

# Lithogeochemistry, petrology, and the acid-generating potential of the Goldenville and Halifax groups and associated granitoid rocks in metropolitan Halifax Regional Municipality, Nova Scotia, Canada

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## ABSTRACT

Detailed geological mapping of the Goldenville and Halifax groups in metropolitan Halifax Regional Municipality, Nova Scotia, resulted in two-fold subdivision of both groups. The Goldenville Group was divided into the metasandstone (feldspathic wacke)-dominated Taylors Head formation and the overlying, metasilstone-dominated, Mn-rich Beaverbank formation. The Halifax Group was divided into the Cunard formation, dominated by sulphide-rich slate, and the overlying Bluestone formation, consisting of mainly metasilstone and metasandstone. Lithogeochemical and petrological studies resulted in the characterization of the Beaverbank, Cunard, and Bluestone formations as potential acid-producing units with pyrrhotite as the main iron-sulphide mineral. The presence of acid rock drainage (ARD) is governed by bulk-rock chemical composition and mineral assemblage. To test the predictability of ARD production, a portable XRF instrument was used to obtain relatively inexpensive whole-rock and sulphur data that were used in conjunction with conventional XRF analyses and acid-base accounting tests. Results from the three methods compare favourably. Use of the portable XRF instrument facilitates a timely and cost-effective approach to predicting ARD but does not replace the legally mandated acid-base accounting procedure.

## RÉSUMÉ

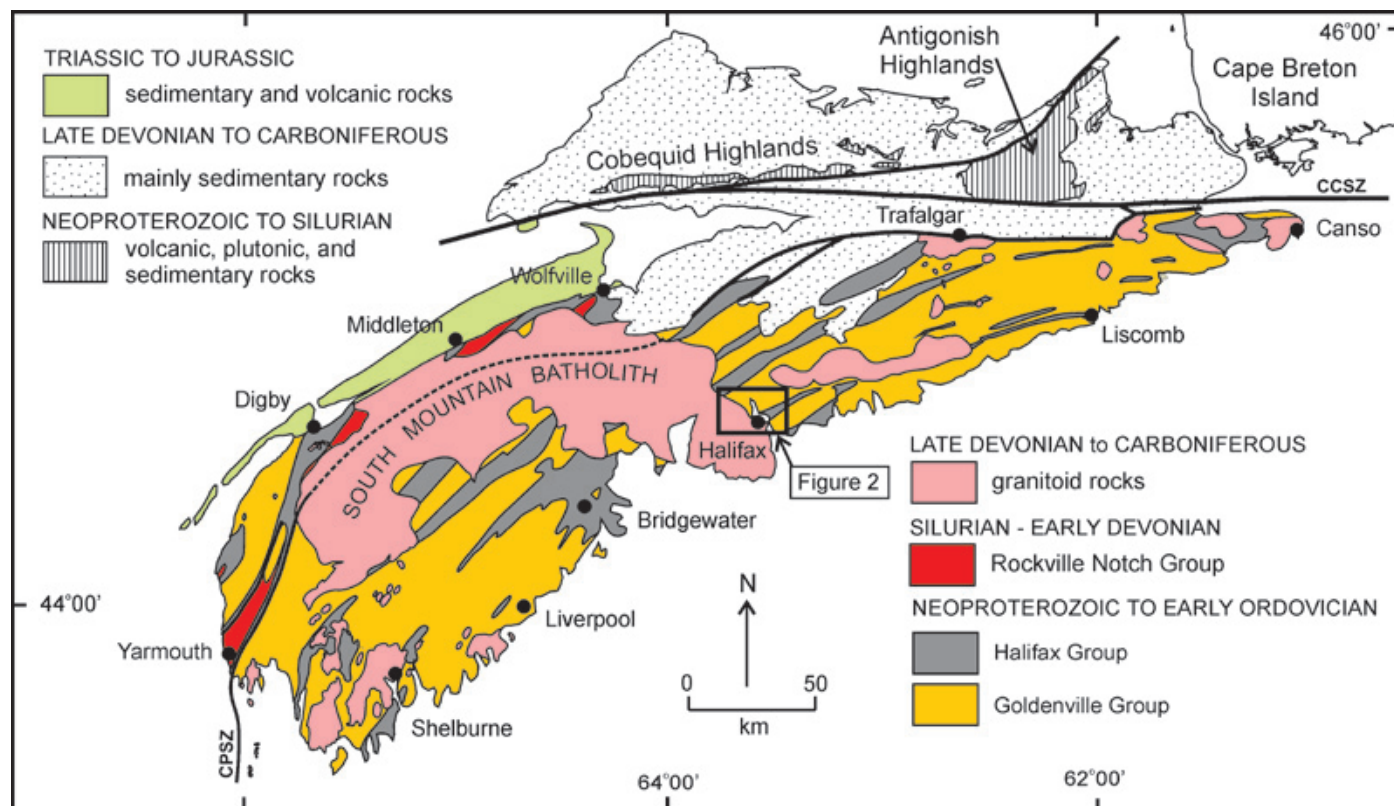
Une cartographie géologique détaillée des groupes de Goldenville et de Halifax dans la municipalité régionale de Halifax, en Nouvelle-Écosse, a donné lieu à deux divisions de ces deux groupes. Pour ce qui est du groupe de Goldenville, les deux formations suivantes ont été établies: la Formation de Taylors Head, composée principalement de métagrès (wacke feldspathique) et la Formation de Beaverbank sus-jacente, composée principalement de métasiltite riche en Mn. En ce qui concerne le groupe de Halifax, les deux formations que voici ont été identifiées: la Formation de Cunard, composée principalement d'ardoise riche en sulfures, et la Formation de Bluestone sus-jacente, composée surtout de métasiltite et de métagrès. Les études lithogéochimiques et pétrologiques ont permis d'établir que les Formations de Beaverbank, de Cunard et de Bluestone étaient susceptibles d'agir comme précurseurs acides, la pyrrhotite étant le principal minéral à sulfure de fer présent. La présence d'un drainage rocheux acide (DRA) est régie par la composition chimique de la roche brute et l'association minérale. Pour vérifier la possibilité d'un DRA, de concert avec des analyses traditionnelles à fluorescence X et de bilan acide-base, un appareil portatif à fluorescence X a été utilisé pour recueillir de manière relativement économique des données sur la roche brute et les sulfures. Les résultats obtenus par les trois méthodes se comparent bien. L'utilisation d'un appareil à fluorescence X portatif permet de prédire de manière économique et rapidement la possibilité du DRA, mais cette technique ne saurait se substituer à l'analyse du bilan acide-base prévue par la réglementation.

[Traduit par la rédaction]

## INTRODUCTION

A detailed bedrock mapping and sampling program combined with petrographic and stratigraphic analysis was undertaken in the metropolitan portion of the Halifax Regional

Municipality (HRM) as part of the much larger southern Nova Scotia Meguma terrane mapping program (Fig. 1) (White *et al.* 2008; White 2010a). The purpose of the mapping program is to better characterize the stratigraphy, economic potential, and tectonic evolution of the Cambrian to Ordovician Golden-



**Fig. 1.** Simplified geological map of the Meguma terrane of southern Nova Scotia, showing the distribution of the Goldenville and Halifax groups and other major units. The area of study is shown in the box. Abbreviations: CCSZ = Cobequid-Chedabucto shear zone; CPSZ = Chebogue Point shear zone.

ville and Halifax groups in southern Nova Scotia (e.g., White 2010a; White and Barr 2010). However, an important outcome from the mapping is the identification of units within HRM and elsewhere in the Goldenville and Halifax groups that have potential acid-generating hazards (e.g., Lewis *et al.* 1998). The production of acid and hence acid rock drainage (ARD) results from the oxidation of naturally occurring sulphide minerals in the rocks, and is a major issue facing development in the metropolitan portion of HRM. The environmental impacts associated with exposed or disturbed sulphide-rich rocks during routine construction activity (i.e., not related to metal or coal mining) are not unique to HRM and have been documented in many parts of the world (e.g., Piispanen and Nykyri, 1997; Morin *et al.* 2003; Peng *et al.* 2005; Schoeffer and Clawson 1996; Kwong *et al.* 2009).

Acid rock drainage is not only detrimental for fish and other aquatic species but also causes excessive premature corrosion of concrete and metal infrastructure. For these reasons many construction companies, geotechnical consulting groups, and public work agencies need to know areas in the city where ARD may be an issue in infrastructure construction projects. With the identification of sulphide-rich geological formations in HRM, the potential for ARD can be better understood, and as a result, the onset of acid drainage can be more effectively avoided.

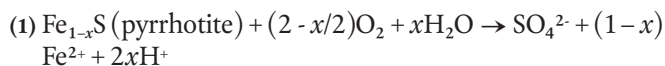
To predict the acid generating potential from any geologic formation requires the characterization of the presence and quantity of both acid-forming minerals and neutralizing minerals in the geologic materials to be unearthed during construction operations. Although a variety of laboratory-based acid-base accounting (ABA) tests are available to determine the potential for generating ARD content, here we employ the static British Columbia Research Initial Test (BC-RIT) method as recommended by the Nova Scotia Environment Act (1995). With the results from this test, combined with a detailed geological map, whole rock lithogeochemistry, and petrography, we can now accurately assess the acid-forming capability of formations which can be used for environmental management and subsequent mitigation of ARD in HRM. The purpose of this paper is to quantify the ARD-generating potential of rocks in the metropolitan portion of HRM.

## ACID ROCK DRAINAGE

Acid rock drainage, also referred to as acid mine drainage (AMD), is a naturally occurring phenomenon that results when sulphide minerals in a rock are oxidized as a result of exposure to oxygen and water. In the absence of neutralizing material (e.g., limestone or dolomite) this oxidation causes the chemical

breakdown of the sulphide minerals which releases sulphuric acid, iron and other metals, and sulphate into the receiving environment, typically a stream, river, or lake.

In HRM, pyrrhotite and pyrite are the primary concerns with regard to ARD, with the oxidation rate of pyrrhotite being much faster than pyrite (Fox *et al.* 1997). The oxidation of pyrrhotite and pyrite is complex and involves a series of multiple reactions but simplified equations can be written as follows:



Other minerals such as arsenopyrite, chalcopyrite, sphalerite, galena, and magnetite are commonly overlooked as potential candidates for ARD but they can also provide additional input to acid generation through the oxidation of  $\text{Fe}^{2+}$  and hydrolysis of  $\text{Fe}^{3+}$  (Moncur *et al.* 2009). In addition, crystal structure plays an important role in the generation of ARD. For example, the monoclinic (vs. hexagonal) form of pyrrhotite has been shown to readily weather and initiate acid production (Robinson 1996).

Waterways affected by ARD can be characterized by their acidity, high sulphate and metal content in their waters, and the metallic content of their sediments (e.g., Grande *et al.* 2005). Often the aesthetic quality of a waterway is reduced by the presence of a red iron hydroxide precipitate that commonly lines the bottom sediment of the receiving waters. Depending on the pH of the water, the rate of oxidation is greatly accelerated by a variety of bacteria (e.g., *Thiobacillus thiooxidans* and *Ferrobacillus ferrooxidans* — pH between 4.5 and 3.5; *Thiobacillus ferrooxidans* — pH below 3.5) (U.S. Environmental Protection Agency 1994; Eba Engineering Consultants Ltd. 2004; Blowes *et al.* 2005). In addition to loss of aquatic life, as well as the loss of potable and industrial water resources, ARD has been responsible for damage to engineered infrastructure such as concrete structures, buried transmission lines, culverts, bridges, and metal pipes (Earle and Callagnah 1998). Acid rock drainage, once it appears, is virtually impossible to reverse and with the current technology, its treatment can cost millions of dollars and go on for centuries (Feasby and Tremblay 1995; Jennings *et al.* 2008).

In addition to the acid contribution to surface waters, ARD may cause trace metals such as aluminum, arsenic, cadmium, copper, manganese, and zinc and to leach from rocks and these metals can contribute to the environmental damage, and in some cases is of greater concern than the acidity.

### History of ARD in the Halifax Group

Acid rock drainage issues in Nova Scotia, in particular in the Halifax Group, were broadly researched in the late 1980s and 1990s (e.g., Pasava *et al.* 1995; Feetham *et al.* 1997; Fox *et al.* 1997; Zentilli and Fox 1997, and references within) but have seen limited research since that time. One of the earliest and

most extensively studied sites associated with ARD in HRM involved the construction and subsequent expansion(s) of the Robert Stanfield International Airport (previously referred to as the Halifax International Airport). Here a direct correlation was demonstrated between construction activity in the Halifax Group and significant fish kills in the nearby Shubenacdie River between 1960 and 1976 (Pasava *et al.* 1995; Worган 1987). Remediation and treatment costs have averaged one million dollars annually at the airport, and treatment of surface waters continues (Hicks 2003).

Construction on Highway 107 east of Dartmouth near West Petpeswick Lake during the late 1980s exposed a continuous section of Halifax Group slate which resulted in the production of ARD and the degradation of water quality and aquatic habitat. Subsequently, the acid-producing outcrop was capped with shotcrete and a small treatment facility was constructed (Fox *et al.* 1997). Other historic ARD issues that have arisen in HRM and elsewhere in Nova Scotia also were outlined in Fox *et al.* (1997).

These incidents led the Nova Scotia Department of Environment to instate the “Sulphide Bearing Material Disposal Regulations” which require testing for ARD prior to ground disturbance (Nova Scotia Environment Act 1995). However, within HRM evidence suggests that current development in Fairview, Hammonds Plains, and Middle Sackville continues to have ARD problems. The local residents in these areas who are on well-water have water softeners and filters to combat the resulting rusty stain on fixtures, discoloured laundry, and sulphur odour (Goodwin 2004). In addition, past and on-going infrastructure development such as the interchange of highways 102 and 103 as well as road building and the development of retail commercial sites in the Bayers Lake Industrial Park continue to be sources of natural ARD and acidification of local lakes (Kerekes *et al.*, 1984; Rajaratnam 2009). More recently, construction was halted during the building of the new Dartmouth bus terminal and Bayers Lake underpass as pyritic slate was encountered on these sites, dramatically increasing project costs (Talpin 2011a, b; Stephenson 2011).

### GEOLOGICAL SETTING

The first step when evaluating the acid generating potential of bedrock is to understand the geological history of the area and describe the geology and mineralogy of rock formations in detail (Coastech Research Inc 1991; U.S. Environmental Protection Agency 1994; Price 2005, 2009; Jennings *et al.* 2008).

The earliest geological study in the Halifax area was undertaken by Faribault (1907, 1908) who divided the area into an older “Quartzite Division” and younger “Slate Division” intruded by coarse-grained granite. Faribault (1907) recognized the rusty character of the “Slate Division” and described the unit as highly ferruginous and altered with metamorphic minerals close to the granite contact. The area was next mapped by MacDonald and Horne (1987) but they focused primarily on the igneous units and compiled data from the earlier work

of Faribault (1908) for the metasedimentary units. Following current practice, they assigned the “Quartzite” and “Slate” divisions to the Cambrian-Ordovician Goldenville and Halifax formations, respectively.

Recent 1:10 000-scale mapping in HRM (White *et al.* 2008) was undertaken to update the old geological map of Faribault (1908). As a result, new formations were recognized and the Goldenville and Halifax formations were elevated to ‘group’ status. The older unit, the Goldenville Group, occurs in the northern and eastern parts of HRM (Fig. 2). It is divided into two formations: Taylors Head and Beaverbank (White *et al.* 2008; White 2010a, b). The Taylors Head formation consists of grey, thickly bedded and weakly cleaved, metasandstone interbedded with minor green to grey, cleaved metasilstone, and rare black to rusty slate. Calc-silicate nodules and pyrite cubes are locally common. The contact with the overlying Beaverbank formation is conformable and marked by a decrease in thickly bedded metasandstone over tens of meters. The Beaverbank formation consists of grey to black, cleaved metasilstone interbedded with minor thin, light grey metasandstone and black graphitic slate. Thin brown to black manganese-rich limestone beds and nodules are common. Close to the contact with granite of the South Mountain Batholith these manganese-rich limestone beds and nodules become garnet (spessartine)-rich cotecules.

The overlying Halifax Group is divided into the Cunard and Bluestone formations (White *et al.* 2008). In the Halifax area, the Cunard formation conformably overlies the Beaverbank formation of the Goldenville Group and is characterized by black, commonly rusty on weathered surfaces, graphitic slate and metasilstone interbedded with 10 to 30 cm thick, cross-laminated fine-grained metasandstone. This formation typically contains abundant pyrrhotite and pyrite, with lesser amounts of chalcopyrite, galena, sphalerite, and arsenopyrite (e.g., Fox *et al.* 1997; Haysom *et al.* 1997; Betts-Robertson 1998; Clarke *et al.* 2009).

The conformably overlying Bluestone formation consists of grey thinly bedded metasilstone and slate, minor metasandstone and calcareous nodules (Jamieson *et al.* 2005a, b, 2011; White *et al.* 2008) and has recently been subdivided into several informal members (Jamieson *et al.* 2011). In contrast to metasandstone in the underlying Cunard formation, the metasandstone lacks prominent cross-laminations. The Bluestone formation generally lacks obvious sulphide minerals.

The Goldenville and Halifax groups were regionally metamorphosed (greenschist facies) and deformed into northeast-striking, upright, tight to open folds (Fig. 1, 2) with a well developed axial planar cleavage during the ca. 406–388 Ma Neocadian Orogeny (van Staal 2007; Moran *et al.* 2007; White *et al.* 2008; White 2010a).

The ca. 380–373 Ma peraluminous South Mountain Batholith (SMB) intruded the Goldenville and Halifax groups and produced a narrow (up to 2 km wide), well developed contact metamorphic aureole that is superimposed on regional greenschist facies mineral assemblages and textures (Jamieson *et al.* 2005a, b, 2011; White *et al.* 2008) (Fig. 2). A major northwest-

striking shear zone is present in the contact aureole adjacent to the northeastern margin of the South Mountain Batholith (Fig. 2) and was active during intrusion (Culshaw and Bhatnagar 2001; White *et al.* 2008).

Within the northeastern margin of the SMB, a narrow (0.5 to 1 km wide) northwest-trending zone of grey, medium grained, equigranular granodiorite with minor alkali feldspar megacrysts is recognized and herein termed the Quarry Lake granodiorite. Locally at the contact with the country rocks this unit contains abundant metasedimentary xenoliths. Farther southwest into the batholith several plutonic units are defined (Sandy Lake and Harrietsfield monzogranites, and Halifax Peninsula leucomonzogranite) which range from fine- to coarse-grained to megacrystic monzogranite to leucomonzogranite (MacDonald and Horne 1987; MacDonald 2001). All these units are intruded by the late-stage medium-grained two-mica Tantallon leucomonzogranite (Fig. 2).

## METHODOLOGY

Field mapping (1:10 000-scale) was performed during the summers from 2007 to 2010 and included a comprehensive and detailed sampling program. A total of 239 samples from the stratified units and 21 samples from granitoid outcrops in the South Mountain Batholith were collected for petrographic analysis. A total of 76 psammitic and 32 pelitic lithologies were thin-sectioned in order to obtain detailed information on mineralogy and grade of metamorphism. An additional 21 thin sections from the South Mountain Batholith were studied to document the mineralogy in the granitoid units. Twenty-eight samples were selected for polished thin sections and whole-rock geochemistry representing each lithology in the Goldenville and Halifax groups.

Magnetic susceptibility data were collected on each sample using a handheld KT-9 Kappameter. The KT-9 uses a 10 kHz LC oscillator and an inductive coil and automatically displays the true measured susceptibility of the sample in dimensionless, System International (SI) units. The maximum sensitivity of the KT-9 is  $1 \times 10^{-5}$  SI units. In this study, all measurements were recorded to  $1 \times 10^{-3}$  SI units.

To determine the background ARD potential, samples were chosen on the basis that they represented the typical lithology at any one outcrop and did not contain abundant visible sulphide mineralization or weathering features. This approach is in contrast to previous ARD studies in HRM (i.e., Fox *et al.* 1997) that specifically targeted sulphide-bearing lithologies. Samples were pre-crushed to <180 microns using a tungsten-carbide mill and major, trace, rare earth element, and total sulphur and carbon analysis were done by ICP-MS at Acme Analytical Laboratories (Vancouver) Ltd. Major oxides and several minor elements were analysed by ICP-emission spectrometry following a lithium metaborate/tetraborate fusion and dilute nitric digestion. Trace elements were determined by ICP mass spectrometry following a lithium metaborate/tetraborate fusion and nitric acid digestion. Loss on ignition

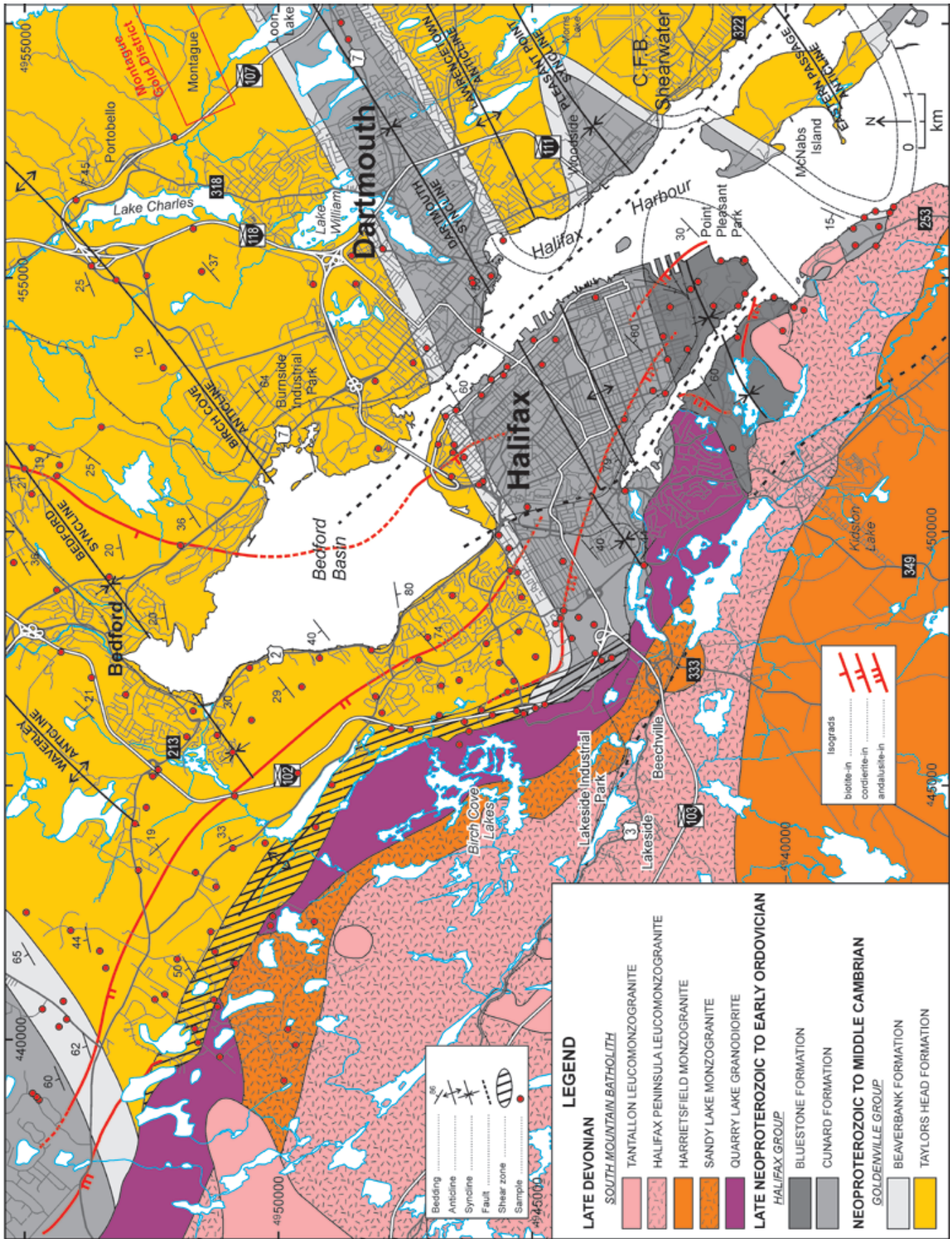


Fig. 2. Simplified geological map of the metropolitan portion of the Halifax Regional Municipality (modified after White *et al.* 2008). Geological boundaries in South Mountain Batholith modified after MacDonald and Horne (1987). UTM coordinates for sample locations are in the appendices.

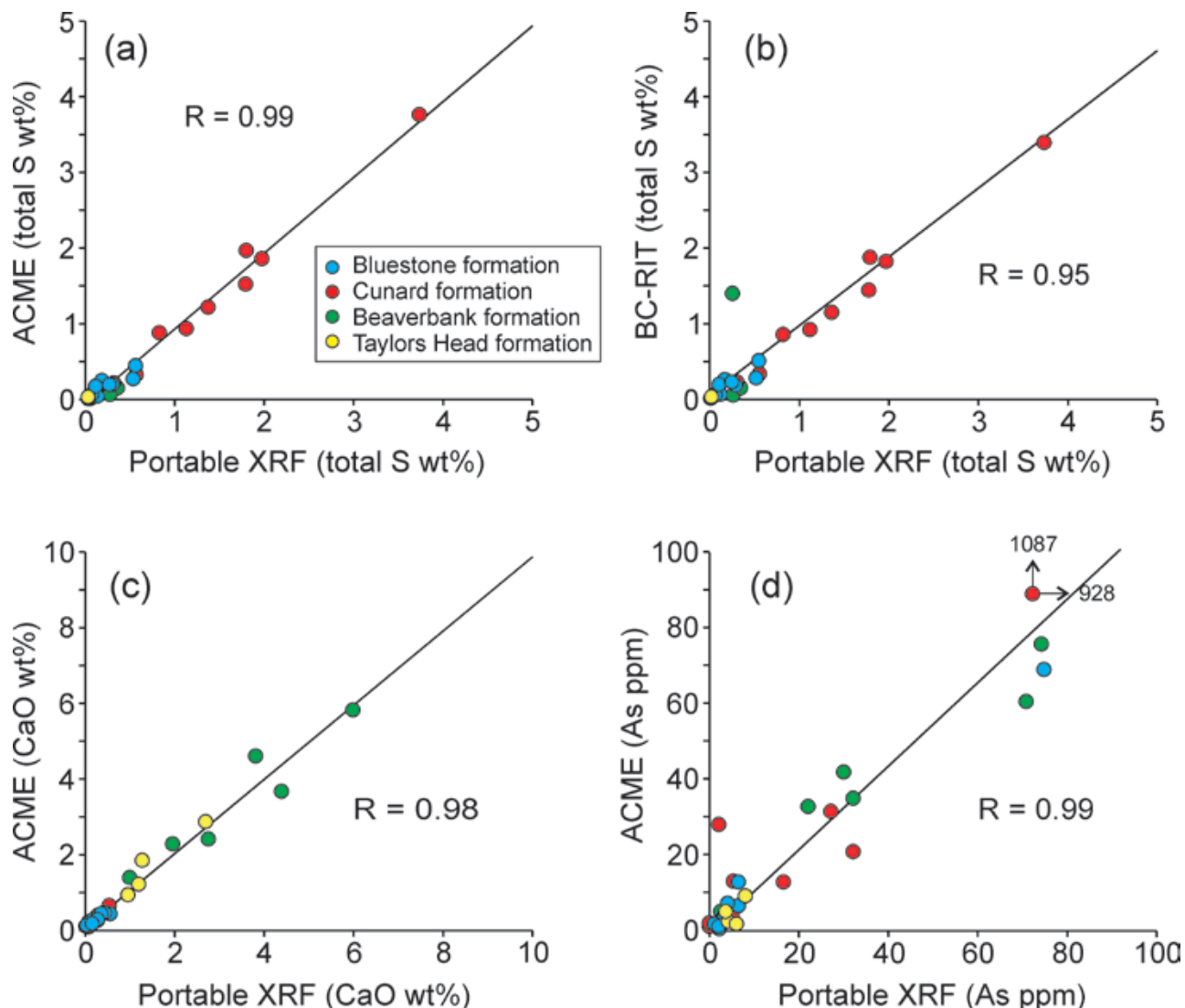


Fig. 3. Selected whole rock results using the portable XRF compared with the ACME and BC-RIT results on the sample samples. (a) Plot of total S (wt.%); portable XRF against ACME. (b) Plot of total S (wt.%); portable XRF against BC-RIT. (c) Plot of CaO (wt.%); portable XRF against ACME. (d) Plot of As (ppm); portable XRF against ACME.

(LOI) is by weight difference after ignition at 1000 °C. Four samples from the Taylors Head formation, 6 from the Beaverbank formation, 10 from the Cunard formation, and 8 from the Bluestone formation were analyzed (Table 1a, b).

In Nova Scotia, the Sulphide Bearing Material Disposal Regulations (Section 66 of the Nova Scotia Environment Act 1995) require that all samples submitted for ARD analysis should use the static British Columbia Research Initial Test (BC-RIT) and rocks having a sulphide sulphur content equal to or greater than 0.4% (12.51 kg H<sub>2</sub>SO<sub>4</sub>/tonne) must be considered as hazardous ARD material. A total of 23 bedrock samples were submitted to the Minerals Engineering Centre (MEC) at Dalhousie University, Halifax, Nova Scotia, for processing and analysis using the BC-RIT method (Table 2). Each sample was analyzed by MEC for total sulphur (LECO furnace), sulphide sulphur (after determining sulphate sulphur by hydrochloric acid diges-

tion, precipitation of the sulphate using barium chloride and gravimetric finish to yield the sulphate sulphur) and for its acid producing/consumption ability using the BC-RIT method (Duncan and Bruynesteyn 1979).

In addition, all 260 samples were analyzed using a portable X-5000 XRF instrument (hereafter termed portable XRF) manufactured by Innov-X which was acquired recently by the Nova Scotia Department of Natural Resources. It uses a 10W tantalum anode light-element X-ray tube with a resolution of < 165eV. The beam is approximate 8 mm in diameter and measures 25+ transition metals including selected rare earth elements. Samples were analyzed using the Soil 3 Beam mode with 60 second counts on each beam; however, this mode does not measure elements lighter than Na (e.g., Si, Al, and Mg).

Traverses across rock slabs, greater than 1 cm thick, were averaged (3–5 spots on fine-grained samples and 5–10 spots

on coarser-grained samples). The samples represent psammitic, pelitic, and calc-silicate rocks in all the formations in the Goldenville and Halifax groups, arranged in stratigraphic order, and include 139 from the Taylors Head formation; 34 from the Beaverbank formation, 39 from the Cunard formation, and 27 from the Bluestone formation. In addition, 21 samples from the South Mountain Batholith were analyzed. Rock type, UTM coordinates, and major and trace data are summarized in Appendices A–E.

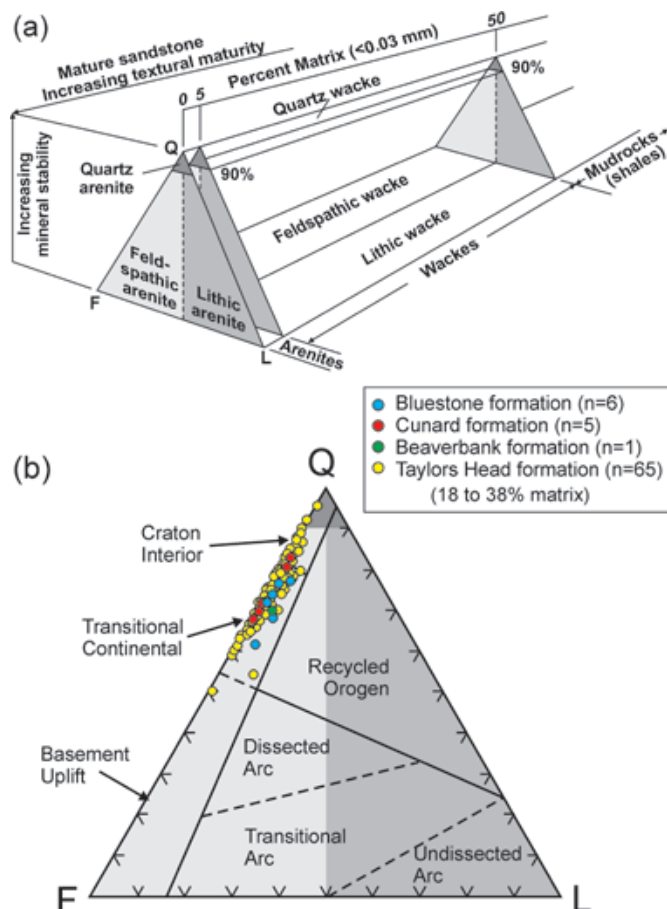
### Quality assurance and quality control

the portable X-5000 XRF provides rapid and simultaneous analyses of several elements with minimal sample preparation. To assess the reliability of analyses using the portable XRF the results are compared with the ACME results on the same samples. In addition, two internal reference samples (metasandstone and slate from the Goldenville and Halifax groups, respectively) were routinely analyzed to evaluate the portable XRF's performance. This check aids in estimation of the precision and accuracy and hence ensures meaningful interpretation of the data. Scatter plots for selected elements (S, Ca, and As) from ACME and the portable XRF results were constructed and compared to the total S analyzed by BC-RIT (Fig. 3). Correlation coefficients (*r*-values) on each pair were also calculated. The results show excellent reproducibility ( $r \geq 0.95$ ). Comparing the results from ACME to the portable XRF data yielded correlation coefficients that range from 0.88 to 0.98 for  $K_2O$ ,  $TiO_2$ ,  $MnO$ ,  $Fe_2O_3^T$ , Ba, Cu, Nb, Pb, Rb, Sr, V, Y, Zn, and Zr pairs (not shown). There is no significant discrepancy in the data between the ACME and portable XRF and hence the portable XRF results can be used with a significant degree of confidence.

## PETROGRAPHY

### Goldenville and Halifax groups

In rocks of the Goldenville and Halifax groups away from the contact metamorphic effects of the South Mountain Batholith in the HRM area, regional greenschist facies (chlorite zone) metamorphic minerals and textures are preserved. Here the original clay-sized material in the slate as well as the matrix in metasandstone and metasilstone has been recrystallized to a mixture of very fine-grained sericite, epidote, and chlorite. Quartz is the most abundant detrital component in the metasandstone, with lesser amounts of feldspar and minor or no lithic fragments (Fig. 4). Most feldspar grains are sub-rounded and consist of albitic plagioclase. It is rarely twinned and partially altered to sericite, epidote, or calcite. Potassium feldspar is rare. The metasandstone has between 18 and 38% matrix and is classified (using the system of Boggs, 2001, shown in Fig. 4a) as feldspathic wacke (Fig. 4b). Detrital muscovite is present in many samples and ranges in abundance up to 5%.



**Fig. 4.** (a) Classification of sandstone based on modal quartz (Q), feldspar (F), lithic fragments (L), and proportion of matrix, after Boggs (2001). (b) Classification and provenance for samples from the Goldenville and Halifax groups with <5% and <50% matrix. Shaded classification fields from (a) are shown on (b). Provenance fields are after Dickinson *et al.* (1983). About 500 to 1000 points were counted in each thin section, using a modified version of the Gazzi-Dickinson method, which includes counting grains where they form part of a lithic fragment to eliminate apparent variations in the composition of samples resulting only from differences in grain size (Ingersoll *et al.*, 1984).

Trace amounts of zircon, titanite, and tourmaline also occur. Lithic fragments are rare and are dominantly quartzite.

Calcite ( $CaCO_3$ ), and to a lesser degree dolomite [ $Ca, Mg(CO_3)_2$ ], occur in nodules and as minor cement in metasandstone of the Taylors Head and Bluestone formations. Calcite nodules and laminations also occur within the slate of the Beaverbank and Bluestone formations, and rhodochrosite ( $MnCO_3$ ) has been documented in units equivalent to the Beaverbank formation (O'Beirne-Ryan 1996). Ankerite [ $Ca(Fe, Mg, Mn)(CO_3)_2$ ] is not common but has been noted in metasandstone units within gold districts of the Goldenville Group (MacDonald 1998).

**Table 1a.** Whole-rock chemical analyses (major oxides, C, and S) of samples from the Goldenville and Halifax groups.

sample	lithology	SO	major oxides (wt %)											(wt %)			
			SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> <sup>T</sup>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Cr <sub>2</sub> O <sub>3</sub>	LOI	total	total C	total S
<b>Bluestone formation</b>																	
D12-W08-023	f.g., feld wacke	28	71.51	0.61	14.02	5.63	0.08	1.11	0.47	1.87	2.63	0.07	0.007	1.8	99.81	0.05	0.20
D12-W08-017	f.g., feld wacke	27	72.02	0.63	13.65	5.59	0.10	1.13	0.46	1.99	2.38	0.05	0.006	1.8	99.80	0.04	0.27
D12-W08-024	hornfels	26	60.60	0.91	20.50	6.33	0.18	1.40	0.32	1.26	4.61	0.09	0.012	3.6	99.77	0.13	0.05
D12-W08-019	spotted slate	25	60.41	0.98	21.48	5.94	0.09	1.35	0.16	1.05	4.52	0.07	0.014	3.7	99.76	0.12	0.07
D12-W08-021	hornfels	24	57.94	1.02	22.35	6.30	0.08	1.36	0.21	1.06	5.37	0.07	0.013	4.0	99.75	0.19	0.45
D12-W08-020-A	hornfels	23	66.17	0.79	16.63	7.09	0.15	1.54	0.49	1.60	3.01	0.10	0.009	2.2	99.78	0.09	0.26
D12-W08-020-B	hornfels	22	61.21	0.81	19.97	6.60	0.11	1.50	0.29	1.14	4.53	0.10	0.010	3.5	99.77	0.12	0.18
D12-W08-027	spotted siltstone	21	68.68	0.61	14.77	7.07	0.14	1.53	0.28	1.49	2.58	0.08	0.008	2.6	99.83	0.08	0.20
<b>Cunard formation</b>																	
D12-W08-026	hornfels	20	57.52	1.02	24.19	4.71	0.07	1.58	0.21	1.20	3.92	0.09	0.015	5.2	99.77	0.43	0.22
D12-W08-014	slate	19	56.63	1.18	25.36	4.06	0.03	1.45	0.11	1.37	4.91	0.07	0.017	4.6	99.77	0.43	0.33
D12-W08-007	siltstone	18	59.81	0.68	16.86	11.36	0.06	2.71	0.24	1.12	2.10	0.06	0.008	4.7	99.77	0.08	1.97
D12-W08-029	hornfels	17	54.49	1.06	26.12	5.26	0.04	1.23	0.30	1.65	4.58	0.05	0.018	5.0	99.75	0.51	0.94
D12-W08-008	slate	16	74.61	0.86	14.56	2.17	0.03	0.94	0.13	1.00	2.49	0.04	0.015	3.0	99.84	0.22	0.01
D12-W08-003	siltstone	15	49.04	0.84	24.21	11.59	0.06	1.87	0.14	1.26	4.65	0.03	0.011	6.0	99.75	0.22	3.77
D12-W08-010	hornfels	14	55.40	0.87	22.86	8.80	0.14	2.15	0.68	1.61	3.70	0.08	0.012	3.5	99.77	0.07	1.22
D12-W08-011	hornfels	13	56.49	0.88	23.38	7.98	0.03	1.81	0.23	1.09	4.61	0.06	0.013	3.2	99.76	0.40	1.86
D12-W08-004	siltstone	12	71.23	0.63	13.57	6.15	0.07	1.74	0.30	1.17	1.94	0.10	0.007	2.9	99.81	0.11	0.88
D12-W08-012	hornfels	11	64.70	0.82	17.78	6.30	0.07	2.51	0.42	0.96	2.30	0.19	0.013	3.7	99.74	0.50	1.53
<b>Beaverbank formation*</b>																	
D12-W08-001-A	siltstone	10	52.80	0.95	17.39	12.61	3.98	3.20	1.42	0.84	2.18	0.27	0.011	4.1	99.74	0.39	0.23
D12-W08-001-B	siltstone	9	49.41	0.86	16.13	10.81	5.64	3.16	3.70	0.60	2.32	0.23	0.010	6.9	99.76	1.38	0.16
D12-W08-013	spotted siltstone	8	56.48	0.98	17.43	11.16	5.01	2.18	2.32	0.64	2.39	0.13	0.013	1.0	99.72	0.03	0.08
D12-W07-079	siltstone	7	55.85	0.83	21.08	7.33	1.33	2.40	2.44	1.24	4.12	0.10	0.013	3.0	99.72	0.12	0.50
D12-W07-068A	siltstone	6	58.75	0.82	17.14	7.65	3.55	2.10	4.65	1.35	2.02	0.11	0.012	1.6	99.73	0.09	0.15
D12-W08-002	siltstone	5	47.73	0.77	15.24	9.99	5.86	3.02	5.87	0.54	2.20	0.17	0.009	8.3	99.74	1.86	0.07
<b>Taylor's Head formation</b>																	
D12-W07-077B	f.g., feld wacke	4	69.24	1.13	13.70	5.26	0.08	1.51	1.88	2.67	2.42	0.10	0.014	1.7	99.70	0.03	0.01
D12-W08-030	f.g., feld wacke	3	71.70	0.50	11.93	3.15	0.11	1.13	2.91	2.74	2.65	0.08	0.006	2.9	99.78	0.49	0.01
D12-W07-001	f.g., feld arenite	2	78.76	0.38	10.58	2.37	0.04	0.81	0.96	2.95	1.83	0.08	0.004	1.1	99.85	0.06	0.01
D12-W07-003	f.g., feld wacke	1	77.69	0.78	9.99	3.71	0.04	0.85	1.26	2.65	1.49	0.11	0.008	1.2	99.78	0.01	0.04

Notes: Analysed at ACME, Vancouver, by ICP-MS in 2009. Abbreviations: SO = stratigraphic order from oldest (1) to youngest (2); f.g. = fine grained; feld = feldspathic. \* All samples contain cotecule-rich laminations and nodules.



**Table 1b.** Whole-rock chemical analyses (trace elements) of samples from the Goldenville and Halifax groups.

sample	SO	trace element (ppm)																												
		As	Au*	Ba	Be	Bi	Cd	Co	Cs	Cu	Ga	Hf	Mo	Nb	Ni	Pb	Rb	Sb	Se	Sn	Sr	Ta	Th	Tl	U	V	W	Zn	Zr	
<b>Bluestone formation</b>																														
D12-W08-023	28	1.1	<0.5	446	2	0.4	<0.1	35.4	7.2	26.8	17.0	8.1	0.1	14.0	27.8	6.3	133.8	<0.1	<0.5	3	191.5	1.3	13.3	0.6	3.0	3.0	52	192.2	68	265.2
D12-W08-017	27	0.5	0.6	459	2	0.1	<0.1	39.4	5.6	38.6	15.8	10.7	0.2	14.0	32.3	7.1	118.1	<0.1	<0.5	2	170.8	1.4	17.7	0.4	3.9	50	235.5	74	378.8	
D12-W08-024	26	12.9	0.8	885	3	0.4	<0.1	24.7	11.1	19.0	26.5	8.0	0.3	19.4	35.1	6.1	199.7	<0.1	0.5	4	160.1	1.6	18.0	0.5	3.9	88	65.7	80	263.3	
D12-W08-019	25	6.6	0.6	1001	4	0.5	<0.1	16.9	9.7	9.6	27.8	5.0	0.1	21.4	23.4	6.5	193.2	<0.1	<0.5	5	155.1	1.8	18.4	0.3	3.6	99	50.5	70	170.7	
D12-W08-021	24	2.9	<0.5	987	4	0.4	<0.1	28.1	10.7	19.7	28.8	6.3	1.0	20.8	38.9	5.1	225.5	<0.1	<0.5	4	149.4	1.7	19.2	0.4	4.4	101	34.8	68	213.9	
D12-W08-020-A	23	7.4	<0.5	603	3	0.2	<0.1	35.9	6.5	25.8	20.9	9.8	0.2	16.2	39.5	5.9	145.5	<0.1	0.6	2	128.0	1.3	15.4	0.5	3.4	70	131.2	89	342.7	
D12-W08-020-B	22	69.2	1.1	827	3	0.5	<0.1	47.1	7.2	32.9	25.8	8.1	0.3	16.9	57.7	9.4	191.2	0.1	0.7	4	114.6	1.3	15.2	0.5	3.2	87	100.8	87	277.5	
D12-W08-027	21	1.8	<0.5	438	2	0.4	<0.1	29.7	4.3	40.5	17.0	6.6	0.2	14.1	28.4	25.8	108.3	<0.1	0.7	2	82.1	1.2	13.4	0.3	2.9	56	112.0	81	225.0	
<b>Cunard formation</b>																														
D12-W08-026	20	13.0	<0.5	717	4	0.2	<0.1	16.2	12.6	11.3	29.8	4.6	0.3	20.6	14.0	1.7	161.9	<0.1	<0.5	4	268.8	1.7	18.4	0.3	3.2	112	37.0	68	141.5	
D12-W08-014	19	3.5	<0.5	918	3	0.4	0.8	21.1	8.6	28.4	32.3	4.6	8.3	21.2	39.0	16.9	201.8	0.1	<0.5	4	230.5	1.6	14.9	<0.1	11.4	198	18.4	125	145.9	
D12-W08-007	18	28.2	<0.5	426	2	0.3	1.1	37.5	4.8	76.0	22.1	4.8	0.9	12.7	98.1	6.6	90.3	0.4	1.7	2	147.9	1.0	8.9	<0.1	2.4	104	83.6	192	166.6	
D12-W08-029	17	31.7	<0.5	801	4	0.2	0.2	27.2	11.2	22.2	30.2	4.2	11.7	19.8	49.1	5.3	164.9	<0.1	0.9	4	306.4	1.5	15.8	0.1	5.5	158	48.3	58	134.7	
D12-W08-008	16	1.1	0.8	485	2	<0.1	<0.1	8.4	4.8	2.4	18.7	3.4	0.4	17.2	1.6	3.0	107.9	<0.1	<0.5	2	120.5	1.3	13.7	<0.1	2.4	87	65.9	26	101.3	
D12-W08-003	15	21.0	<0.5	1001	3	0.6	<0.1	40.5	7.4	93.4	30.7	5.1	1.8	14.1	92.3	23.8	186.8	0.3	1.9	4	234.8	1.1	11.3	<0.1	3.1	139	8.1	91	163.0	
D12-W08-010	14	13.1	0.9	644	5	0.3	<0.1	35.6	21.7	35.4	29.1	3.7	0.5	18.1	45.0	6.1	193.8	<0.1	<0.5	4	188.0	1.5	12.5	0.6	2.5	97	122.1	101	130.6	
D12-W08-011	13	1087	1.8	800	3	0.3	0.6	38.0	8.6	50.1	27.3	3.9	12.5	15.8	47.4	7.6	194.1	0.2	0.8	4	157.6	1.4	11.9	0.6	8.1	166	171.3	108	128.0	
D12-W08-004	12	2.0	0.6	508	2	<0.1	0.1	26.3	2.9	18.3	16.5	6.6	1.3	11.8	25.5	14.4	73.8	0.2	<0.5	2	149.6	1.0	8.1	<0.1	2.7	68	148.5	82	225.3	
D12-W08-012	11	4.3	<0.5	586	3	0.2	0.2	40.1	5.6	36.4	22.5	3.3	15.1	12.2	33.0	6.4	91.1	<0.1	0.9	2	122.2	1.2	8.5	0.2	3.5	105	252.1	84	108.6	
<b>Beaverbank formation</b>																														
D12-W08-001-A	10	32.8	0.6	712	2	<0.1	<0.1	67.4	2.8	64.5	23.3	5.2	0.7	16.6	122.3	3.2	78.4	<0.1	<0.5	3	125.7	1.3	9.5	<0.1	1.8	115	93.1	123	169.6	
D12-W08-001-B	9	60.7	2.1	738	3	0.3	<0.1	64.9	2.8	45.8	22.0	4.3	0.3	15.2	75.6	24.6	84.4	0.1	<0.5	2	120.2	1.0	7.8	<0.1	1.9	113	23.3	108	154.5	
D12-W08-013	8	35.1	3.3	819	3	0.1	<0.1	65.0	4.5	22.5	22.3	5.2	0.5	13.8	81.8	37.2	84.4	<0.1	<0.5	3	180.2	1.2	8.0	0.3	2.1	140	247.2	72	164.7	
D12-W07-079	7	5.1	<0.5	1092	3	<0.1	<0.1	19.6	8.1	39.3	26.3	4.0	0.2	14.4	39.4	5.6	182.7	0.3	<0.5	3	325.7	1.1	12.0	0.4	2.4	128	37.9	93	129.8	
D12-W07-068-A	6	76.1	1.4	717	3	0.3	<0.1	76.2	3.3	42.3	21.1	4.1	0.3	13.9	59.0	13.5	88.4	0.3	<0.5	2	426.8	1.1	9.0	0.2	2.9	108	140.4	63	136.1	
D12-W08-002	5	42.2	1.1	680	2	0.6	<0.1	49.2	2.8	67.7	20.7	4.0	0.4	12.6	61.0	56.3	80.7	0.4	<0.5	3	318.9	0.9	8.0	<0.1	2.0	101	34.0	114	134.3	
<b>Taylor's Head formation</b>																														
D12-W07-077-B	4	2.4	<0.5	500	1	<0.1	<0.1	25.8	3.8	5.2	15.5	28.3	<0.1	17.6	29.0	11.2	95.4	<0.1	<0.5	2	254.0	1.4	18.3	0.2	4.0	72	134.9	66	1033.2	
D12-W08-030	3	5.0	1.0	702	2	<0.1	<0.1	30.3	1.7	14.8	13.1	9.1	0.1	9.8	15.0	21.0	77.2	0.2	0.6	1	185.6	0.9	7.4	0.1	1.9	55	222.6	29	330.6	
D12-W07-001	2	9.2	<0.5	432	2	<0.1	<0.1	36.8	2.1	6.4	9.9	4.4	<0.1	7.6	14.6	9.2	59.8	<0.1	<0.5	<1	187.0	0.9	5.5	<0.1	1.3	48	307.4	40	164.0	
D12-W07-003	1	1.8	<0.5	328	1	<0.1	<0.1	36.5	1.7	11.5	10.4	16.3	0.1	13.4	14.3	6.6	52.6	<0.1	<0.5	1	269.4	1.3	12.9	<0.1	2.6	62	298.6	29	574.5	

Notes: Analysed at ACME, Vancouver, by ICP-MS. Ag (not shown) below detection limit (<0.1 ppm) and Hg (not shown) below detection limit (<0.01 ppm). \* Au in ppb. Abbreviations: SO = stratigraphic order from oldest (1) to youngest (2).

**Table 2.** Analyses of ARD potential in HRM by the BC-RIT analysis. For comparison total S analysis from the portable XRF and ACME are included.

Sample	SO	XRF	ACME	BC-RIT	S (Sulphide) wt. %	APP	ACA	Difference	Problem
		S (Total) wt. %	S (Total) wt. %	S (Total) wt. %		H <sub>2</sub> SO <sub>4</sub> kg/t	H <sub>2</sub> SO <sub>4</sub> kg/t		
<b>Bluestone formation</b>									
D12-W08-023	23	0.291	0.20	0.195	0.174	5.323	5.386	0.063	Maybe
D12-W08-017	22	0.525	0.27	0.289	0.275	8.412	6.359	-2.054	Yes
D12-W08-024	21	0.125	0.05	0.068	0.057	1.744	5.861	4.117	No
D12-W08-019	20	0.061	0.07	0.059	0.052	1.591	5.143	3.552	No
D12-W08-021	19	0.555	0.45	0.509	0.501	15.326	6.830	-8.496	Yes
D12-W08-020-A	18	0.172	0.26	0.262	0.241	7.372	7.085	-0.287	Yes
D12-W08-020-B	17	0.107	0.18	0.200	0.182	5.567	5.870	0.303	Maybe
D12-W08-027	16	0.255	0.20	0.227	0.201	6.149	4.410	-1.739	Yes
<b>Cunard formation</b>									
D12-W08-026	15	0.305	0.22	0.228	0.174	5.323	4.157	-1.166	Yes
D12-W08-014	14	0.557	0.33	0.342	0.298	9.116	3.176	-5.940	Yes
D12-W08-007	13	1.792	1.97	1.880	1.805	55.215	1.960	-53.255	Yes
D12-W08-029	12	1.119	0.94	0.933	0.914	27.959	14.927	-13.032	Yes
D12-W08-008	11	0.05	0.01	0.054	0.042	1.285	7.827	6.543	No
D12-W08-003	10	3.733	3.77	3.415	3.318	101.498	2.687	-98.811	Yes
D12-W08-010	9	1.368	1.22	1.160	1.126	34.444	6.108	-28.336	Yes
D12-W08-011	8	1.971	1.86	1.830	1.803	55.154	0.976	-54.178	Yes
D12-W08-004	7	0.818	0.88	0.867	0.836	25.573	3.430	-22.144	Yes
D12-W08-012	6	1.782	1.53	1.454	1.339	40.960	5.134	-35.826	Yes
<b>Beaverbank formation</b>									
D12-W08-001-B	5	0.347	0.16	0.154	0.139	4.252	93.468	89.216	No
D12-W08-013	4	0.26	0.08	1.404	1.399	42.795	9.615	-33.180	Yes
D12-W08-002	3	0.263	0.07	0.058	0.042	1.285	147.137	145.852	No
<b>Taylor's Head formation</b>									
D12-W08-030	2	0.017	0.01	0.012	0.008	0.245	36.011	35.767	No
D12-W07-003	1	0.019	0.04	0.041	0.034	1.040	1.363	0.323	Maybe

Notes: Abbreviations: SO = stratigraphic order from oldest (1) to youngest (2); APP = acid producing potential; ACA = acid consuming ability.

Magnetite and minor ilmenite are the main magnetic minerals in the metasandstone and metasiltstone beds (King 1997; Pelley 2007). They form small (0.1–0.2 mm), inclusion-rich to inclusion poor, euhedral crystals in the matrix and are metamorphic in origin; however, the more magnetic beds contain magnetite up to 2 mm in diameter, which is likely partly detrital in origin (Pelley 2007).

Cubic pyrite (1 to 2 cm in diameter) is typically rare in metasandstone of the Taylor's Head formation but more abundant in the slaty rocks and metasandstone of the Cunard formation and locally is present in the Bluestone formation at lower metamorphic grades. Based on petrographic evidence the pyrite predates the regional foliation (e.g., Hicks 1996).

Pyrrhotite is not common in metasandstone beds in the Taylor's Head formation but does occur locally with magnetite in the minor interbedded metasiltstone and slate. In the Beaverbank formation pyrrhotite typically occurs in the cores of spessartine garnet grains (e.g., Fox *et al.* 1997; White 2010a). Pyrrhotite, along with pyrite, is common in the Cunard for-

mation (e.g., Pasava *et al.* 1995) and locally present in the Bluestone formation. It can occur as relatively inclusion-free porphyroblasts but is typically inclusion-rich, flattened parallel to foliation, and elongate parallel to the intersection lineation and regional fold axis, indicating it grew during regional chlorite-grade metamorphism that was synchronous with regional deformation.

As metamorphic grade increases toward the contact with the South Mountain Batholith, the matrix minerals in the metasandstone beds are comprised of coarser grained white mica and decussate biotite and ultimately poikiloblastic cordierite at the contact. In these less aluminous metasandstone beds, andalusite and sillimanite are rare. In the pelitic units of the Taylor's Head and Beaverbank formations the matrix material also becomes coarser grained and, like in the metasandstone, decussate biotite appears. Closer to the contact with the South Mountain Batholith, biotite content increases and ovoid cordierite appears; it has typically been weathered out leaving tiny voids in the rock. Plagioclase compositions become in-

creasingly Ca-rich with higher An contents (up to An<sub>50</sub>) at the contact with the South Mountain Batholith (Mahoney 1996; White 2003; Clarke *et al.* 2009).

Jamieson *et al.* (2005 a, b) documented a change in the opaque mineralogy with increasing metamorphic grade where rutile and pyrite in the outer aureole are replaced by ilmenite and pyrrhotite closer to the contact. As noted by Clarke *et al.* (2009), pyrrhotite is the dominant sulphide in the contact aureole adjacent to the SMB, forming up to 15 modal % in some layers in the Halifax Group (Betts-Robertson 1998). Like in the lower grade metamorphic rocks, pyrrhotite remains flattened and elongate parallel to the relict foliation and intersection lineation. The pyrrhotite is typically anhedral and contains abundant inclusions of quartz, sheet silicates, Fe-Ti oxides, and other sulphide minerals that define inclusion trails parallel to the relict foliation in the matrix (i.e., Fox *et al.* 1997; Clarke *et al.* 2009). In contrast, pyrrhotite in the metasandstone beds of the Cunard formation is cubic (up to 1 cm in diameter) because it has pseudomorphed pyrite (Clarke *et al.* 2009).

In the shear zone at the contact between the SMB and country rocks, the intersection lineation becomes steeper and forms a mineral lineation defined by elongate quartz+biotite ± cordierite aggregates and elongate calc-silicate nodules in the metasandstone or boudinaged andalusite and elongate pyrrhotite in the pelitic rocks (Culshaw and Bhatnagar 2001; White *et al.* 2008). In contrast to the Taylors Head formation, the main magnetic mineral is pyrrhotite in the Beaverbank, Cunard, and Bluestone formations. Other minor sulphide minerals associated with pyrrhotite, typically as inclusions, include chalcopyrite, sphalerite, arsenopyrite, and galena. Although pyrrhotite is the dominant sulphide in some layers (Fox *et al.* 1997; Clarke *et al.* 2009), no samples collected in the study contain over 5 modal % total sulphide minerals.

### South Mountain Batholith

The Quarry Lake granodiorite (Fig. 2) is medium- to coarse-grained, equigranular to megacrystic, with alkali feldspar and less abundant plagioclase megacrysts. It has abundant metasedimentary xenoliths of the Goldenville and Halifax groups. Quartz forms anhedral to subhedral grains in the groundmass but in places forms subhedral megacrysts. Plagioclase is typically in the groundmass as subhedral crystals displaying normal to oscillatory zoning, and ranging in composition from An 5–35, whereas alkali feldspar occurs as euhedral perthitic megacrysts (e.g., MacDonald 2001). Biotite is mainly subhedral to euhedral in the groundmass and forms up to 25 modal percent. Muscovite, cordierite, and garnet occur in trace amounts. The monzogranite and leucomonzogranite units to the southwest (Fig. 1) display textures similar to the granodiorite but contain more muscovite and cordierite and less biotite (MacDonald 2001).

Pyrrhotite and chalcopyrite are the main sulphide minerals in the Quarry Lake granodiorite, together with trace amounts of sphalerite, galena, arsenopyrite, and molybdenite which typically occur as inclusions in the pyrrhotite (e.g., Clarke *et al.*

2009). Although the pyrrhotite may retain a similar flattened morphology as in the adjacent country rock, it is inclusion-free, small (<2 mm in size), and in some samples appears to be interstitial. The overall modal abundance of sulphide minerals in the batholith is less than 2%, considerably less than in the adjacent country rocks but can be several volume % of the granite at the contact (Clarke *et al.* 2009). No sample of granitoid rock collected during the present study contains over 1% sulphide minerals.

A detailed description of sulphide mineral textures and chemistry in the contact aureole and adjacent granitoid rocks of the South Mountain Batholith was provided by Clarke *et al.* (2009).

## RESULTS AND DISCUSSION

### Lithogeochemistry

Major element oxide and trace element data can provide useful information on ARD prediction. Because the ARD behaviour of a rock is depended on its mineral assemblage, the effects of changes in mineralogical composition on acid-rock generation and buffering reactions must be considered when predicting ARD. Because the portable XRF does not measure elements lighter than Na, data from ACME is used for SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, Na<sub>2</sub>O, and Fe<sub>2</sub>O<sub>3</sub><sup>T</sup> plots (Table 1a, Fig. 5).

Variations in SiO<sub>2</sub> content and SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio can be linked to the relative proportions of quartz, feldspar, and matrix minerals in the samples. White and Barr (2010) demonstrated this relationship for metasedimentary rocks in the Goldenville and Halifax groups in southwestern Nova Scotia. In the present study, petrographic data also were compared to their chemical compositions (Table 1a) and the results indicate that the boundary between sandstone and siltstone/mudstone is at 65% wt.% SiO<sub>2</sub> with a corresponding SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio of 3.5 (Fig. 5a), identical to the results of White and Barr (2010) from elsewhere in Meguma terrane. Samples with more than 65% SiO<sub>2</sub> when plotted on the chemical discrimination diagram of Herron (1988) are wacke to litharenite, whereas those with less than 65% SiO<sub>2</sub> are mainly shale to Fe-rich shale (Fig. 5b). On the chemical classification of sandstone diagram of Pettijohn *et al.* (1987), samples with more than 65% SiO<sub>2</sub> plot mainly in the litharenite field (Fig. 5c).

Metasandstone, siltstone, slate, and calc-silicate nodules were analyzed in each formation and plotted according to stratigraphic position against several chemical parameters (Figs. 6 and 7). The Taylors Head formation is typically low in CaO and MnO (Fig. 6a, b) and there is no difference between metasandstone and metasiltstone/slate. However, metasandstone samples with a carbonate matrix/cement are slightly higher in CaO with calc-silicate nodules having up to 23 wt. % CaO and no significant MnO (Fig. 6a, b). Fe<sub>2</sub>O<sub>3</sub><sup>T</sup> tends to be higher in the metasiltstone and slate samples than in metasandstone samples (Appendix A–D). The metasiltstone-rich Beaverbank formation is higher in CaO and MnO with the metasandstone

having the lowest concentrations and the metasiltstone and slate slightly higher (Appendix A, B). The cotucle nodules and layers are significantly higher in MnO, CaO, and  $\text{Fe}_2\text{O}_3^T$  (Fig. 6a, b, c) but that correlation is not 1:1 as some metasiltstone samples with high CaO are low in MnO and  $\text{Fe}_2\text{O}_3^T$ . In contrast, all samples in the overlying Cunard formation display low CaO and MnO but  $\text{Fe}_2\text{O}_3^T$  remains high. Metasandstone and metasiltstone samples from the Bluestone formation are somewhat similar in CaO, MnO, and  $\text{Fe}_2\text{O}_3^T$  to those from the underlying Cunard formation; however, the calc-silicate nodules are significantly higher in CaO and only slightly higher in MnO and  $\text{Fe}_2\text{O}_3^T$  (Fig. 6a, b).

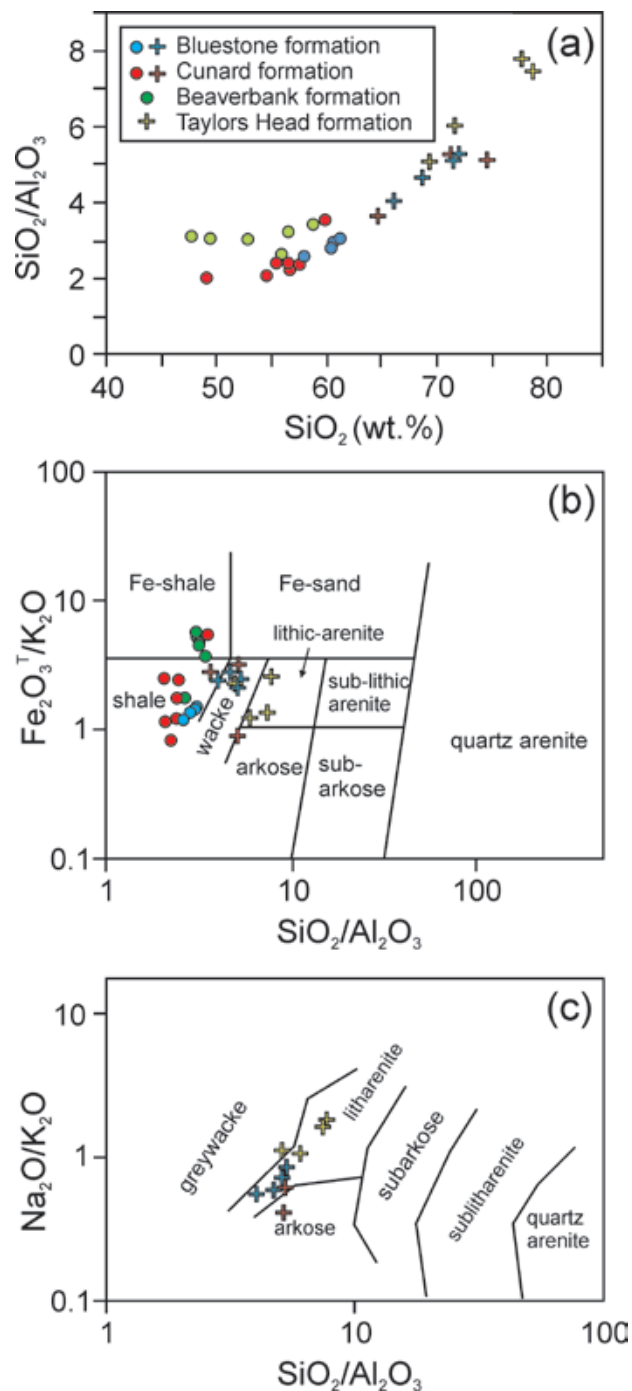
Total weight percent sulphur also varies with stratigraphic position and rock type, with median values of 0.04 in the Taylors Head formation, 0.32 in the Beaverbank formation, 1.29 in the Cunard formation, 0.17 in the Bluestone formation, and 0.01 in the granitoid rocks of the South Mountain Batholith (Fig. 7a; Appendix A–E). The higher values in the Beaverbank, Cunard, and Bluestone formations are attributed to abundant pyrrhotite. Some of the highest values (> 5 wt. %) are in hornfelsic samples from around the South Mountain Batholith. Typically there is a positive correlation between total sulphur and total metals (Cu + Pb + Zn) (e.g., Hammarstrom *et al.* 2003) but only the Cunard formation displays this trend (Fig. 7b). However, Pb, Zn, Cu, and As show no significant differences with stratigraphic position and all of the anomalous samples are located in the contact aureole of the South Mountain Batholith (Fig. 7c, d, e, f).

The chemical change at the contact between the Taylors Head and Beaverbank formations marks a dramatic and rapid change in the original seawater chemistry where conditions were favourable for deposition of Ca, Mn, Fe, and S. Under anoxic conditions Mn-oxide served as the oxidant, thereby leading to the eventual precipitation of manganese carbonate near the sediment-water contact (Graves and Zentilli 1988). These conditions are also favourable for sulphide mineral precipitation. The Beaverbank formation contains some of the highest total carbon values compared to the other formations (Table 1a).

The Beaverbank formation and equivalent Moshers Island formation elsewhere in the Meguma terrane are also enriched in Pb, Zn, Cu, and As (Graves and Zentilli 1988); however, the Taylors Head, Cunard, and Bluestone formations are also locally enriched in these elements (e.g., White 2010b). In the HRM area this enrichment appears to be associated with contact metamorphic effects from the South Mountain Batholith as indicated by the increased presence of chalcopyrite, galena, sphalerite, and arsenopyrite in the contact aureole (Clarke *et al.* 2009).

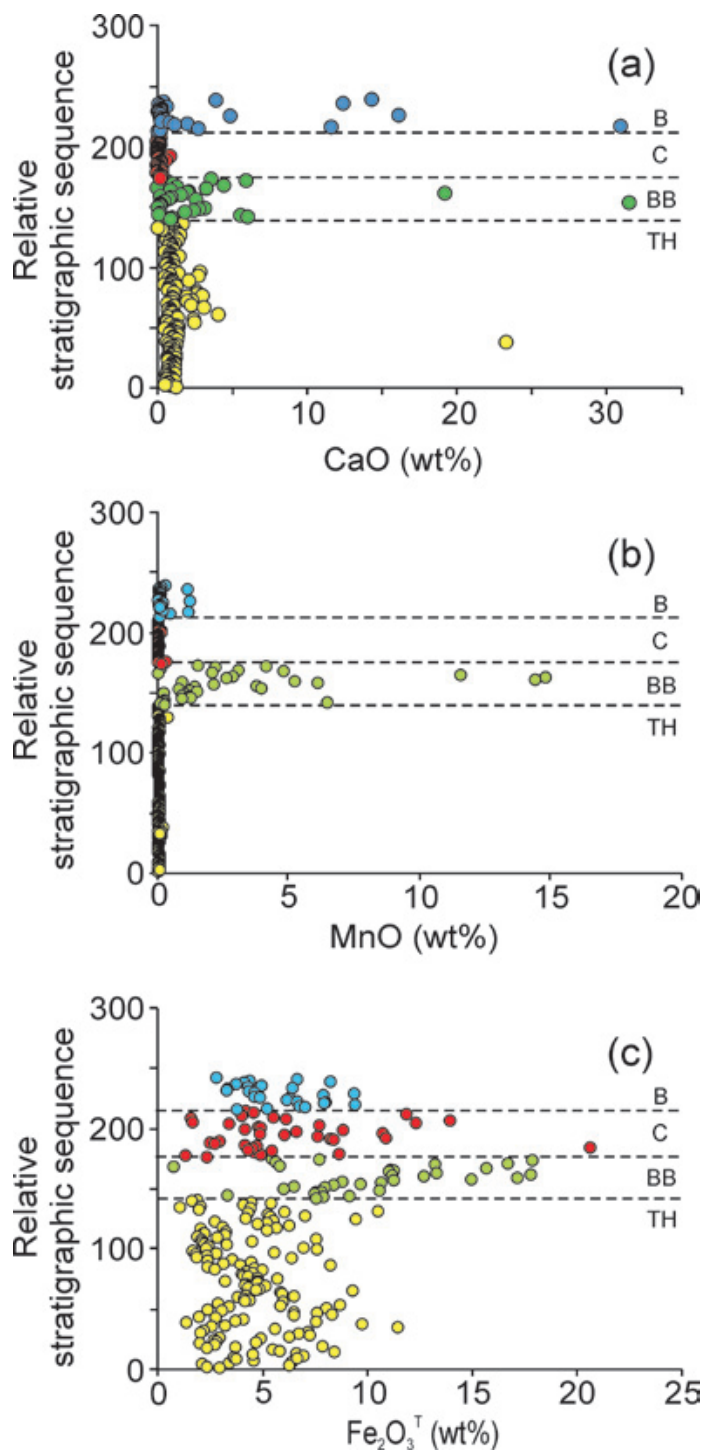
#### Acid generation prediction

In Nova Scotia, the Sulphide Bearing Material Disposal Regulations state that rocks having sulphide sulphur contents equal to or greater than 0.4 weight % must be considered as hazardous ARD material. The portable XRF results, like the results from Acme Analytical Laboratories, are presented as



**Fig. 5.** (a) Plot of  $\text{SiO}_2$  against  $\text{SiO}_2/\text{Al}_2\text{O}_3$  where classification as sandstone (plus symbols) or siltstone/mudstone (circles) is based on petrographic study. (b) Chemical classification using  $\text{Fe}_2\text{O}_3^T/\text{K}_2\text{O}$  versus  $\text{SiO}_2/\text{Al}_2\text{O}_3$ . Fields are from Herron (1988). (c) Chemical classification using  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  versus  $\text{SiO}_2/\text{Al}_2\text{O}_3$ . Fields are from Pettijohn *et al.* (1987).

total weight % sulphur which, based on the data in Table 2, is about 17% higher than total sulphide sulphur, except in samples from the Cunard formation where the ratio is almost 1:1 (Table 2). Although assigning all sulphur to sulphides is per-



**Fig. 6.** Plots of selected chemical parameters against relative stratigraphic position: (a) CaO, (b) MnO, and (c) Fe<sub>2</sub>O<sub>3</sub><sup>T</sup> in the Goldenville and Halifax groups. Abbreviations: B = Bluestone formation; C = Cunard formation; BB = Beaverbank formation; TH = Taylors Head formation. Symbols are as in Fig. 3.

haps overly conservative as it ignores contributions from non-acid generating phases (e.g., sulphates and organic matter), the total weight % sulphur and total sulphide sulphur can be

considered interchangeable; hence, a rock with total sulphur content equal to or greater than 0.47 can be considered hazardous (Fig. 7a). However, this parameter does not take into account the possible neutralizing capacities of minerals in the rock (Weber *et al.* 2005) or the varying reactivities of different sulphide minerals.

The most important acid neutralizing minerals in the Goldenville and Halifax groups are calcite and dolomite and, to a much lesser extent, rhodochrosite and ankerite. The neutralizing power of feldspar varies considerably, depending on its composition. Altered (i.e., sericitized) feldspar has much less neutralizing power than its unaltered or carbonatized equivalents. Potassium-rich feldspar (orthoclase/microcline) and Na-rich plagioclase (albite) have less neutralizing power than the more Ca-rich plagioclase (anorthite). The metasandstone in the lower grade regional metamorphic rocks typically contains albitic plagioclase; however, in the contact metamorphic aureole plagioclase (10–40 modal %) is typically more Ca-rich (oligoclase to andesine) which adds to the neutralizing power. Minerals containing Mg (biotite and chlorite) also contribute to buffering ARD, but play a minor role (Weber *et al.* 2005). In the Goldenville and Halifax groups it is likely that the abundance of plagioclase and its alteration products, along with carbonate minerals, largely determine the neutralizing power in high sulphur samples. In comparison, the granitoid rocks of the SMB have total sulphur less than 0.20 weight % and pose no apparent ARD risk (Fig. 8; Appendix E).

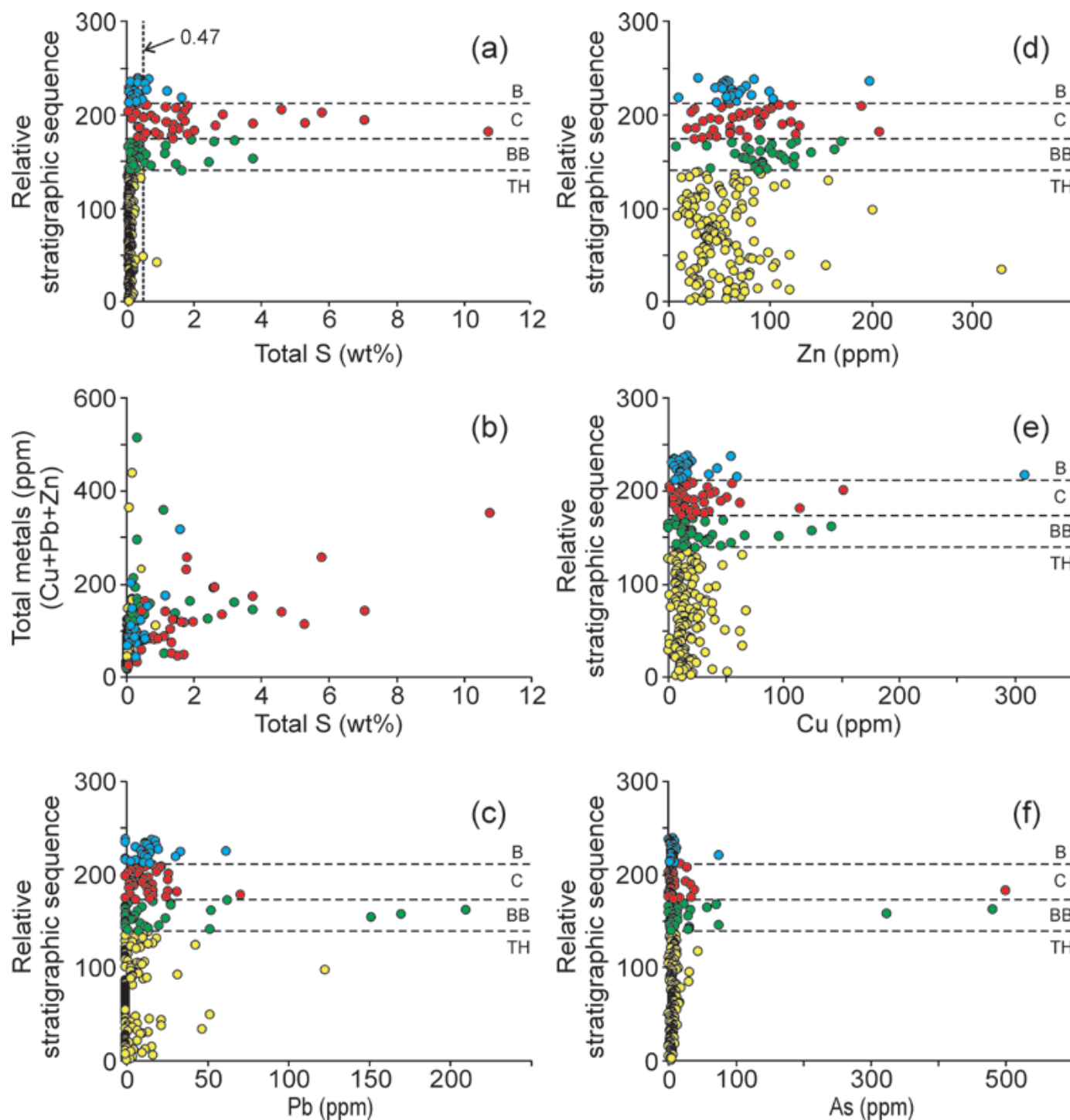
The potential for acid generation is dependent on the ratio of acid-producing potential (APP) to acid-consuming ability (ACA). Following the legally binding British Columbia Research Initial Test the neutralizing power of 23 samples has been calculated (Table 2) and plotted (Fig. 9a). A 1:1 ratio (acid/base) is plotted and assumes that the tested samples that plot below this ratio are net acid consumers (e.g., Schoeffler and Clawson 1996). However, Lawrence and Scheske (1997) noted that different mineral groups have different relative reactivities (i.e., carbonate minerals react faster than feldspar minerals), and hence the control on neutralization varies with mineralogy and a more suitable value for the neutralizing potential is 0.54. Because it is difficult to predict the short- and long-term acid generation potential of a rock unit a “zone of uncertainty” was defined between the 1:1 and 1:2 gradient lines (Fig. 9a, b) (Bell and Bullock 1996; Campbell *et al.* 2001).

Total S wt% versus CaO wt% can be considered equivalent to APP/ACA in a theoretical sense (e.g., Downing and Madisky 1997) and it has been shown that data from the portable XRF is comparable to Acme Analytical Laboratories and British Columbia Research Initial Test results (Fig. 3). Hence, a plot of total S wt. % versus CaO wt. % for data collected from the portable XRF can be used with a significant degree of confidence as a first approximation for acid generating potential of the rock.

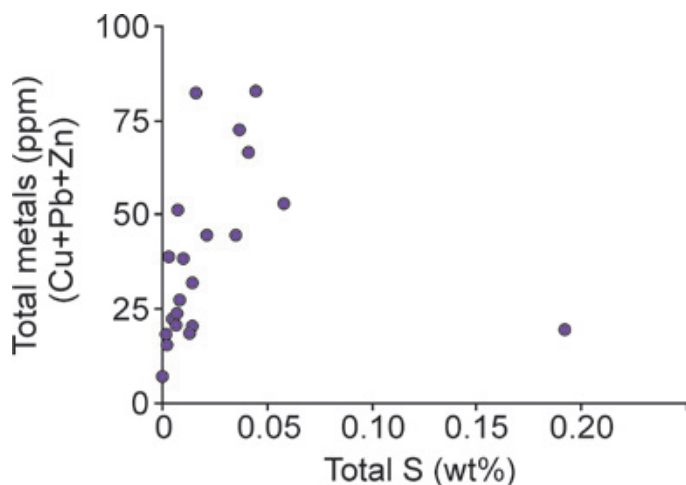
Figure 9b shows a wide distribution of sample populations which indicates that three units are potentially acid producers (Bluestone, Cunard, and Beaverbank formations), and two units are non-acid producing (Taylors Head formation and South Mountain Batholith). About 97% of the samples col-

lected from the Cunard formation are potential acid producers with an APP/ACA and S/CaO ratios of  $>1.0$  (Fig. 9a, b) and a high median total sulphur content of 1.31 %. About 3% of the samples are non-acid producers. In comparison, 26 % of the samples in the stratigraphically higher Bluestone formation and

24 % of the samples from the underlying Beaverbank formation are potential acid producers with average total sulphur of 0.30% and 0.90%, respectively. However, about half (50–55%) of the samples from these two formations lie in the zone of uncertainty and hence can be acid producers under the right



**Fig. 7.** Plots of selected chemical parameters against relative stratigraphic position: (a) S, (c) Pb, (d) Zn, (e) Cu, and (f) As, and (b) plot of total S against total metals in the Goldenville and Halifax groups. Abbreviations: B = Bluestone formation; C = Cunard formation; BB = Beaverbank formation; TH = Taylors Head formation. Symbols are as in Fig. 3.



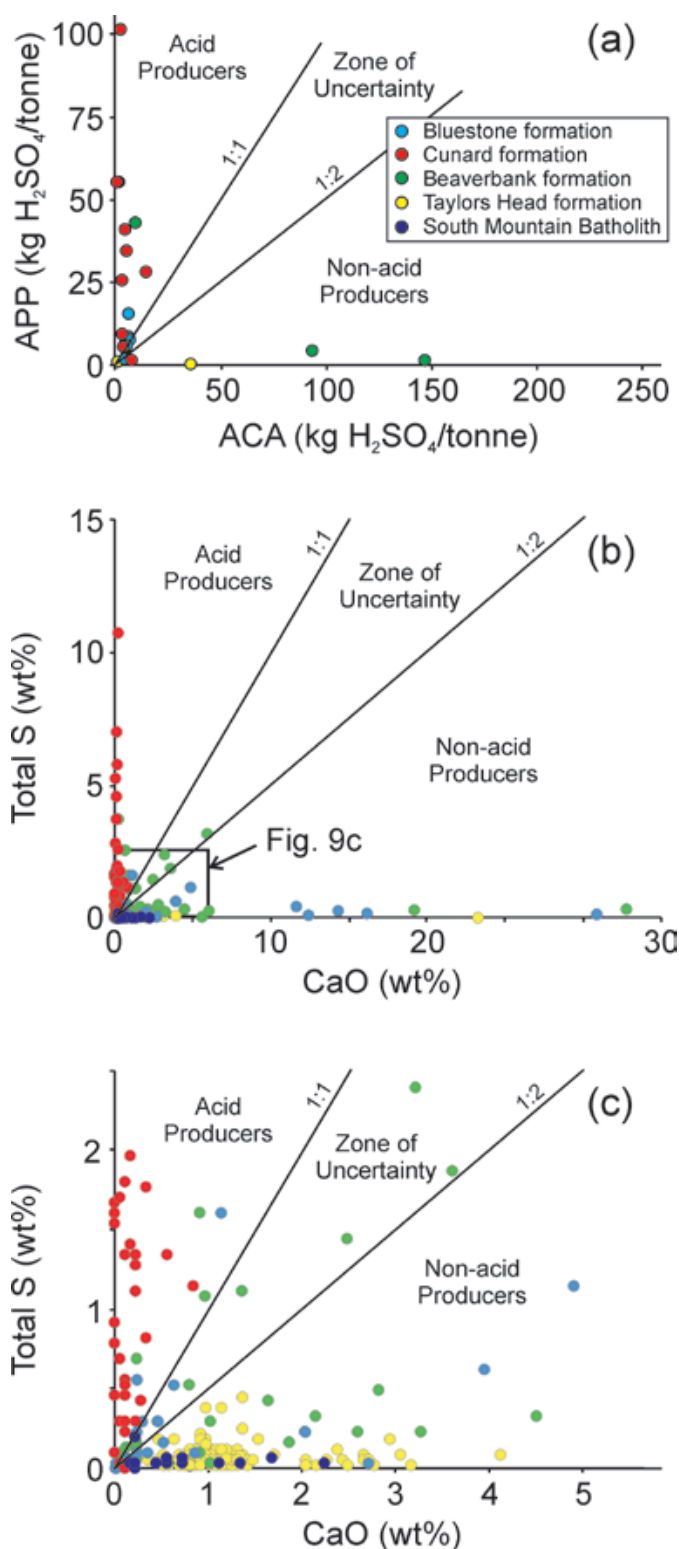
**Fig. 8.** Plot of total S against total metals in the South Mountain Batholith.

conditions. The high sulphur percentage and acid producing potential in the Bluestone, Cunard, and Beaverbank formations is consistent with major basin-wide stagnation in which anoxic conditions existed during the depositional history of these formations (Waldron 1987; Graves and Zentilli 1988). The high proportion of acid-producing rocks in the Cunard formation can be directly linked to the low acid-buffering CaO content (median = 0.09 wt. %) compared to the Bluestone and Beaverbank formations (median = 0.39 and 1.29 wt. %, respectively) (Appendix A–C).

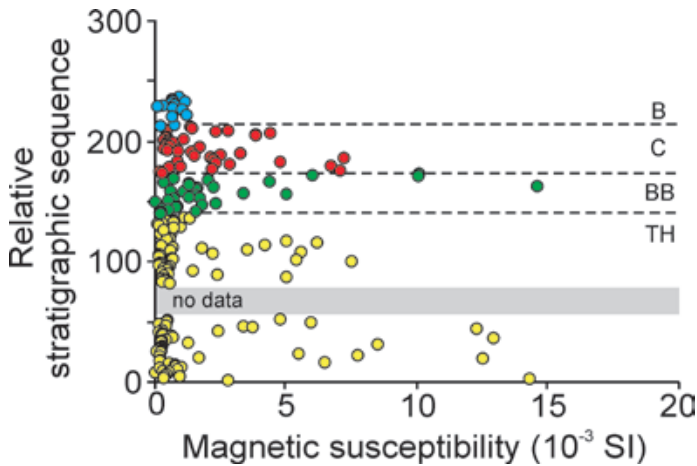
About 99% of the samples from the Taylors Head formation are non-acid producing (Fig. 9b) and have a low total sulphur content (median = 0.04 wt. %) (Appendix D). One sample (D12-W09-101) that is a potential acid producer has low total sulphur (0.023 wt. %) and low CaO (0.01 wt. %) and is one of two samples that is classified as quartz arenite (Fig. 4b) and hence is not likely to produce acid due to the high quartz content. The other sample classified as quartz arenite (D12-W07-015) is a spotted metasiltstone which contains 0.86 wt. % sulphur (Appendix D). It is from a thin (< 20 cm thick) bed within a massive metasandstone bed and, although this sample has the potential to produce acid, the effects would likely be diluted by the surrounding non-acid producing metasandstone.

About 95% of the granitoid samples from the South Mountain Batholith are non-acid producing (Fig. 9b) and have the lowest average total sulphur content (0.017 wt %) of all the units sampled (Appendix E). One sample (CW-270B) plots in the zone of uncertainty and has a total sulphur content of 0.859 wt. %. It has an elevated sulphur percentage compared to the other granitoid samples because it is a pyrite-bearing aplite-pegmatite dyke cutting the South Mountain Batholith. Because this is a minor unit the acid-producing potential is considered as low.

A useful application of susceptibility measurements is to determine the presence of sulphide-bearing minerals in outcrop. High magnetic susceptibility measurements are indicative of the presence of ferromagnetic and paramagnetic minerals



**Fig. 9.** (a) Plot of acid-producing potential (APP) against acid-consuming ability (ACA) using results from the British Columbia Research Initial Test. (b) Plot of total S against CaO using results from the portable XRF. Area of Fig 9c is shown in box. (c) Close-up of data in box shown at origin in Fig. 9b.



**Fig. 10.** Plot of magnetic susceptibility against stratigraphic position in the Goldenville and Halifax groups. Abbreviations: B = Bluestone formation; C = Cunard formation; BB = Beaverbank formation; TH = Taylors Head formation. Symbols are as in Fig. 3.

(e.g., King 1997; Howells and Fox 1998; Fitzgerald and Goodwin 2005). In the Taylors Head formation the high magnetic susceptibility measurements are due to the presence of magnetite and to a lesser degree ilmenite. In contrast, the high readings in the Beaverbank, Cunard, and Bluestone formations are due to the presence of pyrite in the lower metamorphic grade rocks and pyrrhotite in the higher metamorphic grade contact aureole of the South Mountain Batholith (Fig. 10). The susceptibility data aid in delineating problematic, potentially acid-producing units before excavation takes place. However, detailed petrographic analysis is required to determine the character of the magnetic mineral. As shown in Figure 10, the metasandstone in the Taylors Head formation yields high magnetic susceptibility measurements but based on other data this rock type is low risk in terms of producing acid rock drainage.

### CONCLUSIONS

Rock samples lacking abundant sulphide minerals were purposely collected and analyzed to represent the average litho-geochemistry and ARD potential for units in the metropolitan area of HRM. This study showed that many of these unmineralized rocks have the potential to produce acid. The main acid producers are slate, metasiltstone, and metasandstone of the Beaverbank, Cunard, and Bluestone formations, with the Cunard formation having the highest acid-producing potential. The older, dominantly metasandstone-rich Taylors Head formation, as well as the granitoid rocks of the South Mountain Batholith, are non-acid producing. However, the acid-producing potential is greatly increased in contact metamorphosed rocks, especially in the Cunard formation, adjacent to the South Mountain Batholith.

It has been demonstrated that ARD buffering behaviour is

based on the bulk rock chemistry and modal mineralogy of the rock. Hence, knowledge of rock type, alteration characteristics, and depositional environment is important in understanding and predicting the ARD buffering capacity. This study demonstrates that a detailed geological map and petrographic study coupled with litho-geochemical data are needed in order to better ascertain acid rock drainage potential.

Whole rock and sulphur analyses obtained by the portable XRF are a cost-effective way, compared to the acid-base accounting (ABA) test, to estimate the APP/ACA of rocks to provide an early warning of possible ARD problems. Although this approach is not intended as a substitute for the legally mandated ABA test procedure, it could facilitate timely and cost-effective management and mitigation of possible ARD throughout the Goldenville and Halifax groups and in geologically similar areas world-wide.

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*Editorial responsibility Sandra M. Barr*

**Appendix A.** Whole-rock chemical analyses of samples from the Bluestone formation by the portable XRF.

sample	UTM nad 83*		lithology	SO	Mag	major oxides (wt%)				total S (wt%)	trace elements (ppm)										ARD Problem			
	Easting	Northing				CaO	K <sub>2</sub> O	TiO <sub>2</sub>	MnO		Fe <sub>2</sub> O <sub>3</sub> <sup>†</sup>	As	Ba	Cu	Nb	Pb	Rb	Sr	V	Y		Zn	Zr	
PCR07-11A	453802	4940937	calc-silicate	239	n.d.	14.27	1.75	0.49	0.32	2.80	0.28	6	189	16	27	b.l.d	55	567	57	42	28	207	NO	
PCR07-11B	453802	4940937	slate	238	n.d.	3.90	2.20	0.80	0.16	6.66	0.62	b.d.l.	1199	54	17	16	129	347	127	46	84	239	NO	
D12-W08-023	454441	4941429	sandstone	237	0.93	0.39	2.46	0.58	0.06	4.35	0.29	2	410	13	15	18	117	176	67	34	57	207	MAYBE	
WL07-20B	451581	4941093	calc-silicate	236	n.d.	12.41	2.21	0.49	1.16	8.22	0.12	9	398	5	18	b.d.l.	87	196	65	24	198	250	NO	
D12-W08-016	454716	4941866	slate	235	0.66	0.08	4.25	1.07	0.12	4.10	0.08	4	822	6	29	12	182	109	181	52	59	97	MAYBE	
D12-W08-016	454716	4941866	siltstone	234	0.66	0.24	2.91	0.73	0.08	3.73	0.30	3	643	9	19	12	136	114	88	35	53	181	YES	
D12-W08-017	454874	4941771	sandstone	233	1.14	0.60	1.94	0.46	0.10	4.93	0.52	2	296	20	13	14	96	210	43	26	57	302	MAYBE	
D12-W08-024	453567	4941963	silty slate	232	0.63	0.31	4.54	0.95	0.13	4.29	0.13	7	884	3	24	19	187	164	128	41	54	251	NO	
D12-W08-022	454419	4940975	hornfels	231	0.76	0.29	4.06	0.92	0.11	6.43	0.10	4	751	17	21	6	179	156	117	36	76	159	NO	
D12-W08-015A	454405	4942295	sandstone	230	0.31	0.17	1.87	0.51	0.07	3.30	0.12	4	313	16	14	15	88	98	51	24	51	251	MAYBE	
D12-W08-015B	454405	4942295	siltstone	229	0.11	0.01	6.29	0.95	0.06	3.28	0.02	11	1079	9	23	15	235	80	141	35	46	109	YES	
D12-W08-019	455312	4941365	hornfels	228	0.69	0.07	5.04	1.05	0.08	4.33	0.06	7	1191	5	26	20	196	183	132	30	53	167	MAYBE	
D12-W08-021	454673	4940856	hornfels	227	1.02	0.18	5.12	0.85	0.06	4.61	0.56	3	928	12	20	9	209	137	109	38	62	184	YES	
PPP-7C-A	455316	4940871	calc-silicate	226	n.d.	16.14	0.23	0.48	1.26	9.38	0.18	10	33	15	21	62	9	347	53	32	71	78	NO	
PPP-7C-B	455316	4940871	slate	225	n.d.	4.85	1.97	1.15	0.22	7.90	1.16	7	462	42	20	34	119	331	100	29	99	275	NO	
PPP-07-28A	455315	4940870	hornfels	224	n.d.	0.16	5.01	0.86	0.09	4.62	0.04	3	1075	7	22	15	185	115	121	37	64	121	NO	
PPP-07-28B	455315	4940870	sandstone	223	n.d.	0.26	3.87	0.78	0.07	4.86	0.30	5	825	15	20	10	172	103	89	45	66	406	YES	
D12-W08-020A	455321	4940878	sandstone	222	1.22	0.47	3.13	0.77	0.16	6.26	0.17	4	632	10	19	13	136	139	85	32	69	242	NO	
D12-W08-020B	455321	4940878	hornfels	221	0.65	0.23	5.06	0.91	0.10	6.15	0.11	75	880	11	19	12	192	110	115	40	81	182	NO	
PCR07-26B-A	454623	4940370	hornfels	220	n.d.	0.81	4.51	0.83	0.11	6.66	0.09	7	781	16	20	31	167	266	105	32	62	144	NO	
PCR07-26B-B	454623	4940370	hornfels	219	n.d.	1.99	4.00	0.88	0.15	8.04	0.25	3	819	35	22	14	157	255	102	28	57	121	NO	
PCR07-26B-C	454623	4940370	hornfels	218	n.d.	1.11	6.37	0.63	0.21	7.93	1.59	7	2496	308	21	b.d.l.	172	251	221	51	10	55	YES	
PCR07-18A	454610	4940317	calc-silicate	217	n.d.	30.89	1.27	0.58	1.19	9.42	0.14	6	713	9	20	b.d.l.	42	336	111	52	103	90	NO	
PCR07-18B	454610	4940317	calc-silicate	216	n.d.	11.61	3.08	0.71	0.50	6.76	0.44	4	2045	59	16	6	120	510	192	38	58	125	NO	
PCR07-18C	454610	4940317	hornfels	215	n.d.	2.70	2.43	0.60	0.15	7.01	0.06	3	926	12	11	3	187	320	90	9	59	129	NO	
D12-W08-027	453819	4942457	sandstone	214	0.76	0.20	2.58	0.62	0.11	5.21	0.26	1	459	9	17	11	110	85	64	21	67	200	YES	
D12-W08-025	453404	4942374	hornfels	213	0.21	0.01	6.43	1.16	0.10	3.74	0.03	8	1098	6	26	15	211	76	164	51	47	108	YES	
<b>AVERAGE</b>						0.70	3.86	3.50	0.77	0.26	5.74	0.44	7.8	827.6	27.4	19.9	16.6	143.4	213.9	108.0	35.4	66.3	180.7	
<b>STANDARD DEVIATION</b>						0.33	7.22	1.65	0.21	0.35	1.91	0.36	14	521.3	57.9	4.16	12.1	55.8	129.3	44.41	10.3	32.3	79.65	
<b>MEDIAN</b>						0.68	0.39	3.13	0.78	0.11	5.21	0.17	4.3	819.0	12.0	19.7	13.5	156.5	175.5	104.5	35.0	59.0	181.0	

**Notes:** Abbreviations: SO = stratigraphic order from oldest (lower number) to youngest (higher number); Mag = magnetic susceptibility in  $10^{-3}$  SI units; n.d. = not determined; b.d.l. = below detection limit; \* Zone 20. Samples with PPP, PC, and WL prefixes are from Dr. R.A. Jameison's (Dalhousie University) rock collection.

**Appendix B.** Whole-rock chemical analyses of samples from the Cumard formation by the portable XRF.

Sample	UTM nad 83*		lithology	SO	Mag	major oxides (wt%)			total S (wt%)	trace elements (ppm)										ARD Problem			
	Eastng	Northing				CaO	K <sub>2</sub> O	TiO <sub>2</sub>		MnO	Fe <sub>2</sub> O <sub>3</sub> <sup>T</sup>	As	Ba	Cu	Nb	Pb	Rb	Sr	V		Y	Zn	Zr
D12-W08-026	452727	4942408	hornfels	212	1.35	0.18	3.27	0.92	0.07	4.18	0.30	17	598	9	22	5	143	273	103	41	60	119	YES
D12-W08-018	452769	4942614	hornfels	211	1.41	0.08	3.43	0.72	0.07	4.55	0.47	5	629	17	18	17	172	195	94	10	109	135	YES
D12-W08-014	454604	4943794	slate	210	0.44	0.09	4.62	1.06	0.03	3.95	0.56	3	907	21	24	22	191	261	200	12	121	174	YES
D12-W08-007	453773	4944549	siltstone	209	2.81	0.11	2.11	0.62	0.08	11.89	1.79	2	411	55	13	12	83	81	68	24	190	109	YES
D12-W08-029	450825	4943228	hornfels	208	2.32	0.22	4.75	0.99	0.04	3.97	1.12	27	838	15	22	21	183	295	129	40	52	121	YES
D12-W08-028	452222	4943207	sandstone	207	4.41	0.14	3.31	0.72	0.04	5.53	1.42	3	745	16	15	7	170	219	100	32	101	135	YES
D12-W08-006A	453733	4944943	slate	206	3.84	0.07	1.71	0.69	0.02	1.56	0.06	2	343	1	19	4	86	152	89	31	25	94	YES
D12-W08-006A	453733	4944943	sandstone	205	3.84	0.07	3.22	0.95	0.02	6.13	4.59	5	675	34	25	9	148	188	84	65	97	611	YES
D12-W08-006B	453733	4944943	slate	204	4.44	0.00	2.74	0.87	0.04	13.97	1.70	3	807	12	23	19	161	226	287	40	87	115	YES
D12-W08-008	453298	4944845	sandstone	203	0.41	0.11	1.63	0.69	0.03	1.63	0.05	b.d.l.	368	2	22	2	86	180	82	26	22	131	NO
CW-599A	449363	4942774	hornfels	202	1.09	0.16	4.21	0.52	0.17	12.34	5.78	4	785	152	18	27	128	172	102	16	79	128	YES
D12-W09-106	455032	4945816	slate	201	0.32	0.10	3.87	1.08	0.03	3.40	0.24	7	747	12	24	8	162	225	143	41	70	121	YES
D12-W09-109	459789	4948696	slate	200	0.48	0.02	2.63	0.88	0.15	7.69	2.82	1	680	40	15	b.d.l.	96	214	95	24	95	207	YES
D12-W09-108	454934	4946207	slate	199	0.68	0.03	2.25	0.51	0.06	4.80	0.68	3	457	9	14	b.d.l.	95	88	55	15	74	123	YES
D12-W09-105	454898	4946146	slate	198	0.45	0.00	4.11	0.90	0.05	4.10	1.62	6	735	36	17	14	166	223	134	13	69	97	YES
D12-W09-107	453944	4946066	slate	197	0.40	0.00	3.38	0.67	0.04	4.97	0.48	2	760	6	13	11	141	150	91	8	63	126	YES
D12-W10-202	438876	4954651	slate	196	0.56	0.00	3.21	0.92	0.03	8.86	0.11	1	593	30	18	11	131	59	95	14	41	161	YES
CW-359A	438866	4954742	slate	195	1.71	0.00	3.89	0.87	0.05	6.61	0.80	4	706	13	23	26	172	147	146	28	49	118	YES
D12-W10-203	438982	4954843	siltstone	194	0.33	0.00	1.84	0.52	0.06	10.76	7.05	9	351	51	14	4	81	47	58	17	88	119	YES
D12-W09-110A	453213	4945464	slate	193	0.47	0.02	3.39	0.89	0.03	4.87	1.70	26	764	5	22	10	149	226	114	12	34	98	YES
D12-W09-110B	453213	4945464	sandstone	192	0.89	0.83	1.02	0.83	0.08	6.06	1.15	2	207	17	21	5	43	121	48	16	121	510	YES
D12-W08-005	453122	4945564	sandstone	191	1.40	0.05	2.02	0.58	0.07	7.65	5.27	3	463	22	17	2	96	114	55	11	90	208	YES
D12-W08-003	452970	4945793	siltstone	190	3.27	0.06	4.63	0.92	0.07	10.90	3.73	32	1004	45	17	17	186	268	126	9	112	184	YES
D12-W08-010	447558	4943435	hornfels	189	2.49	0.57	3.42	0.73	0.11	8.23	1.37	5	707	31	17	5	170	175	99	19	89	85	YES
CW-432B	447639	4943733	hornfels	188	1.52	0.22	4.50	0.89	0.05	8.41	2.60	8	735	62	19	3	158	77	116	13	129	132	YES
D12-W08-009	447500	4943647	hornfels	187	2.11	0.18	2.63	0.60	0.04	2.92	0.31	3	483	8	17	13	97	69	77	15	60	111	YES
D12-W11-229A	459986	4948797	slate	186	7.22	0.03	1.89	0.82	0.04	2.47	0.33	2	513	5	15	2	77	204	85	29	27	91	YES
D12-W11-229B	459986	4948797	sandstone	185	2.23	0.00	2.43	0.75	0.02	2.71	1.53	3	700	14	15	15	101	202	80	24	18	409	YES
CW-423A	449403	4944404	slate	184	0.85	0.07	5.22	0.99	0.03	4.16	1.33	38	961	14	19	17	172	168	160	15	44	122	YES
D12-W08-011	448186	4943794	hornfels	183	4.77	0.16	6.09	0.89	0.02	4.71	1.97	928	860	22	16	26	217	169	158	14	70	116	YES
D12-W10-228	455620	4938626	hornfels	182	2.31	0.17	2.05	0.82	0.08	20.67	10.76	2	566	113	16	32	156	142	82	43	208	111	YES
D12-W08-004	452714	4946000	sandstone	181	2.87	0.30	2.27	0.74	0.06	4.54	0.82	b.d.l.	580	8	17	14	87	204	88	22	60	241	YES
D12-W10-227	455956	4938753	hornfels	180	6.72	0.08	4.85	1.23	0.04	4.32	0.53	1	1080	18	23	3	144	208	167	50	60	184	YES
D12-W08-012	448218	4944109	siltstone	179	0.98	0.31	2.25	0.68	0.08	5.46	1.78	5	640	35	15	71	92	133	91	60	125	104	YES
D12-W07-081	450480	4945089	sandstone	178	0.54	0.00	4.42	1.23	0.04	4.60	0.93	4	971	24	21	17	171	201	153	18	41	176	YES
D12-W07-055	448456	4944365	hornfels	177	2.17	0.20	4.99	1.16	0.05	8.66	1.29	b.d.l.	1301	31	22	25	172	355	192	17	47	137	YES
D12-W10-226	456117	4938097	hornfels	176	7.08	0.13	5.65	1.06	0.36	4.89	0.30	33	551	22	19	b.d.l.	246	109	130	29	77	129	YES
D12-W07-071	447886	4944220	hornfels	175	0.19	0.27	2.94	1.17	0.03	1.31	0.45	16	969	11	21	15	98	297	143	19	33	148	YES
D12-W07-070	448330	4944499	siltstone	174	0.29	0.18	4.13	0.83	0.17	2.33	1.34	7	1072	20	20	6	162	346	133	33	25	115	YES
<b>AVERAGE</b>					1.99	0.13	3.36	0.84	0.06	6.17	1.82	34	698.9	27.0	18.6	14.3	138.0	184.1	114.1	24.6	75.9	162.9	
<b>STANDARD DEVIATION</b>					1.92	0.16	1.23	0.19	0.06	3.91	2.20	154	231.7	29.2	3.4	12.7	44.7	75.2	46.8	14.1	42.5	109.6	
<b>MEDIAN</b>					1.40	0.09	3.31	0.87	0.04	4.87	1.29	4.00	706.0	18.0	18.0	12.5	148.0	188.0	100.0	19.3	70.0	126.0	

**Notes:** Abbreviations: SO = stratigraphic order from oldest (bottom) to youngest (top); Mag = magnetic susceptibility in 1x10<sup>-3</sup> SI units; b.d.l. = below detection limit; \* Zone 20.

Appendix C. Whole-rock chemical analyses of samples from the Beaverbank formation by the portable XRF.

Sample	UTM nad 83*		lithology	SO	Mag	major oxides (wt%)				total S (wt%)	trace elements (ppm)										ARD Problem		
	Easting	Northing				CaO	K <sub>2</sub> O	TiO <sub>2</sub>	MnO		Fe <sub>2</sub> O <sub>3</sub> <sup>T</sup>	As	Ba	Cu	Nb	Pb	Rb	Sr	V	Y		Zn	Zr
D12-W10-225B	456198	4938502	hornfels	173	10.09	3.58	4.76	1.15	1.54	5.44	1.89	8	2039	11	22	63	188	321	230	21	90	160	MAYBE
D12-W10-225B	456198	4938502	hornfels	172	6.03	5.94	3.16	1.02	4.17	7.69	3.18	6	743	18	17	17	153	212	131	18	126	125	MAYBE
D12-W10-225A	456198	4938502	hornfels	171	10.07	0.65	3.64	0.99	2.22	17.90	2.56	8	1263	21	18	2	135	74	177	64	170	162	YES
CW-404A	446544	4944922	hornfels	170	0.68	0.52	9.09	0.98	0.14	5.62	0.06	7	1500	6	18	28	212	230	166	32	62	150	NO
D12-W08-001A	452352	4946544	siltstone	169	0.72	1.02	2.77	1.10	3.10	16.72	0.31	22	708	47	17	1	78	110	129	31	121	155	NO
D12-W08-001B	452352	4946544	siltstone	168	2.03	4.42	2.61	0.93	4.82	13.26	0.35	71	634	32	16	28	75	124	119	33	101	156	NO
D12-W07-021A	440654	4954627	slate	167	4.37	1.29	0.98	0.36	2.10	5.80	1.12	2	315	14	13	b.d.l.	69	114	44	27	37	184	MAYBE
D12-W07-021B	440654	4954627	sandstone	166	0.33	b.d.l.	1.67	0.39	0.05	0.75	0.00	b.d.l.	545	3	8	10	85	96	68	20	7	78	YES
D12-W07-020	440422	4954267	coticule	165	1.29	3.25	2.74	1.30	11.59	15.71	0.26	57	1374	b.d.l.	12	b.d.l.	80	104	199	46	76	109	NO
D12-W07-020	440422	4954267	siltstone	164	1.29	0.88	4.83	1.43	2.89	11.10	0.12	13	3234	7	21	b.d.l.	145	167	359	39	99	149	NO
D12-W10-224	456266	4938244	coticule	163	14.6	2.08	2.86	1.24	14.86	11.30	0.33	481	891	141	15	210	46	25	263	44	163	109	NO
D12-W08-013	448209	4944531	coticule	162	2.24	1.98	4.23	1.11	2.66	11.03	0.26	32	1204	12	17	53	103	170	186	31	80	125	NO
CW-403A	446562	4944884	coticule	161	1.63	19.19	0.13	0.59	14.45	13.30	0.29	3	b.d.l.	b.d.l.	14	7	3	36	60	54	90	51	NO
CW-403B	446562	4944884	coticule	160	1.57	1.58	0.92	1.10	5.27	17.82	0.43	b.d.l.	85	12	18	1	32	74	81	35	140	134	NO
D12-W07-019	440457	4954147	siltstone	159	0.60	0.18	4.03	0.69	0.97	11.20	0.08	12	692	20	15	b.d.l.	118	80	98	21	102	76	NO
D12-W10-223B	456271	4938015	hornfels	158	1.11	0.92	3.83	1.17	6.15	12.73	1.10	324	1423	124	22	170	120	56	244	83	65	142	YES
D12-W10-223A-2	456271	4938015	siltstone	157	3.39	0.75	3.98	1.28	2.17	17.20	0.54	7	1862	20	22	6	94	81	221	35	109	142	MAYBE
D12-W10-223A-1	456271	4938015	coticule	156	5.01	2.56	3.26	1.18	3.82	15.00	0.25	28	720	11	18	b.d.l.	157	82	134	44	112	123	NO
D12-W07-080A	450979	4945965	siltstone	155	1.60	0.46	3.36	0.99	1.45	11.27	0.33	13	997	20	17	152	107	133	203	38	124	117	MAYBE
D12-W07-080B	450979	4945965	siltstone	154	1.29	32.79	2.57	0.78	4.00	8.81	0.34	7	575	38	13	25	63	423	124	157	73	105	NO
D12-W09-100	453597	4947074	siltstone	153	1.71	0.21	2.93	0.76	0.81	10.69	3.73	5	836	66	15	4	106	101	124	27	76	110	YES
D12-W09-100	453597	4947074	coticule	152	0.71	0.23	3.50	0.95	1.25	9.67	0.20	2	897	96	16	3	112	111	136	31	115	130	MAYBE
D12-W09-104	455587	4947956	sandstone	151	0.50	0.20	3.46	0.81	1.52	8.40	0.14	13	823	26	15	b.d.l.	109	116	117	26	82	103	MAYBE
D12-W10-200	440342	4954322	slate	150	0.01	0.02	4.28	0.74	0.25	6.50	0.11	1	880	14	10	b.d.l.	151	126	116	20	92	96	YES
D12-W07-079	450888	4946021	coticule	149	2.34	3.17	3.82	0.77	1.06	7.97	2.41	4	902	34	17	b.d.l.	163	277	140	45	93	104	MAYBE
D12-W07-079	450888	4946021	siltstone	148	2.34	2.77	4.70	0.82	0.94	6.00	0.52	3	1084	35	15	9	182	327	147	35	93	123	NO
D12-W07-076	450030	4945659	siltstone	147	1.81	2.43	4.55	0.82	1.19	10.58	1.44	2	935	14	16	b.d.l.	157	225	140	35	124	95	MAYBE
D12-W07-068A	449696	4945465	siltstone	146	0.85	3.84	2.96	0.78	1.28	7.54	0.17	74	722	32	15	20	93	387	132	10	86	117	NO
D12-W07-068B	449696	4945465	siltstone	145	0.79	0.20	5.32	0.99	0.95	7.82	0.70	8	1202	54	14	12	157	120	167	29	93	126	YES
D12-W07-075A	451465	4946357	siltstone	144	0.28	0.09	5.80	0.84	0.27	7.47	0.13	30	1160	7	19	b.d.l.	184	106	139	24	85	107	YES
D12-W07-075B	451465	4946357	sandstone	143	0.52	5.54	1.34	0.21	0.23	3.32	0.02	2	280	15	7	14	49	141	35	14	41	77	NO
D12-W08-002	452289	4946650	siltstone	142	1.57	6.00	2.69	0.82	6.49	9.15	0.26	30	550	45	13	52	71	320	111	32	97	88	NO
D12-W07-074	451658	4946632	sandstone	141	0.24	0.98	6.72	1.07	0.13	7.89	0.06	29	1344	13	23	1	210	128	175	38	89	127	NO
D12-W07-069	449195	4945298	siltstone	140	0.23	0.86	6.42	0.82	0.28	7.58	1.61	3	1215	23	18	8	212	73	170	29	88	104	YES
<b>AVERAGE</b>					2.47	3.35	3.64	0.91	3.09	10.01	0.74	41	1019	32.1	15.9	37	118.1	155.0	149.5	37.2	94.1	119.3	
<b>STANDARD DEVIATION</b>					3.25	6.33	1.76	0.27	3.79	4.17	0.96	98.8	580.3	32.8	3.7	57	53.8	101.3	65.2	25.3	32.3	28.6	
<b>MEDIAN</b>					1.43	1.29	3.48	0.94	1.53	9.41	0.32	8.00	897.0	20.0	16.0	13.0	110.7	118.2	137.5	32.0	92.1	120.0	

Notes: Abbreviations: SO = stratigraphic order from oldest (bottom) to youngest (top); Mag = magnetic susceptibility in 1x10<sup>3</sup> SI units; b.d.l. = below detection limit; \* Zone 20.

Appendix D. Whole-rock chemical analyses of samples from the Taylors Head formation by the portable XRF.

Sample	UTM nad 83*		lithology	SO	Mag	major oxides (wt%)				total S (wt%)	trace elements (ppm)											ARD Problem	
	Easting	Northing				CaO	K <sub>2</sub> O	TiO <sub>2</sub>	MnO		Fe <sub>2</sub> O <sub>3</sub> <sup>T</sup>	As	Ba	Cu	Nb	Pb	Rb	Sr	V	Y	Zn		Zr
D12-W07-073	451554	4946609	sandstone	139	0.41	0.75	1.21	0.43	0.06	1.87	0.04	4	260	16	13	14	40	90	50	30	29	431	NO
D12-W07-067A	449272	4945420	sandstone	138	0.35	0.66	1.48	0.52	0.03	1.62	0.03	3	353	7	14	10	57	161	53	27	26	427	NO
D12-W07-067B	449272	4945420	siltstone	137	1.13	0.93	3.59	0.74	0.06	4.47	0.36	9	747	19	16	11	128	172	105	40	91	189	NO
D12-W07-063	446428	4945163	schist	136	1.31	1.65	4.21	1.31	0.07	5.39	0.09	3	1089	8	25	9	115	292	150	39	65	221	NO
D12-W07-062	448708	4945241	sandstone	135	0.37	0.35	3.89	0.84	0.08	4.05	0.04	10	788	16	17	b.d.l.	131	98	112	42	37	195	NO
D12-W07-064	446495	4945350	gneiss	134	0.76	0.76	1.95	0.40	0.04	2.04	b.d.l.	1	623	7	11	6	63	180	64	21	20	228	NO
D12-W09-101	453282	4947297	qtz arenite	133	0.71	0.01	1.56	0.45	0.04	1.03	0.02	7	455	6	12	11	67	81	49	18	13	460	YES
D12-W07-072	451586	4946893	siltstone	132	0.27	1.13	4.55	0.69	0.07	4.40	0.39	7	1040	64	16	19	147	146	133	30	65	135	NO
D12-W10-205A	442528	4954919	sandstone	131	0.1	0.29	1.88	0.37	0.06	1.92	0.02	3	441	5	8	10	72	88	48	14	39	265	NO
D12-W10-205B	442528	4954919	siltstone	130	0.14	0.45	5.56	0.81	0.41	10.50	0.17	11	1073	11	16	b.d.l.	176	70	151	35	158	104	NO
D12-W07-077A	451071	4946618	sandstone	129	0.97	1.33	3.26	0.77	0.09	6.06	0.07	7	726	24	16	b.d.l.	114	178	104	37	77	196	NO
D12-W07-077B	451071	4946618	sandstone	128	0.72	1.31	2.24	1.13	0.07	4.32	0.03	4	465	b.d.l.	16	4	97	256	75	35	70	930	NO
D12-W07-053	447595	4944914	hornfels	127	0.27	1.50	3.47	0.92	0.09	5.26	0.17	8	903	3	17	17	78	158	115	37	64	146	NO
D12-W07-066	447043	4945343	hornfels	126	0.33	0.98	6.53	0.96	0.09	7.04	0.10	9	1445	20	15	14	149	138	174	48	115	118	NO
D12-W07-065	446890	4945495	gneiss	125	0.26	1.17	6.90	0.93	0.07	5.37	0.05	7	1483	7	18	43	203	173	173	32	66	138	NO
D12-W07-018A	442154	4954057	sandstone	124	0.61	0.98	2.67	0.74	0.07	4.17	0.07	4	527	23	15	3	90	122	86	44	49	305	NO
D12-W07-018B	442154	4954057	siltstone	123	0.23	0.58	5.36	0.84	0.13	9.47	0.18	5	951	25	13	b.d.l.	164	56	139	30	104	83	NO
D12-W07-054	448072	4945304	hornfels	122	0.46	1.36	3.74	0.92	0.08	5.51	0.03	3	676	8	20	9	119	161	111	42	70	186	NO
D12-W10-201	441408	4953288	sandstone	121	0.48	0.80	2.51	0.49	0.05	2.71	0.03	3	626	47	10	7	80	216	80	21	31	157	NO
D12-W10-204	441806	4953465	sandstone	120	0.55	1.10	4.96	0.78	0.08	5.19	0.03	11	1085	29	15	b.d.l.	134	214	124	24	51	137	NO
D12-W07-010A	446520	4951680	sandstone	119	0.55	0.90	2.81	0.49	0.07	4.75	0.08	11	553	9	12	b.d.l.	86	124	79	25	51	152	NO
D12-W07-010B	446520	4951680	siltstone	118	0.45	0.86	6.07	0.86	0.09	6.25	0.04	43	1221	14	19	b.d.l.	167	78	161	36	84	112	NO
D12-W10-219A	451619	4954846	sandstone	117	5.01	0.68	1.84	0.35	0.05	3.09	0.07	6	356	27	12	b.d.l.	68	117	51	19	36	133	NO
D12-W10-219B	451619	4954846	siltstone	116	6.2	0.96	4.10	0.75	0.08	5.65	0.04	11	748	19	18	b.d.l.	129	94	112	34	53	143	NO
D12-W10-221A	450658	4954718	siltstone	115	n.d.	1.16	1.64	0.34	0.03	2.02	0.00	1	447	7	10	2	56	227	52	18	18	208	NO
D12-W10-221B	450658	4954718	sandstone	114	4.21	1.09	4.32	0.72	0.08	5.18	0.06	11	1041	15	16	b.d.l.	129	160	126	27	66	150	NO
D12-W07-011	446025	4951189	sandstone	113	0.25	0.46	2.43	0.52	0.05	3.25	0.01	4	562	20	13	b.d.l.	93	70	69	21	35	207	NO
D12-W07-004	449106	4953139	sandstone	112	0.67	0.86	1.84	0.30	0.03	2.14	0.01	2	470	6	8	b.d.l.	67	418	49	15	26	169	NO
D12-W07-012	445671	4950881	sandstone	111	1.81	0.83	1.56	0.45	0.03	2.21	0.00	b.d.l.	332	10	11	b.d.l.	67	230	55	21	22	209	NO
D12-W10-220A	451228	4955126	sandstone	110	3.52	0.95	1.88	0.37	0.05	3.19	0.04	4	371	11	11	b.d.l.	64	146	52	20	27	143	NO
D12-W09-103	455472	4948590	sandstone	109	0.60	1.45	2.00	0.46	0.03	1.89	0.03	9	641	17	9	b.d.l.	57	157	66	19	13	219	NO
D12-W10-212A	449362	4955163	sandstone	108	5.57	0.94	1.97	0.39	0.05	2.82	0.16	1	412	10	11	1	65	145	59	22	23	166	NO
D12-W10-212B	449362	4955163	siltstone	107	2.19	0.95	6.14	0.93	0.10	7.55	0.10	6	1263	23	18	12	172	91	163	40	84	109	NO
D12-W07-005	448837	4954323	sandstone	106	0.16	0.66	2.01	0.33	0.04	2.06	0.01	1	597	7	11	7	59	260	62	20	18	181	NO
D12-W07-024	440025	4951617	hornfels	105	0.20	1.02	3.30	0.61	0.05	4.49	0.06	b.d.l.	793	9	13	9	98	214	94	25	56	116	NO
D12-W07-023	440241	4951659	hornfels	104	0.15	0.73	2.49	0.48	0.02	2.12	0.01	5	355	8	10	10	83	163	55	22	72	174	NO
D12-W07-022	440899	4952511	hornfels	103	0.65	0.77	1.26	0.38	0.05	2.21	0.00	11	290	6	9	2	47	139	48	16	18	163	NO
D12-W07-008	445978	4951822	sandstone	102	0.68	0.63	2.13	0.37	0.05	3.28	0.01	9	480	7	9	b.d.l.	71	106	65	22	41	181	NO
D12-W07-014	446243	4950215	sandstone	101	5.39	1.07	1.42	0.45	0.04	2.42	0.02	2	300	6	10	b.d.l.	57	264	46	21	25	144	NO

## Appendix D. Continued.

Sample	UTM nad 83*		lithology	SO	Mag	major oxides (wt%)				total S (wt%)	trace elements (ppm)										ARD Problem		
	Eastng	Northing				CaO	K <sub>2</sub> O	TiO <sub>2</sub>	MnO		Fe <sub>2</sub> O <sub>3</sub> <sup>T</sup>	As	Ba	Cu	Nb	Pb	Rb	Sr	V	Y		Zn	Zr
D12-W10-217	451326	4954286	siltstone	100	7.51	0.87	5.73	0.86	0.11	6.93	0.21	15	1040	21	16	3	174	77	138	28	73	130	NO
D12-W07-029A	440918	4952233	sandstone	99	0.19	0.79	1.53	0.42	0.03	2.30	0.02	5	408	9	10	6	52	164	58	20	53	134	NO
D12-W07-029B	440918	4952233	siltstone	98	0.22	0.71	6.45	0.92	0.06	7.61	0.08	11	1260	41	18	123	215	93	169	34	201	106	NO
D12-W09-102A	454937	4948504	sandstone	97	0.17	1.09	1.38	0.43	0.03	1.62	0.02	6	353	12	3	47	109	49	19	14	372	NO	
D12-W09-102B	454937	4948504	siltstone	96	0.57	2.86	6.03	0.94	0.08	5.55	0.19	31	1170	35	17	6	185	139	154	43	67	165	NO
D12-W07-059	446422	4945812	gneiss	95	0.47	1.38	0.96	0.80	0.04	2.76	0.01	6	134	10	19	6	36	172	63	33	23	466	NO
D12-W07-052	447315	4945630	sandstone	94	0.34	0.83	1.96	0.38	0.03	1.81	0.02	6	568	7	8	8	55	282	60	17	17	161	NO
D12-W08-030	452970	4948130	sandstone	93	0.45	2.72	2.43	0.36	0.08	2.32	0.02	4	639	8	11	32	70	142	67	24	20	205	NO
D12-W07-060A	447766	4945783	sandstone	92	1.45	0.51	1.76	0.37	0.03	1.82	0.03	5	536	6	8	4	56	164	52	16	8	169	NO
D12-W07-060B	447766	4945783	hornfels	91	0.29	0.78	5.96	0.88	0.08	6.37	0.09	2	941	18	15	4	177	91	138	36	66	114	NO
D12-W07-027	440811	4951253	schist	90	0.52	0.97	4.00	0.68	0.05	3.52	0.03	4	737	23	12	13	126	260	94	24	43	208	NO
D12-W07-028	441618	4952000	siltstone	89	2.37	2.07	1.96	0.45	0.07	2.37	0.01	2	509	1	10	3	68	233	76	21	28	178	NO
D12-W07-051	446513	4945961	gneiss	88	0.32	1.02	3.12	0.60	0.06	4.44	0.03	3	540	15	14	11	101	175	85	24	51	106	NO
D12-W10-218	451958	4953552	siltstone	87	5.01	0.93	2.12	0.52	0.05	3.12	0.03	2	463	9	13	b.d.l.	78	127	64	23	35	157	NO
D12-W09-111A	454778	4949457	slate	86	0.27	0.45	1.97	0.47	0.05	3.94	0.06	5	447	27	10	b.d.l.	65	144	56	17	38	147	NO
D12-W09-111B	454778	4949457	sandstone	85	0.43	0.80	5.38	0.92	0.10	8.23	0.12	30	1059	14	19	b.d.l.	163	116	145	42	81	131	NO
D12-W07-078A	451634	4948018	sandstone	84	0.37	1.26	1.84	0.43	0.03	2.35	0.02	8	489	6	11	b.d.l.	58	144	57	19	20	173	NO
D12-W07-078B	451634	4948018	siltstone	83	0.26	0.84	2.81	0.61	0.05	4.59	0.08	11	722	33	14	b.d.l.	89	133	91	26	55	135	NO
D12-W07-061	448795	4946516	sandstone	82	0.57	0.72	2.26	0.42	0.04	2.72	0.02	9	393	7	8	4	80	127	57	20	31	165	NO
DD98-1.2-5ft	455242	4950876	sandstone	81	n.d.	0.70	2.69	0.62	0.07	4.98	0.07	9	451	32	13	b.d.l.	90	153	88	27	47	192	NO
DD98-1.5-10ft	455242	4950876	sandstone	80	n.d.	2.60	2.46	0.60	0.08	4.23	0.07	6	498	38	12	b.d.l.	90	162	89	33	41	181	NO
DD98-1.10-15ft	455242	4950876	sandstone	79	n.d.	1.08	2.55	0.61	0.07	4.54	0.09	17	450	14	13	b.d.l.	83	164	71	23	44	153	NO
DD98-1.15-22ft	455242	4950876	sandstone	78	n.d.	2.62	2.39	0.67	0.08	4.00	0.03	6	475	8	12	b.d.l.	79	187	68	23	40	181	NO
DD98-1.22-27ft	455242	4950876	sandstone	77	n.d.	2.99	2.27	0.58	0.08	4.08	0.08	9	459	12	12	b.d.l.	77	184	75	25	40	162	NO
DD98-1.27-32ft	455242	4950876	sandstone	76	n.d.	2.01	2.57	0.60	0.08	4.31	0.02	2	478	2	11	b.d.l.	84	152	88	18	42	143	NO
DD98-1.32-37ft	455242	4950876	sandstone	75	n.d.	0.99	2.74	0.60	0.07	4.73	0.05	10	534	24	11	b.d.l.	91	177	96	23	45	150	NO
DD98-1.37-42ft	455242	4950876	sandstone	74	n.d.	1.01	3.25	0.65	0.08	5.70	0.03	6	585	18	14	b.d.l.	102	158	89	24	57	133	NO
DD98-1.42-47ft	455242	4950876	sandstone	73	n.d.	2.32	2.70	0.67	0.09	4.73	0.12	7	455	11	10	b.d.l.	86	153	206	76	46	155	NO
DD98-1.47-52ft	455242	4950876	sandstone	72	n.d.	1.99	2.30	0.51	0.06	3.20	0.04	8	415	67	11	b.d.l.	70	172	78	20	27	177	NO
DD98-1.52-57ft	455242	4950876	sandstone	71	n.d.	0.99	2.95	0.59	0.07	4.75	0.04	11	593	38	12	b.d.l.	91	187	81	22	52	156	NO
DD98-1.57-64ft	455242	4950876	sandstone	70	n.d.	0.66	2.36	0.58	0.06	4.22	0.03	6	475	23	13	b.d.l.	77	179	68	19	36	187	NO
DD98-1.64-69ft	455242	4950876	sandstone	69	n.d.	2.23	2.33	0.52	0.07	4.16	0.06	12	463	26	12	b.d.l.	75	213	86	23	37	154	NO
DD98-1.69-71ft	455242	4950876	sandstone	68	n.d.	1.10	2.96	0.66	0.07	5.14	0.04	5	653	28	16	b.d.l.	95	175	89	34	51	163	NO
DD98-1.74-79ft	455242	4950876	sandstone	67	n.d.	3.10	2.44	0.54	0.08	4.28	0.01	6	449	12	12	b.d.l.	76	184	85	33	40	143	NO
DD98-1.79-85ft	455242	4950876	sandstone	66	n.d.	0.82	2.79	0.57	0.07	4.86	0.01	6	628	14	12	b.d.l.	92	184	76	20	48	154	NO
DD98-2.01-07	455305	4950941	sandstone	65	n.d.	0.68	2.85	0.61	0.07	4.69	0.04	7	497	21	13	b.d.l.	83	165	88	26	47	216	NO
DD98-2.07-12	455305	4950941	sandstone	64	n.d.	0.94	5.39	1.07	0.12	9.30	0.10	8	1060	25	15	b.d.l.	167	108	143	36	84	108	NO
DD98-2.12-17	455305	4950941	sandstone	63	n.d.	0.88	2.90	0.71	0.08	5.86	0.04	16	666	8	15	b.d.l.	89	175	87	22	58	177	NO



Appendix D. Continued.

Sample	UTM nad 83*		lithology	SO	Mag	major oxides (wt%)				total S (wt%)	trace elements (ppm)										ARD Problem		
	Eastng	Northing				CaO	K <sub>2</sub> O	TiO <sub>2</sub>	MnO		Fe <sub>2</sub> O <sub>3</sub> <sup>T</sup>	As	Ba	Cu	Nb	Pb	Rb	Sr	V	Y		Zn	Zr
DD98-2.17-23	455305	4950941	sandstone	62	n.d.	1.03	2.96	0.60	0.08	5.93	0.12	15	513	40	14	b.d.l.	91	176	84	21	56	180	NO
DD98-2.23-28	455305	4950941	sandstone	61	n.d.	4.05	2.73	0.55	0.09	4.19	0.09	6	505	14	11	b.d.l.	84	186	99	24	37	205	NO
DD98-2.28-33	455305	4950941	sandstone	60	n.d.	1.21	3.76	0.71	0.09	6.48	0.06	9	835	14	15	b.d.l.	123	169	107	30	66	125	NO
DD98-2.33-38	455305	4950941	sandstone	59	n.d.	0.73	2.20	0.52	0.05	3.80	0.03	5	431	14	11	b.d.l.	71	179	61	18	35	162	NO
DD98-2.38-44	455305	4950941	sandstone	58	n.d.	1.36	2.37	0.54	0.07	4.10	0.02	3	439	10	11	b.d.l.	71	177	64	17	34	146	NO
DD98-2.44-49	455305	4950941	sandstone	57	n.d.	2.39	2.63	0.57	0.08	4.39	0.04	5	488	17	11	b.d.l.	81	179	94	29	40	145	NO
DD98-2.49-54	455305	4950941	sandstone	56	n.d.	0.53	2.52	0.55	0.06	4.17	0.04	7	439	14	11	b.d.l.	81	180	73	17	38	169	NO
DD98-2.54-60	455305	4950941	sandstone	55	n.d.	0.65	3.03	0.62	0.08	5.99	0.04	11	613	28	14	b.d.l.	100	159	89	23	56	147	NO
D12-W10-215A	455956	4951689	sandstone	54	n.d.	2.47	1.61	0.37	0.07	2.87	0.02	4	341	10	11	b.d.l.	56	199	51	20	30	159	NO
D12-W10-215B	455956	4951689	siltstone	53	n.d.	0.83	5.99	0.88	0.13	8.72	0.08	5	1142	25	17	b.d.l.	179	92	162	38	98	107	NO
D12-W07-035	443881	4950347	siltstone	52	4.79	1.26	5.08	0.85	0.08	5.86	0.09	5	1014	11	16	b.d.l.	165	221	128	38	69	137	NO
D12-W07-056A	444806	4950862	sandstone	51	0.47	1.41	1.43	0.82	0.05	3.37	0.03	b.d.l.	205	49	18	b.d.l.	59	181	56	33	41	490	NO
D12-W07-056B	444806	4950862	hornfels	50	0.45	1.30	7.45	0.93	0.10	8.05	0.44	7	1240	62	18	52	208	168	184	46	119	117	NO
D12-W10-216	451145	4954411	sandstone	49	5.96	0.52	1.98	0.35	0.04	2.36	0.01	4	570	9	10	b.d.l.	62	120	59	17	14	128	NO
D12-W07-048	444125	4949309	sandstone	48	0.16	0.98	1.98	0.48	0.04	3.05	0.02	1	338	11	10	6	75	153	55	21	33	142	NO
D12-W07-009	446809	4953053	sandstone	47	0.43	0.88	4.14	0.71	0.08	6.47	0.08	9	756	10	15	b.d.l.	131	118	111	29	80	104	NO
D12-W07-038A	446074	4946201	hornfels	46	3.39	1.33	8.48	0.91	0.05	7.60	0.23	3	1477	12	16	b.d.l.	381	146	164	33	82	99	NO
D12-W07-043	446469	4947963	hornfels	45	3.74	0.78	6.54	0.92	0.10	8.34	0.03	6	1159	8	16	14	246	116	166	35	90	114	NO
D12-W07-037	446236	4946258	sandstone	44	12.30	1.36	4.75	0.92	0.08	6.48	0.08	7	715	17	17	22	150	200	126	40	70	148	NO
D12-W07-001	447638	4954220	sandstone	43	0.26	1.00	1.69	0.32	0.03	1.96	0.02	8	411	19	9	b.d.l.	60	178	53	17	34	162	NO
D12-W07-030	441725	4951266	schist	42	2.42	1.03	1.97	0.43	0.04	2.74	0.02	1	412	1	10	3	65	229	60	22	32	161	NO
D12-W07-031	441559	4950827	sandstone	41	0.14	1.02	3.45	0.59	0.05	4.09	0.04	4	773	20	12	b.d.l.	115	208	87	28	105	149	NO
D12-W07-007A	445219	4952427	sandstone	40	0.27	1.28	1.76	0.38	0.07	3.69	0.03	9	336	10	8	7	57	87	48	25	61	160	NO
D12-W07-007B	445219	4952427	siltstone	39	0.31	0.59	4.06	0.80	0.11	7.54	0.17	12	781	11	17	1	118	68	111	26	155	130	NO
D12-W07-013	445295	4952276	calc-silicate	38	0.61	23.26	1.21	0.51	0.22	1.35	0.02	7	217	27	14	22	31	182	46	28	12	325	NO
D12-W07-015	447348	4950551	siltstone	37	0.69	0.76	5.52	0.86	0.13	9.74	0.86	4	1040	8	19	1	165	84	156	37	103	127	YES
D12-W07-003	449818	4951714	sandstone	36	12.91	1.22	1.44	0.63	0.04	3.20	0.02	6	309	1	12	4	55	259	70	32	28	511	NO
D12-W07-006A	447220	4953634	sandstone	35	0.42	1.07	1.90	0.36	0.04	2.58	0.02	4	472	6	10	b.d.l.	69	277	62	20	25	232	NO
D12-W07-006B	447220	4953634	siltstone	34	0.26	0.88	4.99	0.86	0.16	11.46	0.16	2	993	64	16	47	155	204	135	30	328	110	NO
D12-W07-017	443377	4952759	siltstone	33	0.24	0.79	5.48	0.77	0.11	5.60	0.11	1	1060	7	14	7	168	112	150	31	64	90	NO
D12-W07-034	443810	4950891	sandstone	32	1.28	0.78	1.31	0.43	0.04	2.18	0.09	2	303	6	11	1	47	184	57	21	21	161	NO
D12-W07-057	445287	4949670	hornfels	31	8.50	1.16	5.23	0.93	0.15	7.19	0.07	7	1195	14	18	14	161	199	147	33	80	117	NO
D12-W07-036	445059	4948915	sandstone	30	0.27	0.78	0.91	0.29	0.03	2.00	0.05	5	216	b.d.l.	8	10	35	129	35	16	43	112	NO
D12-W07-032	442105	4951356	sandstone	29	0.25	1.01	5.65	0.85	0.09	6.72	0.08	4	978	13	15	9	174	113	139	38	78	107	NO
D12-W07-002-1	444652	4952569	siltstone	28	0.19	1.19	5.78	1.00	0.13	7.25	0.08	4	1122	10	18	b.d.l.	181	237	150	33	79	145	NO
D12-W07-002-1	444652	4952569	sandstone	27	0.14	0.86	4.86	0.76	0.08	6.28	0.04	2	975	32	12	b.d.l.	164	186	120	33	72	106	NO
D12-W10-211A	457733	4951963	sandstone	26	0.24	0.64	1.80	0.43	0.05	2.91	0.02	3	387	13	12	b.d.l.	57	145	60	23	24	145	NO
D12-W10-211B	457733	4951963	siltstone	25	0.07	1.20	5.07	1.00	0.08	4.91	0.05	8	1257	10	22	b.d.l.	133	179	184	37	50	146	NO

## Appendix D. Continued.

Sample	UTM nad 83*		lithology	SO	Mag	major oxides (wt%)			total S (wt%)	trace elements (ppm)										ARD Problem			
	Easting	Northing				CaO	K <sub>2</sub> O	TiO <sub>2</sub>		MnO	Fe <sub>2</sub> O <sub>3</sub>	As	Ba	Cu	Nb	Pb	Rb	Sr	V		Y	Zn	Zr
D12-W10-206	444265	4952803	sandstone	24	0.2	0.70	2.37	0.46	0.03	2.66	0.02	1	729	10	11	b.d.l.	78	140	76	31	26	159	NO
D12-W07-016A	443333	4951625	sandstone	23	5.47	0.73	2.38	0.49	0.04	2.78	0.03	4	451	5	11	b.d.l.	79	194	69	22	30	136	NO
D12-W07-016B	443333	4951625	hornfels	22	7.75	1.14	3.74	0.69	0.06	4.69	0.11	1	740	6	14	7	126	175	103	30	59	147	NO
D12-W07-033	443083	4951211	sandstone	21	0.19	1.03	1.12	0.32	0.03	1.98	0.03	1	160	16	8	b.d.l.	48	141	39	18	20	139	NO
D12-W07-050A	447068	4946371	sandstone	20	1.69	1.12	2.08	0.50	0.04	2.71	0.01	2	377	21	12	2	67	230	59	20	30	174	NO
D12-W07-050B	447068	4946371	schist	19	12.50	0.93	5.53	0.78	0.08	7.87	0.07	8	811	18	14	b.d.l.	202	147	128	29	106	106	NO
D12-W07-040	446810	4949318	sandstone	18	0.22	0.96	2.74	0.54	0.06	3.69	0.03	3	482	19	12	b.d.l.	89	177	71	25	40	145	NO
D12-W07-042	446750	4948105	sandstone	17	0.19	0.74	0.80	0.42	0.04	2.34	0.02	b.d.l.	235	11	10	b.d.l.	33	138	41	20	27	149	NO
D12-W07-049	447930	4947057	sandstone	16	6.48	1.11	3.88	0.75	0.08	5.47	0.03	b.d.l.	786	24	14	b.d.l.	128	206	101	30	74	127	NO
D12-W07-039	446051	4947655	sandstone	15	0.54	0.80	4.85	0.78	0.09	5.81	0.08	4	924	11	14	16	120	105	124	31	65	101	NO
D12-W10-208	455007	4951339	siltstone	14	0.78	0.65	5.45	0.76	0.14	8.42	0.06	4	1032	10	16	1	168	66	132	22	88	93	NO
D12-W07-045	446976	4946812	hornfels	13	0.82	0.92	5.28	0.80	0.08	6.61	0.05	5	1122	17	15	12	175	126	149	35	119	102	NO
D12-W07-058	446154	4947278	hornfels	12	1.01	1.14	4.68	0.74	0.09	4.54	0.10	4	1185	13	13	5	136	249	133	32	58	124	NO
D12-W07-041	447572	4949109	siltstone	11	0.18	0.57	5.12	0.96	0.10	6.94	0.05	3	1073	10	18	b.d.l.	153	53	149	31	75	130	NO
D12-W07-046A	447481	4947192	sandstone	10	0.86	0.71	2.01	0.50	0.06	3.60	0.05	5	377	15	10	3	70	110	57	24	37	136	NO
D12-W07-046B	447481	4947192	siltstone	9	0.31	0.91	4.48	0.98	0.09	6.64	0.15	4	976	38	17	10	131	113	154	29	65	114	NO
D12-W10-209A	453189	4952291	sandstone	8	0.54	0.84	2.27	0.46	0.06	3.73	0.03	4	444	13	13	b.d.l.	81	133	67	23	40	146	NO
D12-W10-209B	453189	4952291	siltstone	7	0.01	0.65	4.59	0.69	0.07	4.57	0.03	6	1011	9	17	b.d.l.	136	96	128	26	58	101	NO
D12-W07-044	447728	4948285	siltstone	6	0.46	1.10	3.45	0.69	0.12	6.39	0.13	b.d.l.	679	51	14	17	114	111	102	32	71	92	NO
D12-W10-207	454972	4952596	sandstone	5	0.37	0.69	1.98	0.54	0.05	3.39	0.04	3	404	21	12	b.d.l.	70	82	61	21	34	143	NO
D12-W10-210	456543	4953984	sandstone	4	0.94	0.77	1.02	0.32	0.04	2.08	0.01	3	223	14	10	4	39	234	38	20	26	174	NO
D12-W07-047	446446	4946878	siltstone	3	0.34	0.50	3.88	0.81	0.10	6.26	0.08	4	747	19	13	b.d.l.	142	97	100	27	57	117	NO
D12-W10-213	455137	4953590	sandstone	2	14.3	0.86	1.24	0.36	0.04	2.35	0.01	4	282	7	11	3	47	249	43	21	21	167	NO
D12-W10-214	454947	4953118	sandstone	1	2.8	1.27	2.00	0.47	0.05	2.92	0.03	3	429	12	12	1	72	224	58	23	33	184	NO
<b>AVERAGE</b>					1.75	1.26	3.22	0.63	0.07	4.51	0.06	6.3	659.2	17.1	13.2	12.0	103.2	161.9	93.1	27.1	54.2	171.3	
<b>STANDARD DEVIATION</b>					3.98	0.21	1.55	0.19	0.03	1.96	0.04	1.6	317.2	10.2	2.5	5.8	46.2	58.8	38.8	5.0	27.0	26.7	
<b>MEDIAN</b>					0.66	0.85	3.09	0.61	0.06	4.14	0.04	4.0	704.0	13.3	13.0	4.5	101.5	139.0	87.8	25.3	48.5	136.0	

**Notes:** Abbreviations: SO = stratigraphic order from oldest (bottom) to youngest (top); Mag = magnetic susceptibility in  $1 \times 10^{-3}$  SI units; n.d. = not determined; b.d.l. = below detection limit; \* Zone 20. Samples with a DD prefix are from H.I. Cross's rock collection.

**Appendix E.** Whole-rock chemical analyses of samples from the South Mountain Batholith by the portable XRF.

Sample	UTM nad 83*		lithology	Mag	major oxides (wt%)					total S (wt%)	trace elements (ppm)										ARD Problem	
	Easting	Northing			CaO	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	Fe <sub>2</sub> O <sub>3</sub> <sup>T</sup>		As	Ba	Cu	Nb	Pb	Rb	Sr	V	Y	Zn		Zr
CW-107A	432365	4950699	f-m.g. granite	0.69	0.23	4.29	0.03	0.02	0.49	0.00	1	4	1	5	13	328	7	b.d.l.	11	4	38	NO
CW-157A	435436	4945069	f-m.g. granite	2.66	0.13	4.27	0.04	0.03	0.77	0.00	3	41	1	6	8	329	11	5	13	7	25	NO
CW-227B	455667	4938222	m.g. granite	1.48	0.22	3.50	0.02	0.01	0.24	b.d.l.	2	6	b.d.l.	11	7	244	7	2	4	b.d.l.	8	NO
CW-237A	454212	4939761	c.g. granite	2.89	0.42	3.85	0.10	0.02	0.88	0.01	1	168	2	7	12	227	34	13	11	7	43	NO
CW-238A	453978	4940073	f.g. granite	0.24	0.21	5.27	0.03	0.02	0.40	0.00	1	76	2	3	15	235	29	5	11	6	34	NO
CW-238B	453981	4940012	m.g. granite	1.09	0.23	4.42	0.26	0.06	1.90	0.01	3	162	4	14	10	247	33	19	24	39	80	NO
CW-240A	454417	4939852	c.g. granite	2.31	0.24	4.35	0.08	0.02	0.73	0.01	2	134	1	6	13	246	32	9	7	6	23	NO
CW-243	445892	4946446	c.g. granite	2.84	2.25	3.92	0.57	0.07	3.34	0.02	7	432	5	12	13	134	243	62	23	27	175	NO
CW-248A	441580	4950810	c.g. granite	1.76	1.33	3.79	0.43	0.05	2.27	0.02	3	457	6	8	28	123	131	48	15	49	97	NO
CW-258A	442319	4950165	c.g. granite	2.19	1.63	4.51	0.76	0.07	4.06	0.04	3	546	8	11	19	147	177	78	26	56	135	NO
CW-259A	442437	4950160	c.g. granite	3.09	1.62	3.96	0.43	0.05	2.17	0.04	2	779	3	8	17	120	199	58	27	25	85	NO
CW-270B	442353	4949291	aplite/peg	2.13	0.24	2.05	0.07	0.03	1.15	0.19	6	16	11	27	5	257	8	2	7	4	12	MAYBE
CW-315A	439926	4949630	c.g. granite	1.91	0.70	3.49	0.10	0.02	0.76	0.01	1	189	1	7	16	158	53	18	24	10	60	NO
CW-319A	440204	4949755	c.g. granite	1.02	1.09	3.24	0.16	0.04	1.12	0.01	1	156	4	6	15	199	106	21	24	19	52	NO
CW-343A	438910	4949850	f-c.g. granite	2.01	0.41	4.77	0.14	0.03	1.12	0.01	4	401	2	5	17	233	51	35	20	13	45	NO
CW-363A	430112	4950163	c.g. granite	2.13	0.21	4.60	0.16	0.02	1.39	0.01	3	241	8	8	12	227	40	19	9	4	47	NO
CW-367A	429630	4950220	f.g. granite	3.18	0.52	3.64	0.09	0.02	0.87	0.00	10	176	3	7	13	242	62	13	14	23	47	NO
D12-W07-025	439683	4951186	granite	0.43	0.55	7.97	0.57	0.06	2.87	0.04	1	839	7	10	30	222	108	95	21	30	93	NO
D12-W07-026	440701	4951166	granite	0.51	0.71	6.01	0.72	0.08	4.11	0.04	3	515	4	10	24	194	119	78	17	45	95	NO
D12-W10-222	456364	4937980	granite	6.97	0.43	2.00	0.13	0.03	0.95	0.01	2	64	1	16	5	212	22	8	14	13	39	NO
D12-W07-038B	446074	4946201	c.g. granite	0.46	2.63	2.29	0.43	0.04	2.31	0.06	2	423	8	11	14	76	235	50	18	31	138	NO
<b>AVERAGE</b>				1.99	0.79	4.21	0.26	0.04	1.64	0.02	2.7	290.4	3.7	8.5	14.9	207.1	85.0	33.4	16.5	21.9	67.8	
<b>STANDARD DEVIATION</b>				1.47	0.73	1.32	0.24	0.02	1.17	0.04	2.3	247.7	2.9	5.1	6.6	64.5	76.3	29.1	6.9	16.3	44.2	
<b>MEDIAN</b>				2.01	0.43	3.96	0.14	0.03	1.12	0.01	2.0	175.8	3.4	8.0	13.2	226.5	51.3	18.9	14.7	16.3	47.4	

**Notes:** Abbreviations: Mag = magnetic susceptibility in  $1 \times 10^{-3}$  SI units; n.d. = not determined; b.d.l. = below detection limit; \* Zone 20.