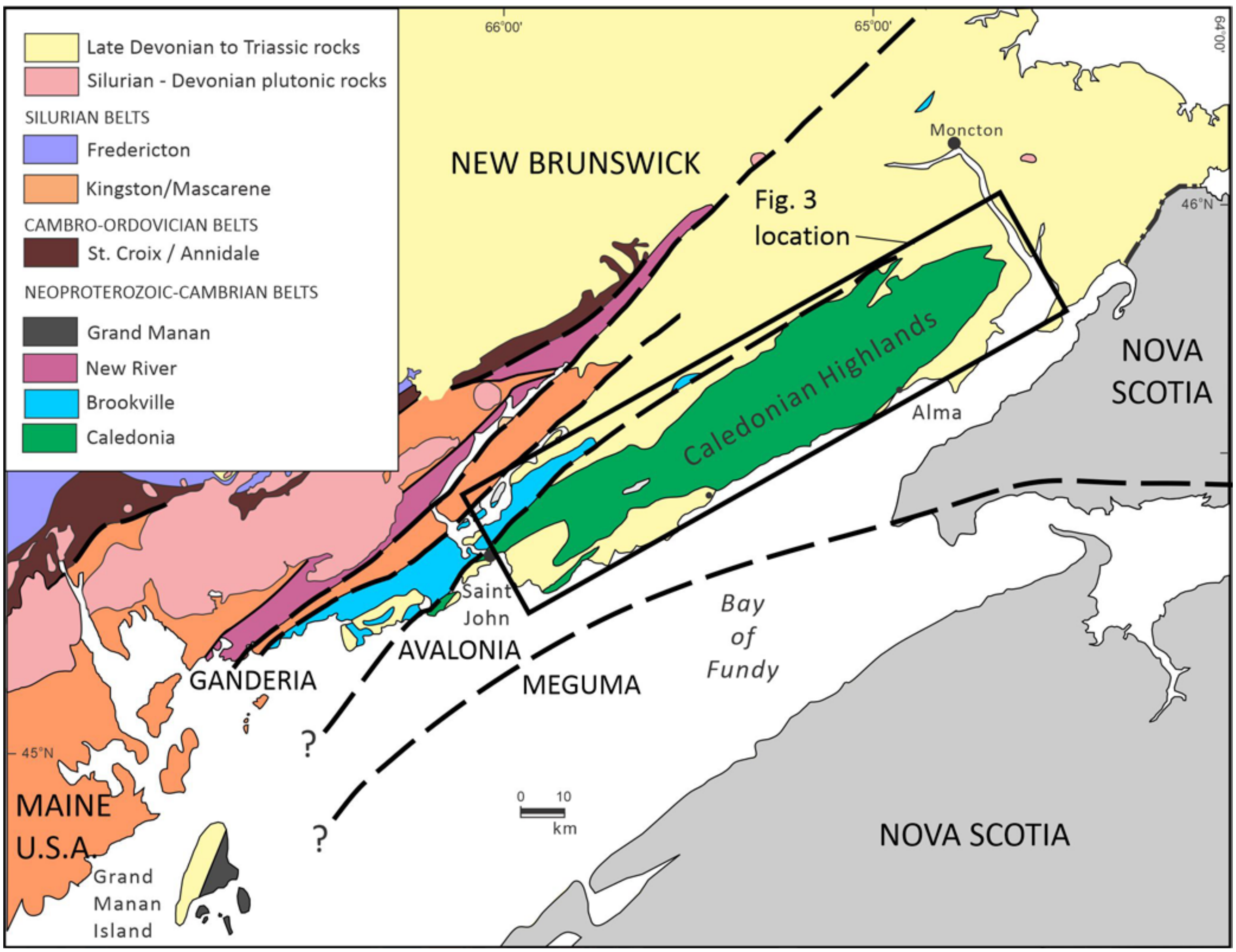

Figure 2. Simplified geology of lithotectonic terranes in New Brunswick. After Fyffe et al. (2011).

Caledonia, New River and Grand Manan all contain early Ediacaran (ca. 620 - 625 Ma) calc-alkaline, volcanic and intrusive rocks that formed in similar tectonic settings, but the former two are isotopically less-evolved (Whalen et al. 1994, 1996; Samson et al. 2000). In contrast, early Ediacaran rocks in the Brookville belt (White and Barr 1996), and equivalent Bras D'Or terrane on Cape Breton Island (Barr et al. 2003) are unique and represent a passive margin sequence of quartzite, marble and deeper water siliciclastic rocks, and their gneissic equivalents (Green Head Group and Brookville Gneiss), most likely deposited between ca. 650 Ma and ca. 600 Ma. A break in magmatism from ca. 600 Ma to ca. 560 Ma in the Grand Manan, New River and Caledonia belts and from ca. 650 Ma to ca. 555 Ma in the Brookville belt, was followed by voluminous Late Ediacaran magmatism across all four belts. Magmatism continued into the earliest Cambrian (ca. 540 - 530 Ma) except in the Caledonia belt. The tectonic setting of Late Ediacaran magmatism in New River and Brookville is somewhat ambiguous, as both I - and A -type plutonic rocks are present, however based on trace element patterns and the compositionally expanded nature of the intrusive rocks it has been suggested that the magmatism is arc - related (White et al. 2002; Johnson and Barr 2004). Voluminous late Ediacaran (ca. 560 - 550 Ma) magmatism in the Caledonia belt, not yet documented elsewhere in Avalonia, is attributed to an intra-arc extensional environment (Barr and White 1996, 1999; Escribano 2021).

One of the biggest remaining questions is why the Avalonian cover sequence (Saint John Group) occurs not only in the Caledonia belt, but in the Brookville and New River belts as well. White and Barr (1996) argued that small enclaves of Saint John Group in the Brookville belt were tectonically emplaced, however, the Saint John Group clearly forms a stratigraphic succession overlying latest Ediacaran (ca. 555 - 541 Ma) volcanic rocks in the New River belt (Johnson and McLeod 1996; Johnson 2001), one of the main reasons that these rocks are still considered to be part of Avalonia by some workers (eg. Landing et al. 2022).

The Caledonia, Brookville and New River belts are currently separated by major northeast-trending faults that in some cases bound belts of post-middle Ordovician cover (Fig. 2). Most recent tectonic models suggest that the Late Ordovician to Late Silurian Mascarene back-arc basin and associated Early Silurian Kingston arc and associated Pocologan Metamorphic Suite (Fyffe et al. 1999; Barr et al. 2002; White et al. 2006; Massonne et al. 2018) are related to Avalonia-Ganderia convergence by closure of the Acadian Seaway (Fyffe et al. 2011; van Staal and Barr 2012). If this is indeed the case one would expect that the Kingston arc to lie between the Caledonia (Avalonia) and Brookville (Ganderia) belts whereas it presently separates the Ganderian Brookville and New River belts. To circumvent this problem, the models assume major reorganization of crustal slices during significant dextral strike-slip movement on large northeast-trending faults in the Late Devonian and Carboniferous (Waldron et al. 2015). However, if the Brookville belt was originally on the upper plate during Early Silurian convergence with Avalonia one would expect voluminous magmatism of this age, whereas none has been recognized in the Brookville belt. These problems are well beyond the scope of this field guide, however, which will focus on the easternmost Neoproterozoic rocks of the Avalonian Caledonia belt.

In addition to Early Cambrian to Early Ordovician rocks of the Saint John Group, the Caledonia belt is overstepped by rocks of the Late Devonian to Early Permian Maritimes Basin, a large post-orogenic basin presently covering the eastern half of the province and parts of the southern coastal areas (St. Peter and Johnson 2009; Fyffe et al. 2011). The youngest successor basin is the Mesozoic Fundy Basin, a rift basin related to the initial opening of the Atlantic Ocean (Olsen and Et-Touhami 2008), which is well-represented within small fault-bounded basins along the Bay of Fundy coast.

GEOLOGY OF THE CALEDONIAN HIGHLANDS

The Caledonian Highlands are a northeast-trending series of prominent hills in southeastern New Brunswick that cover an area of approximately 3800 km^2 (Fig. 3). The highlands are part of the Caledonia belt, the easternmost of four Neoproterozoic basement belts in the province (Barr and White 1996, 1999; Johnson and McLeod 1996; White and Barr 1996; Fyffe 2014). As previously discussed, the Caledonia belt is the only one that is widely considered to be part of Avalonia (Fig.1). The Caledonia terrane is separated from the Ganderian Brookville terrane to the north by the Caledonia-Clover Hill Fault and adjacent Hammondvale Metamorphic Suite (Fig. 3), the latter a sliver of high-pressure/low temperature metamorphic rocks interpreted as the remains of an early Ediacaran accretionary complex (White et al. 2001). The southern boundary of the Caledonia terrane is the extension of the Cobequid - Chedabucto Fault in the Bay of Fundy, which separates it from the Meguma terrane in Nova Scotia.

Like other areas of Avalonia, the Caledonia terrane is typified by several pulses of Neoproterozoic arc-related magmatism, however it also preserves voluminous late Ediacaran (ca. 560 - 550 Ma), rift - related silicic magmatism not seen elsewhere in Avalonia (Barr and White 1999; Escribano 2021). The Neoproterozoic volcanic and comagmatic intrusive rocks are unconformably to disconformably overlain by the Cambrian to Early Ordovician Saint John Group. Minor units of felsite and rhyodacite yielded maximum Silurian - Devonian ages (Barr et al. 2020). The youngest rocks in the Caledonia terrane are continental clastic and minor marine rocks of the Late Devonian to Early Permian Maritimes Basin (Park and Hinds 2021), and Late Permian to Jurassic rocks of the Fundy rift basin (Nadon and Middleton 1984,1985).

Barr and White (1999) divided the Neoproterozoic volcanic, volcaniclastic and epiclastic rocks and comagmatic intrusions in the Caledonia terrane into two major groups (Fig. 3); the early Ediacaran (ca. 625 - 615 Ma) Broad River Group and the late Ediacaran (ca. 560 - 550 Ma) Coldbrook Group. Contacts between the Broad River and Coldbrook groups are now tectonic, but the original relationship is assumed to have been unconformable. Because of structural complexities and the potential for facies changes in the dominantly

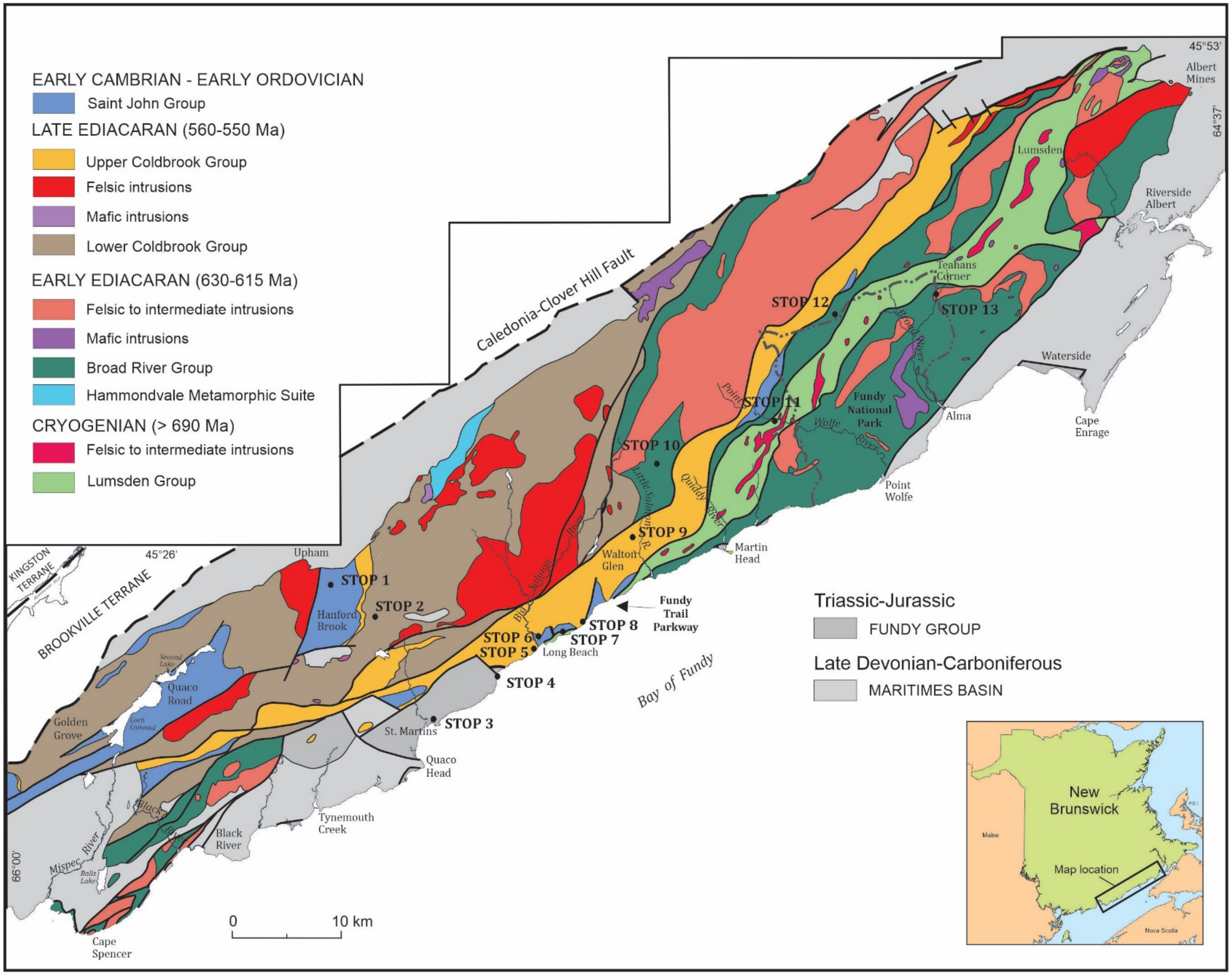

Figure 3. Simplified geological map of the Caledonian highlands showing field stops. Modified after Barr and White (2004).

volcaniclastic Broad River Group, Barr and White (1999) cautioned that the stratigraphy was poorly known. Recent mapping and U-Pb dating has shown that the Broad River Group, as it is currently defined, contains rocks much older than previously thought. A series of elongate felsic intrusions emplaced into the group have yielded preliminary U-Pb zircon ages, all within error around ca. 690 Ma (Barr et al. 2019, 2020). This demonstrates that the Crooked Creek Formation in the Lumsden area and rocks hosting these intrusions along strike which were previously assigned to the Broad River Group (Barr and White 2004), are at least 60 my older. This indicates that there is a cryptic boundary (fault or unconformity) in the central core of the Broad River Group in the eastern highlands that was not previously recognized. These older strongly schistose volcaniclastic, epiclastic and tuffaceous volcanic rocks are here informally named Lumsden Group (Fig. 3). The western boundary of the Lumsden Group has been delineated by recent mapping in the Point Wolfe River and Quiddy River areas (Johnson 2019) and in those areas corresponds with the location of the Cradle Brook thrust of McLeod (1986). A maximum age for the Lumsden Group has not yet been determined, but if it is not much older than the intrusions themselves it would be similar age as the ca. 680 Ma Stirling Group in the Avalonian Mira terrane of Nova Scotia (MacDonald and Barr 1993). Both areas contain stratiform base-metal deposits hosted within laminated pyritic siltstone-chert-carbonate sequences (the Lumsden deposit in the Caledonian Highlands and the Mindamar deposit in Nova Scotia and both sequences are intruded by younger (< ca. 630 Ma) Ediacaran plutons (Barr et al. 2019).

The distribution of Broad River/Lumsden and Coldbrook groups roughly corresponds to Ruitenberg et al.'s (1973, 1979) division of the highlands into two major structural domains; the Loch Lomond deformed zone in the western highlands and the Fundy cataclastic zone in the eastern highlands, although they considered both domains to be Coldbrook Group or equivalents. In the western highlands the Coldbrook Group and Cambrian cover is relatively undeformed, and only locally affected by a single slatey cleavage associated with broad open folding or tilting, as you will see on the first two stops on this field trip. Barr and White (1999) also mapped a narrow belt of Coldbrook Group along the western margin of the Fundy Cataclastic zone where along with the adjacent Broad River Group is very strongly deformed. A structural study by Park et al. (2008) describes a major (> 5 km wide) ductile high strain zone, in which rocks of the Coldbrook and Broad River groups are both mylonitic, with the former being recognized only within low-strain enclaves. Outside of the high strain zone the Broad River Group is affected by an intense penetrative foliation that is generally parallel to bedding (S_{0-1}). A second foliation (S_2) forms a widespread crenulation cleavage throughout outcrops of the Broad River Group (Park et al. 2008).

Lumsden Group (informal)

Preliminary mapping indicates that the Lumsden Group consists primarily of strongly cleaved phyllitic and schistose tuffaceous volcanic and epiclastic rocks. Dominant lithologies in the northeastern part of the group are dark grey laminated metasiltstone, tuffaceous siltstone, and metasandstones interlayered with dacitic, and andesitic to basaltic crystal and lithic crystal tuffs and chert (Barr and White 1999). Pyrite is common throughout the succession but is particularly abundant in the more felsic lithologies rendering them more difficult to date. The rocks in the northeastern part of the group were assigned to the Crooked Creek Formation by Barr and White (2004). The western and southwestern part of the group contains more abundant mafic volcanic rocks (mostly chlorite schist) that are basaltic to andesitic in composition (Gebru 2021). These are locally interlayered with narrow horizons of dacitic to rhyolitic volcanic and tuffaceous sedimentary rocks. As currently mapped these mafic rocks are assigned to the Hayward Brook Formation, however preliminary observations suggest that this is a misidentification of the unit outside of its type area. These mainly basaltic to andesitic volcanic rocks are given the name Long Beach Formation, which we will see at Stop 7.

Petrogenetic studies on the Cryogenian intrusive rocks emplaced into the Lumsden Group in the Goose Creek area indicate that are part of a tonalite, trondhjemite, granodiorite series (Gebru 2020), but elsewhere also include quartz-feldspar porphyry. Electron probe microanalyses of biotite from the Rat Tail Brook Granodiorite near the Lumsden deposit indicates a peraluminous affinity, in contrast to the calc-alkaline composition of the early Ediacaran intrusions (Barr and White 1999; Gebru 2021). Van Staal et al. (2021a) recently suggested that the “Goose River Group” (here tentatively replaced by the name Lumsden Group due to homonymy) represents a Cryogenian continental margin subduction zone, however lithogeochemical data for mafic volcanic rocks in the Lumsden area suggest a tholeiitic, possible island arc affinity (Gebru 2021). Since a maximum age for the Lumsden Group has not been established it is interesting to speculate that it may be significantly older than ca. 690 Ma, as in other parts of Avalonia suprasubduction-related oceanic rocks are only known to occur in the ca. 760 Ma ophiolitic Burin Group in Newfoundland (Murphy et al. 2008).

Broad River Group

The Broad River Group is characterized by ca. 615 Ma to ca. 625 Ma intermediate to felsic metavolcanic and metasedimentary rocks and comagmatic intrusive rocks that are exposed in the eastern and extreme southwestern parts of the highlands east of Saint John. (Barr and White 1996, 1999). The comagmatic intrusions range in composition from diorite to granite. In the southwestern highlands, metasedimentary rocks and granodiorite host the Cape Spencer gold deposit, which was mined for a short period in the mid-1980s (Watters 1993). Volcanic lithologies in the Broad River Group include felsic to intermediate crystal and crystal-lithic tuffs, flow-banded rhyolite and lesser andesitic to basaltic tuffs and flows. Distinct units of phyllite and quartzo-feldspathic and arkosic metasedimentary rocks, polymictic- and granite-cobble-conglomerate and minor limestone also occur (Watters 1993; Barr and White 1999; Satkoski 2010). Detrital zircon ages from quartz- and feldspathic- wacke from one of these sedimentary units (Pine Brook Formation) indicate a maximum depositional age of around 630 Ma. A minimum age for these sedimentary rocks is ca. 618 Ma, the age obtained for the cross-cutting Forty-Five River Granodiorite (Barr et al. 2019) that will be seen at Stop 13. The age of the volcanic rocks in the Broad River Group is constrained by a U-Pb zircon age of 613 ± 2 Ma for felsic tuff in the Bennett Brook Formation (Bevier and Barr 1990; Barr et al. 1994) and more recent ages of 622 ± 1.9 Ma and 615.5 ± 0.14 Ma for the East Branch Black River Formation and Little Salmon River Formation, respectively (Barr et al. 2020; pers. communication J. Crowley). Magmatism related to the Broad River Group is interpreted to have formed within an Andean-type convergent margin setting (Barr and White 1996, 1999).

Coldbrook Group

The late Ediacaran Coldbrook Group is characterized by voluminous, subaerial pyroclastic dacitic to rhyolitic tuffs, lava flows and breccia, basalt, and basaltic breccia, epiclastic rocks and minor basaltic to andesitic tuff (Barr and White 1999). The volcanic and associated gabbroic/dioritic and granitic plutons form most of the western highlands (Fig. 3), but are also well represented along the Fundy Trail Parkway and to the northeast within the St. Martins – Stuart Mountain high strain zone in the eastern highlands (Park et al. 2008). The group is divided into a lower sequence of dacitic, andesitic and rhyolitic tuffs and flows and epiclastic sedimentary rocks intruded by ca. 550 Ma granite and an upper sequence of rhyolitic (commonly ignimbrite) and basaltic volcanic rocks considered comagmatic with the associated plutons (Barr and White 1999). Numerous ages for volcanic and co-magmatic plutonic units have a narrow age range from ca. 560 Ma to ca.550 Ma, including errors, suggesting that the Coldbrook Group was deposited in less than 10 million years (Barr et al. 2019, 2020; Escribano 2021). Recent U-Pb ages of 551.19 ± 0.20 Ma for distinctive black, dacitic lithic-crystal tuff previously assumed to be from the lower Coldbrook Group, and 551.7 ± 0.15 Ma for rhyolite from the upper Coldbrook Group suggests that the stratigraphy needs revision. In addition, mylonitic granite (L-tectonite) thought to be part of the ca. 615 Ma Kent Hills pluton in the northeastern highlands recently yielded a poorly constrained U-Pb zircon age of ca. 550 Ma (Barr et al. 2019), indicating that plutonic rocks associated with the Coldbrook Group extend into that area.

The Coldbrook Group locally exhibits a single cleavage, except along major shear zones where it can be intensely sheared to mylonitic (Barr and White 1999; Park et al. 2008, 2017). In areas affected by intense mylonitization it is difficult to distinguish between the Coldbrook and Broad River groups. Intercalated basaltic and rhyolitic volcanic and laminated tuffaceous sedimentary rocks of the Hayward Brook Formation, previously assigned to the Broad River Group is one such case. Park et al. (2008) suggested that the presence of low-strain basaltic enclaves within the Hayward Brook Formation in the type area indicated that it is most likely part of the Coldbrook Group and detailed mapping of this sequence to the southwest in the Quiddy River area supports this view (Johnson 2019). Consequently, a flow-banded rhyolite was collected from this sequence and yielded a U-Pb zircon age of 549.2 ± 0.1 Ma age (Escribano 2021). This age is compatible with an earlier age of 548 ± 1 Ma (Bevier and Barr 1990) for felsic mylonite along strike that was assigned to the Silver Hill Formation. This suggests that the felsic mylonite is also part of the Hayward Brook Formation, which is only slightly younger than the Silver Hill Formation, which yielded an age of 551.7 ± 0.15 Ma in the type area (Escribano 2021).

Early geochemical studies utilizing both felsic and mafic rocks suggested a somewhat ambiguous, but probable within-plate extensional setting for the Coldbrook Group (Barr and White 1999). This is supported by more recent lithogeochemical data that indicates A-type characteristics, although not pronounced, for most of the silicic magmatism in the upper Coldbrook Group. Sm-Nd isotopic data indicate that they are crustal melts derived from the same relatively juvenile source as the older arc-related Broad River Group, which could explain the low Nb values in some of these rocks (Escribano 2021). A recent study utilizing chemical data from the entire group shows a wide range of compositions from basalt to basaltic andesite, andesite, dacite and rhyolite (Gebru 2016), therefore the group overall, is not bimodal. Major and trace element geochemistry from this study also demonstrates that the basaltic and rhyolitic rocks define different population trends indicating that they are not cogenetic. Although the felsic rocks have within-plate affinities and are equivalents of A2 granites (anorogenic granites derived from continental crust), the mafic rocks exhibit mixed mid-ocean-ridge basalt (MORB) / island arc signatures (Gebru 2016).

Saint John Group

The platformal sedimentary rocks of the Saint John Group are part of the classic Avalonian cover sequence (Landing 1996). From base to top, the group includes the Lower Cambrian Ratcliffe Brook, Glen Falls, and Hanford Brook formations; Middle Cambrian Forest Hills and King Square formations; Upper Cambrian Silver Falls Formation; and Lower Ordovician Reversing Falls Formation (Tanoli and Pickerill 1988), most of which are separated by depositional hiatuses (e.g., Landing and Westrop 1998; Palacios et al. 2011, 2017). Most of the following description is taken from Tanoli and Pickerill (1988). The basal Ratcliffe Brook Formation consists of coarse siliciclastic rocks including grey to maroon conglomerate, pebbly sandstone, feldspathic quartzite, and reddish and grey green, fine-grained sandstone, and siltstone. The overlying Glen Falls Formation consists of coarse-grained, white quartzite and coarse-grained, quartzose sandstone, and black (phosphatic) quartzite. The overlying Hanford Brook Formation is fine-grained, olive grey to dark grey sandstone, siltstone, and shale. The Forest Hills Formation contains dark grey, siliceous limestone and light grey mudstone overlain by fine-grained, grey sandstone and light to dark grey, micaceous siltstone and shale of the King Square Formation. The Late Cambrian and Early Ordovician rocks are dark grey to black shale with thin calcareous sandstone interbeds of the Silver Falls Formation; and black, pyritiferous, carbonaceous shale of the Reversing Falls Formation.

Maritimes Basin

Late Devonian to Late Carboniferous continental clastic and minor marine rocks of the Maritimes Basin occur throughout eastern New Brunswick where they form an extensive cover sequence lying unconformably on the older basement rocks (St. Peter and Johnson 2009). These rocks are also exposed in strongly deformed, fault-bounded enclaves along the Bay of Fundy coast (Park and Hinds 2021), where they have complex relationships with Ediacaran and older basement as seen at Stops 7 and 8. The stratigraphic succession comprises fluvial, alluvial, and minor lacustrine red and grey beds and marine carbonates and evaporites that can be up to 6 km thick and show sufficient regional similarity to be divisible into six disconformity–unconformity-bounded groups (St. Peter and Johnson 2009), and references therein. Strata of the Maritimes Basin host economic deposits of oil and natural gas in the Tournaisian Horton Group, and potash in the Viséan Windsor Group, the only marine member within the basin.

Fundy Group

The youngest rocks in the Caledonian highlands are those of the Late Permian to Jurassic Fundy Group (Nadon and Middleton 1984, 1985; Wade et al. 1996; Olsen and Et-Touhami 2008), which occur in St. Martins and adjacent areas along the Bay of Fundy coast. The Fundy Group is part of the larger Newark Supergroup of eastern North America (Olsen 1988), a sequence of continental redbeds and rift basalts that were deposited in a series of rift basins associated with the breakup of Pangea and opening of the present-day Atlantic Ocean. The Fundy basin has been compared to the Argana and Essaouria basins in western Morocco and basins of the High Atlas and Central High Atlas (Olsen and Et-Touhami 2008).

The Fundy rift basin of Atlantic Canada is a half graben structure containing alluvial fan and flood plain-alluvial fan redbeds and lacustrine deposits, eolian sandstone, fluvial sandstone- conglomerate, and rift basalts (Wade et al. 1996; Olsen and Et-Touhami 2008). In New Brunswick, the rocks of the Fundy Group are divided into, in ascending order, the Honeycomb Point, Quaco, and Echo Cove formations (Nadon and Middleton 1985) and the North Mountain Formation basalt (Wade et al. 1996; Marzoli et al. 1999; Pe-Piper and Piper 1999). The lower two formations can be seen at the sea caves near St. Martins at Stop 3 (Fig 7). The continental flood basalts and associated tholeiitic dikes occur on Grand Manan Island in New Brunswick (McHone 2011) and along the Minas Basin and southern Bay of Fundy in Nova Scotia, including on Isle Haute. Isle Haute can be seen from several parkway lookouts on a clear day. Although the basalts are not exposed in the St. Martins area, an olivine diabase dyke that cuts the Cambrian rocks in the large outcrop north of the Mitchell-Franklin Bridge is considered part of the Mesozoic dyke swarm associated with the mafic lavas of the Fundy Group (Park et al. 2017).

STOPS

STOP 1: Saint John Group, Hammond River – King Square Formation (45.4664º; -65.6350º)

Under the Hammond River bridge on Route 111 (near the community of Hanford Brook) is a typical exposure of the shallow marine siliciclastic rocks of the Saint John Group. Here it consists of gently folded, interbedded sandstone and shale that are from the upper part of the King Square Formation (Fig. 4). The wave-deposited sandstone and shale have been interpreted as a wave- storm-influenced shelf sequence (Tanoli and Pickerill 1989). The King Square Formation has been correlated with the upper Middle to lower Upper Cambrian (Miolingian-Furongian) MacLean Brook Group in Newfoundland (Landing and Westrop 1998).

Figure 4. Folded sandstone and shale of the upper King Square Formation (Saint John Group) on Hammond River near the community of Hanford Brook.

STOP 2: Coldbrook Group, Hanford Brook area – Fletcher Brook and Ben Lomond formations (45.4481º; -65.5827º)

On a logging road east of Route 111 an exposure of brecciated rhyolite tuff shows spectacular, brecciated, eutaxitic banding and locally well-developed spherulites (Fig. 5a, b). The tuff at this location is at the base of the Fletcher Brook Formation and is overlain by a variety of rhyolitic to dacitic, lithic, crystal and vitric tuff and dacitic flows and coarse basaltic lithic tuff, tuff breccia (Fig. 5c), and amygdaloidal basaltic flows. The rhyolite tuff here yielded a U-Pb (zircon) age of 555.5 ± 1.9 Ma (Barr et al. 2020), providing a minimum age for the underlying Ben Lomond Formation (Fig. 5d), exposed on the same logging road a further 1.8 km to the northeast. The dacitic tuffs of the Ben Lomond Formation are hematitized and transected by a sharp redox boundary at this location. The Fletcher Brook Formation is overlain by the Silver Hill Formation that yielded a precise U-Pb age of 551.7 ± 0.15 Ma, providing a minimum age for the Fletcher Brook Formation.

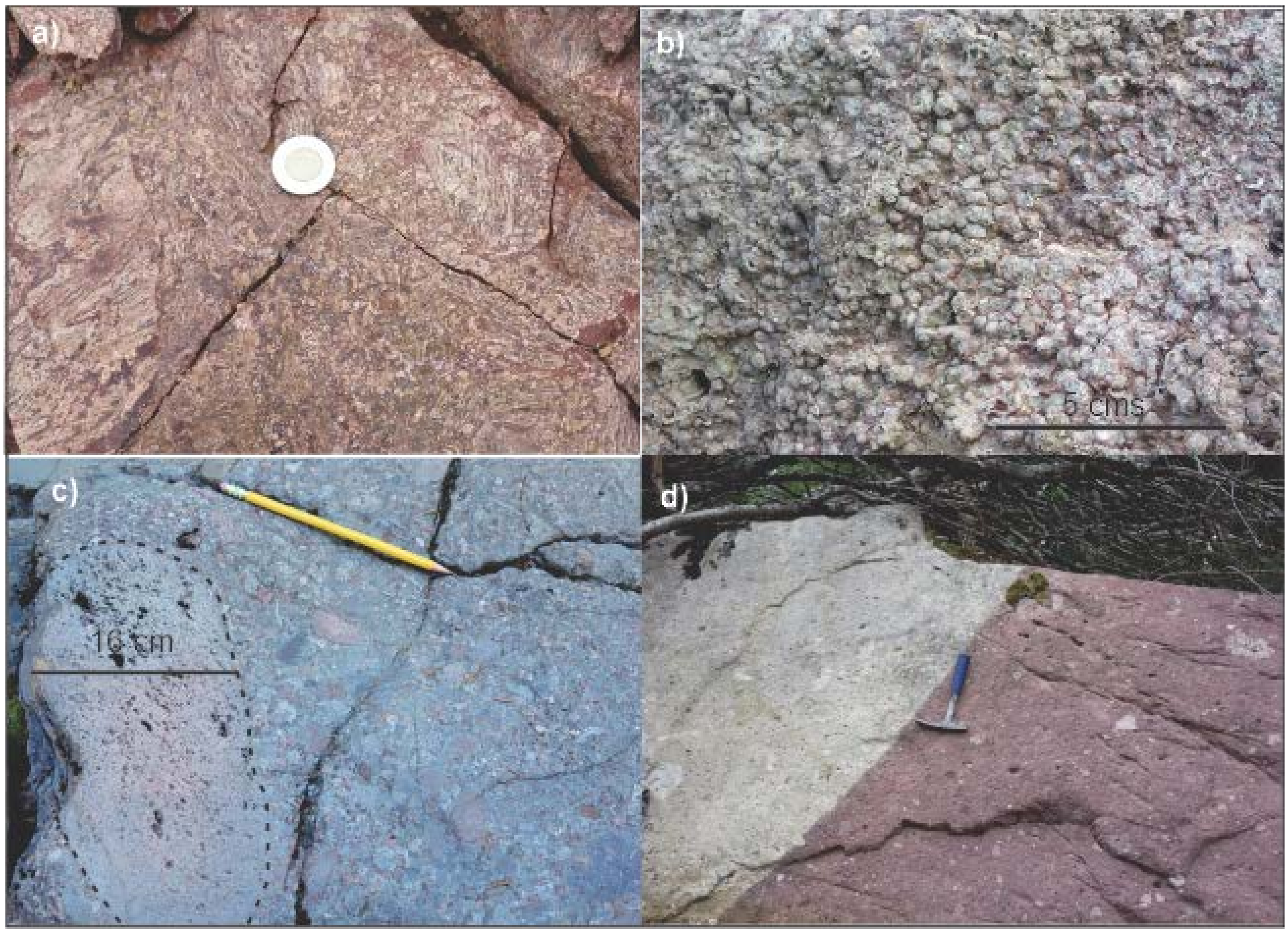

Figure 5. Typical lithologies of the Coldbrook Group in the western Caledonian Highlands. a) brecciated flow-banded rhyolite b) spherulitic rhyolite c) basaltic tuff breccia d) dacitic lithic-crystal tuff cut by sharp redox boundary.

***The next stop on Macs Beach (Stop 3) and the following stops on the Fundy Trail Parkway (Stops 4 to 9) are within Stonehammer Geopark, the first North American member of the Global Geoparks Network.**

STOP 3: Macs Beach, St. Martins – contact between the Honeycomb Point and Quaco formations, Late Permian to Triassic Fundy Group (45.3576º; -65.5233º)

At the east end of Macs Beach, one of the highlighted geosites within Stonehammer Geopark, you see the low angle unconformity between the Honeycomb Point Formation and overlying Quaco Formation, the lower two formations of the Fundy Group in New Brunswick. The Quaco conglomerate rests with abrupt, erosional contact on the underlying Honeycomb Point Formation (Fig. 6). The section dips moderately to the north toward the fault marking its boundary with Neoproterozoic Coldbrook Group volcanic rocks. The Honeycomb Point Formation is comprised of gravely sandstone and conglomerate with angular clasts of mostly local volcanic rocks, and interbedded red shale. Eolian sandstone and caliche occur lower in the formation (Nadon and Middleton 1985; Olsen and Et-Touhami 2008). Tetrapod trackways have been reported from mud-cracked red shale on the roof of a cave at this locality, and in the type area near Honeycomb Point, although none are age diagnostic (Sues and Olsen 2015). However, the discovery in 2020 of well-preserved trackways from the latter locality are promising (New Brunswick Museum press release Dec 8, 2020). The Honeycomb Point Formation is probably Late Permian based on paleomagnetic data and correlation with units in the Argana basin in Morocco (Olsen and Et- Touhami 2008). The overlying Quaco conglomerate shows a rapid change to grey, mostly clast-supported conglomerate with well-rounded pebbles and cobbles and local sandstone lenses. The most conspicuous clasts are banded quartzite that display crescentic percussion marks and circular dissolution pits (Nadon and Middleton 1985). The Quaco Formation was deposited in a large river with sustained flow, therefore a more humid environment than the underlying Honeycomb Point Formation (Olsen and Et-Touhami 2008). This is supported by the presence of plant detritus in some of the grey sandstones.

Figure 6. Sharp erosional contact between Honeycomb Point Formation below, and grey Quaco Formation above, Fundy Group, Macs Beach, St. Martins.

*** The next stops on the Fundy Trail Parkway require an entrance fee that can be paid at the kiosk.**

STOP 4: Melvin Beach Lookout (45.3945º; -65.4539º)

Moderately dipping, red sandstone, and conglomerate form the barrier between Melvin and Pangburn beaches at high tide (Fig. 7). These bright red sandstones are Triassic age, and part of the Echo Cove Formation of the Fundy Group. The steeping dipping cliffs at the northeast end of the beach are strongly deformed rhyolitic and basaltic volcanic rocks of the late Ediacaran Silver Hill Formation, which is part of the Coldbrook Group.

Figure 7. View of Pangburn beach showing gently dipping sandstone of Triassic Echo Cove Formation in foreground and steeply-dipping, Coldbrook Group rhyolite in the distance.

STOP 5: Coldbrook Group rhyolite and basal Saint John Group (45.4148º; -65.4119º)

At this location the outcrop on your left (to the west) is rhyolite assigned to the Silver Hill Formation. The rhyolite is strongly sheared and cut by numerous quartz-filled tension gashes. It locally exhibits intense, light green sericite alteration and is best described as a quartz-chlorite-white mica phyllite that locally displays a mylonitic fabric. The deformation seen in this outcrop contrasts with that of the Coldbrook Group inland in the western highlands but is typical throughout the St. Martins-Stuart Mountain high-strain zone (Park et al. 2008).

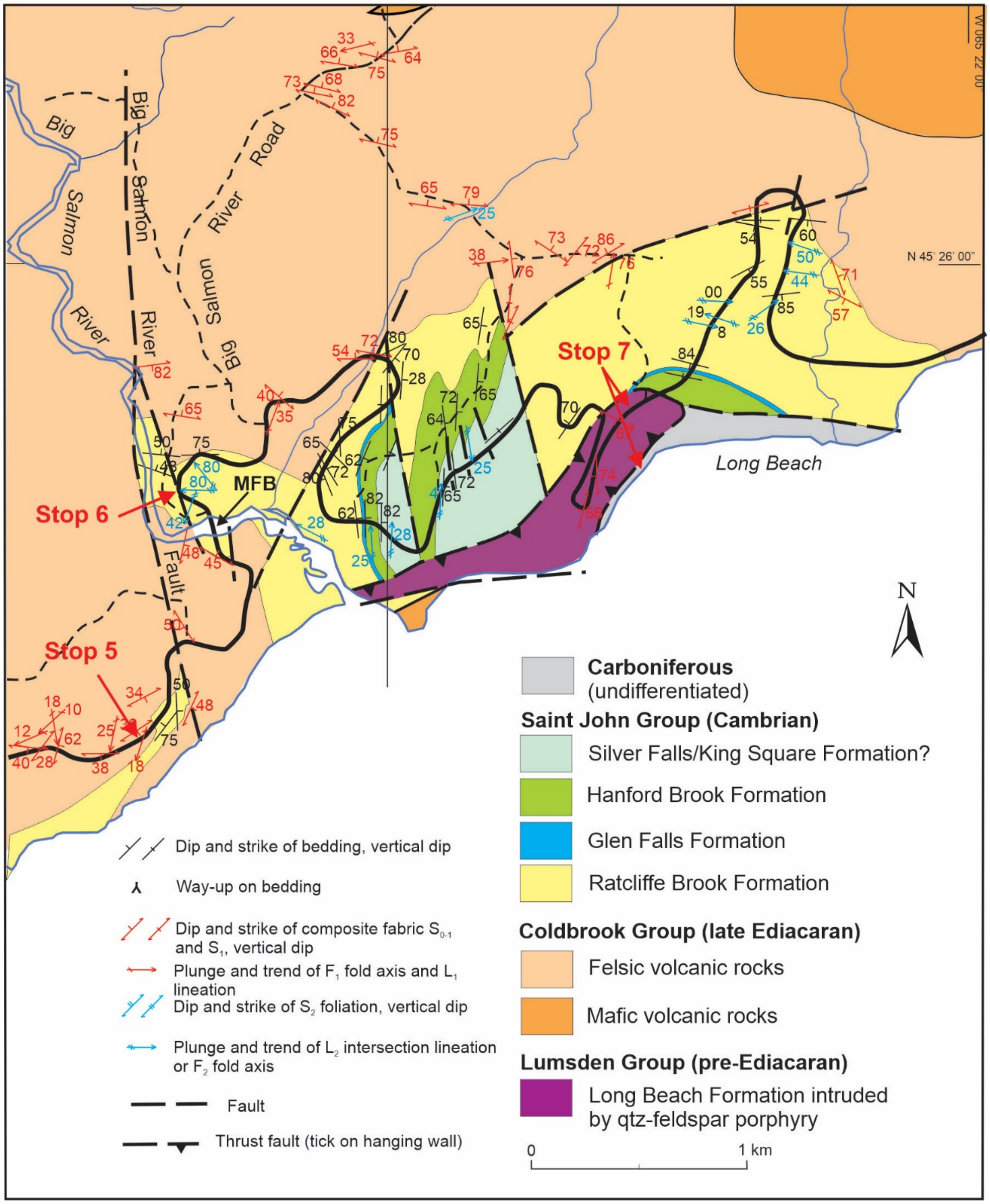

Figure 8. Geological map of the Big Salmon River – Long Beach area, modified from Park et al. (2017) showing location of Stops 5–7; MFB-Mitchell Franklin Bridge.

A concealed zone to the east (to the right) separates the Silver Hill Formation from the basal beds of the Cambrian Saint John Group, which are exposed in the next outcrop to the east. The Cambrian rocks here occupy a synclinal keel with the older Coldbrook Group exposed on both limbs (Fig. 8). The thick-bedded, greyish maroon pebbly sandstone and conglomerate are characteristic of the basal Ratcliffe Brook Formation, the lowermost formation within the Early Cambrian to Early Ordovician Saint John Group. Highly micaceous maroon siltstone and sandstone beds are present locally (Park et al. 2017).

The deformation visible at this location and other areas along the parkway is most likely related to movement along the Cobequid – Chedabucto Fault, that lies just offshore in the Bay of Fundy, and defines the boundary between the Avalonian Cobequid Highlands and the Meguma terrane on mainland Nova Scotia. However, it is not clear if this movement was related to dextral oblique docking of the Meguma terrane to Avalonia during Neo-Acadian events (Middle Devonian to Viséan) or the accretion of the main mass of Gondwana and final assembly of Pangea during the Alleghanian orogeny (Upper Mississippian to Middle Permian) (van Staal and Barr 2012). We do know that the alteration accompanying the gold mineralization at Cape Spencer along the coast to the southwest is Early Permian based on $^{40}Ar/^{39}Ar$ dating of the associated illite (Watters 1993).

STOP 6: Ratcliffe Brook Formation, Saint John Group, Big Salmon River (45.4252º; -65.4102º)

Please note it is advisable to stay away from the cliff face here as there is danger of falling rocks. The description and map provided below are from Park et al. (2017).

The spectacular outcrop just north of the Mitchell Franklin bridge, affectionately known as “the mess”, consists mainly of strongly sheared and deformed Ratcliffe Brook Formation sedimentary rocks (Fig. 9). Immediately north of the bridge near the base of the hill there is a brownish-weathered mafic dyke cutting the Ratcliffe Brook Formation. The dyke post-dates all tectonic fabrics and petrological analysis shows it is an olivine-pyroxene diabase, like the Mesozoic dykes associated with the rift basalts at the top of the Fundy Group. Driving uphill, most of the exposure is sheared Ratcliffe Brook Formation cut by numerous deformed quartz and carbonate veins. The Ratcliffe Brook Formation is divided into two members following Landing (1996); the lower Quaco Road member and upper Mystery Lake member. Both members can be seen here.

The Quaco Road Member is typically buff to reddish or maroon, and predominantly coarse- grained, with minor shaly partings. Feldspathic quartz arenite, arkose and interbedded micaceous siltstone and fine-grained sandstone with rare ash beds are the dominant rock types. The finer grained sedimentary rocks of the overlying Mystery Lake Member are more varied, from red and red-brown to green or grey-green. They are fine- to medium-grained, wave deposited, feldspathic and micaceous sandstone and siltstone with several thin volcanic ash beds and local beds of quartz-pebble conglomerate. An Early Cambrian (late Fortunian) U-Pb zircon age of 530.7 ± 0.9 Ma was obtained from a thin volcanic ash bed in the Ratcliffe Brook Formation in the city of Saint John (Isachsen et al. 1994).

Around the turn, the Cambrian strata are infolded with intensely sheared phyllitic to mylonitic rhyolite of the Neoproterozoic Coldbrook Group. The contact with the rhyolite can be seen near the northeastern end of the outcrop toward the top of the hill.

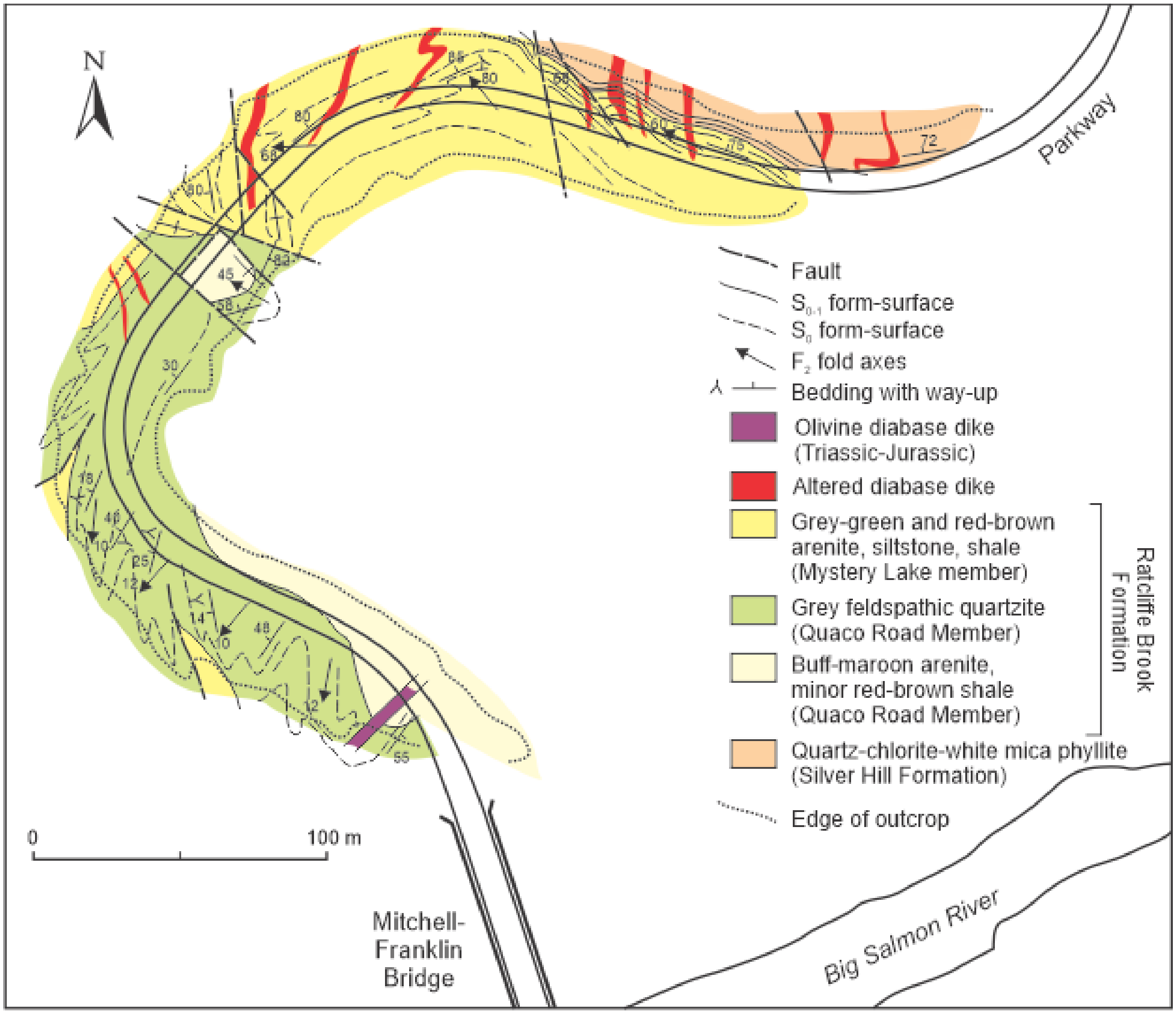

Figure 9. Form-surface map of bedding and F2 folds at Stop 6 in the large roadcuts on the Fundy Trail Parkway north of the Mitchell-Franklin Bridge. From Park et al. 2017.

STOP 7: Long Beach Formation basalt cut by felsic porphyry, Long Beach Lookout (45.4272º; -65.3859º)

On a clear day, Isle Haute and Cape Chignecto in Nova Scotia can be observed across the Bay of Fundy from the Long Beach Lookout. The outcrop on the north side of the road is comprised of deformed and metamorphosed basalt that is part of the newly defined Long Beach Formation (Lumsden Group). Here and at the west end of Long Beach, the basalt is cut by a quartz-feldspar porphyry intrusion that is deformed with the basalt. The porphyry exposed in this roadcut yielded a preliminary U-Pb (zircon) age of 685 ± 10 Ma (Barr et al.

2020). Prior to determining its age, the basalt was considered part of the ca. 555 Ma Coldbrook Group, or even possibly Carboniferous age, as enclaves of basalt farther west along the coast near Saint John are part of the ca. 358 Ma Lorneville Group (Park et al. 2014).

This same basalt forms part of the headland and shore below between Big Salmon River and Long Beach (45.4246º; -65.3849º) where it structurally overlies Carboniferous red siltstone and grey sandstone that locally contain plant fossils (Fig. 10a). The outcrop in the cliff and along the shore at this location show a zone of strongly tectonized red siltstone and mudstone containing isolated blocks of reddish grey to grey sandstone and pebbly sandstone. These sediments are locally strongly altered and crosscut by abundant carbonate veins and masses. At the top of the cliff face, a reverse fault that dips steeply into the cliff brings the basalt to the south over the redbeds (Fig. 10a). The faulted contact between the redbeds and strongly epidotized and deformed pillow basalt (Fig.10b) is exposed on the shore a further 250 m to the southwest.

Figure 10. Long Beach Formation on Long Beach. a) basalt in the high cliff, reverse-faulted against overturned early Carboniferous red siltstone with isolated blocks of grey sandstone. Note person (circled) for scale. b) strongly epidotized pillow basalt of the Long Beach Formation, Lumsden Group.

STOP 8: Martin Head Lookout – Triassic, Carboniferous, and Cryogenian? basalt (45.4387º; -65.3553º)

Looking up the coast towards the northeast you get a view of Martin Head, the rocky headland at the mouth of Quiddy River (Fig. 11). The headland is composed of strongly deformed and epidotized pillow basalts of uncertain age (Fig. 12a). Although similar to basalt in the Long Beach Formation, its age is difficult to decipher here due to a lack of stratigraphic context and the presence of similar pillowed basalt exposed near the mouth of Cradle Brook to the southwest that is intermingled with rhyolite which yielded a U-Pb age of ca. 554 Ma (Barr et al. 2019). Pillow basalt is not known to occur in the mainly subaerial Coldbrook Group and the structural complexity at Cradle Brook precludes a definitive correlation of the basalt there with the late Ediacaran Coldbrook Group.

A gravel bar separates the pillow basalt from gently northwest dipping strata assigned to the Echo Cove Formation (Fig. 12b). The Echo Cove Formation overlies the Quaco Formation conglomerates seen at Stop 3 and was deposited in a fluvial environment (Nadon 1982; Nadon and Middleton 1984). Wood fragments and plant fossils that occur in the sandstone at this locality (Fig. 12c) are consistent with a Carnian age (Olsen and Et-Touhami 2008). The gently dipping Triassic section at Martin Head is juxtaposed against very strongly deformed rocks of the Viséan Windsor Group (Fig.12d), indicating that the deformation is likely late Mississippian or possibly Pennsylvanian age, and related to movement along the Cobequid Chedabucto Fault.

Figure 11. View from Martin Head Lookout showing coastal locations mentioned in text.

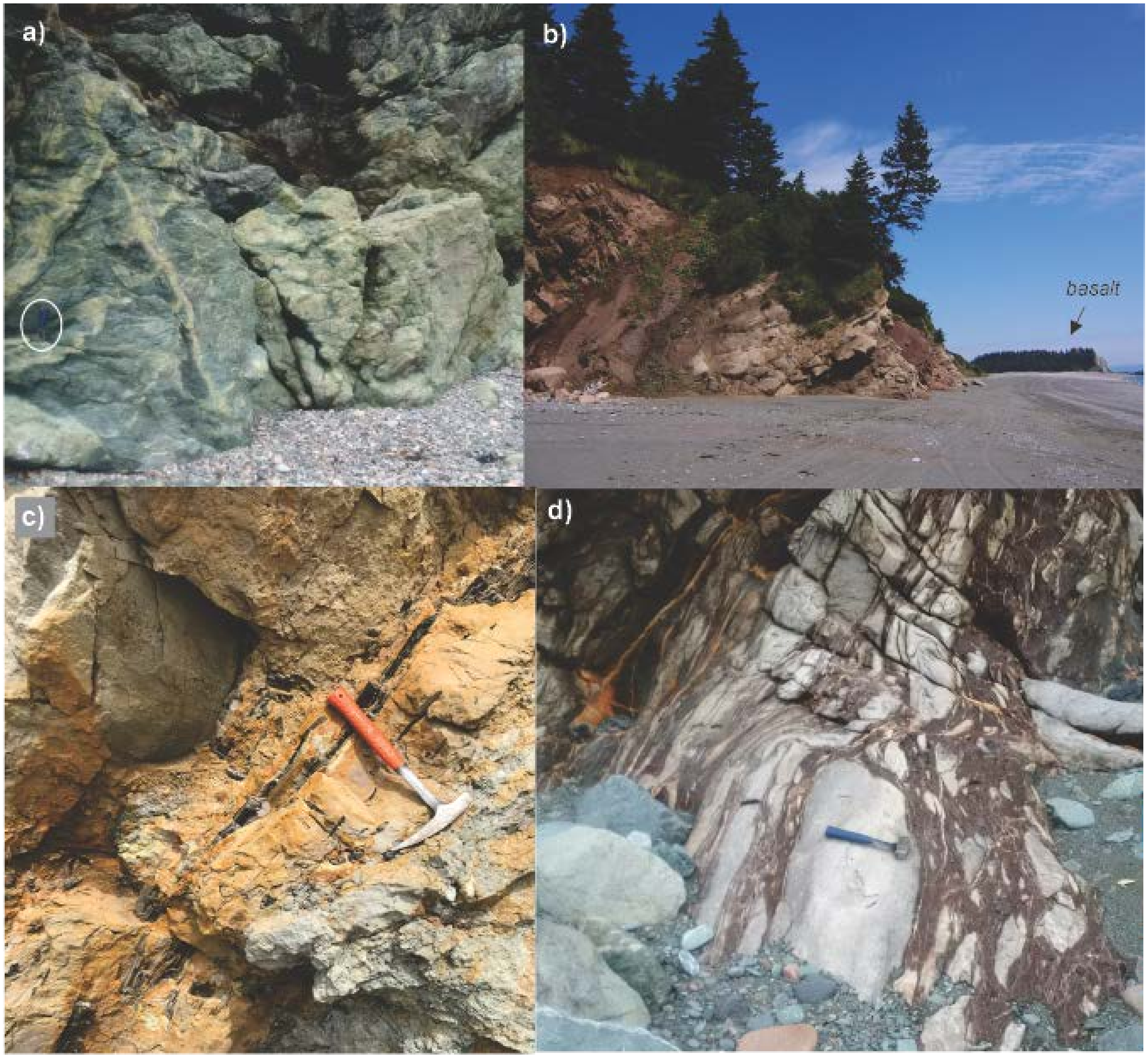

Figure 12. Lithological units at Martin Head. a) at the head itself, strongly epidotized and deformed pillow basalts of uncertain age. Hammer for scale (circled) is 28 cm. b) gently tilted Triassic sandstone of the Echo Cove Formation on shore northwest of Martin Head c) close-up of Triassic sandstone with coalified wood fragments d) gypsum boudins in the Windsor Group immediately west of the normal fault bounding Triassic rocks to the east.

STOP 9: Walton Glen Gorge Lookout (45.4933º; -65.3008º)

Walton Glen Gorge is part of Walton Glen Brook, a south-flowing tributary of the Little Salmon River. The cliffs within the gorge are composed of light maroon rhyolitic flows and massive rhyolite of the Coldbrook Group (Fig. 13), assigned to the Silver Hill Formation by Barr and White (1999). The flows occur in layers 1 to 2 m thick and commonly exhibit contorted flow laminations. The igneous layering may be transposed by deformation and is oriented parallel to the regional tectonic fabric (McLeod 1987). Mapping of these rocks to the northeast on Quiddy River indicate that the rhyolite is part of a mixed sequence containing nearly equal proportions of rhyolite, basalt, and tuffaceous sedimentary rocks (Johnson 2019). Porphyritic rhyolite from the Quiddy River sequence yielded an age of 549.2 ± 0.1 Ma, nearly 2 m.y. younger than the 551.7 ± 0.15 Ma age obtained for the Silver Hill Formation in the type area. These two sequences also display differences in whole-rock and zircon chemistry, suggesting that the rhyolite along the Fundy Trail Parkway and along strike to the northeast are not part of the Silver Hill Formation (Escribano 2021).

Figure 13. View of Coldbrook Group rhyolite from the Walton Glen Gorge Lookout platform. Note the flat, southeast-dipping tectonic fabric that is parallel to layering in the volcanic rocks.

STOP 10: Little Salmon River Formation, Broad River Group (45.5464º; -65.2674º)

Dacitic crystal tuffs and crystal-lithic tuffs of the Little Salmon River Formation were assigned to the Broad River Group based on their location along the southern margin of the ca. 618 Ma Old Shepody Road Granite. However, an apparent lack of contact metamorphic features in the tuffs and a complex relationship with adjacent units in the Coldbrook Group brought this interpretation into question (Barr and White 1999), therefore the Little Salmon River Formation was chosen for dating in 2020. A foliated, dacitic feldspar-quartz crystal tuff (Fig.14) yielded a new U-Pb (zircon) age of 615.5 ± 0.14 Ma (Jim Crowley personal comm) confirming that it is part of the ca. 630-615 Ma Broad River Group.

Figure 14. Cut slab of the dated dacitic crystal tuff from the Little Salmon River Formation.

STOP 11: Lumsden Group – Broad River Group contact, Point Wolfe River Gorge (45.5936º; -65.1420º)

In Point Wolfe River Gorge, dark green chloritic schist assigned to the Lumsden Group is intercalated with light grey, coarse-grained, granitic sheets that are similar to elongated trondhjemite bodies described by Gebru (2020) less than 2 km south in the Goose Creek area. The Goose Creek Trondhjemite (Goose Creek Leucotonalite of Barr and White 1999) yielded a U-Pb (zircon) age of 686.8 ± 3.7 Ma (Barr et al. 2019). Less than a few metres west of the chlorite schist on Point Wolfe River (Fig. 15 a) occur less deformed, metasandstone and conglomeratic metasandstone of the Pine Brook Formation (Broad River Group), which exhibit a moderate northwest-dipping bedding parallel cleavage (Fig. 15 b, c). A lack of shearing in the metasandstones suggests that the contact may be unconformable suggesting that the Broad River Group was deposited on the Lumsden Group, however a faulted contact cannot be ruled out.

STOP 12: Pine Brook Formation, Broad River Group, Shepody Road (45.6734º; -65.0633º)

These outcrops on the Shepody Road are part of the Pine Brook Formation. At this location the formation consists of strongly banded and crenulated quartz- and feldspathic wacke, purple siltstone, and matrix-supported conglomerate with abundant vein quartz clasts (Fig. 16 a, b). The Pine Brook Formation is spatially associated with phyllites tentatively assigned to the Lumsden Group, and its overall lithological distribution and structure suggests that it overlies the latter on the limbs of a large anticlinal structure in this area (Barr and White 1999).

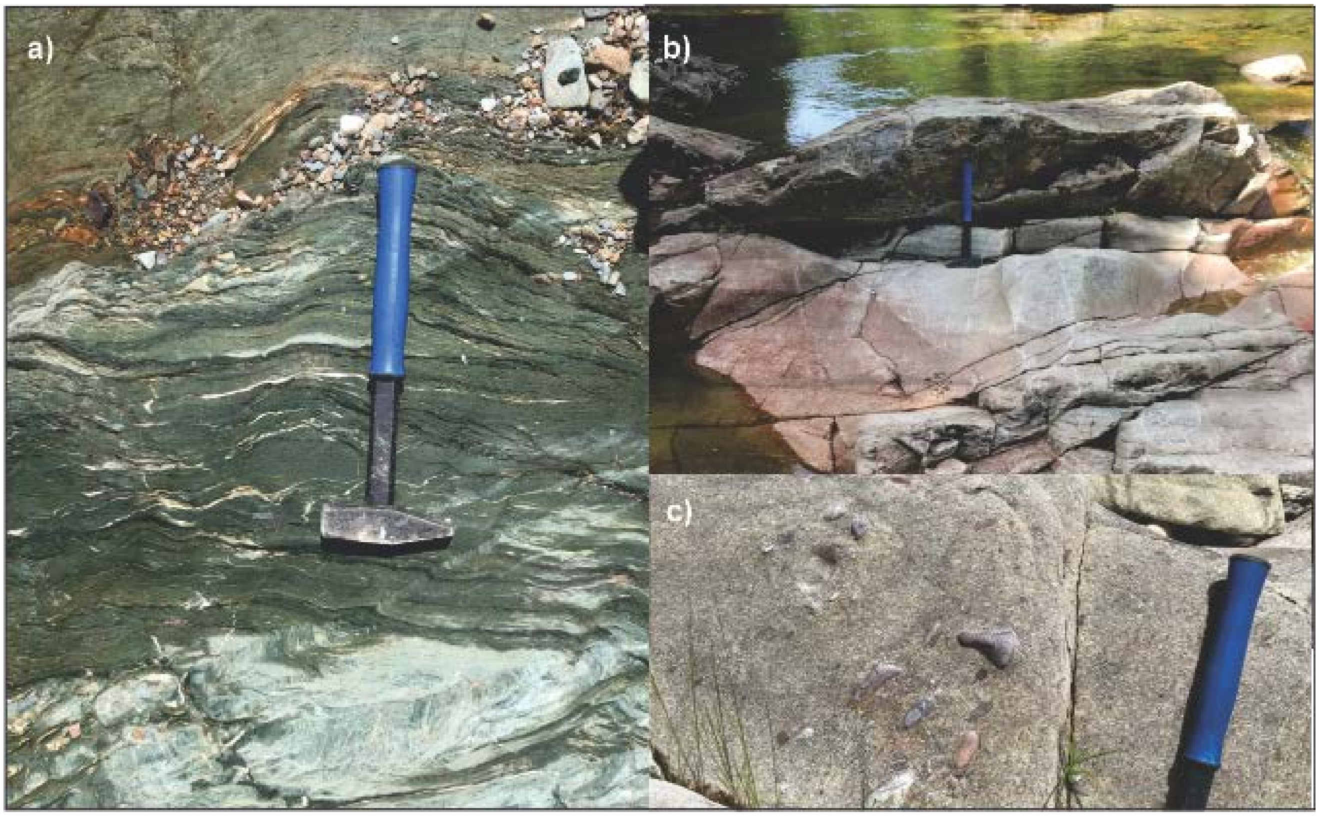

Figure 15. Lumsden Group/Broad River Group contact on Point Wolfe River. a) strongly deformed chloritic schist of Long Beach Formation (Lumsden Group) b) massive quartz wacke and c) conglomeratic sandstone of the Pine Brook Formation (Broad River Group). Hammer handle approximately 15 cms.

STOP 13 Forty Fiver River Granodiorite, Fundy National Park (45.6867º; -64.9533º)

South of the covered bridge crossing Forty-Five River on the eastern boundary of Fundy National Park felsic intrusive rocks of the Forty-Five River Granodiorite are well exposed (Fig.17). The granodiorite at this location recently yielded a U-Pb (zircon) age of 618.8 ± 2.6 Ma (Barr et al. 2019). The granodiorite intrudes metasedimentary rocks of the Pine Brook Formation to the east on the Forty-Five Road where detrital zircon from the feldspathic metasandstone yielded ages as young as ca. 630 Ma constraining the age of these rocks to the early Ediacaran.

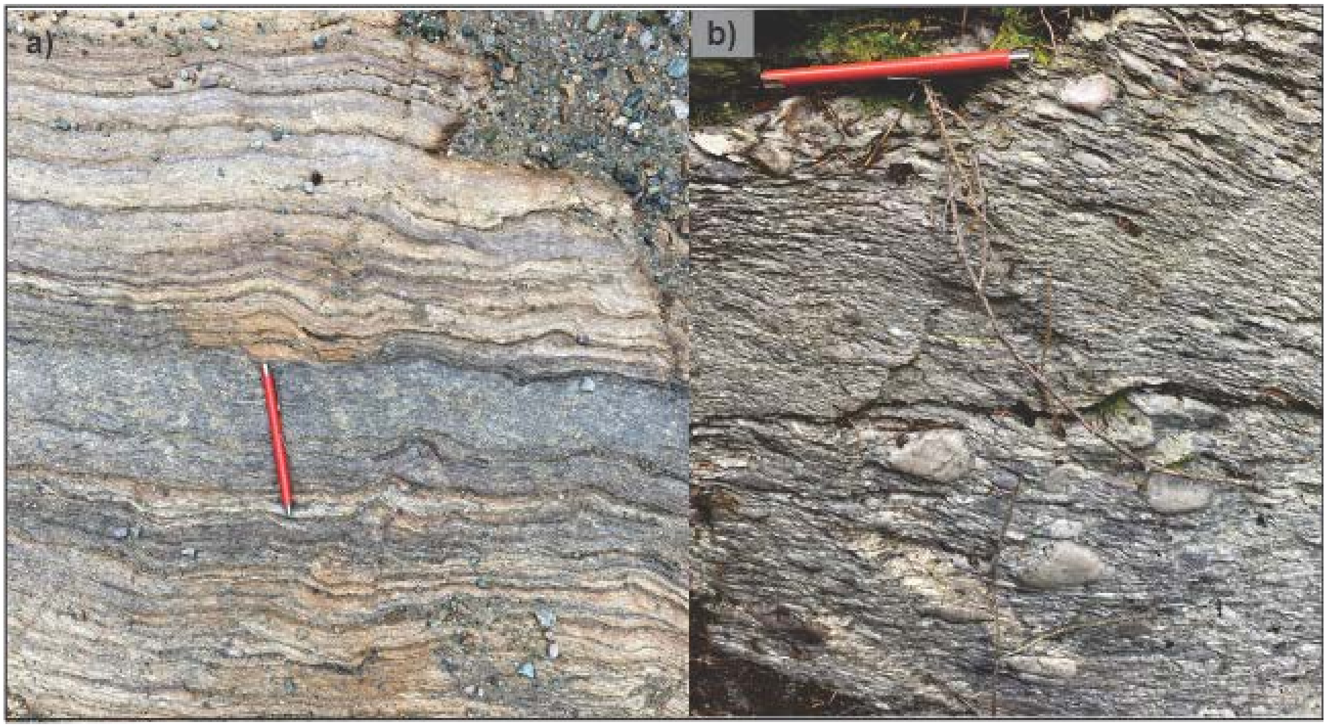

Figure 16. Mylonitic metasedimentary rocks of the Pine Brook Formation on Shepody Road. a) crenulated quartz-and feldspathic wacke and siltstone b) conglomeratic layers with abundant vein quartz.

Figure 17. View of Forty-Five River Granodiorite from covered bridge.

ACKNOWLEDGEMENTS

The support of the Geological Surveys Branch of New Brunswick Department of Natural Resources and Energy Development is greatly appreciated. We gratefully acknowledge Ayalew Gebru for his important work in the Caledonian Highlands and to Steven Rossiter, Alex Smith and Andy Parmenter for their very capable field assistance. Sandra Barr and Chris White are thanked for their continued support and insight into the geology of southern New Brunswick, and for lively discussions during numerous field excursions to the Caledonian Highlands and beyond.

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