Preliminary Geology of the Northernmost Antigonish Highlands, Northern Mainland Nova Scotia

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Introduction

The purpose of this report is to present preliminary results from mapping of the northernmost part of the Antigonish Highlands (Fig. 1). This mapping in the summer of 2012 completed the Antigonish Highlands Bedrock Mapping Project (White and Archibald, 2011; White *et al*., 2011, 2012a, b; White, 2013). Previous work in the Antigonish Highlands by Benson (1974) and Murphy *et al*. (1991) and other background information on the project were summarized by White *et al*. (2011). A preliminary map at a scale of 1:75 000 (White *et al*., 2012b) is available from the Nova Scotia Department of Natural Resources, Mineral Resources Branch website (http://novascotia.ca/natr/meb/download/mg/ofm/htm/ofm_2012-002.asp). Detailed 1:50 000 scale maps will be published at a later date.

Field Relations and Map Units

Introduction

Geological mapping in the northernmost Antigonish Highlands in the area between the Greendale Fault to the south and the Hollow Fault to the north (Fig. 2) was done at a scale of 1:10 000 during the summer of 2012. As a result of this new mapping, some units previously defined in areas to the south (cf. White and Archibald, 2011; White *et al*., 2012b) have been assigned new formation names (Fig. 1). Stratified units in the northernmost area include the (1) Back Settlement, Morar Brook and Chisholm Brook formations of the Late Neoproterozoic Georgeville Group; (2) Silurian Arisaig Group; (3) Devonian Ballantynes Cove formation; (4) Devonian to Carboniferous Horton Group; and (5) various younger Carboniferous formations. Plutonic units include the Greendale plutonic suite, Georgeville Pluton and a newly defined Browns Brook gabbro (Fig. 2).

Stratigraphic Units

Back Settlement Formation

The Back Settlement formation is a new name proposed for a package of mainly mafic volcaniclastic rocks located in the northeastern part of the map area where they are best exposed along new logging roads and in the upper part of Morar Brook (Fig. 2). The formation appears to be the oldest in the 2012 map area (Fig. 2) and consists of green to green-grey to pale grey basaltic lapilli tuff to crystal tuff interbedded with minor amygdaloidal and pillow basalt, conglomerate and black siltstone. Overall, the formation appears to grade upwards from dominantly lithic-rich tuff to more crystal-rich tuff. Crystal tuff contains locally abundant thin (<1 cm thick) pyrite-rich layers. Clasts in the conglomerate are well rounded and include grey-green to black siltstone, various volcanic rocks and fine- to medium-grained, locally porphyritic, diorite. Many of the lapilli in the volcaniclastic rocks are also dioritic. Dark green, fine-grained to porphyritic mafic dykes and sills are common.

Although the age of the Back Settlement formation is unknown, it is included in the Late Neoproterozoic Georgeville Group based on similarity in degree of deformation and metamorphism to volcanic formations in that unit elsewhere in the highlands, and the fact that it is intruded by Neoproterozoic plutonic units (Fig. 2).

Morar Brook Formation

The Morar Brook Formation (Murphy *et al*., 1991) is the most extensive unit in the map area and is

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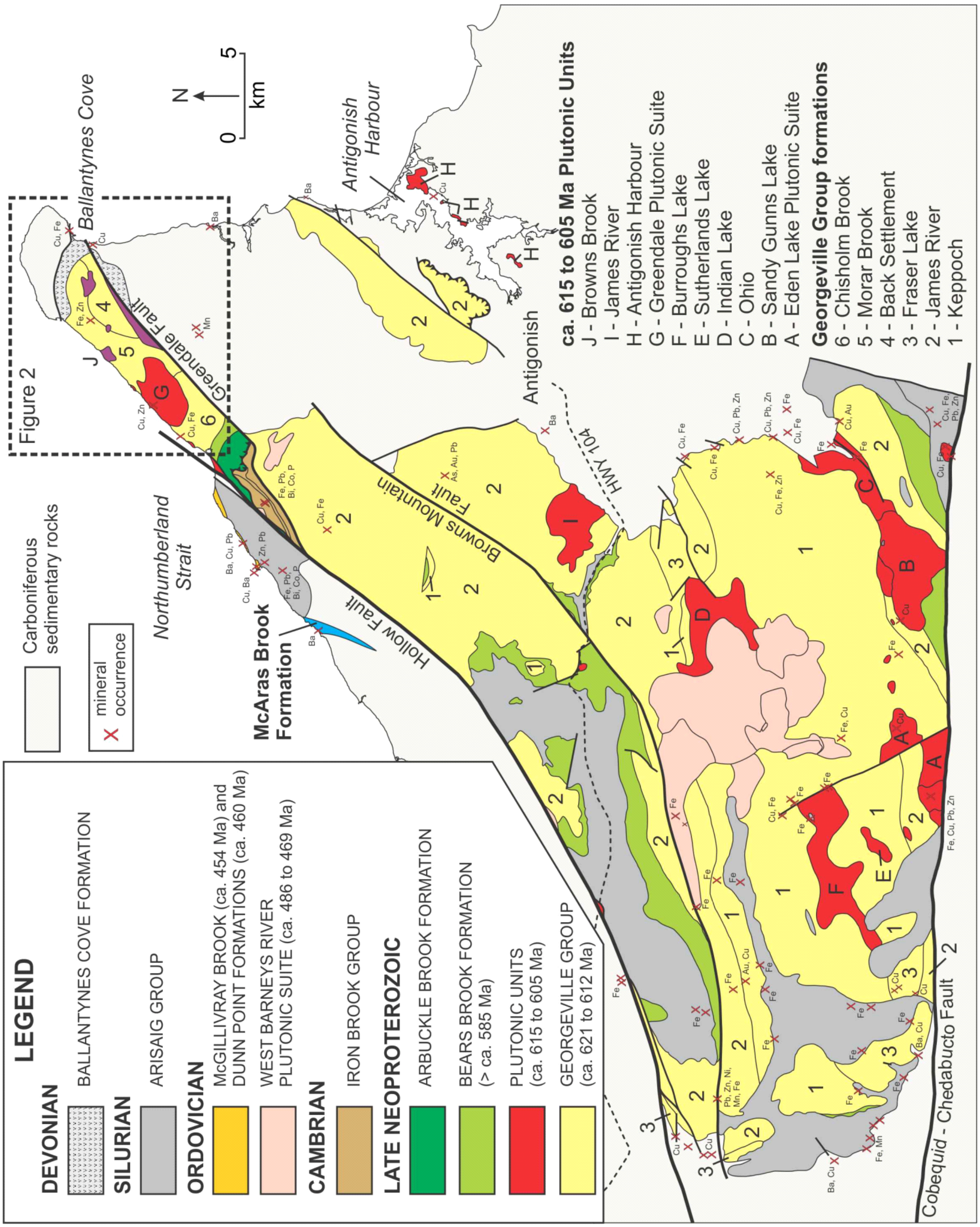

Figure 1. Simplified geological map of the geology in the Antigonish Highlands after White *et al.* (2012b). Location of 2012 map area (dashed box) in the Antigonish Highlands is indicated.

best exposed along the Northumberland Strait coast and in Morar Brook. It consists of grey to black to green, well laminated to thinly bedded cherty siltstone (Fig. 3a), similar to that in the James River Formation farther south; however, unlike the James River Formation, it also contains pale green calc-silicate beds, white limestone and numerous conglomeratic beds. Many of the laminations and thin beds in the siltstone contain abundant pyrite. The overall dark color of the siltstone is attributed to contact metamorphism because rocks in the vicinity of the Greendale plutonic suite and Georgeville Pluton are recrystallized to hornfels. Cordierite spots are well developed in outcrops around the Georgeville Pluton (Fig. 3b). Minor slump features are preserved in laminated siltstone and conglomeratic beds and locally display graded- and cross-bedding. Thin beds of tuffaceous ash and crystal tuff of intermediate composition occur rarely. The contact with the underlying Back Settlement formation is exposed in the upper part of Morar Brook and appears to be abrupt and conformable.

The conglomeratic beds contain well rounded, pebble- to boulder-sized volcanic, sedimentary and plutonic clasts (Fig. 3c) and do not have the 'volcanogenic' appearance characteristic of conglomerate layers in the James River Formation (White *et al*., 2011; White, 2013). The plutonic clasts range in composition from granitic to dioritic and have fine-grained aphyric to porphyritic textures. These conglomeratic rocks were included in the Livingstone Cove Formation by Murphy *et al*. (1991), but during the present study it was not possible to map them as a unit separate from the Morar Brook Formation. U-Pb ages for detrital zircon grains from a conglomeratic unit range from ca. 621 to 612 Ma (Keppie *et al*., 1998), providing a maximum age for deposition. As in the Back Settlement formation, dark green fine-grained aphyric to porphyritic mafic dykes and sills are common.

Chisholm Brook Formation

The type area for the Chisholm Brook Formation (Murphy *et al*., 1991) is located in and around the Chisholm Brook area (Fig. 2). The formation consists of light grey to green basaltic lapilli tuff interlayered with grey to black, well laminated cherty siltstone and minor green, amygdaloidal basaltic flows, and beds of marble, calc-silicate rock and conglomerate (Fig. 3d). Like the Morar Brook Formation, many of the rocks are recrystallized to hornfels. The contact with the Morar Brook Formation is not exposed, but based on the similarity of sedimentary components in the two formations, as well as structural features described below, the Chisholm Brook Formation is interpreted to conformably overlie the Morar Brook Formation. Dark green, fine-grained aphyric to porphyritic mafic dykes and sills are common.

Bears Brook Formation

The Bears Brook Formation (Maehl, 1961) crops out mainly in the southern highlands but is also exposed in the southwestern part of the current map area (Fig. 2). It consists of red to red-brown to maroon conglomerate and arkosic sandstone, and siltstone with minor grey cherty siltstone and dacitic lithic and crystal tuff, as described in more detail by White *et al*. (2011). In the current map area, this unit was previously termed the Malignant Cove Formation and included the basal part of the Cambrian Iron Brook Group (Murphy *et al*., 1991) exposed farther to the south (Fig. 1); however, based on its similar lithologies and detrital zircon ages, no younger than ca. 585 Ma (Murphy *et al*., 2004a, b), these rocks are now included in the Bears Brook Formation (White and Archibald, 2011; White *et al*., 2011, 2012b; White and Barr, 2012; White, 2013). The Bears Brook Formation in the current map area is cut by minor grey, fine- to medium-grained equigranular mafic dykes.

The contact with the underlying Chisholm Brook Formation is not exposed, but based on U-Pb age of the youngest detrital zircon (ca. 585 Ma) reported by Murphy *et al*. (2004a), the formation is interpreted to unconformably overlie the older units and hence is not included in the Georgeville Group (Fig. 2).

Arisaig Group

A narrow, fault-bound belt of brecciated rocks near Cape George Point (Fig. 2) were first mapped by students under the supervision of A. J. Boucot, C. F. Hickox and N. Sage (Boucot *et al*., 1959).

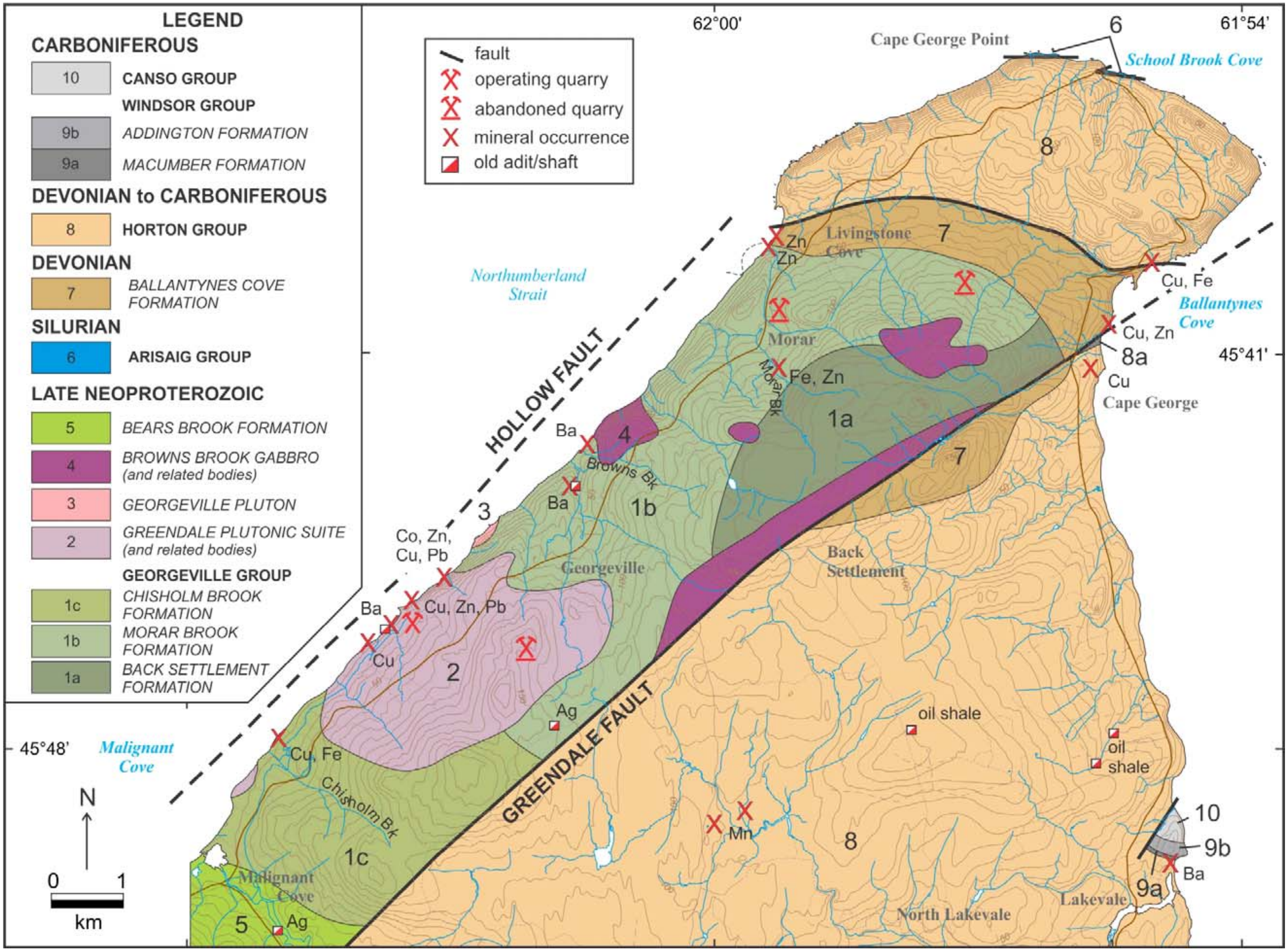

Figure 2. Simplified geological map of the northernmost Antigonish Highlands after White *et al*. (2012b).

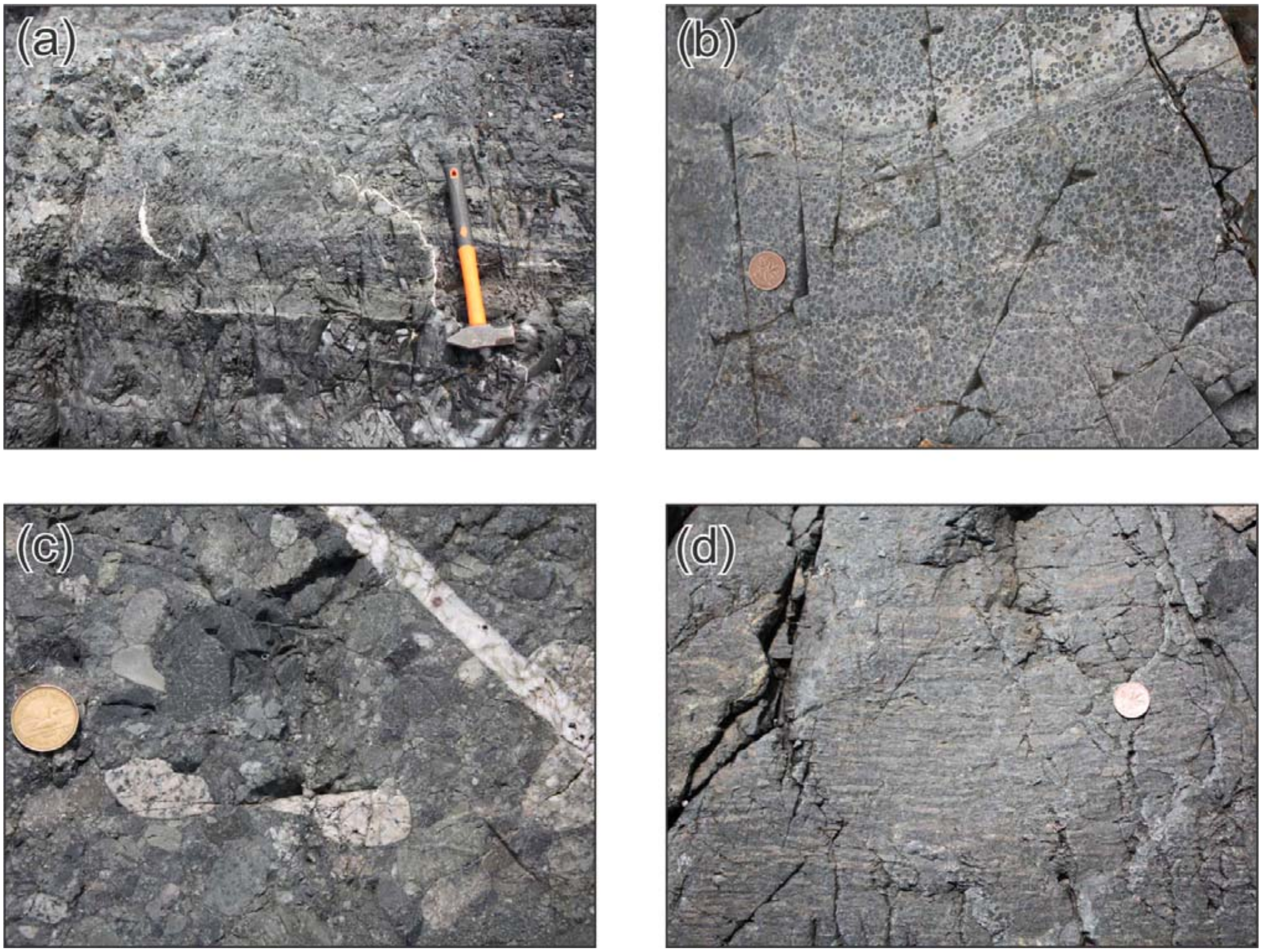

Figure 3. (a) Laminated to thinly bedded cherty siltstone from the Morar Brook Formation. Hammer is about 30 cm long. (b) Cordierite spots in a hornfelsic siltstone of the Morar Brook Formation. (c) Conglomerate in the Morar Brook Formation. (d) Mafic lithic lapilli tuff in the Chisholm Brook Formation.

They regarded this sequence, consisting of interbedded grey and red sandstone, shale, limestone and quartzite, as ranging from middle Ordovician to Devonian (Boucot *et al*., 1974). Keppie (1980) resampled a limestone bed from a sequence of interbedded quartzite and shale and recovered Early Silurian conodonts, thelodonts and ostracods that indicate that these rocks are equivalent to the Beechill Cove Formation and the lower part of the Ross Brook Formation exposed at Arisaig. Later workers (e.g. McNamara, 1984; Reilly, 1984) confirmed the presence of redbeds similar to the upper parts of the Arisaig Group. This section is intruded by a gabbro to syenite sill that has an A-type affinity (Somers, 1980) and hence may be similar to the Barneys River plutonic suite (Archibald, 2012).

Late Devonian to Carboniferous Units

Some parts of the Late Devonian to Carboniferous rocks in the area (McAras Brook Formation and Horton, Windsor and Mabou groups) were mapped during this study (Fig. 2), and the locations of contacts have been modified from previous maps and reports (e.g. Keppie *et al*., 1978; Boehner and Giles, 1982, 1993; Murphy *et al*., 1991).

The Ballantynes Cove formation (White *et al*., 2012b; White, 2013) is a new name proposed for a package of red-brown conglomerate-breccia interbedded with flow basalt and rhyolite, and shale that were previously included in the McAras Brook Formation (see below). The conglomeratic beds consist of angular to rounded, pebble- to boulder-

Figure 4. (a) Brown sedimentary breccia of the Ballantynes Cove Formation. (b) Peperitic texture in flow basalt of the Ballantynes Cove Formation. Hammer is about 30 cm long. (c) Igneous layering in the Greendale plutonic suite. (d) Lineated amphibole crystals in a hornblendite dyke in the Greendale plutonic suite.

size clasts of volcanic, sedimentary and plutonic clasts typical of the underlying rocks (Fig. 4a). The basaltic flows are green to grey-green and have chilled lower margins and amygdaloidal tops. Locally, the lower parts of the flows display peperitic textures (Fig. 4b). The rhyolitic flows are pink to red-brown and flow-banded, and contain numerous feldspar and quartz phenocrysts up to 5 mm in size. The conglomeratic beds are locally cut by distinctive brown-weathered, medium- to coarse-grained mafic dykes.

A rhyolitic flow yielded a U-Pb zircon crystallization age of 370 ± 1.5 Ma (Dunning *et al*., 2002), and associated shale interbeds have previously yielded late Famennian palynomorphs (Keppie *et al*., 1978; Martel *et al*., 1993). Hence, this formation is Devonian. Chemical characteristics indicate that the volcanic rocks are rift-related continental tholeiites with some samples that are transitional to alkalic (Pe-Piper and Piper, 1998).

The name McAras Brook Formation (Williams, 1914) has been retained for basalt and interbedded sedimentary rocks in the McAras Brook area (Fig. 1). These rocks are considered to be Carboniferous based on the reported presence of a Late Visean spore assemblage collected just above the highest basalt unit (Barss, 1977 in Keppie *et al*., 1978; Fralick 1977). This interpretation is supported by the fact that the basalts in the two formations display differences in texture and chemical characteristics (Pe-Piper and Piper, 1998).

Plutonic Units

Greendale Plutonic Suite

The Greendale Complex of Murphy *et al*. (1991, 1997) is a large plutonic body in the centre of the map area (Fig. 2). It consists of fine-grained to pegmatitic hornblende gabbro, medium-grained diorite to granodiorite and minor leucogranite. Because all of the components are plutonic, it is better termed a plutonic suite than a complex (e.g. North American Commission on Stratigraphic Nomenclature, 2005), and that terminology is adopted here. The main body of the pluton appears to be dominated by the dioritic rocks, which locally display igneous layering and contains medium-grained 'gabbroic' enclaves (Fig. 4c). The dioritic rocks are cut by numerous hornblendite and felsic pegmatite dykes. Many of the hornblende crystals in the hornblendite dykes are strongly lineated (Fig. 4d). A small body of medium- to coarse-grained diorite along the coast to the southwest of the main body (Fig. 2) is interpreted to also be part of the suite. It is also cut by hornblendite dykes as well as granodioritic dykes. Locally, these mafic plutonic rocks are tectonically foliated and brecciated with steep, northeast-trending pseudotachylite veins. The Greendale plutonic suite intruded the Morar Brook and Chisholm Brook formations, based on the presence of hornfelsic rocks in the surrounding area and a large number of marble, calc-silicate, metasiltstone and volcanic xenoliths. Chemically, this pluton displays arc-like affinity (Murphy *et al*., 1997). Amphibole from two 'gabbroic' samples yielded $^{40}Ar/^{39}Ar$ ages of 620 ± 5 Ma and 611 ± 4 Ma (Keppie *et al*., 1990). A gabbroic pegmatite sample previously yielded a U-Pb (titanite) age of 607 ± 3 Ma and an upper intercept age of 606.6 ± 1.6 Ma (Murphy *et al*., 1997). These ages likely approximate the emplacement age of the suite.

Georgeville Pluton

The Georgeville Pluton (Murphy *et al*., 1998), or Georgeville Granite (Anderson *et al*., 2008), is a small (ca. 1.5 km across) epizonal body that is exposed along the shoreline northeast of the Greendale plutonic suite. The pluton consists of leucocratic, medium- to coarse-grained alkali-feldspar granite intruded by steeply to moderately dipping aplite and pegmatite dykes. Intrusive contacts with the host rocks of the Morar Brook Formation are sharply defined, and the host rocks show development of hornfels spotted with cordierite. Siltstone and marble xenoliths are also present in the granite. Many, but not all, geochemical and mineralogical features resemble those of A-type, within-plate granite. Muscovite yielded an $^{40}Ar/^{39}Ar$ plateau age of 579.8 ± 2.2 Ma, interpreted by Murphy *et al*. (1998) as the age of intrusion. The unique mineralogy associated with the granite and associated niobium-yttrium-fluorine -type pegmatite dykes (e.g. amazonitic microcline, topaz, Hf-rich zircon, with minor ferrocolumbite and polycrase) has been studied previously (e.g. Hay, 2001; Anderson *et al*., 2008; Dalby *et al*., 2010).

Browns Brook Gabbro

A small but mappable plutonic body of green, fine- to locally medium-grained, porphyritic gabbro occurs along the coast (Fig. 2) and is herein referred to as the Browns Brook gabbro. Several smaller bodies occur through the map area (Fig. 2) and are considered to be related (White *et al*., 2012b). Where contacts are exposed, these bodies have finer grained (chilled) margins. These epizonal to subvolcanic bodies may be related to basaltic flows and tuffs in the Back Settlement, Morar Brook and Chisholm Brook formations and the numerous dykes and sills that are associated with these formations. Lithogeochemical work is underway to test this hypothesis.

Mafic Dykes and Sills

Based on field observations, pre-Carboniferous rock units in the map area are cut by at least three sets of mafic dykes and sills. The oldest set consists of dark green, fine-grained gabbro with well developed chilled margins. Some are porphyritic with phenocrysts of plagioclase. These dykes and sills are similar in appearance to rocks in the Browns Brook gabbro bodies and are interpreted to be related to mafic volcanic rocks of the Back Settlement, Morar Brook and Chisholm Brook formations. These dykes and sills are cut by leucogranite dykes related to the Georgeville Pluton (ca. 580 Ma; Murphy *et al*., 1998) and locally display recrystallized hornfelsic texture in thin section.

A younger set of mafic dykes and sills cuts the Bears Brook Formation as well as the older units. These dykes and sills are typically grey, fine- to medium-grained, and are typically equigranular with chilled margins. Locally, these dykes and sills contain abundant plagioclase phenocrysts. They range in composition from monzogabbro to gabbro to quartz gabbro and may be related to the Ordovician West Barneys River plutonic suite (e.g. Archibald, 2012).

A third set of dykes and sills are interpreted to be related to basaltic flows in the Late Devonian Ballantynes Cove formation because they cut the associated conglomeratic beds. These dykes and sills are medium- to coarse-grained, distinctly brown on the weathered surface and black on fresh surfaces, and display columnar joints at their margins.

Structural Features

A contoured stereonet plot of poles to bedding in the Back Settlement, Morar Brook and Chisholm Brook formations displays considerable scatter but indicates a moderately developed girdle distribution with a shallow, north-northwest-plunging fold axis (Fig. 5a). This pattern broadly mimics the spatial distribution of formations (Fig. 2). No minor folds related to this major structure were observed in the field. None of the units in the map area show well developed cleavage or other foliation except near the Hollow and Greendale faults. Poles to these foliations are less scattered than the bedding measurements and trend northeast, parallel to the faults (Fig. 5a). Like foliation, minor outcrop-scale folds are best developed near the bounding faults. They are scattered in orientation but display a girdle distribution, which suggests refolded or sheath-fold

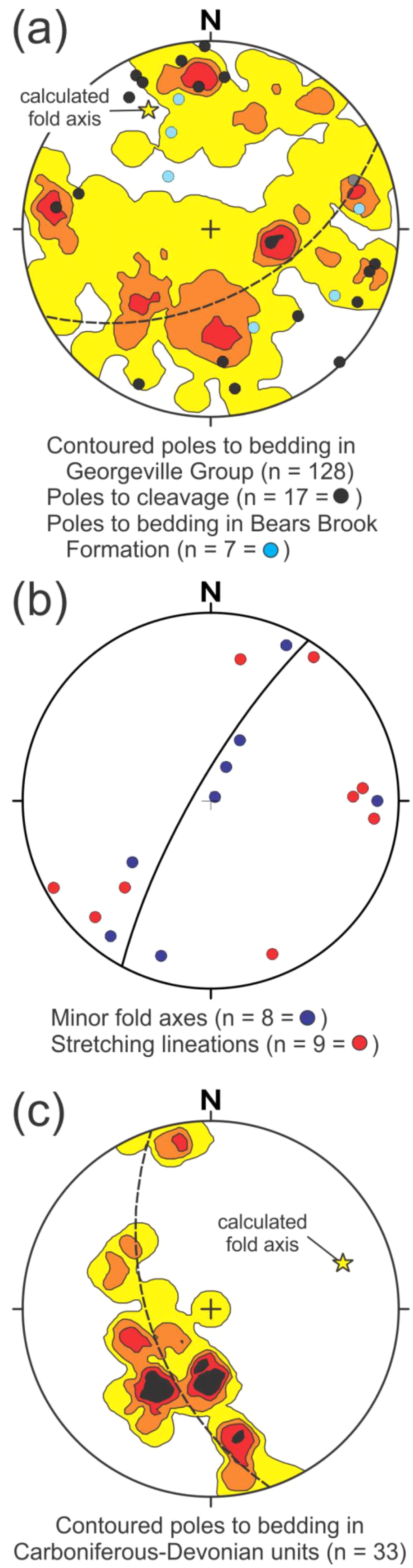

Figure 5. Equal-area stereonets of structural data from the map area. (a) Contoured poles to bedding in the Georgeville Group, poles to cleavage, and poles to bedding in the Bears Brook Formation. (b) Minor fold axes and stretching lineations in the Georgeville Group. (c) Contoured poles to bedding in the Ballantynes Cove Formation and Horton Group. Great circle shows average orientation of planar features, and the yellow star shows the calculated average fold axis. Contours at 1, 3, 5, and greater than 7% per 1% area; darkest shading indicates highest contour area.

geometry (Fig. 5b). Lineations defined by elongated quartz rods and amphibole in the Greendale plutonic suite, and asymmetric feldspar crystals in mafic volcanic rocks and associated dykes and sills in the Chisholm Brook and Morar Brook formations plunge shallowly to the northeast and southwest (Fig. 5b). All these data orientations are consistent with those measured and described by Murphy *et al*. (2001) near the Hollow Fault and confirm dextral strike-slip sense of movement. Where exposed on the coast near Cape George, the Greendale Fault is nearly vertical; however, rare stretching lineations recorded in inland areas have shallow, but consistent, plunge to the east (Fig. 5b). These observations suggest that some motion on the Greendale Fault may have had a thrust component.

Few structural data were obtained from the Bears Brook Formation due to limited outcrop; however, the few data available indicate that bedding orientations are similar to those in the underlying Back Settlement, Morar Brook and Chisholm Brook formations (Fig. 5a). The similarity suggests that these units were folded together, as was inferred also from structural data in the southern part of the highlands (e.g. White *et al*., 2011; White, 2013).

Contoured stereonet plots of poles to bedding in the Ballantynes Cove formation and Horton Group define a well developed girdle distribution indicating a fold axis with a shallow plunge to the east (Fig. 5c). This deformational event may be in part responsible for the scatter in structural orientations observed in the older units.

Metamorphism

Regional metamorphic grade throughout the map area, as well as the remainder of the Antigonish Highlands, is low, reaching to a maximum of the chlorite zone of the greenschist facies (White *et al*., 2011; White, 2013). The typical metamorphic mineral assemblage is chlorite + white mica + albite + epidote in the pelitic rocks. The Greendale plutonic suite and Georgeville Pluton produced a wide contact metamorphic aureole, which resulted in a darkening of the country rocks and granoblastic texture. Rounded cordierite crystals are present in pelitic hornfels around the Georgeville Pluton (Fig. 3b), and amphibole + biotite crystals in mafic hornfelsic tuffs in the Chisholm Brook formation; these are all characteristic of the hornblende-hornfels facies of metamorphism (e.g. Yardley, 1989). The large area of hornfelsic texture in the rocks of the Chisholm Brook Formation indicates that the Greendale plutonic suite is more widespread at depth than previously recognized.

Economic Geology

Mapping during 2012 confirmed the presence of many of the known mineral occurrences and indicated some previously unreported occurrences. Much of the mineralization is in the Morar Brook and Chisholm Brook formations exposed along the coast from Malignant Cove to Livingstone Cove (Fig. 2). Cherty siltstone and associated marble of the Morar Brook Formation contain pyrite/ marcasite, pyrrhotite, sphalerite, chalcopyrite and galena as disseminated sulphides and as fracture coating and filling mineralization. Mineralization is also associated with quartz-carbonate veins. In the Greendale plutonic suite many of the cherty siltstone and marble xenoliths contain pyrite, sphalerite, chalcopyrite and galena. Analyses of some of this xenolithic material, using a portable X -5000 X-ray Fluorescence instrument manufactured by Innov-X, yielded anomalous cobalt values (up to 125 ppm).

Two abandoned adits/shafts were documented during the 2012 field season, one in the Georgeville area (Fig 6a) and the other in the Greendale plutonic suite (Fig. 6b) on the coast (Fig. 2). The Georgeville adit/shaft was previously recognized and classified as an abandoned gold mine in the Nova Scotia Abandoned Mine Openings Database (Nova Scotia Department of Natural Resources, 2009a), and warning signs are posted in the area. However, no documentation was provided in the database for the coastal adit/shaft. Analyses of samples from the workings using the portable XRF instrument yielded no base or precious metal anomalies, although barium values ranged from 3000–5000 ppm, significantly higher than in other samples from the map area. Faribault and Fletcher (1893) reported the presence of two abandoned silver mines/shafts in the map area (Fig. 2); the

Figure 6. (a) Abandoned adit in the Morar Brook Formation in the Georgeville area. (b) Abandoned adit in a metasedimentary xenolith in the Greendale plutonic suite.

existence of these was later verified (Nova Scotia Department of Natural Resources, 2009a). The presence of silver was not confirmed, but exploration and drilling in the 1970s near the northernmost shaft encountered extensive low-grade zinc (sphalerite) mineralization (e.g. O'Reilly, 2001). O'Reilly (2001) attributed the mineralizing event in the northern Antigonish Highlands to hydrothermal fluids associated with the Greendale plutonic suite, synchronous with fracturing related to movements along the Hollow and Greendale faults. Hence, this mineralization is considered to be Late Neoproterozoic.

Copper (covellite and malachite) and zinc (sphalerite) have been documented (e.g. Bishop and Wright, 1974) on fracture surfaces and disseminated throughout basaltic flows and associated sedimentary rocks in the Devonian to Carboniferous Ballantynes Cove Formation and Horton Group (Fig. 2). This mineralization is likely related to a younger (Carboniferous?) hydrothermal -faulting event.

In addition, barite and manganese have been documented in Carboniferous rocks (Bishop and Wright, 1974; Felderhof, 1978). In the past oil shale has been explored for, and several small pits were excavated in the Horton Group (Fig. 2). A complete list of mineral occurrences and former mines in the map area is shown in the Nova Scotia Department of Natural Resources Mineral Occurrences Database for NTS map sheets 11E/16 and 11F/13 (Nova Scotia Department of Natural Resources, 2009b).

The Greendale plutonic suite is currently being used as a source of aggregate and armour stone. Several seasonal and/or abandoned aggregate pits are located in cherty siltstone units of the Morar Formation.

Summary

A major result of mapping during the summer of 2012 is the identification of the Back Settlement formation, interpreted to be the oldest unit in the northernmost Antigonish Highlands. The overlying Morar Brook Formation is lithologically similar to the James River Formation exposed in the southern Antigonish Highlands. The Chisholm Brook Formation conformably overlies the Morar Brook Formation. The previously defined Livingstone Cove Formation (Murphy *et al.*, 1991) is now abandoned because conglomerate associated with that formation could not be mapped as a separate unit but instead is part of the Morar Brook Formation.

The late Neoproterozoic Greendale plutonic suite, Georgeville Pluton and the subvolcanic gabbroic bodies of the Browns Brook gabbro intruded the Back Settlement, Morar Brook and Chisholm Brook formations. A large contact metamorphic aureole is associated with the Greendale plutonic suite and Georgeville Pluton.

The former Malignant Cove Formation is now included in the Late Neoproterozoic Bears Brook Formation based on similar lithologies and the age of detrital zircons.

Three sets of mafic dykes and sills are recognized. The older set is interpreted to be Late Neoproterozoic and related the Browns Brook gabbro and mafic volcanic rocks in the Back Settlement, Morar Brook and Chisholm Brook formations. A younger set of mafic dykes and sills is interpreted to be related to the Ordovician West Barneys River plutonic suite and cuts the Bears Brook formation as well as the older units. The youngest mafic dykes are likely related to the Late Devonian Ballantynes Cove formation.

Rocks characteristic of the Silurian Arisaig Group are exposed in the extreme northern parts of the map area and are in faulted contact with the Horton Group. Rocks representing the Early Cambrian to Early Ordovician Iron Brook Group appear to be absent from the map area.

Much of the copper, zinc and lead mineralization along the Georgeville shore are related to deformation and hydrothermal alteration related to the Hollow Fault and Greendale plutonic suite. Similar mineralization may be related to the Greendale Fault, but rocks along this fault are poorly exposed.

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