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PRELIMINARY NOTES ON SOME GEOCHEMICAL CHARACTERISTICS OF PLUTONIC AND VOLCANIC SUITES IN THE REGION BETWEEN MANUELS AND CAPE ST. FRANCIS, AVALON PENINSULA, EASTERN NEWFOUNDLAND

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ABSTRACT

The eastern margin of the Holyrood Horst is characterized by a protracted and episodic late Neoproterozoic magmatic history associated with the local development of high- and low-sulphidation epithermal systems. Elements of this magmatic environment include granite and rhyolite dome and breccia complexes, which are spatially associated with low-sulphidation epithermal systems near Manuels and reoccur ca. 25 km to the northeast (east of the Topsail Fault), in the region between Grog Pond and Cape St. Francis. In the Manuels region, precious-metal-bearing, low-sulphidation vein systems are developed proximal to ca. 582 Ma pyrophyllite–diaspore high-sulphidation epithermal alteration. Arc-related, calc-alkalic subaerial felsic volcanic rocks of the White Mountain Volcanic Suite constitute the oldest stratigraphic unit in the region. These are locally intruded by calc-alkalic, peraluminous granitoid rocks of the 620 Ma Holyrood Intrusive Suite east and west of the Topsail Fault. Both suites are juxtaposed with geochemically similar, 584 Ma subaerial felsic volcanic rocks of the Manuels Volcanic Suite, in the region of Conception Bay. Epithermal alteration and veining affects both 584 Ma and 620 Ma rocks. Plutonic and volcanic rocks, geochemically similar to those identified along the eastern margin of the Holyrood Horst in the Manuels area, re-appear to the east of the Topsail Fault, and are correlated with units from that region.

Termination of the high-sulphidation style alteration is marked by the onset of marine sedimentation, recorded by the Wych Hazel Pond Complex, and marked by the transition from subaerial felsic-dominated volcanism to submarine, predominantly alkalic, mafic-dominated flows and intrusion of feldspar-porphyry dykes. Late-stage, metaluminous, dioritic to gabbroic intrusions of the Herring Cove Diorite and Beaver Hat Intrusive Suite crosscut marine sedimentary rocks of the Wych Hazel Pond Complex and occupy an elongate zone that has a broad spatial association with the regional trace of the Topsail Fault. Mafic intrusions correlated with the Herring Cove Diorite are locally crosscut by calc-alkalic, peraluminous feldspar-porphyry dykes correlated with dated 585 ± 5 Ma feldspar porphyry of the Wych Hazel Pond Complex. Fine-grained gabbroic intrusions of the Beaver Hat Intrusive Suite crosscut the folded sedimentary rocks of the Conception Group, providing a syn- to posttectonic age for the emplacement of this suite.

Felsic volcanic rocks and intrusions of the Holyrood Intrusive Suite display typical arc-related geochemical signatures, whereas younger feldspar-porphyry and mafic volcanic rocks of the Wych Hazel Pond Complex display geochemical variations more indicative of a back-arc-type setting. This geochemical evolution reflects the development and submergence of the volcanic-arc sequence, and development of late Neoproterozoic epithermal systems within this portion of the Avalon Zone of eastern Newfoundland.

INTRODUCTION

This paper provides a brief summary of some salient geochemical characteristics of the principal volcano-plutonic units from the type area of the Avalon Zone, on the Avalon Peninsula, eastern Newfoundland. The geochemical data are from late Neoproterozoic (Ediacaran) igneous rocks along the eastern margin of the Holyrood Horst, east and west of the Topsail Fault, between Cape St. Francis in the north, and Manuels to the south (Figures 1 and 2). Several of these units either host or otherwise share a close spatial association with well-preserved late Neoproterozoic high-

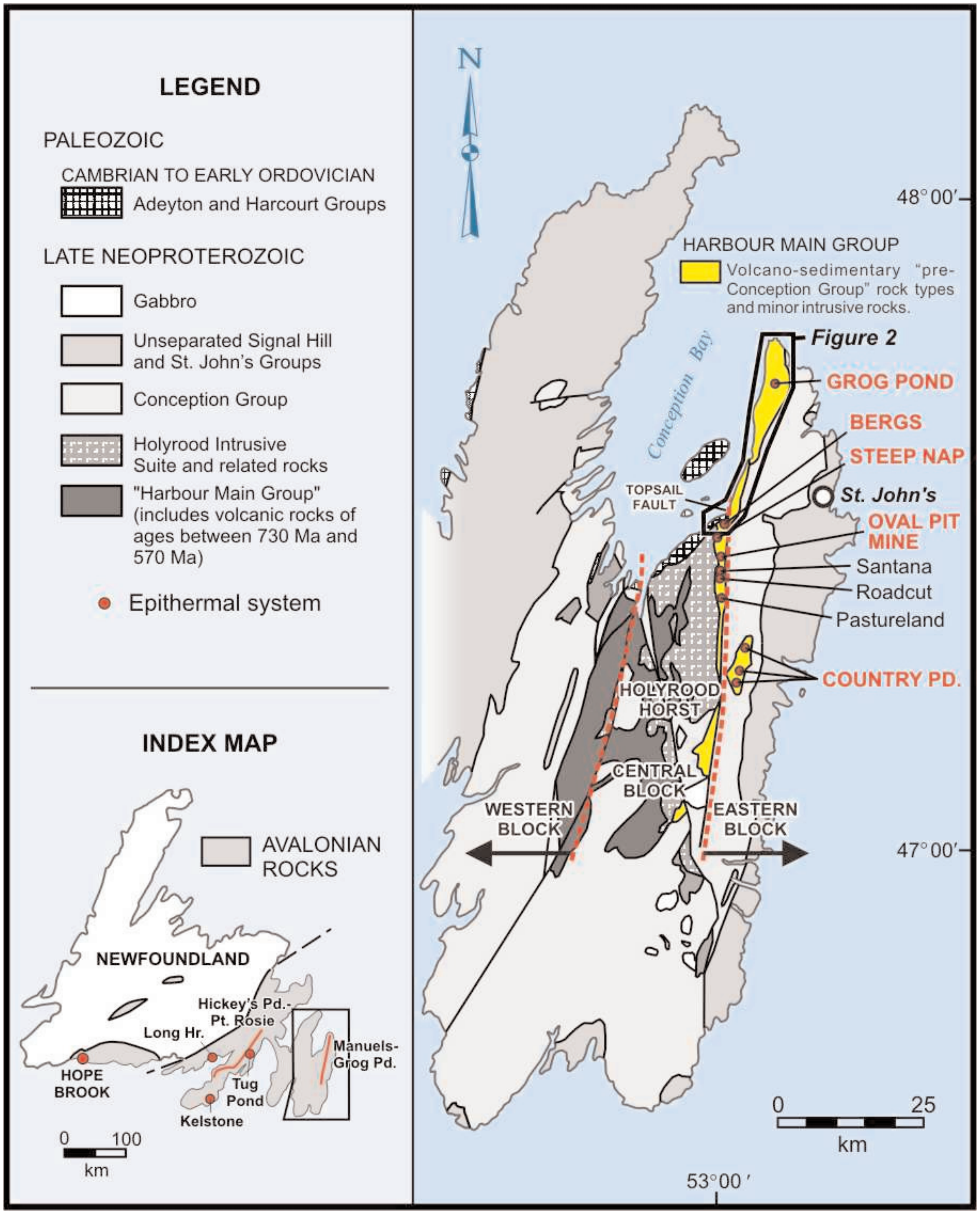

Figure 1. *Simplified geological map of the Avalon Peninsula (modified from King, 1988). Shaded area on inset map bottom left shows approximate distribution of "Avalonian" rocks, red dots and lines delineate epithermal prospects and/or deposits (modified from O'Brien* et al.*, 1998).*

and low-sulphidation epithermal systems (O'Brien *et al.*, 1997, 2001; Sparkes *et al.*, 2005). These units include: 1) subaerial felsic volcanic rocks of the White Mountain and Manuels volcanic suites, 2) regionally extensive felsic and lesser mafic intrusions of the Holyrood and Beaver Hat intrusive suites and Herring Cove Diorite, and 3) feldspar-porphyry dykes and submarine mafic volcanic rocks of the Wych Hazel Pond Complex (*cf.,* Sparkes, 2006). Emplaced

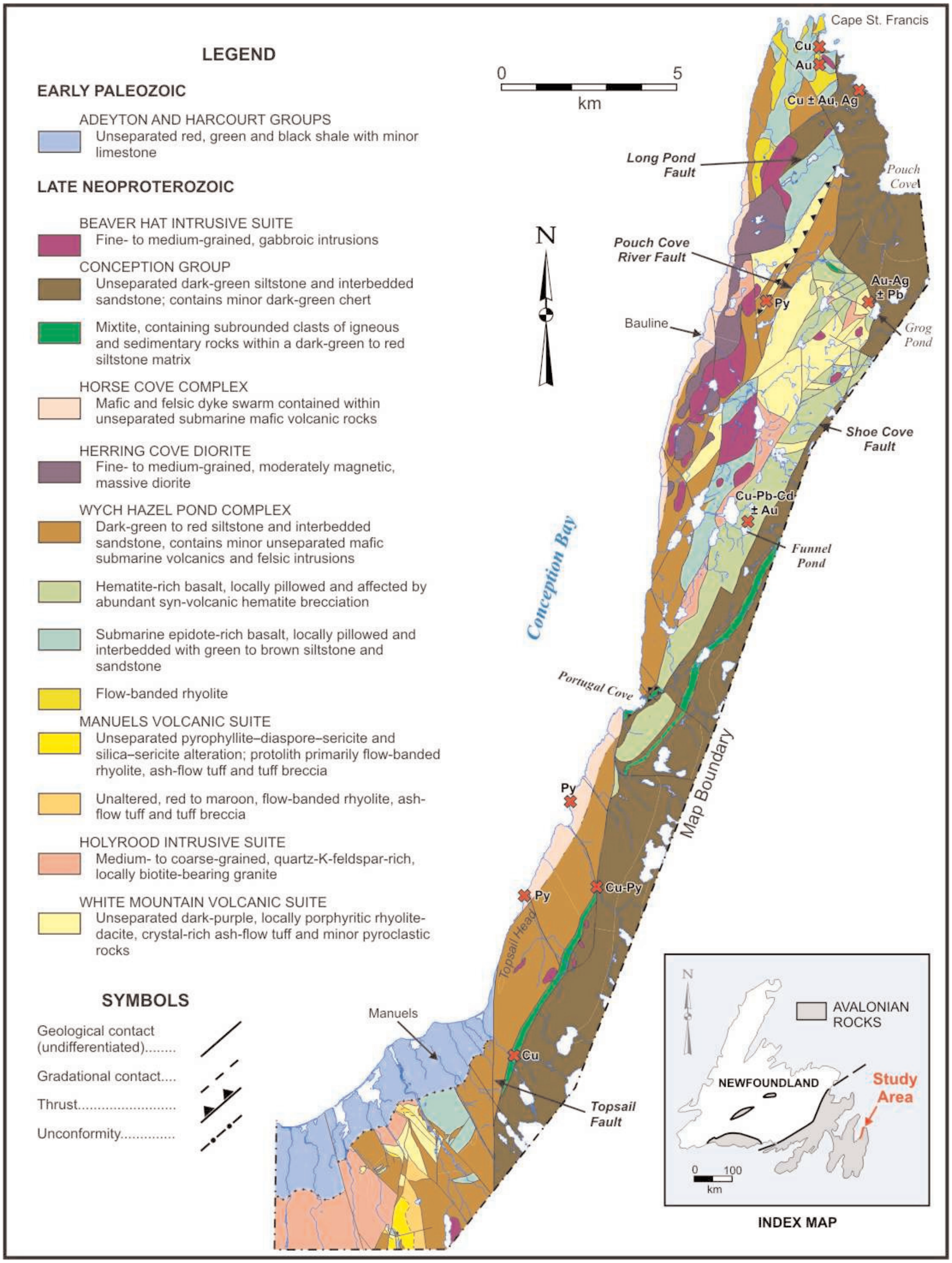

Figure 2. *Simplified geological map of Manuels and the eastern side of Conception Bay, Avalon Peninsula; compiled in part from Hsu (1975) and King (1990).*

or erupted over a period of at least 40 Ma, these rocks are a partial record of the formation, uplift, erosion, and collapse of a mineralized volcanic-arc complex that is host to some of the most well-preserved ancient epithermal systems known globally. The collapse of this volcanic arc, marked by the onset of marine sedimentation, is associated with a transition from predominantly subaerial felsic volcanism to a mafic-dominated submarine volcanic regime characterized by flows, breccias and hyaloclastites (Sparkes, 2006).

The major-element and select trace-element geochemistry summarized below was selected from a regional whole-rock geochemical dataset that include data collected during the thesis studies and contractual work carried out by the senior author, and during metallogenic and regional mapping studies by the second author (O'Brien *et al.*, 1997, 2001; Sparkes *et al.*, 2005; Sparkes 2006; G. Sparkes and S. O'Brien, unpublished data, 2007). These geochemical data include previously published and unpublished material extracted from ongoing geological investigations of the late Neoproterozoic epithermal systems. In addition to further characterizing the rocks hosting the epithermal systems, the geochemical data presented here, provide further evidence supporting the continuation of rock units first identified within the Holyrood Horst, east of the Topsail Fault between the area of Topsail Head and Cape St. Francis (Figure 2).

The following report includes selected geochemical plots only; a more extensive presentation of the entire trace-element dataset, including assays, is being prepared for open-file release.

REGIONAL GEOLOGY

The Holyrood Horst represents the core of a late Neoproterozoic volcano-plutonic complex and is exposed in the eastern portion of the Avalon Zone, in the eastern Avalon Peninsula (Figure 1; McCartney, 1969; O'Brien *et al.*, 2001). This complex contains dated 730 to 584 Ma felsic volcanic rocks, and includes some of the oldest known volcanic rocks within the region (O'Brien *et al.*, 1997, 2001; Israel, 1998). The 620 Ma and earlier volcanic successions, which consist of primarily subaerial felsic volcanic rocks and lesser mafic volcanic rocks, are intruded by the 620 Ma Holyrood Intrusive Suite (King, 1988); the latter is locally host to syn-plutonic Cu–Au and Mo mineralization (cf., B. Sparkes, 2001; O'Brien *et al.*, 2001). Volcano-plutonic rocks within the horst structure are bordered by a shallowing-upward sequence of marine, siliciclastic sedimentary rocks of the Conception Group (*see* King, 1988).

Along the eastern margin of the horst, dated 584 Ma subaerial felsic volcanic rocks of the Manuels Volcanic Suite are juxtaposed with the 620 Ma Holyrood Intrusive Suite (O'Brien *et al.*, 2001; Sparkes *et al.*, 2005). There, felsic volcanic rocks of the White Mountain Volcanic Suite are locally intruded by granitic rocks correlated with the Holyrood Intrusive Suite (Sparkes *et al.*, *op. cit.*). In this area, volcanic rocks of both ages are affected by the development of pyrophyllite–diaspore advanced argillic alteration, associated with the formation of a late Neoproterozoic high-sulphidation system, dated at ca. 582 Ma (Sparkes *et al.*, 2005; Sparkes, 2005). This regionally extensive, late Neoproterozoic epithermal belt includes Au-bearing low-sulphidation veins, which are developed marginal to the high-sulphidation alteration (O'Brien *et al.*, 2001; O'Brien, 2002). These vein systems typically share a close spatial association with the contact between rocks of the Holyrood Intrusive Suite and both older and younger volcanic successions of the White Mountain and Manuels volcanic suites.

The 584 Ma subaerial felsic volcanic succession is unconformably overlain by red to green, marine siliciclastic sedimentary rocks of the Wych Hazel Pond Complex (O'Brien *et al.*, 2001), the base of which is dated at 582 ± 1.5 Ma (Sparkes *et al.*, 2005). Deposition of this sedimentary package is interpreted to represent the onset of arc collapse and marks the termination of the high-sulphidation style alteration (O'Brien *et al.*, 2001; Sparkes *et al., op. cit.*). Sedimentary rocks of the Wych Hazel Pond Complex are also associated with the eruption of submarine mafic volcanic rocks. These mafic flows and pyroclastic rocks, combined with gabbroic to dioritic intrusions of the Herring Cove Diorite and Beaver Hat Intrusive Suite, signify the regional transition to mafic-dominated igneous activity. Along the eastern margin of the Topsail Fault, sedimentary and mafic volcanic rocks similar to those seen within the Wych Hazel Pond Complex are associated with the localized development of a mafic and felsic dyke swarm (*cf.,* Horse Cove Complex; Sparkes, 2006), related to episodic magmatism along that structure. The transition into a submarine setting also marks the development of a new form of mineralizing environment with the localized development of VMS-style mineralization within the Wych Hazel Pond Complex (*cf.,* Hayes and O'Driscoll, 1990; O'Brien *et al.*, 2001).

The eastern boundary of the volcanic and sedimentary rocks associated with the Holyrood Horst has historically been defined by the regionally significant Topsail Fault (*see* O'Brien *et al.*, 1997, 2001). Recent mapping of the volcanic and plutonic units in the region immediately east of the Topsail Fault, however, has led to correlation of several units with those found within the Holyrood Horst (G. Sparkes and S. O'Brien, unpublished data, 2007; Sparkes, 2006; G. Sparkes, unpublished data, 2007.). These include: 1) volcanic rocks of the White Mountain Volcanic Suite, 2) granitic rocks of the Holyrood Intrusive Suite, 3) possible equivalents to the Manuels Volcanic Suite, 4) marine siliciclastic sedimentary rocks, mafic volcanic rocks, and feldspar-porphyry dykes of the Wych Hazel Pond Complex, and 5) late-stage mafic intrusions of the Beaver Hat Intrusive Suite (Sparkes *et al.*, 2006). These rocks represent the eastern extension of variably mineralized arc-related units, and provide further insight into the regional development of epithermal-style mineralization. The salient major- and trace-element geochemical features of the plutonic and volcanic units are presented separately below.

ANALYTICAL METHODS

In total, one hundred and sixty-five samples were selected from a whole-rock major- and trace-element geochemical database, providing a representative population of the major igneous units along the eastern margin of the Holyrood Horst, and east of the adjacent Topsail Fault. Geochemical data from hydrothermally altered granites from the Manuels area are excluded from this review, and have been dealt with earlier (Sparkes, 2005). Samples from the subaerial felsic volcanic rocks locally contain variable amounts of hydrothermal alteration due to the development of high- and low-sulphidation epithermal systems, and therefore only the immobile trace-elements are relied upon when classifying these units.

Major- and trace-element determinations were made by Inductively Coupled Plasma-Emission Spectrometry, at the Department of Natural Resources Geochemical Laboratory, St. John's, Newfoundland. For a summary of detection limits and analytical procedures refer to Finch (1998). Normalizing values for ocean-ridge granite-normalized plots are from Pearce *et al.* (1984), and MORB normalized values are taken from Pearce (1983).

MAJOR PLUTONIC SUITES

HOLYROOD INTRUSIVE SUITE

The Holyrood Intrusive Suite occupies a major portion of the Holyrood Horst and includes various phases ranging from early diorite and monzonite intrusions to later granite and quartz-feldspar porphyry (King, 1988; O'Brien *et al.*, 1997, 2001). These intrusions range in age from ca. 640 to 620 Ma (Krogh *et al.*, 1988; O'Brien *et al.*, 2001; Sparkes *et al.*, 2005) and are interpreted, in part, to represent sub-volcanic intrusions of the overlying volcanic carapace (O'Brien *et al.*, 1990). Locally, intrusions within the Holyrood Intrusive Suite contain rafts and roof pendants of the overlying volcanic successions and rare marine sedimentary rocks (O'Brien *et al.*, 2001; Sparkes *et al.*, 2002). Eastern portions of the Holyrood Intrusive Suite, locally dated at 623 ± 3 Ma, are composed primarily of quartz-rich, fine- to medium-grained biotite–hornblende-bearing granite, with localized development of a distinctive pink, white, and green propylitic alteration (O'Brien *et al.*, 1997, 2001). Granitic rocks of the Holyrood Intrusive Suite, including rocks east of the Topsail Fault that have been correlated with that suite, locally display comagmatic relationships with more mafic to intermediate phases (O' Brien *et al.*, 1997, 2001; Sparkes *et al.*, 2002; Sparkes, 2005). Some of these more mafic to intermediate intrusions, although indicated by field relationships to be comagmatic, do not everywhere display normal chemical fractionation trends with more differentiated units (*cf.,* Sparkes, *op. cit.*, 2002).

HERRING COVE DIORITE

The Herring Cove Diorite is the oldest of several intermediate to mafic intrusions, newly recognized in the region, immediately east of the Topsail Fault (Sparkes, 2006). The diorite consists of fine- to medium-grained, subhedral, white feldspar phenocrysts and interstitial dark-green chlorite and epidote. It intrudes rocks as young as the Wych Hazel Pond Complex, and locally contains screens of quartz–K-feldspar-rich granite correlated with the Holyrood Intrusive Suite. The Herring Cove Diorite is locally crosscut by feldspar-porphyry dykes correlated with dated 585 ± 5 Ma feldspar porphyry of the Wych Hazel Pond Complex west of the Topsail Fault (Sparkes, 2005; Sparkes *et al.*, 2005).

BEAVER HAT INTRUSIVE SUITE

A suite of massive, fine-grained gabbroic to locally dioritic plugs, dykes and plutons, assigned to the Beaver Hat Intrusive Suite by Sparkes *et al.* (2005) and Sparkes (2006), occurs east and west of the Topsail Fault and on a broad regional scale shares a spatial association with that structure. Intrusions of the Beaver Hat Intrusive Suite represent the youngest known intrusive event within the region; locally crosscutting folded rocks of the upper Conception Group in the region of Cape St. Francis. Typically, the unit forms small isolated plugs and/or dykes, with local development of rare magmatic layering in the region of Cape St. Francis. The predominant portion of the unit is gabbroic in composition, dark-green, fine to medium grained, chlorite-rich, and contains minor disseminated pyrite.

Intrusions similar to the Beaver Hat Intrusive Suite have been previously documented east and west of the Topsail Fault (King, 1990; O'Brien *et al.*, 2001; Sparkes *et al.*, 2005). In southern regions of the Avalon Peninsula, mafic intrusions of the Whalesback gabbro (Williams and King, 1979) were emplaced into the sedimentary rocks of the Conception Group (O'Brien *et al.*, 2001; Sparkes *et al.*, 2002).

These rocks may represent southern equivalents to the Beaver Hat Intrusive Suite.

FELDSPAR PORPHYRY

Numerous high-level porphyries of varying age occur throughout the Holyrood Horst (O'Brien *et al.*, 1997, 2001). Porphyry intrusions identified along the eastern margin of the horst structure represent the youngest such hypabyssal intrusions yet identified, and are chemically distinct from older porphyries associated with the Holyrood Intrusive Suite (Sparkes *et al.*, 2005). This younger porphyry unit has been dated at 585 ± 5 Ma (Sparkes, 2005) and is included within the regionally extensive Wych Hazel Pond Complex east and west of the Topsail Fault, and within the Horse Cove Complex along the eastern coastline of Conception Bay. A grey porphyritic rhyolite dyke intruding dioritic and gabbroic rocks along the eastern coast of Conception Bay is one of the feldspar-porphyry dykes of the Horse Cove Complex, and is believed to be the dyke dated at 585 Ma by Krogh *et al.* (1988). The feldspar porphyry typically contains 1- to 2-mm white subhedral feldspar crystals within a purple to grey-green, fine-grained groundmass. This porphyry unit is intrusive into siliciclastic sedimentary rocks and associated submarine mafic volcanic rocks of the Wych Hazel Pond and Horse Cove complexes, and into the Herring Cove Diorite (Sparkes, 2006).

VOLCANIC ROCKS

SUBAERIAL FELSIC VOLCANIC ROCKS

White Mountain and Manuels Volcanic Suites

The area along the eastern margin of the Holyrood Horst contains pre-620 Ma subaerial felsic volcanic rocks of the White Mountain Volcanic Suite and dated 584 Ma rhyolitic flows and ash-flow tuff of the Manuels Volcanic Suite (O'Brien *et al.*, 2001; Sparkes *et al.*, 2005). Rhyolitic flows, regardless of age, display well-developed flow-banding textures, as well as syn-volcanic autobrecciation textures; flows are locally associated with volcaniclastic sedimentary rocks. In the region east of the Topsail Fault, subaerial felsic volcanic rocks intruded by granitic rocks correlated with the Holyrood Intrusive Suite represent the eastern continuance of the White Mountain Volcanic Suite. Flow-banded rhyolites occurring in the region of Cape St. Francis are lithologically similar to the Manuels Volcanic Suite, and share a close spatial association with overlying mafic volcanic and marine sedimentary rocks correlated with the Wych Hazel Pond Complex. It is unclear whether the two flow-banded rhyolite units are related or if, in fact, the flows in the Cape St. Francis region represent a younger period of felsic volcanism. Significantly, these rhyolites contain thin hematite–chalcedonic silica veinlets and breccia similar to that developed in the epithermal system near Manuels.

MAFIC VOLCANIC FLOWS AND DYKES

Wych Hazel and Horse Cove Complexes

Siliciclastic sedimentary rocks of the Wych Hazel Pond and Horse Cove complexes, which flank the eastern margin of the Holyrood Horst, contain interbedded mafic volcanic rocks and associated hyaloclastites. In the region east of the Topsail Fault, submarine pillow basalts of the Wych Hazel Pond Complex are common exposures, north of the Portugal Cove area (Figure 2). Mapping in the region east of the Topsail Fault has identified two distinct mafic volcanic units within the Wych Hazel Pond Complex (Sparkes, 2006; King, 1990). The older of the two, consists of a dark-green, locally feldspar-phyric, epidote-rich basalt with local development of pillowed structures and associated breccias. This unit is lithologically similar to mafic volcanic rocks contained within the Wych Hazel Pond Complex west of the Topsail Fault and is therefore correlated with it. The second mafic volcanic unit consists of hematite-rich pillowed basalt, commonly affected by syn-volcanic, hematite-rich brecciation and contains rafts of fine-grained dark-red siltstone and interbedded sandstone. This unit is unique to the region east of the Topsail Fault; float from this unit contains rare pale-grey chalcedonic silica veins that contain Au mineralization (Funnel Pond area, *cf.,* Sparkes, 2006; Figure 2). If these veins are associated with the regionally extensive low-sulphidation epithermal system, then the host rock would represent the youngest upper limit yet defined for the hydrothermal system.

Mafic dykes are common throughout the region immediately east and west of the Topsail Fault. In the Manuels region, mafic dykes crosscut the subaerial felsic volcanic rocks of the White Mountain and Manuels volcanic suites, where they locally share a close spatial association with low-sulphidation veins, and on a regional scale, follow the trace of the Topsail Fault. The relationship of dyke emplacement to this structure is further highlighted by the development of a mafic and felsic dyke swarm along the eastern coastline of Conception Bay (Horse Cove Complex; Sparkes, 2006). Within this dyke swarm, several generations of mafic dykes are evident: early dark-green epidote-rich dykes are cut by a feldspar-phyric epidote-rich variant, later crosscut by dark-purple, strongly magnetic mafic dykes. These dykes average between 20 cm to 2 m in width, locally attaining widths up to 8 m in the Manuels region.

MAJOR- AND TRACE- ELEMENT CHARACTERISTICS

HOLYROOD INTRUSIVE SUITE

From the analyses of forty seven whole-rock samples collected from granitic rocks of the Holyrood Intrusive Suite, the following results were obtained: SiO_2 values between 70.20 and 77.58 weight percent (mean 73.58%), K_2O between 2.88 and 5.07 weight percent (mean 3.93%), Na_2O between 3.58 and 6.01 weight percent (mean 4.19%), CaO between 0.09 and 1.79 weight percent (mean 0.68%), Al_2O_3 between 11.83 and 15.49 weight percent (mean 13.74%) and TiO_2 between 0.01 and 0.38 weight percent (mean 0.18%). The Holyrood Intrusive Suite is subalkalic and plots within the calc-alkalic field on an AFM diagram (Figure 3a, b). Samples from the granite, have K_2O/ Na_2O values that range from 0.53 to 1.3 (mean of 0.95), and plot within the high- to medium-K fields of Le Maitre *et al.* (1989). This unit also has a weakly elevated alumina content that has a mean Al_2O_3/(Na_2O+K_2O) value of 1.7, plotting in the lower left portion of the peraluminous field (Figure 3c).

Samples of the Holyrood Intrusive Suite from both east and west of the Topsail Fault display a similar trace-element pattern (Figure 3d), supporting the correlation of these intrusions (*e.g.*, Sparkes, 2006). The granite along the eastern Holyrood Horst is characteristically enriched in the large ion lithophile elements (LILE) K, Rb, Ba and Ce. The variable concentrations of the high-field strength elements (HFSE) Zr and Y can be related to the affects of fractional crystallization, as sampling covers an area of approximately 360 km^2. Two samples from the western margin of the horst (near Seal Cove: *see* O'Brien *et al.*, 2001) represent a high-level, locally granophyric granitic intrusion from the Holyrood Intrusive Suite; these are included in Figure 3d to display the distinct trace-element enrichment pattern of that phase. Granitic rocks from the eastern margin of the Holyrood Intrusive Suite display similar characteristics to volcanic arc-related intrusions described in Pearce *et al.* (1984); and when plotted on a Y *vs* Nb diagram, samples fall within the volcanic-arc granite/syn-collisional granite field of Pearce *et al.* (*op. cit.*).

Three samples of granodiorite are also included from the Holyrood Intrusive Suite and are presented here for geochemical comparison with younger, less differentiated units of the Herring Cove Diorite and Beaver Hat Intrusive Suite (*see below*). Of the three samples included herein, two were collected in the region west of the Topsail Fault and one from the area east of the fault. Values from the three samples range between 59.24 and 62.69 weight percent SiO_2 (mean 61.16%), 3.48 and 4.89 weight percent K_2O (mean 4.11%), 3.27 and 3.83 weight percent Na_2O (mean 3.62%), 1.12 and 3.15 weight percent CaO (mean 1.82%), 15.80 and 17.93 weight percent Al_2O_3 (mean 17.01%) and between 0.59 and 0.63 weight percent TiO_2 (mean 0.61%). Samples of the granodiorite plot closer to the alkalic-subalkalic boundary in comparison to the more differentiated granite, with one sample plotting slightly to the left within the alkalic field (Figure 3a). When plotted on an AFM diagram, a possible cogenetic relationship between the granite and the granodiorite could be implied; however more detailed trace-element geochemistry suggests otherwise (Sparkes, 2001; Sparkes, *et al.*, 2002). Samples from the granodiorite contain K_2O/Na_2O ratios ranging from 0.91 to 1.5 (mean 1.15) and plot within the high-K calc-alkalic field (Le Maitre, 1989). The granodiorite displays enrichment in alumina with respect to the granite, with a mean Al_2O_3/(Na_2O+K_2O) value of 2.2. As a result samples from the granodiorite plot higher in the peraluminous field (Figure 3c). It is also evident from this diagram that the granodiorite sample from east of the Topsail Fault plots away from samples collected west of the fault, falling on the peraluminous-metaluminous boundary. This is due to a slightly lower Al_2O_3 and higher CaO concentrations within the sample, possibly representing the effects of fractional crystallization. As is evident in Figure 3d, all three samples from the less differentiated granodiorite display a similar trace-element pattern to the granitic rocks of the Holyrood Intrusive Suite and therefore are not described in more detail.

As noted in previous work, trace-element geochemistry does not support a cogenetic relationship between the granodiorite and granite from the Holyrood Intrusive Suite via simple fractional crystallization (*cf.,* Sparkes, 2001). Figure 4a displays supporting evidence, because samples from the granodiorite plot above a simple fractionation trend with respect to the granite. This is further substantiated by Figure 4b, which show the granite and granodiorite have similar concentrations of Y. If the granite and granodiorite were related through simple fractionation, then the granodiorite should contain less Y than the more differentiated granite unless a Y-bearing phase is crystallizing and being removed from the granite.

HERRING COVE DIORITE AND BEAVER HAT INTRUSIVE SUITE

Three samples were collected from the Herring Cove Diorite. These have SiO_2 values ranging from 53.08 to 58.71 weight percent (mean 55.06 wt.%), K_2O between 0.08 and 1.27 weight percent (mean 0.85%), Na_2O between 5.00 and 6.90 weight percent (mean 5.90%), CaO between 2.95 and 5.13 weight percent (mean 4.36%), Al_2O_3 between 15.03 and 16.74 weight percent (mean 15.94 %) and TiO_2 between

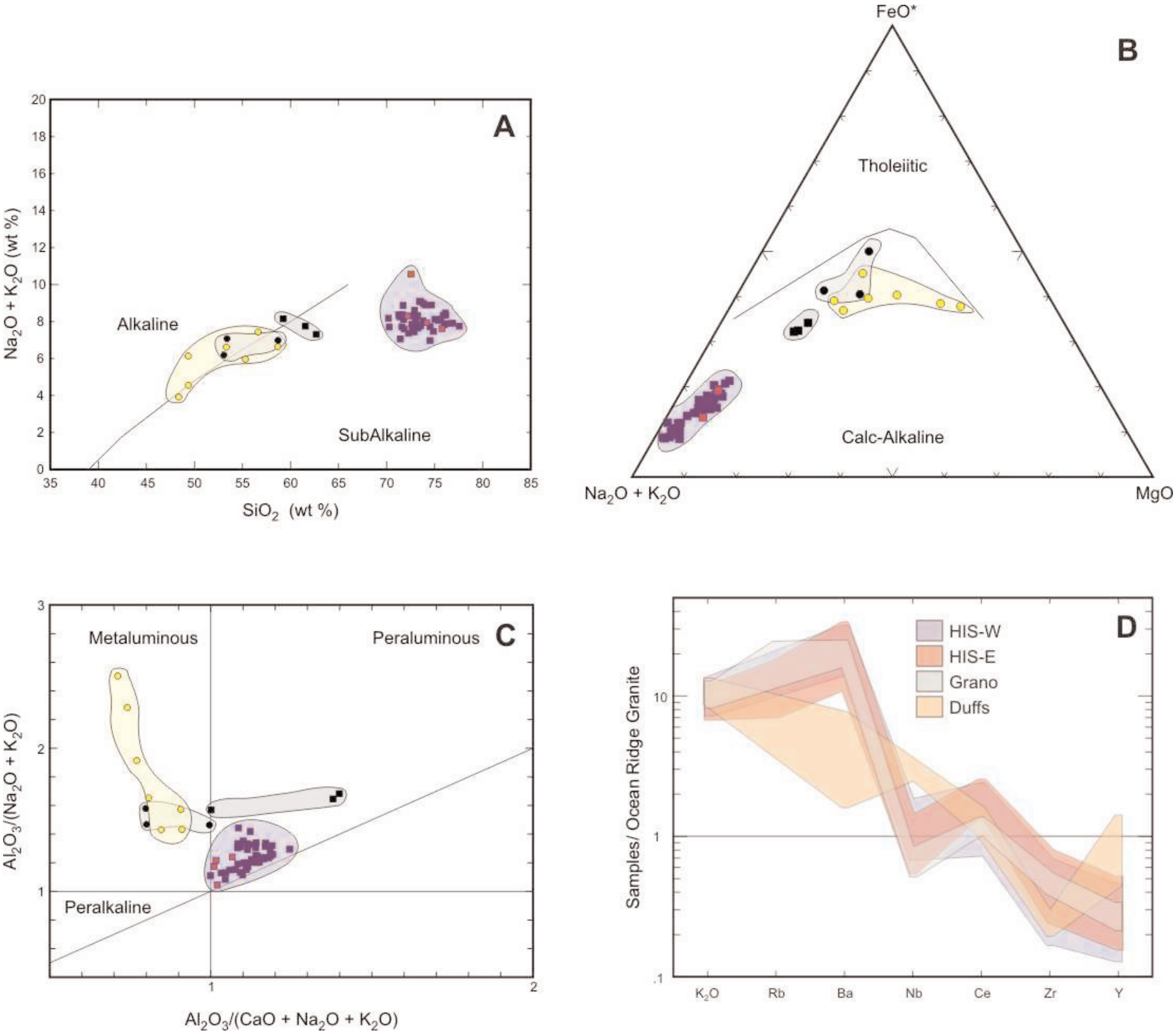

Figure 3. *Select major- and trace-element composition diagrams for samples from the Holyrood and Beaver Hat intrusive suites and Herring Cove Diorite. Legend: purple square - Holyrood granite (from within the Holyrood Horst); red square - Holyrood granite (east of the Topsail Fault); black square - granodiorite of the Holyrood Intrusive Suite; black circle - Herring Cove Diorite; yellow circle - Beaver Hat Intrusive Suite. (A) Total alkalis* vs *silica plot with alkalic-subalkalic boundary of Irvine and Baragar (1971). (B) AFM diagram with calc-alkalic and tholeiitic fields of Irvine and Baragar (1971). (C) Alumina saturation diagram of Maniar and Piccoli (1989), showing limits of metaluminous, peraluminous and peralkline fields. The $Al_2O_3/(Na_2O+K_2O)$ and $Al_2O_3/(CaO+Na_2O+K_2O)$ ratios are calculated from molar values. (D) Ocean ridge granite-normalized trace-element patterns for granite samples from east and west of the Topsail Fault, HIS-E and HIS-W, respectively; granodiorite from the eastern margin of the Holyrood Horst (Grano); and a high-level granitic intrusion from the Duff's region (Duffs).*

1.23 and 1.84 weight percent (mean 1.48%). Regionally, both the Herring Cove Diorite and the less differentiated Beaver Hat Intrusive Suite exhibit a broad spatial association with the trace of the Topsail Fault. Both units also share many geochemical features that may suggest a cogenetic relationship. Seven samples of the Beaver Hat Intrusive Suite are included within this report; all but two of these are from east of the Topsail Fault. This unit is characterized by SiO_2 values between 48.38 and 58.69 weight percent (mean 53.02%), K_2O between 0.13 and 2.91 weight percent (mean

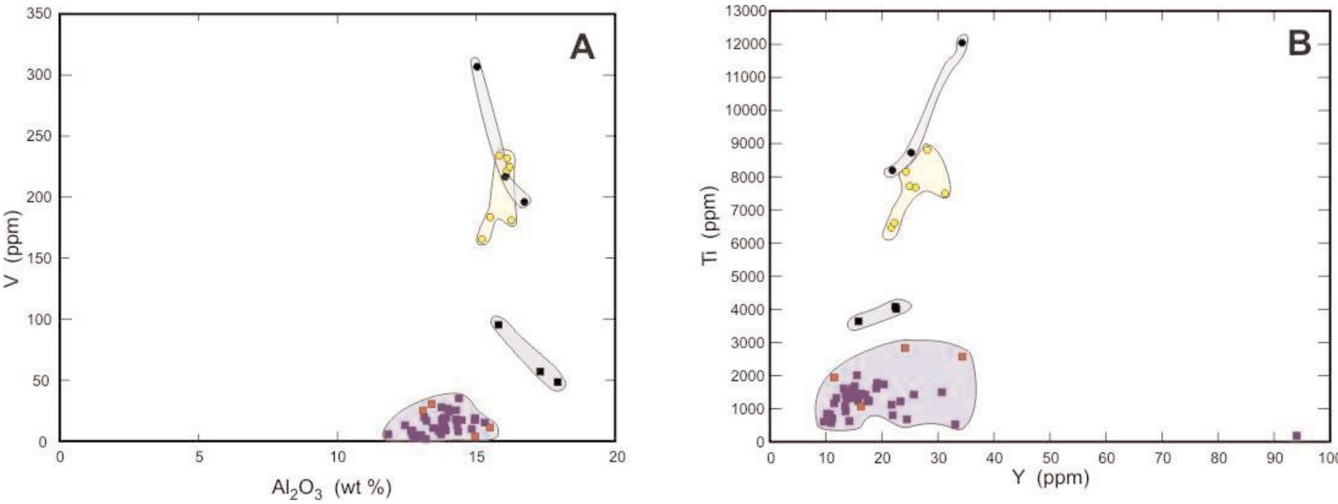

Figure 4. *Select bivariate trace-element plots for samples from the Holyrood and Beaver Hat intrusive suites and Herring Cove Diorite (for legend refer to Figure 3). (A) Immobile-compatible* vs *immobile-compatible bivariate plot. (B) Immobile-incompatible vs. immobile-compatible bivariate plot.*

1.13%), Na_2O between 3.23 and 6.07 weight percent (mean 4.77%), CaO between 3.35 and 8.59 weight percent (mean 5.78%), Al_2O_3 between 15.20 and 16.26 weight percent (mean 15.89%) and TiO_2 between 1.05 and 1.44 weight percent (mean 1.23%). Both units cluster along the alkalic-subalkalic boundary in Figure 3a, with the Beaver Hat Intrusive Suite showing greater amounts of variation, possibly due to chemical differentiation. Samples from both units plot closer to the tholeiitic–calc-alkalic divide with respect to the granodiorite of the Holyrood Intrusive Suite (Figure 3b). If it is assumed that the Herring Cove Diorite and the Beaver Hat Intrusive Suite are cogenetic, possible evidence for a weakly developed tholeiitic trend is evident for samples plotted in Figure 3b.

Both the Herring Cove Diorite and Beaver Hat Intrusive Suite display similar K_2O/ Na_2O ratios, with mean values of 0.16 and 0.27, respectively. Due to the characteristically low K_2O concentrations, both units plot within the low- to medium-K fields of Le Maitre *et al.* (1989). One exception to this is a sample from the Beaver Hat Intrusive Suite that has an anomalous K_2O value of 2.91 weight percent; as a result this sample plots within the high-K calc-alkalic field. One major distinction that separates these intrusions from those of the Holyrood Intrusive Suite is that both the Herring Cove Diorite and the Beaver Hat Intrusive Suite plot within the metaluminous field of Maniar and Piccoli (1989), except for one outlier, which falls on the metaluminous–peraluminous boundary (Figure 3c).

Rocks from the Herring Cove Diorite are interpreted to have intruded shortly after the cessation of subaerial felsic volcanism and subsequent to the onset of marine sedimentation. Data presented here suggest this unit could be cogenetic with the Beaver Hat Intrusive Suite, and therefore it is assumed to be coeval with that suite. These intrusions retain geochemical characteristics similar to volcanic arc-related intrusions, including the enrichment in the LILE K, Rb, Ba and Ce, relative to the HFSE Nb, Zr and Y. Both units plot within the volcanic-arc granite/syn-collisional granite field of Pearce *et al.* (1984). Individual samples from both suites are locally depleted in K_2O and one sample from the Herring Cove Diorite displays a rare depletion in Ba (Figure 5). These late-stage intrusions along the eastern margin of the Holyrood Intrusive Suite are chemically distinct from the less differentiated rocks of the Holyrood Intrusive Suite, displaying a positive Zr–Y slope (Figure 5). This is further demonstrated by the bivariate plots in Figures 4a and 4b. From these plots, it is evident that both the Herring Cove Diorite and Beaver Hat Intrusive Suite share a close compositional association (aside from one outlier that has anomalous values of V, and Ti) and therefore could be cogenetic.

PORPHYRY INTRUSIONS

Two porphyry units from the eastern margin of the Holyrood Horst are included in this report; a dated 625 ± 2.5 Ma quartz–feldspar porphyry of the Holyrood Intrusive Suite and a younger 585 ± 5 Ma feldspar porphyry of the Wych Hazel Pond Complex (Sparkes, 2005). The quartz–feldspar porphyry represents a relatively late-stage intrusion of the Holyrood Intrusive Suite, developed along the northeastern margin of the Holyrood Horst (Sparkes, 2005). Six samples are included from the quartz–feldspar porphyry; within these samples SiO_2 values range between 71.10 and 74.40 weight percent (mean 72.78 %), K_2O between 3.06 and 3.77 weight percent (mean 3.34%), Na_2O

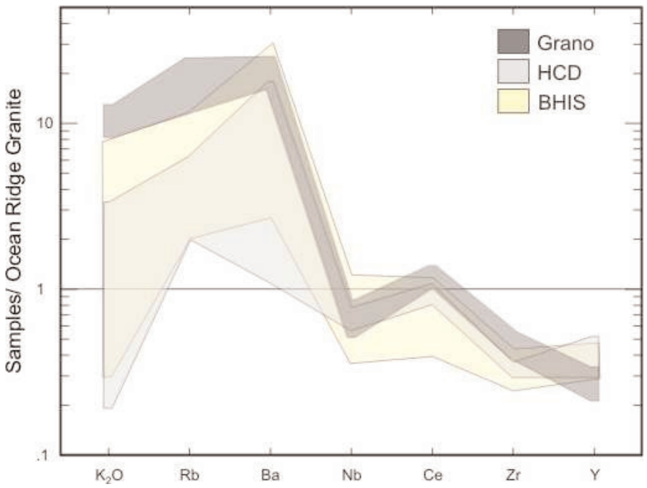

Figure 5. *Ocean ridge granite-normalized trace-element plot displaying the comparison of arc-related granodiorite from the Holyrood Intrusive Suite (Grano) with late-stage mafic intrusions of the Herring Cove Diorite (HCD) and Beaver Hat Intrusive Suite (BHIS).*

between 4.22 and 5.13 weight percent (mean 4.67%), CaO between 0.48 and 1.02 weight percent (mean 0.79%), Al_2O_3 between 13.47 and 14.24 weight percent (mean 13.94%) and TiO_2 between 0.15 and 0.26 weight percent (mean 0.21%). The quartz–feldspar porphyry displays major- and trace-element characteristics similar to the rest of the Holyrood Intrusive Suite; the data plot in both the subalkalic and peraluminous fields on major-element discrimination diagrams. Samples from this unit have a much more restricted distribution compared to the feldspar porphyry samples, and as a result, the unit has a very homogeneous trace-element pattern (Figure 6a). As noted above, this intrusion is related to the main Holyrood Intrusive Suite, and therefore displays similar arc-related trace-element characteristics, including the enrichment in LILE relative to the HFSE, and low concentrations of Y with respect to normalizing values.

Samples of the feldspar porphyry were collected along a 42 km strike-length, east and west of the Topsail Fault. Twelve representative samples are included here, with equal numbers from opposing sides of the fault. Values for the feldspar porphyry unit range from 54.51 to 77.24 weight percent SiO_2 (mean 70.49%), 0.40 to 9.59 weight percent K_2O (mean 3.46%), 1.10 to 6.27 weight percent Na_2O (mean 4.80%), 0.09 to 1.56 weight percent CaO (mean 0.61%), 12.35 to 18.85 weight percent Al_2O_3 (mean 14.34%) and between 0.14 and 0.88 weight percent TiO_2 (mean 0.33%). These samples display a wide range in major-element concentrations, which is attributed to the porphyritic nature of the unit and the large geographical area covered by sampling. The variation due to the feldspar porphyritic nature is highlighted by the K_2O/ Na_2O ratio, which ranges from 0.6 to 8.7 (mean 1.37). Regardless of the major-element variation, the majority of samples still cluster within the subalkalic and peraluminous fields of Irvine and Baragar (1971), and of Maniar and Piccoli (1989), respectively.

Geochemically, the feldspar porphyry intrusions can be divided into two distinct phases. One phase represents feldspar porphyry that displays an arc-related geochemical signature (here named Pastureland feldspar porphyry). These occur in the region of VMS-style mineralization known as the Pastureland Road prospect (cf., Hayes and O'Driscoll, 1990; O'Brien *et al.*, 2001). The second includes most of the feldspar porphyry dykes exposed along the eastern margin of the Holyrood Horst, and is informally known as the Fowlers Road feldspar porphyry (Sparkes, 2005). The Pastureland feldspar porphyry displays chemical similarities to the arc-related quartz–feldspar porphyry, including enrichments in the LILE K, Ba, and Ce with respect to the HFSE, and low concentrations of Y relative to normalizing values (Figure 6a). The geochemistry of the Fowlers Road feldspar porphyry displays more significant variation, most notably in the LILE, which are both enriched and depleted. These samples also contain higher concentrations of Nb and Y, and as a result, several samples plot within the within-plate granite field of Pearce (*op. cit.*; Figure 6b). The differences between the Pastureland feldspar porphyry and the Fowlers Road feldspar porphyry are further highlighted by the ratio/ratio plot of Winchester and Floyd (1977; Figure 6c); the Pastureland feldspar porphyry plot within the rhyodacite/dacite and andesite/basalt fields, whereas the Fowlers Road feldspar porphyry plot entirely within the rhyodacite/dacite to rhyolite fields.

SUBAERIAL FELSIC VOLCANIC ROCKS

The geochemistry of the felsic volcanic rocks within the Manuels area has been described in more complete detail in Sparkes (2005), and is only briefly described here. As previously noted, the felsic volcanic rocks along the eastern margin of the Holyrood Horst are affected by various degrees of hydrothermal alteration. Due to this hydrothermal alteration the major-element data is only used for broad classification of the units. For comparison purposes, dated 730 Ma felsic volcanic rocks from the western margin of the Holyrood Horst (Israel, 1998) are included in the following plots but are not discussed in detail in this report.

Volcanic rocks of the White Mountain Volcanic Suite generally consist of flow-banded rhyolite and minor ash-flow tuff and are mostly identified by intrusive contacts with the Holyrood Intrusive Suite. A total of twenty nine samples from this unit are included within the dataset, spanning an area some 54 km in length. These samples contain SiO_2 values between 67.74 and 81.41 weight percent (mean

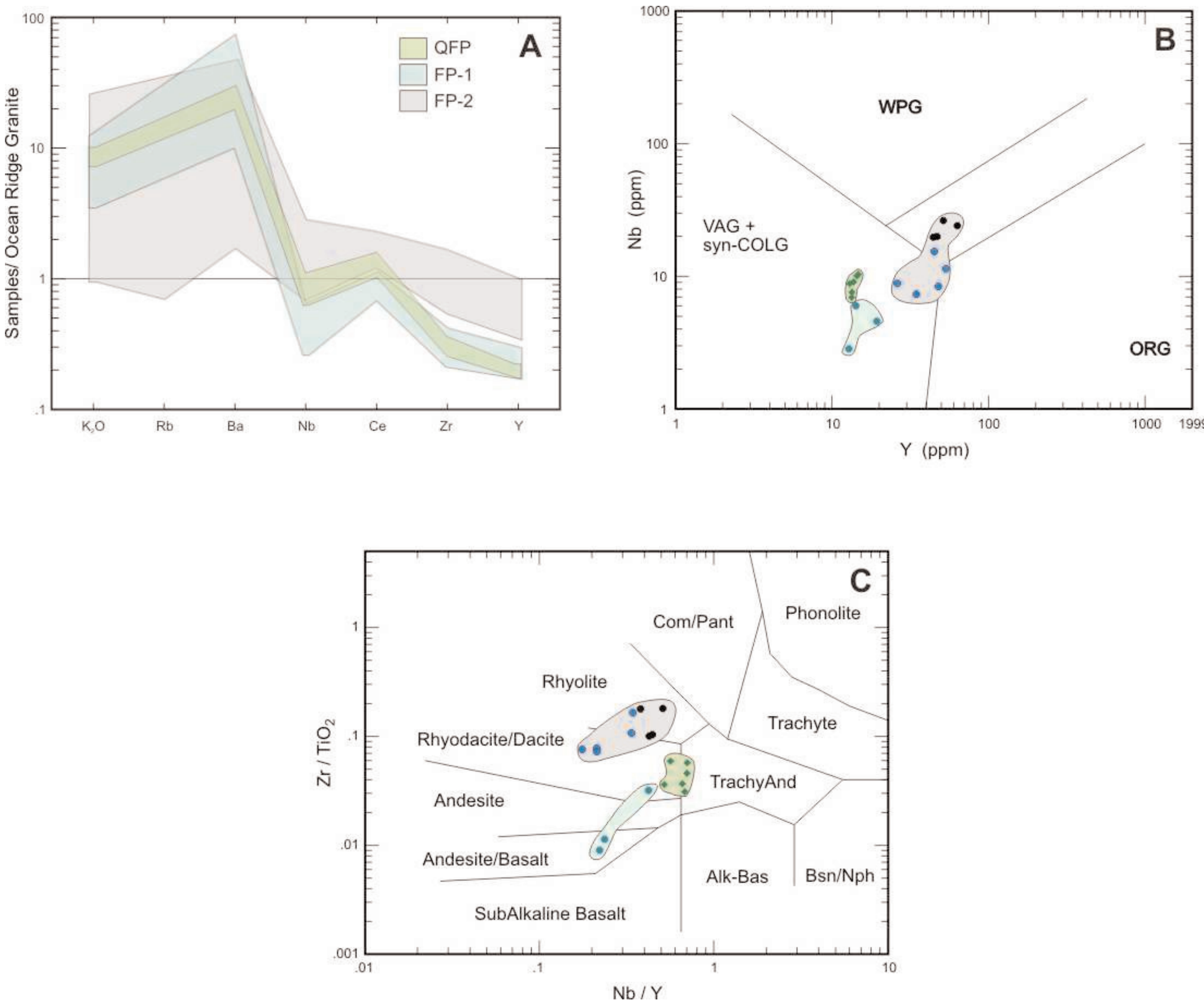

Figure 6. *Ocean ridge granite-normalized trace-element diagram and bivariate trace-element discrimination diagrams for quartz–feldspar porphyry of the Holyrood Intrusive Suite and feldspar porphyry of the Wych Hazel Pond Complex. Legend: green diamond - quartz–feldspar porphyry; green circle - feldspar porphyry from the Pastureland Road prospect; blue circle - feldspar porphyry from east of the Topsail Fault; black circle - dated feldspar porphyry unit of the Wych Hazel Pond Complex. (A) Comparison of arc-related quartz–feldspar porphyry (QFP) with late-stage feldspar porphyry, segregated into feldspar porphyry from the Pastureland Road prospect (FP-1) and samples from the Fowlers Road Feldspar Porphyry (FP-2). (B) Y* vs *Nb tectonic discrimination diagram of Pearce* et al. *(1984); WPG - within-plate granite; ORG - ocean ridge granite; VAG + syn- COLG - volcanic-arc + syn-collisional granite. (C) Trace-element discrimination diagram of Winchester and Floyd (1977).*

75.11%), K_2O between 0.10 and 9.17 weight percent (mean 3.87%), Na_2O between 0.15 and 7.98 weight percent (mean 4.16%), CaO between 0.03 and 2.21 weight percent (mean 0.34%), Al_2O_3 between 10.50 and 16.19 weight percent (mean 13.04%) and TiO_2 between 0.09 and 0.80 weight percent (mean 0.27%). The large variation in mobile element concentrations (K_2O, Na_2O, CaO and SiO_2) is attributed mainly to the effects of hydrothermal alteration, which is generally in the form of silicification, sericitization and localized potassic alteration.

Equally affected by the hydrothermal alteration are rocks included within the 584 Ma Manuels Volcanic Suite. This unit is locally host to the main portion of the pyrophyllite–diaspore high-sulphidation alteration; only weak to moderately altered samples from the margin of this alteration are included within this dataset. For a more detailed

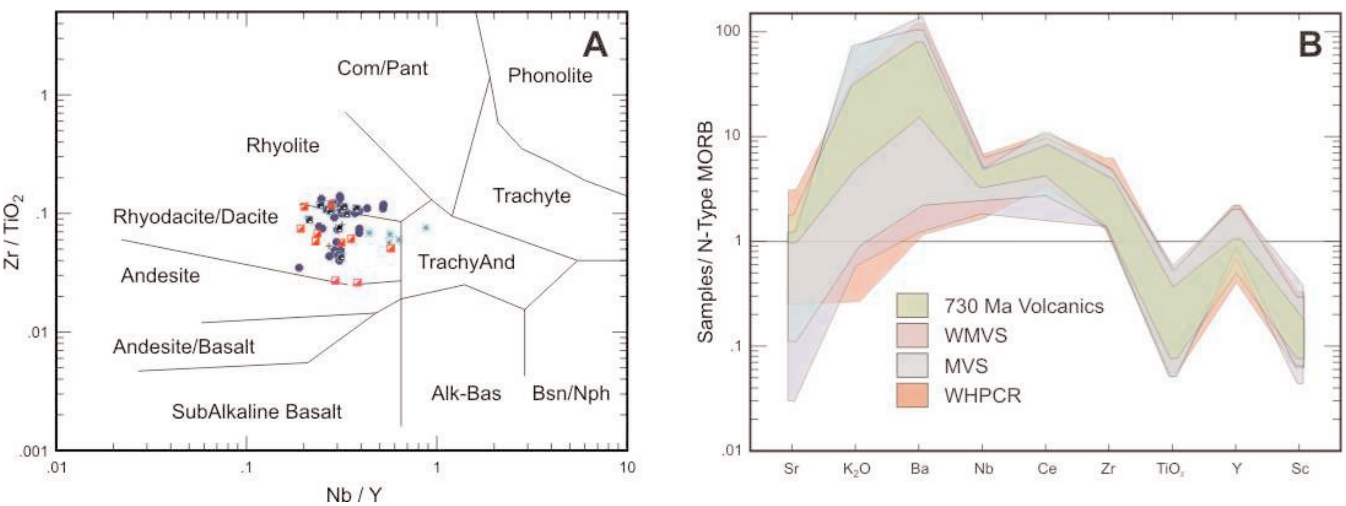

Figure 7. *Trace-element discrimination diagrams for felsic volcanic rocks of the White Mountain and Manuels volcanic suites and flow-banded rhyolite from east of the Topsail Fault (also included are 730 Ma felsic volcanic rocks from the western margin of the Holyrood Horst). Legend: asterisk - 730 Ma volcanic suite; blue circle - White Mountain Volcanic Suite and equivalents (WMVS); filled square - Manuels Volcanic Suite (MVS); half filled square - rhyolites from east of the Topsail Fault (WHPCR). (A) Trace-element discrimination diagram of Winchester and Floyd (1977). (B) N-type MORB-normalized trace-element diagram displaying the arc-related signature of the felsic volcanic rocks.*

description on the effects of the hydrothermal alteration within this volcanic succession the reader is referred to Sparkes (2005). From the thirteen samples analyzed, SiO_2 values ranged from 69.38 to 79.67 weight percent (mean 75.29%), K_2O from 0.15 to 9.93 weight percent (mean 5.45%), Na_2O from 0.24 to 7.61 weight percent (mean 2.91%), CaO from 0.02 to 0.57 weight percent (mean 0.20%), Al_2O_3 from 10.90 to 14.40 weight percent (mean 12.82%) and TiO_2 from 0.08 to 0.73 weight percent (mean 0.25%). These samples show variations in the mobile elements similar to that seen in the White Mountain Volcanic Suite. The alteration precludes any segregation of units on the basis of major-element geochemistry.

In the region east of the Topsail Fault restricted flow-banded rhyolite domes share a close spatial association with submarine mafic flows and breccias, along with associated sedimentary rocks of the Wych Hazel Pond Complex in the area around Cape St. Francis (Figure 2). Ten samples from this volcanic succession are included within this dataset; these samples contain SiO_2 values that ranged from 66.14 to 76.26 weight percent (mean 75.29%), K_2O from 0.04 to 4.65 weight percent (mean 2.54%), Na_2O from 2.41 to 7.38 weight percent (mean 5.40%), CaO from 0.20 to 2.03 weight percent (mean 0.74%), Al_2O_3 from 10.57 to 15.48 weight percent (mean 13.62%) and TiO_2 from 0.09 to 0.63 weight percent (mean 0.31 %). This unit does not display any significant macroscopic hydrothermal alteration, such as that seen in the Manuels region, and this is reflected by less variation within the major mobile elements. Notable differences with the Manuels area include lower mean concentrations of K_2O and SiO_2 and higher mean Na_2O. However, it is unclear at this juncture whether these volcanic rocks represent the eastern equivalent of the Manuels Volcanic suite or, alternatively, a separate volcanic unit within the Wych Hazel Pond Complex.

Felsic volcanic rocks analyzed in this study, regardless of the effects of alteration, plot within the subalkalic and calc-alkalic fields of Irvine and Baragar (1971), and most plot within the peraluminous field of Maniar and Piccoli (1989). With a few exceptions, the subaerial felsic volcanic rocks, irrespective of age, plot within the rhyodacite/dacite and rhyolite fields of Winchester and Floyd (1977; Figure 7a); one exception are the 730 Ma samples from the central Holyrood Horst, some samples of which display overlap with the adjacent Trachytic Andesite field. As noted in Sparkes (2005), these units display very similar trace-element patterns other than that attributed to hydrothermal alteration (Figure 7b). Thus major- and trace-element geochemistry is ineffective when attempting to characterize volcanic events. Figure 7b, shows the similar trace-element patterns of all the rhyolite samples from this study, which includes rocks ranging in age from 730 to 584 Ma. Like the Holyrood Intrusive Suite, these rocks have trace-element patterns (including the enrichment of the LILE relative to the HFSE) indicative of formation in a volcanic arc environment. One common feature of volcanic rocks (other than the 730 Ma suite) is the broad range in the LILE. This variation could reflect further internal complexity, the localized effects of hydrothermal alteration, or the difference in sampling density. The felsic volcanic rocks do not plot entirely within the volcanic-arc/syn-collisional field of the Y *vs* Nb plot of Pearce *et al.* (1984) and display minor overlap with the within-plate granite field.

SUBMARINE MAFIC VOLCANIC FLOWS AND DYKES

Of the sixteen samples analyzed from the Wych Hazel Pond and Horse Cove complexes, twelve are from the epidote-rich unit and four are from the hematite-rich unit. Major-element concentrations within the epidote-rich volcanics vary from 49.53 to 57.36 weight percent SiO_2 (mean 53.93 %), 0.09 to 3.36 weight percent K_2O (mean 0.75%), 2.66 to 7.25 weight percent Na_2O (mean 5.70%), 2.35 to 7.01 weight percent CaO (mean 4.84%), 14.30 to 17.41 weight percent Al_2O_3 (mean 15.75%) and from 0.79 to 2.09 weight percent TiO_2 (mean 1.42%). The hematite-rich unit is less extensive than epidote-rich volcanic rocks. The limited sampling density is reflected in the homogeneous geochemistry; with SiO_2 values ranging from 49.32 to 50.12 weight percent (mean 49.68%), K_2O between 0.75 and 1.05 weight percent (mean 0.77%), Na_2O between 4.40 and 4.62 weight percent (mean 4.51%), CaO between 6.58 and 8.34 weight percent (mean 7.43%), Al_2O_3 between 14.47 and 15.68 weight percent (mean 15.26%) and TiO_2 between 1.29 and 1.61 weight percent (mean 1.44%). Samples from the hematite-rich unit have weakly elevated Fe_2O_3 + FeO values, with a mean of 10.08 weight percent, in comparison to a mean of 8.50 weight percent for the epidote-rich unit. However the iron staining that is characteristic of the unit is interpreted to be more a function of the eruptive environment, with little petrologic significance.

The mafic volcanic rocks of the Wych Hazel Pond and Horse Cove complexes plot along the alkalic-subalkalic boundary of Irvine and Baragar (1971). Samples from both units fall within the metaluminous field of Maniar and Piccoli (1989); however rocks from the epidote-rich unit display minor overlap with the peraluminous field (Figure 8a). The mafic volcanic rocks plot in the andesite/basalt and subalkaline basalt fields of Winchester and Floyd (1977). The N-type MORB-normalized trace-element signatures of the mafic volcanic rocks do not display patterns typical of volcanic-arc basalts as outlined by Pearce (1982; Figure 9a). The pattern shows enrichment in the LILE Sr, K, Rb and Ba relative to the HFSE; however, the elements Nb, Ce, P_2O_5 and Zr are also enriched relative to normalizing values. These characteristics could reflect modification of the source region, and may indicate changes associated with a transition in the tectonic environment and the onset of extensive marine sedimentation. Samples from the epidote-rich unit also develop rare depletions in K and Cr, which are attributed to the effects of localized fractional crystallization. Although the epidote- and hematite-rich volcanic rocks display similar trace-element patterns, the two units are separable on the basis of certain trace-element ratios (see the Zr–Zr/Y plot of Pearce and Norry (1979), and the Zr–Nb–Y plot of Meschede (1986); Figures 8b and 8c). On the Zr–Nb–Y plot, the epidote-rich volcanics plot mainly in the within-plate tholeiite and volcanic-arc basalt field, whereas samples from the hematite-rich unit fall within the N-type MORB and volcanic-arc basalt field. Figure 8c further highlights the overall Zr enrichment of the epidote-rich unit. Samples of the latter plot in the within-plate basalt field whereas those of the hematite-rich unit plot within the MORB and volcanic-arc basalt field. Several samples of the epidote-rich unit plot in close proximity to samples from the hematite-rich unit, which may imply a cogenetic link between the two. These outliers do not display the characteristic hematization associated with the hematite-rich unit and may represent cogenetic flows erupted within a deeper marine environment.

Mafic dykes within the region display many chemical similarities to the mafic volcanic rocks and may represent feeder dykes to some of the mafic volcanic successions. In the seventeen dyke samples analyzed, SiO_2 values ranged from 43.33 to 63.95 weight percent (mean 53.46%), K_2O from 0.12 to 5.44 weight percent (mean 1.93%), Na_2O from 0.40 to 6.44 weight percent (mean 4.08%), CaO from 0.50 to 7.47 weight percent (mean 3.39%), Al_2O_3 from 12.83 to 20.09 weight percent (mean 16.19%) and TiO_2 from 0.51 to 2.40 weight percent (mean 1.56%). Based on these major-element data three different groups of dykes can be recognized; those having molar values of $Al_2O_3/(CaO + Na_2O + K_2O) > 1$ (group 1), those with $Al_2O_3/(CaO + Na_2O + K_2O) < 1$ (group 3), and those having relatively high SiO_2 contents (group 2). Like the mafic volcanic units, most of the mafic dykes plot along the alkalic-subalkalic boundary, and fall within the andesite/basalt to subalkaline basalt fields of Winchester and Floyd (1977). Exceptions are the more differentiated mafic dykes, which range from the andesite to subalkalic basalt fields. On the alumina saturation diagram (Figure 8a), two of the main groups of mafic dykes can be distinguished. Both groups share a close spatial association in the field, which may suggest that the two units are cogenetic and the observed differences are the result of chemical fractionation.

Other than the localized enrichment and depletion of predominantly compatible elements, which can be attributed to crystal fractionation, trace-element patterns displayed by the mafic dykes are similar. These patterns match those of the mafic volcanic rocks, and show enrichments in the LILE and select HFSE. This geochemical similarity suggests that at least some of these dykes represent feeder conduits to the

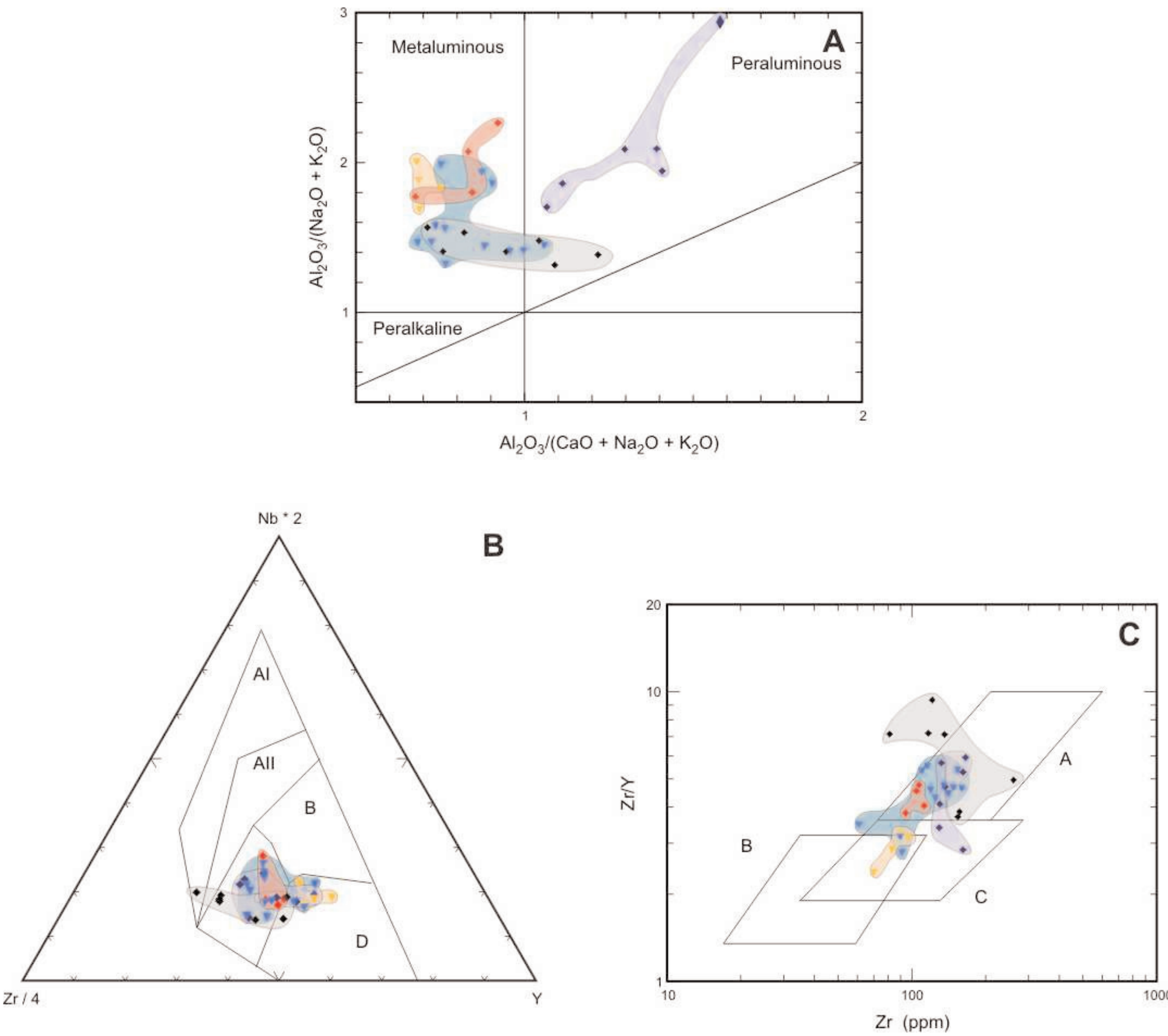

Figure 8. *Major- and trace-element discrimination diagrams for mafic volcanic rocks of the Wych Hazel Pond and Horse Cove complexes and mafic dykes from the eastern Holyrood Horst. Legend: pale blue triangle - epidote-rich mafic volcanics; pale orange triangle - hematite-rich mafic volcanic rocks; pale purple diamond - dykes, group 1; red diamond - dykes, group 2; black diamond - dykes, group 3. (A) Alumina saturation diagram of Maniar and Piccoli (1989), showing limits of metaluminous, peraluminous and peralkaline fields. The $Al_2O_3/(Na_2O+K_2O)$ and $Al_2O_3/(CaO+Na_2O+K_2O)$ ratios are calculated from molar values. (B) Tectonic discrimination diagram after Meschede (1986) displaying fields for: AI - within-plate alkali basalt; AII within-plate alkali basalt and within-plate tholeiites; B - E-type MORB; C - within-plate tholeiites and volcanic-arc basalt; D - N-type MORB and volcanic-arc basalt. (C) Trace-element discrimination diagram with fields from Pearce and Norry (1979); A - with-plate basalt; B - island-arc basalt; C - mid-ocean ridge basalt.*

mafic volcanics within the Wych Hazel Pond Complex. The transitional geochemistry evident in both the dykes and the volcanic rocks may reflect a change in the tectonic environment, and may indicate the transition into a back-arc type setting.

SUMMARY AND CONCLUSIONS

1) Granitic rocks of the Holyrood Intrusive Suite represent typical volcanic-arc related intrusions, displaying enrichment in the LILE, relative to the HFSE, and hav-

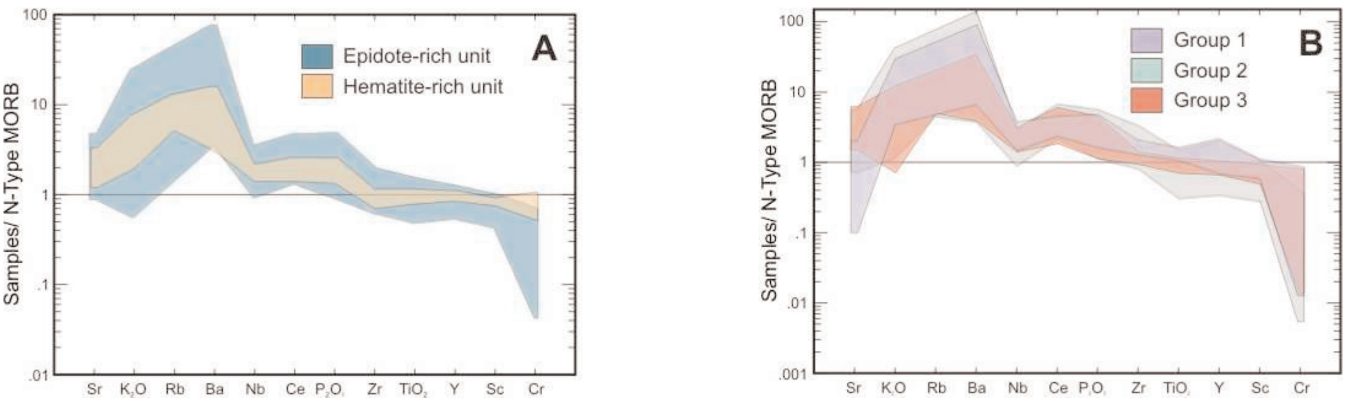

Figure 9. *N-type MORB-normalized trace-element diagrams for mafic volcanic rocks and dykes of the eastern Holyrood Horst and region east of the Topsail Fault. (A) Comparison of epidote- and hematite-rich mafic volcanic rocks of the Wych Hazel Pond and Horse Cove complexes. (B) Comparison of three different groups of mafic dykes emplaced along the eastern margin of the Holyrood Horst.*

ing relatively low concentrations of Y, relative to ocean ridge granite of Pearce *et al.* (1984). These geochemical data support current geological interpretations with regards to the formation and setting of the Holyrood Intrusive Suite.

2) Samples collected from granitic rocks exposed east of the Topsail Fault display trace-element patterns similar to typical granitic compositions of the Holyrood Intrusive Suite, providing supporting evidence for the correlation with that suite. Locally, granitic intrusions of the Holyrood Intrusive Suite are associated with less differentiated comagmatic intrusions of granodiorite. These intrusions are not related to the more differentiated granite through normal chemical fractionation, implying either a more complex geochemical history, which may involve contamination of the parental magma, or possibly a separate source altogether.

3) Intrusive rocks of the Herring Cove Diorite and Beaver Hat Intrusive Suite share many lithological and geochemical similarities and are interpreted to be cogenetic. Although these intrusive rocks postdate the Holyrood Intrusive Suite by at least 40 Ma, they retain trace-element patterns similar to those of the older volcanic-arc related granites, suggesting similar source regions for all these intrusions.

4) Feldspar porphyries represent the youngest known felsic intrusions along the eastern margin of the Holyrood Horst. There are two geochemically distinct porphyry phases; the Pastureland feldspar porphyry still retains an arc-related signature and is assumed to represent early intrusions of the feldspar porphyry. The Fowlers Road feldspar porphyry, which is assumed to have undergone crustal or parental magma contamination, displays more varied concentrations of the LILE and has a minor enrichment in Zr and Y with respect to the Pastureland feldspar porphyry. This modification in the trace-element pattern is unique to the feldspar porphyry and is not seen in the late-stage mafic intrusions of the Herring Cove Diorite or Beaver Hat Intrusive Suite. This may support crustal contamination as opposed to modification of the source region if both intrusive rocks are sourced from the same region.

5) Subaerial felsic volcanic rocks range in age from 730 to 584 Ma and display similar trace-element patterns, indicating prolonged magmatism from a similar source region. This similarity prohibits the segregation of units on the basis of geochemistry, placing increased reliance on geochronology and field relationships for identifying and separating the various units.

6) The felsic volcanic rocks throughout the region display similar geochemical characteristics to granitic rocks of the Holyrood Intrusive Suite. Previously published mapping, supported by precise geochronology (*e.g.*, Sparkes *et al.*, 2005), shows the intrusion to be basement to the volcanic rocks of the Manuels Volcanic Suite, not their magmatic roots. It is possible that the Holyrood Intrusive Suite, however, may be coeval and comagmatic with the White Mountain Volcanic Suite.

7) Mafic volcanic rocks of the Wych Hazel Pond and Horse Cove complexes display geochemical differences that are interpreted to represent changes within the tectonic environment. The epidote-rich mafic volcanic rocks predominantly plot within the fields of within-plate basalt and within-plate tholeiite/volcanic-arc basalt of Pearce and Norry (1979) and Meschede (1986), respectively. These volcanic rocks are assumed

to have formed early in basin development and still display more significant crustal interaction in contrast to the hematite-rich unit. The hematite-rich unit generally plots within the fields of mid-ocean ridge basalt and N-type MORB/volcanic-arc basalt of Pearce and Norry (1979) and Meschede (1986), respectively. As the hematite-rich unit is interpreted to form later than the epidote-rich unit, this change in geochemistry may reflect further basin development and the transition to a back-arc setting.

ACKNOWLEDGMENTS

The geochemistry reported here draws from a variety of recent and ongoing investigations by the Geological Survey of Newfoundland and Labrador into the late Neoproterozoic stratigraphy and associated mineralization along the eastern margin of the Holyrood Horst. The authors acknowledge the important contributions made by B. Dubé of the Geological Survey of Canada to early stages of the investigation of the Neoproterozoic epithermal systems, which was focused on the Manuels area, west of the Topsail Fault. Major and ICP trace-element data were provided by C. Finch and colleagues at the Geological Survey's geochemical laboratory.

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