Pre-Carboniferous Bedrock Geology of the Annapolis Valley Area (NTS 21A/14, 15 and 16; 21H/01 and 02), Southern Nova Scotia

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Introduction

Bedrock mapping continued through the summer of 2008 and 2009 on the Bridgetown (NTS 21A/14), Gaspereau Lake (NTS 21A/15), Windsor (NTS 21A/16), Wolfville (21H/01) and Berwick (21H/02) map areas in southern Nova Scotia. This work completes the mapping in all the pre-Carboniferous stratified units in southern Nova Scotia related to the South Shore Bedrock Mapping Project (Fig. 1) and has added to the understanding of the stratigraphy, structure, metamorphism, tectonic setting and mineral deposits of southwestern Nova Scotia. Geological map data were collected at a scale of 1:10 000 and compiled to produce a 1:50 000 scale bedrock map showing the distribution of units and mineral occurrences.

Stratigraphy

Previous work

The first systematic regional bedrock mapping in the Annapolis Valley area was conducted by the

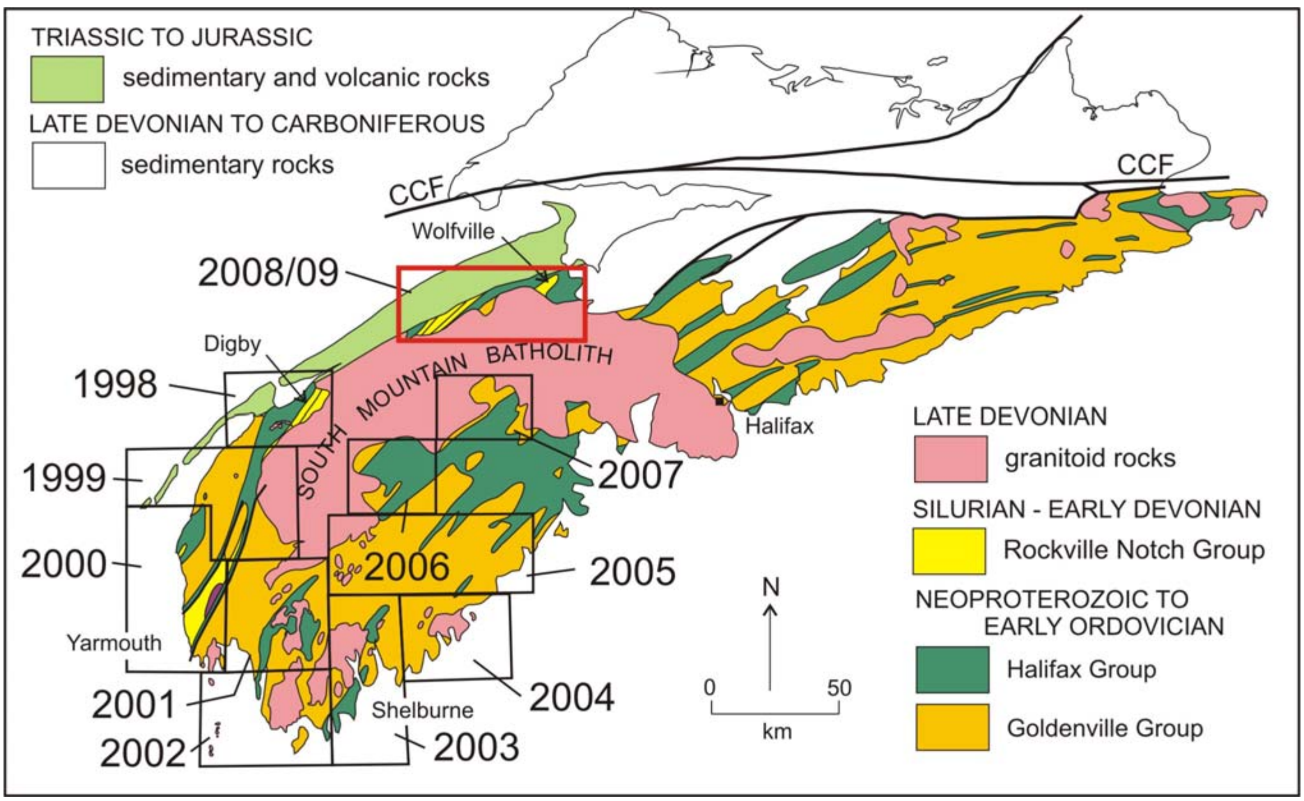

Figure 1. Simplified geological map of the Meguma Terrane, Nova Scotia, showing location of the Annapolis Valley map area (red box) in relation to the Southwest Nova and South Shore mapping projects.

White, C. E. 2010: *in* Mineral Resources Branch, Report of Activities 2009; Nova Scotia Department of Natural Resources, Report ME 2010-1, p. 137-155.

Geological Survey of Canada to establish the Silurian stratigraphy in this part of Nova Scotia. In 1949 and 1950, Crosby (1962) mapped the Wolfville area at a scale of 1:63 360, and later (1957 to 1959) Smitheringale (1960, 1973) mapped the Nictaux-Torbrook and Digby map areas at a scale of 1:50 000. During this period Hickox (1958) mapped some of the same area in conjunction with a glacial geology study. In 1960 and 1961, Taylor (1965, 1969) completed reconnaissance mapping (1:126 720 scale) in southwestern Nova Scotia, which also included the Nictaux-Torbrook area and parts of the Wolfville area. The next systematic detailed (1:10 000 scale) bedrock mapping was completed by Ferguson (1983, 1985, 1986, 1988, 1989, 1990a, b, c, d, e, f, g) in the Wolfville-Gaspereau Lake areas. Although these maps showed much more outcrop and structural data in the major formations, they did not differ significantly from those of Crosby (1962) and Smitheringale (1973) and a report was not forthcoming. Additional mapping (1:10 000 scale) was conducted by Cullen *et al*. (1996) in the Nictaux-Torbrook area to better understand the mineral resource potential of the Silurian to Devonian units. Cullen *et al*. (1996) compiled all the existing and new mineral occurrences.

Crosby (1962), Smitheringale (1960, 1973), Taylor (1965, 1969), Ferguson (1983, 1985, 1986, 1988, 1989, 1990a, b, c, d, e, f, g) and Cullen *et al*. (1996) subdivided the stratified rocks into six formations which included, from oldest to youngest, the Goldenville, Halifax, White Rock, Kentville, New Canaan, and Torbrook formations. The Late Cambrian or Early Ordovician greywacke, quartzite and siltstone of the Goldenville Formation and Early Ordovician dark siltstone and slate of the Halifax Formation were assigned to the Meguma Group. Smitheringale (1960, 1973) considered the contact between the Goldenville and Halifax formations to be conformable and provided no other details. Based on mapping elsewhere in the Meguma Group, Taylor (1969) placed the contact at the top of the highest ‘arenaceous’ bed in the Goldenville Formation.

Overlying the Halifax Formation in the Wolfville area are quartzite and slate that Crosby (1962) named the White Rock Formation, although earlier Faribault (1909) had recognized the distinct character of this unit and called it the Whiterock quartzite. Crosby (1962) defined the White Rock Formation as “two massive quartzite beds with slate between them.” This was later referred to as the “double quartzite member” by Smitheringale (1973). Smitheringale (1960, 1973) extended the “double quartzite member” southwest into the Gaspereau Lake - Bridgetown map areas, but in those areas the member overlies a distinctive argillaceous quartzite and rhyolite-basalt unit, which in turn overlies the Halifax Formation. To avoid confusion he redefined the contact between the White Rock and Halifax formations by placing the base of the White Rock Formation below either the lowest quartzite or the lowest volcanic member, whichever is lowermost. Because the slate units in the White Rock Formation are indistinguishable from those in the Halifax Formation, Smitheringale (1960, 1973) concluded that there was no hiatus in accumulation of sediments between the two formations, although in places erosion could have occurred. In the Wolfville area Faribault (1909) and Crosby (1962) agreed that the Halifax and White Rock formations are conformable. Taylor (1965), however, considered the contact in the Wolfville area to be a paraconformity. No identifiable fossils have been recovered from the White Rock Formation in the current map area but based on fossil occurrences in units below and above, the formation was considered to be Ordovician or Silurian, or both (e.g. Taylor, 1965). The upper part of the White Rock Formation in the Digby area contains Late Silurian (Ludlovian) fossils (Smitheringale, 1973).

The Kentville Formation (Ami, 1900) is a unit of interbedded slate and siltstone that is defined as conformably overlying the White Rock Formation and conformably underlying the New Canaan and Torbrook formations (Crosby, 1962; Smitheringale, 1960, 1973; Taylor, 1965, 1969). The Kentville Formation in the Nictaux-Torbrook area contains Late Silurian (Ludlovian) marine fossils (Smitheringale, 1960, 1973; Taylor, 1965).

Crosby (1962) introduced the name New Canaan Formation for a unit consisting of sedimentary and volcanic rocks that conformably overlies the Kentville Formation in the Wolfville map area.

Based on fossils, Crosby (1962) interpreted a marine, shallow warm-water environment of deposition for the formation in the Silurian.

Historically, the strata that overlie the Kentville Formation have received much of the geological attention in the map area, largely due to their impressive fossil occurrences and iron ore potential (e.g. Dawson, 1855; Honeyman, 1878; Bailey, 1895, 1898; Ami, 1900; Fletcher, 1905) and has been variably named the Bear River formation, Nictaux iron beds, and Torbrook sandstone (Ami, 1900). Hickox (1958) grouped these units together and assigned the name Torbrook Formation. Based on the fossils this formation was interpreted to have been deposited in a shallow marine setting during the Early Devonian (Hickox, 1958; Smitheringale, 1960, 1973; Taylor, 1965, 1969).

Both Smitheringale (1960, 1973) and Taylor (1969) noted numerous mafic sills and dykes in all the formations. Smitheringale (1973), however, recognized that an older set of 'spilitic' sills was restricted to the Halifax Formation. The younger mafic sills were interpreted to be related to the extrusive rocks in the White Rock Formation (Taylor, 1969).

Granitoid plutons in the area were considered to be Devonian based on field relationships and early radiometric ages (Crosby, 1962; Smitheringale, 1960, 1973; Taylor, 1965, 1969). Taylor (1969) suggested that some might be Carboniferous. The granitic rocks in the map area were studied by Ham and Horne (1987) and MacDonald and Ham (1992, 1994) as part of the South Mountain Batholith mapping project and, although the position of contacts between the granite and metasedimentary units was slightly modified, the geology plotted in the adjacent Meguma Group on those maps was primarily after Crosby (1962) and Smitheringale (1960, 1973).

Lane (1975, 1979) did a detailed, systematic investigation of the White Rock Formation. Based on detailed stratigraphic sections he subdivided the formation into several members and sedimentary facies. Schenk (1995, 1997) upgraded the White Rock, Kentville, New Canaan, and Torbrook formations to group status and included these in the Annapolis Supergroup. Based on the subdivisions established by Lane (1979), Schenk (1995, 1997) further subdivided the groups into several formations. A map showing the distribution of these units was not produced, however, and hence the newly erected divisions were not generally accepted.

The traditional two-fold division of the Meguma Group into the Goldenville and Halifax formations has currently been undergoing major revisions (White, in press; White and Barr, in press). These revisions are largely the result of mapping related to the South Shore Bedrock Mapping Project and the earlier Southwest Nova Mapping Project, which have led to the definition of regionally mappable 'formations' in the traditional Goldenville and Halifax formations. As a result, the Goldenville and Halifax formations have been elevated to group status, and that terminology is followed here.

Present Study

Mapping and follow-up petrographic studies on the pre-Carboniferous stratified units in the Annapolis Valley in 2008-2009 have resulted in a redefinition of many of the established formations and show that many of the units defined in the Digby-Yarmouth area (White *et al*., 1999, 2001; Horne *et al*., 2000) have stratigraphically equivalent formations in the present map area (Figs. 2a, b). In addition, several new formations have been established in the Halifax Group. The lower part of the Goldenville Group is a metasandstone-dominated unit termed the Church Point Formation, whereas the upper part consists of metasiltstone of the Tupper Lake Brook Formation. Units in the overlying slate-rich Halifax Group have been upgraded to formations and include the Cunard Formation and overlying Lumsden Dam, Elderkin Brook and Hellgate Falls formations. The younger Silurian to Devonian units (White Rock, Kentville, New Canaan and Torbrook formations) are now included in a newly defined Rockville Notch Group (Fig. 3). In contrast to formations in the Digby-Yarmouth area, the grade of regional metamorphism is lower in the pre-Carboniferous units of the Annapolis Valley and thus the 'meta' prefix is not required.

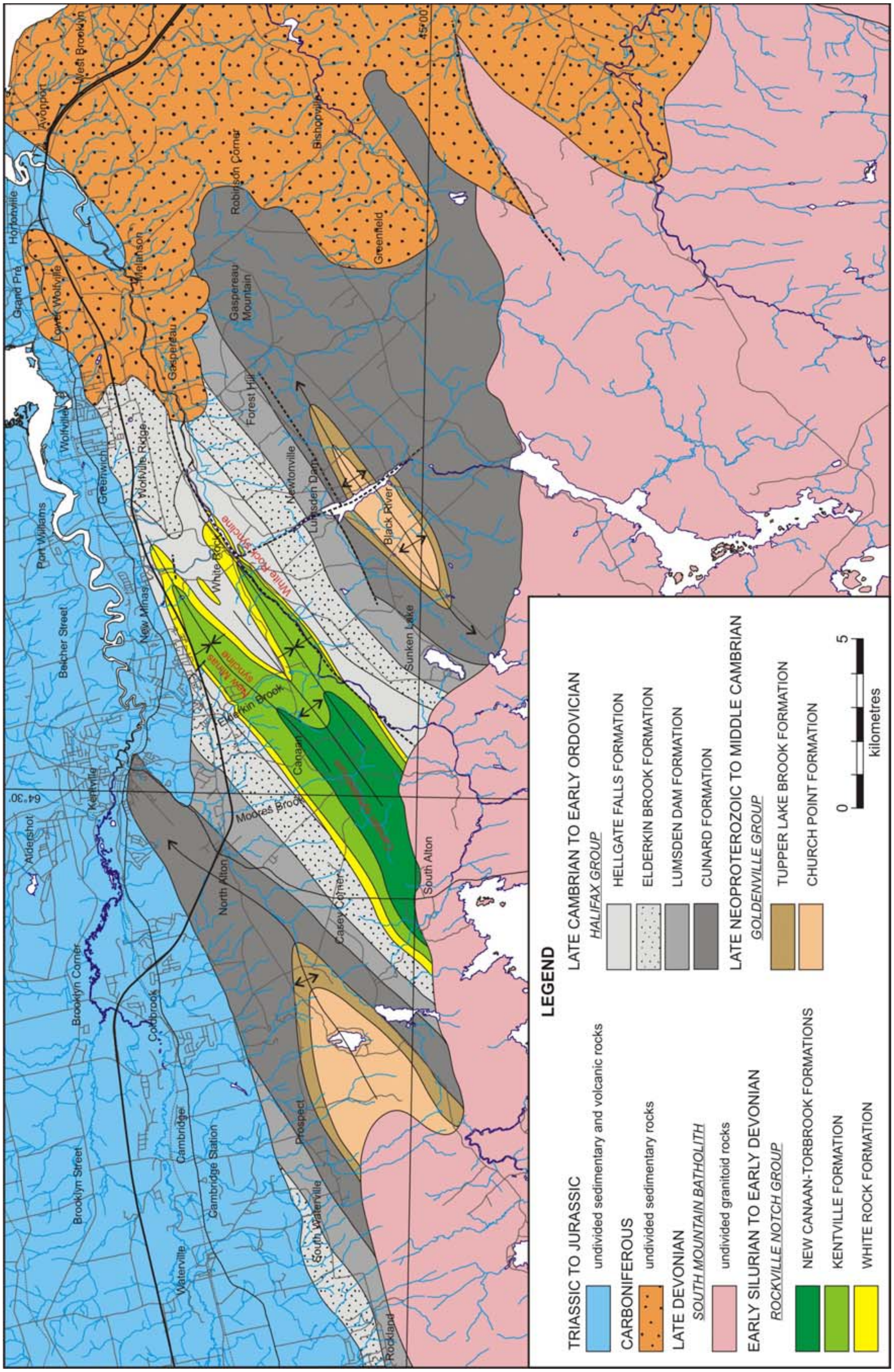

Figure 2a. Simplified geological map of the Wolfville area.

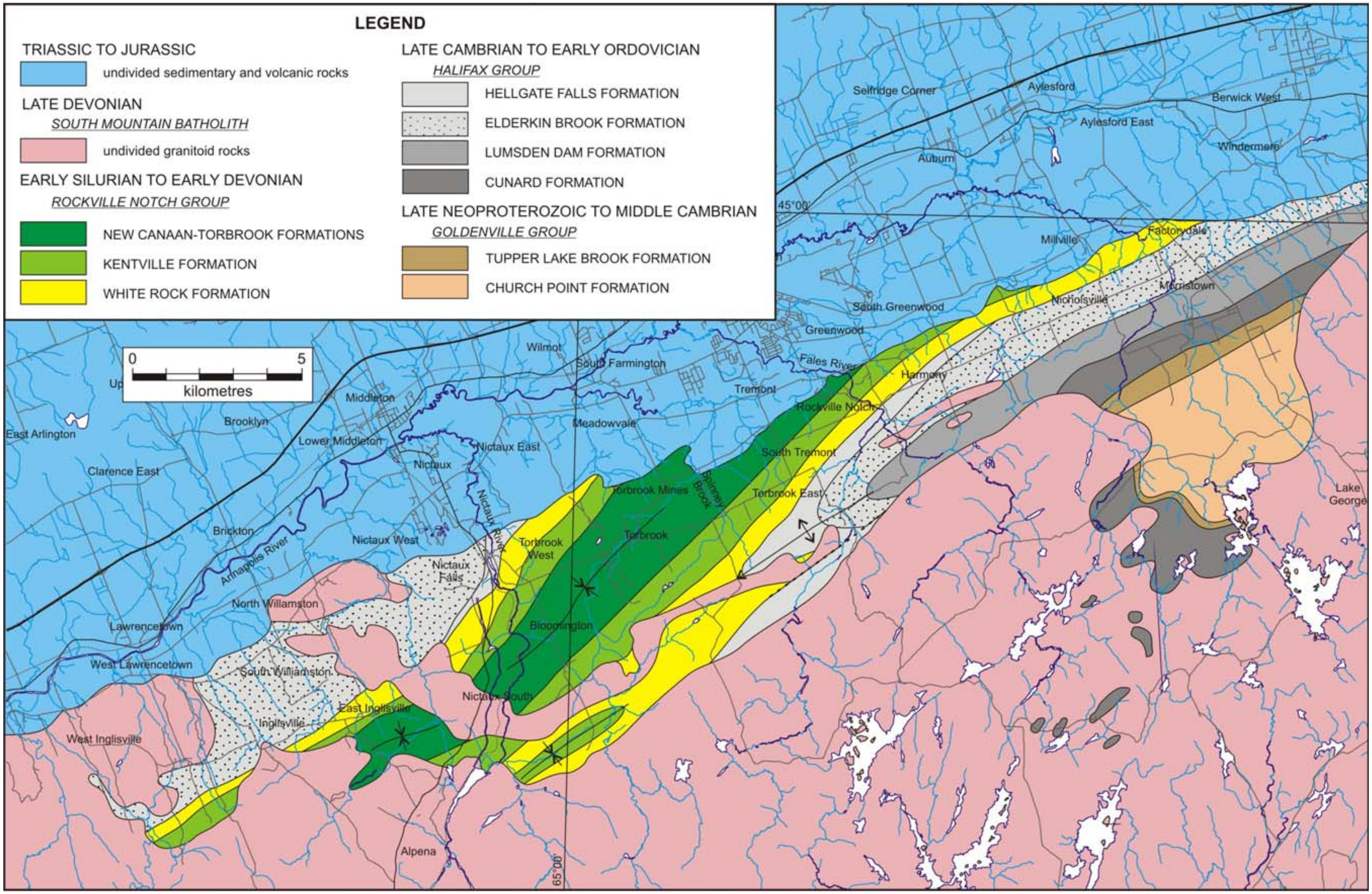

Figure 2b. Simplified geological map of the Nictaux-Torbrook area.

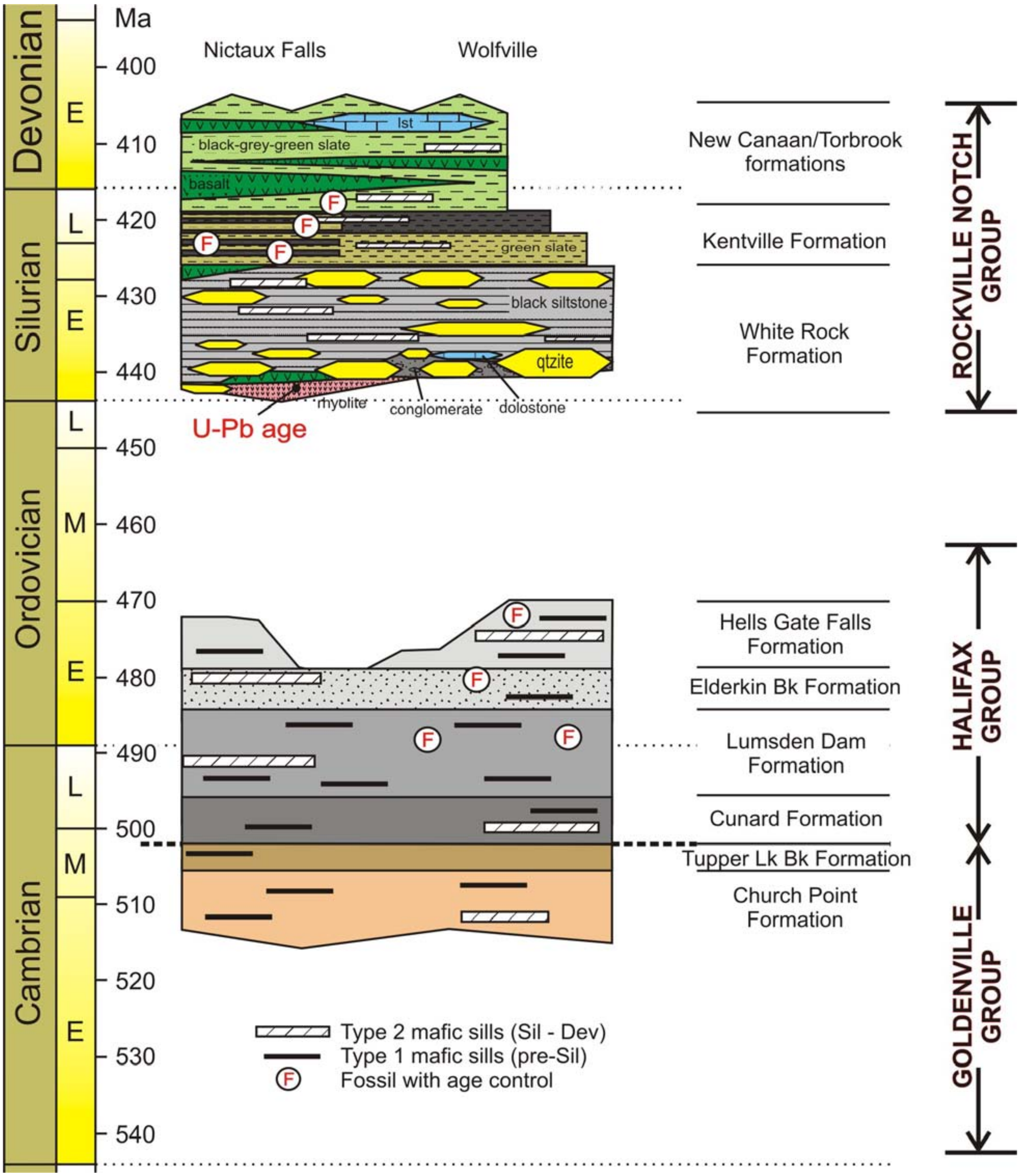

Figure 3. Simplified stratigraphic column for pre-Carboniferous units in the Annapolis Valley.

Goldenville Group

Church Point Formation

The Church Point Formation (White, 2008a, in press) occurs in the core of a domal structure in the Black River area, the core of a northeasterly-plunging anticline in the Prospect area, and the northwestern limb of an anticline west of Lake George (Figs. 2a, b). It consists of grey medium- to thick-bedded sandstone, locally interlayered with green, cleaved siltstone and rare black slate. The sandstone typically lacks sedimentary structures, although in places it is thinly bedded. Siltstone interbeds locally preserve cross-bedding, ripple marks and graded bedding. The sandstone locally contains abundant elliptical calc-silicate lenses. Close to the contacts with the South Mountain Batholith, the cleaved siltstone beds have been thermally metamorphosed to hornfels. The contact with the overlying Tupper Lake Brook Formation is exposed near Black River and is sharp and conformable as it is in the map areas to the southwest (e.g. White *et al.*, 1999, 2001; Horne *et al.*, 2000). Approximately 2500 m of the upper Church Point Formation is exposed.

Tupper Lake Brook Formation

The Tupper Lake Brook Formation (new name) occurs in a narrow (200 to 400 m wide) unit around the core of a domal structure in the Black River area, around the core of a northeasterly-plunging anticline in the Prospect area, and on the northwestern limb of an anticline west of Lake George (Figs. 2a, b). The formation is well exposed in several quarries in the Prospect area. The Tupper Lake Brook Formation is a pale green to purple to grey-brown, well laminated siltstone to slate, interlayered with rare 1 to 5 cm thick sandstone beds. In contrast to the equivalent Bloomfield Formation in the Digby-Yarmouth area (White *et al.*, 1999, 2001; Horne *et al.*, 2000; White, in press), the Tupper Lake Brook Formation locally contains 5 to 20 mm wide, ptygmatically folded, Mn-rich brown carbonate laminations and lenses, and proximal fractures are stained with steel-blue manganese. Within the contact metamorphic aureole of the South Mountain Batholith, these laminations and lenses are pink (converted to coticule) due to the presence of spessartine garnet. The contact of the Tupper Lake Brook Formation with the overlying Cunard Formation was not observed.

Halifax Group

Cunard Formation

The Cunard Formation occurs in the same areas as the Tupper Lake Brook Formation (Figs. 2a, b) and consists of black to rust-brown slate with thin beds and lenses of minor black cleaved siltstone interbedded with cross-laminated, fine-grained, pyritiferous sandstone. The sandstone beds, up to 25 cm thick, are common throughout the formation. This contrasts with the Cunard Formation elsewhere in southwestern Nova Scotia where sandstone beds are generally lacking in the basal section (White, 2008b). This unit is stratigraphically equivalent to the Acacia Brook Formation in the Digby-Yarmouth area (White, in press). The slate locally contains abundant pyrite, arsenopyrite and pyrrhotite that form beds and nodules up to 5 cm thick and may be the source of potential acid rock drainage (ARD). Close to the contacts with the South Mountain Batholith, slate in the Cunard Formation is thermally metamorphosed to hornfels and contains cordierite + andalusite ± sillimanite. The best exposures of the Cunard Formation are in pits south and east of Lumsden Dam. Contacts with the overlying Lumsden Dam Formation are gradational over a 5 m interval. The Cunard Formation is about 1000 m thick, although in areas of abundant folds it appears much thicker.

Lumsden Dam Formation

The best continuous sections of the Lumsden Dam Formation (new name) are exposed at Lumsden Dam and along the lower part of Moores Brook (Fig. 2a). It consists of light grey, well laminated to thinly bedded, cleaved siltstone, with minor, thin (<10 cm thick) slate beds. Fine-grained, cross-laminated sandstone beds (up to 20 cm thick) are a characteristic feature of this formation and are typically continuous over tens of metres. Pyrite and arsenopyrite are less common than in the underlying Cunard Formation.

Primary sedimentary structures are common and include cross- and graded-bedding, groove, tool and load marks, as well as ripples and small-scale slump features. Fossil occurrences are generally sparse, although trace fossils (burrowing and grazing) and bioturbated layers are common. The lower and middle parts of the Lumsden Dam Formation locally contain the Early Ordovician graptolite *Rhabdinopora flabelliformis* (White *et al*., 1999) and Early Tremadoc acritarch microfossils (T. Palacios, personal communication, 2009) (Fig. 3) and hence is stratigraphically equivalent to the Bear River Formation exposed in the Digby area (White, in press). The contact with the overlying Elderkin Brook Formation is gradational. The formation varies in thickness from about 1000 to 1500 m.

Elderkin Brook Formation

The Elderkin Brook Formation (new name) is best exposed in Elderkin Brook near New Minas and Black River (Fig. 2a). In the type section of Elderkin Brook, the Lumsden Dam Formation is gradationally overlain by light grey to red-brown, laminated slate and mudstone, which locally contain numerous trace fossils. Coarse siltstone and sandstone beds are virtually missing in all outcrops. The formation apparently undergoes a lateral facies change because in the section at Black River the Lumsden Dam Formation grades upward into a grey, well laminated to thinly bedded very fine-grained sandstone-siltstone unit with thin (< 5 cm thick) cross-laminated siltstone and sandstone beds and lenses. Carbonate-rich to silty carbonate-rich beds and lenses locally occur. Trace fossils are not abundant. Close to the top of the formation in Black River is a 350 m wide laminated siltstone unit similar to that exposed in Elderkin Brook, confirming the correlation between the two areas. The formation is about 900 to 1200 m thick.

Hellgate Falls Formation

Rocks of the Hellgate Falls Formation (new name) occur in the lower part of Black River, Fales River and at Nictaux Falls (Figs. 2a, b). The formation is composed of light to dark grey slate rhythmically interbedded with laminated to thinly bedded siltstone and light grey sandstone. Thin lenses of cross-laminated sandstone are common. Characteristic features of the Hellgate Falls Formation include abundant bioturbation textures and trace fossils. Many of the burrows are infilled with fine-grained white sandstone that locally has a carbonate matrix. Compared to trace fossils in the underlying Elderkin Brook Formation, these fossils display a more diverse assemblage of larger and more complex trails. Based on morphology, these trace fossils appear to be similar to other Early Ordovician traces exposed in Spain (S. Jensen, personal communication, 2009) (Fig. 3). Locally, the upper part of the formation is capped by laminated black slate. Because this is the uppermost formation in the Halifax Group, the maximum thickness is difficult to know with certainty, but at least 1100 m are exposed.

Rockville Notch Group

White Rock Formation

In the Wolfville area, the White Rock Formation occurs on the limbs of the Canaan synclinorium (New Minas and White Rock synclines), whereas in the Torbrook area it occurs on both limbs of the Torbrook syncline (Figs. 2a, b). In the White Rock syncline the base of the formation rests on either the Hellgate Falls or Elderkin Brook formation. It is composed of a series of thick quartzite beds (1.5 to 10 m thick) separated by thin (1 to 5 m thick) beds of black slate. These slate beds are similar to those in the underlying Halifax Group (cf. Crosby, 1962; Smitheringale, 1960, 1973), but in most outcrops they contain phosphate nodules which distinguish them from slate beds in the older units. Along strike the quartzite and slate appear to vary in thickness with an overall lensoid distribution. It is unclear if this ‘pinch and swell’ character is the result of the original sedimentary environment or later deformation.

Above this quartzite series is a unit of grey to light-green, cleaved siltstone to slate, locally interlayered with thin (5 to 15 cm thick) beds of pale sulphide-rich dolostone. Above the slate package is another series of quartzite beds (1-5 m thick) interlayered with green-grey siltstone and sandstone. The contact with the overlying Kentville Formation is gradational, with the quartzite beds thinning and becoming non-existent over 50 m.

In the New Minas syncline the stratigraphy in the White Rock Formation is slightly different. The base of the formation is marked by a series of quartzite beds (up to six beds with thickness ranging from 2 to 10 m) interlayered with dark grey to red-brown conglomerate to breccia and black siltstone to slate. In some localities quartzite rests on the Halifax Group, whereas in others it overlies the conglomerate or slate. The quartzite continues above this unit to the base of the Kentville Formation, but is interlayered with grey cleaved siltstone to slate and no conglomerate. In this area, it is difficult to map a middle ‘slate’ unit or the double quartzite member as defined by Crosby (1962) and Smitheringale (1960, 1973). Like in the White Rock syncline, this unit varies in thickness along strike with many of the quartzite beds displaying an overall lenticular morphology on a scale from tens to hundreds of metres. This broadly correlates with the informal Deep Hollow Formation of Schenk (1995). The White Rock Formation in the Wolfville area varies in thickness from about 100 to 200 m.

In the Torbrook syncline the White Rock Formation is best exposed in Fales and Nictaux rivers and the stratigraphy differs from that exposed in the Wolfville area. Where exposed, the base of the formation is marked by a rhyolitic tuff or flow that is overlain by amygdaloidal to pillowed basaltic flows. These correspond to the “Nictaux Volcanics” as defined by Schenk (1995). Locally, the basalt displays a peperitic texture with limestone as the interstitial material. Along strike the volcanic rocks are missing and the basal unit is a quartzite and siltstone package up to 5 m wide. On Fales River, stratigraphically above the basalt, is a well bedded, heavily bioturbated, quartz arenite (~50 m thick) with numerous grazing and burrowing trace fossils. Schenk (1995) considered this typical of his Fales River Formation but this unit was not observed elsewhere.

The upper part of the White Rock Formation varies. In places (Fales River) it appears to have the ‘double quartzite member’ separated by black featureless siltstone to slate. The black slate is identical to that in the overlying Kentville Formation in the area. In other places (Nictaux River) a green mafic lithic tuff tops off the formation. This unit was observed at extremely low-water conditions. Like the White Rock Formation in the Wolfville area, many of the quartzite and volcanic beds are lenticular along strike as also noted by Smitheringale (1973). The White Rock Formation in the Torbrook syncline area varies in thickness from about 300 m to 550 m.

Fossils in the White Rock Formation are sparse. Lane (1975) reported the occurrence of shelly fossils in the White Rock Formation in the Yarmouth area. A castellated rhynconellid brachiopod from this area has a maximum age of Caradocian, but it is probably much younger (Boucot, personal communication, 1971, *in* Lane, 1975). In the New Minas syncline Lane (1979) reported a shelly fossil hash in a quartzite outcrop but this observation was not confirmed during the present study. Rhyolite at the base of the formation in Fales River yielded a U-Pb zircon crystallization age of 442 ± 4 Ma (Keppie and Krogh, 2000) which is interpreted as the age of eruption (Fig. 3). Ludlovian graptolite specimens, identified as *Monograptus* sp. Cf. *M. tumescens* Wood (Smitheringale, 1960, 1973), were collected from the upper part of the White Rock Formation in the Torbrook area. Although this area was included in the White Rock Formation (Smitheringale, 1973), Smitheringale (1960) formally assigned the strata to the Kentville Formation, in agreement with the current map (Fig. 2).

Kentville Formation

Like the White Rock Formation, the Kentville Formation occurs on the limbs of the Canaan synclinorium (New Minas and White Rock synclines) in the Wolfville area where it is best exposed on the upper part of Elderkin Brook (Fig. 2a). It is also present on both limbs of the Torbrook syncline in Torbrook and is best exposed in Nictaux and Fales rivers, and Spinney Brook (Fig. 2b). Although Smitheringale (1960) recognized and mapped the distribution of the Kentville Formation in the Torbrook area, on his later map Smitheringale (1973) reversed his “arbitrary use of map-units” and considered the Kentville Formation to merge with the White Rock Formation through a facies change.

In the Wolfville area the Kentville Formation consists of pale grey-green, well laminated siltstone and slate overlain by black slate. The lower slate unit locally contains pyritiferous limestone nodules. As noted by Crosby (1962) the black slate is virtually identical to that in the Halifax Group (Cunard Formation). The Kentville Formation in this area was included in the Elderkin Formation of Schenk (1995). The upper contact is sharp with the overlying New Canaan Formation and is marked by a basal basaltic flow.

In the Torbrook area the Kentville Formation consists of dark grey to black or pale green-grey, featureless to laminated siltstone and slate interlayered with thin laminae to thin beds of pale sandstone and siltstone. In Fales and Nictaux rivers, close to the bottom of the unit, black limestone nodules are locally common. This was part of the Tremont Formation of Schenk (1995). The contact with the overlying Torbrook Formation is gradational. In Spinney Brook the green slate in the upper part of the Kentville Formation becomes increasing interlayered with thicker, coarser-grained sandstone beds over a 10 m interval. This change marks the base of the Torbrook Formation. In Nictaux River the upper contact is marked by the presence of black fossiliferous limestone that forms the lowermost unit in the Torbrook Formation. The Kentville Formation ranges in thickness from about 500 to 600 m.

Several graptolites and other fauna were reported by Smitheringale (1973) from the Fales River section and the area east of Spinney Brook and identified as (Ludlow) Silurian (Fig. 3). Bouyx *et al*. (1997) also described graptolites and other fossils collected from the base of the Kentville Formation in Fales River and assigned an age of Upper Wenlockian to Lower Ludlovian (Middle-Late Silurian boundary). Samples collected from the top of the Kentville Formation in Spinney Brook yielded Pridolian (Late Silurian) microfossils (Bouyx *et al*., 1997).

New Canaan Formation

The New Canaan Formation was proposed by Crosby (1962) for a package of marine sedimentary and volcanic rocks that form the core of the Canaan synclinorium (Fig. 2a). Clark (1977) subdivided the formation into four sedimentary and volcanic units and suggested additional areas to drill to better constrain the geology. Smith (1992) drilled in the area but no published reports were produced. James (1998) compiled the previous work, logged the core, and remapped the area. He subdivided the formation into seven informal units; three mainly volcanic, three sedimentary, and one mixed volcanic/sedimentary. These units are too small to show at the scale of Figure 2a.

The base of the formation is exposed in the upper part of Elderkin Brook and is dark green-grey amygdaloidal basalt that laterally grades into mafic lithic tuff and volcanic breccia. Clark (1977) and James (1998) both placed the base below a mainly calcareous siltstone and slate unit. Mapping, however, has shown that these rocks are part of the underlying Kentville Formation. Overlying the volcanic rocks is a succession of dark grey to black siliceous siltstone, sandstone and limestone, all of which are locally interlayered with amygdaloidal basalt. The limestone and sandstone locally contain numerous large shelly fossils that appear to be identical to those in the Torbrook Formation. Geochemical data from the volcanic units show that the rocks are alkali and consistent with a within-plate continental setting (James, 1998). Although the upper boundary is not present a minimum thickness of 530 m was assigned to the formation (James, 1998).

The age of the formation is not well constrained. It contains crinoids, brachiopods (?*Conchidium*) and corals (Wilson, *in* Crosby, 1962) that indicate a possible Middle Silurian age. Boucot *et al.* (1974) placed the formation in the latest Silurian (Pridoli) (Fig. 3).

Torbrook Formation

The Torbrook Formation occurs in the core of the Torbrook syncline and is best exposed in Nictaux River and Spinney Brook (Fig. 2b). The Spinney Brook section was described in detail by Hickox (1958), Smitheringale (1973) and Jensen (1975). The basal part of the section in Spinney Brook consists of a coarsening-upward sandstone package interlayered with siltstone. Rare macroscopic fossils occur in the finer-grained sandstone. In Nictaux River the base is marked by a fossiliferous limestone and black siltstone. The remainder of the formation consists of interbeds of sandstone, siltstone, slate and limestone that are typically heavily bioturbated and fossil-rich. Phosphate nodules are common. A characteristic feature of the formation is the presence of quartz-rich and oolitic ironstone beds that are locally fossiliferous. Mafic lithic tuff is also present near the middle of the formation. The Torbrook Formation is about 1500 m thick.

The age of the formation is well constrained. It contains abundant fauna that Boucot (1960) and Cumming (*in* Smitheringale, 1973) considered to be Gedinnian to Siegenien, and maybe as young as Lower Emsian (Early Devonian). In the sandy basal part of the Torbrook Formation on Spinney Brook, Bouyx *et al*. (1997) collected samples bearing *Urnochitina urna* (Eisenack), a Pridolian chitinozoan. This fossil indicates that the Torbrook Formation extends into the Late Silurian and overlaps in age with the New Canaan Formation, consistent with the field observations during this mapping project (Fig. 3).

Igneous Units

Mafic Sills

Two prominent sets of mafic sills are present in the map area (Fig. 3), similar to those exposed in the Digby-Yarmouth area (White and Barr, 2004). Type I sills are restricted to the Goldenville and Halifax groups and are inferred to be penecontemporaneous with their host rocks and, therefore, Late Neoproterozoic to Early Ordovician in age. Type II sills intruded the Goldenville and Halifax groups as well as the White Rock, Kentville, New Canaan and Torbrook formations, but predate the South Mountain Batholith; hence, they are early to middle Devonian in age and likely related to the volcanism in the Rockville Notch Group. Because of the similarities between the Type I and II sills in the map area and those in the Digby-Yarmouth area they likely have the same within-plate tholeiitic to alkalic characteristics (Trapasso, 1979; Barr *et al*., 1983; White and Barr, 2004).

South Mountain Batholith

The parts of the South Mountain Batholith in the study area were mapped and subdivided by Ham and Horne (1987) and MacDonald and Ham (1992, 1994) and hence were not systematically investigated during this study. The batholith is well exposed in the map area (Figs. 2a, b) and consists of medium- to coarse-grained granodiorite to leucomonzogranite. The batholith contains numerous xenoliths of Goldenville Group and Halifax Group rocks, ranging from a few centimetres in size to mappable areas (Fig. 2). The South Mountain Batholith has yielded U-Pb and $^{40}Ar/^{39}Ar$ zircon, monazite and muscovite ages of ca. 385–370 Ma (Clarke *et al*., 1993; Kontak *et al*., 2003; Reynolds *et al*., 2004).

Deformation and Metamorphism

The Goldenville, Halifax and Rockville Notch groups were regionally metamorphosed (chlorite zone) and deformed into northeast-trending, generally upright, tight to open folds with a well developed axial planar cleavage during the ca. 406–388 Ma Neoacadian Orogeny (van Staal, 2007; White *et al*., 2007; Moran *et al*., 2007). The Neoacadian structures were overprinted by hornblende-hornfels facies metamorphism around the late syntectonic South Mountain Batholith.

Deformation

Radiometric and fossil ages have shown that a considerable time gap exists between the top of the Halifax Group and deposition of the Rockville Notch Group. To test the possibility that the older

Goldenville and Halifax groups are more deformed than the younger Rockville Notch Group, structural data from these two domains are plotted on separate stereonets for comparison.

The Goldenville and Halifax groups are folded into a series of upright, shallow northeast- and southwest-plunging F_1 anticlines and synclines around major regional northeast-trending folds (Fig. 4). Contoured poles to bedding define a well developed girdle distribution with a shallow, northeast-plunging fold axis (Fig. 4a). Contoured poles to foliation are consistent with a steep axial planar foliation that strikes northeast (Fig. 4b). Minor F_1 folds are upright and plunge gently to the southwest and northeast (Fig. 4a), with axial plane orientations parallel to the foliation (Fig. 4a). Intersection lineations (L_1) (bedding/foliation) have shallow northeast and southwest plunges (Fig. 4b), parallel to the minor fold axes, suggesting the occurrence of doubly plunging folds. Two sets of kink bands are present. The main set has steep fold axes with steep northwest-striking kink planes (Fig. 4c). The minor set has shallow northeast and southwest plunges with near horizontal kink planes (Fig. 4c). Structures associated with the steep kinks have been observed elsewhere in the Meguma terrane and linked to northwest-trending steep faults (e.g. Smith, 1973; Horne and Pelley, 2007; White, 2008b). Contoured poles to joints display a prominent, steep, northwest-trending joint set, which is parallel to the main faults in the area and steep kink bands (Fig. 4d).

Type I sills also have been deformed into upright, shallowly northeast-plunging, northeast-trending F_1 folds with a steep axial planar cleavage (Fig. 4e). These structures mimic those in the folded host rocks (Fig. 4a) and indicate that the sills were originally emplaced horizontally along bedding planes in the Meguma Group.

The Rockville Notch Group, like the Goldenville and Halifax groups, is folded into a series of upright, shallow northeast- and southwest-plunging F_1 anticlines and synclines around regional southwest-trending folds (Fig. 5). Contoured poles to bedding define a well developed girdle distribution with a shallow, southwest-plunging fold axis (Fig. 5a). Contoured poles to foliation are consistent with a steep axial planar foliation that strikes northeast (Fig. 5b). Minor F_1 folds are upright and typically plunge gently to the southwest (Fig. 5a), with axial plane orientations parallel to the foliation (Fig. 5a). Intersection lineations (L_1) (bedding/foliation) have shallow southwest plunges (Fig. 5b), parallel to the minor fold axes. Like the older rocks, two sets of kink bands are present with identical features to the older units (Fig. 5c). Contoured poles to joints display a prominent, steep, northwest-trending joint set which is parallel to the main faults in the area and steep kink bands (Fig. 5d) A minor joint set strikes east-west and is near vertical. Type II sill orientations mimic structures in the folded country rocks (Fig. 5e and a).

The similarity between the structures in the Goldenville/Halifax groups and the Rockville Notch Group suggest that despite the apparently considerable age gap, the Goldenville and Halifax groups were not strongly deformed prior to deposition of the Rockville Notch Group and both domains were deformed together during the Neoacadian orogeny.

Metamorphism

Regional metamorphism in the map area reached chlorite zone (chlorite + muscovite + albite ± epidote), greenschist facies conditions in the pelitic rocks. Cleavage is defined by aligned fine-grained muscovite and chlorite. Intrusion of the South Mountain Batholith produced a wide, well developed contact metamorphic aureole that is superimposed on regional greenschist facies mineral assemblages and textures. The wide contact zone suggests that the edge of the batholith dips shallowly under the stratified rocks. As with other areas around the South Mountain Batholith, the first evidence of contact metamorphism is an increase in decussate biotite content.

Depending on the bulk-rock chemistry, poikilitic cordierite appears first in the mica-rich layers, produced by reactions consuming chlorite and muscovite. As metamorphic grade increases towards the batholith, poikilitic andalusite forms, which typically develops as rims on the cordierite porphyroblasts. In cordierite-poor rocks chiastolitic andalusite is common. Sillimanite (fibrolite) occurs

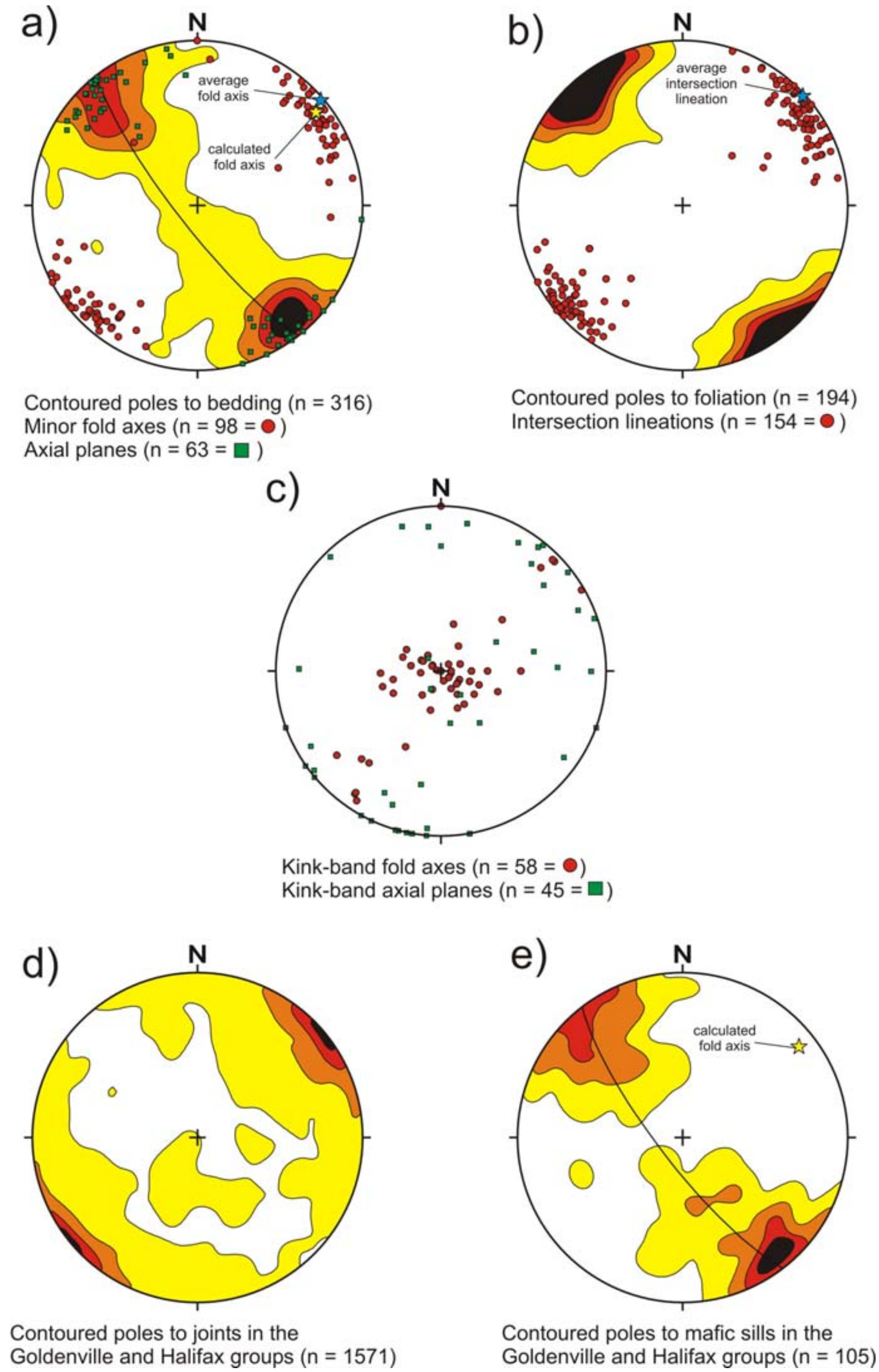

Figure 4. Equal-area stereonets of structural data from the Goldenville and Halifax groups in the map area. (a) Contoured poles to bedding, and minor F_1 fold axes and related axial plane orientations; solid great circle shows the calculated orientation of S_0 and the yellow star shows the calculated average fold axis. Blue star shows average fold axis. Contours at 1, 3, 5 and greater than 7% per 1% area; darkest shading indicates highest contour area. (b) Contoured poles to foliation and bedding-cleavage intersection lineations (L_1). Contours at 1, 3, 5 and greater than 7% per 1% area; darkest shading indicates highest contour area. (c) Plot of kink band axes and associated axial planes. (d) Contoured poles to joints in the Goldenville and Halifax groups. Contours at 1, 5, 10 and greater than 15% per 1% area; darkest shading indicates highest contour area. (e) Contoured poles to Type I mafic sills in the Goldenville and Halifax groups. Contours at 1, 3, 5 and greater than 7% per 1% area; darkest shading indicates highest contour area. The yellow star shows the calculated average fold axis.

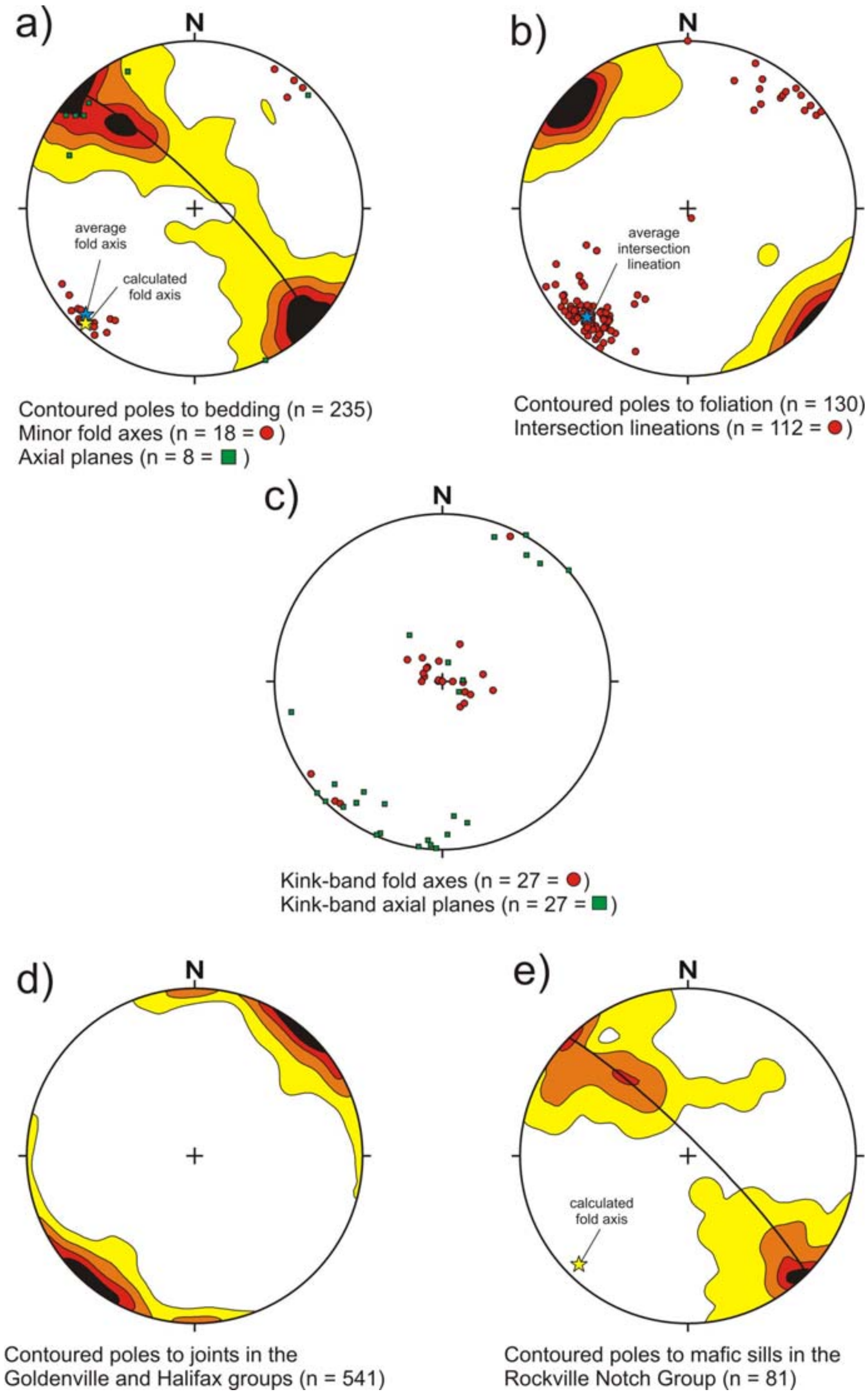

Figure 5. Equal-area stereonets of structural data from the Rockville Notch Group in the map area. (a) Contoured poles to bedding, and minor F_1 fold axes and related axial plane orientations; solid great circle shows the calculated orientation of S_0 and the yellow star shows the calculated average fold axis. Blue star shows average fold axis. Contours at 1, 3, 5 and greater than 7% per 1% area; darkest shading indicates highest contour area. (b) Contoured poles to foliation and bedding-cleavage intersection lineations (L_1). Contours at 1, 3, 5 and greater than 7% per 1% area; darkest shading indicates highest contour area. (c) Plot of kink band axes and associated axial planes. (d) Contoured poles to joints. Contours at 1, 5, 10 and greater than 15% per 1% area; darkest shading indicates highest contour area. (e) Contoured poles to Type II mafic sills in the Rockville Notch Group. Contours at 1, 3, 5 and greater than 7% per 1% area; darkest shading indicates highest contour area. The yellow star shows the calculated average fold axis.

in pelitic rocks adjacent to the contact. The mineral assemblage is characteristic of the hornblende-hornfels facies of metamorphism (e.g. Yardley, 1989).

Economic Geology

Compared to other areas in the Meguma terrane, the rocks of the Goldenville and Halifax groups in the map area do not host any known gold deposits, although Faribault (1921) described gold-bearing quartz veins in sandstone of the Goldenville Group in the Gaspereau Lake map area. A number of manganese occurrences are known in the map area (e.g. Smitheringale, 1973) but none appear to have economic potential due to their low grade and small size. The newly recognized Tupper Lake Brook Formation contains Mn-bearing siltstone and coticule nodules and may have potential. Several iron deposits were mined from 1825 to 1913 in the Nictaux-Torbrook area. Minerals consist of hematite and magnetite (± manganese minerals) occurring in narrow beds and interlayered with slate. The iron ore occurs in discrete stratigraphic horizons in the Torbrook Formation (Smitheringale, 1973).

The South Mountain Batholith has several areas with anomalous concentrations of U associated with copper and arsenic sulphides (MacDonald and Ham, 1992). The granitic rocks associated with the South Mountain Batholith and contact metamorphosed rocks of the Goldenville, Halifax and Rockville Notch groups continue to be favourable targets for base- and precious-metal exploration in the map area.

The map area has high potential for industrial minerals. Sand and gravel deposits are currently used to produce asphalt. Sandstone and slate in the Church Point and Cunard formations are currently being quarried for local aggregate use. In the past the granitic rocks of the South Mountain Batholith were quarried for local monument stone and thinly bedded rocks associated with the Kentville Formation on Gaspereau River have been used for local flagstone and building stone. The Nova Scotia Department of Natural Resources Mineral Occurrences Database for NTS map sheets 21A/14, 15 and 16; 21H/01 and 02, and the report of Cullen *et al*. (1996) contain a complete summary of mineral occurrences in the map area.

Summary

The Goldenville and Halifax groups in the map area are subdivided into several mappable formations, many of which are similar to those recognized in the Digby-Yarmouth area (White *et al*., 1999, 2001; Horne *et al*., 2000). Many new graptolite and trace fossil locations with possible age control have been documented. The stratigraphy within the newly defined Silurian to Early Devonian Rockville Notch Group has been better defined.

Regional F_1 folds trend northeast with gentle southwest- and northeast-plunging fold axes. Folds have well developed axial planar cleavage. Well developed hornblende-hornfels facies contact metamorphism was associated with emplacement of the South Mountain Batholith and overprinted chlorite grade, greenschist facies regional metamorphism. Mapping of contact metamorphic effects shows that granitic rocks of the South Mountain Batholith extend under the Goldenville and Halifax groups at shallow depths.

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