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The Grand Manan Terrane of New Brunswick: Tectonostratigraphy and Relationship to the Gondwanan Margin of the Iapetus Ocean

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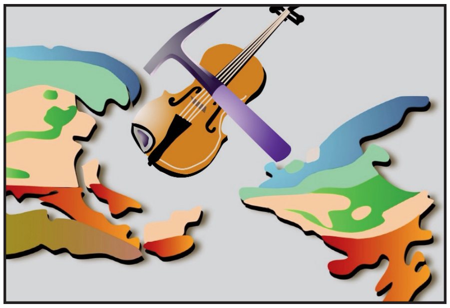
Article abstract

Recently gathered stratigraphic and U–Pb geochronological data indicate that the pre-Triassic rocks of the Grand Manan Terrane on the eastern side of Grand Manan Island can be divided into: (1) Middle Neoproterozoic (late Cryogenian) quartzose and carbonate sedimentary sequences (The Thoroughfare and Kent Island formations); (2) a Late Neoproterozoic (early Ediacaran) volcanic-arc sequence (Ingalls Head Formation); and (3) Late Neoproterozioc (mid- Ediacaran) to earliest Cambrian (early Terreneuvian) sedimentary and volcanic-arc sequences (Great Duck Island, Flagg Cove, Ross Island, North Head, Priest Cove, and Long Pond Bay formations). A comparison to Precambrian terranes on the New Brunswick mainland (Brookville and New River terranes) and in adjacent Maine (Islesboro Terrane) suggests that the sedimentary and volcanic sequences of the Grand Manan Terrane were deposited on the continental margin of a Precambrian ocean basin that opened during the breakup of Rodinia in the Middle Neoproterozoic (Cryogenian) and closed by the Early Cambrian (Terreneuvian) with the final assembling of Gondwana. Rifting associated with the initial opening of the Paleozoic Iapetus Ocean began in the Late Neoproterozoic (late Ediacaran) and so overlapped in time with the closing of the Precambrian Gondwanan ocean. The southeastern margin of the Iapetus Ocean is defined by thick sequences of quartz-rich Cambrian sediments (within the St. Croix and Miramichi terranes of New Brunswick) that were largely derived from recycling of Precambrian passive-margin sedimentary rocks preserved in the Grand Manan and Brookville terranes of New Brunswick and in the Islesboro Terrane of Maine. These Precambrian terranes are interpreted to represent dextrally displaced basement remnants of the Gondwanan continental margin of Iapetus, consistent with the model of a two-sided Appalachian system proposed by Hank Williams in 1964 based on his work in Newfoundland.

HAROLD WILLIAMS SERIES



The Grand Manan Terrane of New Brunswick: Tectonostratigraphy and Relationship to the Gondwanan Margin of the Iapetus Ocean

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SUMMARY
Recently gathered stratigraphic and U–Pb geochronological data indicate that the pre-Triassic rocks of the Grand Manan Terrane on the eastern side of Grand Manan Island can be divided into: (1) Middle Neoproterozoic (late Cryogenian) quartzose and carbonate sedimentary sequences (The Thoroughfare and Kent Island formations); (2) a Late Neoproterozoic (early Ediacaran) volcanic-arc sequence (Ingalls Head Formation); and (3) Late Neoproterozioc (mid-Ediacaran) to earliest Cambrian (early Terreneuvian) sedimentary and volcanic-arc sequences (Great Duck Island, Flagg Cove, Ross Island, North Head, Priest Cove, and Long Pond Bay formations). A comparison to Precambrian terranes on the New Brunswick mainland (Brookville and New River terranes) and in adjacent Maine (Islesboro Terrane) suggests that the sedimentary and volcanic sequences of the Grand Manan Terrane were deposited on the continental margin of a Precambrian ocean basin that opened during the breakup of Rodinia in the Middle Neoproterozoic (Cryogenian) and closed by the Early Cambrian (Terreneuvian) with the final assembling of Gondwana. Rifting associated with the initial opening of the Paleozoic Iapetus Ocean began in the Late Neoproterozoic (late Ediacaran) and so overlapped in time with the closing of the Precambrian Gondwanan ocean. The southeastern margin of the Iapetus Ocean is defined by thick sequences of quartz-rich Cambrian sediments (within the St. Croix and Miramichi terranes of New Brunswick) that were largely derived from recycling of Precambrian passive-margin sedimentary rocks preserved in the Grand Manan and Brookville terranes of New Brunswick and in the Islesboro Terrane of Maine. These Precambrian terranes are interpreted to represent dextrally displaced basement remnants of the Gondwanan continental margin of Iapetus, consistent with the model of a two-sided Appalachian system proposed by Hank Williams in 1964 based on his work in Newfoundland.

SOMMAIRE
Des données stratigraphiques et géochronologiques U-Pb obtenues récemment indiquent que les roches prétriasiques du terrane de Grand Manan du côté est de l'île Grand Manan peuvent être répartis en : 1) séquences sédimentaires quartzeuses et carbonatées du Néoprotérozoïque moyen (Cryogénien tardif) (formations de Thoroughfare et de Kent Island); 2) séquence d'arc volcanique du Néoprotérozoïque tardif (Édiacarien précoce) (formation d'Ingalls Head); 3) séquences sédimentaires et d'arc volcanique du Néoprotérozoïque tardif (milieu de l'Édiacarien) au tout début du Cambrien (Terreneuvien précoce) (formations de Great Duck Island, Flagg Cove, Ross Island, North Head, Priest Cove et Long Pond Bay). Une comparaison avec des terranes du Précambrien dans la partie continentale du Nouveau-Brunswick (terranes de Brookville et New River) et dans le Maine adjacent (terrane d'Islesboro) semble indiquer que les séquences sédimentaires et volcaniques du terrane de Grand Manan se sont déposées sur la marge continentale d'un bassin océanique précambrien qui s'est ouvert durant la fracturation de la Rodinia au Néoprotérozoïque moyen (Cryogénien) et s'est fermé au Cambrien précoce (Terreneuvien) avec l'assemblage final du Gondwana. La distension continentale associée à l'ouverture initiale de l'océan Iapetus au Paléozoïque a commencé au Néoprotérozoïque tardif (Édiacarien tardif) et a donc partiellement coïncidé avec la fermeture de l'océan précambrien du Gondwana. La marge sud-est de l'océan Iapetus est définie par d'épaisses séquences de

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sédiments cambriens riches en quartz (dans les terranes de St. Croix et de Miramichi du Nouveau-Brunswick) issus en grande partie du recyclage de roches sédimentaires de la marge continentale passive du Précambrien préservées dans les terranes de Grand Manan et de Brookville au Nouveau-Brunswick et dans le terrane d'Islesboro dans le Maine. Ces terranes précambriens sont interprétés comme la représentation de vestiges, ayant subi un déplacement dextre, du socle de la marge continentale gondwanienne de l'océan Iapetus, ce qui concorde avec le modèle d'un système appalachien à deux côtés proposé par Hank Williams en 1964 sur la base de ses travaux à Terre-Neuve.

INTRODUCTION

The New Brunswick mainland has been divided into eight lithotectonic terranes (Fig. 1), each with a distinctive stratigraphic and structural history that can be related to its paleogeographic position within the Iapetus Ocean during the Early Paleozoic (Fyffe et al. 2011a). However, the relationship of the pre-Triassic rocks of Grand Manan Island, located in the Bay of Fundy off the southwestern coast of New Brunswick, to the terranes on the

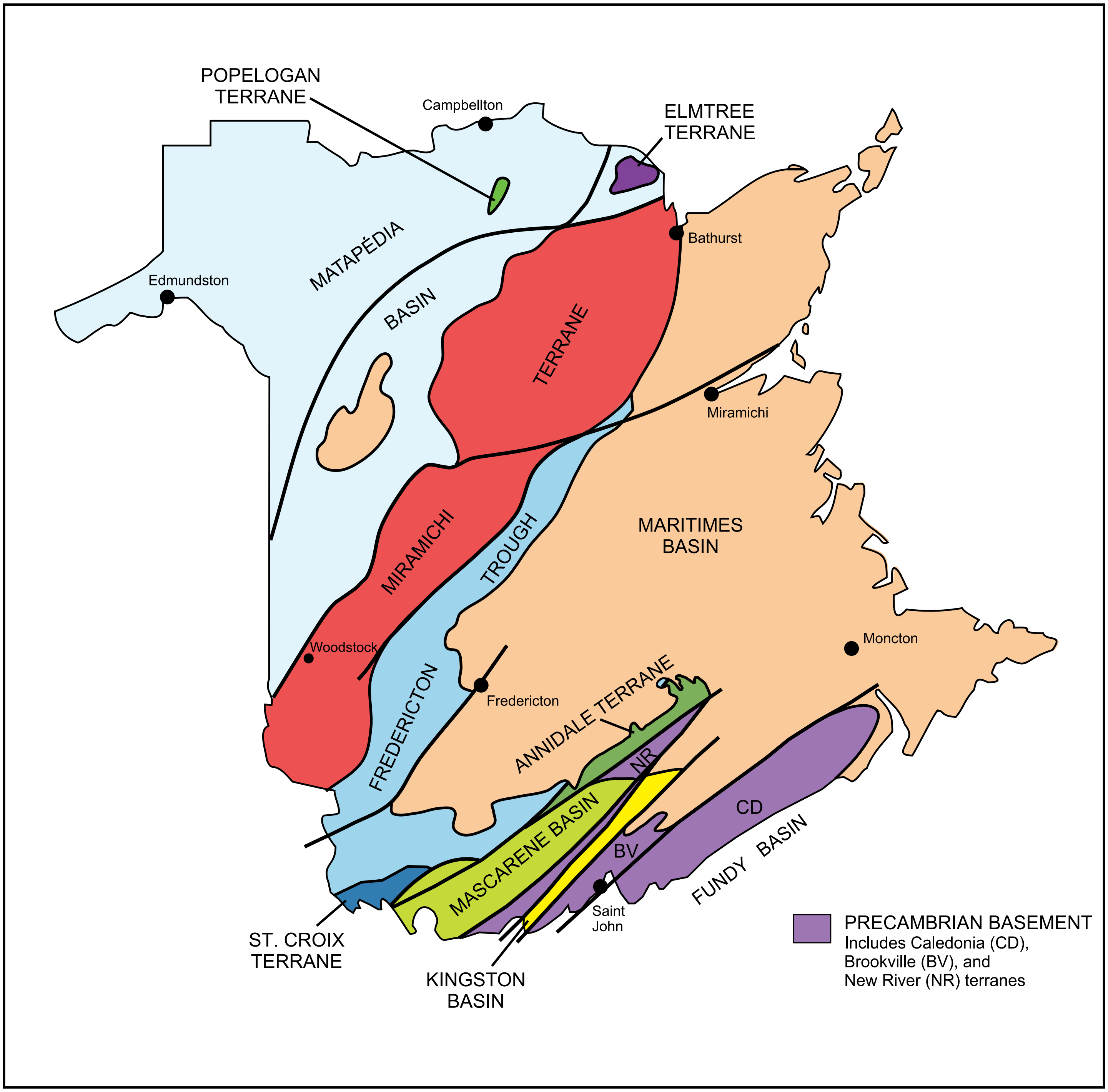

Figure 1. Lithotectonic map of New Brunswick, Canada (after Fyffe et al. 2011b).

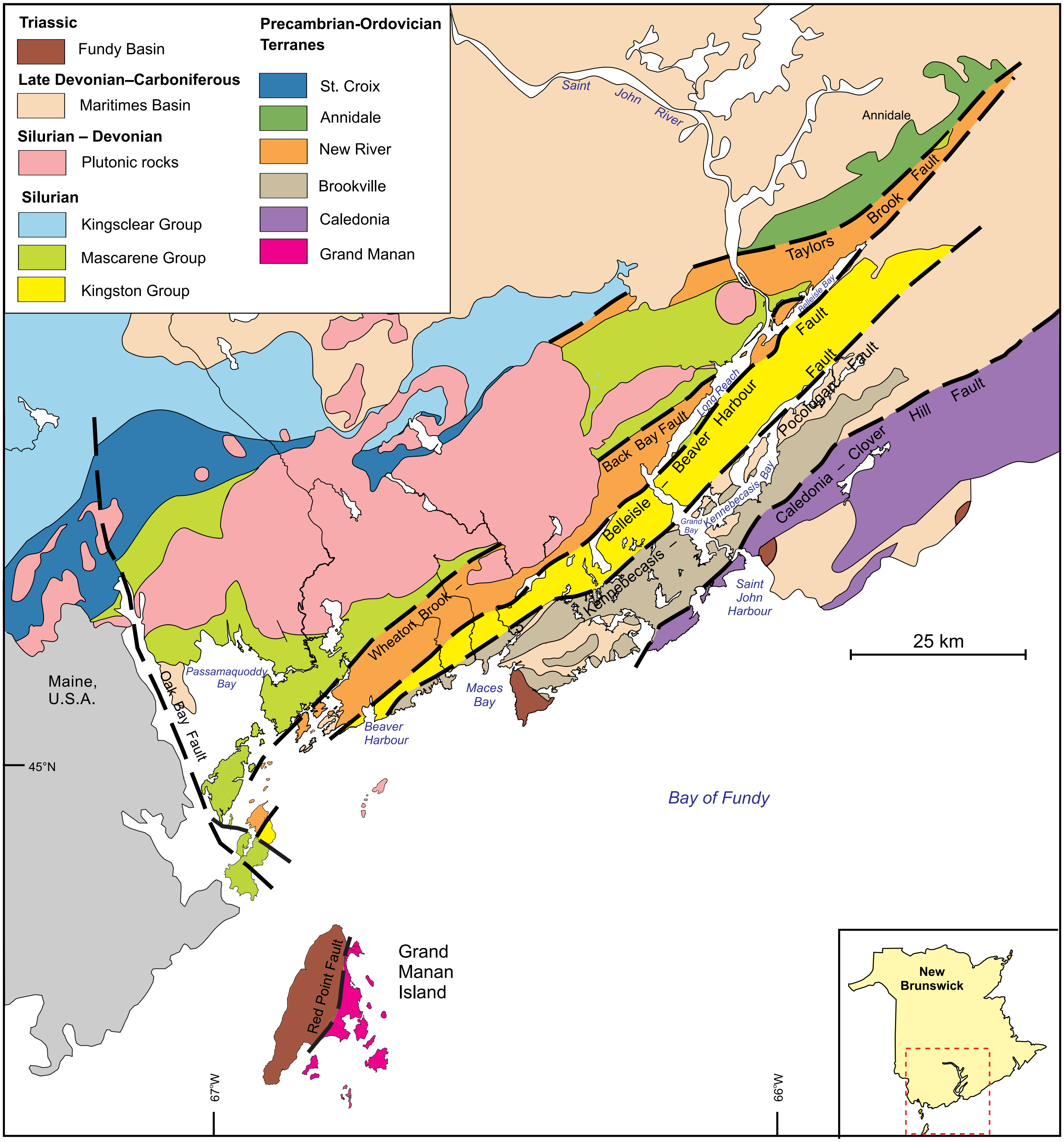

Figure 2. Lithotectonic terranes in southwestern New Brunswick (modified from Fyffe et al. 2011b).

mainland has not been examined in detail (Fyffe et al. 2009). Grand Manan has long been known for its spectacular cliff sections of columnar-jointed basaltic flows, exposed on the western part of the island. These Triassic basalts mark the initial breakup of the supercontinent of Pangea and opening of the modern Atlantic Ocean (Wade et al. 1996; Olsen 1997). The complexly deformed pre-Triassic rocks on the eastern part of Grand Manan occupy an isolated horst within the Fundy Basin (McHone 2011) and are herein referred to as the Grand Manan Terrane (Fig. 2). These rocks have previously been mapped only on a reconnaissance basis and have been variously correlated with the Precambrian Green Head Group of the Brookville Terrane, the Precambrian Coldbrook

Group of the Caledonia Terrane, the Cambrian – Ordovician Cookson Group of the St. Croix Terrane, and the Silurian Kingston and Mascarene groups on the New Brunswick mainland (Gesner 1839; Verrill 1868; Bailey and Matthew 1872; Ells 1905; Alcock 1948; Stringer and Pajari 1981; McLeod et al. 1994).

Recent detailed bedrock mapping and accompanying U–Pb geochronological analyses of magmatic and detrital zircon, carried out jointly by the New Brunswick Geological Survey, Acadia University, and the Geological Survey of Canada, have led to the establishment of distinct stratigraphic successions within the Grand Manan Terrane (Barr et al. 2003a, 2010; Black et al. 2004; Miller et al. 2007; Fyffe et al. 2009, 2011b). They consist of older sequences of carbonate and quartzose sedimentary rocks, and younger sequences of volcanic and reworked volcaniclastic sedimentary rocks (Fig. 3). Metamorphic grade generally does not exceed greenschist facies, and in many places, primary sedimentary and igneous textures are well preserved. Contacts between the newly recognized sequences are generally covered or faulted, making it difficult to determine original stratigraphic relationships. As discussed below, the new field and geochronological data indicate that the deformed rocks comprising the eastern part of Grand Manan Island range in age from at least as old as Middle Neoproterozoic to likely no younger than Early Cambrian. Comparisons presented herein with Precambrian terranes defined on the mainland of coastal New Brunswick and adjacent Maine suggest that the pre-Triassic rocks of Grand Manan more closely resemble those of Ganderia than Avalonia (Hibbard et al. 2006).

GEOLOGY OF THE GRAND MANAN TERRANE

Based on exposed and inferred stratigraphic relationships, lithological composition, and U–Pb ages, the Precambrian to Early Cambrian formations underlying the eastern part of Grand Manan and nearby islands have been divided into the pre-600 Ma Grand Manan Group, and the post-600 Ma Castalia Group (Fyffe et al. 2009, 2011b). The Grand Manan Group comprises sedimentary rocks of The Thoroughfare and Kent Island formations and volcanic rocks of the Ingalls Head Formation. The Castalia Group comprises sedimentary rocks of the Great Duck Island and Flagg Cove formations, and mainly volcanic and volcaniclastic rocks of the Ross Island, North Head, Priest Cove, and Long Pond Bay formations. The contact between the two groups is generally faulted, but an unconformity between the Ingalls Head and Great Duck Island formations is preserved on Great Duck and Long islands (Figs. 3, 4). The four units of volcanic and volcaniclastic rocks in the Castalia Group are considered to represent lateral facies equivalents of each other; only the stratigraphic position of the dated Priest Cove Formation is shown on Figure 4.

Grand Manan Group

The Thoroughfare Formation is exposed on Ross, Nantucket, and White Head islands off the southeastern coast of Grand Manan Island (Fig. 3). It is composed of very thick- to thin-bedded, locally cross-bedded, white to light grey quartzite interbedded with grey to black carbonaceous shale. The thick units of massive quartzite (Fig. 5) may represent prograding fan lobes sourced from winnowed shelf sand during a fall in sea level. Where exposed on the western shore of The Thoroughfare, the contacts between The Thoroughfare Formation and the volcanic sequences of the Ingalls Head Formation (Grand Manan Group) and Priest Cove Formation (Castalia Group) are highly sheared and are interpreted as thrust faults based on the presence of low-angle cleavages in the vicinity of their mutual boundaries (Fig. 3). The Thoroughfare quartzite could be as old as 1.425 ± 0.098 Ga (Mesoproterozoic) based solely on the age of its youngest detrital zircon population (B. Miller, written communication 2013). Alcock (1948) correlated the quartzite of The Thoroughfare Formation with quartzite interstratified with platformal stromatolitic carbonates of the Green Head Group in the Saint John area on the New Brunswick mainland. The implications that this correlation has for providing further constraints on the age of The Thoroughfare Formation are discussed later in the text.

The *Kent Island Formation* is exposed only on Kent Island about seven kilometres off the southern coast of Grand Manan Island, where it occurs as large blocks of white to buff marble incorporated in the Three Islands Granite. These carbonate rocks and their host granite are interpreted to occupy a thrust slice that structurally overlies other pre-Triassic formations exposed on Grand Manan Island (Fig. 3). The Kent Island Formation can be no younger than 611 ± 2 Ma (early Ediacaran) based on the emplacement age of the Three Islands Granite (Barr et al. 2003a). Alcock (1948) correlated the Kent Island marble with the stromatolitic carbonates of the Green Head Group (Fig. 4).

The *Ingalls Head Formation* is best exposed on Ingalls Head along the southeastern coast of Grand Manan Island and on Long Island and Great Duck Island off the northeastern coast of Grand Manan (Fig. 3). It comprises a sequence of intermediate tuffs and breccias, and felsic flows interbedded with purple to maroon laminated siltstone and mudstone (Fyffe et al. 2011b). The intermediate tuffs locally contain thin beds and lenses of iron formation (Fig. 6). A felsic flow on Ingalls Head yielded a Late Neoproterozoic (early Ediacaran) U–Pb zircon date of 618 ± 3 Ma (Barr et al. 2003a; Miller et al. 2007). Limited chemical analyses indicate that the intermediate volcanic rocks range from andesite to dacite in composition and have a calc-alkaline affinity (Pe-Piper and Wolde 2000; Black et al. 2004). The similarity in the age of the volcanism represented by the Ingalls Head Formation to the age of emplacement of the Three Islands Granite (611 ± 2 Ma; Miller et. al 2007) suggests the possibility of a magmatic linkage between the thrust slices of eastern Grand Manan Island and Kent Island (Figs. 3, 4).

Black (2005) considered the volcanic rocks on Long Island and Great Duck Island, which were included in the Ingalls Head Formation by Fyffe and Grant (2001), to be younger than those at the type-section on Ingalls Head. He, therefore, introduced the term Long Island Bay Formation

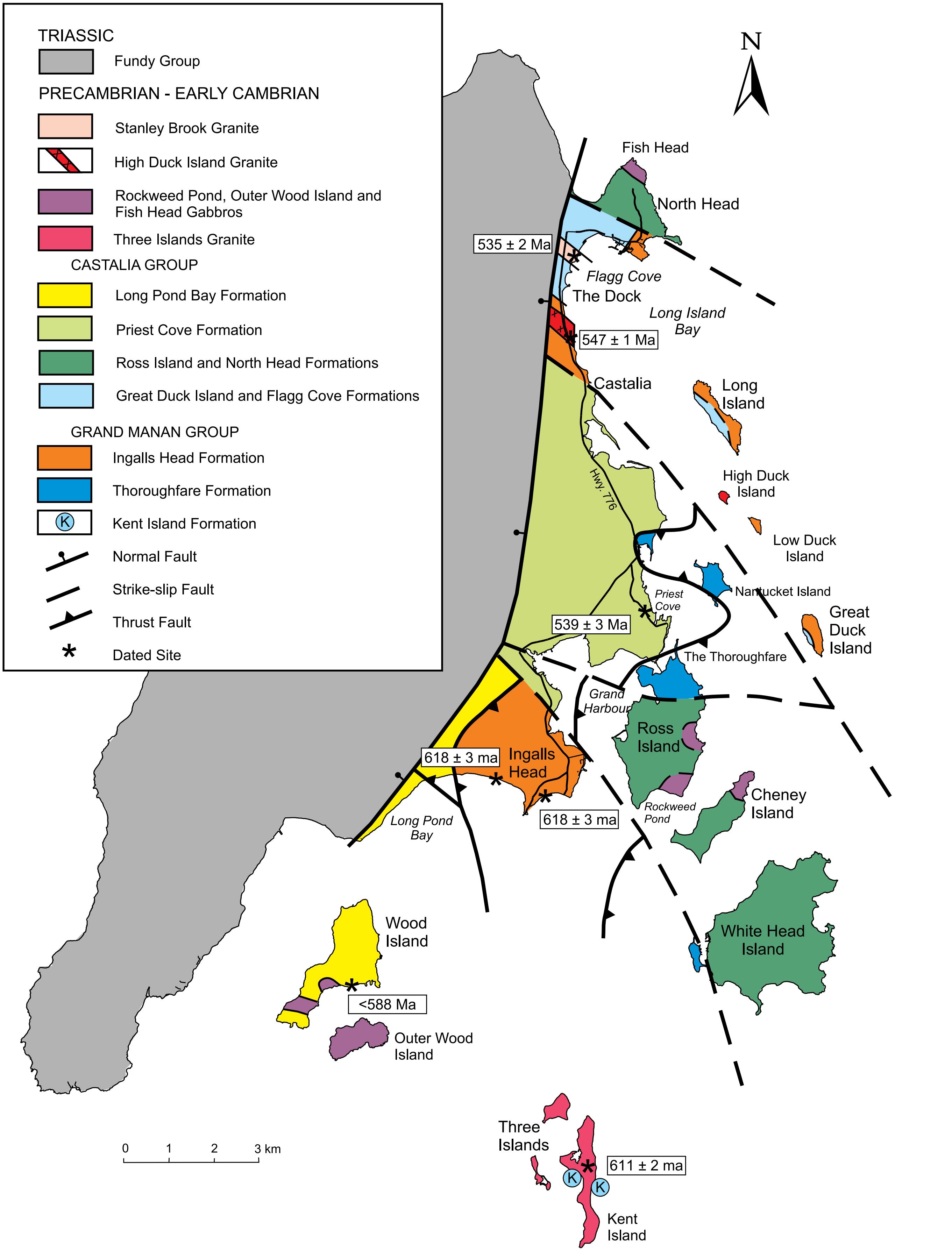

Figure 3. Bedrock geology map of Grand Manan Island (simplified from Fyffe et al. 2011b).

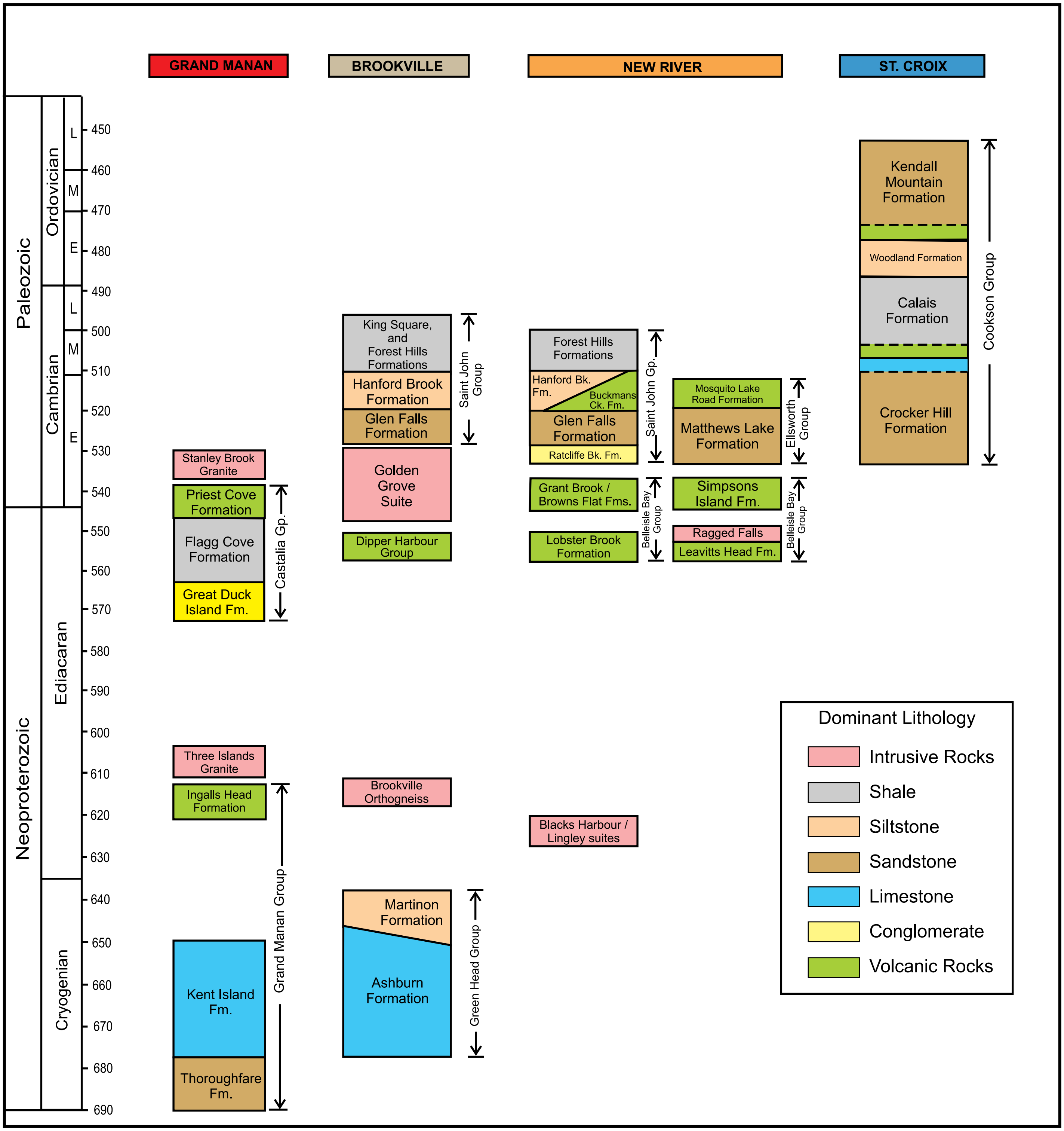

Figure 4. Stratigraphic columns for Ganderian terranes of southwestern New Brunswick. Time scale is from Ogg et al. (2008).

for the volcanic rocks on these two islands. The younger age assignment for these rocks was based on an inferred comagmatic relationship with the High Duck Island Granite, which intrudes maroon siltstone of the Ingalls Head Formation (as mapped by Fyffe and Grant 2001) on the shore north of Castalia (Fig. 3). This granitic dyke yielded a Late Neoproterozoic (late Ediacaran) age of 547 ± 1 Ma (Black et al. 2004). However, the suggested comagmatic relationship seems unlikely because the sandstone sequence of the Flagg Cove Formation, which stratigraphically overlies the volcanic rocks on Long and Great Duck islands, does not contain detrital zircons younger than 574 ± 7 Ma (mid-Ediacaran). The original terminology of Fyffe and Grant (2001) is retained in the present paper.

Figure 5. Thick-bedded quartzite of The Thoroughfare Formation at the north end of Ross Island.

Figure 6. Schistose andesitic tuff of the Ingalls Head Formation at Ox Head on Grand Manan Island. Note the maroon lenses of magnetic chert in the tuff.

Castalia Group

Strata assigned to the Castalia Group are divided into six formations–two that are sedimentary (Great Duck Island and Flagg Cove), and four that are volcanic-rich (North Head, Ross Island, Priest Cove, and Long Pond Bay). The contacts between the latter three adjacent volcanic-rich formations are not exposed and assumed to be faulted; the fourth (North Head Formation) is restricted to an isolated fault block to the northeast of Flagg Cove (Fig. 3). Thrust contacts separating the Priest Cove Formation from The Thoroughfare and Ingalls Head formations of the older Grand Manan Group are exposed on the western shore of The Thoroughfare. The Long Pond Bay Formation is interpreted to be in thrust contact with the Ingalls Head Formation along Long Pond Bay. An unconformity is preserved between the Great Duck Island Formation and underlying Ingalls Head Formation on Great Duck and Long islands in Long Island Bay (Fig. 3).

The *Great Duck Island Formation* is exposed on the western shore of Great Duck and Long islands, and at The Dock on the eastern coast of Grand Manan (Fig. 3). It is a sequence of medium-bedded, maroon and olive green sandstone and silty shale interstratified with thick-bedded, light grey to maroon quartz-pebble conglomerate. The conglomerate is massive, matrix-supported, and locally cross-bedded, and likely represents debris flows deposited in channels on the inner part of a submarine delta. On Great Duck Island, the pebble-to-cobble conglomerate of the Great Duck Island Formation contains volcanic clasts derived from an immediately underlying plagioclase-phyric mafic flow of the Ingalls Head Formation. The conglomerate, therefore, is no older than 618 ± 3 Ma (early Ediacaran), the eruptive age of the Ingalls Head volcanic rocks. A coarser conglomerate, exposed at The Dock on Grand Manan Island, contains abundant quartzite clasts likely derived from The Thoroughfare Formation of the Grand Manan Group, and is therefore correlated with the Great Duck Island Formation (Fyffe et al. 2011b). Although outcrop along the shoreline of Long Island Bay is not continuous, the conglomerate-rich sequence, which youngs to the northeast at The Dock, appears to grade upsection into the sandstone-rich sequence of the Flagg Cove Formation exposed farther north in Flagg Cove (Fig. 3).

The *Flagg Cove Formation* is exposed along Flagg Cove in Long Island Bay near the Grand Manan ferry terminal (Fig. 3). It is a sequence of thin- to medium-bedded, commonly graded, light grey quartzose sandstone and minor quartzite-pebble conglomerate interstratified with light green to dark grey silty shale (Fig. 7). The trace fossil *Planolites* has been identified on bedding surfaces along Stanley Beach. The sequence is interpreted to be a

Figure 7. Medium-bedded, quartzose sandstone and laminated silty shale of the Flagg Cove Formation in Flagg Cove south of the Grand Manan ferry terminal.

deeper water facies of the conglomeratic Great Duck Island Formation and to have been deposited in a distal marine fan environment. The stratigraphic age of the Flagg Cove Formation is no older than 574 ± 7 Ma (mid-Ediacaran) based on its youngest contained detrital zircon population (Fyffe et al. 2009). Its predominant detrital zircon population is dated at 611 ± 7 Ma, reflecting erosion of volcanic detritus from the Ingalls Head Formation (see above) and Three Islands Granite (see below). The presence of sedimentary xenoliths in the Stanley Brook Granite indicates that the Flagg Cove Formation is no younger than 535 ± 2 Ma (earliest Cambrian), based on the age of emplacement of this intrusion (see below). The age of the Flagg Cove Formation and Great Duck Island Formation, its near-shore lateral equivalent, is therefore restricted to between the Late Neoproterozoic (mid-Ediacaran) and earliest Cambrian (early Terreneuvian) (Fig. 4).

The *Ross Island Formation* underlies the greater part of Ross and White Head islands off the southeastern coast of Grand Manan (Fig. 3). It comprises interstratified plagioclase-phyric mafic and intermediate flows and breccias intruded by numerous diabase dykes and dykelets. The flows are locally pillowed and interbedded with green laminated siltstone on White Head Island. Compositionally, these volcanic rocks range from calc-alkaline basalt to basaltic andesite and andesite (Hilyard 1992; Hewitt 1993; Hodgins 1994; Pe-Piper and Wolde 2000). The flows and breccias of the Ross Island Formation have been interpreted by Stringer and Pajari (1981) to represent proximal equivalents of the mafic tuffs and volcaniclastic sandstones of the Priest Cove Formation exposed to the northwest on Grand Manan Island (see below).

A mafic debris flow, exposed along the western shore of Ross Island within the Ross Island Formation, contains subangular, cobble- to boulder-sized clasts of granite, granitic pegmatite, and micaceous white quartzite (Fig. 8). Muscovite from the granite and quartzite clasts has yielded K–Ar dates of 640 Ma and 590 Ma, respectively (Lowdon et al. 1963; Leech et al. 1963; Stringer and Pajari 1981). The volcanic rocks of the Ross Island Formation appear to be truncated by faults that separate them from quartzite of The Thoroughfare Formation on the northern tip of Ross Island and western tip of White Head Island (Fig. 3). However, the presence of quartzite and granite clasts in the Ross Island debris flow indicates that at least this part of the Castalia Group was deposited on an older continental substratum. Possible source rocks of comparable age and composition to these clasts are exposed in the Islesboro Terrane of coastal Maine. In that area, marble and quartzite of the Seven Hundred Acre Island Formation has been intruded by the Spruce Island Pegmatite, which has yielded a Late Neoproterozoic (late Cryogenian) U–Pb zircon age of 647 ± 3 Ma (Stewart et al. 2001).

The *North Head Formation* underlies North Head near the northern tip of Grand Manan Island (Fig. 3). It consists of massive mafic to intermediate volcanic flows and breccia that are locally veined by quartz and barite. To the south, the volcanic rocks of the North Head Formation are separated from sedimentary rock of the Flagg Cove Formation by a fault trending to the west-northwest. They are separated from flat-lying Triassic basalt underlying the western part of Grand Manan Island by the north-trending Red Point Fault. A Triassic dyke has intruded the North Head Formation at Sawpit Cove along the trail to Swallow Tail Point (Fig. 3).

The *Priest Cove Formation* underlies much of the eastern part of Grand Manan Island (Fig. 3). Coastal exposures between Grand Harbour in the south and Castalia in the north are composed of greyish-green, medium- to thick-bedded, mafic lithic tuff interstratified with medium-bedded to laminated volcaniclastic sandstone. Bedding in the sandstone ranges from 3 to 30 cm in thickness and generally dips to the north at shallow to moderate angles; normally graded beds with scoured bases indicates that sections generally young to the north. A felsic crystal tuff, interstratified with mafic volcaniclastic sandstones on the Shore Road to Priest Cove (Fig. 3), has yielded an earliest Cambrian (early Terreneuvian) U–Pb zircon date of 539 ± 3 Ma (Black et al. 2004; Miller et al. 2007). Normally graded, coarse-grained volcaniclastic sandstone of the Priest Cove Formation, exposed on the southeastern tip of Nantucket Island, youngs northward toward the faulted boundary with quartzite of The Thoroughfare Formation (Fig. 9).

The similarity in timing of the eruption of the Priest Cove felsic tuff at 539 ± 3 Ma and emplacement of the Stanley Brook Granite at 535 ± 2 Ma (see below) suggests a cogenetic relationship between these two mag-

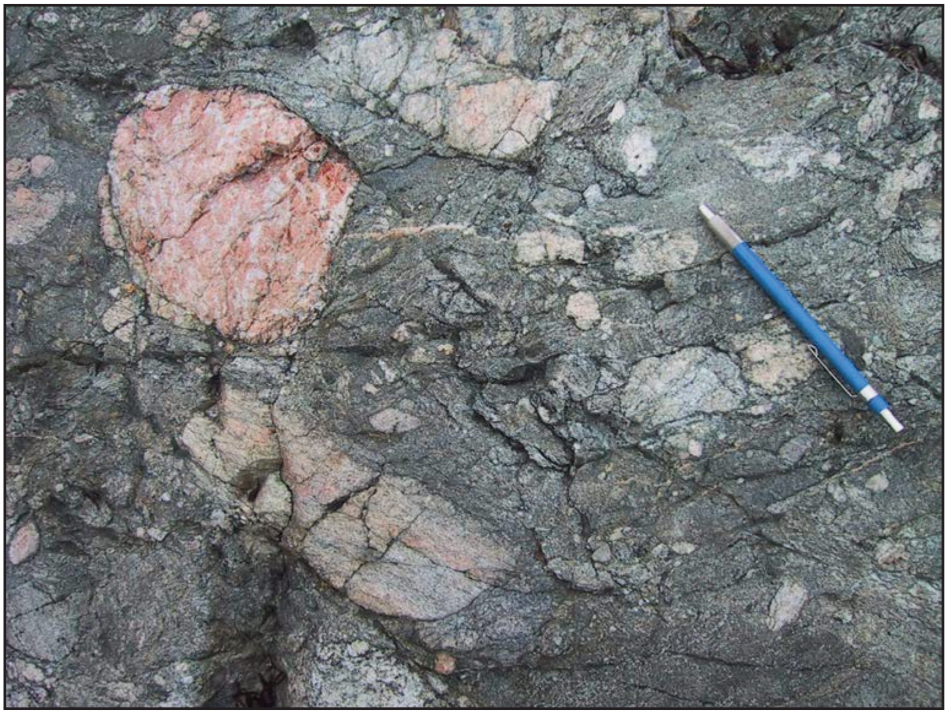

Figure 8. Mafic debris flow of Ross Island Formation on west side of Ross Island, containing large clasts of granite and micaceous quartzite (photograph from Black 2005).

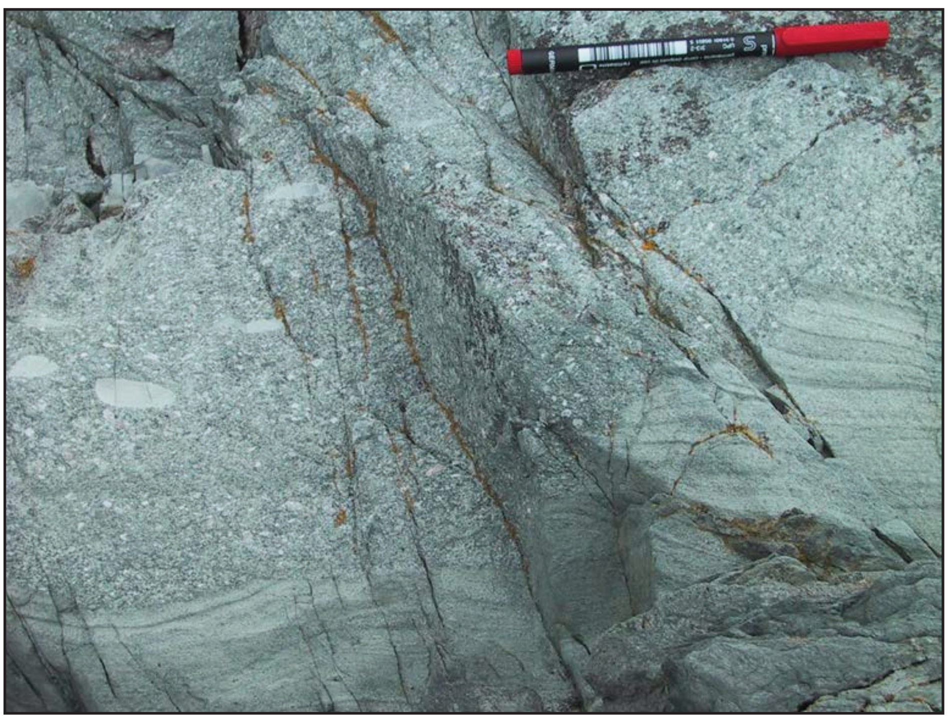

Figure 9. Laminated, fine-grained, volcaniclastic sandstone and overlying medium-bedded, coarse-grained, volcaniclastic sandstone of the Priest Cove Formation, southern end of Nantucket Island (photograph from Black 2005).

matic events (Fig. 4). Although the substratum to the Priest Cove Formation is not exposed, the above cogenetic relationship suggests that the Priest Cove volcanic strata were deposited on sedimentary rocks of the Flagg Cove Formation, because the latter is intruded by the granite. The Flagg Cove and Great Duck Island formations of the Castalia Group, in turn, are known to unconformably overlie the Ingalls Head Formation of the Grand Manan Group on Great Duck Island. Stringer and Pajari (1981) proposed that the mafic tuffs and volcaniclastic sandstones of the Priest Cove Formation represent a distal facies of the mafic flows and breccias of the Ross Island Formation. Although the volcanic rocks of the Ross Island Formation have not been dated, they are younger than 590 Ma (mid-Ediacaran) based on K–Ar dating of previously described clasts in the mafic debris flow on Ross Island (Fig 8).

The *Long Pond Bay Formation* is exposed along Long Pond Bay and on Wood Island off the southern coast of Grand Manan Island (Fig. 3). It comprises a sequence of mafic volcanic and sedimentary rocks that are transected by a series of southwest-directed thrusts. The southwestern part of the sequence consists of mafic hyaloclastic tuffs and breccias interbedded with rhythmically interstratified, laminated, greyish-green volcaniclastic siltstone and fine-grained sandstone (Fig. 10). The presence of these fine-grained sedimentary rocks suggests that the mafic volcanic rocks of the Long Pond Bay Formation at this locality were deposited in a deeper marine environment than the coarse, reworked mafic tuffs of the Priest Cove Formation, exposed to the northeast of Grand Harbour (Fig. 9).

A predominantly sedimentary sequence exposed farther to the northeast along Long Pond Bay is separated from the predominantly volcanic sequence to the southwest by a black shale breccia (Fig. 11). To the northeast of the black shale, rhythmically interbedded, laminated grey siltstone locally grades to a sandier section containing angular fragments of the laminated siltstone ranging from 1 to 10 cm in length. This 10 m thick fragmental unit is interpreted as the distal part of a mass flow that incorporated material ripped up from a silty substrate. The sedimentary section becomes coarser farther to the northeast, where medium-bedded, grey feldspathic sandstone displays sedimentological features characteristic of a proximal mass flow deposit (Fig. 12). Beds in the sandstone typically grade upward from a coarse base, containing rip-up clasts

Figure 10. Thin-bedded, laminated, volcaniclastic siltstone of the Long Pond Bay Formation on Long Pond Bay, Grand Manan Island.

Figure 11. Volcanic block in black shale of the Long Pond Bay Formation on Long Pond Bay, Grand Manan Island. Note hammer for scale in upper right of photo.

of the underlying shale, through to medium-grained sandstone into a laminated shale interval at the top.

A subaerial to shallow-water sequence of volcanic and sedimentary rocks exposed on Wood Island is also included in the Long Pond Bay Formation (Fig. 3). This north-facing sequence comprises oxidized, coarsely amygdaloidal mafic and minor felsic flows interstratified with 50 m thick intervals of medium-bedded, grey and green volcaniclastic sandstone grading to laminated maroon mudstone. Red arkosic grits and silty red shale are locally interbedded with the mafic volcanic rocks, consistent with deposition, in part, in a subaerial environment. Xenocrystic zircons from felsic volcanic rock provide a maximum age of ca. 588 Ma (mid-Ediacaran) for the Wood Island section (Miller et al. 2007).

The Long Pond Bay volcanic and sedimentary rocks on Wood Island are similar to subaerial sequences of the Simpsons Island Formation exposed on Simpsons, Adams, and Barnes islands in the Passamaquoddy Bay area of coastal New Brunswick (Fig. 2). A flow-banded rhyolite from Adams Island yielded a U–Pb zircon date of 539 ± 4 Ma (Barr et al. 2003b), virtually identical to the age of the Priest Cove Formation. It is proposed here that differences in textural features observed between the volcanic-rich sequences of the Castalia Group (Ross Island, North Head, Priest Cove, and Long Pond Bay) are mainly a reflection of lateral variations in depositional environment rather than in the timing of eruption.

Felsic Plutonic Rocks

The *Stanley Brook Granite* is exposed for a distance of about 400 m along the shore of Flagg Cove to the south of Stanley Brook on Grand Manan Island (Fig. 3). The granite is light pink, foliated, medium-grained, and along its northern boundary contains elongated xenoliths of greyish-green siltstone and quartzose sandstone derived from the adjacent sedimentary rocks of the Flagg Cove Formation. The southern part of the Stanley Brook Granite consists of a mixture of intermingled pink granite veins and hybridized inclusions of greyish-green, fine- to medium-grained, plagioclase-phyric diorite. U–Pb analyses on zircon from the granite yielded a date of 535 ± 2 Ma (Fyffe et al. 2011c).

The *High Duck Island Granite*, which intrudes maroon siltstone of the Ingalls Head Formation (Fyffe and Grant 2001) on the shore north of Castalia (Fig. 3), yielded a Late Neoproterozoic (late Ediacaran) U–Pb date of 547 ± 1 Ma (Black et al. 2004).

The *Three Islands Granite* underlies Kent, Hay, and Sheep islands (Three Islands) off the southern coast of Grand Manan Island. This medium-grained, dark pinkish red, equigranular granite is locally sheared and transected by thick quartz veins and diabase dykes, and contains large blocks of Kent Island marble. Zircons from the granite yielded a date of 611 ± 2 Ma (Barr et al. 2003a). The similarity of this age to that of the volcanic rocks of the Ingalls Head Formation (618 ±

Figure 12. Open fold in medium-bedded, feldspathic sandstone of the Long Pond Bay Formation on Long Pond Bay southwest of Long Pond, Grand Manan Island.

3 Ma) on Grand Manan Island suggests that these two magmatic events may be cogenetic (Fig. 4).

Mafic Plutonic Rocks

The *Fish Head Gabbro,* which is exposed on Fish Head at the northern tip of North Head on Grand Manan Island (Fig. 3), is dark grey, medium-grained, massive, and locally veined by gabbroic pegmatite. The pluton is tentatively assigned an Early Cambrian age on the basis of its intrusive and assumed comagmatic relationship with the supposedly latest Neoproterozoic to earliest Cambrian mafic volcanic rocks of the North Head Formation (Castalia Group).

The *Rockweed Pond Gabbro* is exposed on Ross Island just northeast of Rockweed Pond and on Cheney Island off the eastern coast of Grand Manan Island (Fig. 3). The pluton is composed of dark grey, medium-grained gabbro, locally veined by greyish pink, foliated, medium-grained granite. It is assigned an Early Cambrian age on the basis of its intrusive relationship with mafic volcanic rocks of the Ross Island Formation. Diabase dykes intruding volcanic rocks of the Late Neoproterozoic Ingalls Head Formation at Ingalls Head and injecting into quartzites of The Thoroughfare Formation on the eastern shore of Ross Island (Hodgins 1994) may be contemporaneous with the gabbro.

The *Outer Wood Island Gabbro* underlies Outer Wood Island off the southeastern coast of Grand Manan Island (Fig. 3). The pluton is composed of dark grey, medium-grained, massive gabbro, locally veined by gabbroic pegmatite. The gabbro is tentatively assigned an earliest Cambrian age on the basis of its similarity to the Rockweed Pond Gabbro.

STRUCTURAL GEOLOGY

The following summary of structural features in the pre-Triassic rocks of Grand Manan Island is taken largely from Stringer and Pajari (1981). Bedding in the sedimentary rocks and primary layering in the volcanic rocks show considerable variation in strike and dip because of polyphase deformation. Five phases of deformation (D_1 to D_5) have been established on the basis of overprinting relationships and characteristic style and orientation of minor structures formed during each phase. At least some of this penetrative deformation post-dates emplacement of the highly sheared, Early Cambrian Stanley Brook Granite, the youngest pre-Triassic unit recognized on Grand Manan Island.

The S_1 foliation formed during D_1 is defined by an alignment of fine-grained, mainly sericitic micaceous minerals and elongate quartz grains, which constitutes a penetrative fabric subparallel to bedding in sedimentary rocks of The Thoroughfare and Flagg Cove formations. A spaced platy cleavage subparallel to the primary layering in volcanic rocks of the Ingalls Head Formation and locally in those of the Priest Cove Formation is interpreted as S_1 foliation. Volcaniclastic fragments oriented parallel to the S_1 foliation appear flattened and elongated within S_1, forming a lineation (L_1) that trends predominantly northwest within the composite S_1/S_0 surface. F_1 minor folds have not been observed.

The S_2 crenulation cleavage is defined by microfolds of the composite S_1/S_0 foliation. The S_2 cleavage generally trends to the northwest and dips moderately toward the northeast or southwest, varying locally as a result of later folding. F_2 minor folds are tight, asymmetrical, and mostly plunge steeply to the southeast. The S_3 crenulation cleavage strikes northwest and is mainly subvertical. F_3 folds are upright, open to tight, symmetrical or slightly asymmetrical, and deform F_2 folds in the vicinity of The Thoroughfare and the south side of Flagg Cove. The F_3 folds mostly plunge gently to the southeast or northwest.

The S_4 cleavage is defined by spaced (1 to 30 mm) partings that are particularly well developed in thick-bedded volcaniclastic sandstone of the Priest Cove Formation. The cleavage strikes northerly, dips gently to moderately westward, and is associated with open to tight asymmetrical F_4 folds. The regular orientation of S_4 cleavage suggests that the variation in F_4 fold plunge is largely a result of pre-D_4 variation in dip and strike of the earlier planar structures. The S_5 cleavage is defined by spaced (5 to 50 mm) partings that are developed in only a few localities, such as the volcaniclastic rocks at Woodwards Cove. The S_5 cleavage is subvertical with a west to northwest strike.

Chloritoid crystals 0.1–0.5 mm in length are locally abundant in pelitic and graphitic sedimentary rocks of

The Thoroughfare Formation. The chloritoid crystals overprint S_2, S_3 and S_4 cleavage films but their time relationship with respect to the D_5 deformation has not been observed. The rosettes of chloritoid suggest that the mineral crystallized under static conditions, which may have succeeded D_5 deformation.

Westward-directed thrusts that place the Ingalls Head and The Thoroughfare formations of the Grand Manan Group over the Long Pond Bay and Priest Cove formations of the Castalia Group can be observed on the west side of The Thoroughfare. Southwest-directed thrusts and associated black shale breccia transect the mafic volcanic sequence of the Long Pond Bay Formation in the section exposed along Long Pond Bay (Fyffe et al. 2011b).

PRECAMBRIAN TERRANES OF MAINLAND NEW BRUNSWICK

Precambrian basement rocks exposed on the mainland of southern New Brunswick have been divided into three fault-bounded terranes based on their unique stratigraphic and magmatic histories (Figs. 1, 2), namely the Caledonia, Brookville, and New River terranes (see Fyffe et al. 2011a, and references therein). The Brookville and New River terranes are considered to represent remnants of the Gondwanan continental margin fringing the Paleozoic Iapetus Ocean. During the opening of the Rheic Ocean in the mid-Cambrian, these terranes were rifted from Gondwana to form the microcontinent of Ganderia (Hibbard et al. 2006; van Staal et al. 2012). Ganderia is characterized by the presence of thick, Cambrian quartz-rich sandstone sequences that were sourced from the Gondwanan margin of Iapetus, and which are notably absent in Avalonia (van Staal et al. 2009; Fyffe et al. 2009). The Caledonia Terrane on the New Brunswick mainland is considered to be part of the microcontinent of Avalonia and to have accreted to Ganderia in the Late Silurian (Barr and White 1999; White et al. 2006; van Staal et al. 2009).

The St. Croix Terrane, lying just to the northwest of the New River Terrane, is underlain by the Cookson Group, a thick sequence of Cambrian to Middle Ordovician sandstone and shale. Other New Brunswick terranes (Annidale, Miramichi, Elmtree, and Popelogan) represent progressively younger Paleozoic arcs and backarc basins that developed on the active margin of Ganderia (Figs. 1, 2). These terranes record the episodic expansion and contraction of the Iapetus Ocean that led to the transfer of Ganderia from the Gondwanan to the Laurentian margin (van Staal et al. 2009, 2012; Fyffe et al. 2011a; Johnson et al. 2012).

The geology of each terrane on the mainland of New Brunswick that contains exposed Precambrian basement (Caledonia, Brookville, and New River) is summarized below in order to facilitate comparison with rocks of similar age on Grand Manan Island.

Caledonia Terrane

Precambrian stratified rocks of the Caledonia Terrane are divided into the Late Neoproterozoic (Ediacaran) Broad River and Coldbrook groups. The Broad River Group comprises a sequence of mainly intermediate to felsic crystal tuffs, lithic-crystal tuffs, and tuffaceous sedimentary rocks. Two tuff samples yielded U–Pb zircon dates of 613 ± 2 Ma and 601 ± 1 Ma (Bevier and Barr 1990; Barr and White 1999). Associated comagmatic plutonic rocks (Point Wolfe River Suite) range in age from 625 ± 5 Ma to 616 ± 3 Ma (Bevier and Barr 1990; Barr and White 1999). The younger Coldbrook Group consists of intermediate to felsic lithic tuff and breccia, crystal tuffs, and flows, interbedded with laminated, green tuffaceous siltstone and maroon to red arkose, sandstone, and siltstone. Tuffs from the Coldbrook Group yielded U–Pb zircon dates ranging from 559 ± 1 Ma to 548 ± 1 Ma. Associated comagmatic plutons of the Bonnell Brook Suite range in age from 557 ± 3 Ma to 550 ± 1 Ma (Bevier and Barr 1990; Barr et al. 1994, 2003b; Barr and White 1996a, b, 1999).

The volcanic rocks of both the Broad River and Coldbrook groups are interpreted on the basis of geochemistry to have formed in a continental magmatic arc setting (Currie and Eby 1990; Barr and White 1996a), although an extensional setting has been proposed for the younger bimodal part of the latter group (Barr and White 1996b). They are similar in age and tectonic setting to the Precambrian basement rocks of Ganderia (in particular the New River Terrane) but are isotopically less evolved (Whalen et al. 1994; Barr et al. 1998; Samson et al. 2000; Satkoski et al. 2010).

The Precambrian rocks of the Caledonia Terrane are locally overlain by Cambrian to Early Ordovician platformal sedimentary strata of the Saint John Group (Hayes and Howells 1937; Alcock 1938; McLeod and McCutcheon 1981; Tanoli and Pickerill 1988; Landing et al. 1998; Palacios et al. 2011; Barr et al. 2012).

Brookville Terrane

Precambrian rocks of the Brookville Terrane comprise the Green Head Group, Brookville Gneiss, Dipper Harbour Group, and Golden Grove plutonic suite (Fig. 4). The platformal rocks of the Green Head Group include marble, which locally contains stromatolites, and lesser quartzose sandstone of the Ashburn Formation; and limestone breccia, siltstone, quartzose sandstone, and quartzite-pebble conglomerate of the Martinon Formation (Hofmann 1974; Currie 1991; White and Barr 1996). Currie (1991) interpreted the Martinon Formation to disconformably overlie the Ashburn Formation whereas White and Barr (1996) considered them to be at least in part laterally equivalent.

The Ashburn Formation is no older than 1.228 ± 0.003 Ga (Mesoproterozoic), the age of its youngest contained detrital zircon population, and no younger than 615 ± 4 Ma (Ediacaran), the age of the emplacement of orthogneiss within the Brookville Gneiss (Bevier et al. 1990; Barr et al. 2003c, 2014). However, if the Ashburn Formation is a correlative of the carbonates of the Seven Hundred Acre Island Formation in the Islesboro Terrane of coastal Maine, then it is no younger than 647 ± 3 Ma (late Cryogenian) based on U–Pb dating of zircon from the cross-cutting Spruce Island Pegmatite (Stewart et al. 2001). The Martinon Formation is no older than 649 ± 12 Ma, the age of its youngest contained detrital zircon population (Barr et al. 2014). Plutonic rocks of the Golden Grove suite have intruded the Green Head Group. They range from Late Neoproterozoic to Early Cambrian (548 ± 2 Ma to 528 +1/–3 Ma) and possess mainly calc-alkaline, continental-arc geochemical signatures (Whalen et al. 1994; Eby and Currie 1996; White and Barr 1996; Currie and McNicoll 1999; White et al. 2002; Barr et al. 2003b).

Volcanic rocks of the Dipper Harbour Group occur in a fault panel that was thrust over Green Head carbonate strata along the Bay of Fundy coast. Felsic flows and crystal tuffs (Round Meadow Cove Formation) from the Dipper Harbour Group yielded a Late Neoproterozoic (late Ediacaran) U–Pb zircon date of 553 ± 3 Ma (Currie and McNicoll 1999; White et al. 2002; Barr et al. 2003b).

The Precambrian basement rocks of the Brookville Terrane are locally in fault contact with Cambrian platformal quartzose sandstone of the Saint John Group (Hayes and Howell 1937; Alcock 1938; Landing and Westrop 1996).

New River Terrane

The New River Terrane is the most outboard of the Precambrian terranes with respect to the southeastern margin of the Paleozoic Iapetus Ocean (Fig. 1) and the only one known to contain volcanic remnants (Ellsworth Group) of a possible Iapetan arc system (Johnson and McLeod 1996; Johnson et al. 2012). The Late Neoproterozoic Lingley and Blacks Harbour plutonic suites are the oldest rocks in the New River Terrane (Fig. 4). The Lingley suite includes mainly hornblende granodiorite, tonalite, and red leucogranite (Currie 1987; Johnson 2001; Johnson and Barr 2004). Late Neoproterozoic (early Ediacaran) U–Pb zircon dates of 625 ± 2 Ma and 629 ± 1 Ma have been obtained from the granodiorite and granite, respectively (Currie and McNicoll 1999). Granodiorite of the Blacks Harbour suite yielded a U–Pb zircon date of 622 ± 2 Ma, essentially the same age as the Lingley suite (Barr et al. 2003b; Bartsch and Barr 2005).

Volcanic rocks in the New River Terrane are included in the Late Neoproterozoic (late Ediacaran) to earliest Cambrian (early Terreneuvian) Belleisle Bay Group (Fig. 4). The volcanic and associated comagmatic intrusive rocks are all in faulted contact with the older plutons (Lingley and Blacks Harbour). The lower part of the Belleisle Bay Group (Leavitts Head and Lobster Brook formations) comprises felsic flows and pyroclastic tuffs that yielded U–Pb zircon dates of 554 ± 3 Ma and 554 ± 6 Ma, respectively (McLeod et al. 2003). Comagmatic granodiorite and granite of the Ragged Falls plutonic suite yielded U–Pb zircon dates of 553 ± 2 Ma and 555 ± 10 Ma, respectively (Currie and Hunt 1991; Johnson and McLeod 1996; Johnson 2001; McLeod et al. 2003). The upper part of the Belleisle Bay Group (Simpsons Island, Browns Flat, and Grant Brook formations) comprises felsic flows and pyroclastic tuffs interbedded with arkosic sandstone and red and green siltstone, and mafic breccias (McLeod 1995; Johnson and McLeod 1996; Johnson 2001). A felsic flow from the Simpsons Island Formation and intermediate tuff from the Grant Brook Formation yielded earliest Cambrian (early Terreneuvian) U–Pb zircon dates of 539 ± 4 Ma and 541 ± 3 Ma, respectively (Barr et al. 2003a; Bartsch and Barr 2005; Johnson et al. 2012).

Platformal Cambrian strata assigned to the Saint John Group unconformably overlie Precambrian basement rocks along Beaver Harbour and Long Reach in the southwestern and northeastern parts of the New River Terrane, respectively (Figs. 2, 4). In the Beaver Harbour area, Early Cambrian alluvial to shallow-marine conglomerate and sandstone (Ratcliffe Brook Formation) and quartzite (Glen Falls Formation) are overlain by late Early Cambrian subtidal purple siltstone and fossiliferous limestone interstratified with locally pillowed mafic flows and hyaloclastic tuff (Buckmans Creek Formation). Middle Cambrian greyish-green mudstone, fossiliferous limestone (lower member of Forest Hill Formation), and black shale (upper member of Forest Hills Formation) overlie the mafic volcanic rocks (Helmstaedt 1968; Tanoli and Pickerill 1988; Currie 1988; Landing et al. 2008). The mafic volcanic rocks have an evolved, continental tholeiitic geochemical signature (Greenough et al. 1985). The section in the Long Reach area is similar except that a sequence of interstratified grey mudstone and fine-grained sandstone (Hanford Brook Formation) replaces mafic volcanic rocks of the correlative Buckmans Creek Formation in the Beaver Harbour area (Landing and Westrop 1996).

Along the northwestern margin of the New River Terrane, a sequence of Cambrian quartzose sedimentary rocks and overlying volcanic rocks sits on granodiorite of the Late Neoproterozoic Ragged Falls plutonic suite (Fig. 4). These Cambrian strata are included in the Ellsworth Group, named after rocks of similar lithology in adjacent Maine dated at 509 ± 3 Ma (Schultz et al. 2008; Fyffe et al. 2009). In New Brunswick, the Ellsworth Group comprises interbedded quartzose sandstone and quartzite-pebble conglomerate of the Matthews Lake Formation in the lower part; and felsic flows, tuffs and breccia, and fine-grained, iron-rich volcaniclastic sandstone and siltstone of the Mosquito Lake Road Formation in the upper part. The Matthews Lake Formation is no older than 539 ± 5 Ma (i.e. earliest Cambrian), the age of its youngest contained detrital zircon population. U–Pb analyses of zircon from a felsic volcanic breccia near the top of the Mosquito Lake Road Formation yielded an age of 514 ± 2 Ma based on two zircon fractions (Johnson and McLeod 1996; Johnson 2001; McLeod et al. 2003; Fyffe et al. 2009). The Ellsworth volcanic rocks are interpreted to represent a small ocean rift or a remnant arc that was located along the southeastern margin of the Iapetus Ocean (Schultz et al. 2008; Fyffe et al. 2011a; Johnson et al. 2012).

COMPARISON OF THE GRAND MANAN TERRANE TO TERRANES ON THE NEW BRUNSWICK MAINLAND

The Precambrian terranes on the New Brunswick mainland are separated from each other by northeast-trending, dextral strike-slip faults along which movement had occurred as late as Carboniferous (Nance 1986a; Léger and Williams 1986; Park et al. 1994). The Caledonia, Brookville, and New River terranes can be traced to the southwest as far as Saint John Harbour, Maces Bay, and Passamaquoddy Bay, respectively, from whence they become buried beneath the Triassic rocks underlying the Bay of Fundy (McLeod and Rast 1988; McLeod et al. 1994; McHone 2011). Correlation of rocks from Grand Manan with those on the mainland is further complicated by Grand Manan's location to the southwest of the Oak Bay Fault (Fig. 2); at least five kilometres of pre-Triassic sinistral offset has been documented along this fault (Fyffe et al. 1999).

As described above, U–Pb magmatic and detrital zircon age determinations have for the first time established the timing of deposition of sedimentary and volcanic sequences and emplacement of plutonic rocks in the eastern part of Grand Manan Island. One of the more obvious similarities to the New Brunswick mainland is the presence of earliest Cambrian volcanic rocks in the Castalia Group that are identical in age to volcanic rocks of the Belleisle Bay Group in the New River Terrane (see below). Neoproterozoic ages determined for volcanic and plutonic rocks on Grand Manan appear not to be restricted to a particular terrane on the mainland (Fig. 4).

The presence of platformal quartz-rich and carbonate sedimentary rocks in the Grand Manan Group suggests a possible lithotectonic linkage of the Grand Manan Terrane to the Ganderian Brookville and New River terranes on the New Brunswick mainland (Fig. 2). As previously noted, Alcock (1948) correlated the quartzite of The Thoroughfare Formation and marble of the Kent Island Formation with the interbedded stromatolitic carbonate-quartzite sequence of the Ashburn Formation in the lower part of the Green Head Group (Fig. 4). If this correlation is correct, then The Thoroughfare and Kent Island formations are no younger than 649 ± 12 Ma (late Cryogenian), the age of the youngest detrital zircon population within the Martinon Formation in the upper part of the Green Head Group (Barr et al. 2014).

The Late Neoproterozoic (early Ediacaran) age of volcanic rocks of the Ingalls Head Formation (dated at 618 ± 3 Ma) in the Grand Manan Terrane (Fig. 4) is similar to volcanic rocks (dated at 613 ± 2 to 600 ± 1 Ma) of the Broad River Group in the Caledonia Terrane, although no associated iron-rich cherts of that age range have been reported on the mainland. Plutonic rocks similar in age to the Ingalls Head volcanic rocks occur both in the Caledonia Terrane (dated at 625 ± 5 to 616 ± 3 Ma) and New River Terrane (dated at 629 ± 1 to 622 ± 2 Ma). However, volcanic rocks equivalent in age to those of Coldbrook Group (dated at 559 ± 1 Ma to 548 ± 1 Ma) of the Caledonia Terrane have not been identified on Grand Manan. Thus Alcock's suggested correlation of volcanic rocks on Grand Manan with those of the Coldbrook Group appears unlikely. Furthermore, major plutons (dated at 557 ± 3 Ma to 550 ± 1 Ma) in the Caledonia Terrane that are comagmatic with the Coldbrook Group are lacking in the Grand Manan Terrane.

Deposition of conglomerate of the Great Duck Island Formation and overlying quartzose sedimentary rocks of the Flagg Cove Formation in the lower part of the Castalia Group began no earlier than 574 ± 7 Ma based on the age of the youngest contained detrital zircon population in the latter sequence and ended prior to emplacement of the Stanley Brook Granite at 535 ± 2 Ma. The earliest Cambrian age of the overlying Priest Cove Formation (539 ± 5 Ma) in the upper part of the Castalia Group is identical in age to volcanic rocks of the Simpsons Island and Grant Brook formations of the Belleisle Bay Group (dated at 539 ± 4 Ma and 541 ± 3 Ma) in the New River Terrane on the New Brunswick mainland (Fig. 4). However, no older volcanic rocks similar in age (~ 554 Ma) to those in the Dipper Harbour Group of the Brookville Terrane and in lower part of Belleisle Bay Group (Leavitts Head and Lobster Brook formations) of the New River Terrane have been identified on Grand Manan Island. Instead, it was during this time interval that sedimentary rocks of the Great Duck Island and Flagg Cove formations were being deposited in the Grand Manan Terrane (Fig. 4).

The age of 535 ± 2 Ma for the Stanley Brook Granite and 547 ±1 Ma for the High Duck Island dyke on Grand Manan Island, and the 542 ± 1 Ma age of the Machias Seal Island monzodiorite to the southwest of Grand Manan (Barr et al. 2010) all are within the age range of plutonic rocks (dated at 548 ± 2 to 528 ± 3 Ma) in the Brookville Terrane on the New Brunswick mainland. Plutonic rocks of the Ragged Falls suite (dated at 553 ± 2 Ma and 555 ± 10 Ma) in the New River Terrane are not known to occur on Grand Manan (Fig. 4).

TECTONIC EVOLUTION OF THE GRAND MANAN TERRANE

The geological evolution of the Appalachian Orogen can be understood in terms of the assembly and breakup of three supercontinents. The supercontinent of Rodinia was assembled over a period extending from 1300 to 900 Ma and broke apart beginning at about 780 Ma. Large cratons and smaller continental fragments that rifted from Rodinia had been largely reconfigured into the supercontinent of Gondwana by 630 Ma (Li et al. 2008). The protracted magmatic, metamorphic, and tectonic events related to the closure of Precambrian ocean basins and assembling of Gondwana have been termed 'Pan African' by Kennedy (1964) and more recently as 'Brasiliano – Pan African' by da Silva et al. (2005). In the northern Appalachians, evidence for the breakup of Rodinia is recorded in the Avalon Terrane of Newfoundland by ophiolitic rocks that have yielded a U–Pb date of 763 ± 2 Ma (Strong et al. 1978; Krogh et al. 1988; Murphy et al. 2008).

Rifting associated with the opening of the Iapetus Ocean was initiated around 570 Ma, when Laurentia began to break away from Gondwana. At the same time, a Precambrian ocean basin remained in existence in the western part of Gondwana and did not close until 530 Ma during the Pampean Orogeny (Escayola et al. 2011; van Staal et al. 2012). With the later opening of the Rheic Ocean in the mid-Cambrian, the microcontinent of Ganderia separated from the northern margin of Gondwana (Nance and Linnemann 2008; van Staal et al. 2012). Expansion and subsequent closure of the Iapetus and Rheic oceans led to the rearrangement and amalgamation of Gondwana and Laurentia to form the supercontinent of Pangea by the end of the Permian (Murphy et al. 1999).

The subsequent breakup of Pangea began with rifting in the Late Triassic and the opening of the Atlantic Ocean by the Early Jurassic (Wade et al. 1996; Olsen 1997).

Platformal rocks on Grand Manan Island are too ancient to have been deposited on the passive margin of the Iapetus Ocean. Instead, the pre-600 Ma quartzites and carbonates of The Thoroughfare and Kent Island formations (and correlative Green Head Group on the New Brunswick mainland) likely were deposited along the margin of a Precambrian ocean basin associated with the breakup of Rodinia around 780 Ma (Rast and Skehan 1983; Nance 1986b, 1987; Nance et al. 2002). Anorthositic rocks of the Lower Coverdale complex (dated at 976 +8/-7 Ma), buried beneath Carboniferous cover in southeastern New Brunswick (Tesfai 2011) may represent a remnant of basement rocks rifted from the southeastern (present-day coordinates) passive margin of the proposed Precambrian ocean. Basement rocks from the conjugate margin may be represented by the Blair River complex (dated at 1040 +10/-40 Ma) in northern Cape Breton Highlands, Nova Scotia (Barr et al. 1987) and by a clast of foliated granodiorite (dated at 1088 +3/-5 Ma) found within limestone beneath the backarc volcanic rocks of the Ordovician Tetagouche Group in the Miramichi Terrane of northern New Brunswick (van Staal et al. 1996).

Southeastward subduction of Precambrian oceanic crust beneath the northern margin of Gondwana is proposed to account for the older arc magmatism (documented above) in the New River (629–622 Ma) and Grand Manan (618–611 Ma) terranes (Fyffe et al. 2009). Erosion of these pre-600 Ma New River plutonic rocks (and missing volcanic host rocks) may be marked in the Brookville Terrane (Fig. 4) by the shift in provenance for detrital zircons from a Mesoproterozoic continental-basement source (1.228 ± 0.003 Ga) in the Ashburn Formation in the lower part of the Green Head Group to a dominantly Late Neoproterozoic source (649 ± 12 Ma) in the Martinon Formation in the upper part of the Green Head Group. A change in source areas is also found in the Grand Manan Terrane between The Thoroughfare (1.425 ± 0.098 Ga) and Flagg Cove formations (611 ± 7 Ma). These changes are reflected in the significantly more juvenile ε_{Nd} signatures in the sedimentary rocks of the Martinon and Flagg Cove formations compared to those of the Ashburn and The Thoroughfare formations (Hodgins 1994; Samson et al. 2000).

A significant time gap exists between this older arc magmatism (early Ediacaran) and a younger period of arc activity (late Ediacaran to earliest Cambrian) documented both on the New Brunswick mainland and on Grand Manan Island. Localized collision of an oceanic spreading ridge or an oceanic aseismic ridge (a chain of hotspot seamounts) with the continental margin has been proposed to account for the cessation of the pre-600 Ma arc activity in this part of Gondwana (Fyffe et al. 2009). Underthrusting of a buoyant oceanic ridge following such a collision may cause shallowing of the subduction angle so that arc activity shuts down above the flattened slab (Thorkelson and Taylor 1989; Gutscher et al. 1999; Collins 2002). Ridge subduction also leads to compression in the far backarc region of the upper plate, where it is commonly accompanied by partial melting and arching (Espurt et al. 2007). Such a collisional event would, therefore, explain the intrusion of orthogneiss into the Brookville Terrane at 615 ± 4 Ma (Barr et al. 2014).

Geochronological data indicate that arc activity was re-established along the northern continental margin of Gondwana following a lull of approximately 50 million years. This younger magmatism lasted from 555 to 539 Ma in the New River Terrane, from 553 to 528 Ma in the Brookville terrane, and from 547 to 535 Ma in the Grand Manan Terrane. The tendency of larger volumes of volcanic and plutonic rocks at the younger end of this age range to occur in the Brookville and Grand Manan terranes compared to the New River Terrane may be attributed to subduction of progressively younger and hence more buoyant oceanic crust during progressive closure of the Precambrian ocean basin. As a result, the subduction angle will decrease and arc magmatism will encroach farther onto the continental margin (Collins 2002; Kay et al. 2005). The cessation of magmatic arc activity by 528 Ma may mark the final closure of the Precambrian ocean in southern New Brunswick and, if so, coincides in time with the Pampean Orogeny along the western edge of Gondwana (van Staal et al. 2012).

The Gondwanan margin of the Iapetus Ocean in southern New Brunswick is marked by the deposition of platformal sedimentary strata of the Saint John Group unconformably on Precambrian basement rocks of the Caledonia, Brookville, and New River terranes. The stratigraphic succession of the Saint John Group within Ganderia is best preserved in the Beaver Harbour area of the New River Terrane as described above. The transgression from basal alluvial conglomerate and sandstone (Ratcliffe Brook) to shelf quartzite and limestone (Glen Falls and Buckmans Creek formations) in the Early Cambrian section is interpreted here to record the transition from the rift-to-drift stage of Iapetan ocean development. Subsequent onlap of Middle Cambrian limestone and black shale (Forest Hill Formation) over the Early Cambrian sequence may be attributed to foundering of the trailing edge of Ganderia during the initial opening of the Rheic Ocean farther to the south. This second transgressive event is also recorded in the St. Croix Terrane in the deeper offshore region of Iapetus, where a thick sequence of quartzose sandstone (Crocker Hill Formation) is separated from an overlying sequence of Middle Cambrian to Early Ordovician black shale (Calais Formation) by a thin interval of limestone and tholeiitic pillow basalt (Fyffe et al. 1988). An Iapetan backarc basin opened within Ganderia (Annidale Terrane, Figs. 1, 2) in the Late Cambrian to Early Ordovician, contemporaneously with the expansion of the Rheic Ocean and separation of Ganderia and Avalonia from Gondwana (Johnson et al. 2012; van Staal et al. 2012). Subsequent closure of the Annidale backarc basin in the Early Ordovician juxtaposed the New River and Miramichi terranes during the Penobscot Orogeny (van Staal et al. 2009).

The timing of tectonism that produced tight folding and thrusting in the Grand Manan Terrane is poorly understood; however, some of the deformation must have post-dated intrusion of the Stanley Brook Granite in the Early Cambrian. It is possible that some of the thrusting was synchronous with deposition of the earliest Cambrian (early Terreneuvian) black shale breccia within the Long Pond Bay Formation (Fig. 11), and that this thrusting was related to final closure of the Precambrian ocean in southern New Brunswick. Alternatively, the thrusting events on Grand Manan Island may be related to emplacement of Avalonia over Ganderia during the Acadian Orogeny (cf. Keen et al. 1991). Similar thrusts are present along the Fundy coast on the mainland of New Brunswick, the Kennebecasis – Pocologan Fault being a prime example (Fig. 2). Both dextral strike-slip and thrust displacement is known to have occurred on this fault during the Late Silurian – Early Devonian and in the Carboniferous (Rast and Grant 1973; Nance 1986a; Léger and Williams 1986; Park et al. 1994). The Late Silurian – Early Devonian displacement may have been associated with accretion of the Avalonian Caledonia Terrane to Ganderia by northwestward subduction of the Avalonian plate beneath the Silurian Kingston arc and Mascarene backarc basin (Fyffe et al. 1999; White et al. 2006; van Staal et al. 2009). Later fault movement in the Carboniferous may have been related to closure of the Rheic Ocean during the Alleghenian Orogeny (Nance 1986a; Murphy et al. 1999).

CONCLUSIONS

The bedrock underlying the eastern side of Grand Manan Island has been divided into the pre-600 Ma Grand Manan Group, and post-600 Ma Castalia Group, based on recently published U–Pb magmatic and detrital zircon age determinations and exposed and inferred stratigraphic relationships. Contacts between the three formations comprising the Grand Manan Group (Kent Island, The Thoroughfare, and Ingalls Head formations) are faulted but the following evidence suggests that all were deposited prior to the deposition of the Castalia Group: (1) the absence of detrital zircons younger than 1.42 Ga (Mesoproterozoic) age in quartzite of The Thoroughfare Formation; (2) the U–Pb zircon date of 618 ± 3 Ma for the eruptive age of the Ingalls Head Formation; (3) the U–Pb zircon date of 611 ± 2 Ma for emplacement of the Three Islands Granite into marble of the Kent Island Formation; (4) the presence of large clasts of quartzite and granite in volcanic rocks of the Ross Island Formation, which indicates that rocks of the Castalia Group were likely deposited on a substratum that was no younger than 590 Ma (Fig. 8); (5) the existence of an unconformity exposed between volcanic rocks of the Ingalls Head Formation and overlying conglomerate of the Great Duck Island Formation at the base of the Castalia Group; and (6) the age range of detrital zircons in sandstone of the Flagg Cove Formation, which suggests that deposition of the gradationally underlying conglomerate and sandstone of the Great Duck Island Formation took place after 574 ± 7 Ma.

The presence of platformal quartz-rich and carbonate sedimentary rocks of The Thoroughfare and Kent Island formations in the Grand Manan Group provides a lithotectonic linkage between the Grand Manan Terrane and the Green Head Group (Brookville Terrane) on the New Brunswick mainland, and to the Seven Hundred Acre Island Formation (Islesboro Terrane) of coastal Maine. Also, the ages of volcanic rocks in the Ingalls Head Formation (618 ± 3 Ma) of the Grand Manan Group and the Priest Cove Formation (539 ± 5 Ma) of the Castalia Group are, respectively, similar to the ages of older plutons in the mainland New River Terrane (629 ± 1 to 622 ± 2 Ma), and to volcanic rocks of the Simpsons Island (539 ± 4 Ma) and Grant Brook (541 ± 3 Ma) formations (Belleisle Bay Group) in the New River Terrane. It is therefore concluded that the Grand Manan, Brookville, New River, and Islesboro terranes all represent blocks that originated near the margin of a Precambrian ocean and were later rifted from Gondwana during the opening of the Iapetus Ocean. These rifted blocks were the source of the characteristic Ganderian quartzose sediments (e.g. the Cambrian Miramichi Group and the Crocker Hill Formation at the base of the Cookson Group) that were deposited along the southeastern side of Iapetus (Fyffe et al. 2009), and provides support for the two-sided orogenic system proposed by Hank Williams that eventually led to our present understanding of plate tectonic interactions in the Appalachians of Atlantic Canada (Williams 1964).

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