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BEAVER BROOK ANTIMONY MINE REVISITED: AN UPDATE ON OPERATIONS AND NEW STRUCTURAL AND GEOLOGICAL OBSERVATIONS

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ABSTRACT

Epithermal, fracture-controlled stibnite–quartz mineralization at Beaver Brook in central Newfoundland was discovered in 1989 during regional gold exploration surveys. Mineralization occurs along three zones (West, Central and East), disposed along a 4-km strike length outboard of the eastern margin of the Mount Peyton intrusive suite; the latter two zones have delineated reserves. The mine is in the East zone, where mineralization consists of massive stibnite veins, vein breccia, vug fillings and fracture coatings that occur in the hanging wall of an 065º-trending, steeply to moderately southeast-dipping fault. Gold abundances are typically low in the East zone stibnite–quartz ore, however, near the Central zone, diamond-drill hole (DDH) intercepts have yielded up to 26 g/t Au over 2 m, with and without coincident Sb. Beaver Brook Antimony Mine opened in 1997, but ceased after 8 months of operations. In 2007, after an ownership change, the mine was dewatered, reopened and processed ore until 2012. Exploration of the mine lease has continued through the acquisition of IP geophysical surveys, soil surveys and completion of a further 100 DDH throughout previously unexplored parts of the property. Present-day indicated resources consist of 0.5 Mt of ore at 4.17% Sb.

*Data is presented of post-Silurian, northwest-directed thrusting of the Ordovician Davidsville Group over the Silurian Indian Islands Group. Structural analysis indicates that at least three low-angle reverse faults (thrusts) place Darriwilian to Katian units over Wenlock to Lockovian units, with the thrust panels widening to the southwest. At the East zone, all rocks exposed at surface comprise Silurian rocks of the Indian Islands Group and the Ten Mile Lake formation. The discovery of more Sb resources requires a better understanding of the major fault structures in the region (*i.e.*, which faults control and/or host the mineralization) and might be assisted through detailed aeromagnetic and other geophysical surveys. Moreover, the positive indication of new auriferous zones on the lease indicates an alternative commodity for further exploration.*

INTRODUCTION

Antimony (Sb) is a non-precious but globally 'strategic' metal (BGS, 2015; Mudd *et al.*, 2017), whose most common ore mineral is stibnite (Sb_2S_3). Antimony is widely used in flame-retardants, but is also used in alloys with other metals, lead-acid batteries, low-friction metals, and cable sheathing. Antimony compounds are also commonly used in the manufacturing of paints, ceramic enamels, glass and pottery. Very pure antimony is used in some semiconductor diodes and in infrared detectors (Butterman and Carlin, 2004; Grund *et al.*, 2006). For most of the last century, the global antimony market has been largely under the control of China as that country presently holds almost 50% of the worlds antimony reserves and, in 2016, produced >75% of the global supply (Guberman, 2016). Antimony is, therefore, a metal that is considered at strategic risk in terms of supply, and new resources need to be discovered (BGS, 2015).

Relative to the precious and base metals, antimony is not a particularly well-studied commodity. In many mineralizing systems, antimony may be closely associated with a number of other ore metals such as tungsten, molybdenum and gold (*e.g.*, Lake George Mine area, Seal *et al.*, 1988; Yang *et al.*, 2003, 2004; Costerfield Mine, Wilson *et al.*, 2017; Quinglong deposit, Chen *et al.*, 2018). Antimony and gold together, commonly occur with anomalous and variable enrichment of a number of other characteristic trace elements such as As, Pb, W, Mo, Hg, Bi and Te. These diverse metal associations are a notable characteristic of the intrusion-related gold systems such as those of the Tintina Gold Belt of Alaska and Yukon (*e.g.*, Fort Knox, Donlin Creek; Sillitoe and Thompson, 1998;

Thompson *et al.*, 1999; Hart, 2007), but also of the Carlin-type of epithermal, structurally controlled calcareous sediment-hosted gold deposits (Cline *et al.*, 2005; Muntean *et al.*, 2011). A notable characteristic of many epithermal, fracture-controlled antimony deposits (*e.g.*, Bliss and Orris, 1986; Gumiel and Arribas, 1987; Berger, 1993; Kontak *et al.*, 1996; Neiva *et al.*, 2008; Bortnikov *et al.*, 2010; Liang *et al.*, 2014; Wilson *et al.*, 2017; Chen *et al.*, 2018) is the close spatial and temporal association with Py–Aspy ± Au ± W ± Mo ± Pb mineralization.

The Beaver Brook Antimony Mine in central Newfoundland is located ~42 km southwest of the town of Glenwood-Appleton, and 1 km northwest of the Northwest Gander River (Figures 1 and 2) in the Eastern Pond map area (NTS 2D/11). Exploration for gold and precious metals in the region commenced as part of the island-wide, grass-roots gold exploration boom of the late 1980s. This exploration was a result of financial market conditions and the relatively high and steady price of gold (~US$350–450 /oz) at that time, and resulted in the discovery of many precious-metal-mineralized zones throughout Newfoundland. In 1989, prospectors exploring for gold with the Noranda–Noront Grub Line Syndicate discovered stibnite-mineralized boulders in Beaver Brook, a small southeast-flowing tributary of the Northwest Gander River (Tallman, 1989a). This discovery prompted extensive further exploration of the surrounding area, and the subsequent delineation of the stibnite mineralization now defined at the East zone of the Beaver Brook Antimony Mine.

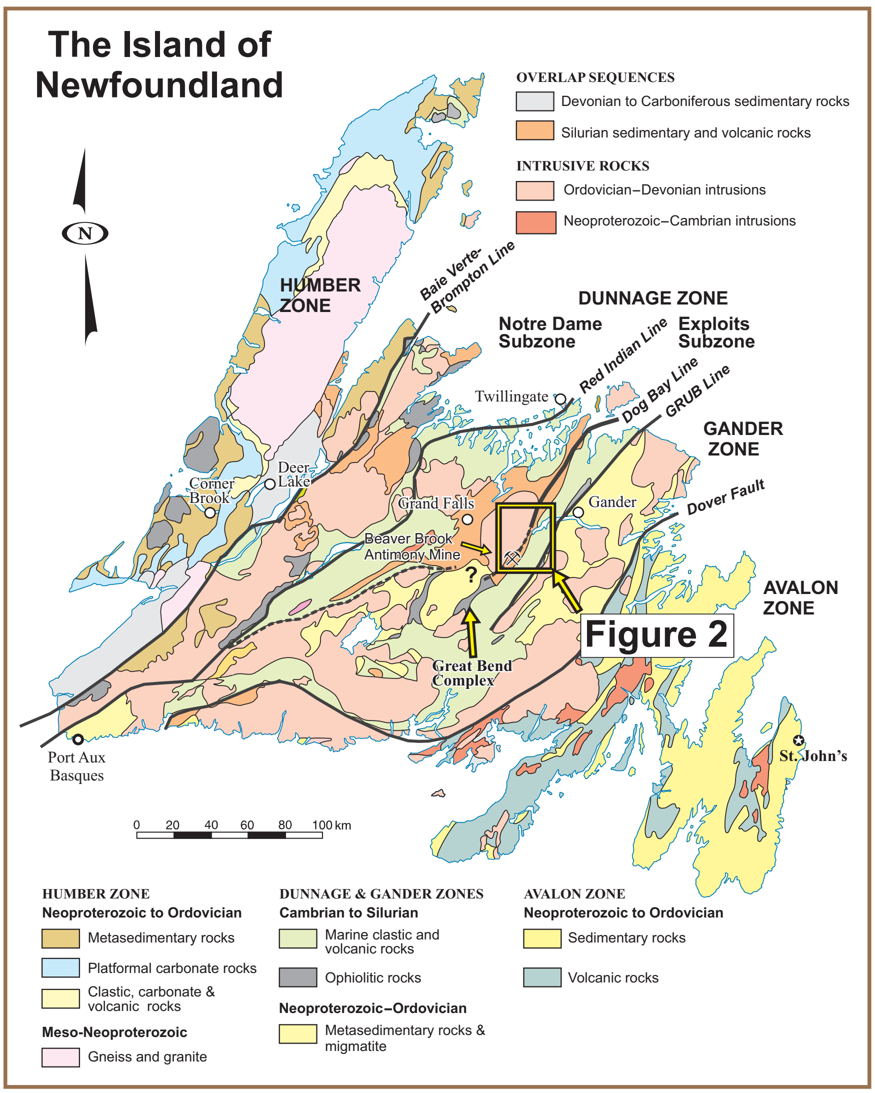

Figure 1. *Simplified geological map of Newfoundland showing the major lithotectonic domains and their bounding structures. Also shown is the location of Figure 2 and the Beaver Brook Antimony Mine with respect to major geological elements of the region (after Williams* et al.*, 1988; Colman-Sadd* et al.*, 1990).*

Although the mine has been in existence for 20 years, and considering the relatively large size (2.2 million tons) and high grade (avg. 3.99% Sb at 1.5% cut off) of the East zone deposit (Morrissy and House, 1998), the mineralization, host rocks, and structural setting are poorly understood. This is a result of a number of factors including: thick fluvioglacial deposits and a dearth of exposed bedrock (Batterson, 1999); a lack of regional, property-wide and deposit-scale geophysical data; structural complexity of the host rocks; a variable, but commonly low, price of antimony over much of the past two decades, and, turnover in mine lease ownership and a lack of continuity of mine site knowledge.

This report forms a component of an ongoing, broader study (Sandeman *et al.*, 2017; H. Sandeman, unpublished data, 2017) of the nature and style of polymetallic Au–Ag–Sb–As mineralization spatially associated with the major structural feature termed the Dog Bay Line (Figures 1 and 2; Williams *et al.*, 1993). This study builds upon extensive previous work including: geological mapping (Anderson and Williams, 1970; Blackwood, 1980a, b, 1981a, b, 1982; Dickson, 1992, 1993, 1994, 1996, 2006); geochronology (Dunning, 1992, 1994; Dunning and Manser, 1993; O'Driscoll and Wilton, 2005; McNicoll *et al.*, 2006; Dickson *et al.*, 2007;

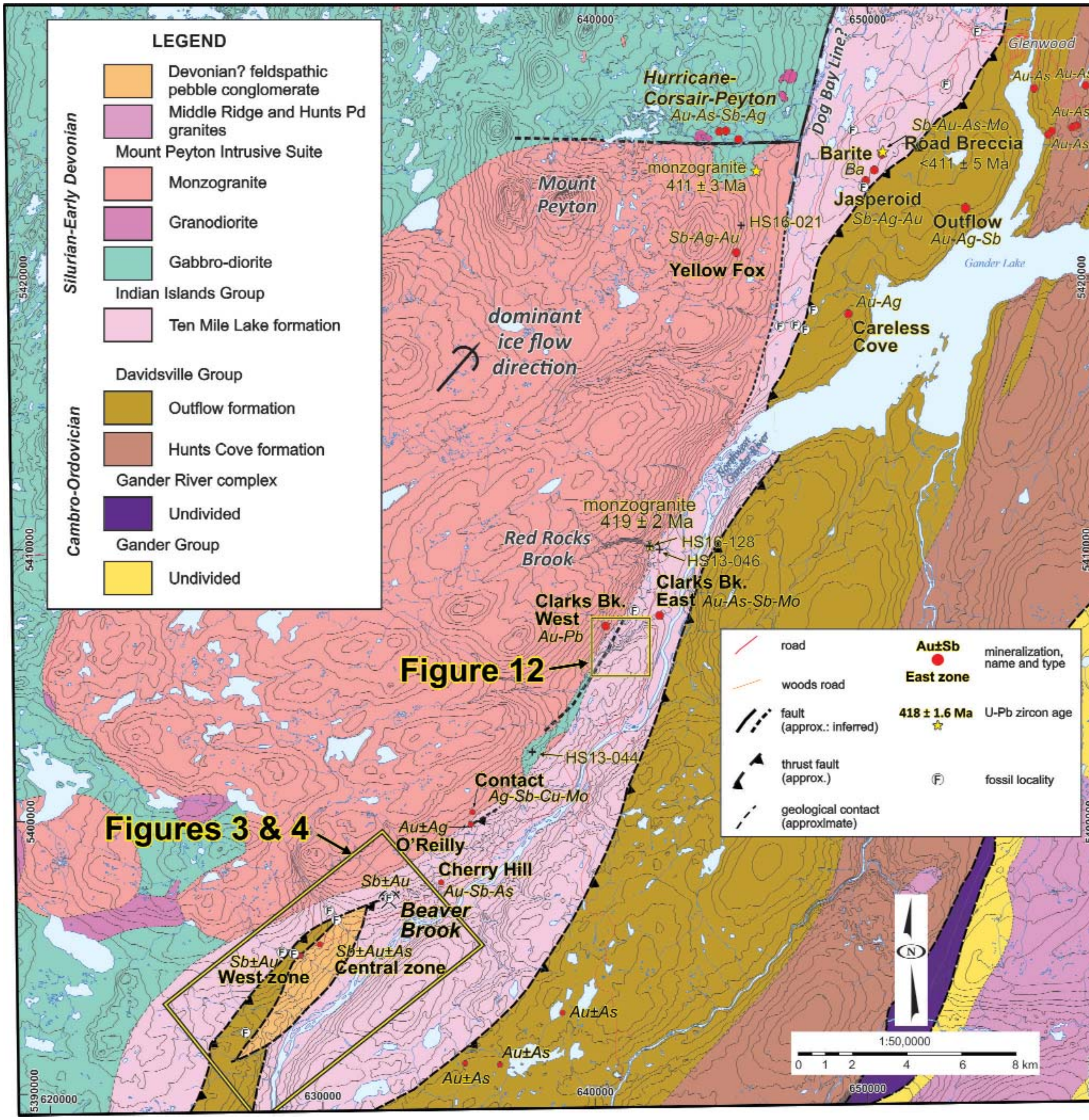

Figure 2. *Simplified geological map of central northeastern Newfoundland (http://geoatlas.gov.nl.ca/Default.htm: after Colman-Sadd* et al.*, 1990 with some adaptations from Dickson, 1996 and Sandeman* et al.*, 2017). Also shown are the locations of the Beaver Brook Antimony Mine, and other affiliated mineralization (Tallman, 1989a, b; Evans, 1996; Wilton, 2003; Barbour and Churchill, 2004; O'Reilly and Churchill, 2004; O'Reilly, 2005; O'Reilly* et al.*, 2008, 2010) with respect to major geological elements of the region.*

Sandeman *et al.*, 2017); biostratigraphy (Anderson and Williams, 1970; Blackwood, 1982; Williams, 1993; Boyce *et al.*, 1993; Boyce and Ash, 1994; Williams and Tallman, 1995; Boyce and Dickson, 2006; Dickson *et al.*, 2007) and, lithogeochemistry (Dickson, 1996; Dickson and Kerr, 2007; Sandeman *et al.*, 2017) in the greater study area. Also forming part of the framework for this contribution are the more detailed mineral deposit studies (O'Driscoll and Wilton, 2005; O'Reilly, 2005; Squires, 2005; O'Driscoll, 2006; Lake and Wilton, 2006; Sandmann *et al.*, 2011; Seifert and

Sandmann, 2013; Sandeman *et al.*, 2017), and numerous mineral exploration industry, assessment work reports that were submitted to the Government of Newfoundland and Labrador over the past three decades. All of these datasets collectively provide a framework upon which a better understanding of the mineralization, as well as the magmatic and tectonic history of the region may be constructed.

Herein, the Beaver Brook Antimony Mine production and exploration information is updated (*see* Lake and Wilton, 2006), the geological units and their complexity are discussed and, a more robust treatment of the structural geology of the mine area is advanced. This study, in conjunction with ongoing investigations (*e.g.*, Sandeman *et al.*, 2017; H. Sandeman, unpublished data, 2017), attempts to: 1) provide a higher public profile and a better understanding of the structural geology and mineralization at Beaver Brook; 2) emphasize the abundance and diversity of the polymetallic mineralization surrounding the mine area, and, 3) stimulate further precious-metal and antimony exploration in the greater region. Collectively, the new data and interpretations provide better constraints on the structural setting of the mineralization; more clearly refine the probable age of the mineralization to the Early Devonian, and suggest a probable genetic link with other Au–Ag–Sb–As mineralized zones in the region. Herein, the time scale used for discussion is the Internation-al Chronostratigraphic chart v2017/02 (Cohen *et al.*, 2013; http://www.stratigraphy.org/index.php/ics-chart-timescale).

REGIONAL SETTING AND PREVIOUS WORK

The study area lies in the Mount Peyton map area (NTS 2D/14), in the eastern Exploits Subzone of the Dunnage Zone of the Newfoundland Appalachians (Figures 1 and 2). The Exploits Subzone consists of a collage of intra-oceanic arcs, back-arcs and related marine sedimentary rocks formed in the Iapetus Ocean during the Cambro-Ordovician. These assemblages were tectonically emplaced eastward (present-day coordinates) over the Ordovician passive margin sequences of the Gander Zone, during Late Ordovician (Penobscott) orogenesis (Colman-Sadd *et al.*, 1990; van Staal and Barr, 2012).

The Exploits Subzone is divided into two lithostratigraphic assemblages, separated by the Dog Bay Line, a major structural feature consisting of shear zones and faults and characterized at Dog Bay on the north coast by intensely foliated dark-shale mélange (Williams *et al.*, 1993). Cambro-Ordivician rocks of both lithostratigraphic assemblages of the Exploits Subzone are overlain by Late Ordovician to Silurian sedimentary units that are interpreted to represent synorogenic overstep assemblages (Williams *et al.*, 1988; O'Brien, 2003; van Staal *et al.*, 2014). Volcanic rocks occur in the overstep sequences to the west, but are not recorded to the east of the Dog Bay Line. The progressive northwest to southeast destruction of these overstep assemblage basins is interpreted to represent the terminal closure of Iapetus (LaFrance and Williams, 1992; O'Brien, 2003). Williams *et al.* (1993) proposed that the Dog Bay Line likely extended south southwestward, inland toward Glenwood and along the eastern margin of the Mount Peyton intrusive suite.

Subsequent to the historical geological surveys of the late 1800's and early half of the 20th century, the first modern mapping of the greater Mount Peyton area was undertaken by Anderson and Williams (1970) who produced a 1:250 000-scale geological map of the western half of the Gander Lake (NTS 2D) map area. Anderson and Williams (*op. cit.*) recognized that the Beaver Brook Antimony Mine area was underlain by a Silurian sequence of shallow-marine and terrestrial, reddish sandstones and siltstones (then Botwood Group: *see* Williams, 1962), that was interpreted to conformably overlie an Ordovician sequence of pebble conglomerate, greywacke and black shale. Those authors considered that this conglomerate–greywacke–black-shale sequence "resembled facies of the Goldson conglomerate" (now Badger Group, O'Brien, 2003) exposed on the northwest coast of Newfoundland near Twillingate. Paleontological studies (L.M. Cumming, 1963, *cited in* Anderson and Williams, *op. cit.*) indicated that rocks of this pebble conglomerate–greywacke–black-shale unit encountered in Cooper Brook (Figure 3) contained both Late Ordovician and Silurian fauna, and that the rocks therefore represented a sequence transitional between the Ordovician turbidites and shales to the southeast and the Silurian, shallow-marine sandstone and shale of the Botwood Group to the west. This Ordovician–Silurian sequence was therefore considered to represent a 'connecting link' between the Gander Group (to the east) and the Baie D'Espoir Group (to the southwest). Anderson and Williams (*op. cit.*) also noted a contact aureole in sedimentary rocks proximal to the southeastern Mount Peyton granitoid rocks and indicated that the Silurian rocks of the mine area were disrupted by a northeast-trending fault.

Blackwood (1980a, b, 1981a, b, 1982) mapped the eastern margin of the Mount Peyton intrusive suite from north of Glenwood, south to the Beaver Brook area. In the mine area, Blackwood (1981a, b) mapped a fault-bound wedge of fossiliferous (Caradocian; now Sandbian to Early Katian) graphitic black shale and greywacke that was inferred to represent the upper parts of the Davidsville Group as exposed to the north and east (*see* Kennedy and McGonigal, 1972). This unit was mapped as a fault bound sliver enclosed in a thick sequence of fine- to coarse-grained grey sandstone, siltstone, shale and calcareous fossiliferous Silurian rocks of the Botwood Group.

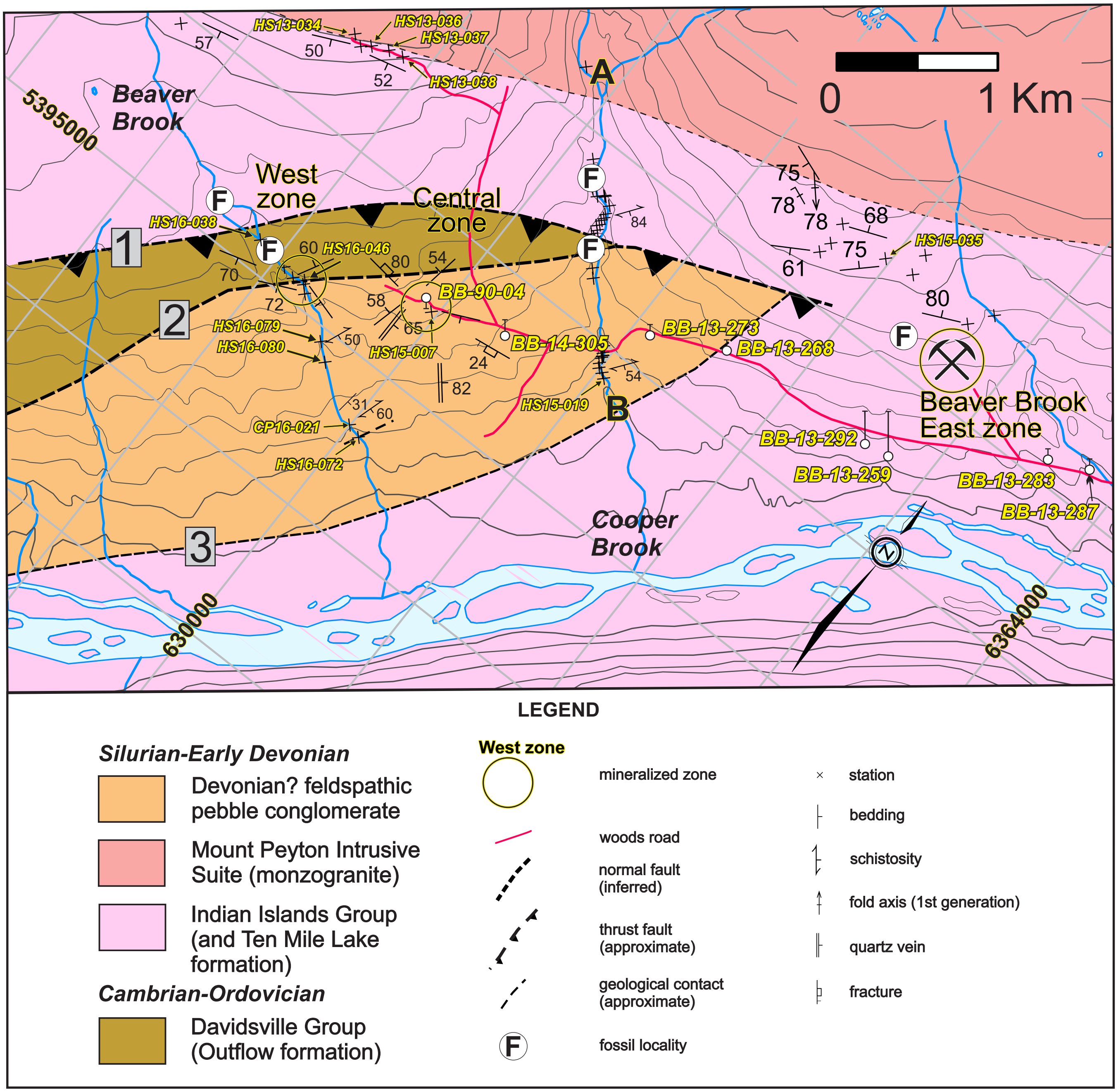

Figure 3. *Simplified geological map of the Beaver Brook Antimony Mine area (http://geoatlas.gov.nl.ca/Default.htm) showing the locations of the West, Central and East zones, as well as other sites discussed in the text.*

Additional work in the mine area followed the discovery of stibnite-bearing boulders in Beaver Brook and includes the initial descriptions of the mineralization at the Central zone (Tallman, 1991; Tallman and Evans, 1994), and the detailed mapping and paleontological investigations of the local host rocks in Cooper, Beaver and Webber brooks (Figure 3; Williams, 1993; Williams and Tallman, 1995). Dickson (1992, 1993) mapped the areas around the south and southeastern parts of the Mount Peyton intrusive suite and extended the package of Silurian rocks exposed in the Beaver Brook area southwestward to near the Great Bend complex (*e.g.*, Donovan *et al.*, 1997). Dickson (*op. cit.*) noted an abundance of massive to thick-bedded, feldspathic sandstone, siltstone and pebble conglomerate exposed in and around the Great Bend complex (Figure 1) and interpreted these as Devonian rocks. Dickson (1996) similarly recognized an abundance of feldspathic greywacke and pebble conglomerate in the central parts of both Cooper and

Beaver brooks and re-interpreted the fault-bound wedge of Ordovician rocks as a tripartite wedge of Ordovician, Silurian and probable Devonian feldspathic conglomerate in fault contact with both Ordovician rocks of the Davidsville, as well as Silurian rocks of the Indian Islands groups (Figure 2). In order to re-align the major lithostratigraphic units of the mine area with the nomenclature proposed by Williams *et al.* (1993), Dickson (1996) also indicated that the Silurian strata near the Beaver Brook Antimony Mine likely comprises part of the Indian Islands Group, rather than Botwood Group. More recent investigations into the setting of the antimony deposit and ore genesis at Beaver Brook comprise the report of Lake and Wilton (2006), and two conference abstracts (Sandmann *et al.*, 2011; Seifert and Sandmann, 2013). Lake and Wilton (2006) outlined and updated mining operations and exploration activity since discovery, described the nature of the mineralization at the three antimony showings, and presented an overview of the host rocks of the mine area including a revised geological map (Figure 4), which is significantly different from that of Dickson (1996). Lake and Wilton (*op. cit.*) further proposed that the rocks exposed in the mine area form two separate thrust panels. Their northwestward-lying nappe (1 on Figure 4) consisted of a tripartite sequence of structurally overturned, broadly northwest-younging Ordovician Davidsville Group rocks comprising Sandbian–Katian black shale, greywacke and Darriwilian siltstone and sandstone, respectively. This nappe was emplaced northwestward over Silurian, northwest-younging, structurally overturned Indian Islands Group rocks. Their southeastward-lying imbricate stack (2 on Figure 4) was interpreted to consist of the same Ordovician lithological units in the same structural repetition and order. The oldest inferred unit in imbricate stack 2, the southeastward-lying Darriwilian siltstone and sandstone, is in fault contact with Indian Islands Group siltstone and sandstones lying farther southeast (Figure 4). Unfortunately, Lake and Wilton (*op. cit.*) did not present a structural analysis to substantiate their hypothesis.

Many of the previous investigations appear to agree that the mine area is underlain by faulted, and likely thrust-imbricated, Ordovician and Silurian rocks. However, the assignations of the stratigraphic units have changed through time and remain problematic. This lithostratigraphic confusion is, in part, because of the poor exposure in the region, but in our opinion, may also be attributed to the lithostratigraphic complexities arising through introduction of the Dog Bay Line and the geotectonic significance of the geological constraints associated with the presence of this major structural feature (Currie, 1993; Williams, 1993; Williams *et al.*, 1993; Pollock *et al.*, 2007). Thus, the overstep sequences of the Badger and Botwood groups are now interpreted to occur only to the northwest, whereas the Davidsville, Hamilton Sound (Currie, 1993) and overstep sequence of the Indian Islands groups occur only southeast of the Dog Bay Line. The current study area and the Beaver Brook Antimony Mine (Figures 2 and 3) occur directly along the proposed southwestern trace of the Dog Bay Line (Currie, 1993; Williams, 1993; Williams *et al.*, 1993; Pollock *et al.*,

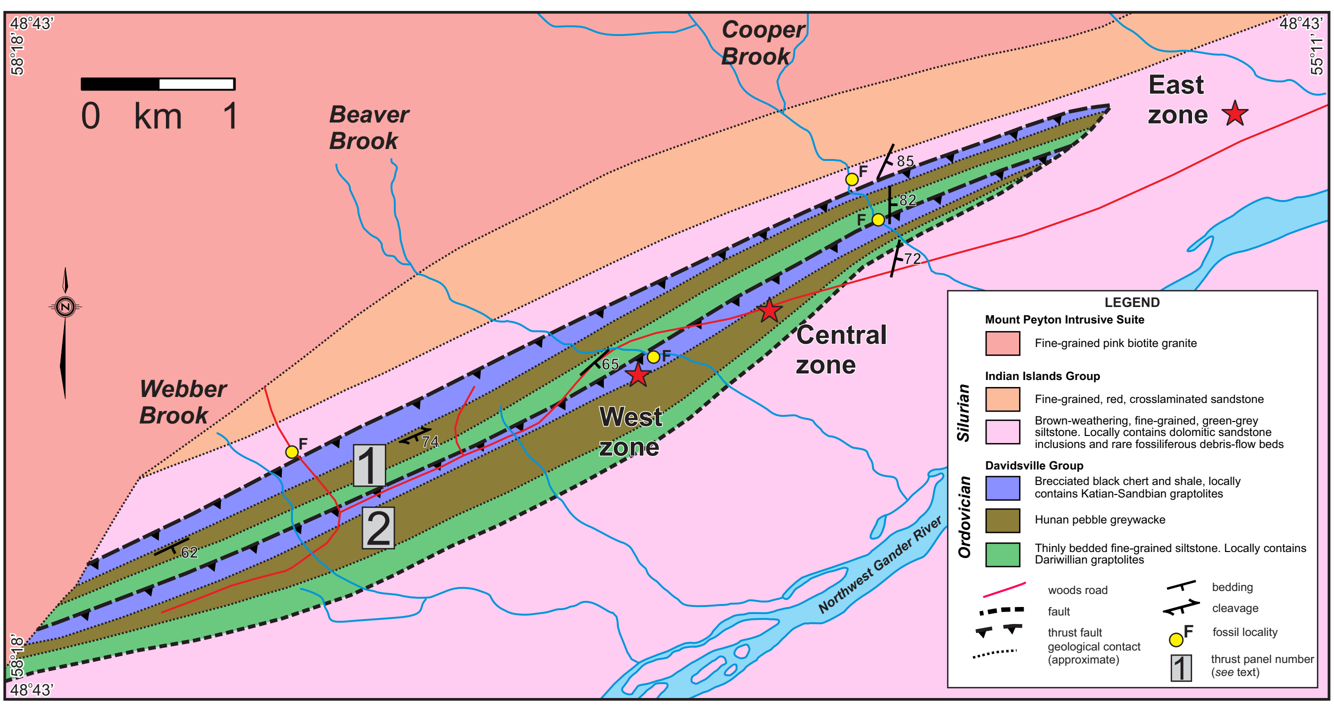

Figure 4. *Geological map of the Beaver Brook Antimony Mine area after Lake and Wilton (2006).*

2007), but the location of this major strike-slip dextral fault in the mine area, and along the eastern margin of the Mount Peyton intrusive suite, is presently unknown.

EXPLORATION HISTORY

In the mine area (Figures 2 and 3), the earliest exploration work was undertaken by the Noranda–Noront Grub Line Syndicate between 1989 and 1995. During that time they discovered three, antimony-mineralized zones occurring along a northeast–southwest (065°) trend. At the time of discovery, these were termed, from southwest–northeast, the Xingchang, Hunan and Szechuan showings (Tallman, 1989a), after the major antimony-producing regions of China. For simplicity, however, the mineralized zones were renamed the West, Central and East zones, respectively (Bourgoin, 1993). Early exploration results of soil sample and ground magnetic and VLF geophysical surveys indicated that the mineralized trend was transected by at least 2, and perhaps 3, east–west-trending, dextral fault zones, which were inferred to offset the stratigraphy by 200 to 500 m (Tallman, 1989a; Tallman and Evans, 1994). The existence of these purported east–west faults has not yet been demonstrated.

Significant antimony mineralization was first discovered at surface and drilled at the Central zone (Figures 3 and 4), but further exploration and drilling at the East zone resulted in the eventual delineation of a resource of 2.2 million tonnes of ore grading 3.99% Sb, at a 1.5% cut off (Morrissy and House, 1998). In all three zones, the ore is interpreted to be hosted in the hanging wall of a ~065°-trending fault zone inferred to represent a regional thrust (Morrissy and House, 1998; House, 1999; Newman, 2012). The Beaver Brook Antimony Mine has changed ownership several times since original discovery in 1989. The early exploration history at Beaver Brook has been further outlined and discussed in detail by Lake and Wilton (2006 and references therein). Below we outline the activity on the mine lease since 2006.

Although Roycefield Resources Ltd. brought the mine into production in 1997 (Morrissy, 1997; Morrissy and House, 1998; House, 1999), it only operated for 8 months because of a precipitous drop in global antimony price (~US$5000/metric ton in 1995 *versus* ~US$1500/metric ton in 1997: Butterman and Carlin, 2004). Canadian Antimony Mine reopened the mine in 2008. In 2009, the Chinese-owned company Hunan Nonferrous Metals (HNC) purchased the operation. At the end of 2009, China Minmetals Corporation, China's biggest metal trader, acquired 51% equity of Hunan Holdings Group (HNG), the state-owned parent of HNC. The Beaver Brook Antimony Mine returned to full production in the summer of 2010 and continued to operate until November 20, 2012, when it went into care and maintenance. Nine employees presently ensure the property is kept in good condition and meets all government requirements. The underground workings are kept dewatered for a smooth restart when economic conditions improve. Table 1 shows the mines production statistics from 2008 to 2012.

Table 1. Table documenting Beaver Brook Antimony Mine production statistics during the five years of operation from 2008 to 2012

	2008	2009	2010	2011	2012	Total
Tonnes Milled DMT	73 710	83 524	137 355	162 598	142 105	599 283
Head Grade %	3.40	4.47	4.23	3.19	2.63	3.5
Concentrate Produced DMT	3492	5595	8945	8061	5814	31 906
Metal Produced DMT	2219	3593	5578	4958	3554	19 902

DMT - dry metric tonnes

Exploration programs were carried out from 2009 to 2015, inclusively. A 70.5-line-km cut grid was established across the property and two induced polarity (IP) surveys (shallow/deep) were completed over the grid. Although the surveys were unsuccessful in outlining mineralized zones, they provided clear evidence for a number of abrupt breaks in zones of anomalous chargeability that corresponded to known graphitic shale horizons (Reeves, 2009). More than 4000 soil samples were collected (Newman, 2012) and a number of new Sb- and Au- in-soil anomalies were identified ~800 m southwest of the West zone. The Au-in-soil anomalies clustered to the south and southwest of the Sb anomalies. A total of 124 diamond-drill holes have been completed since 2008, bringing the mine lease total to 315. Prior to 2013, drilling was focused on down-dip expansion of the East zone, but subsequently (from 2013 to 2015), the focus changed to exploration of the area between the East and Central zones. Nineteen diamond-drill holes have been completed on a new target discovered in 2013, approximately 300 m northeast from the Central zone. A number of these step-out holes (*see* Figure 3) intersected Sb, Au–As and Sb–Au–As mineralized zones. Diamond-drill hole BB-13-259 intercepted 3 m @ 3.79 g/t Au at 372–375 m depth and DDH BB13-287 intercepted 2.1 m @ 3.8 g/t Au at 66.5–68.6 m depth. Similarly, DDH BB13-268 cut 5.5 m @ 2.11 % Sb at 63.5–69 m depth and DDH BB-13-292 cut 8 m of 3.0% Sb at 380.7–388.7 m depth. Of particular note, brecciated and altered greywacke at a depth of 221 m in

DDH BB-14-305 yielded an assay of 7.01% Sb with 6.3 g/t Au over a 5.05 m interval (Figure 3). Two drillholes to the southwest of the West zone provide lithostratigraphic information but did not intersect mineralization.

Based on a Geo Stat International Inc. technical report (Reeves, 2009), the total indicated resources at the East zone deposit, prior to restarting of the mine, was 1 062 600 tonnes @ 5.15% Sb (Reeves, 2009). Based on an internal resource calculation (Beaver Brook Antimony Mine, internal report, 2013) a total of 533 370 tonnes @ 4.17% Sb remains at the East zone. Resources at the Central zone were determined to include 154 570 tonnes of ore at 5.62% Sb (Reeves, 2009); however, this does not include the results from the 2008– 2013 exploration drilling. The current reserves at the East zone are based on a plan to continue mining upward from the bottom of the mine (9660 level), to the 9800 level, and finish with the recovery of the crown pillar at surface (9950 level).

GEOLOGY OF THE MINE AREA

As stated earlier, the lack of exposed bedrock and the widespread presence of thick fluvioglacial deposits are the major stumbling blocks for obtaining a better understanding of the geology of the Beaver Brook Antimony Mine area. The only exposures consist of either northwest–southeast-oriented, partially exposed stream-bed sections, or anthropogenic disturbances of the surficial deposits such as roads, trenches or road materials quarries. A survey of the depth-to-initial-bedrock in 139 of the 315 diamond-drill holes indicates that the fluvioglacial deposits range in thickness from 2.3 to 29.2 m (average depth = 7.7 m), a clear reason why few exploration trenches have succeeded in exposing bedrock. To better constrain the geological and structural setting of the mineralization at Beaver Brook, this project includes construction of a geological database for the region (Figure 2) comprising: 1) ~150 regional outcrops, including multiple structural observations per station; 2) detailed traverses along with a high density of stations and structural measurements along four streams in the region, including the Cooper, Beaver and Webber brooks (Figures 3 and 4) and one on Clarks Brook (13 km to the north northeast, Figure 2); 3) examination of 139 diamond-drill holes and their first bedrock intercepts; 4) a compilation of biostratigraphic constraints from fossiliferous strata; 5) a compilation of radiometric geochronological age constraints and, 6) incorporation of data from pre-existing geological maps of the area.

The bedrock is divided into eight lithologically distinct units, six of which are noted in the Cooper Brook transect (*see* Figure 5). Like Dickson (1996) and Lake and Wilton (2006), the geological units are interpreted to correspond to rocks of the Ordovician Davidsville (Kennedy and McGonigal, 1972; Blackwood, 1981a, b; O'Neill and Blackwood, 1989) and Silurian Indian Islands (Williams *et al.*, 1993; Dickson, 1993, 1996) groups of the eastern Exploits Subzone, as well as granitoid rocks of the Mount Peyton intrusive suite (Blackwood, 1982). The nomenclature of the granitoid rocks follows that of Dickson (1996) with the additions from Dickson and Kerr (2007) and Sandeman *et al.* (2017). A suite of young, mafic dykes that cut both rocks of the Indian Islands Group and the Mount Peyton intrusive suite are also recognized. Below, the difficulty in the correct assignation of the rocks is emphasized in the light of the current nomenclature and geological maps. A preliminary geological map and cross section for a Cooper Brook transect are presented, whereas similar transects for Beaver and Webber brooks and an updated geological map of the area have as yet not been completed.

ORDOVICIAN ROCKS: DAVIDSVILLE GROUP

The oldest rocks of the study area (Unit 1, Figures 5 and 6) consist of dark-green to grey-black, well-cleaved siltstone and less common fine-grained sandstone (Plate 1A, B), which crop out in the middle sections of Cooper Brook (Figures 3 to 6). These rocks are typically strongly cleaved, folded and locally form mullions (Plate 1A, B). The graptolite fauna, *Aulograptus cf. cucullus* and *Undulograptus primus* (Williams and Tallman, 1995), is locally recognized in areas of lower strain rocks (*e.g.*, Figure 5: station HS15-051, 630574E, 5396326N), and indicative of a Darriwilian, Middle Ordovician age (Williams and Tallman, 1995; Bergström *et al.*, 2009), comparable to faunal assemblages described from the Davidsville Group near Glenwood (Williams, 1969; Anderson and Williams, 1970; Blackwood, 1982).

Unit 2 (Figure 5), referred to as the Hunan greywacke (Tallman, 1989a; Tallman and Evans, 1994; Lake and Wilton, 2006), occurs throughout the central part of the mine area and in the middle sections of Cooper Brook (Figures 3 to 6). Greywacke is typically black to dark brown but locally grey, massive and thickly bedded (Plate 1C) containing abundant quartz, plagioclase and common mafic volcanic clasts and pebbles. Other lithic clasts include dark-shale, fine-grained sandstone, siltstone and felsic volcanic clasts. Greywacke is locally interbedded on <1 to 10 m scale with green-grey, brown-grey and black, fine- to medium-grained sandstone, siltstone and fissile black shale. Although greywacke is typically interbedded with siltstone and sandstone, it appears to both structurally overlie, and is structurally overlain by, Unit 1. In the southern part of the large trench that exposed the mineralization at the Central zone (Tallman, 1989a; Tallman and Evans, 1994), the greywacke is locally mineralized and has typically narrow (≤15 cm) bedding parallel northeast-, north- and east-trending, quartz ± stibnite–carbonate veins (Plate 1D). Tallman (1989, 1990) reported that the main stibnite mineralization at the Central zone consisted of a ≤1.6-m-wide zone of quartz–stibnite veins and vein breccia on the north side of the large trench (now mainly water filled: *see* Plate 13 in Squires, 2005). Channel samples yielded up to 30.4% Sb over 1.6 m. Intersections in drillcore (*e.g.*, Figure 3: DDH BH90-04_41.8-49.03 m) yielded similar quartz–stibnite veins and vein breccias yielding up to 8.99% Sb over 7.23 m (Tallman, 1990). In a number of DDH that penetrated the mineralized Central zone, the greywacke structurally overlies grey siltstone and black shale.

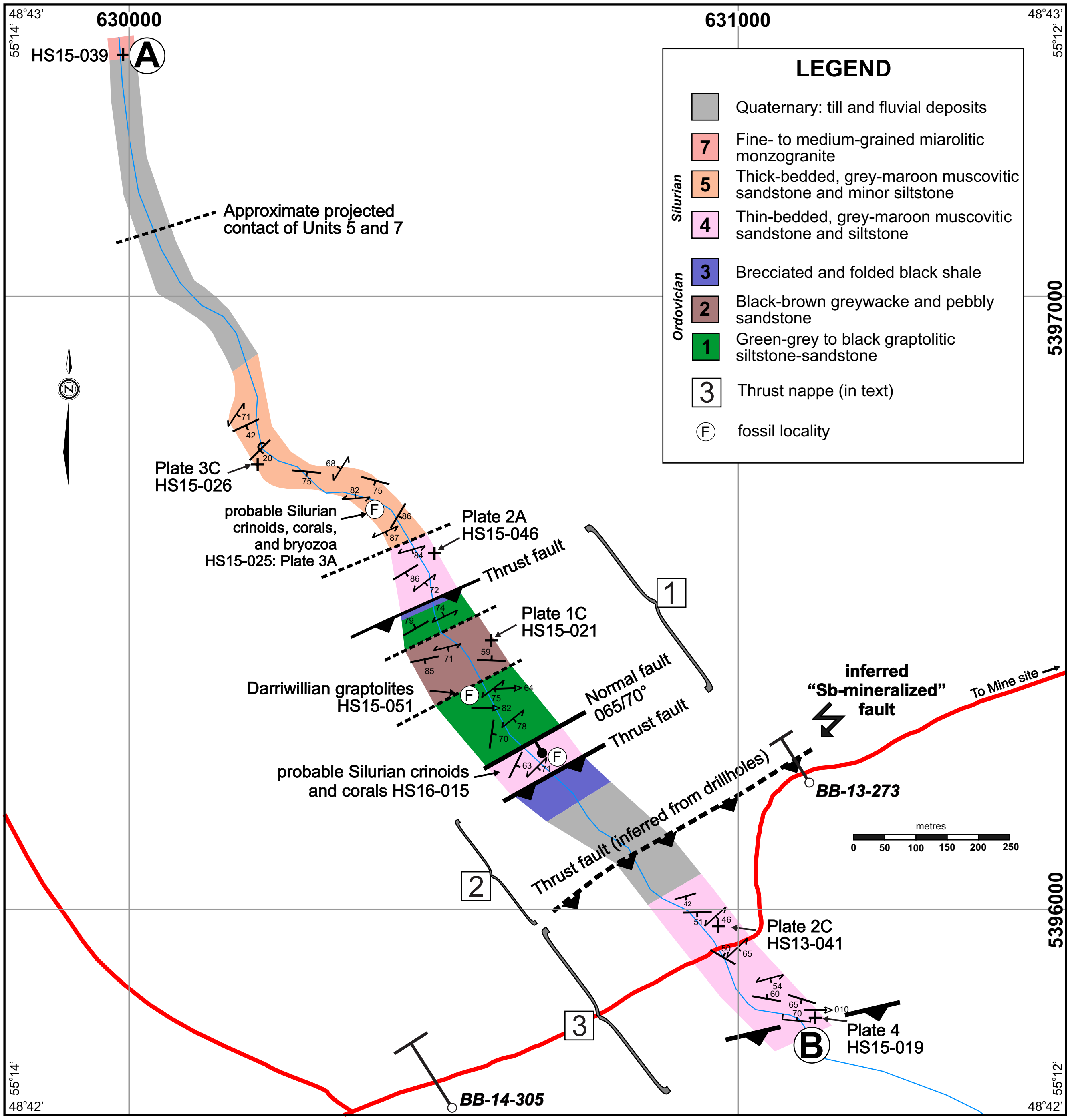

Figure 5. *Simplified geological map of Cooper Brook. The locations of thrust and normal faults, significant localities mentioned in text including biostratigraphic control horizons and noteworthy rock types and structures are also noted. Modified after Blackwood (1981b); Tallman (1991); Tallman and Evans (1994); Dickson (1993, 1996) and Lake and Wilton (2006).*

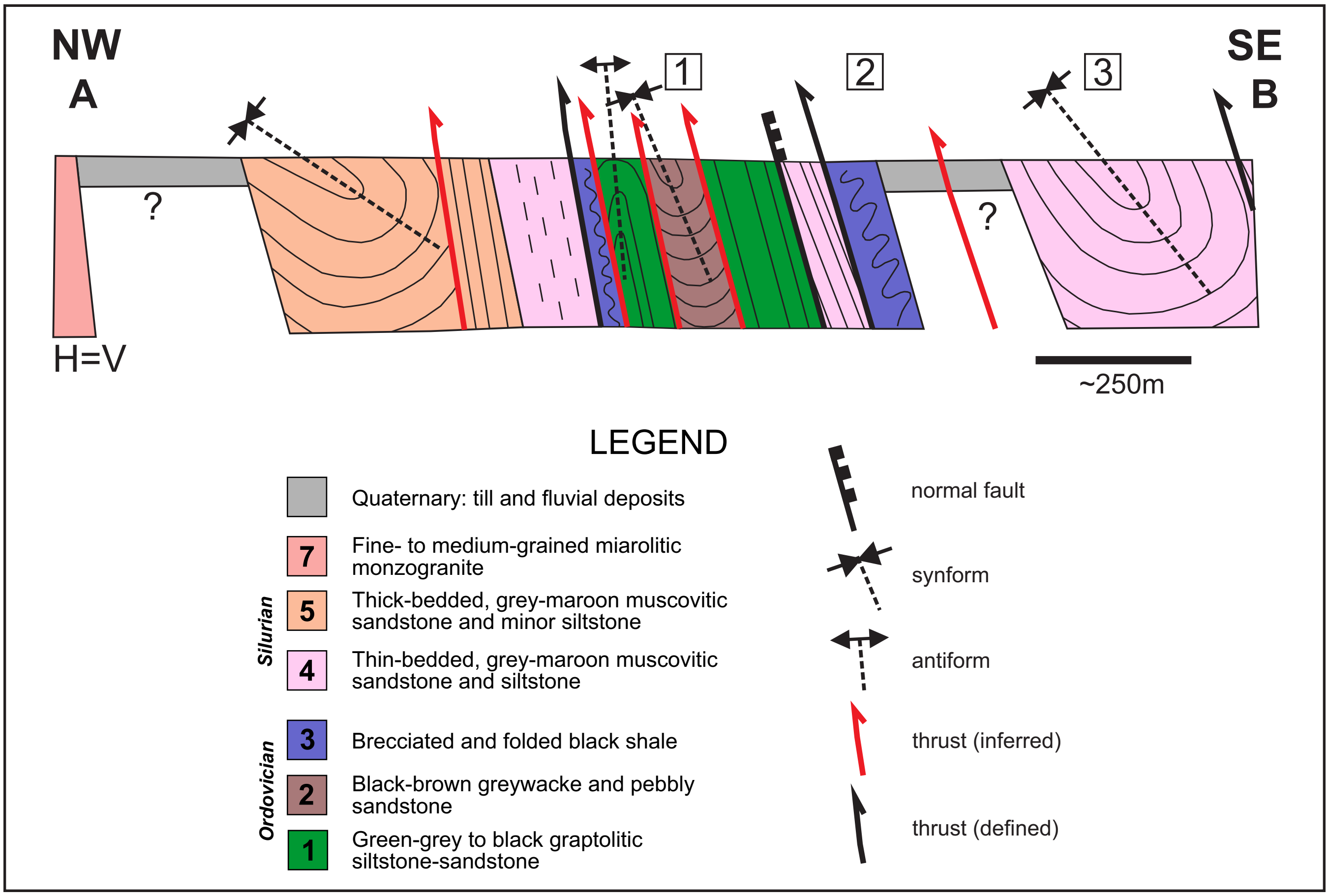

Figure 6. *Schematic geological cross-section through Cooper Brook.*

Structurally below the wacke–siltstone–sandstone sequence is a relatively narrow (≤50 m), brecciated, mullioned and chaotically folded sequence of graphitic black shale (Unit 3; Plate 1E) that is exposed in two localities in Cooper Brook (Figures 5 and 6). In Beaver Brook, similar, strongly cleaved, graphitic black shale was reported by Blackwood (1982) and confirmed by Williams and Tallman (1995) to contain the graptolite assemblage *Pseudoclimacograptus scharenbergi*, *Climacograptus? brevis* and *Corynoides calicularis* indicating a Middle Ordovician, Sandbian to early Katian age (Bergström *et al.*, 2009). The Ordovician sequences of the area either represent a telescoped, 30 M.y. depositional interval (*i.e.*, Darriwilian to Katian) or, alternatively, two temporally and lithostratigraphically distinct, Ordovician, sandstone–siltstone ± shale ± greywacke sequences. The graptolitic black shale occurs as the basal unit of a number of the mapped thrust panels and is a critical, easily recognized marker horizon in diamond-drill core (Plate 1F). All of these rock types (Units 1 to 3) are inferred to collectively comprise the Outflow formation of the Davidsville Group (O'Neill and Blackwood, 1989).

SILURIAN SEDIMENTARY ROCKS: INDIAN ISLANDS GROUP AND TEN MILE LAKE FORMATION

All rocks lying to the west of the continuously exposed, north-northeast–south-southwest-trending belt of Ordovician rocks of the Davidsville Group, and east of the Mount Peyton intrusive suite (Figure 2) are inferred (*see* Dickson, 1996; Dickson *et al.*, 2007; Barbour and Churchill, 2004; Lake and Wilton, 2006; O'Reilly *et al.*, 2010) to comprise part of the Silurian Indian Islands Group (Williams *et al.*, 1993) or Ten Mile Lake formation (Currie, 1993; Williams *et al.*, 1993; Dickson, 1996, 2006; Dickson *et al.*, 2007). A diagnostic feature of both of these units is common detrital muscovite in the sandy beds. Moreover, in the mine area, and particularly to the west-northwest of the mine site, these units weather orange to tan, commonly have a thick-weathering rind interpreted to be related to their carbonate-rich composition.

The most extensive unit in the mine area (Unit 4, Figure 5) typically consists of 2–20-cm-thick interbedded, medium-

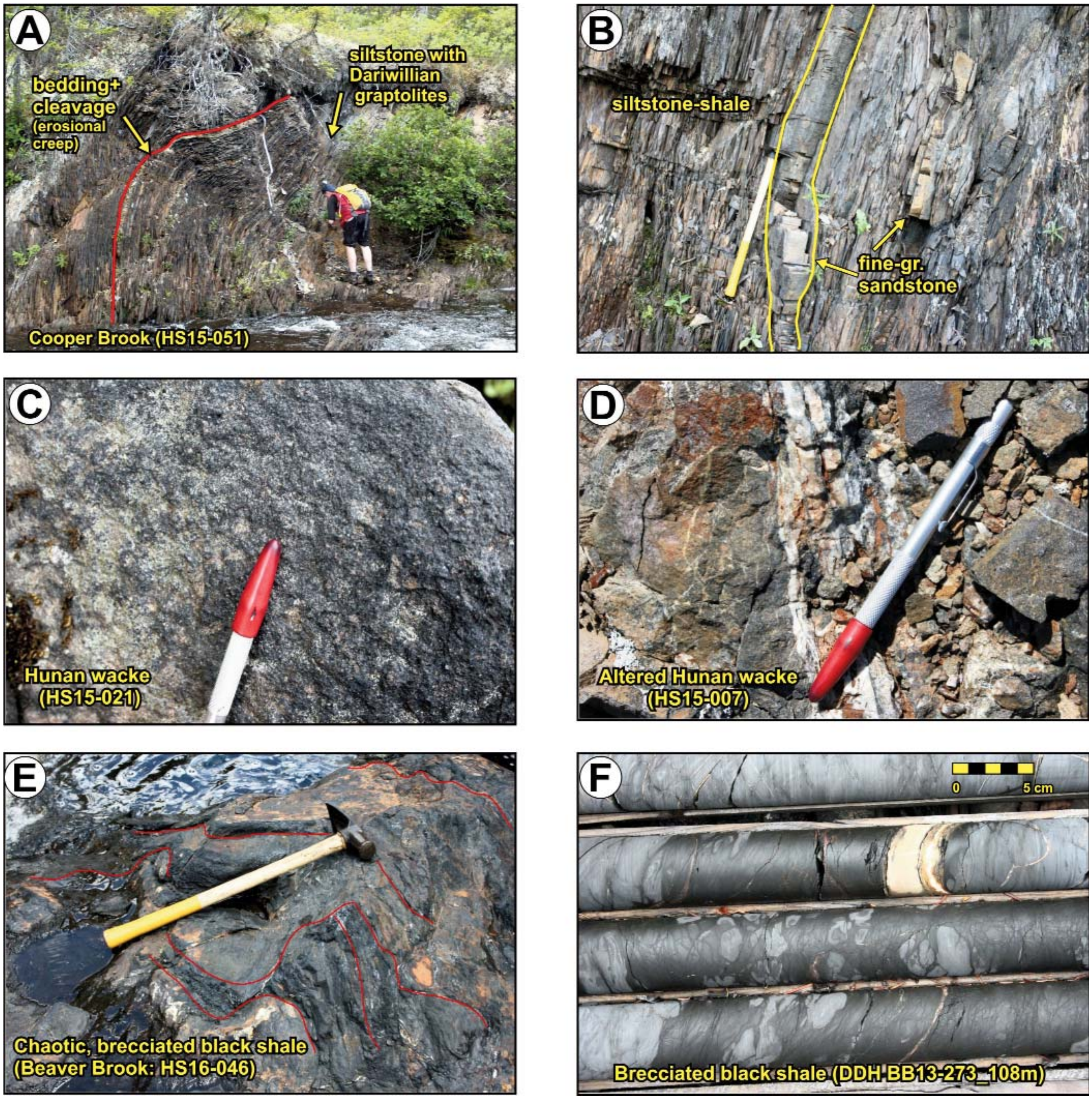

Plate 1. *Photos of representative rock types inferred to comprise the Davidsville Group in the mine area. A) Graptolitic, folded and cleaved, grey–black siltstone and sandstone in Cooper Brook viewed looking southwest (Figure 3: station HS15-051); B) Close-up of A, pen is 15 cm in length; C) Massive, brown-black pebble greywacke exposed in Cooper Brook (Figure 5: station HS15-021). Pen magnet is 16 cm in length; D) Locally quartz-veined, sericitized and silicified pebble wacke exposed in the main trench at the Central zone (Figure 3: station HS15-007). Pen magnet is 16 cm in length; E) Brecciated and chaotically folded graphitic black shale exposed in Beaver Brook (Figure 3: station HS16-046). Red lines highlight anastomosing cleavage. Geotul is 73 cm in length; F) Brecciated and chaotically folded graphitic black shale noted in diamond-drill core (Figures 3 and 5: DDH BB13-273_108m).*

grey to locally green and maroon, siltstone and shale and fine-grained muscovitic sandstone in varying proportions (Plate 2A–C). A characteristic feature of Unit 4 in the mine area is the occurrence of discontinuous, bedding-parallel, orange dolomitic sandstone beds that locally either pinch-and-swell, abruptly terminate, or form stratiform lenses and nodules (Plate 2A, B). These likely represent *in-situ* diagenetic replacement deposits of primary features. Unit 4 is inferred to correlate with the Charles Cove formation of the Indian Islands Group, exposed along the Gander Bay coast (Williams *et al.*, 1993; Dickson, 2006; Boyce and Dickson, 2006; Dickson *et al.*, 2007). The siltstone–shale layers in Unit 4 are typically well cleaved and exhibit consistent bedding-cleavage intersections that indicate the sequence is folded and inclined to the northwest (Plate 2C). Diamond-drill holes on the Beaver Brook Antimony Mine lease have intersected at least fifteen examples of thin, shelly fossil-bearing, calcareous debris flows in interbedded sandstone and siltstone of the Charles Cove formation that also commonly exhibits soft-sediment deformation features (Plate 2D).

In the mine area, Unit 5 (Figure 5) is only exposed along the eastern margin of the Mount Peyton intrusive suite in the upper sections of Cooper Brook, and near the Beaver Brook Antimony Mine tailings ponds. It typically consists of massive, weakly cleaved, medium-grey, fine- to medium-grained muscovitic sandstone having ≥20-cm-thick beds having thin (≤5 cm) and less common siltstone beds. Locally, these rocks contain <0.5-m-thick calcareous sandstone debris-flow deposits (Figure 5, Plate 3A, station HS15-025) containing Wenlock to earliest Ludfordian fossils (Lake and Wilton, 2006; Boyce and Dickson, 2006). Unit 5 locally contains

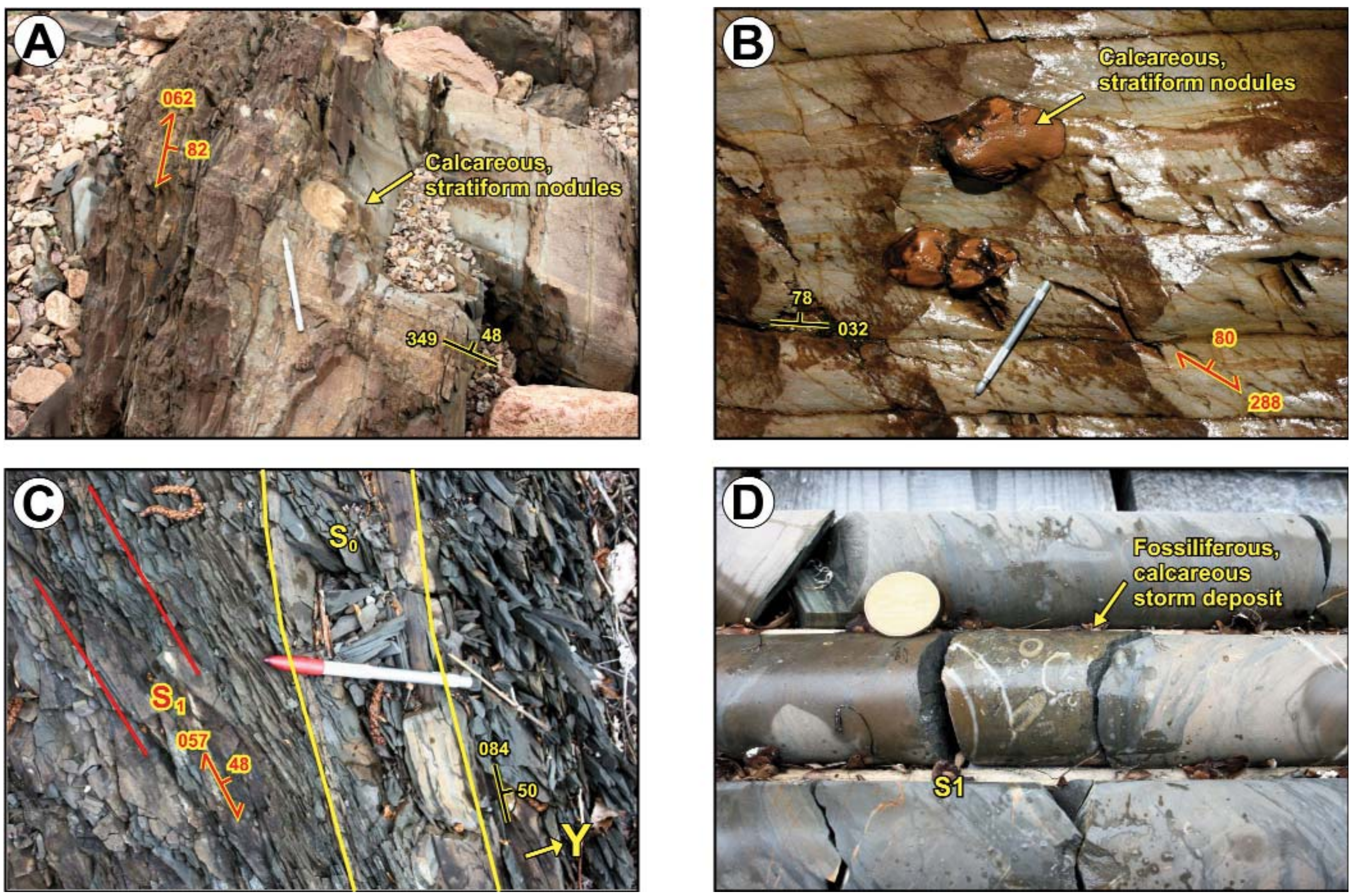

Plate 2. *Photos of representative features of rocks inferred to comprise the Indian Islands Group (Charles Cove formation). A) 2- to 15-cm-thick beds of muscovitic fine-grained grey sandstone and siltstone with interbedded calcareous stratiform sandstone lenses in Red Rocks Brook (Figure 2: station HS13-046; UTM's – 642373E, 5410004N). Note cleavage is perpendicular to bedding indicating the hinge zone of an F_1 fold. Pen magnet is 16 cm in length; B) Similar to A, but from Clarks Brook (Figure 12: station HS16-137: UTM's – 641180E, 5406690N). Pen magnet is 16 cm in length; C) Bedding cleavage relationships in Indians Islands Group, Unit 4 immediately above the bridge over Cooper Brook (Figure 5: HS13-041; UTM's – 630930E, 5395987N); D) Drillcore intercept of a 50-cm-thick, fossiliferous calcareous sandstone that occurs as a thin debris flow in cm-scale interbedded fine-grained sandstone and siltstone of the Charles Cove formation (Figure 3: DDH BB-13-283_120.35 m). The dollar coin is 26 mm in diameter.*

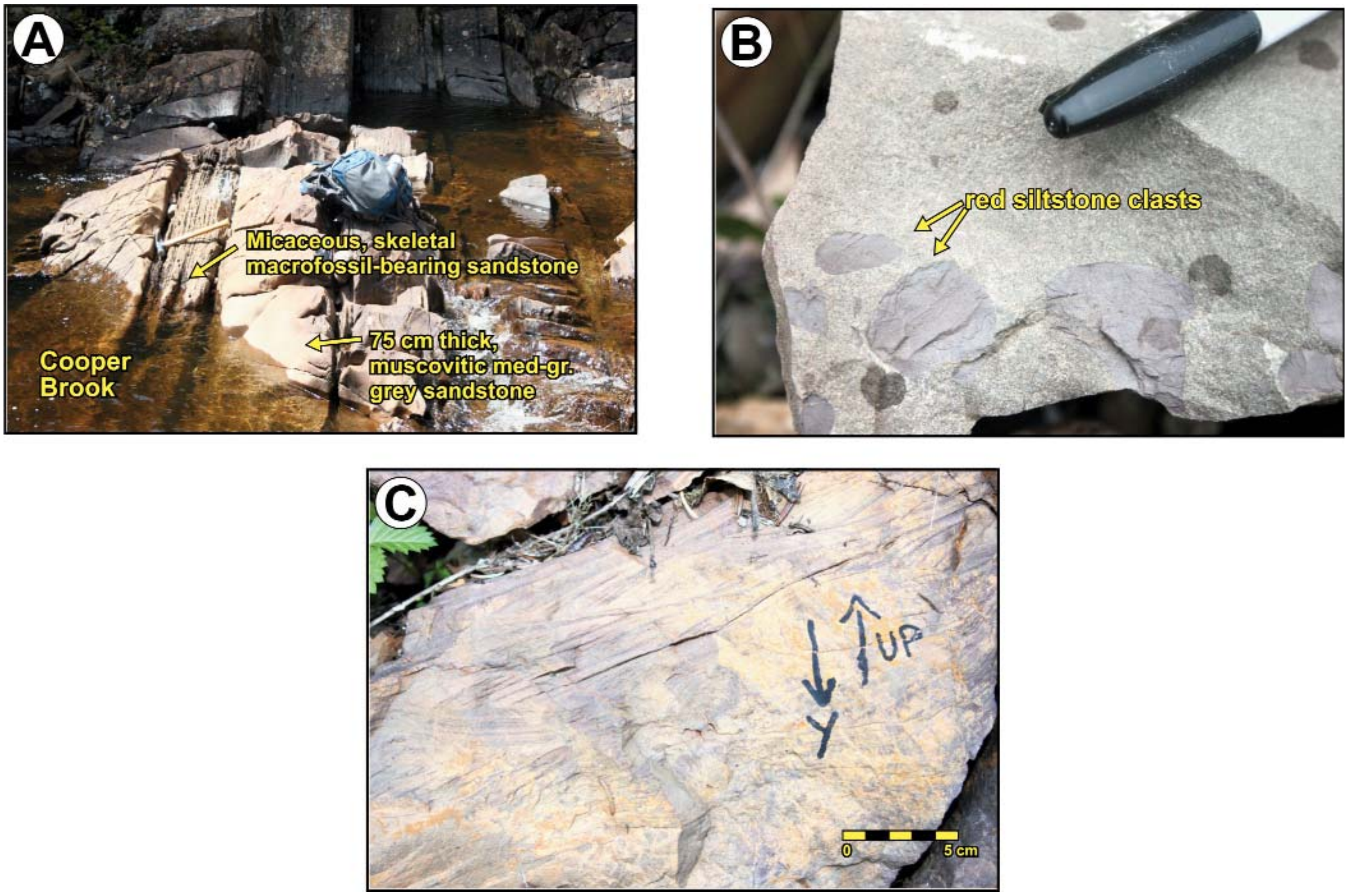

Plate 3. *Photographs of representative features of rocks that are inferred to comprise the Ten Mile Lake formation in the mine area. A) 10-cm- to 1-m-thick beds of muscovitic fine-grained grey sandstone and siltstone interbedded with calcareous stratiform sandstone horizons in Cooper Brook (Figure 5: HS15-025; UTM's – 630430E, 5396640N). Geotul is 58 cm in length; B) Fine-grained maroon to tan muscovitic sandstone with subrounded red-maroon siltstone clasts (Figure 3: station HS15-035; UTM's – 631968E, 5397499N). Marker top is 5 cm in length; C) Section view looking northwest at overturned trough crossbedding in medium-grained maroon to tan muscovitic sandstone in Cooper Brook (Figure 5: station HS15-026; UTM's – 630201E, 5396779N).*

beds having abundant, angular red siltstone clasts (Figure 4: Plate 3B, station HS15-035). These clasts strongly resemble maroon siltstone of Unit 4 that is commonly observed in drillcore and exposed in Beaver and Cooper brooks. Trough crossbedding is relatively common and locally indicates both right-way-up and overturned stratigraphy (Figure 4: Plate 3C, station HS15-027). Rocks of Unit 5 are less common than those of Unit 4, appear to be terrestrial to shallow marine, and are inferred to correlate with the reddish, dominantly terrestrial muscovitic sandstone of the Ten Mile Lake formation exposed to the north along the Dog Bay Line (Currie, 1993; Williams *et al.*, 1993).

Cooper Brook Transect

Figure 5 represents a simplified, new geological interpretation (*this study*) of a transect along Cooper Brook, and includes significant localities mentioned in the text. Figure 6 is a schematic geological cross-section derived from Figure 5. In the northwest (A), fine- to medium-grained, miarolitic and granophyric monzogranite (Unit 7: Figures 5 and 6) is exposed immediately southwest of Cooper Brook. This monzogranite is characterized by spaced (~20 cm) northeast-trending and steeply to moderately southeast-dipping fractures. Approximately 600 m downstream from station HS15-039 (Figure 5), the first exposures consist of massive, weakly cleaved, medium-grey, fine- to medium-grained muscovitic sandstone, less-common siltstone beds and calcareous shelly fossil debris flows of Unit 5 (*e.g.*, Figure 5: Plate 3A, station HS15-025). These rocks are tightly folded, as indicated by overturned bedding and variable bedding orientations, and extend ~350 m to the southeast of the Quaternary-covered interval. Unit 5 is in relatively abrupt contact, along a steeply dipping surface, with

~100 m of moderately cleaved and interbedded, medium-grey to locally green, siltstone and fine-grained muscovitic sandstone in varying proportions (*i.e.*, Unit 4: *e.g.*, Plate 2A–C). These rocks are structurally overlain by a ~70° south-dipping, 20-m-thick panel of intensely sheared, brecciated and lineated black graphitic shale of Unit 3 (Figure 5). The incompetence and structural complexity of the black shale suggests that this unit has preferentially focussed structural slip and represents a significant thrust surface (base of thrust panel 1: Figures 5 and 6). Structurally above the black shale is a 40-m-thick panel of strongly cleaved grey to black siltstone and sandstone (Unit 1) overlain by a 100-m-thick sequence of dominantly pebble greywacke and minor sandstone of Unit 2 (*e.g.*, Figure 5: Plate 1C, station HS15-021). The greywacke is overlain to the southeast by a second, ~125-m-thick panel of strongly cleaved grey to black siltstone and sandstone that contains Darriwilian graptolites (*e.g.*, Figure 5: Plate 1A, station HS15-051). The graptolitic shale is bound to the southeast by a steeply southeast-dipping normal fault that places a ~60-m-thick panel of locally crinoid-bearing, medium-grey to locally green, siltstone and fine-grained muscovitic sandstone of Unit 4, northwestward over the graptolite-bearing Ordovician sequence. This package of black shale, grey-black siltstone, sandstone and greywacke as well as the 60-m-thick slice of Unit 4, is herein interpreted to constitute thrust panel 1 (Figures 5 and 6). After a 10 m covered interval, the next rock-type exposed to the southeast is a ~60-m-thick sequence of chaotically folded and brecciated black shale of Unit 3. Although the contact is not exposed, the black shale horizon is interpreted to represent the base of a second prominent thrust panel (thrust panel 2, Figures 5 and 6). The next ~225 m downstream is covered by coarse fluvial gravels with no exposure. Numerous diamond-drill holes collared near the adjacent woods road (*e.g.*, DDH BB-13-273; Figures 3 and 5) and oriented along an azimuth of 340°, initially intersected rocks of Unit 4, but consistently intersected a third brecciated black shale horizon at depth. This third black shale horizon is interpreted as a thrust fault and is projected to surface in Figure 5. Like the other two brecciated black shale horizons, the base of the third brecciated black shale horizon is interpreted to mark a prominent regional thrust fault. The remaining downstream exposures on Cooper Brook consist of ~300 m of moderately cleaved, southeast-dipping and tightly to openly folded, interbedded, medium-grey to locally green and maroon, siltstone and fine-grained muscovitic sandstone of Unit 4, which likely forms most of the third thrust panel (thrust panel 3: Figures 5 and 6). At the extreme southeast of the transect (near B in Figure 5), the upper limb of a closed, gently northeast-plunging, northwest verging synform with shale and sandstone of Unit 4 is truncated by a northwest-directed thrust fault (Figure 5; Plate 4). This last exposure at station HS15-019 (Figure 5) indicates that intraformational thrusting may be more prominent in the area than presently recognized.

Plate 4. *A closed, >10 m wavelength upright to weakly northwest-vergent F_1 syncline of grey sandstone and siltstone of the Indian Islands Group in Cooper Brook below the road bridge (Figure 5: station HS15-019). Yellow lines trace bedding. Note that the southeastern fold limb is truncated by a thrust.*

Beaver Brook Transect

Mapping and interpretation of the units in Beaver Brook are more difficult, owing to an apparently more rapid and progressive change in rock type, greater variations in lithofacies and bed thicknesses and, the resultant inherent problems with assigning lithostratigraphic names. Nevertheless, the approximate traces of two thrust faults were confirmed; however, the trace of a third indicated, southeastward-lying fault (*e.g.*, Figures 3 and 4), is in an area of no exposure. A different thrust fault was noted to transect rocks near the south easternmost exposures in Beaver Brook (Figure 3, station HS16-072), where strongly cleaved, grey-green sandstone and siltstone (inferred Davidsville Unit 1) are emplaced north westwards over moderately cleaved grey calcareous sandstone and siltstone inferred to represent rocks of the Indian Islands Group (inferred Unit 4).

The westernmost outcrop exposed in Beaver Brook consists of thick-bedded sandstone to pebbly sandstone that locally appears to contain shelly fossil debris, and is interpreted to be part of Unit 5, the Ten Mile Lake formation. After a covered interval of ~30 m, the next exposures consist of a ~500-m-thick sequence consisting of strongly cleaved, fine-grained grey-black shale and buff, fine-grained sandstone containing grey-black shale clasts (Plate 5A). These rocks are locally interbedded with both right-way-up, and overturned, graded greywacke beds (Plate 5B). Brecciated, strongly cleaved and chaotically folded black

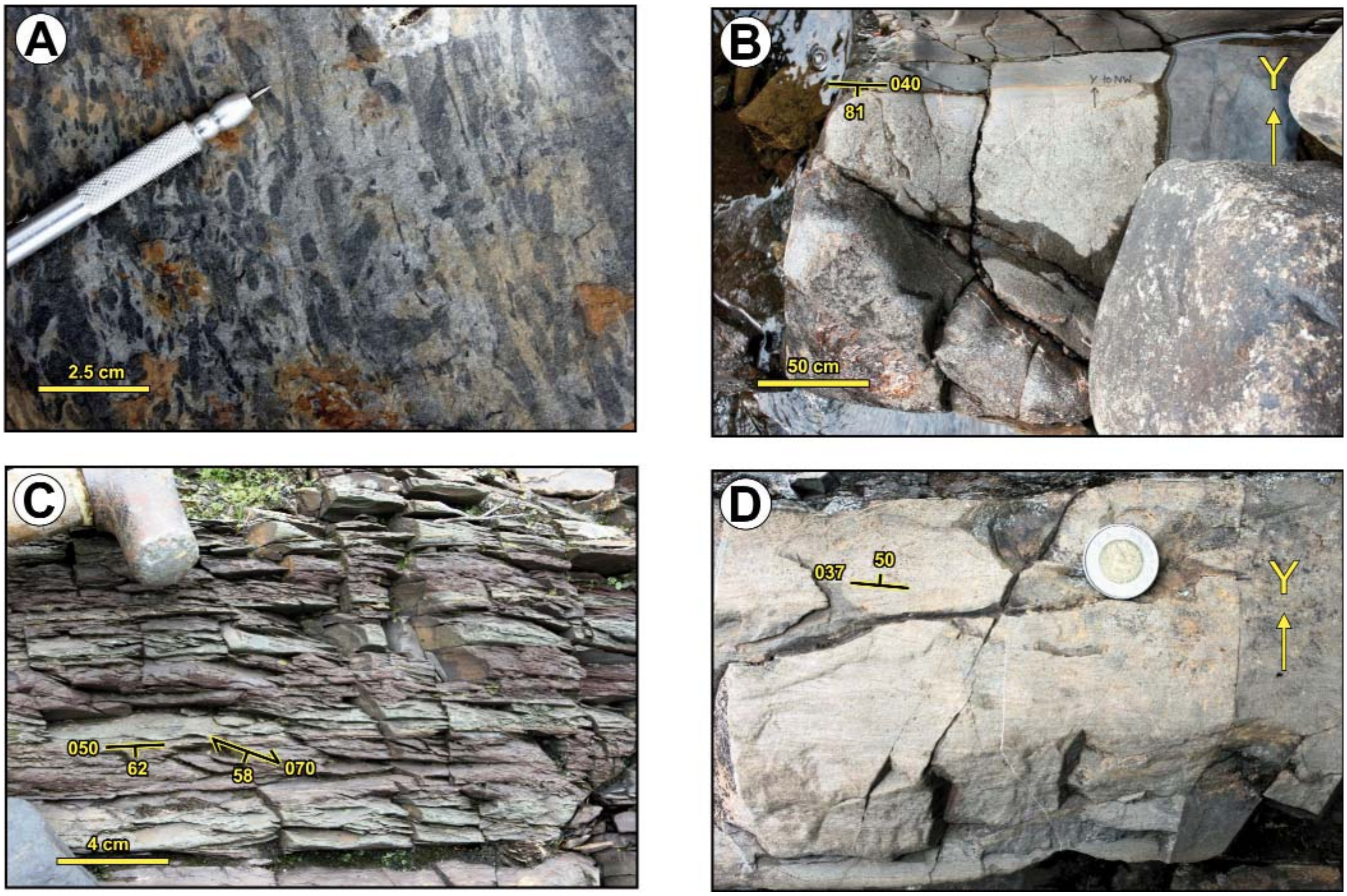

Plate 5. *Photographs of representative units exposed along Beaver Brook. A) Relatively massive, fine-grained grey sandstone having abundant black siltstone rip-up clasts in the upper section of Beaver Brook (station HS16-034: 15 m west of HS16-038 on Figure 3); B) Overturned graded bedding in pebble to sandy greywacke interbedded with grey–black siltstone (Figure 3: station HS16-038); C) A 2-cm-scale interbedded maroon and medium-grey siltstone exposed in the middle section of the brook (Figure 3: station HS16-079); D) A 15-cm-thick, crossbedded fine-grained sandstone (Figure 3: station HS16-080).*

graphitic shale occurs, locally, throughout, and in particular, near station HS16-046 (Figure 3), where it forms the structurally highest unit in thrust panel 1. Thus, these rocks (Units 1 to 3) collectively comprise the stratigraphy lying between the thrust faults labelled 1 and 2 (Figure 3).

Between faults 2 and 3 (Figure 3), and including what was interpreted by Dickson (1996) as Devonian rocks, the sedimentary units comprise a folded, variably cleaved sequence of alternating thin- and thick-bedded, medium-grey sandstone and siltstone, and maroon and green-grey sandstone, siltstone and pebbly sandstone (Plate 5C) locally with clear younging indicators (Plate 5D). These units form the bulk of what was interpreted by Dickson (1993, 1996) as a poorly bedded Devonian(?) sandstone–conglomerate sequence, but interpreted by Lake and Wilton (2006) as comprising Ordovician rocks of their thrust nappe #2 (Figure 4). The rocks lying east of thrust fault 2 are herein interpreted to be lithofacies representatives of the Charles Cove formation of the Indian Islands Group (after Currie, 1993; Williams *et al.*, 1993). Both Beaver and Webber brooks will be revisited during future field work.

Intrusive Rocks

Granitoid rocks of the Mount Peyton intrusive suite (Anderson and Williams, 1970; Strong, 1979; Blackwood, 1982; Strong and Dupuy, 1982; Dickson, 1992; 1996) dominate in the west of the map area (Figure 2). There, the intrusive suite consists of two main rock types. The oldest, Unit 6 (not shown on Figure 5), outcrops infrequently along the eastern margin of the Mount Peyton intrusive suite and consists of fine- to, locally, medium-grained, ilmenite–magnetite–hornblende ± biotite gabbro grading to diorite (Figure 2: Plate 6A, station HS13-044). The second rock type, Unit 7, consists of fine- to medium-grained and typically miarolitic, magnetite–ilmenite–biotite ± hornblende granophyric-textured monzogranite (Plate 6B).

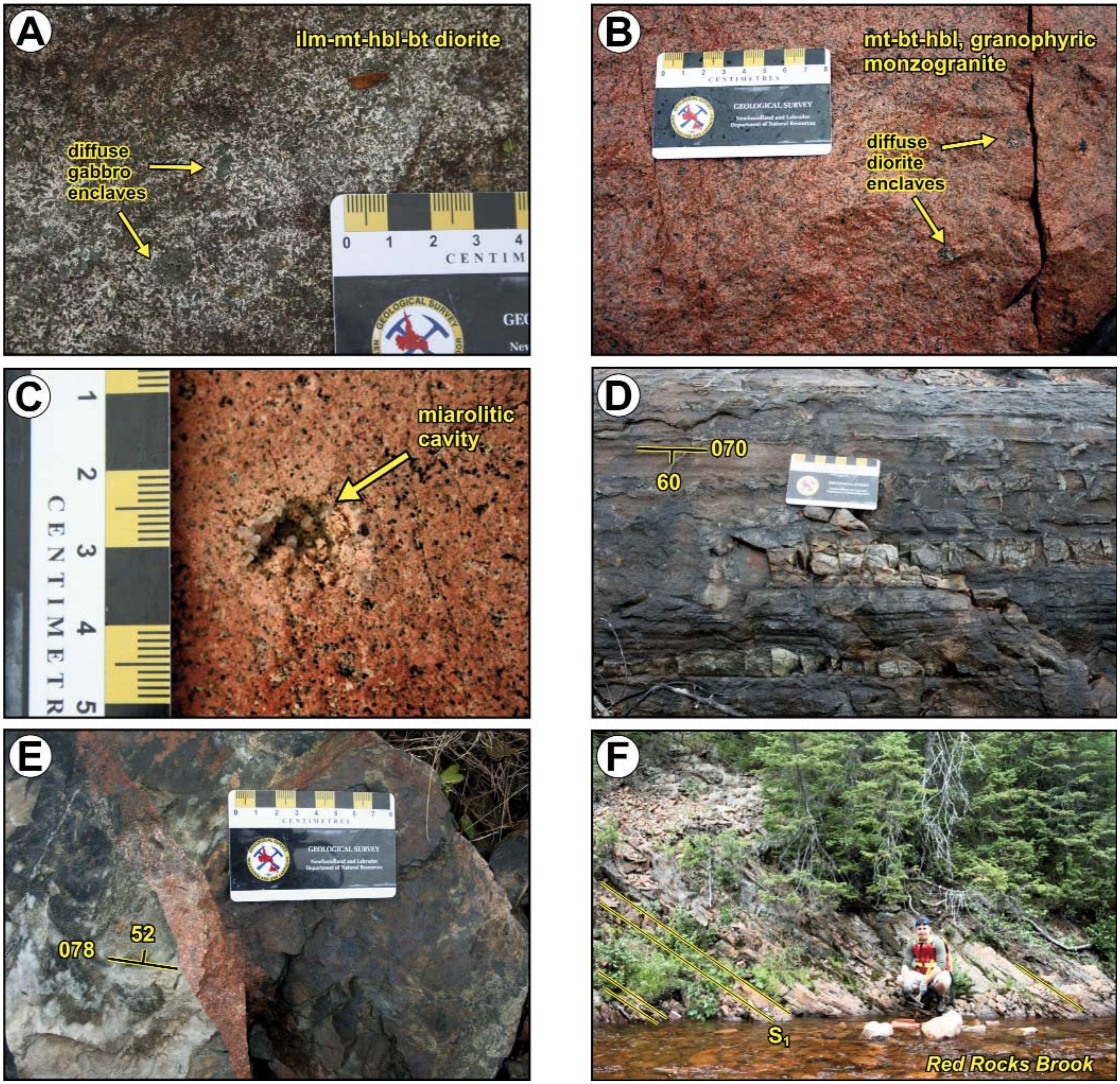

Plate 6. *Photographs of representative features of intrusive rocks and contact relationships along the eastern margin of the Mount Peyton intrusive suite. A) Medium-grained ilmenite–magnetite–biotite–hornblende diorite with diffuse gabbro enclaves exposed ~8 km north of the mine site (Figure 2: station HS13-044: UTM's – 637663E, 5402522N); B) Fine- to medium-grained magnetite–biotite–hornblende monzogranite with diffuse diorite enclaves exposed in the new road quarry northwest of the mine site (Figure 3: HS13-034; UTM's 628517E, 5396555N); C) Centimetre-scale miarolitic cavity in fine- to medium-grained monzogranite exposed southwest of the mine site (Figure 3: station HS13-037; UTM's – 628745E, 5396604N); D) Dark-grey to black, 2- to 15-cm-thick-bedded fine-grained sandstone and siltstone within a few metres of the contact with the monzogranite (Figure 3: station HS13-036; UTM's – 628643E, 5396559N); E) A 3-cm-wide dyke of fine-grained monzogranite cuts southeast-dipping dark-grey to black, fine-grained sandstone and siltstone (Figure 3: station HS13-037; UTM's – 628745E, 5396604N). It is not clear from field observations to which lithostratigraphic unit these hornfelsed rocks belong; F) Pervasive, spaced fracture S_1 cleavage (~20 cm spacing) developed in the Mount Peyton granite immediately west of the contact with the Indian Islands Group in Red Rocks Brook (Figure 2: station HS16-128: UTM's – 642027E, 5410106N). Photograph looking north. The cleavage has a mean orientation of 035/60°.*

Smaller stocks of medium-grained biotite granodiorite occur (Strong, 1979; Strong and Dupuy, 1982; Dickson, 1996), but were not noted in the present study. The monzogranite cuts the gabbro–diorite as net veins (*see* Dickson *et al.*, 2007; Sandeman *et al.*, 2017) and near the mine area, monzogranite locally contains abundant, dispersed and diffuse enclaves of fine-grained diorite (Plate 6B). The diffuse character and abundant acicular apatite grains in the diorite enclaves, suggest hybridization between the two magmas (Wylie *et al.*, 1962; Perugrini and Poli, 2012). The intrusive rocks in the immediate mine area are exclusively fine- to medium-grained miarolitic monzogranite (Plate 6C), locally with diorite enclaves, and commonly containing numerous, variously spaced, manganese-coated fractures, and widespread orange–yellow siderite–limonite staining.

The contact between the Mount Peyton intrusive suite and the surrounding country rocks is rarely exposed and has been variably interpreted as being faulted (Barbour and Churchill, 2004; Squires, 2005), and intrusive (Dickson, 1993, 1996; Barbour and Churchill, 2004; Lake and Wilton, 2006). Examination of a number of exposures proximal to the contact indicate that both of these observations are likely correct, depending upon the location along the eastern margin of the Mount Peyton intrusive suite (Figure 2). A new road-materials quarry and its access road, 4 km west of the Beaver Brook Antimony Mine (Figure 3: station HS13-037), expose the contact between miarolitic monzogranite and a sequence of cm- to dm-thick beds of grey-weathering, glassy black, hornfelsed siltstone and fine-grained sandstone (Plate 6D) lacking a regional foliation. Narrow (≤20 cm), broadly east-trending veins and dykes of massive, fine- to medium-grained biotite monzogranite (Plate 6E) cut the tilted (and folded?) sedimentary rocks that have bedding trending 065/55°. Younging directions could not be determined.

In Red Rocks Brook, approximately 16 km to the north-northeast of the Beaver Brook Mine, (Figure 2), 5- to 10-cm-thick beds of interbedded, grey, locally calcareous siltstone and sandstone of the Indian Islands Group are in inferred fault-contact with medium-grained, weakly sericite-altered biotite–monzogranite. The contact zone is characterized by an approximately 10-m-wide covered interval, but the monzogranite adjacent to the contact is characterized by a spaced (10–20 cm) fracture cleavage oriented 020/55° (Plate 6F). Such intrusive margin-parallel fracture cleavage has been noted at a number of localities, but an unambiguous faulted contact has not yet been observed.

Gabbro dykes and/or sills (Unit 8: not on geological map) cut a number of rock types in the wider mine area, including monzogranite of the Mount Peyton intrusive suite and also rocks observed in drillcore at the Beaver Brook Mine. Gabbro dykes and sills are also described from a number of examples of auriferous mineralized zones along the Dog Bay Line including the Road Breccia showing (Figure 2: Squires, 2005; McNicoll *et al.*, 2006), Big Pond–Blue Peter prospect (Evans, 1996) and, the Titan, Flirt, Corvette and Goldstash prospects farther north near the Gander Bay coast (Churchill and Evans, 1992; Churchill *et al.*, 1993; Squires, 2005; McNicoll *et al.*, 2006). A mafic dyke that cuts sandstone and siltstone of the Indian Islands Group in drillcore at Beaver Brook Antimony Mine (Figure 3: DDH BB13-292_434.5 m), a mafic dyke that cuts monzogranite of the Mount Peyton intrusive suite (Figure 2: station HS16-21B) and, a mafic dyke that cuts Unit 4 of the Indian Islands Group (Figure 12: station CP16-080B) were petrographically examined and analyzed for their lithogeochemical compositions. Two of the three dykes are olivine + clinopyroxene porphyritic, whereas the third is fine grained having extensively altered primary phases. All three samples, however, have bulk-rock compositions of alkaline lamprophyres and, are interpreted to likely be associated with either the Dildo Pond, or Budgells Harbour pyroxenite intrusions (Strong and Harris, 1974) on the northern coast of the island, as suggested by Strong and Dupuy (1982) and Dickson (1993).

REGIONAL GEOCHRONOLOGICAL CONSTRAINTS

Although the ore at Beaver Brook has not been directly dated, a number of lines of evidence, including regional geological, paleontological and sparse U–Pb geochronological data, help constrain the age and the nature of the mineralizing environment. These data are summarized in Figure 7. The most recent mapping (Dickson, 1996; Lake and Wilton, 2006) proposed that the host rocks of the stibnite mineralization comprise two distinct lithological units, the Davidsville Group (*sic.* O'Neill and Blackwood, 1989) and the Indian Islands Group (Williams *et al.*, 1993). Faunal assemblages collected from five widely separated localities in dark argillite and black shale of the Davidsville Group have yielded diagnostic graptolite assemblages. The oldest are characteristic of the early Darriwilian (*ca.* 467 Ma: Williams and Tallman, 1995; Bergström *et al.*, 2009) and were identified in locally ripple-marked, dark-grey siltstone associated with pebble greywacke in Cooper Brook (Figures 3 to 7). The remaining four localities, including those in Beaver and Webber brooks to the immediate south (Figures 3 and 4), and in Careless Brook and an unnamed tributary ~28 km to the north (Figure 2), yielded a number of fauna including, *Climacograptus sp.*, *Climacograptus bicornis*, *Normalograptus miserabalis* and *Geniculograptus typicalis*, fauna diagnostic of the *P. linearis*, *D. Clingani* and *D. Multidens* zones of the Sandbian to Katian (Figure 7: *ca.*

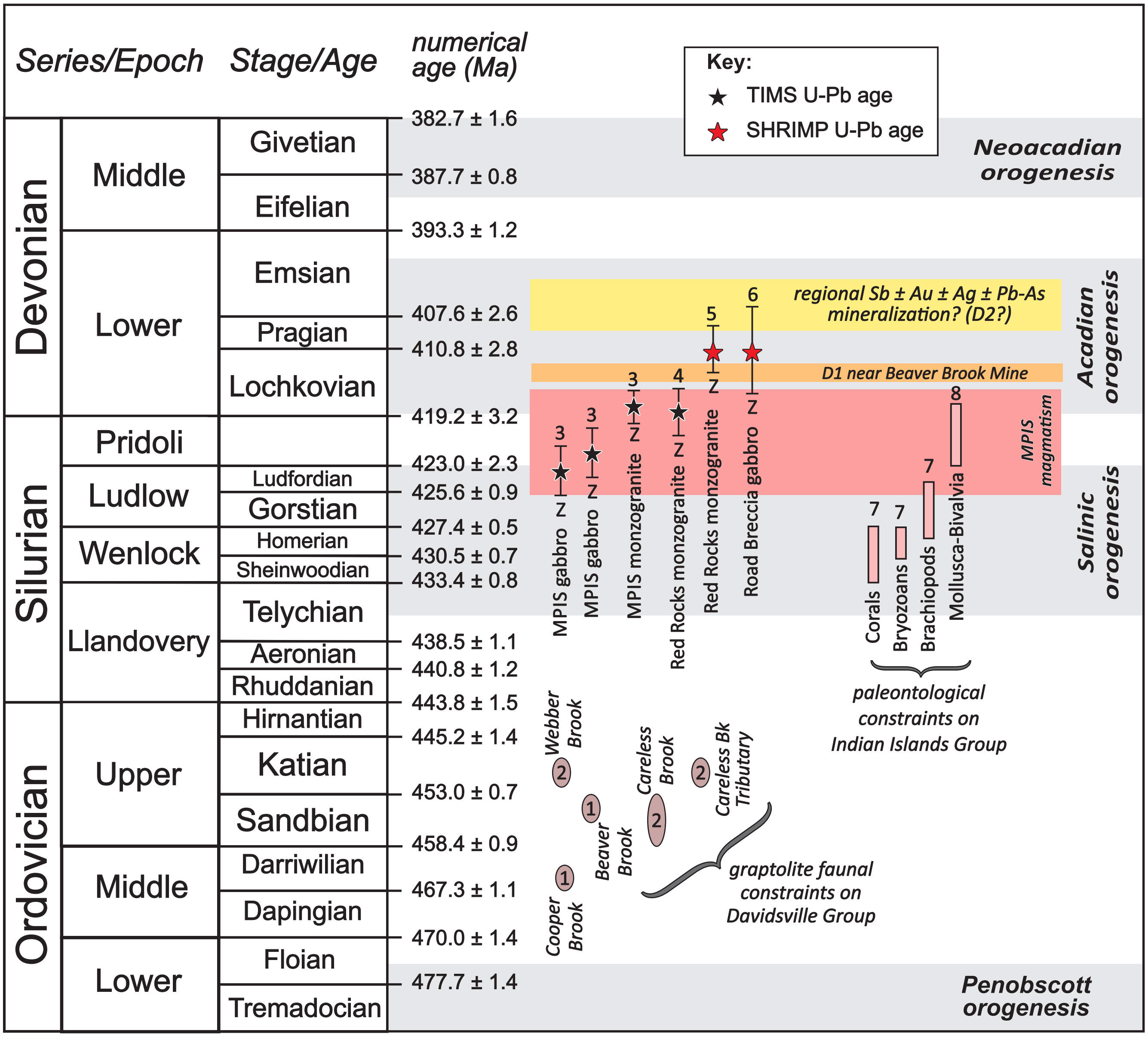

Figure 7. *Diagram summarizing geochronological constraints on the rocks of the Mount Peyton intrusive suite. Also outlined are the approximate time envelopes for the orogenic events of the Newfoundland Appalachians (van Staal and Barr, 2012) and the age of the "intrusion-related" mineralized miarolitic monzogranitic dykes at the Slip showing. Note that the refined, Middle to Late Silurian macrofossil ages for the eastward-lying Indian Islands Group (Boyce and Dickson, 2006) are permissible with the new U–Pb ages for the Mount Peyton intrusive suite (*viz. Dickson et al.*, 2007). Also shown are the approximate locations of fossil localities and their implied biostratigraphic age constraints. Subscripts refer to data source: 1) Williams and Tallman (1995); 2) Williams (1993); 3) Sandeman* et al. *(2017); 4) Dunning and Manser (1993); 5) Dickson* et al. *(2007); 6) McNicoll* et al. *(2007); 7) Boyce and Dickson (2006); 8) Boyce and Ash (1994).*

458-445 Ma: Bergström *et al.*, 2009). These younger graptolites were obtained from steeply southeast-dipping, cleaved, dark-grey to graphitic black shale interbedded with greywacke in fault contact with westward-lying, calcareous siltstone and sandstone containing Wenlock to earliest Devonian shelly fauna (Boyce *et al.*, 1993; Boyce and Ash, 1994; Dickson, 1996; Boyce and Dickson, 2006). At the Beaver and Cooper brooks localities (Figures 3 to 6), Darriwilian to Katian greywacke, grey-green siltstone and black shale structurally overlie decimetre-scale-interbedded, grey shale and micaceous sandstone of the Indian Islands Group. The age of the Indian Islands Group is now constrained by shelly fossil assemblages (Figure 7) from a number of widespread localities extending from the Gander Bay coast, southwestward through Glenwood, the Beaver Brook Antimony Mine site, and beyond to the Bay d'Espoir Highway. Boyce and Dickson (2006) summarize the biostratigraphy of the calcareous siltstone and sandstone of the Indian Islands Group and constrain the Bryozoa *Stictopora scalpellum*-bearing horizons to the Late Homerian. Rocks containing the Brachiopoda Articulata *Isorthis orbicularis* and, in particular, *Atrypa sowerbyi* are constrained to the middle Ludlow. Crinoid-bearing assemblages, including *Gissocrinus goniodactylus*, suggest a late Homerian to earliest Gorstian age (Figure 7). The colonial corals *Favosites sp.*, *Halysites catenularius*, *Heliolites interstinctus* and the solitary coral *Ketophyllum* sp., collectively suggest that some rocks are slightly older, and are constrained to the Wenlock.

The age of the monzogranite near the mine is not known, however, three U–Pb zircon ages have been determined for Mount Peyton intrusive suite monzogranite (*see* discussion in Sandeman *et al.*, 2017). Sixteen kilometres to the northeast of the mine, in Red Rocks Brook, Dunning and Manser (1993) reported a bulk-zircon, thermal ionization mass spectrometry (TIMS), U–Pb lower concordia intercept age of 419 ± 2 Ma for a granophyric monzogranite comparable to that near Beaver Brook. A second large sample of fine-grained monzogranite obtained from the intrusive suite ~30 km north of the Beaver Brook Antimony Mine (Figure 2), yielded a Sensitive High Resolution Ion Microprobe (SHRIMP II) U–Pb age for zircon of 411 ± 2.5 Ma (Dickson *et al.*, 2007). A third monzogranite sample from the Neyles Brook Quarry (45 km north-northeast) was dated by U–Pb chemical abrasion (CA)-TIMS on zircon. The sample was obtained from an auriferous granitic dyke that cuts 422 Ma, Mount Peyton diorite–gabbro. The granitic dyke yielded a concordant zircon age of 418 ± 1.6 Ma (Sandeman *et al.*, 2017), identical, within error, to the analysis of Dunning and Manser (*op. cit.*). These data indicate that much of the monzogranite exposed in the Mount Peyton intrusive suite was emplaced between *ca.* 418 and 411 Ma, a similarity emphasized by their essentially identical bulk-rock compositions (Sandeman *et al.*, 2017). Moreover, the nearly identical, high-precision CA-TIMS ages, relative to the statistically younger SHRIMP age (Figure 7), suggests that the majority of the monzogranite is *ca.* 418 Ma.

STRUCTURAL GEOLOGY

Field relationships indicate that rocks of the Davidsville Group everywhere are in fault contact with rocks interpreted as the Silurian Indian Islands Group. This relationship has been observed at a number of localities near the mine site in Cooper and Beaver brooks (Blackwood, 1981b; Williams and Tallman, 1995; Lake and Wilton, 2006; *this study*) as well as in Careless Brook (Blackwood, 1982; O'Reilly *et al.*, 2010; *this study*), ~30 km along strike to the north-northeast (Figure 2). Structural imbrication is, in part, constrained by graptolite faunal assemblages in the Ordovician rocks and by a range of Wenlock to Lochkovian fauna, including Corals, Bryozoa, Brachiopoda and Mollusca-Bivalvia preserved in the Silurian lithofacies (*see* above). Based on the presence of Ordovician and Silurian fossils in the hanging wall and footwall successions, respectively (Figures 3 and 4), Lake and Wilton (2006) proposed that the Davidsville Group greywacke–sandstone–shale sequences were thrust northwestward over rocks of the Indian Islands Group and that the entire package was imbricated by a number of faults. Until now, however, this proposal has not been fully documented, or supported by structural field evidence.

Regional structural observations, along with detailed geological mapping in the Beaver, Cooper and Clarks brooks' areas, provide evidence for at least two major phases of deformation. The first event (D_1) has affected all of the geological units in the area except the young mafic dykes. Competency contrast between the units resulted in the development of a range of both brittle and brittle–ductile structures. All rocks, with the exception of the mafic dykes (Unit 8), preserve at least one generation of weak to penetrative cleavage.

D_1 DEFORMATION

F_1 folds in both the Davidsville and Indian Islands groups are northeast trending and northwest verging, however, folds in the two groups exhibit different styles (Figures 8 to 10). Folds affecting the Davidsville Group are tight-to-isoclinal and have a strong axial-planar slaty cleavage (*e.g.*, Plate 1A, B), whereas folds within the Indian Islands Group and Ten Mile Lake formation are closed-style and their associated fabrics range from a spaced fracture, to a moderately developed slaty cleavage (*e.g.*, Plate 2A–C: Figure 9) that are broadly axial planar to the F_1 fold axes. A composite plot of D_1 structures, including measured fold axes and calculated bedding-cleavage intersection lineations of all rock successions show two moderately constrained data populations that illustrate that F_1 folds are doubly plunging to the northeast and southwest (Figure 10). The doubly plunging fold geometry is interpreted to have developed during subsequent D_2 dome-and-basin development (*see* below). At Red Rocks Brook (Figure 2), the Mount Peyton granite contains a spaced S_1 fracture cleavage that strikes northeast (035°) and dips moderately to steeply to the southeast (Plate 6F) and suggests the Mount Peyton granite was intruded prior to D_1 deformation.

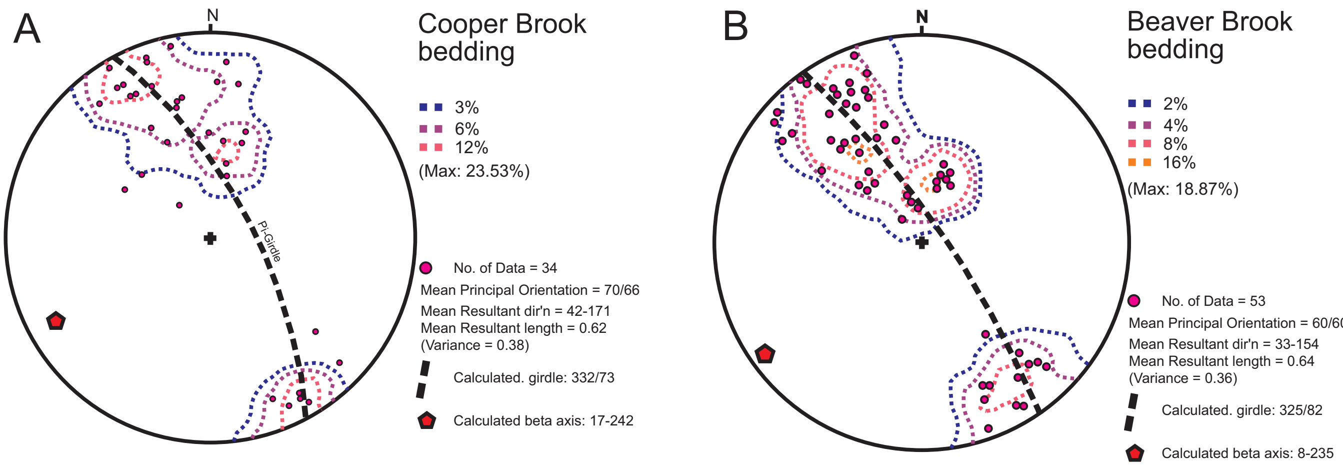

Figure 8. *Lower hemisphere, equal-area, pi-plot showing the pole distribution for bedding planes along Cooper Brook (A) and Beaver Brook (B).*

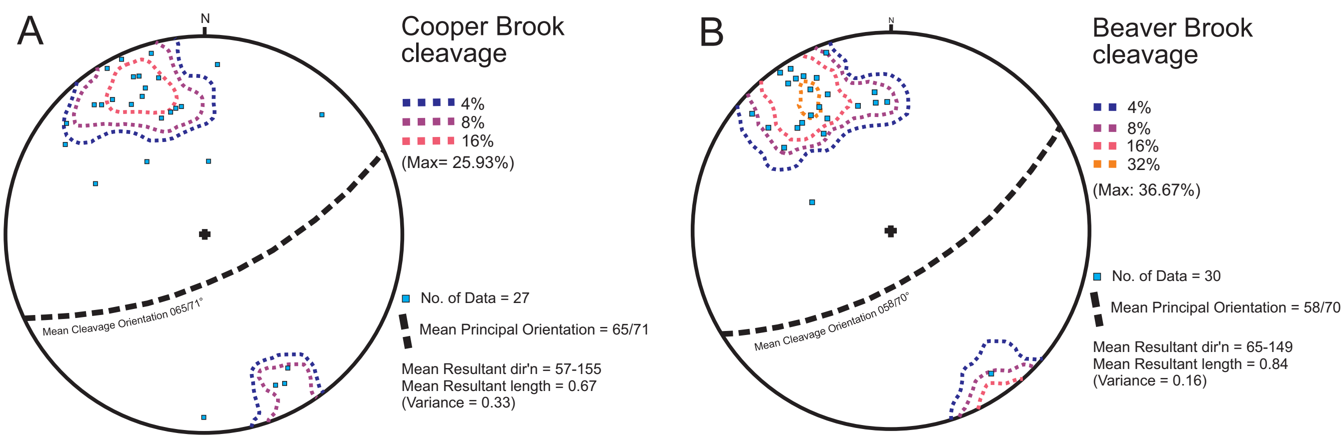

Figure 9. *Lower hemisphere, equal-area plot showing the pole distribution for cleavage planes along Cooper Brook (A) and Beaver Brook (B).*

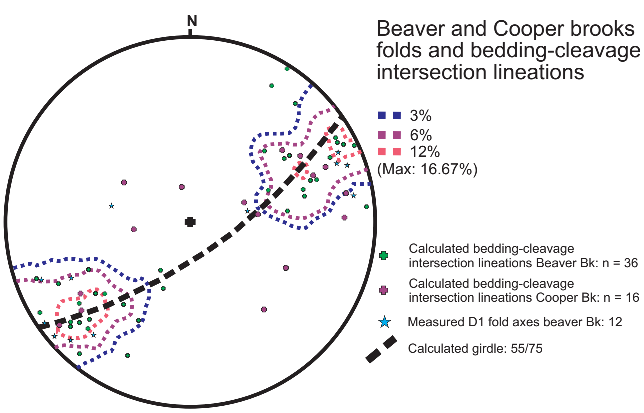

Figure 10. *Lower hemisphere, equal-area plot showing calculated bedding-cleavage intersection lineation's and measured D_1 fold axes along Beaver Brook and Cooper Brook.*

Intra-formational imbrication of units along unambiguous thrust fault geometries (*e.g.*, Plate 4) have been documented in both the Davidsville and Indian Islands groups, and include slip surfaces with associated fibre-mineral packages (Plate 7A) and thrust-related folds (Plate 7B). Commonly, in recognized thrust zones, the black shale of the Davidsville Group exhibits intense shearing and brecciation (*e.g.*, Plate 1E and F), as well as veining that collectively reflect cyclic changes in fluid pressure during deformation. Kinematic analysis of C-S fabrics in these sheared zones shows northwest-directed motion and suggests these structures developed during D_1 deformation. All measured mesoscopic fault planes are northeast striking (~060 to 072°) and dip moderate to steeply (~050 to 085°) to the southeast, with similar orientations to the regional thrust fault inferred to host the Beaver Brook Antimony Mine East zone deposit and the dominant S_1 cleavage (Figure 11).

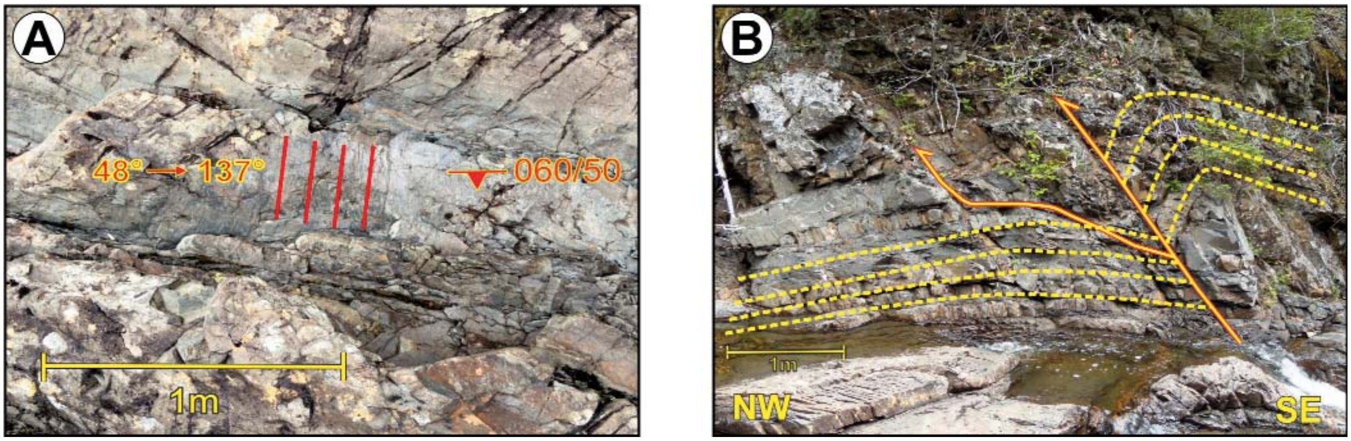

Plate 7. *Photographs of representative fault-related structures. A) A fault surface with down-dip mineral-fibre packages indicating a reverse sense of motion (Figure 3: station HS16-072); B) A thrust-related fold developed in green-grey sandstone and siltstone of the Indian Islands Group (Figure 3: station CP16-021).*

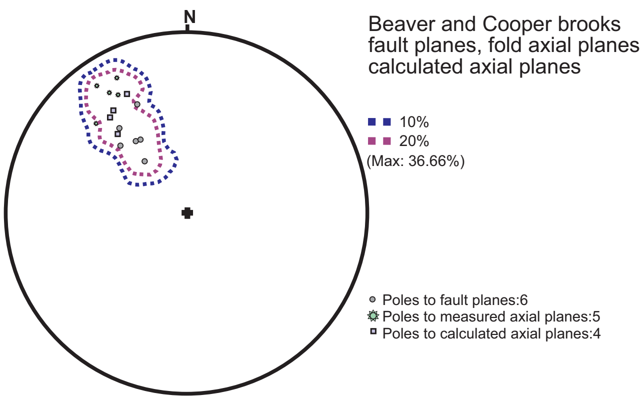

Figure 11. *Lower hemisphere, equal-area plot showing pole distributions for fault planes, fold axial planes and calculated axial planes for the Beaver Brook and Cooper Brook transects.*

Consistency in orientation patterns suggests these structures formed in a similar kinematic regime and thus are considered D_1 structures.

EVIDENCE FOR A SECOND PHASE OF DEFORMATION (D_2)

D_2 deformation is best documented along a Clarks Brook section near the contact between the Indian Islands Group and the Mount Peyton monzogranite (Figures 2 and 12) where a southeast dipping F_1 fold limb and associated cleavage is refolded about a southeast-plunging fold axis (Figure 12). Stereographic analysis of bedding and cleavage in this area (Figure 13) constrains open-to-closed, upright, and moderately southeast-plunging F_2 folds. Folding of the bedding and S_1 cleavage, and the resultant pi plot (Figure 13) confirms post D_1 deformation produced the moderately southeast-plunging antiform–synform pairs (Figure 12). The D_2 deformation caused dome-and-basin fold interference patterns (Ramsay and Huber, 1987) of F_1 folds and is reflected in the non-cylindrical and doubly plunging F_1 fold geometry noted from exposures around the mine (Figure 10). A model showing the present day northeast–southwest-plunging D_1 fold geometry after inferred D_2 overprinting is shown in Figure 14.

DISCUSSION

The stibnite ore extracted at the Beaver Brook East zone deposit comprises a pinch-and-swell, quartz–stibnite–carbonate breccia-vein-system ranging up to 2 m in thickness that extends for over 300 m in strike length (Reeves, 2009; Newman, 2012). The economic ore zone is confined to a ~065°-trending, ~70° southeast-dipping planar feature, parallel to D_1 fabrics and interpreted as a D_1 thrust fault. The ore shoot is interpreted as having a ~65° southwest-rake along this planar feature (Newman, 2012) which provides an ore shoot orientation of ~58° towards ~209°. The antimony ore consists of open space, void filling stibnite that is typically euhedral and commonly coarse grained (up to 15 cm in length, Lake and Wilton, 2006) and accompanied by quartz, calcite and minor chlorite. Minor wall-rock silicification, calcification and supergene oxidation of sulphides to siderite–goethite, along with the void-filling textures indicate that the resource at the East zone comprises a structurally controlled, epithermal stibnite–quartz style of deposit (*see* Bliss and Orris, 1986; Berger, 1993; Seal *et al.*, 1995). Although low levels of gold have been detected and noted in assays during trenching and drilling at Beaver Brook (*e.g.*, Tallman, 1989a; Morrissey and House, 1997; Reeves, 2009), gold and other associated metals have not been consistently analyzed or reported, particularly in assay

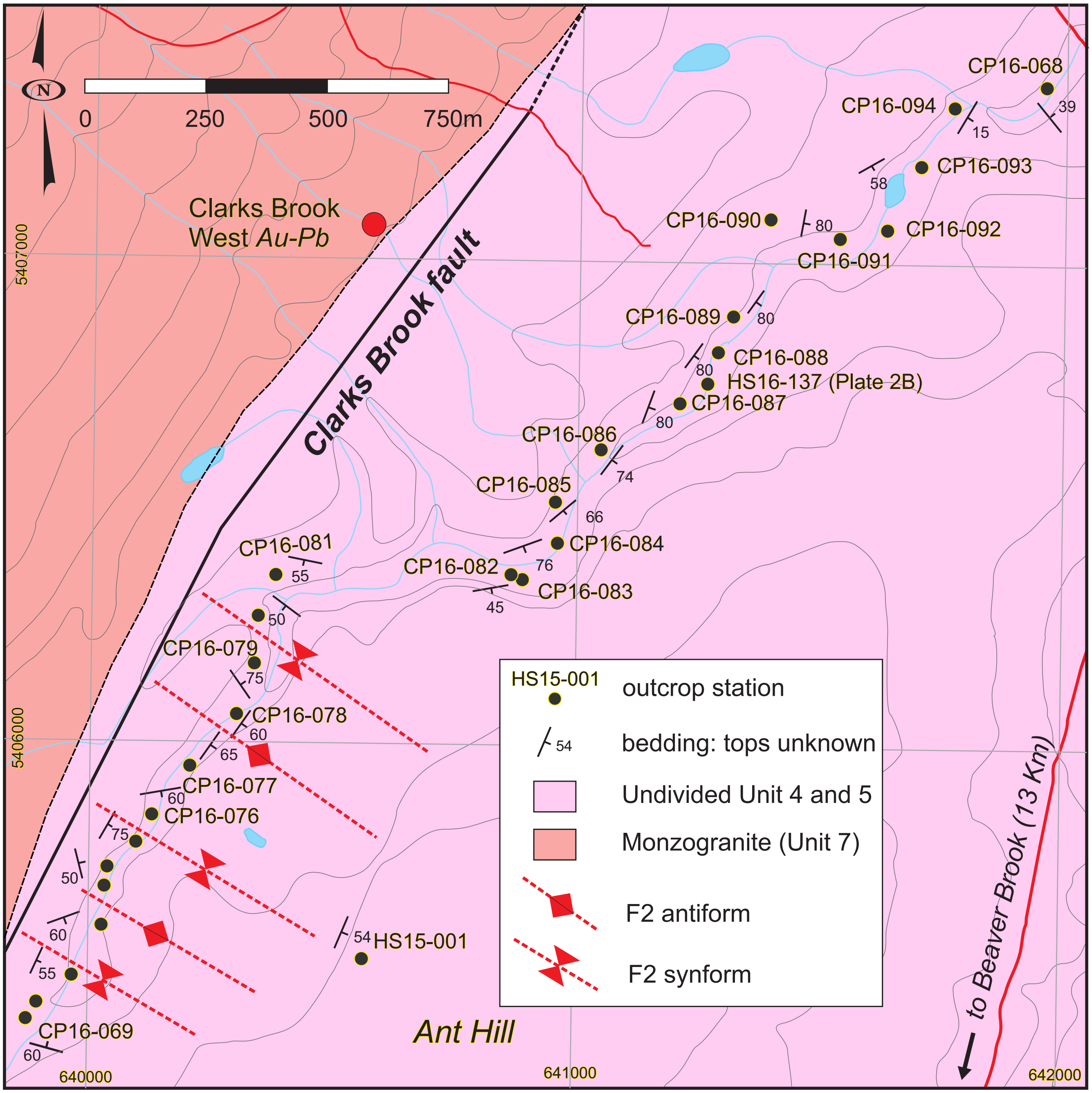

Figure 12. *A map of the Clarks Brook area with bedding measurements outlining a D_2 fold pattern. The intensity of folding appears to increase near the contact between the Mount Peyton intrusive suite and the Indian Islands Group.*

samples focussed on antimony resource delineation (*e.g.*, Morrissy and House, 1998).

A number of recent step-out holes near the Central zone intersected Sb, Au–As and Sb–Au–As mineralized zones. Of particular note, at a depth of 221 m in DDH BB14-305 (Figure 3) brecciated and altered greywacke yielded an assay of 7.01% Sb with 6.3 g/t Au over a 5.05 m interval. These gold-bearing intervals may potentially represent a second style of Sb–Au mineralization (*viz.* Berger, 1993), or a different part of a zoned, polymetallic ore body, more typical of stibnite–gold deposits such as the Costerfield Mine of Australia (Wilson *et al.*, 2017) or the Sarylakh and Sentachan deposits of Russia (Bortnikov *et al.*, 2010). The drillholes between the Central and East zones that have auriferous intercepts cut greywacke–quartz hydrothermal

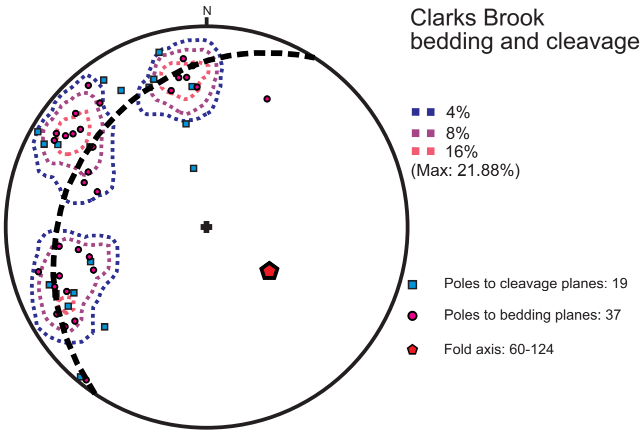

Figure 13. *Lower hemisphere, equal-area, pi-plot showing pole distributions for bedding and cleavage planes along the Clarks Brook transect.*

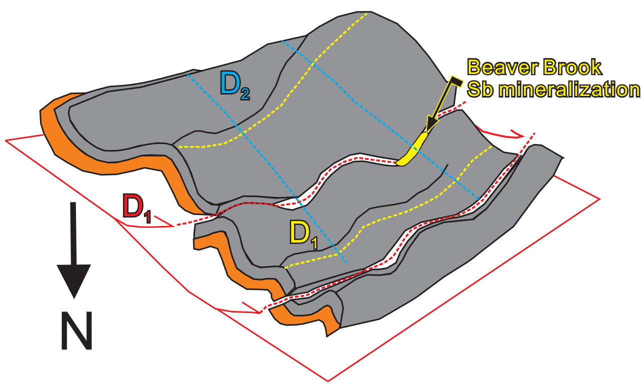

Figure 14. *A schematic diagram illustrating D_1 northwest-verging folds and thrusts overprinted by northeast–southwest D_2 shortening. It shows a series of open F_2 folds and the apparent setting of the Beaver Brook Antimony Mine mineralization.*

breccias that are accompanied by strong sericitization of the adjacent wall rock and breccia fragments, and abundant fine-grained euhedral arsenopyrite, fine-grained, subhedral pyrite, quartz and chlorite. This alteration and mineralization is cut by translucent stibnite–quartz ± carbonate veins with stibnite representing the final paragenetic phase.

All rock units exposed in the Beaver Brook Antimony Mine area and along the western side of the Northwest Gander River appear to have been affected by two compressional events, only the first of which is characterized by a penetrative cleavage. Sedimentary units exposed in Beaver and Cooper brooks provide geological and structural evidence of northwest-vergent, open-to-tight folds related to imbricated thrust faults. Similarly, the eastern margin of the Mount Peyton intrusive suite is commonly transected by decimetre-spaced, northeast-trending and southeast-dipping spaced fracture cleavage. At the East zone, drilling and underground observations have outlined a well-defined hanging-wall-flat and footwall-ramp thrust geometry. It is interpreted to have formed by progressive translation of a D_1 blind thrust that breached the free surface, forming a break-thrust, which isolated an overturned syncline to the footwall domain. To the northwest, more tightly folded rocks are bound to southeast-dipping panels that are separated by moderately dipping thrusts and normal faults. The normal faults share a similar orientation to the D_1 thrust faults and it is likely that they represent early, D_1 thrust faults that were reactivated during a subsequent phase of transtension. The data from the Cooper and Beaver brooks transects demonstrate that at least three, and likely more, thrust faults place Darriwilian to Sandbian-Katian conglomerate–sandstone–siltstone–black shale assemblages over Wenlock to Lochkovian, shelly-fossil-bearing calcareous siltstone and sandstone.

The age of the mineralization and deformation is better constrained by the relationships outlined here. The U–Pb geochronological constraints indicate that the Mount Peyton gabbro–diorite, forming most of the Mount Peyton intrusive suite, was intruded into the eastern Exploits Subzone at *ca.* 425–420 Ma, followed shortly thereafter at *ca.* 418 Ma, by the miarolitic and granophyric Mount Peyton monzogranite (Figure 7). Neither of these intrusive units has been documented to preserve evidence of ductile deformation fabrics. Structural analysis indicates that at Beaver Brook, S_1 was developed during D_1 northwest-directed folding and thrusting. This is interpreted to have occurred after emplacement of all the rocks of the region with the exception of the young mafic dykes. West-southwest of the mine, the monzogranite intrudes southeast-dipping, tilted, uncleaved and hornfelsed, medium-bedded fine-grained sandstone and siltstone (Plate 6D, E), but the lithostratigraphic association of the sedimentary rocks there is uncertain. The upper most parts of Cooper Brook and exposures to the northwest of the mine, however, all comprise thin- to thick-bedded micaceous sandstone and siltstone of the Pridoli to lowermost Devonian Ten Mile Lake formation. Therefore, D_1 deforms Pridoli to lowermost Devonian rocks. The sedimentary rocks of the Ten Mile Lake formation are interpreted to have been intruded by the monzogranite shortly after deposition. The presence of uncleaved, hornfelsed Ten Mile Lake formation rocks, along with the absence of ductile fabrics in the monzogranite indicate that the latter had sufficiently cooled in order to behave as a rigid block during D_1 deformation. These observations collectively indicate that the deformation, as well as the Sb–Au mineralization at the Beaver Brook Mine, are younger than the Earliest Devonian, the youngest age determined for the rocks of the Indian Islands Group. The D_1 event and Beaver Brook mineralization are therefore, younger than *ca.* 410 Ma, and correlates with the Acadian orogenic cycle (Figure 7; van Staal and Barr, 2012). Whether the mineralization is significantly younger is not presently known. Further investigation of the mineralization at Beaver Brook, along with other auriferous showings of the region having comparable settings and metal associations, may help to further constrain the timing of mineralization.

The rocks at Beaver Brook were subsequently affected by a deformation event that locally refolded the $S_1 + S_0$ surfaces into upright southeast-plunging open-to-closed megascopic F_2 folds. Proximal to the Mount Peyton intrusive suite, this F_2 folding and D_2 bedding parallel slip characterize deformation in the sedimentary rocks and may have translated into further brittle fracturing of the more competent granitoid rocks.

All evidence indicates that faulting and fracturing controlled the structure of the rocks and the setting of mineralization in the Beaver Brook Antimony Mine area. Furthermore, of critical importance to the geological interpretation of the area is the evidence for east–west faulting. This evidence includes offsets in magnetic and VLF patterns and IP conductive and resistive horizons (Reeves, 2009), as well as anomalous Sb-in-soil survey dispersal patterns (Tallman, 1991; Tallman and Evans, 1994). Moreover, the moderate (~58°), south (209°) plunge of the stibnite–quartz ore body along the apparent thrust surface requires explanation. If correct, these observations may collectively indicate that second-order geological structures may control the disposition of the main stibnite–quartz (± gold) ore zones such as the intersection of D_2 thrusts and an east–west fault and/or focussed along the intersection of D_1 and D_2 structures.

These observations all emphasize that the structural complexity of the rocks of the mine area inhibits potential discovery of other mineralization. The structural complexity of the area may only be better understood through the application of detailed aeromagnetic and other geophysical methods. These may not provide direct vectors to ore, but will facilitate the delineation of regional structures and, in particular, elucidate the existence and geometry of late east–west faults. Such studies might be accentuated and complemented by a compilation of multi-element ICP soil surveys. Moreover, considering a common global association of antimony with gold and because of the sporadic, but now locally impressive gold assays in the recent drilling near the Central zone (*e.g.*, DDH BB14-305; Figures 4 and 5), it is suggested that there may be potential for significant gold mineralization spatially associated with the stibnite ore. Gold deposition at Beaver Brook is inferred to predate the majority of the antimony mineralization (Tallman and Evans, 1994; *this study*), as auriferous mineralization is characterized by an alteration assemblage (quartz–sericite–pyrite–arsenopyrite–chlorite) distinct from that associated with stibnite deposition (quartz–dolomite–calcite). Therefore, careful attention to gold and other associated minerals (quartz + sericite + arsenopyrite + pyrite) and metals (K + As + Cd + Mo + Cu + Ba + Ag) in recent and future exploration drillholes may help to vectorin on hydrothermal alteration relating to gold deposition. Gold in a number of other comparable mineralized systems is typically considered a product of hotter and/or deeper hydrothermal activity and may not necessarily be spatially or temporally coincident with antimony mineralization (*i.e.*, zoned alteration system; Bortnikov *et al.*, 2010). Sporadic elevated gold assays in the Beaver Brook East zone (*e.g.*, 8.9 g/t Au over 0.3 m in DDH BB97-84; Morrissy and House, 1998) suggest that deeper drilling below the main stibnite ore lodes at the East zone deposit may be warranted in order to test for a spatially associated gold-bearing mineralized system. Future investigations should also examine the setting, paragenesis and conditions of deposition of the gold using modern microanalytical techniques such as laser ablation - inductively coupled mass spectrometry (LA-ICPMS) or secondary ion mass spectrometry (SIMS).

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