Preliminary Geology of the Eastern Cobequid Highlands, Northern Mainland Nova Scotia

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Introduction

The Cobequid Highlands of northern mainland Nova Scotia form part of the southern margin of Avalonia (Hibbard *et al*., 2006), a fault-bounded terrane positioned inboard from Meguma and outboard from Ganderia (Fig. 1). Previous studies have shown that the area predominantly comprises Late Neoproterozoic to Late Devonian to Early Carboniferous volcanic, sedimentary and intrusive rocks (e.g. Murphy *et al.*, 1997; Nance and Murphy, 1990; Pe-Piper and Piper, 2002).

Investigations conducted within the eastern Cobequid Highlands by the Department of Natural Resources between 2010 and 2011 have highlighted the mineral potential of the area through the discovery of a significant granite-related high-field-strength/rare earth element (HFSE/REE) prospect (MacHattie, 2011) and widespread volcanic-related epithermal Au-style mineral occurrences (MacHattie, 2012, 2013). In addition, new U-Pb zircon ages indicate the presence of some of the oldest Neoproterozoic crust found within Avalonia, as well as previously unrecognized Ordovician and Devonian intrusive units (MacHattie and White, 2012; MacHattie *et al*., 2012).

As a result of the newly identified economic potential of the area and possibility for significant improvements to the geological framework of the area, the Nova Scotia Department of Natural Resources has undertaken a bedrock-mapping program within the eastern Cobequid Highlands (MacHattie and White, 2012). In unison with the bedrock-mapping program, an extensive whole-rock lithogeochemical database (> 2000 samples) is being created, employing the department's mobile x-ray fluorescence (XRF) analyzer, to better constrain the tectonic events and mineralization in the highlands. Here we present our initial results from this mapping program.

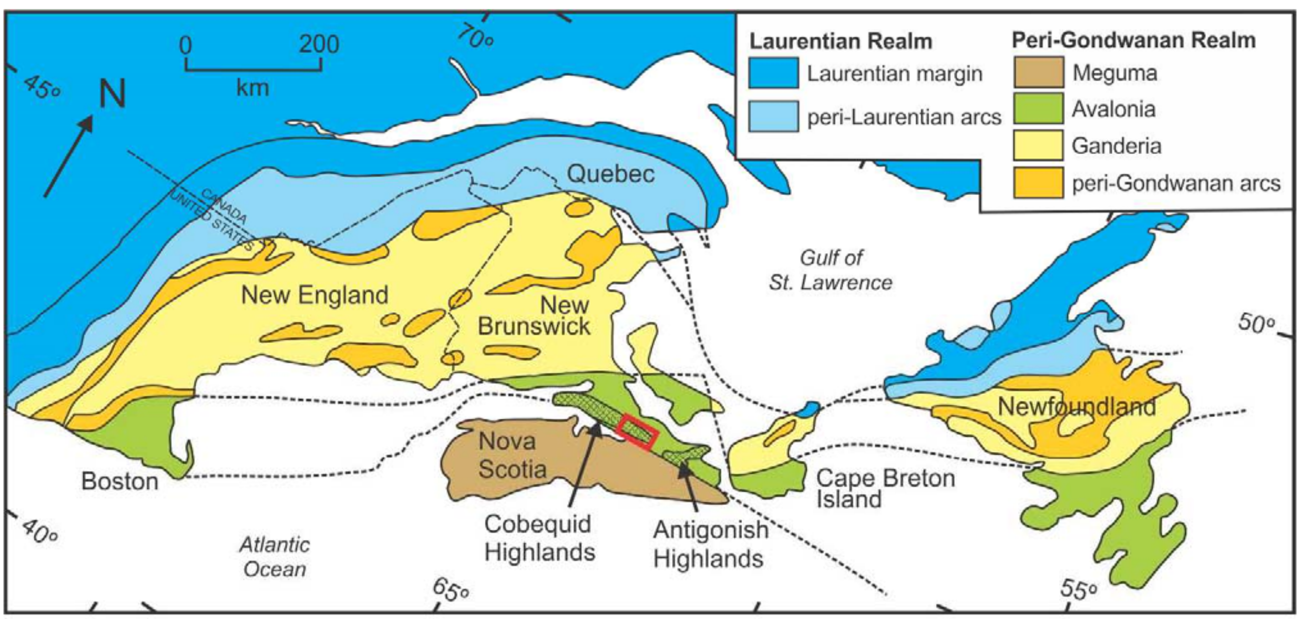

Figure 1. Lithotectonic elements of the northeastern Appalachian Orogen, modified from Hibbard *et al*. (2006). Red rectangle is area in Figure 2.

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Regional Geology

The eastern Cobequid Highlands are an uplifted crustal block composed of Late Neoproterozoic volcanic, sedimentary and plutonic rocks; significant amounts of Late Devonian to Early Carboniferous volcanic, plutonic and lesser sedimentary rocks; and minor Silurian sedimentary rocks. The southern boundary of the highlands is marked by the Cobequid-Chedabucto Fault Zone, and to the north, the highlands are unconformably overlain by Late Carboniferous sedimentary rocks of the Cumberland Basin (Fig. 2). The highlands are part of Avalonia, a composite terrane within the Appalachian Orogen that extends from the Boston area, through southern New Brunswick and northern Nova Scotia, to southeastern Newfoundland (Fig. 1).

The Neoproterozoic sedimentary and volcanic sequences preserved within the eastern Cobequid Highlands are interpreted to reflect deposition and extrusion within a rifted continental arc environment (Pe-Piper and Murphy, 1989; Murphy, 2002). These sequences are intruded by Late Neoproterozoic plutonic rocks that are interpreted to have formed within a continental volcanic-arc environment (Pe-Piper *et al*., 1996; Murphy *et al*., 2001) along the northern margin of Gondwana (e.g. Nance *et al*., 2002).

The voluminous Late Devonian to Early Carboniferous volcanic and plutonic rocks within the eastern Cobequid Highlands are bi-modal, contain within-plate geochemical signatures, and are interpreted to have formed in a plume-related intra-continental rift (e.g. Dessureau *et al*. 2000). Minor Early Carboniferous siliciclastic sedimentary sequences devoid of volcanic rocks are interpreted to have formed in more isolated fault-bound basins (e.g. Pe-Piper and Piper, 2002).

Previous Mapping

Within the last 30 years several map products covering all or portions of the Cobequid Highlands have been produced. The first ‘modern’ mapping was completed by Donohoe and Wallace (1982a, b, c, d). They produced a series of four 1:50 000 scale maps of the entire Cobequid Highlands that included portions of the adjacent Carboniferous strata. As part of the Geological Survey of Canada Magdalen Basin NATMAP project, a set of digital geology maps were produced for the Cobequid Highlands (Lynch *et al*., 1998). These maps were essentially the preliminary map products by J. B. Murphy and G. Pe-Piper as outlined below.

The area was next mapped by Murphy *et al*. (2000a, b), who produced two 1:50 000 scale maps exclusively of the eastern Cobequid Highlands, excluding the bounding Late Carboniferous strata. However, a part of their easternmost map was compiled from Donohoe and Wallace (1982a). These maps replaced those produced by Lynch *et al*. (1998). Murphy *et al*. (2001) also provided a detailed report on the geology of the highlands to accompany the maps. The last major mapping programme was conducted by Pe-Piper and Piper (2005a, b, c, d), who largely concentrated on the western half of the Cobequid Highlands. However, they produced a series of four 1:50 000 scale maps of the entire Cobequid Highlands. Like Murphy *et al*. (2000a, b), these maps did not include adjacent Late Carboniferous strata.

Geology of the Eastern Cobequid Highlands

Introduction

Mapping of the area defined by the Cobequid-Chedabucto fault zone in the south to Highway 256 in the north and by Brookline in the east to Debert Lake in the west (Fig 2) was completed at 1:10 000 scale during the summer of 2012 (MacHattie and White, 2012). This mapping, combined with the work of Broughm *et al*. (2012), confirmed previous studies (e.g. Pe-Piper *et al*., 1996), which found that the map area can be divided into two distinct geological packages or blocks (Bass River and Jeffers blocks) with several stratigraphic formations and plutonic units (Fig. 2). The Bass River block is defined as the area between the Cobequid-Chedabucto Fault Zone to the south and the Rockland Brook Fault to the north, and the Jeffers block is bounded to the south by the Rockland Brook Fault and to the north by the

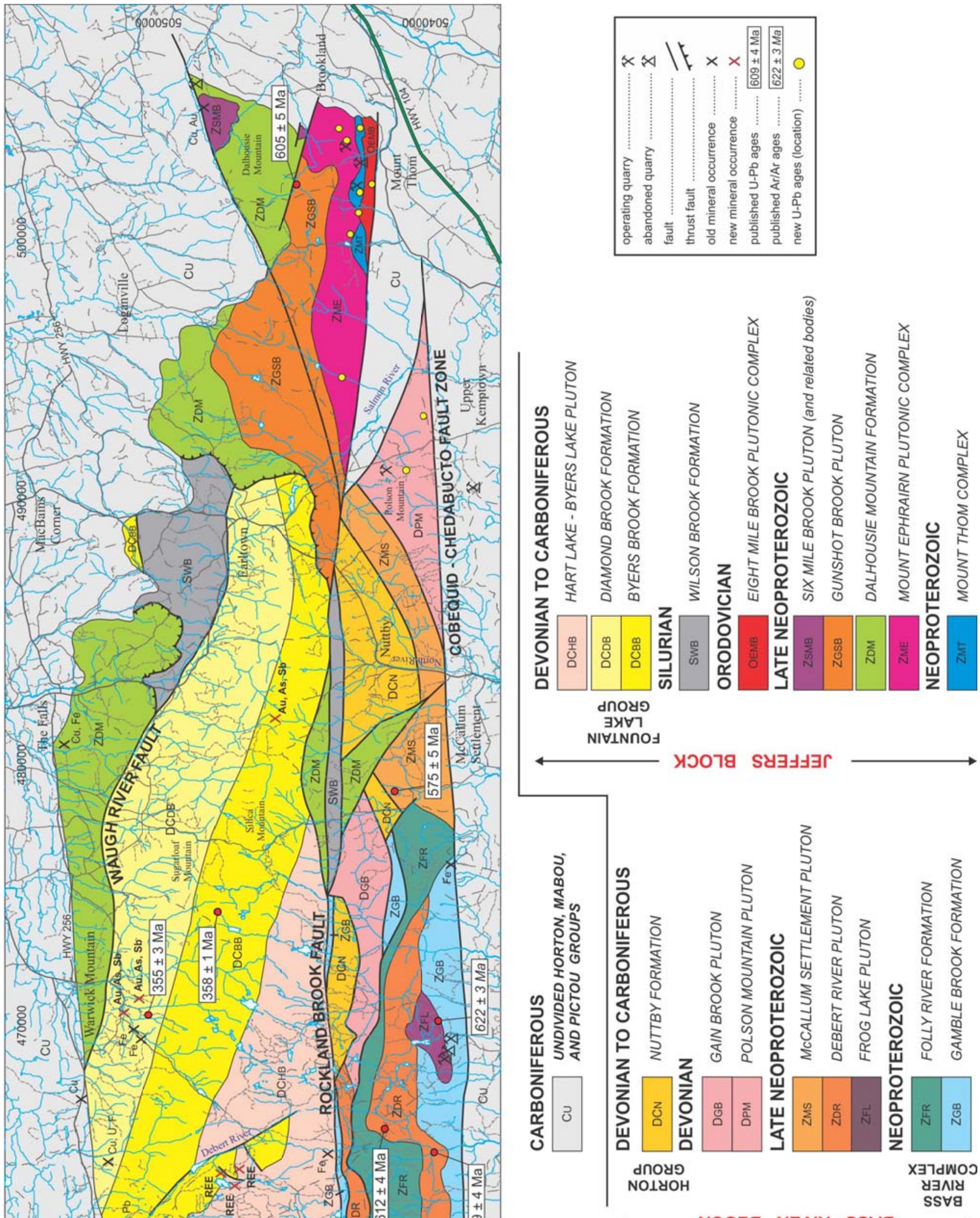

Figure 2. Geological map of the northeastern Cobequid Highlands of northern mainland Nova Scotia.

unconformably overlying Carboniferous rocks. The stratigraphic units in the Bass River block include (1) Gamble Brook and Folly River formations of the Bass River Complex and (2) Nuttby Formation. The plutonic units include (1) Frog Lake Pluton, (2) Debert River Pluton, (3) McCallum Settlement Pluton, (4) Polson Mountain Pluton and (5) Gain Brook Pluton. The stratigraphic units in the Jeffers block include (1) Mount Thom Complex, (2) Dalhousie Mountain Formation of the Jeffers Group, (3) Wilson Brook Formation and (4) Byers Brook and Diamond Brook formations of the Fountain Lake Group. The plutonic units include (1) Mount Ephrairn Plutonic Suite, (2) Gunshot Brook Pluton, (3) Six Mile Brook Pluton, (4) Eight Mile Brook plutonic complex and (5) Hart Lake-Byers Lake Pluton. These unit names are tentative at this time because the mapping in the western Cobequid Highlands has not been completed and may result in the necessity of further changes in terminology.

Stratified Units in the Bass River Block

Gamble Brook Formation

The Gamble Brook Schist (Donohoe and Wallace, 1980), or Formation (Murphy *et al*., 1988), of the Bass River Complex (Donohoe, 1975) occurs along the bounding faults of the Bass River block (Fig. 2). It consists of white quartzite interlayered with grey metasiltstone (Fig. 3a) and metamudstone, with minor calc-silicate rocks and marble. Where regional metamorphic grade is higher the more pelitic rocks become biotite-muscovite phyllite and schist that locally contain garnet, typical of greenschist facies metamorphism (Murphy *et al*., 1988; Nance and Murphy, 1990). Bedding is typically subparallel to foliation due to mylonitic transposition, and hence many of the original sedimentary structures are obliterated. Associated mineral lineations are well developed near the bounding faults and plunge shallowly to the west-southwest. The formation is intruded by varied gabbroic dykes and sills.

The depositional setting for the Gamble Brook Formation has been interpreted as a shallow marine platformal environment (Donohoe and Wallace, 1985; Murphy *et al*., 1988; Nance and Murphy, 1988, 1990). However, based on lithogeochemistry, Murphy (2002) suggested the formation was deposited along a basin margin within a rifted-arc environment. A depositional age for the Gamble Brook Formation is provided by U-Pb single-grain analyses on detrital zircons for a quartzite sample collected farther to the west of the current map area. Zircon grains yielded ages ranging from 997 ± 2 Ma to 2796 ± 2 Ma and clustered around 1000 Ma (Keppie *et al*., 1998; Barr *et al*., 2003). The youngest zircon provides the maximum age for the formation.

Folly River Formation

The Folly River Schist (Donohoe and Wallace, 1980, 1982d), or Formation (Murphy *et al*., 1988), of the Bass River Complex (Donohoe, 1975) occurs in the core of the Bass River block (Fig. 2). It consists dominantly of dark green to dark grey basaltic lapilli tuff, interlayered with amygdaloidal basaltic flows, grey to black tuffaceous siltstone and sandstone, ironstone, and rare quartzite. Many of the basaltic mafic tuffs are welded and include mafic clasts displaying fiamme-like structures. Some flows consist of angular clasts up to several centimetres in diameter that appear to have formed by autobrecciation processes (hyaloclastites); pillow-like structures were locally observed. Interbedded tuffaceous siltstone and sandstone are thinly to thickly bedded and rarely exhibit cross-laminations and graded bedding. Locally they are complexly folded on the outcrop scale, which is attributed to original slump deformation. The ironstone beds are deep purple to black, massive to faintly laminated and range in thickness from a few centimetres to several tens of metres thick. Several small bodies of green, fine- to locally medium-grained porphyritic diorite occur throughout the formation. Where contacts are exposed, these bodies have finer grained (chilled) margins. These bodies are interpreted to be the subvolcanic ‘feeders’ to basaltic flows and tuffs. Many of the rocks in the Folly River Formation are magnetic; in some of the ironstone beds, the values range from 300 to over 500 SI. Like the Gamble Brook Formation, this formation is intruded by varied gabbroic dykes and sills, some of which may be related to the subvolcanic diorite. The sheet mafic dyke swarm noted by Nance and Murphy (1990)

Figure 3. (a) Quartzofeldspathic paragneiss of the Gamble Brook Formation. (b) Polymictic pebble conglomerate of the Nuttby Formation. (c) Granodioritic sheet of the Debert River Pluton intruded into semi-pelitic rocks of the Gamble Brook Formation. (d) Alkali-feldspar granite of the Devonian Polson Mountain pluton cut by a thin Carboniferous(?) diabase dyke. (e) Syenogranite of the Gain Brook pluton.

and Murphy *et al*. (2001) could not be confirmed. Examination of the gravity survey conducted by Minotaur Exploration (Belperio *et al*., 2008, 2009) indicates that the Folly River Formation is characterized by an anomalously elevated gravity signature relative to surrounding rocks of the Bass River Block.

Compared to the Gamble Brook Formation, the rocks in the Folly River Formation are less deformed, largely because it resides in the core of the Bass River block away from the deformation related to the mylonitic bounding faults. Many of the primary volcanic and sedimentary features are preserved. However, locally the rocks are well cleaved and phyllitic, and have foliations defined by chlorite, sericite and biotite, Like the Gamble Brook Formation, they are regionally metamorphosed to greenschist facies (Murphy *et al*. 1988, 2001). In addition, some of the more pelitic rocks display hornfelsic textures with rounded cordierite spots. It is unclear at this time if this contact metamorphism is caused by the ca. 630 -610 Ma plutons or the younger ca. 375-365 Ma intrusions.

The Folly River Formation was interpreted to unconformably overlie the Gamble Brook Formation (Murphy *et al*., 1988, 2001; Nance and Murphy, 1990; Murphy, 2002). Based on stratigraphy, geochemistry, structure and age, Nance and Murphy (1990) and Murphy *et al*. (2001) suggested that the Folly River Formation may be equivalent to the ca. 630 Ma Jeffers Group exposed farther to the north. Pe-Piper *et al*. (1996) and Pe-Piper and Piper (2002) considered the contact as tectonic and considered the Folly River Formation as Middle Neoproterozoic. Our mapping in the eastern Cobequid Highlands shows that the Folly River and Gamble Brook formations are never in contact and are separated by the Debert River Pluton. However, based on the similar metamorphic conditions and the presence of quartzite beds in the Folly River Formation that are similar to those in the Gamble Brook Formation, MacHattie and White (2012) considered the two formations to be related and likely facies equivalents.

The tectonic setting for the Folly River Formation is unclear. Previous workers suggested it was deposited on the ocean floor or an intracontinental extensional setting within a volcanic-arc environment (Pe-Piper and Murphy, 1989; Pe-Piper and Piper, 2002).

Nuttby Formation

The Nuttby Succession (Donohoe, 1975), or Formation (Donohoe and Wallace ,1979; 1982d), occurs in three fault-bounded blocks in the eastern part of the Bass River block. The distribution of the formation is much more restricted than that shown on the maps of Murphy *et al*. (2000b) and Pe-Piper and Piper (2005d). In the type section established by Donohoe and Wallace (1979) on North River (Fig. 2), it consists of grey siltstone and sandstone interbedded with minor conglomerate (Fig. 3b), black to maroon siltstone and rare grey to pink limestone. Greenish-grey felsic volcanic rocks were reported to occur in the Nuttby Formation (e.g. Donohoe and Wallace, 1979), but our mapping did not verify this observation. Instead our mapping discovered several previously unrecognized basaltic flows interbedded with the sedimentary rocks. Early Tournasian (Early Mississippian) spore assemblages have been recovered from the formation.

Igneous Units in the Bass River Block

Frog Lake Pluton

The Frog Lake Pluton (Donohoe and Wallace, 1980, 1982d) is more restricted in its distribution than shown on previous maps (e.g. Donohoe and Wallace, 1982d; Murphy *et al*., 2000b; Pe-Piper and Piper, 2005d) and hence has been redefined (MacHattie and White, 2012). Although Pe-Piper *et al*. (1996) considered the pluton to be gabbroic in character, and hence called it the “Frog Lake gabbro assemblage,” we concur with Donohoe and Wallace (1982d) and Murphy *et al*. (2000b, 2001) that the pluton is dominantly dioritic. We include the granodioritic to granite phase of the pluton (Murphy *et al*., 2001) with the Debert River Pluton. It is best exposed near Frog Lake and along logging roads and quarries in the area (Fig. 2). It is dominantly a grey, medium- to locally coarse-grained diorite to quartz diorite, and locally it displays igneous layering. The more hornblende-rich layers are very magnetic (~100 SI). Geochemical analyses indicate that the pluton formed in a volcanic-arc environment (e.g. Murphy *et al*., 2001). Fine- to medium-grained equigranular dykes cut the pluton.

The Frog Lake Pluton intruded the Gamble Brook Formation and has several quartzite xenoliths. It appears to be intruded by the Debert River Pluton (see below). Amphibole from the diorite yielded an $^{40}Ar/^{39}Ar$ cooling age of 622.1 ± 3.3 Ma (Keppie *et al*., 1990), which was considered to be close to the crystallization age of the pluton.

Debert River Pluton

The Debert River Pluton (Donohoe and Wallace, 1982d) forms two east-trending bodies on the northern and southern margins of the Folly River Formation (Fig. 2). The northern body was previously termed the Shatter Brook Pluton (Donohoe and Wallace, 1982d). The pluton consists of pink to grey, medium- to coarse-grained equigranular granodiorite, plus minor granite and tonalite (Pe-Piper *et al*., 1996). The southernmost body of the pluton locally contains abundant dark grey, medium-grained dioritic to quartz dioritic enclaves. The pluton commonly displays mylonitic textures with a well developed, subvertical to moderately south dipping, west-trending foliation and a related shallow, west-southwest-plunging mineral lineation. Quartzite, cordierite-bearing metasiltstone and mafic volcanic xenoliths are common along the margins of the pluton (Fig. 3c). These are interpreted to be related to the Gamble Brook and Folly River formations. The presence of dioritic “xenoliths” in the granodiorite was used by Pe-Piper *et al*. (1996) and Murphy *et al*. (2001) to indicate an intrusive contact into the Frog Lake Pluton. The pluton has geochemical characteristics typical of a volcanic-arc environment (Pe-Piper *et al*, 1996; Murphy *et al*., 2001). Fine- to medium-grained equigranular dykes cut the pluton.

Originally the pluton was consider to be Carboniferous (Donohoe and Wallace, 1982d). However, a granite sample from near the northern margin of the pluton and a granodiorite sample from the southern margin yielded poorly constrained U-Pb zircon ages of 612 ± 4 Ma and 609 ±4 Ma, respectively (Doig *et al*., 1991; Murphy *et al*., 2001), confirming a Late Neoproterozoic age. However, based on field relations, the Debert River and Frog Lake plutons appear to be co-mingled at the contacts and are likely the same age. Using the same data as Doig *et al*. (1991), a lead-loss line through the four zircon fractions and 0 Ma yielded an upper intercept age ca. 624 Ma for the southern granodiorite, similar to the amphibole age from Frog Lake. To confirm this interpretation, samples from the Debert River Pluton are being assessed for additional U-Pb work.

McCallum Settlement Pluton

As redefined by MacHattie and White (2012), the McCallum Settlement Pluton forms two east-trending, faulted-bounded bodies: the western body is well exposed in West Branch North River and logging roads in the area, and the eastern body is exposed in the area between North River and Upper Kemptown (Fig. 2). The pluton includes parts of the Carboniferous Salmon River Pluton of Donohoe and Wallace (1982d) and Murphy *et al*. (2000b) and parts of the Late Neoproterozoic Frog Lake, Debert Lake and McCallum Settlement plutons as defined by Pe-Piper and Piper (2005d). It consists of pink to grey, medium- to coarse-grained granite to granodiorite and minor dark grey, medium-grained quartz diorite and diorite. The quartz diorite and granite locally display co-mingling textures. Quartzite xenoliths, presumably related to the Gamble Brook Formation, occur along the southern margin of the pluton. Like the Frog Lake and Debert River plutons, the granitoid rocks are cut by fine- to medium-grained equigranular dykes.

Previous geochemical analyses suggest that the pluton displays a “within-plate” character (Pe-Piper *et al*., 1996); however, later workers showed it has more of a volcanic-arc signature (Murphy *et al*., 2001). It is likely that the McCallum Settlement Pluton represents the more evolved parts of an expanded I-type volcanic-arc granitoids suite. The age of the McCallum Settlement Pluton is not well constrained. Donohoe and Wallace (1982d) considered the pluton as Cambrian in age based on

Rb-Sr whole rock and muscovite ages. Doig *et al*. (1991) obtained discordant U-Pb zircon ages but cited the youngest $^{207}Pb/^{206}Pb$ age of 575 ± 5 Ma as the crystallization age of the pluton. Using the same data as Doig *et al.* (1991), a lead-loss line placed through the three zircon fractions and 0 Ma yields an upper intercept age ca. 603 Ma. To confirm this interpretation samples are being evaluated for additional U-Pb work.

Polson Mountain Pluton

The Polson Mountain pluton is a new name proposed by MacHattie and White (2012) for a fault-bounded pluton exposed along logging roads in the Polson Mountain area (Fig. 2). It includes the southern part of the Carboniferous Salmon River and Late Neoproterozoic Cranberry Brook plutons of Donohoe and Wallace (1982d) and Murphy *et al*. (2000b, 2001). It is mainly a grey to red, medium- to coarse-grained alkali-feldspar granite. Large (mappable at 1:10 000 scale) enclaves of grey, equigranular, medium- to coarse-grained quartz diorite to diorite occur along the southern margin of the pluton. Magma mingling textures are locally observed between the granitic and dioritic parts of the pluton. The pluton is cut by fine- to medium-grained equigranular dykes (Fig. 3d).

The granitic and dioritic rocks display a within-plate geochemical signature (MacHattie and White, 2012). U-Pb age determinations from zircons in a standard petrographic thin section from two granitic samples were completed using the laser-ablation microprobe–inductively coupled plasma–mass spectrometry (LAM-ICP-MS) system at the University of New Brunswick and following the procedure outlined by Archibald *et al*. (in press). The analyses show that the data points are concordant and yielded ages of ca. 375 and 368 Ma, confirming a Late Devonian age (MacHattie *et al*., 2012).

Gain Brook Pluton

The Gain Brook Pluton (Donohoe and Wallace 1982d; Pe-Piper and Piper 2002) is located north of the Folly River Formation and is exposed along logging roads in the area around Guyon Brook (Fig. 2). MacHattie and White (2012) mistakenly called this body the Guyon Brook pluton because they were unaware of the brook's name change from Guyon to Gain on recent topographic maps. Hence, based on the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005) the name Gain Brook Pluton takes precedence. The pluton is fault bounded and mainly composed of grey, medium-to coarse-grained alkali-feldspar granite (Fig. 3e) and minor dark grey, medium-grained diorite. It is also intruded by several fine- to medium-grained gabbroic dykes. There is no age control on the Gain Brook Pluton, but because it is lithologically and chemically similar to the Polson Mountain pluton, it is considered here to be Late Devonian in age (MacHattie and White, 2012) and to have formed in a within-plate environment.

Stratified Units in the Jeffers Block

Mount Thom Complex

The Mount Thom Complex (Donohoe, 1975) crops out in the far eastern area of the Cobequid Highlands and is well exposed in several quarries in the area (Fig. 2). It is intruded on its southern margin by the Ordovician Eight Mile Brook plutonic suite (see below) and on the north by the Neoproterozoic Mount Ephrairn plutonic complex (see below). The complex consists dominantly of quartzofeldspathic, semipelitic and pelitic gneiss (Fig. 4a) plus minor calc-silicate gneiss and rare amphibolite (e.g. Meagher, 1995). Some of the quartzofeldspathic gneisses may represent igneous protoliths, but it is difficult to distinguish from the sedimentary protoliths. The near vertical, east-trending foliation is defined by biotite and muscovite and is locally isoclinally folded with axial planes parallel to the regional fabric. Mineral lineations are locally well developed and plunge steeply to the south. The more pelitic gneisses contain garnet and possible cordierite (now pseudomorphed by sericitic). The mineral assemblage is indicative of greenschist- to amphibolite-facies metamorphism. The complex is cut by numerous, variably textured gabbroic and granitic dykes and sill.

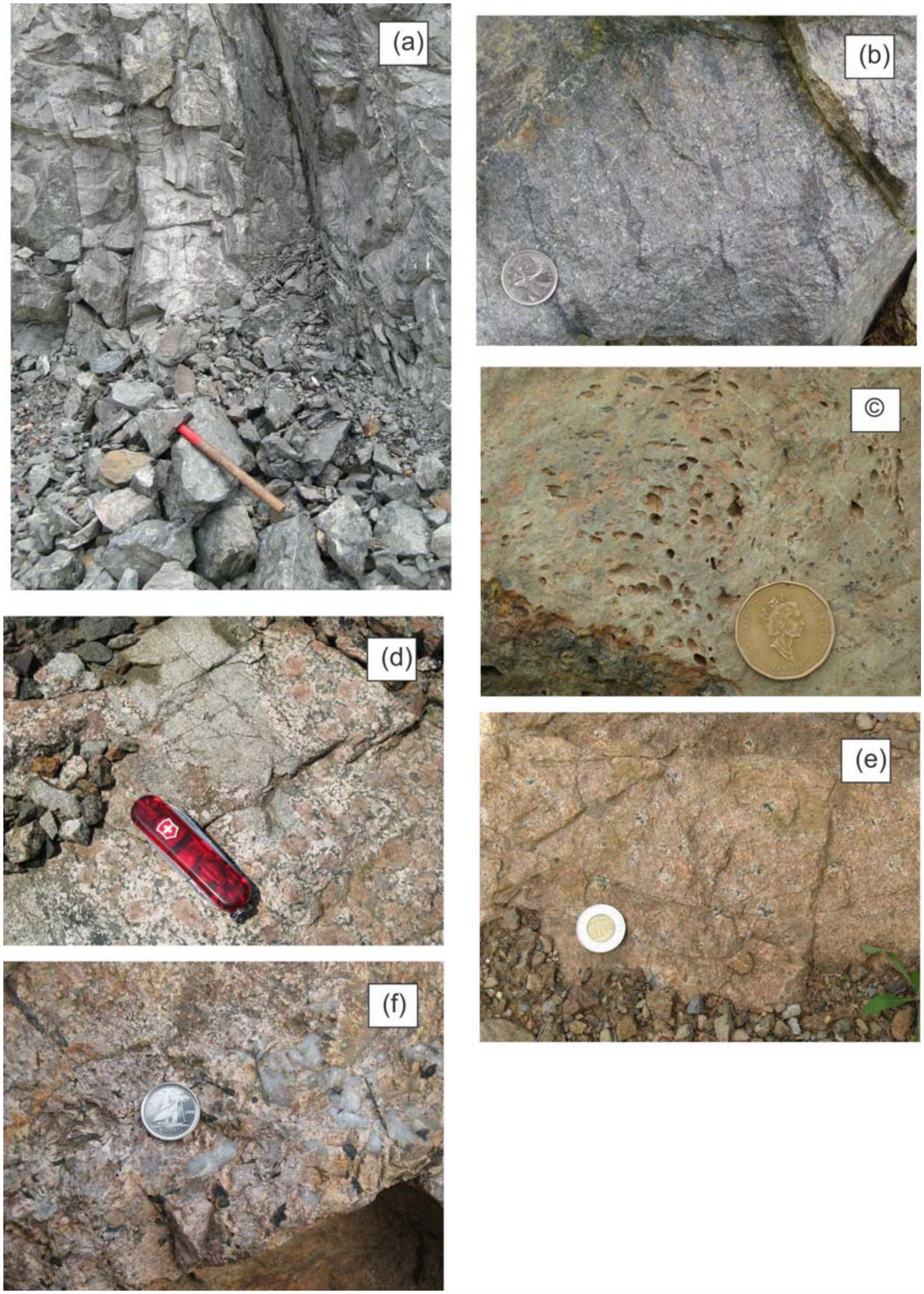

Figure 4. (a) Quartzofeldspatic paragneiss of the Mount Thom Complex; hammer is ~50 cm in length. (b) Fiamme in felsic pyroclastic flow of the Byers Brook Formation. (c) Vesicular basalt from the top of the Byers Brook Formation. (d) Mingling between granitic and gabbroic phases of the Mt. Ephrairn plutonic suite; knife is ~6 cm long. (e) Alkali-feldspar syenite of the Ordovician Eight Mile Brook plutonic complex. (f) Pegmatitic arfvedsonite-bearing alkali-feldspar granite of the Hart Lake-Byers Lake pluton.

The relationship of the Mount Thom Complex to the Gamble Brook and Folly River formations is unknown. Donohoe and Wallace (1982b) considered the complex as representing the basement upon which the Helikian or Hadrynian Gamble Brook and Folly River formations were deposited. Pe-Piper and Piper (2002) considered the complex to be Middle Neoproterozoic, similar in age to the Gamble Brook and Folly River formations. A minimum depositional age for the Mount Thom Complex is provided by the ca. 755 to 735 Ma Mount Ephrairn plutonic complex, which intrudes the complex. U-Pb (LAM-ICP-MS) zircon analyses from two quartzofeldspathic paragneisses of the Mount Thom Complex yielded maximum depositional ages of ca. 1190 and 840 Ma, respectively (MacHattie *et al*., 2012). These ages are similar to those previously obtained from the Gamble Brook Formation.

Dalhousie Mountain Formation

The Dalhousie Mountain Volcanics (Murphy *et al*., 1988), or Formation (Murphy *et al*., 2001), of the Jeffers Group (Pe-Piper and Piper, 1989) occurs along the northern margin of the Jeffers block and is largely in faulted contact with adjacent units (e.g. Waugh River Fault; Donohoe and Wallace, 1982d; Pe-Piper and Piper, 2005d); however, along its northern and eastern extents it is unconformably overlain by Late Carboniferous sedimentary rocks (Fig. 2). A small, fault-bounded wedge of volcanic and sedimentary rocks is found in the central part of the Bass River block and is tentatively assigned to the Dalhousie Mountain Formation (Fig. 2). The formation consists of weakly cleaved green to grey, dacitic to andesitic crystal to crystal lithic tuff; minor pale pink to grey, rhyolitic lapilli tuff with abundant crystal and lithic fragments; and rare green basaltic tuffaceous rocks and amygdaloidal basalt flows. Common throughout the Dalhousie Mountain Formation are pale grey to green, well laminated ‘cherty siltstone’ units that are interpreted, in part, to have been originally volcanic ash layers. Cross-laminations and graded beds are locally preserved. Foliations are defined by sericite, chlorite, white mica and rare biotite indicative of lower greenschist facies metamorphism (e.g. Murphy *et al*., 2001). Varied gabbroic, and to a lesser extent granitic, porphyry dykes and sills are common.

The age of the Dalhousie Mountain Formation is unknown. Donohoe and Wallace (1980, 1982d) included these rocks in the Silurian Earltown Volcanics, or Formation, based on the perceived similarity between the sedimentary rocks and those in the Silurian Arisaig Group exposed in the Antigonish Highlands. Murphy *et al*. (1988, 2001) suggested that the Dalhousie Mountain Formation was more similar to the Late Neoproterozoic Keppoch Formation in the Antigonish Highlands. We agree with Murphy *et al*. (1988, 2001) that the Dalhousie Mountain Formation is probably Late Neoproterozoic, but we would suggest that it more closely resembles the James River Formation in the Antigonish Highlands (e.g. White *et al*. 2011; White, 2013). Although Murphy *et al*. (2001) presented no lithogeochemistry, they speculated that the Dalhousie Mountain Formation formed in a volcanic arc environment.

Wilson Brook Formation

The type section for the Wilson Brook Formation is on the Portapique River near the Wilson Brook tributary (Donohoe and Wallace, 1979, 1982c), which is a considerable distance to the west of the current map area. The Silurian rocks in the current map area were originally included the Earltown Volcanics, or Formation (Donohoe and Wallace, 1980, 1982d). However, this fossiliferous Silurian unit was assigned the Wilson Brook Formation by Murphy *et al*. (2000b, 2001) and Pe-Piper and Piper (2005d), and that designation is retained here. The Wilson Brook Formation crops out in streams and brooks north of Earltown and in a fault sliver associated with the Rockland Brook Fault (Fig. 2). The formation is fault bounded and consists of grey to black micaceous siltstone and shale, and minor quartz arenite. Thin (<10 cm wide), brown, carbonate-rich coquina beds are common throughout the formation. Faunas range from Wenlock to Pridoli (Donohoe and Wallace, 1982d). In contrast to Donohoe and Wallace (1982d) and Murphy *et al*. (2001), no volcanic rocks were observed in the formation. Only one mafic dyke was noted.

Byers Brook and Diamond Brook Formations

The Byers Brook and Diamond Brook formations compose the Fountain Lake Group (Donohoe and Wallace, 1982d) in the northwest-trending Earltown-Byers Lake belt (Dessureau *et al*., 2000) that extends from Earltown to Debert Lake (Fig. 2). The lower Byers Brook Formation consists of orange to pale brown rhyolitic flows and ignimbrites (Fig. 4b) interlayered with dacitic flows and crystal tuff, and grey to green siltstone and sandstone. Basaltic flows are a minor component (Fig. 4c). The overlying Diamond Brook Formation consists of basaltic flows and interbedded red sandstone and siltstone. Rhyolitic flows are minor.

Spores extracted from siltstone from the middle part of the Diamond Brook Formation were interpreted as Emsian to early Tournaisian (Donohoe and Wallace, 1982d), but these were re-interpreted as late Famennian by Martel *et al*. (1993). Zircons extracted from a rhyolitic flow near the upper part of the Byers Brook Formation yielded concordant results with a weighted mean $^{206}Pb/^{238}U$ age of 358 ± 1 Ma (Dunning *et al*., 2002). A rhyolite flow from the middle part of the Diamond Brook Formation yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 355 ± 3 Ma (Dunning *et al*., 2002). The bimodal character of the Fountain Lake Group combined with its within-plate geochemical signatures suggest it formed in a continental-rift tectonic environment.

Igneous Units in the Jeffers Block

Mount Ephrairn Plutonic Suite

Mount Ephrairn plutonic suite is a new name proposed by MacHattie and White (2012) for an assemblage of co-mingled granite, granodiorite and diorite in the eastern part of the map area (Fig. 2). It includes parts of several previously described plutons: the former Carboniferous Salmon River and Late Neoproterozoic Brookland, Mount Thom, and Gully Brook plutons of Donohoe and Wallace (1982d); and the Carboniferous Gunshot Brook Pluton and Late Precambrian Frog Lake plutons of Pe-Piper and Piper (2005d). The plutonic suite intrudes the Mount Thom Complex to the south and appears to be intruded by the mainly granitic rocks of the Gunshot Brook Pluton (Pe-Piper and Piper, 2005d) on its northern margin. The plutonic suite consists dominantly of diorite to quartz diorite with textures that range from fine- to coarse-grained and equigranular to porphyritic. The more felsic units are a minor component of the suite and consist of medium- to coarse-grained, slightly porphyritic granodiorite to granite; phenocrysts are quartz and K-feldspar. Mingling between mafic and felsic phases of the plutonic suite is common (Fig. 4d). Compared to other, younger units in the eastern Cobequid Highlands, this suite is remarkably undeformed except for a few brittle faults along its margins. Varied gabbroic, and to a lesser extent granitic, porphyry dykes and sills are common.

Lithogeochemistry indicates this plutonic suite formed in a continental-margin volcanic-arc environment (MacHattie and White, 2012). Two dioritic and two granitic samples collected for U-Pb (LAM-ICP-MS) analysis yielded four concordant zircon ages that range from ca. 755 to 735 Ma (MacHattie *et al*. 2012).

Gunshot Brook Pluton

The distribution of the Gunshot Brook granite (Pe-Piper and Piper, 2002) or pluton (Pe-Piper and Piper, 2005d) has changed as a result of the current mapping but the name is tentatively retained. It includes parts of the Carboniferous Salmon River Pluton (Donohoe and Wallace, 1982d). The Gunshot Brook Pluton is located north of the Mount Ephrairn Plutonic Suite and is intruded into the Dalhousie Mountain Formation (Fig. 2). It consists of pink to orange, medium- to coarse-grained, equigranular to locally porphyritic granite to granodiorite. Medium- to coarse-grained dioritic enclaves are present along the southern margin. Fine- to medium-grained gabbroic dykes are common.

Based on petrography and geochemistry, Pe-Piper *et al*. (2002) and Pe-Piper and Piper (2002) indicated a volcanic-arc affinity for the Gunshot Brook Pluton, similar to other Late Neoproterozoic plutons (e.g. Jeffers Brook Pluton) exposed to the west. Published data on the age of the pluton is not available, but R. Doig in Murphy *et al*. (2001) cited a U-Pb zircon age of 605 ± 5 Ma, further corroborating a Late Neoproterozoic age.

Six Mile Brook Pluton

Six Mile Brook pluton (Jeffers Block gabbro of Pe-Piper and Piper, 2005d) is a new name proposed for a dioritic pluton in the easternmost part of the map area (Fig. 2) that is intruded into the volcanic rocks of the Dalhousie Mountain Formation. It consists of medium- to coarse-grained, equigranular to porphyritic diorite to quartz diorite. Although not dated, the petrological similarities with the mafic enclaves in the Gunshot Brook Pluton and its intrusive nature with the Dalhousie Mountain Formation suggest it is Late Neoproterozoic and probably calc-alkalic in character.

Eight Mile Brook Plutonic Complex

Eight Mile Brook Pluton (Donohoe and Wallace, 1982d), or plutonic complex (MacHattie and White, 2012), is an assemblage of co-mingled syenite and gabbro that intrudes the Mount Thom Complex and the Mount Ephrairn plutonic complex. It also occurs as dykes in the Gunshot Brook Pluton. This plutonic complex is well exposed in the eastern part of the map area along several new logging roads, brooks and quarries (Fig. 2). It consists of pink to black, equigranular, medium- to coarse-grained syenite to alkali-feldspar granite (Fig. 4e) and medium- to coarse-grained monzogabbro. Fine- to medium-grained gabbroic dykes cut the complex. Lithogeochemistry indicates that this plutonic complex has chemical characteristics of A-type granitoid suites and formed in a within-plate environment (MacHattie and White, 2012).

Donohoe and Wallace (1982d) recognized the unique character of this unit and considered the rocks to be Late Neoproterozoic. To better constrain the age, three samples (two alkali-feldspar granite and one syenite) were collected for U-Pb (LAM-ICP-MS) analysis. All three rocks yielded concordant zircon ages that range from ca. 470 to 480 Ma (MacHattie *et al*., 2012). This Early Ordovician plutonic unit was not recognized previously in the Cobequid Highlands but is known to exist in the Antigonish Highlands (White *et al*., 2012), where it has similar ages and chemical features (Escarraga *et al*., 2012; Archibald, in press).

Hart Lake-Byers Lake Pluton

The Hart Lake-Byers Lake Pluton (Donohoe and Wallace, 1982d) forms a large body north of the Rockland Brook Fault and south of the Byers Brook Formation in the western part of the map area (Fig. 2). It consists predominantly of medium- to coarse-grained, locally pegmatitic alkali-feldspar granite (Fig. 4f). Igneous layering is locally present. Mafic minerals include amphibole, biotite and Fe-Ti-oxides, and prominent accessory phases include zircon, allanite, titanite and epidote. An intrusive relationship between the Hart Lake-Byers Lake Pluton and Byers Brook Formation is locally preserved (MacHattie, 2011). The granitic rocks have within-plate trace element characteristics (MacHattie and White, 2012) but are more alkaline and less aluminous than similar within-plate granitoids rocks in the western Cobequid Highlands. An alkali-feldspar granite from the pluton yielded a U-Pb zircon age of 362 ± 2 Ma (Doig *et al*., 1996), which is interpreted to be the crystallization age.

Economic Geology

Mineral exploration in the Cobequid Highlands has been sporadic over the last century or more. Significant uranium exploration occurred in the early 1980s, prior to the uranium moratorium, on the Late Devonian to Early Carboniferous volcanic and plutonic rocks. The surrounding Carboniferous basins were also extensively explored for base metals and uranium (Ryan, 1990). The most significant exploration targets currently known within the eastern Cobequid Highlands include the granite-related high-field-strength/rare earth element (HFSE/REE) prospect located near Debert Lake and the volcanic-associated epithermal-style gold occurrences discovered near Warwick and Nuttby mountains (MacHattie, 2011; MacHattie, 2012, 2013). Both types of mineralization are associated with the Late Devonian to Early Carboniferous bi-modal magmatism (Fig. 2).

Within the Debert Lake area the granite-related HFSE/REE mineralization (sum REE up to ~1 wt.%) occurs along the top of the Hart Lake-Byers Lake pluton where it intrudes volcanic rocks of the Byers Brook Formation. It is manifested in the form of granite dykes (up to 50 cm wide) within the volcanics and as pegmatitic segregations within the granite. As this mineralization is spatially and genetically related to a relatively HFSE/REE-rich arfvedsonite-bearing phase of the pluton it is suggested that targeting this particular phase elsewhere in the pluton, particularly if located along its upper margin, might yield HFSE/REE mineralized targets.

Within the Warwick and Nuttby mountain areas anomalous Au (up to 650 ppb) was found in samples of highly silicified and sulphidized basalt and rhyolite. Associated with the Au are variable but anomalous concentrations of As, Sb, Cd, Pb and Se. Within the Warwick Mountain area the Au mineralization occurs where basaltic rocks are intercalated with rhyolite flows, felsic volcaniclastic rocks and lesser siliciclastic sedimentary rocks. In contrast, the Nuttby Mountain Au mineralization occurs within a rhyolite flow/dome complex. This diversity in epithermal-style mineralization and the significant aerial extent and vertical dip of the volcanic succession suggest significant potential for new Au discoveries.

Despite the emphasis on REE and Au, the potential for iron oxide copper-gold (IOCG)-style mineralization along the southern flank of the eastern Cobequid Highlands should be considered significant. To the immediate west are the historic Londonderry Fe deposits and Bass River magnetite prospect. In addition, a regional gravity survey was recently conducted in the search for IOCG-style mineralization through the northern mainland of Nova Scotia, including the eastern Cobequid Highlands (Belperio *et al*., 2008, 2009), and many of the targets identified in that survey remain to be fully evaluated.

The map area has high potential for industrial minerals. Sand and gravel deposits are numerous and some are currently exploited. The granitoids rocks in the Frog Lake Pluton and Mount Ephrairn plutonic complex, and the metamorphic rocks in the Gamble Brook Formation and Mount Thom Complex are currently being quarried for local aggregate and asphalt use. The Nova Scotia Department of Natural Resources Mineral Occurrences Database for NTS map sheet 11E/10 and 11E/11 contains a complete summary of mineral occurrences in the map area (Nova Scotia Department of Natural Resources, 2009).

Summary

Detailed bedrock mapping combined with geochemistry, geochronology and geophysical studies have added to our knowledge of the geology in the Cobequid Highlands and as a result have highlighted the economic potential of the area.

A major result of the mapping during the summer of 2012 and related U-Pb analysis is the identification of the ca. 755 to 735 Ma volcanic-arc-related Mount Ephrairn plutonic complex, a previously unrecognized plutonic unit in the Cobequid Highlands. Its intrusive relationship with the Mount Thom Complex provides a minimum depositional age for the gneissic protolith; the maximum age of deposition is tentatively constrained at ca. 840 Ma from detrital zircon ages. This suggests that the Mount Thom Complex maybe the higher metamorphic grade equivalent of the Gamble Brook Formation. This is the oldest crust exposed in Avalonia and likely formed along the margins of the supercontinent Rodinia.

In addition, the previously assumed Late Neoproterozoic Eight Mile Brook Pluton has been confirmed to be Early Ordovician, and it is likely related to the Early Ordovician West Barneys River Plutonic Suite in southern Antigonish Highlands. The age of the Polson Mountain Pluton is confirmed to be Late Devonian.

The Folly River Formation contains large areas of mafic metavolcanic rocks with significant ironstone beds. Lithogeochemical data suggest it may have formed in a back-arc basin, which increases its potential for VMS deposits. The significant magnetic and associated gravity anomalies in the area suggest this unit may extend to great depths.

The Devonian (ca. 375-365 Ma) and Devonian-Carboniferous bi-modal, within-plate intrusive suites and related volcanic rocks have been shown to have great potential for REE and epithermal Au-style mineralization. The IOCG-style of mineralization continues to have great potential along the southern flank of the eastern Cobequid Highlands.

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