Middle Cambrian (Miaolingian) acritarchs from the Flagg Cove Formation, Grand Manan Island, New Brunswick, Canada: stratigraphic implications and possible correlations

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ABSTRACT

The upper Ediacaran to lower Cambrian Castalia Group as originally defined comprises a basal sequence of clastic marine sedimentary rocks assigned to the Great Duck Island and Flagg Cove formations and an upper sequence of mainly mafic volcanic and volcaniclastic rocks of the Ross Island, North Head, Priest Cove, and Long Pond Bay formations. A few previously reported specimens of the long-ranging trace fossil *Planolites* in the Flagg Cove Formation were not inconsistent with the U–Pb age of 539.0 ± 3.3 Ma age for the Priest Cove Formation or the interpreted intrusive relationship between the Flagg Cove Formation and 535 ± 2 Ma Stanley Brook Granite.

During a recent visit, abundant morphologically simple trace fossils, including *Planolites*, were recognized in strata south of Stanley Beach in Flagg Cove, together with vertically or obliquely oriented trace fossils more than 10 mm in diameter, and probable *Teichichnus*. The age of this association of trace fossils is post-earliest Fortunian. More significantly, grey silty shale interbedded with the sandstone that contains the traces yielded organic-walled microfossils. The microfossils include the acritarch *Micrhystridium* spp of a type also found in the King Square Formation in the Saint John area. The microfossils suggest a Miaolingian (middle Cambrian) age for the Flagg Cove Formation, requiring that its relationship with the Stanley Brook Granite and Castalia Group needs to be re-examined. It also raises the possibility of correlation with middle Cambrian clastic sedimentary sequences exposed on mainland southern New Brunswick and elsewhere in the region.

RÉSUMÉ

Le groupe de l'Édiacarien supérieur au Cambrien inférieur de Castalia originalement défini est constitué d'une séquence basale de roches sédimentaires marines clastiques rattachées aux formations de Great Duck Island et de Flagg Cove ainsi qu'une séquence supérieure de roches principalement volcanomafiques et volcanoclastiques des formations de Ross Island, North Head, Priest Cove et Long Pond Bay. Les quelques spécimens précédemment signalés de l'ichnofossile relevé sur de longues distances *Planolites* dans la Formation de Flagg Cove n'étaient pas incompatibles avec l'âge U–Pb de 539,0 ± 3,3 Ma attribué à la Formation de Priest Cove ou au lien intrusif établi entre la Formation de Flagg Cove et le granite de 535 ± 2 Ma du ruisseau Stanley.

Durant une visite récente, une abondance d'ichnofossiles morphologiquement simples, dont des *Planolites*, a été repérée dans des strates au sud de la plage Stanley dans l'anse Flagg, conjointement avec des ichnofossiles verticalement ou obliquement orientés de plus de 10 mm de diamètre ainsi que de probables *eichichnus*. Cette association d'ichnofossiles remonte à une période ultérieure au Fortunien le plus précoce. Fait plus significatif, le schiste silteux gris interlité avec le grès qui abrite les traces a livré des microfossiles à parois organiques. Les microfossiles comprennent l'espèce d'acritarche *Micrhystridium* d'un type également présent dans la Formation de King Square dans la région de Saint John. Les microfossiles laissent supposer que la Formation de Flagg Cove remonte au Miaolingien (Cambrien moyen), ce qui nécessiterait un réexamen de son lien avec le granite du ruisseau Stanley et le groupe de Castalia. La datation fait surgir en plus la possibilité d'une corrélation avec les séquences sédimentaires clastiques du Cambrien moyen affleurant sur la partie continentale dans le sud du Nouveau-Brunswick et ailleurs dans la région.

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INTRODUCTION

Grand Manan Island is located at the southwestern end of the Bay of Fundy between the provinces of New Brunswick and Nova Scotia and the state of Maine, USA. (Fig. 1). The island is best known geologically for its spectacular exposures of late Triassic basalt that form the western side of the island and are part of the Central Atlantic Magmatic Province (e.g., Marzoli *et al.* 2018). In contrast the pre-Mesozoic rocks on the eastern side and surrounding islands have eluded direct correlation with the surrounding mainland. The Triassic basalt and minor associated red beds are part of the Fundy Group of Maritime Canada (Klein 1962; McHone 2011). The Fundy Group was deposited in one of several Lower Mesozoic rift basins during the break-up of the supercontinent Pangea (Wade *et al.* 1996; Olsen 1997; Marzoli *et al.* 2018). On Grand Manan Island the gently tilted Fundy Group occupies the down-thrown side of the Red Point Fault, a normal fault that separates this younger flat-lying sequence from complexly deformed, mostly Ediacaran, metasedimentary and metavolcanic rocks on the eastern side of the island (McHone and Fyffe 2014). Since the mid 2000s, significant advances have been made in our understanding of the age and stratigraphy of the older rocks on Grand Manan (e.g., Pe-Piper and Wolde 2000; Fyffe and Grant 2000, 2001; Barr *et al.* 2003a; Black *et al.* 2004; Black 2005; Fyffe *et al.* 2011a; Fyffe 2014; Barr and Mortensen 2019), although many questions remain, including those raised by the new biostratigraphic constraints presented in this paper.

REGIONAL TECTONIC SETTING

Grand Manan Island and small offshore islands to the east and south (Fig. 1) lie within the northeastern Appalachians, a long-lived Paleozoic accretionary orogen involving several distinct, but diachronous orogenic events related to the closure of the Iapetus and Rheic oceans (e.g., Williams 1979; van Staal *et al.* 1998; van Staal and Barr 2012; Waldron *et al.* 2022). The Appalachian cycle was complete when Gondwana (Amazonia and West Africa) collided with composite Laurentia during the early Permian to form the supercontinent Pangea (e.g., van Staal 2005; van Staal and Barr 2012; Waldron *et al.* 2022). Proterozoic and early Paleozoic rocks in the northeastern Appalachian orogen in Atlantic Canada are currently recognized as being part of three major micro-continental fragments assigned to the larger domains Avalonia, Ganderia, and Megumia (van Staal *et al.* 2021a, b; Waldron *et al.* 2022). Proterozoic and early Paleozoic rocks occur extensively on the mainland in southern New Brunswick and are divided into three, fault-bounded lithotectonic terranes (Fyffe *et al.* 2011a) which from east to west include the Avalonian Caledonia terrane and the Brookville and New River terranes, considered to be part of Ganderia (Barr and White 1996; Fyffe *et al.* 2011a). Offshore to the south, Grand Manan archipelago comprises a fourth Proterozoic terrane recognized in southern New Brunswick, the Grand Manan terrane of Fyffe (2014), which he also considered part of Ganderia. These terranes include a diverse assemblage of Tonian to Ediacaran intrusive, volcanic, and volcaniclastic rocks that are overlain by Early Paleozoic cover sequences. Latest Cryogenian–early Ediacaran (ca. 650–600 Ma) marble and gneiss in the Brookville terrane are clearly distinct from widespread ca. 625–610 Ma calc-alkaline magmatism in the Caledonia, New River, and Grand Manan terranes; however, all of these terranes have extensive ca. 555–540 Ma late Ediacaran volcanic and plutonic rocks and, with the exception of Grand Manan Island, contain strata that have been correlated with the Cambrian Saint John Group (Barr and White 1996; Fyffe *et al.* 2011a).

PRE-MESOZOIC GEOLOGY OF GRAND MANAN ISLAND

Detailed mapping and U–Pb zircon dating conducted in the 2000s helped to resolve the stratigraphy of Grand Manan Island, although it remains poorly understood. Alcock (1948) considered the intensely deformed sedimentary and volcaniclastic rocks to be in the Precambrian Green Head Group and the volcanic rocks in the Precambrian Coldbrook Group. Stringer and Pajari (1981) did the first detailed structural analysis and recognized four generations of folding. McLeod *et al.* (1994) included sedimentary rocks at Flagg Cove and The Thoroughfare (Fig. 2) in the Cambrian–Ordovician and the volcanic rocks on Ingalls Head, and on Ross, White Head, and Wood islands in the Precambrian–Cambrian. They assigned an Ordovician–Silurian age to the volcaniclastic rocks near Priest Cove based on purported Silurian fossil debris observed microscopically in volcaniclastic sandstone (Hilyard 1992); however, no fossils have been found during subsequent studies and a dacitic tuff intercalated with the volcaniclastic rocks yielded a U–Pb zircon age of 539.0 ± 3.3 Ma, indicating that the Priest Cove Formation is latest Ediacaran to earliest Cambrian, not Silurian (Black *et al.* 2004; Miller *et al.* 2007).

Our current understanding of the bedrock geology and structure of Grand Manan Island largely comes from mapping by Stringer and Pajari (1981), Fyffe and Grant (2000, 2001), Black (2005), Fyffe *et al.* (2011a) and Fyffe (2014) along with geochemical and geochronological studies (Hilyard 1992; Hewitt 1993; Hodgins 1994; Pe-Piper and Wolde 2000; Barr *et al.* 2003a; Black *et al.* 2004; Miller *et al.* 2007; Fyffe *et al.* 2009; Fyffe *et al.* 2011b; Barr *et al.* 2019; Barr and Mortensen 2019). The following description of pre-Mesozoic stratigraphy of Grand Manan Island is mostly after Fyffe (2014), who divided the rocks into two groups; the Mesoproterozoic (?) to Neoproterozoic Grand Manan Group and upper Neoproterozoic to lower Cambrian Castalia Group (Fig. 2). Black (2005) showed similar stratigraphy but with significant differences as discussed below.

Grand Manan Group

The oldest known rocks on Grand Manan and surrounding islands are those of the Grand Manan Group (Fyffe and Grant 2000, 2001). The group is comprised of the Kent Island and Thoroughfare formations and overlying Ingalls Head and Long Island Bay formations (Fig. 2). Although they are considered part of the same group, stratigraphic relationships among the formations are poorly known as the structure is complex and contacts between the units are either faulted or not exposed. The Ediacaran Ingalls Head Formation comprises the youngest part of the group. The Kent Island and Thoroughfare formations may be much older, possibly part of Mesoproterozoic or older basement (Reusch *et al.* 2018).

The Kent Island Formation has limited distribution as it

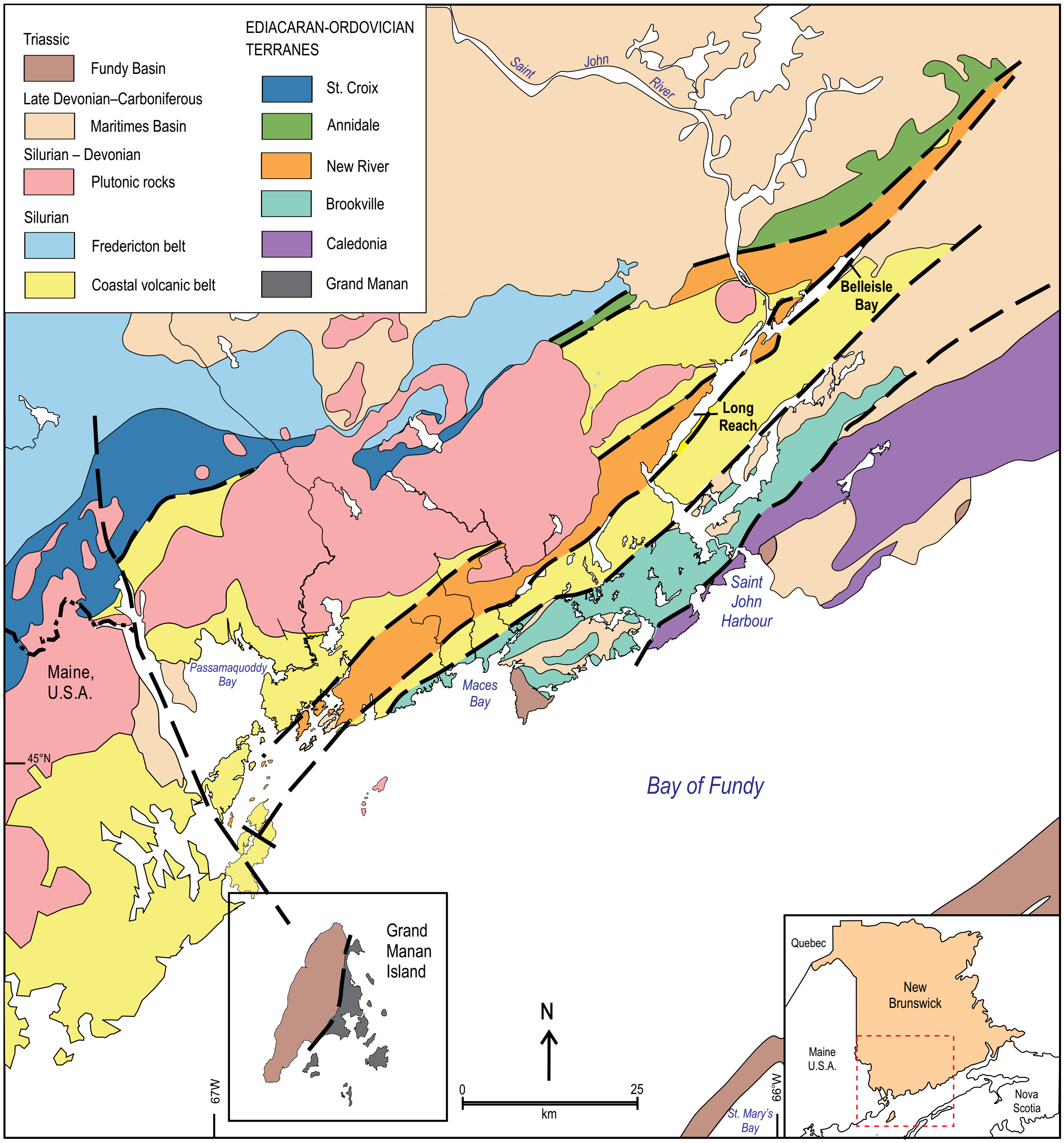

Figure 1. Pre-late Ordovician terranes and post-Ordovician cover sequences in southern New Brunswick after Barr *et al.* (2014). Black box shows location of Figure 2.

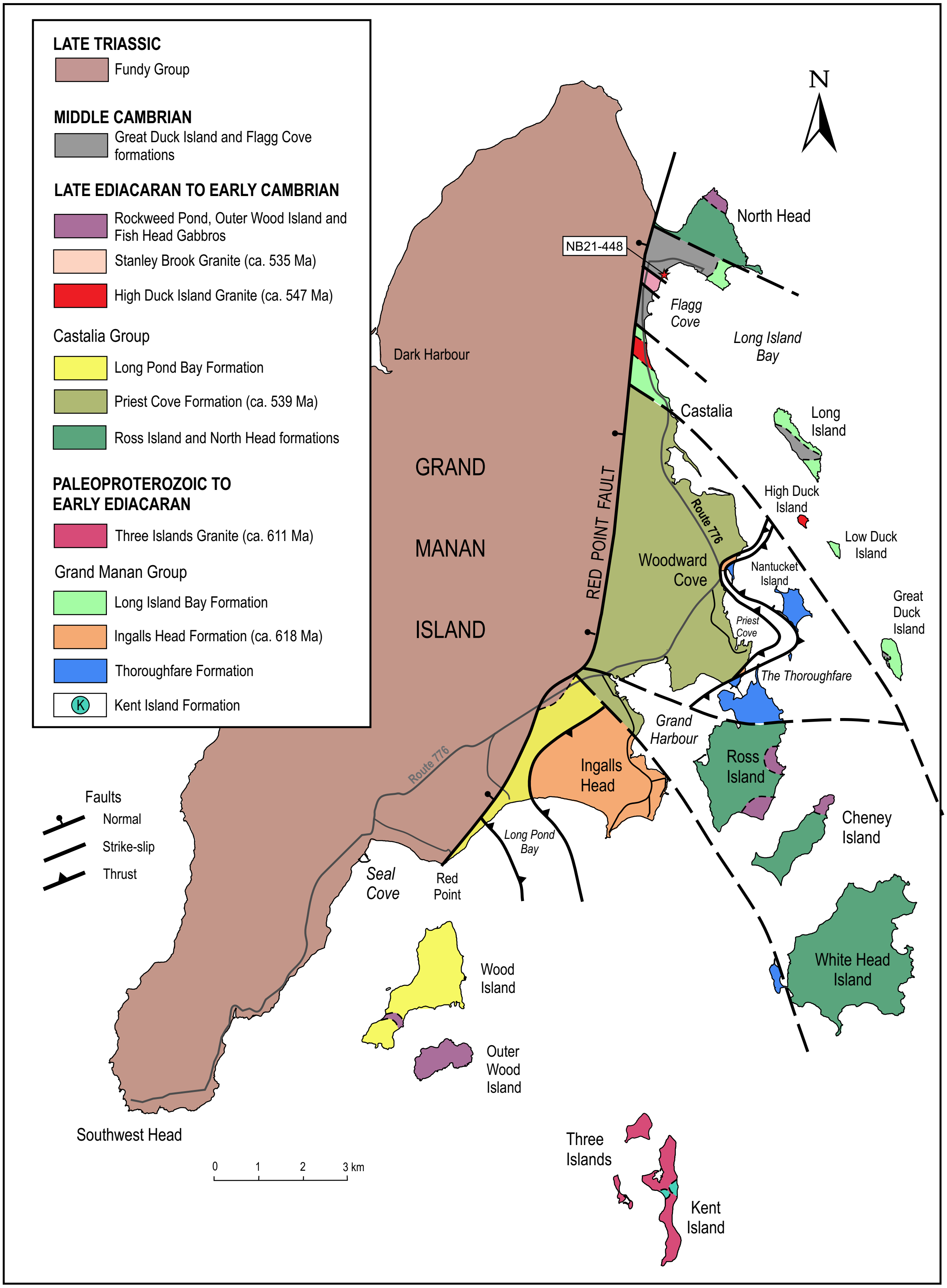

Figure 2. Geology of Grand Manan Island and offshore islands modified after Fyffe and Grant (2001) and Black (2005). Red star shows location of trace fossils and acritarch sample NB21-448.

occurs only on Kent Island located about 8 kms south of Ingalls Head. On both the western and eastern sides of Kent Island carbonate rocks occur as large blocks of re-crystallized marble within the Ediacaran Three Islands Granite. An age of 611.1 ± 2.4 Ma for the Three Island Granite indicates a minimum age of early Ediacaran for the carbonates (Barr *et al.* 2003a). The Thoroughfare Formation comprises white, massive to thick-bedded quartzite and black, carbonaceous chloritoid schist interbedded with thin quartzite layers. A maximum age for the Thoroughfare Formation is ca. 1.65 Ga, the age of the youngest detrital zircons obtained from the quartzite (Barr *et al.* 2019), although we recognize that the depositional age may be considerably younger. The Kent Island and Thoroughfare formations have been correlated with a Proterozoic platform sequence of carbonate, quartzite, schist, and amphibolite in the Islesboro block in Penobscot Bay, Maine (Reusch *et al.* 2018). Within this sequence the Hutchins Island Quartzite has a detrital zircon spectrum similar to that in the Thoroughfare Formation (Reusch *et al.* 2018; Barr *et al.* 2019). The Hutchins Island Quartzite is older than ca. 650 Ma, the age of a cross-cutting pegmatite dyke (Stewart *et al.* 2001). Barr and Mortensen (2019) reported an age of 664.1 ± 4.6 Ma for a pegmatite clast from conglomerate assigned to the base of the Ross Island Formation of the Castalia Group, thereby strengthening the link between Grand Manan Island and the Penobscot Bay area. The youngest rocks in the Grand Manan Group are those of the Ingalls Head Formation. The unit comprises schistose andesitic to dacitic tuff and volcanic breccia containing thin beds and lenses of maroon iron formation and minor rhyolite flows, bedded felsic crystal tuff, sideritic sandstone and shale (Fyffe and Grant 2001). Two rhyolite tuff samples from the Ingalls Head Formation yielded overlapping U–Pb zircon ages of 617.6 ± 3.2 and 618.3 ± 2.8 Ma (Miller *et al.* 2007). Both the Ingalls Head and Thoroughfare formations are interpreted to structurally overlie the younger Castalia Group (Fyffe and Grant 2001; Black *et al.* 2004; Fyffe 2014).

Castalia Group

The upper Ediacaran to lower Cambrian Castalia Group as defined by Fyffe (2014) is divided into a lower sequence of marine clastic rocks (Great Duck Island and Flagg Cove formations) and an upper sequence of mainly mafic volcanic and volcaniclastic rocks (Priest Cove, Ross Island, North Head, and Long Pond Bay formations). The mafic volcanic and volcaniclastic rocks are interpreted to be lateral facies equivalents (Fyffe 2014); therefore, a U–Pb (zircon) age of 539.0 ± 3.3 Ma for a dacitic tuff in the Priest Cove Formation (Miller *et al.* 2007) was considered to represent the age of the entire upper sequence. Mafic tuff and volcaniclastic sandstone of similar age occur in the Belleisle Bay Group in the New River terrane (Barr *et al.* 2003b; Johnson *et al.* 2009). The age of the Great Duck Island and Flagg Cove Forma tions has been more elusive as nowhere are these clastic sedimentary rocks in stratigraphic contact with the mafic volcanic and volcaniclastic units of the Castalia Group, and no age diagnostic fossils were known prior to this study. The clastic sequence, however, was considered to be no younger than earliest Cambrian age based on an interpreted intrusive relationship between the Flagg Cove Formation and the earliest Cambrian Stanley Brook Granite (535 ± 2 Ma, Fyffe *et al.* 2011b). Together with detrital zircon data that indicates a maximum depositional age of ca. 574 Ma (Fyffe *et al.* 2009), these data seemingly bracket the age of the Flagg Cove Formation to between latest Ediacaran and earliest Cambrian. The Great Duck Island Formation comprises massive, matrix- and clast-supported, pebble to boulder polymictic conglomerate and grey to maroon quartz-pebble conglomerate interbedded with maroon and olive-green silty shale and sandstone. The conglomerate typically contains clasts of basalt, maroon siltstone, quartzite, and granite in addition to granules of quartz and plagioclase (Black 2005). The contact with the overlying Flagg Cove Formation is not exposed but younging directions and interbeds of grey sandstone and shale within the Great Duck Island Formation suggest that it grades into or is in part a lateral facies of the Flagg Cove Formation. The depositional environment of the Great Duck Island and Flagg Cove formations was interpreted by Fyffe (2014) to represent proximal and distal facies of a marine fan. Polymictic conglomerate comprising the entire offshore island of Gannet Rock about 13 km south of Grand Manan Island was also tentatively assigned to the Great Duck Island Formation by Black (2005). Distinctive cobbles and boulders of marble, chloritoid schist, and quartzite are most likely derived from the Kent Island and Thoroughfare formations. If the conglomerate is part of the Great Duck Island Formation it suggests that the volcanic-rich part of the Castalia Group was not deposited or was removed prior to exhumation of the Grand Manan Group; however, the age and affiliation of the Gannet Rock conglomerate is uncertain.

The Flagg Cove Formation consists of thin to medium-bedded, grey to greyish pink, quartz-rich sandstone intercalated with grey laminated siltstone and shale (Fig. 3). Minor interbedded arkosic grit and pebble conglomerate occur locally. The Flagg Cove section is complexly folded and sandstone beds are locally boudinaged. Disharmonic folding in some beds is attributed to soft-sediment deformation (Fig. 4). A few trace fossils identified as *Planolites* were previously reported to occur on a bedding surface in Flagg Cove (Fyffe and Grant 2001). During our examination of the section south of Stanley Beach abundant trace fossils were discovered on several bedding surfaces (Fig. 5), as described in more detail below. A sample of grey siltstone from this outcrop was sampled for acritarchs (see subsequent section on Organic-walled Microfossils).

North of Stanley Brook on the northeastern shore of Flagg Cove (Fig. 2) a separate unit of fissile black shale with detrital muscovite, laminated grey siltstone, and thin beds of grey quartzite was also included in the Flagg Cove Formation by Black *et al.* (2004) and Black (2005). The contact with the rocks containing the acritarchs is covered beneath the beach but if younging direction is consistent the black shale unit

Figure 3. Dark grey siltstone and thin-bedded quartzose sandstone of the Flagg Cove Formation, south end of Stanley Beach. Hammer is about 25 cm long.

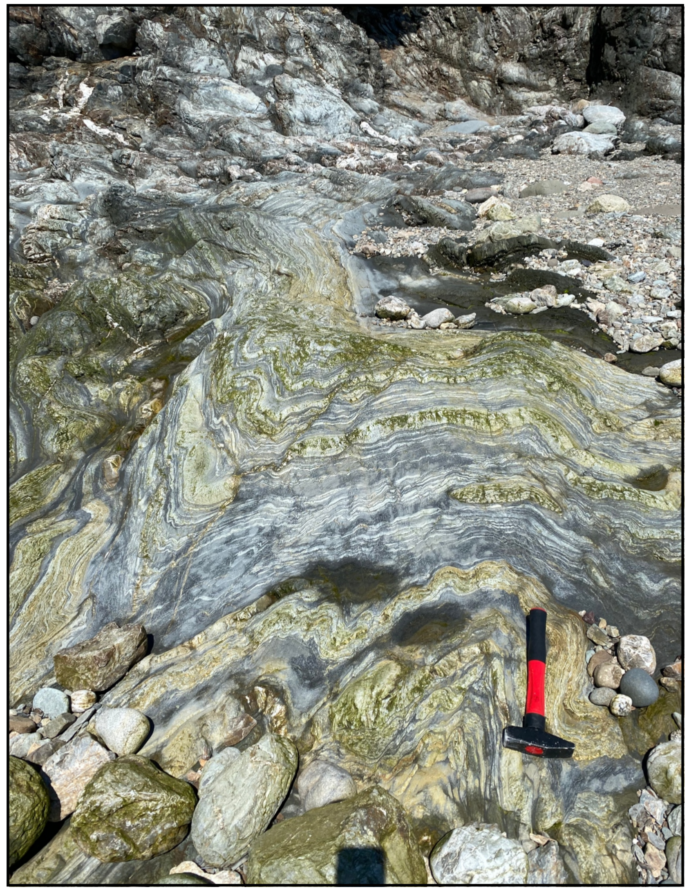

Figure 4. Intensely folded and boudinaged beds of the Flagg Cove Formation exposed in the intertidal zone south of Stanley Beach. Hammer is about 40 cm long.

would overlie the rocks to the south. The Great Duck Island and Flagg Cove formations were interpreted to underlie the mafic volcanic and volcaniclastic succession of the Castalia Group by both Fyffe and Grant (2000) and Black (2005). Several lines of circumstantial evidence were used to support the interpreted stratigraphic order within the Castalia Group, the first being the assumption that the ca. 535 Ma Stanley Brook Granite is "cogenetic" with ca. 539 Ma tuff in the Priest Cove Formation (Fyffe 2014). Because the Flagg Cove Formation was thought to be intruded by this granite it was inferred that the Flagg Cove was older than the Priest Cove Formation. Another line of evidence was the apparent absence of volcanic detritus derived from the mafic volcanic and volcaniclastic rocks of the Priest Cove, Ross Island, North Head, and Long Pond Bay formations in the Great Duck Island conglomerate; however, the Great Duck Island and Flagg Cove formations occur within a structural panel separate from the rest of the Castalia Group, and hence any mutual relationship is speculative. The fault separating the two structural panels is interpreted to be an extension of the northwest-trending Oak Bay Fault (McCutcheon and Robinson 1987). Lastly, the deformation and metamorphism in the Priest Cove Formation is not as intense as in the Flagg Cove Formation and the Stanley Brook Granite (Black 2005) suggesting that it was not subjected to the same deformational events. A definitive link can be made between the Great Duck Island Formation and an underlying basalt unit on Great Duck Island where the contact is an erosive unconformity (Black *et al.* 2004). The conglomerate contains clasts clearly derived from the underlying plagioclase-phyric basalt. Fyffe and Grant (2001) and Fyffe (2014) considered the basalt to be part of the ca. 618 Ma Ingalls Head Formation, whereas Black *et al.* (2004) included it in a new unit named Long Island Bay Formation (not to be confused with the Long Pond Bay Formation of the Castalia Group). Black (2005) considered the Long Island Bay Formation to be younger than the Ingalls Head Formation, in part based on an interpreted comagmatic relationship with the spatially associated High Duck Island Granite, which yielded a U–Pb zircon age of 547 ± 1 Ma (Miller *et al.* 2007). A discussion on the age of the Long Island Bay Formation is beyond the scope of this paper; however, the dominant detrital zircon population in quartzose sandstone from the Flagg Cove Formation is 611 ± 7 Ma (Fyffe *et al.* 2009), consistent with derivation from the Ingalls Head Formation, and lending support to the interpretation that the Long Island Bay Formation is part of the Grand Manan Group. Consequently, we follow Fyffe (2014) by including these rocks in the Grand Manan

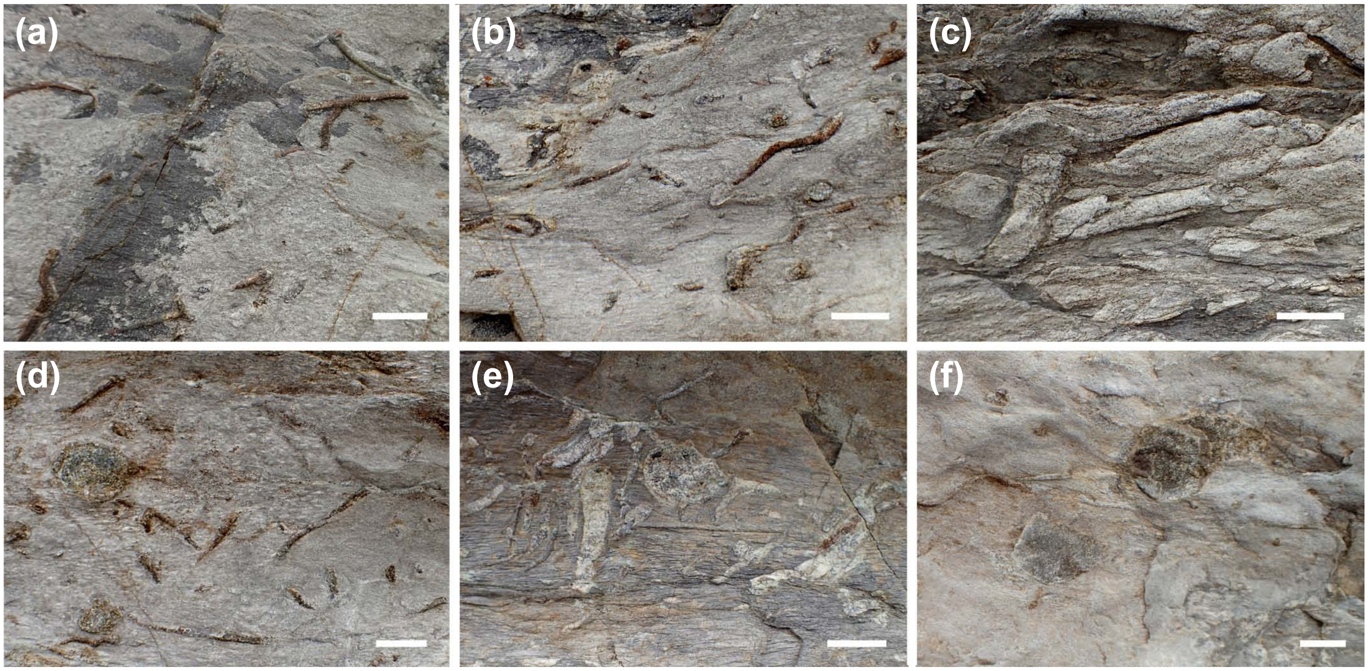

Figure 5. Trace fossils in the Flagg Cove Formation south of Stanley Beach (NAD 83; Grid Zone 19T, 677332E, 4958943N). All photographed in the field on upper bedding surfaces. Scale bars in all parts represent 10 mm. (a, b) *Planolites* and fragments of other, unidentified trace fossils. (c) Dense concentration of trace fossils, some with evidence for a spreite, tentatively identified as *Teichichnus*. (d) *Planolites* and, on the left, a section through a large unidentified trace fossil. (e) Several specimens in the shape of a flat U, with indication of vertical stacking best seen in specimen near right margin. At centre, section through large unidentified trace fossil. (f) A trace fossil entering the strata in the form of a spiral.

Group, even though future radiometric dating may prove it to be considerably younger than the Ingalls Head Formation, dated at 618 Ma. Regardless of its age, the Long Island Bay Formation and overlying Great Duck Island and Flagg Cove formations appear to comprise a stratigraphic succession that is distinct from the adjacent fault panel containing the ca. 539 Ma mafic volcanic and volcaniclastic rocks of the Castalia Group and structurally overlying Grand Manan Group. In this latter structural panel, a massive conglomerate at the base of the Ross Island Formation (Castalia Group) contains abundant cobbles and boulders of granite, granite pegmatite, and metamorphic rocks with no known local source. As noted above, an igneous crystallization age of 664.1 ± 4.6 Ma for one of the pegmatite clasts suggests affinity with the Isleboro block in Maine (Barr and Mortensen 2019; Reusch *et al.* 2018).

Stanley Brook Granite

The Stanley Brook Granite consists of highly strained, cataclastic, pinkish-white, coarse- to medium-grained granite complexly intermingled with green fine-grained diorite (Black 2005; Fyffe *et al.* 2011b). The intrusion is exposed along the shore of Flagg Cove south of Stanley beach for about 150 m. The granite contains more plagioclase than potassium feldspar indicating a granodioritic composition; however, we use the term granite due to the almost complete lack of ferromagnesian minerals. Black (2005) suggested that the intermingling and deformed minerals observed in the Stanley Brook Granite indicate syntectonic intrusion of the granite.

Both the northern and southern contacts of the granite are faulted against sedimentary rocks of the Flagg Cove Formation, but their original relationship is less clear. The northern contact is a 2 m-wide, NNW-trending shear zone of strongly deformed granite juxtaposed against complexly folded siltstone and sandstone of the Flagg Cove Formation (Fig. 6). Near the fault, the granite contains what have been described as sedimentary xenoliths folded together with dykes of pinkish-white granite (Fyffe *et al.* 2011b), although all of the contacts are strongly sheared. The southern contact of the granite is also faulted and is represented by a late NW-trending brittle fault that cuts a wide zone of NNE-trending phyllonite containing cataclastic fragments of granite faulted against sedimentary rocks of the Flagg Cove Formation (McHone and Fyffe 2014; Fyffe 2014). Fyffe *et al.* (2011b) reported that "pink, medium-grained granite sampled from the northern part of the exposure of Stanley Brook Granite in Flagg Cove" yielded a U–Pb zircon (ID-TIMS) upper intercept age of 535.1 ± 2.4 Ma, although no location coordinates were given.

Figure 6. Field photograph of the northern faulted contact (red dashed line) between the Stanley Brook Granite (left) and Flagg Cove Formation (right). Box in centre shows the location of brown-weathered siltstone inclusions infolded with pink granite. View is looking northwest.

TRACE FOSSILS

Trace fossils were observed during this study on upper bedding surfaces in the Flagg Cove Formation south of Stanley Beach, Flagg Cove. Essentially horizontal, morphologically simple, 1–2 mm wide trace fossils (Fig. 5a, b, d), probably correspond to the previous identification (Pickerill in Fyffe and Grant, 2001) of *Planolites* in the Flagg Cove Formation. However, specimens with sharp turns, which are not typical of *Planolites*, suggest that other ichnogenera in addition to *Planolites* may also be represented by these millimetric traces. The absence of preferred orientations of the turns rules out a secondary origin by deformation. Without fuller views of trace trajectories, speculation on their identification is not warranted. Fragmentary trace fossils up to approximately 6 mm wide (Fig. 5c, e) appear to be low, U-shaped forms with spreite (gradual displacement of a causative burrow), tentatively identified as *Teichichnus*. A further type of trace fossil is seen by their near-circular intersections on the bedding plane, some only a few millimetre wide (Fig. 5b, upper left in 5f) but others with widths of 12 mm (Fig. 5e), 13 mm (Fig. 5d), and 13 by 15 mm. Because of their essentially 2D preservation, it is not known with certainty if they represent sections through a plug-shaped burrow, such as *Conichnus* or *Bergaueria*, or sections through a vertical or inclined cylindrical burrow. However, a specimen 15 mm wide extends into the rock in what appears to be a spiral turn (Fig. 5f), which makes the interpretation of the circular bedding-plane intersections as cylindrical burrows the more likely.

The Stanley Beach trace fossil association does not provide precise age information because it could be expected in virtually any Phanerozoic stratum. The size and vertical orientation of some of the burrows, and trace fossils with probable spreite do, however, rule out a late Ediacaran age, as well as an earliest Fortunian age (e.g., Mángano and Buatois 2020). *Teichichnus* is the earliest trace fossil in the geological record with a spreite, first appearing in late Fortunian strata but only becoming common from Cambrian Age 2 onwards (Gougeon *et al.* 2018; Mángano and Buatois 2020). The most probable age inference for the Flagg Cove Formation trace fossils is that they are Cambrian Age 2 or younger (< approximately 530 Ma). Based on the Flagg Cove trace fossils, the 539 Ma age from a dacitic tuff in the Priest Cove Formation is inconsistent with the prevailing interpretation that the Flagg Cove Formation is stratigraphically lower than the Priest Cove Formation. This anomaly is further accentuated by the more precise age information provided by the organic-walled microfossils described below.

ORGANIC WALLED MICROFOSSILS

Sample NB21-448 (NAD83; Grid Zone 19T, 677338E, 4958946N)

The sample produced scarce organic-walled microfossils, primarily consisting of *Micrhystridium* (*Micrhystridium* spp Fig. 7a–c). *Micrhystridium* spans throughout the Phanerozoic, with species that exhibit conservative morphological characters and the genus therefore has little chronostratigraphic significance (Palacios *et al.* 2022). Nevertheless, certain morphological attributes as well as assemblages dominated by *Micrhystridium* allow for biostratigraphic deductions. In the material of *Micrhystridium* from the Flagg Cove Formation a circular opening in the vesical wall (Fig. 7c), known as a pylome, is significant. The earliest occurrence of pylome-bearing *Micrhystridium* is in the middle Miaolingian (Drumian) *Adara alea* Zone, specifically in the K1 Member of Kistedalen Formation, northern Norway (Palacios *et al.* 2022). However, the main *Micrhystridium*-dominated Miaolingian assemblages, including specimens with a pylome, have been identified in the late Miaolingian (Guzhangian) *Cristallinium dubium* Zone (Palacios *et al.* 2022). In eastern Canada occurrences of this approximate age include the King Square Formation (Saint John Group), New Brunswick (Fig. 7d–f), and the upper part of the Trout Brook Formation and basal MacLean Brook Formation (Mira River Group) in southeastern Cape Breton Island, Nova Scotia, in levels with the trilobite *Paradoxides forchhammeri* (T. Palacios, unpublished data). A further occurrence in Nova Scotia is in the lower part of MacMullin Formation, Bourinot belt (Palacios *et al.* 2012, fig 11E). In Spain this type of *Micrhystridum* assemblage has been found in the Adrados Member of the Oville Formation, Cantabrian Mountains, and the Borobia Formation of the Celtiberian Chains (Palacios 2015). In the East European Platform it appears in the Lukov Form-

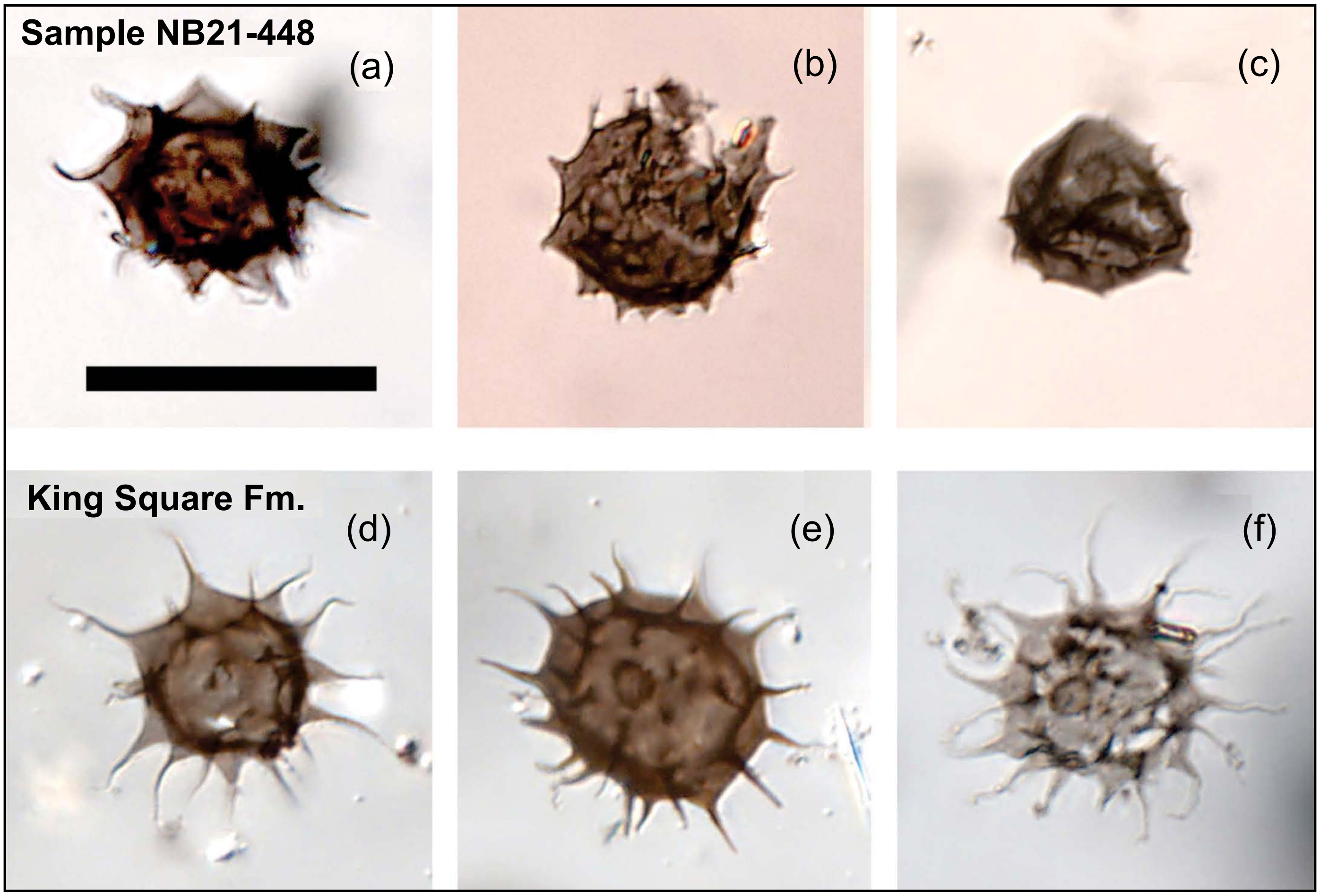

Figure 7. The acritarch *Micrhystridium* spp from the Flagg Cove Formation, Great Manan Island (a–c), and King Square Formation, Saint John area (d–f). Scale bar represents 20 µm for all image parts. Slide number is followed by England Finder coordinates. (a, b) Specimens from sample NB21-448, collected at Flag Cove, Slide NB21-448-1, D-29-2 and O-45-3. (c) Specimen showing small circular pylome, Slide NB21-448-2, Y-18-4. (d, e) Specimens from the King Square Formation in section at King Square (d, Slide KS09-3-1, K-24-2; e, Slide KS09-3-1, F-36-1-3). (f) Specimen from the King Square Formation in the abandoned quarry section, Slide Ab and 08-10-1, W-25-4. Specimens in e and f show small circular pylome. See Tanoli and Pickerill (1989, fig. 2) for location of King Square Formation sections.

ation (SK2a Zone equivalent to *paradoxissimus* Superzone (Volkova and Kir'yanov 1995). Hence, acritarchs in the Flagg Cove Formation indicate a Miaolingian age, possibly approximating that of the King Square Formation (see Palacios *et al.* (2022, fig. 14) for position of those litho-stratigraphic units within the Miaolingian (middle Cambrian) Series).

DISCUSSION

A Miaolingian age for the Flagg Cove Formation indicates that both it and the underlying Great Duck Island Formation are much younger than the mafic volcanic- and volcaniclastic-rich rocks of the latest Ediacaran Castalia Group. More importantly, the data challenge previous interpretations of a cross-cutting relationship between the latest Ediacaran–earliest Cambrian Stanley Brook Granite and the Flagg Cove Formation. Such a relationship is not possible based on the Miaolingian age of the acritarchs, and the complexity and intensity of deformation makes it difficult to say with any certainty what the original relationship was. The most plausible explanation is that the Flagg Cove Formation was deposited on the Stanley Brook Granite nonconformably and that the contact was subsequently modified by deformation and shearing. It is also possible that the sedimentary blocks in the granite are derived from an older sedimentary sequence, but this seems unlikely based on the similarity of the siltstone clasts to the adjacent rocks of the Flagg Cove Formation and their close spatial relationship.

The presence of middle Cambrian clastic sedimentary rocks on Grand Manan Island also has implications for correlations with the mainland, critical for understanding the tectonic history of southern New Brunswick. Fyffe (2014) suggested that the Grand Manan terrane is most like the New River terrane based mainly on the presence of ca. 540 Ma mafic volcanic and volcaniclastic rocks (Castalia Group on Grand Manan and Belleisle Bay Group in the New River terrane), not recognized in the other tectonostratigraphic terranes. The Priest Cove Formation in the Castalia Group and Simpsons Island and Grant Brook formations in the Belleisle Bay Group have yielded nearly identical latest Ediacaran radiometric ages (539.0 ± 3.3, Miller *et al.* 2007; 538.8 ± 4 Ma, Barr *et al.* 2003b; and 541 ± 3 Ma, Johnson *et al.* 2012, respectively). A middle Cambrian age for the Flagg Cove Formation strengthens this association as Cambrian clastic sedimentary rocks are a distinguishing feature of the New River terrane (Johnson 2001; Fyffe *et al.* 2011a; Johnson *et al.* 2018). In the New River terrane northwest of Belleisle Bay (Fig. 1), volcaniclastic sandstones of the Grant Brook Formation are disconformably overlain by Cambrian rocks of the Almond Road Group (Johnson *et al.* 2018). The Almond Road Group comprises orthoquartzite and quartzite-pebble rich conglomerate of the Snider Mountain Formation and overlying light grey quartzose sandstone, dark grey to black laminated, light green to dark grey siltstone and shale of the Ketchum Brook Formation. The Snider Mountain and Ketchum Brook formations lack trough cross-beds, hummocky cross-stratification, or other indications of wave and/or storm action or fluvial processes that may be present in shallow marine settings; consequently, a more distal marine depositional environment was proposed for the Almond Road Group (Johnson *et al.* 2018). The Almond Road Group has yielded no fossils, but its age is constrained to between ca. 530 Ma, the maximum depositional age of the Snider Mountain Formation based on detrital zircon, and an Early Ordovician (Floian) age of 475 ± 2 Ma, obtained from a pluton that intrudes the Ketchum Brook Formation (Johnson *et al.* 2018).

Although a middle Cambrian age for the Almond Road Group has not been demonstrated, fossils of early and middle Cambrian age have been recovered from clastic sedimentary sequences elsewhere in the New River terrane. For example, in the Long Reach and Beaver Harbour areas (Fig.1) clastic sedimentary rocks have been lithologically and biostratigraphically correlated with units in the Saint John Group in the Caledonia terrane (Tanoli and Pickerill 1988; Landing and Westrop 1996; Johnson 2001; Boyce and Johnson 2004; Landing *et al.* 2008). The lower Cambrian to lower Ordovician Saint John Group was deposited in a relatively shallow marine sedimentary basin that deepened over time. The juxtaposition of relatively shallow marine sedimentary rocks of the Saint John Group and relatively deep marine sedimentary rocks of the Almond Road Group in different fault-bounded belts within the New River terrane has been attributed to telescoping of related inner and outer platform sequences, respectively (Fyffe *et al.* 2009, 2011a; Johnson *et al.* 2018).

As discussed above under "Organic-walled Microfossils" Miaolingian age acritarchs similar to those in the Flagg Cove Formation also occur in the King Square Formation in the Caledonia terrane. The King Square Formation consists of interbedded sandstone, siltstone, and shale, deposited on a wave- and storm-influenced marine subtidal shelf (Tanoli and Pickerill 1989); however, the lowermost facies of the King Square Formation is dominated by shale with siltstone laminae and thin (2–10 cm) fine-grained sandstone beds deposited in "relatively deep water" with no evidence of wave activity (Tanoli and Pickerill 1989), not unlike the Flagg Cove Formation. A comparison of detrital zircon signatures from the King Square and Flagg Cove formations suggests a similar provenance. The dominant detrital zircon populations in the King Square Formation are ca. 624 Ma and ca. 636 Ma, (Barr *et al.* 2012) somewhat older than the 611 ± 7 Ma age for the dominant detrital zircon population in the Flagg Cove Formation (Fyffe *et al.* 2009). Although the ages are not identical, it is important to consider that in any detrital zircon suite it is unlikely that they represent a single population of zircon. The youngest concordant population of zircon in the Flagg Cove is 574 ± 7 Ma, and within error of the 590 ± 12 Ma age for the youngest concordant zircon population in the King Square Formation (Barr *et al.* 2012). Hence the youngest zircon in both samples is significantly older than the depositional age of the units based on the paleontological evidence, and much older than the ca. 540 Ma Belleisle Bay Group and ca. 550 Ma Coldbrook Group that clearly underlie these rocks in the New River and Caledonia terranes, respectively. Detrital zircon data are not available for the Ketchum Brook Formation, but a sample from the underlying Snider Mountain Formation is dominated by zircon that is ca. 575 Ma (Johnson *et al.* 2018), similar to the youngest zircon population in the Flagg Cove Formation. The maximum depositional age for the Snider Mountain Formation is ca. 530 Ma based on the youngest concordant zircon population in the sample. Although zircon of this age was not found in the Flagg Cove Formation it is interesting to note that two analyses of a single zircon grain from the Flagg Cove Formation gave identical ca. 507 Ma ages (Miaolingian), warranting additional detrital zircon analyses using a more robust sample set.

CONCLUSIONS

A Miaolingian (middle Cambrian) age for the Flagg Cove Formation demonstrates that the Flagg Cove Formation and probably the underlying Great Duck Island Formation are considerably younger than, not older than, the latest Ediacaran to earliest Cambrian mafic volcanic and volcaniclastic rocks of the Castalia Group. We therefore recommend that the Flagg Cove and Great Duck Island formations be removed from the Castalia Group and the group be restricted to mafic volcanic and volcaniclastic rocks of the Priest Cove, Ross Island, North Head and Long Pond Bay formations. It also indicates that the complex contact relations with the earliest Cambrian Stanley Brook Granite need to be reevaluated. It is impossible to say with certainty whether the "elongate xenoliths" within the cataclased Stanley Brook Granite are part of an older sedimentary sequence or are not xenoliths but instead represent remnants of an originally nonconformable contact between the Flagg Cove Formation and Stanley Brook Granite that was subsequently sheared and folded. A detailed structural analysis of the Flagg Cove Formation and Stanley Brook Granite and their contact relations, along with a detailed sedimentological study of the Flagg Cove and Great Duck Island formations, might help to clarify some of these Issues. Similarities in the paleontological age and detrital zircon spectra of the Flagg Cove Formation and King Square Formation of the Saint John Group suggest a biostratigraphic and provenance connection between the Grand Manan and Caledonia terranes. This connection may also extend to the New River terrane, with the Snider Mountain, Ketchum Brook, and Flagg Cove formations representing more distal, deeper water facies of the Saint John Group, corresponding to outer and inner platform sequences, respectively, deposited on Ediacaran basement during the Cambrian (Fyffe *et al.* 2011a; Johnson *et al.* 2018).

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