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The Big Dig: Geological and other outcomes of the 2008–2009 Freshwater Brook sewer replacement project, Halifax, Nova Scotia, Canada

Le grand creusage : répercussions géologiques et autres du projet de remplacement des égouts du ruisseau Freshwater à Halifax (Nouvelle-Écosse), Canada, en 2008-2009

Rebecca A. Jamieson

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Article abstract

In 2008 Halifax Regional Municipality undertook a major construction project to replace the underground sewer system that carries Freshwater Brook from the Halifax Commons to its outlet at the southeastern end of the Halifax Peninsula. The project was necessary because the existing system did not meet modern standards and the old pipes ran under city blocks and were therefore inaccessible in many places for maintenance and repair. The first part of the project (2008-09) involved installing a modern dual pipe system along a route that crossed the predicted locations of the boundary between the Cunard and Bluestone Quarry formations of the Halifax Group, and the biotite-in and andalusite-in isograds of the contact aureole of the South Mountain Batholith. Bedrock was exposed along much of the excavated trench, which was nearly 10 m deep in many places. Outcrop observations and samples from the trench revealed that the Cunard-Bluestone Quarry contact runs under the Sobeys parking lot, between Fenwick and Queen streets. The andalusite-in isograd in the Cunard Formation can be traced as far as the west end of Fenwick Street. The cordierite-in isograd lies east of the study area, and the biotite-in isograd to the west. The lithology and isograd map for south end Halifax has been updated based on these results. Problems including uncertain subsurface location of the old pipes, contaminated soil, and carbon monoxide migration into residential buildings contributed to significant delays and cost overruns; some of these might have been mitigated with better knowledge of the subsurface geology.

The Big Dig: geological and other outcomes of the 2008–2009 Freshwater Brook sewer replacement project, Halifax, Nova Scotia, Canada†

Rebecca A. Jamieson

Department of Earth and Environmental Sciences, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada
Corresponding author: <beckyj@dal.ca>

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ABSTRACT

In 2008 Halifax Regional Municipality undertook a major construction project to replace the underground sewer system that carries Freshwater Brook from the Halifax Commons to its outlet at the southeastern end of the Halifax Peninsula. The project was necessary because the existing system did not meet modern standards and the old pipes ran under city blocks and were therefore inaccessible in many places for maintenance and repair. The first part of the project (2008-09) involved installing a modern dual pipe system along a route that crossed the predicted locations of the boundary between the Cunard and Bluestone Quarry formations of the Halifax Group, and the biotite-in and andalusite-in isograds of the contact aureole of the South Mountain Batholith. Bedrock was exposed along much of the excavated trench, which was nearly 10 m deep in many places. Outcrop observations and samples from the trench revealed that the Cunard-Bluestone Quarry contact runs under the Sobeys parking lot, between Fenwick and Queen streets. The andalusite-in isograd in the Cunard Formation can be traced as far as the west end of Fenwick Street. The cordierite-in isograd lies east of the study area, and the biotite-in isograd to the west. The lithology and isograd map for south end Halifax has been updated based on these results. Problems including uncertain subsurface location of the old pipes, contaminated soil, and carbon monoxide migration into residential buildings contributed to significant delays and cost overruns; some of these might have been mitigated with better knowledge of the subsurface geology.

RÉSUMÉ

La Municipalité régionale de Halifax a entrepris en 2008 un projet de construction d'envergure visant le remplacement du réseau d'égout souterrain acheminant le ruisseau Freshwater du parc municipal de Halifax à son embouchure à l'extrémité sud-est de la presqu'île d'Halifax. Le projet s'avérait nécessaire parce que le réseau existant ne répondait pas aux normes modernes : les vieux tuyaux se trouvaient sous des pâtés de maisons et étaient en conséquence inaccessibles en de nombreux endroits pour l'entretien et les réparations. La première tranche du projet (2008-2009) a comporté l'installation d'un réseau moderne à deux tuyaux franchissant les emplacements prévus de la limite entre les formations de Cunard et de Bluestone Quarry du Groupe de Halifax, ainsi que les isogrades d'apparition de la biotite et de l'andalousite de l'auréole de contact du batholite du mont South. le substrat rocheux a été dénudé le long d'une vaste part de la tranchée creusée, qui avait près de 10 m de profondeur en nombre d'endroits. Des observations de l'affleurement et d'échantillons de la tranchée ont révélé que la zone de contact de Cunard-Bluestone Quarry s'étendait sous le terrain de stationnement du Sobeys, entre les rues Fenwick et Queen. l'isograde d'apparition de l'andalousite dans la Formation de Cunard peut être retracé jusqu'à l'extrémité ouest de la rue Fenwick. l'isograde d'apparition de la cordiérite se situe à l'est du secteur d'étude et celui de la biotite est à l'ouest. les intervenants ont mis à jour la carte de la lithologie et des isogrades du quartier sud de Halifax en fonction de ces observations. Divers problèmes, dont l'emplacement souterrain incertain des vieux tuyaux, le sol contaminé et la migration du monoxyde de carbone dans les bâtiments résidentiels, ont contribué à des retards importants et des dépassements des coûts. On aurait pu atténuer certains de ces problèmes en connaissant mieux la géologie de subsurface.

[Traduit par la redaction]

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INTRODUCTION

The South Mountain Batholith (SMB), the largest plutonic complex in the Appalachian orogen, intruded deformed late Proterozoic to early Paleozoic rocks of the Meguma Supergroup, southern Nova Scotia, at ca. 380 Ma (Fig. 1; McKenzie and Clarke 1975; Horne and Culshaw 2001; MacDonald 2001; White and Barr 2012; Bickerton *et al.* 2022). Deformation was accompanied by greenschist-facies metamorphism at ca. 410–400 Ma (Hicks *et al.* 1999) during the Kejimkujik orogeny (Barr *et al.* 2022). Intrusion of the Halifax Pluton of the SMB at ca. 375–370 Ma (MacDonald and Horne 1988; Bickerton *et al.* 2022) produced a low-pressure contact metamorphic aureole in Halifax and Goldenville Group rocks (White and Goodwin 2011; Jamieson *et al.* 2012; Hilchie and Jamieson 2014). In the Halifax Regional Municipality (HRM), mineral assemblages and isograds within the Halifax Group (Fig. 1) indicate pressures (P) on the order of 2.5–3.0 kb (0.25–0.3 GPa) and temperatures (T) ranging from 360°C in the outermost part of the contact aureole to 650°C near the contact with the Halifax Pluton (Jamieson *et al.* 2012; Hilchie and Jamieson 2014). The pluton itself is not exposed on the Halifax Peninsula (White *et al.* 2008, 2014; Jamieson *et al.* 2012).

The urban setting of the Halifax Regional Municipality (HRM) poses a major challenge in documenting isograds and other systematic changes in the petrology and geology of the contact aureole. Exposures are limited to scattered outcrops in parks and private yards, increasingly limited sections of public shoreline, highway roadcuts on the outskirts of the city, and the railcut that runs from south to north along the western side of the Halifax Peninsula (Fig. 1). Access to many of these exposures can be difficult owing to traffic and private property issues. Moreover, since its construction 100 years ago, the railcut has undergone significant weathering, with outcrop details partly obscured by rust, soot, and graffiti. To compensate for this problem, construction sites in HRM were systematically sampled by the author, students, and colleagues over a couple of decades (roughly 1997–2017). Although ephemeral, these exposures offered the opportunity to observe and sample fresh outcrops throughout HRM, allowing detailed documentation of the geology and petrology of the contact aureole (Jamieson *et al.* 2012).

In 2008, Halifax Water began a major construction project to replace the long-buried Freshwater Brook Sewer system. During the first 3 phases of the project, trenches dug to house the new pipes ran along parts of Inglis, Queen, Fenwick, and South Park streets in the south end of HRM, including directly past the author's former home. The proposed trench route crossed the poorly exposed geological contact between the Cunard and Bluestone Quarry formations of the Halifax Group (e.g., Waldron *et al.* 2015) and inferred isograds in the outer part of the contact aureole. This paper reports results from a set of samples and other observations collected along the Freshwater Brook trench in 2008–2009 (Jamieson 2010).

FRESHWATER BROOK SEWER REPLACEMENT PROJECT

Early maps of Halifax (Hopkins 1878; Figs. 2a, 3a) show that Freshwater Brook (also Fresh Water Brook or Freshwater River) originated in the north end of the city near what is now Fort Needham, ran south to a marshy area where the Halifax Common is now, and from there continued south, meeting Halifax Harbour near present-day Pier 23 and the grain elevator (Reid 2012; Halifax Public Libraries 2022). Except for a short exposed section in the Halifax Public Gardens, most of the brook was subsequently confined below the surface (e.g., Fig. 3b) in cast-iron pipes more than a century old. Some of the largest buildings in peninsular Halifax, including Fenwick Tower and Park Victoria, were constructed directly over the buried pipes, making access by Halifax Water for inspection, maintenance, or repair virtually impossible.

In 2006, Halifax Water and HRM Council proposed an ambitious infrastructure project to be funded by the then recently established Canada Strategic Infrastructure Fund (Halifax Regional Council 2006a), to maintain HRM regulatory compliance for its stormwater and wastewater systems. The aging sewer system housing the former Freshwater Brook would be replaced with a modern dual system that would separate storm and sanitary water streams and relocate the pipes to a more accessible route running underneath city streets. The project arose from a study that addressed the feasibility of daylighting several former brooks and streams that had been buried beneath city buildings and streets over the past century (Halifax Regional Council 2006b). Given its location within a highly developed urban environment, daylighting Freshwater Brook was ultimately considered unfeasible, and the decision was made to upgrade and replace the existing underground system instead. In 2006 the cost was estimated to be $5 million, but this had risen to $10.2 million by the time the project was approved in July 2007 (Halifax Water 2008a). Following tendering the revised cost had increased to $13.7 million (Halifax Water 2008b, 2009), and in July 2010 additional funds were approved, bringing the total cost for the completed project to $16.7 million (Halifax Water 2010).

The project involved laying new pipes beneath parts of Inglis Street, Victoria Road, Queen Street, Fenwick Street, and South Park Street (Fig. 2b), and was originally anti-

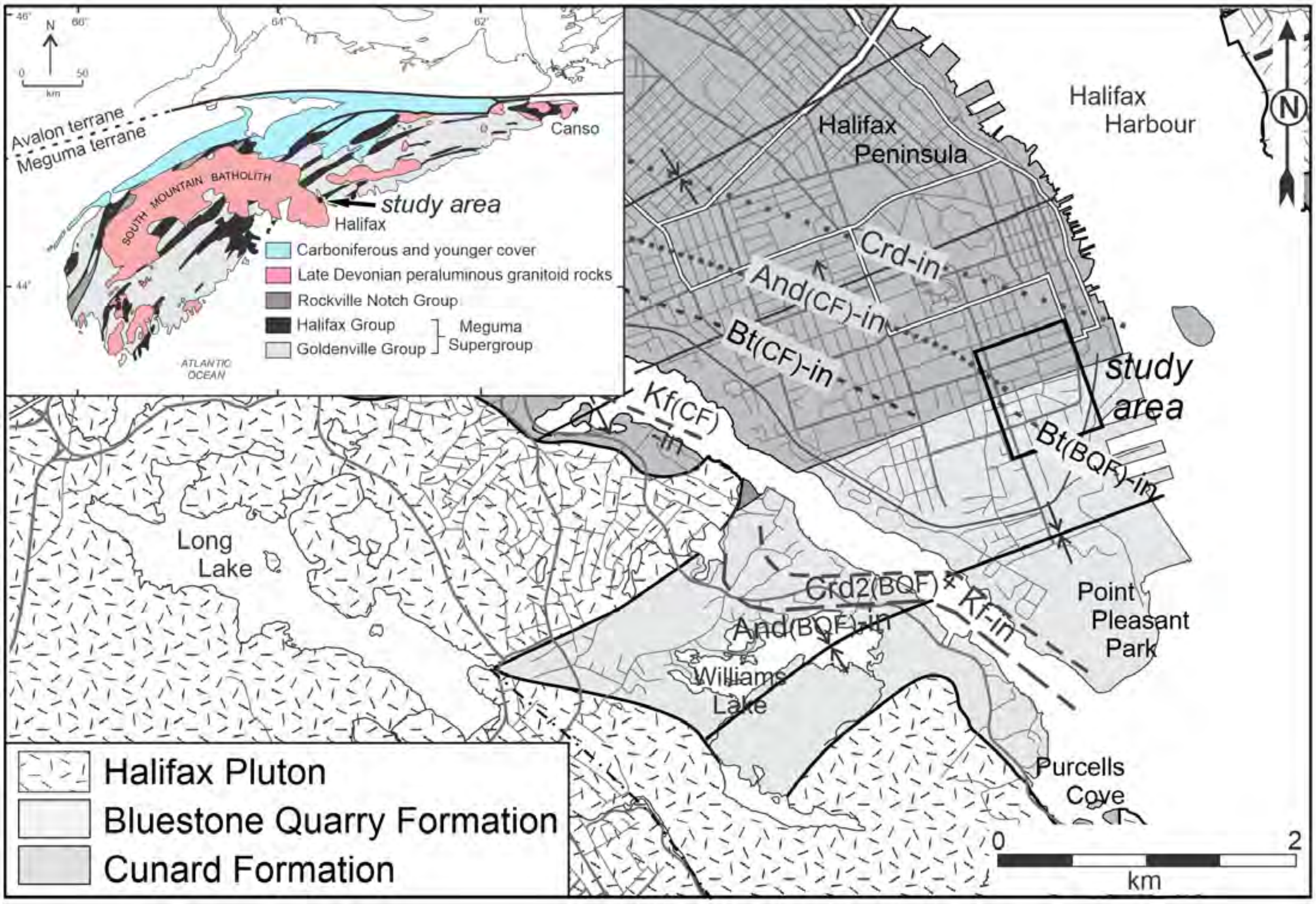

Figure 1. Geology of the Halifax Peninsula and adjacent mainland, showing distribution of the Halifax Pluton, Halifax Group metasedimentary units (Bluestone Quarry and Cunard formations), and isograds within the contact aureole (dashed lines; after Jamieson *et al.* 2012; Hilchie and Jamieson 2014). Abbreviations CF and BQF in isograd names indicate contrasting assemblages in Cunard and Bluestone Quarry formations, respectively, reflecting different bulk compositions; abbreviations omitted for clarity in Figures 4 and 6. Inset shows simplified Meguma terrane geology (modified with permission from White and Nickerson 2021). Box outlines study area (details in Figs. 2b, 4).

cipated to take about 6 months. Work on the Victoria Road – Queen Street section started in summer 2008 and had reached the Queen Street Sobeys parking lot by October. Delays were encountered during this phase of construction when testing revealed that contaminated soil was present near some former industrial sites. When excavation of the east end of Fenwick Street began in late October, it was determined that the buried pipes were not where they were expected to be ("unexpected subsurface conditions"; Halifax Water 2010). Work was suspended for a few months while the part of the system linking Queen and Fenwick streets was redesigned. However, the old, excavated pipes were in very poor condition and could not be reburied; consequently the east end of the street remained closed until spring 2009 when construction resumed. Work along Fenwick Street continued through the summer, with a brief interruption in early July when carbon monoxide (CO) leaked into the basements of homes near the intersection of Fenwick and Lucknow streets (CBC Archives 2009). Bedrock blasting in this area was initially done under the existing street surface with the intention of limiting potential damage to nearby structures. Unfortunately, CO released by the blasting material was confined beneath the pavement, and leaked into the pipes linking the homes to the main system, a problem that should have been anticipated (e.g., Martel *et al.* 2004a, b). The street surface was removed prior to subsequent blasting and the problem did not recur. Work on the South Park Street section began in August 2009. The two sec-

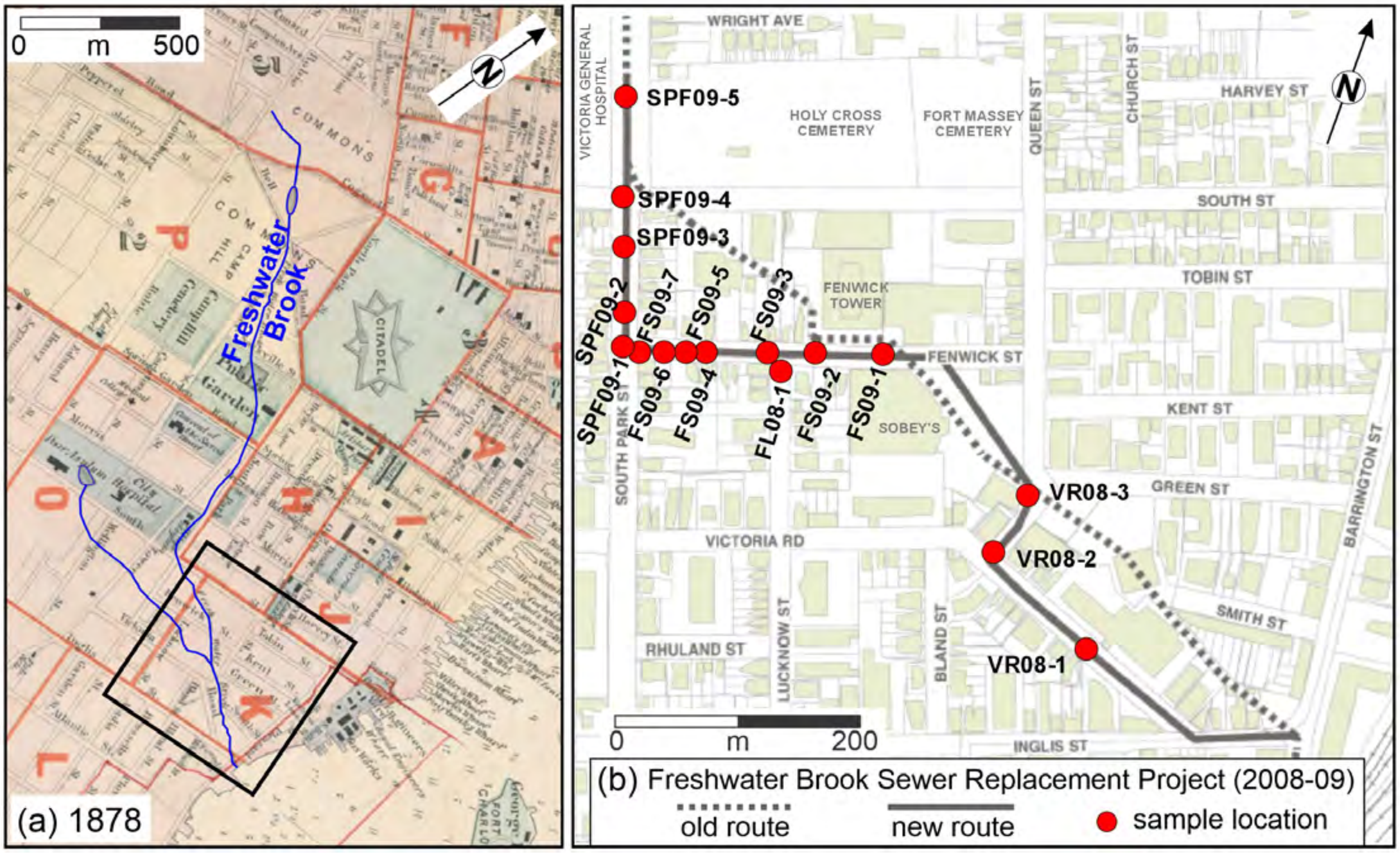

Figure 2. (a) Excerpt from index map to 1878 Halifax City Atlas (Hopkins 1878). Freshwater (Fresh Water) Brook, then mostly exposed, is highlighted in blue. Older maps (Reid 2012; Halifax Public Libraries 2022) suggest that the brook originated near Fort Needham in the north end of the city; only its southern part is shown here. Box outlines area shown in panel b. (b) Route of Freshwater Brook buried sewer lines pre-2008 (dashed line) and post-2009 (solid line) (Halifax Water 2008). Numbered red dots are locations of samples taken from excavated trench; observations plotted in Figure 4.

tions were linked and the streets repaved and reopened in December 2009, a year after the original completion date. This brought welcome relief to residents and businesses along Fenwick Street, which had been closed in whole or in part for most of the previous 12 months.

Work was finally completed in 2011 with the abandonment of the old pipe beneath the Sobeys parking lot between Fenwick and Queen streets (CBC Archives 2011). The long-term project continued in the 2020's with replacement of a section beneath the south Halifax Common in conjunction with construction of a new parkade for the QEII Health Sciences Centre (2020-2021), and the Cathedral Lane section (begun in 2024) between Spring Garden Road and University Avenue adjacent to Victoria Park.

BEDROCK GEOLOGY OF THE TRENCH

The geology and structure of the Meguma Supergroup in the Halifax area are well documented (Horne and Culshaw 2001; White *et al.* 2008, 2014; White and Goodwin 2011; Jamieson *et al.* 2012; Waldron *et al.* 2015); only aspects directly relevant to the present work are reviewed here. The study area is underlain by the Cunard and Bluestone Quarry formations of the Halifax Group. The stratigraphic contact between the two units runs across south end Halifax, south of and approximately parallel to South Street (Fig. 1); its location on the eastern side of the Halifax Peninsula is not well constrained owing to lack of exposure.

The rocks were folded into a series of regional-scale upright folds (e.g., Horne and Culshaw 2001), including the Point Pleasant syncline in the study area (White *et al.* 2008, 2014; Waldron *et al.* 2015). The associated slaty cleavage dips steeply to the northwest. Deformation was

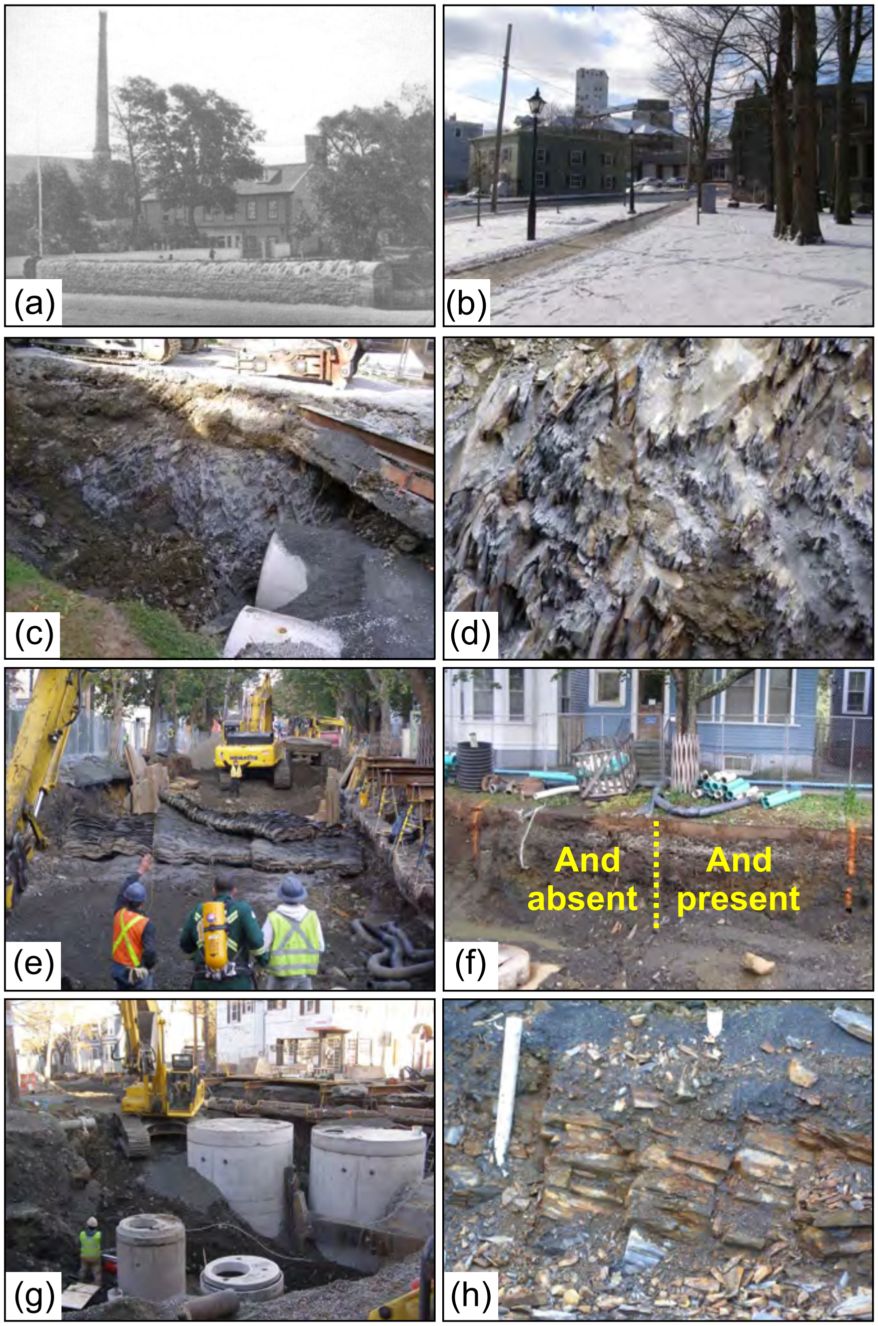

Figure 3. **Freshwater Brook historical image and 2008-09 excavation trench. (a) "Kissing Bridge" at intersection of Inglis and Pleasant (now Barrington) streets, ca. 1920, near southern end of Freshwater Brook, then exposed. (b) Same site, now Raymond Taavel Park, in January 2010; brook completely confined to buried pipes. (c) Excavation trench near corner of Queen Street and Victoria Road, September, 2008, with dual pipe system partly installed. (d) Outcrop of Bluestone Quarry Formation metasiltstone in trench walls, south end of Queen Street, near sample site VR08-2. (e) Excavation in progress, Fenwick Street, late July 2009. Rubber blasting mats were used to damp effects of blasting following decision to remove pavement to prevent CO from migrating into nearby buildings. (f) Cunard Formation slate in trench wall on south side of Fenwick Street (directly outside author's former home), August 2009, near sample site FS09-4. Approximate position of andalusite (And) isograd shown. Vertical orange paint lines mark locations of broken sewer pipes (not capped or diverted during construction). (g) Excavation at corner of South Park and Fenwick streets, September, 2009, showing dual vertical access pipes. (h) Cunard Formation slate in trench wall near corner of South Park and Fenwick streets, near sample site SPF09-1.**

accompanied by greenschist-facies regional metamorphism, which was overprinted by the contact metamorphism described below. The bedrock geology of the trench is described from south to north, the order in which various sections of the trench were excavated. Halifax Water denied civilians direct access to the trench owing to potential “contamination” (i.e., raw sewage) released during the excavations. Although some structural measurements were made from the top of the trench, they are subject to considerable uncertainty. Bedrock samples were obtained from specified sites by construction workers at the request of (and directed by) the author, but collecting oriented samples was not possible.

Victoria Road to Queen Street – Bluestone Quarry Formation

Construction began along this section in the late summer and fall of 2008, with observations and samples (VR08-1–3; Fig. 2b) collected in September 2008. The outcrops consist mostly of blue-grey metasiltstone with some black slate horizons (Fig. 3c, d) observed locally. Bedding dips moderately to the south and is cut by a steep, northwest-dipping, slaty to spaced cleavage (Fig. 3d) striking oblique to the trench walls (Fig. 4). The dominance of blue-grey metasiltstone over black slate, along with well preserved cross-bedding observed in some parts of the trench, indicates that this part of the section should be assigned to the Bluestone Quarry Formation. However, calcareous concretions characteristic of this unit (Jamieson *et al.* 2012; Waldron *et al.* 2015) were not observed in the relatively short section that was exposed.

Fenwick Street – Cunard Formation

Following redesign of the system linking Fenwick and Queen streets, excavation at the east end of the street began in May 2009, reaching South Park Street by August. No bedrock was exposed at the eastern end of the trench, which cut through the southwestern edge of the Queen Street drumlin, but semi-continuous bedrock was observed and sampled from Fenwick Tower to South Park Street (FS09-1–7; Fig. 2b). The bedrock consists of thinly bedded black slate of the Cunard Formation (Fig. 3f, h) with subordinate metasiltstone layers. Bedding dips moderately to the south and the rocks exhibit a strong northwest-dipping slaty cleavage; both strike approximately parallel to the street (Fig. 4). The trench-parallel strike meant that there was minimal variation in bedrock characteristics along the length of the trench; orientation measurements were difficult to make and are therefore imprecise.

South Park Street – Cunard Formation

Excavation along South Park Street began in July 2009 and continued through the fall as far north as the entrance to the Victoria General Hospital parking lot. Unfortunately, traffic and pedestrian barriers along this busy thoroughfare were placed well back from the trench walls, making systematic observations of the bedrock geology difficult and measurement nearly impossible except near the intersection of Fenwick Street. Samples SPF09-1–5 (Fig. 2b) were collected between August and October 2009. The trench exposed a ca. 200 m cross-section through the upper part of the Cunard Formation (Figs. 2b, 4). Like the Fenwick Street section, the rocks consist mainly of thinly bedded black slate with minor metasiltstone; metasiltstone horizons appeared to be more common near the northern end of the trench. Bedding dips moderately to the south and cleavage steeply to the northwest, except near the South Street – South Park Street intersection, where orientations of bedding and cleavage appear to be irregular. Sample SPF09-4 from this location has well developed slickensides. On this basis, it seems likely that a fault runs beneath this intersection (Fig. 4), although without access to the trench no specific information could be obtained about its orientation or kinematics.

PETROGRAPHY AND MINERAL ASSEMBLAGES

All the samples collected during this study are fine-grained slate and metasiltstone with a well-developed slaty cleavage (S_1). All contain the regional greenschist facies mineral assemblage muscovite + chlorite + albite + quartz+ graphite + Fe-sulphide + Ti-Fe-oxide (MCAQGFT; e.g., Jamieson *et al.* 2012), in addition to characteristic porphyroblast phases (“ghost” cordierite, andalusite) formed during contact metamorphism. Neither biotite nor fresh cordierite was observed in any of the samples.

Bluestone Quarry Formation

This unit is dominated by well-bedded fine-to medium-grained slate and quartz-rich metasiltstone with S_1 defined by aligned micas and chlorite (Fig. 5a, b). Fine-grained layers (Fig. 5a, c) contain the MCAQGFT regional assemblage, as well as poorly defined, ovoid, chlorite + muscovite-rich patches interpreted as retrogressed cordierite by Jamieson *et al.* (2012). The non-genetic term “ghost” cordierite is used here for these features, as it is not clear whether they represent formerly fresh cordierite crystals that have been completely retrogressed, or whether they represent incipient cordierite that had just begun to form. The slate is similar in texture and mineral assemblage to Cunard Formation slate, and it would be difficult to distinguish the two units based on thin sections alone. Metasiltstone layers (Fig. 5a, d) are significantly coarser-grained, with more quartz +

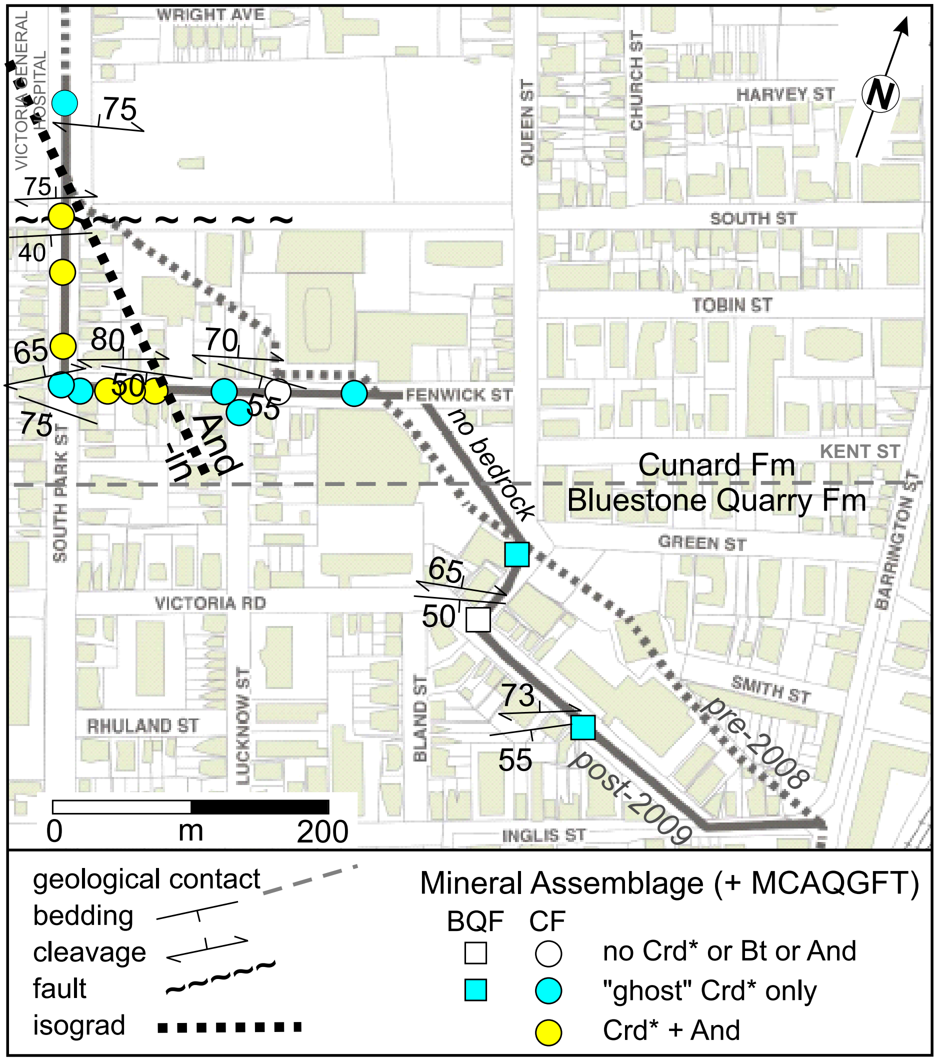

Figure 4. Observations from outcrops and samples along the excavated trench (pre-2008 = old route; post-2009 = new route). Sample numbers in Figure 2b. Bedding and cleavage measurements made from the top of the trench and are therefore approximate. Cunard-Bluestone Quarry contact inferred from outcrop farther west (see Fig. 6) and the present study. Trace of South Street fault not known east of the study area. Mineral assemblages from bedrock samples: Crd* = "ghost" cordierite (explanation in text); And = andalusite (variety chiastolite); Bt = biotite; MCAQGFT = regional greenschist facies assemblage (Ms+Chl+ Ab+Qz+Gr+Fe sulphide+Ti-Fe oxide; Jamieson *et al.* 2012).

plagioclase and less sheet silicate than interlayered slate. Large pyrrhotite porphyroblasts in the metasiltstone layers (Fig. 5a) are elongate parallel to S_1 in the plane of the thin section and partly altered to pyrite and Fe-hydroxides. Accessory apatite, zircon, and allanite are present in some samples and the dominant oxide mineral is rutile. Both slate and metasiltstone contain ovoid chlorite-muscovite stacks (Fig. 5d) interpreted to have formed during the early stages of cleavage formation (Jamieson *et al.* 2012); at higher grades biotite first nucleates in these stacks. The trench did not intersect the predicted position of the biotite-in isograd (Fig. 6), and no biotite was observed in any of the samples collected.

Cunard Formation

The lowest-grade samples are mainly fine-grained black slate with the characteristic MCAQGFT assemblage and a strong slaty cleavage (S_1) defined by aligned mica, chlorite, and graphite (Fig. 5b, e, f). Some variation in grain size and composition is evident within and between samples, with coarser-grained layers (Fig. 5b, h) containing more quartz and less chlorite, graphite, and mica than finer-grained layers. Both lithologies contain relatively fine-grained chlorite-muscovite stacks typical of this unit elsewhere (Fig. 5e); biotite is not present. "Ghost" cordierite is found in

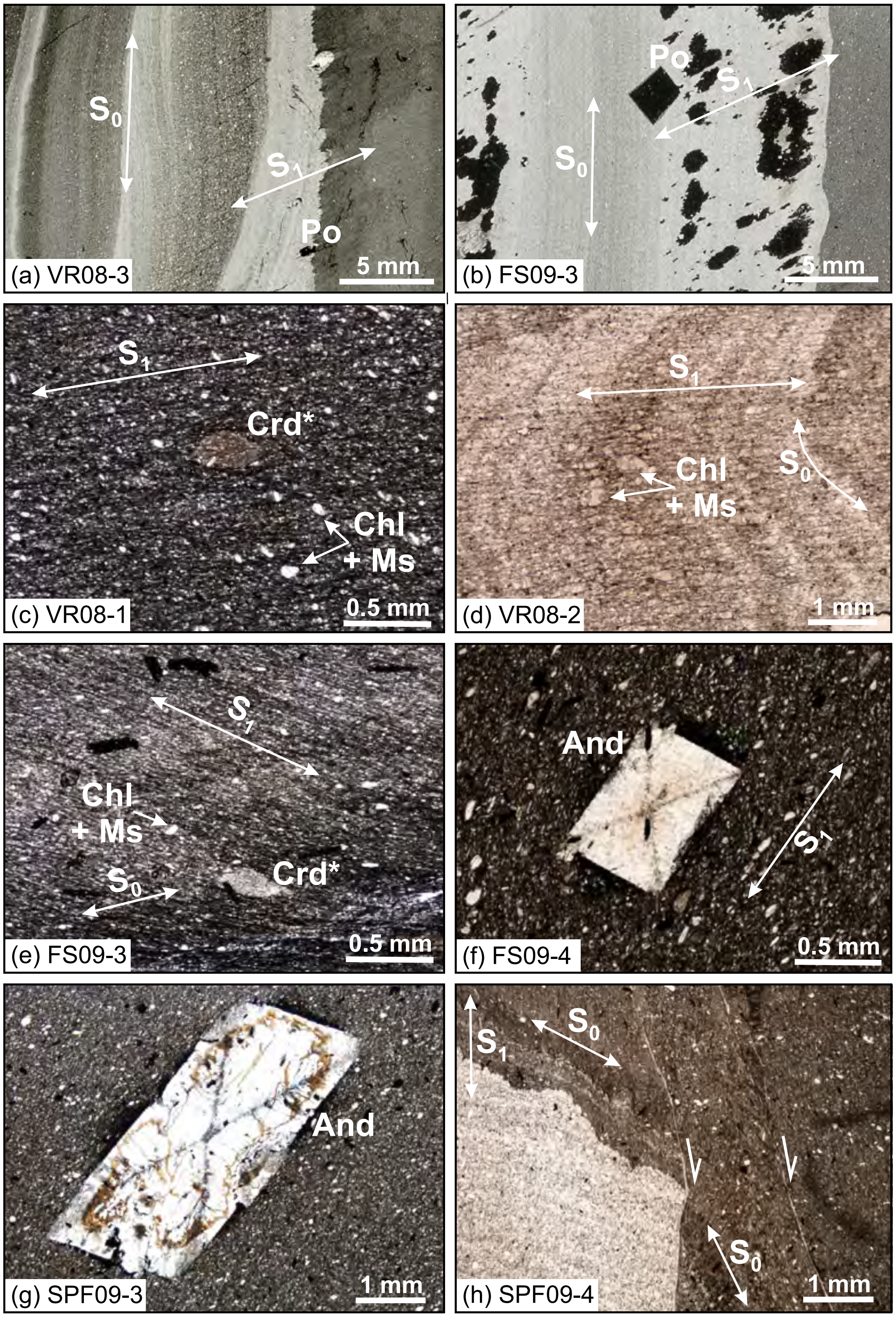

Figure 5. Petrography of representative samples from the trench (locations in Fig. 2b). (a, b) Low-magnification views of compositional layering in VR08-3 (Bluestone Quarry Formation) and FS09-3 (Cunard Formation); note concentration of pyrrhotite in coarser-grained layers. (c, d) Bluestone Quarry Formation samples, showing details of slate (VR08-1) and metasiltstone (VR08-2) layers. (e-h) Cunard Formation samples. Note andalusite porphyroblasts with graphitic shadows in samples FS09-4 (f) and SPF09-3 (g), and offsets along fractures in sample SPF09-4 (h) attributed to effects of South Street fault. Porphyroblast phases: Po = pyrrhotite; Crd* = ovoid patches referred to as "ghost" cordierite (see text); And = andalusite (chiastolite); Chl + Ms = chlorite-muscovite stacks. S_0 = bedding; S_1 = slaty cleavage.

most samples (Fig. 5e), and pyrrhotite porphyroblasts are abundant in coarser-grained layers (Fig. 5b). Pyrrhotite is elongate parallel to S_1 (Fig. 5b), variably altered to pyrite and Fe-hydroxide, and locally hosts very small chalcopyrite and galena grains. Accessory monazite and apatite are present in most samples; the dominant oxide mineral is rutile below the andalusite-in isograd and ilmenite at higher grades.

The appearance of andalusite porphyroblasts (FS09-4; Fig. 5f) marks a significant change in mineral assemblage along the Fenwick Street section of the trench. In samples FS09-4 and FS09-5 andalusite (variety chiastolite) is sparse, small (~1 mm across), and strongly retrogressed to fine-grained white mica (Fig. 5f). However, samples collected along South Park Street contain abundant andalusite porphyroblasts up to 5 mm long (Fig. 5g). In most samples andalusite is accompanied by graphite-rich mica-depletion

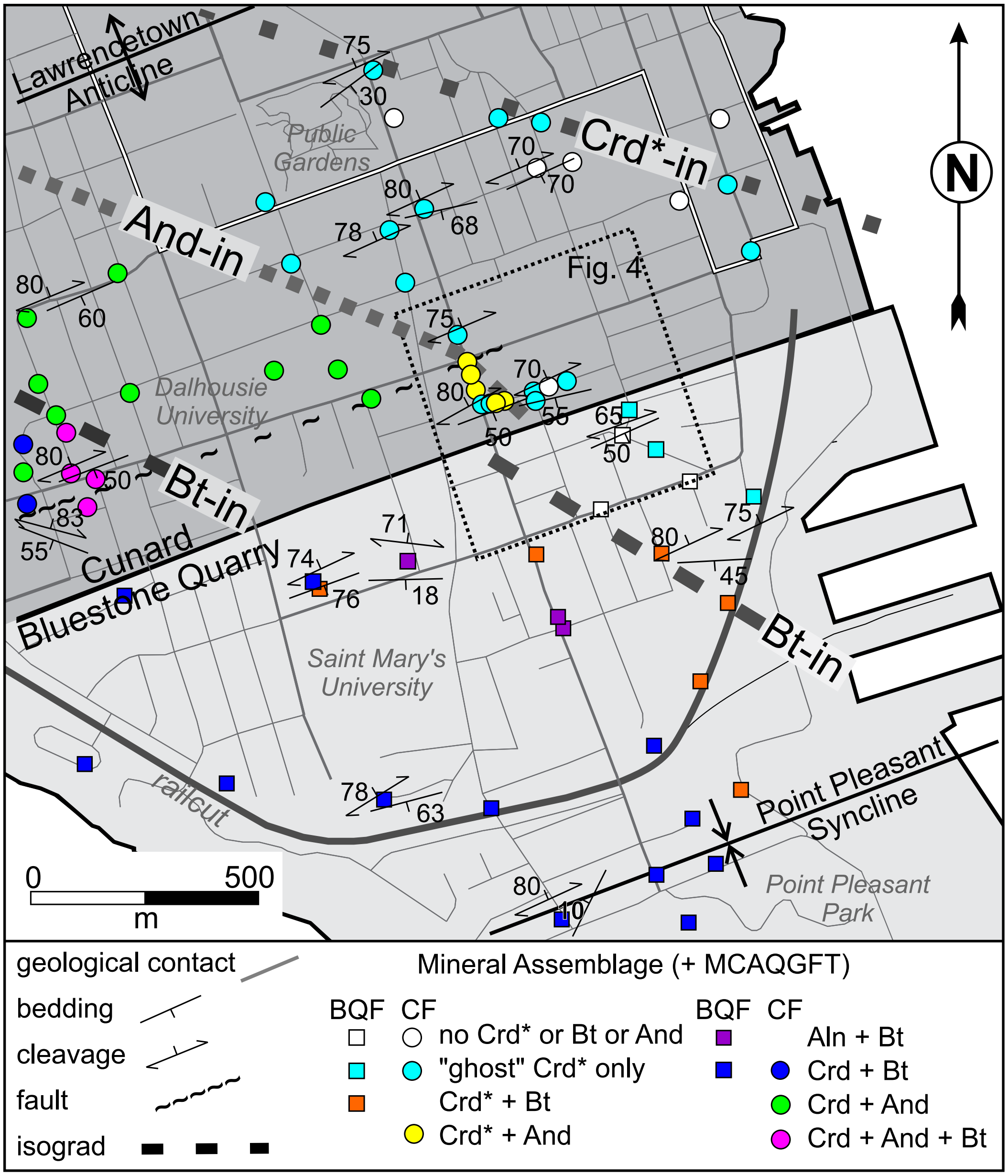

Figure 6. **Bedrock geology and mineral assemblages in south end Halifax, showing study area (dotted outline, Fig. 4) in context. Results outside the study area from Jamieson *et al.* (2012) and unpublished data collected since 2012. For more detail on the lithology and structure of the Bluestone Quarry Formation see Waldron *et al.* (2015). Porphyroblast phases: Crd* = "ghost" cordierite (see text); Crd = fresh cordierite; Bt = biotite; And = andalusite (chiastolite); Aln = allanite; MCAQGFT = Ms + Chl + Ab + Qz + Gr + Fe-sulphide + Ti-Fe oxide (regional greenschist-facies assemblage).**

shadows (Fig. 5f, g), in some cases slightly elongate parallel to S_1 (Fig. 5f). The first appearance of andalusite in FS09-4, and its absence from otherwise similar samples FS09-3 and SPF09-5, is interpreted to mark the location of the andalusite-in isograd in the study area (Figs. 4, 6). Sample SPF09-4, collected from the intersection of South Park and South streets (Fig. 4), displays a spaced fracture cleavage that offsets bedding (Fig. 5h). This is interpreted to reflect proximity to the South Street fault, consistent with prominent slickensides on hand samples from this location.

DISCUSSION

The systematic changes in lithology and mineral assemblage described above place constraints on the location of the stratigraphic contact between the Bluestone Quarry and Cunard formations, and on the position of the andalusite-in isograd in the Cunard Formation. Although the cordierite-in and biotite-in isograds are interpreted to run close to the study area (Fig. 6), samples obtained for this study offer no additional constraints on their positions. In addition, a previously unmapped post-metamorphic fault was recognized in the vicinity of South Street. In combination with previously reported results (Jamieson *et al.* 2012) these data contribute to improved documentation and better understanding of the geology and petrology of the Halifax Group in south end Halifax which can be used to test and refine existing petrological and tectonic interpretations (e.g., Hilchie and Jamieson 2014). The results are also relevant to improving estimates of construction costs linked to testing for metallic contaminants (e.g., arsenic and manganese; Jacques Whitford 2008b; White and Goodwin 2011), excavation methods (drilling vs blasting in slate vs hornfels), disposal of waste rock (mitigation of acid rock drainage from sulphidic slate; e.g., Jacques Whitford 2008a, White and Goodwin 2011), and mitigation of carbon monoxide (CO) produced by blasting (e.g., Martel *et al.* 2004a, b).

Bluestone Quarry – Cunard contact

The stratigraphic contact between the Bluestone Quarry and Cunard formations runs east-west across the south end of Halifax, south of and approximately parallel to South Street (Figs. 1, 4; Jamieson *et al.* 2012, Waldron *et al.* 2015). West of the Northwest Arm it is obscured by the Halifax Pluton, which was intruded approximately along the contact (Fig. 1; Jamieson *et al.* 2012). On the west side of the Halifax Peninsula it is well located in the railway cut (Waldron *et al.* 2015) but lack of exposure in the central and eastern peninsula made its location there uncertain. Criteria for distinguishing the two units include the dominance of graphitic black slate vs. blue-grey metasiltstone in the Cunard vs. Bluestone Quarrie formations and the presence of calcareous concretions in the latter, as well as distinctive bulk compositions and metamorphic mineral assemblages (White and Goodwin 2011; Jamieson *et al.* 2012; Waldron *et al.* 2015). The actual contact was not exposed in the Freshwater Brook trench owing to lack of bedrock outcrop beneath the Queen Street drumlin (Fig. 2b), but its location was narrowed down to within 100 m based on a clear contrast between metasiltstone-dominated and slate-dominated lithologies. Although calcareous concretions were not observed, contrasting metamorphic mineral assemblages are compatible with those noted elsewhere in the outer part of the contact aureole. On this basis, the contact is inferred to run just south of Fenwick Street, beneath the parking lot of the Sobeys supermarket on Queen Street (Figs. 2b, 4). Its orientation was not observed but it is interpreted to strike northeast-southwest and dip moderately to the southeast.

Sample SPF09-4 from the intersection of South and South Park streets (Fig. 2b) displays slickensides and centimetre-scale offsets of bedding in thin section (Fig. 5h); variable orientations of bedding and cleavage were observed in the trench. On this basis a fault has been inferred at this location, although no direct information could be obtained about its orientation or kinematics. A bedrock ridge trending approximately parallel to South Street from the Dalhousie campus to the Victoria General Hospital may mark its trace further to the west (Figs. 4, 6). Samples obtained from the south-facing wall of this ridge in 2016 during excavation for an extension to Dalplex are fractured and retrogressed, consistent with the possible presence of a nearby fault, although no slickensides or obvious lithological offsets were observed at the site.

Isograds

The dominant regional metamorphic assemblage in both units consists of muscovite + chlorite + quartz + albite + graphite + Fe-sulphide and Ti-Fe oxide. In both units, the appearance of "ghost" cordierite at ca. 360°C (RSCM thermometry; Hilchie and Jamieson 2014) marks the outer limit of the contact aureole (Jamieson *et al.* 2012; Fig. 1). The cordierite-in isograd is predicted to run northeast of the study area (Fig. 6) and its position was not constrained further by the present results.

At higher grades, contrasting bulk compositions of the Cunard and Bluestone Quarry formations result in contrasting sequences and placement of key isograds (Figs. 1, 6; Jamieson *et al.* 2012; Hilchie and Jamieson 2014). The position of the andalusite-in isograd in the Cunard Formation was refined based on observations from the study area. Previous work (Jamieson *et al.* 2012) showed that andalusite appears before biotite in highly aluminous Cunard Formation graphitic slate, at ca. 420°C (Hilchie and Jamieson 2014). This unusual sequence was confirmed in this study; the first appearance of andalusite part way along the Fenwick Street trench section (FS09-4; Fig. 5f) allowed the position of the isograd to be determined within about 20 m. The orientation of the isograd can be approximated from the presence of large chiastolite porphyroblasts in several samples from the South Park Street section (Fig. 5g) and its absence from the only sample collected north of South Street (SPF09-5; Figs. 2b, 4). In the latter case, the lack of andalusite could also indicate minor offset of the isograd by the South Street fault or a slightly less aluminous bulk composition for that sample. The mineral assemblage in andalusite-cordierite zone samples is andalusite + cordierite + mica + chlorite + quartz + albite + graphite + Fe-sulphide (mostly pyrrhotite) + (Fe-)Ti oxide (ilmenite with minor rutile), with accessory monazite and apatite.

In the Bluestone Quarry Formation, biotite appears after cordierite (Jamieson *et al.* 2012) at ca. 420–430°C (Hilchie and Jamieson 2014). Biotite is not present in Bluestone Quarry Formation samples from the excavated section, which lies east of the predicted position of the isograd (Fig. 6; Jamieson *et al.* 2012). Although the present study offered no further constraints on its position, the observations are consistent with previous interpretations. The mineral assemblage in nearby biotite-cordierite zone samples is biotite + muscovite + cordierite + quartz + albite + graphite + rutile ± chlorite ± Fe-sulphide (mostly pyrrhotite), with accessory apatite, allanite, and zircon (possibly detrital). Variations in the typical mineral assemblage (e.g., absence of cordierite, rare allanite porphyroblasts; Fig. 6) are attributed to local variations in bulk composition.

Practical applications

This study points to the relevance of understanding details in the bedrock geology when major construction projects are planned and costed. For example, arsenic, manganese, and lead detected during testing of contaminated soil excavated along Queen Street (Jacques Whitford 2008b) were predictable given knowledge of the bedrock geochemistry (e.g., White and Goodwin 2011). The metal content was considered "naturally occurring" and no further action was taken (Jacques Whitford 2008b), although the potential for elevated levels of metallic contaminants should be considered in planning and costing similar future projects. In addition, better knowledge of subsurface conditions (the location and burial depth of century-old pipes) would certainly have avoided costly delays to Halifax Water, and inconvenience to residents and businesses, arising from the need to stop work for several months while part of the system was redesigned.

Disposal of waste rock from construction sites is a major issue in HRM, as much of the Meguma Supergroup has abundant sulphides, especially pyrrhotite, with a corresponding high acid drainage potential (Jacques Whitford 2008a; White and Goodwin 2011). By the time the Freshwater Brook project was planned the problem had been recognised by the construction industry and waste rock was routinely disposed of in approved salt-water sites. As expected, pyrrhotite is present in most of the samples obtained during this study (Fig. 5a, b). Waste rock removed from the trench was disposed of at infill sites along the western edge of Bedford Basin (Halifax Water 2009). The construction boom affecting HRM over the past few years and corresponding increase in excavated acid-prone waste rock requiring disposal has heightened public awareness of the problem, with protests in summer 2024 over waste rock disposal at a controversial infill site on the Dartmouth shoreline.

A less obvious aspect of bedrock geology relevant to the construction industry is the physical state of the bedrock and the corresponding cost of excavation. For example, the Dalhousie campus is underlain by Cunard Formation graphitic slates; at the eastern end of the campus these retain a strong slaty cleavage and can be broken up by drilling. However, at the western end of the campus the slaty cleavage has been annealed by contact metamorphism (Jamieson *et al.* 2012), transforming the bedrock into massive hornfels that requires blasting for efficient excavation. The transition takes place in the vicinity of the biotite-in isograd which runs through the campus between the Killam Library and the Chemistry Building (Jamieson *et al.* 2012; Fig. 6). Maps showing this effect (after fig. 4 of Jamieson *et al.* 2012) were provided to Dalhousie Facilities Management for planning purposes; I do not know if they were ever used. Bedrock in the study area retains a strong cleavage and is well fractured. Although it might have been possible to excavate parts of the trench without blasting, this would have extended the time required for completion of the project.

However, the blasting led to a different, apparently unforeseen but predictable problem. The production of carbon monoxide (CO) during blasting is well known, with the potential to produce up to 10–24 L of CO per 1 kg of explosive detonated (e.g., Martel *et al.* 2004a), depending on the composition of the blasting material and the conditions of blasting. There is a high potential for CO migration and accumulation where blasting is done below a confined surface, such as pavement or impermeable clay. In residential areas, CO produced by blasting can migrate over distances of 8–15 m through new or pre-existing fractures or cleavage in the rock into sewer lines and other underground conduits, manholes, basements, or homes. Health Canada (2024) lists maximum residential exposure limits of 25 ppm (28.6 mg/m^3) averaged over 1 hour, or 10 ppm (11.5 mg/m^3) for 24 hours.

In July 2009, blasting was conducted along Fenwick Street without removing the pavement. On the afternoon and evening of 8 July, CO seeped into the basements of two small apartment buildings near the corner of Lucknow and Fenwick streets, triggering an overnight evacuation of about 10 residents (CBC Archives 2009). Once discovered, the CO was vented and by the next afternoon the affected buildings were declared safe. Following the incident, homes along Fenwick Street (including ours) were issued CO detectors, residents near future blast sites were informed in advance, and street pavement was removed before any further blasting was done (Fig. 3e). The latter is the preferred mitigation method in similar situations (Martel *et al.* 2004b). Although CO is a known by-product of blasting that can migrate beneath confined surfaces (Martel *et al.* 2004a, b), a spokesperson for Halifax Water was quoted as saying that the cause of the CO seepage was unknown (CBC Archives 2009). On Fenwick Street, CO probably migrated into the adjacent buildings along the pre-existing slaty cleavage and joints, new fractures produced by blasting, and broken sewer lines (e.g., Fig. 3f). The problem may not have arisen earlier because previous excavation had mainly been in unconsolidated overburden (e.g., till associated with the Queen Street drumlin) and in a commercial zone with few residential buildings. Better knowledge of the potential for CO production and subsurface conditions in the blast area might have led those in charge to take preventive action sooner.

CONCLUSIONS

1. Excavation of a deep trench along several south end Halifax streets during the Freshwater Brook sewer replacement project provided an opportunity to examine a semi-continuous section through the outer part of the SMB contact aureole and across the stratigraphic contact between the Bluestone Quarry and Cunard formations.

2. The stratigraphic contact between the two units was located within about 100 m and the position of the andalusite-in isograd was narrowed down to within about 20 m. Mineral assemblages constraining the positions of the cordierite-in and biotite-in isograds were not present in the collected samples. Observations from the intersection of South and South Park streets are consistent with the presence of a post-metamorphic fault running across south end Halifax roughly parallel to South Street.

3. Better knowledge of bedrock geology and geochemistry might have allowed Halifax Water to anticipate and mitigate some of the costly delays encountered during project construction.

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