U–Pb GEOCHRONOLOGICAL CONSTRAINTS ON THE TIMING OF MAGMATISM, EPITHERMAL ALTERATION AND LOW-SULPHIDATION GOLD MINERALIZATION, EASTERN AVALON ZONE, NEWFOUNDLAND

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ABSTRACT

Contrasting high- and low-sulphidation epithermal systems of late Neoproterozoic age, identified by the mineral assemblages of pyrophyllite–diaspore and colloform–crustiform chalcedonic silica + adularia ± calcite, respectively, are well preserved adjacent to the eastern margin of the Holyrood Horst, in the eastern Avalon Zone. The epithermal systems occur in the composite, mainly felsic Manuels Volcanic Suite, which is overlain by siliciclastic sedimentary and associated mafic volcanic rocks of the Wych Hazel Pond Complex. New U–Pb zircon ages from these units and from spatially related intrusive rocks, coupled with new and previously described field relationships, provide new time constraints for the development of both the pyrophyllite–diaspore-bearing advanced argillic alteration and the precious-metal-bearing, low-sulphidation veining. Together, these data also provide new insight into the regional distribution of disparate ca. 580 Ma and ca. 620 Ma elements of the eastern Holyrood Horst, and further define the nature of their boundary.

The age of the volcanic host to the largest zone of pyrophyllite–diaspore alteration, established in earlier stages of this investigation, is now precisely defined at 584 ± 1 Ma. The basal sedimentary rocks of the Wych Hazel Pond Complex that overlie and contain detritus from the high-sulphidation alteration in the Oval Pit mine, contain pumiceous tuff beds that are now dated at 582 ± 1.5 Ma. Together, these data constrain the formation, uplift and erosion of the high-sulphidation alteration to a period from 585 to 580.5 Ma.

A lower time limit for the development of the low-sulphidation system is provided by a U–Pb age from a crystal-rich ash flow of the Manuels Volcanic Suite that hosts colloform–crustiform-banded, chalcedonic silica–adularia-bearing auriferous veins. The 582 ± 4 Ma maximum age for this unit, together with the Early Cambrian fossil age of the unconformably overlying Paleozoic cover sequence, provides an approximate time bracket between 586 and 541 Ma for the development of the low-sulphidation system.

A composite suite of locally altered, felsic to mafic intrusive rocks (White Hills Intrusive Suite) that lies adjacent to the altered and mineralized volcanic rocks has previously been considered as a possible source for the epithermal fluids responsible for the high-sulphidation alteration. New U–Pb ages from this suite coupled with new and existing field and geochemical data demonstrate that the intrusive rocks are significantly older than the alteration, and correlative with the larger Holyrood Intrusive Suite to the west.

New U–Pb data from a feldspar porphyry intrusive into Wych Hazel Pond Complex sedimentary rocks confirm the existence of a second, widespread, and significantly younger (post-Holyrood Intrusive Suite) magmatic event, establishing its age at 589 ± 7 Ma. The emplacement of the porphyry may be related to late stages of a magmatic event linked to the formation of the regional epithermal system. This younger unit is chemically distinct from the older (e.g., 620 Ma) porphyries, and may prove to have played an important role in the development of the low-sulphidation system as a heat source. The presence of such porphyries may be a regional indicator of other potential areas of similar epithermal mineralization.

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INTRODUCTION

Ancient metamorphosed analogues of modern mineralized epithermal systems are well-preserved hallmarks of Neoproterozoic magmatic arc development within the Avalonian and related accreted terranes of the Paleozoic Appalachian orogen (O'Brien *et al*.,1998; Dubé *et al*., 1998). Prospective tectono-magmatic environments for such epithermal systems are preserved in the late Neoproterozoic rocks of eastern and southern Newfoundland, and extensive, variously deformed epithermal and related magmatic Au ± Cu ± Ag systems have been documented there (e.g., O'Brien *et al*., 1998, 1999a,b; Dubé *et al*., 1998; Sparkes *et al*., 2002; Figure 1).

One such area of epithermal alteration and mineralization occurs in the Avalon Zone of the eastern Avalon Peninsula, along the eastern margin of a major late Neoproterozoic volcano-plutonic uplift, the Holyrood Horst. There, felsic volcanic and plutonic rocks host both high- and low-sulphidation alteration and mineralization in a 15-km-long belt, extending south from Conception Bay (Figure 1). Alteration minerals (pyrophyllite) associated with regional-scale, high-sulphidation-style advanced argillic alteration within this belt were discovered in the late 1800s and have been mined intermittently since that time (Buddington, 1916; Vhay, 1937; Papezik *et al*.,

Figure 1. *Regional geology of the Avalon Peninsula, showing hydrothermal alteration systems discussed in text; inset shows location of other examples of low- and high-sulphidation systems in Avalonian rocks.*

1978). It was much later that significant gold mineralization was first documented in the same area (Saunders, 1986). Subsequent studies have shown that gold occurs, with or without silver, mainly in hydrothermal veins and breccias of low-sulphidation epithermal origin, in several areas along the length of this belt (*see* reviews in O'Brien *et al*., 1998, 2001a). The region surrounding this low-sulphidation vein- and breccia-hosted gold mineralization is currently the focus of exploration by Rubicon Minerals Corporation.

This area presents the unique opportunity to study not only the nature and setting of a well-preserved example of late Neoproterozoic mineralized hydrothermal systems, but
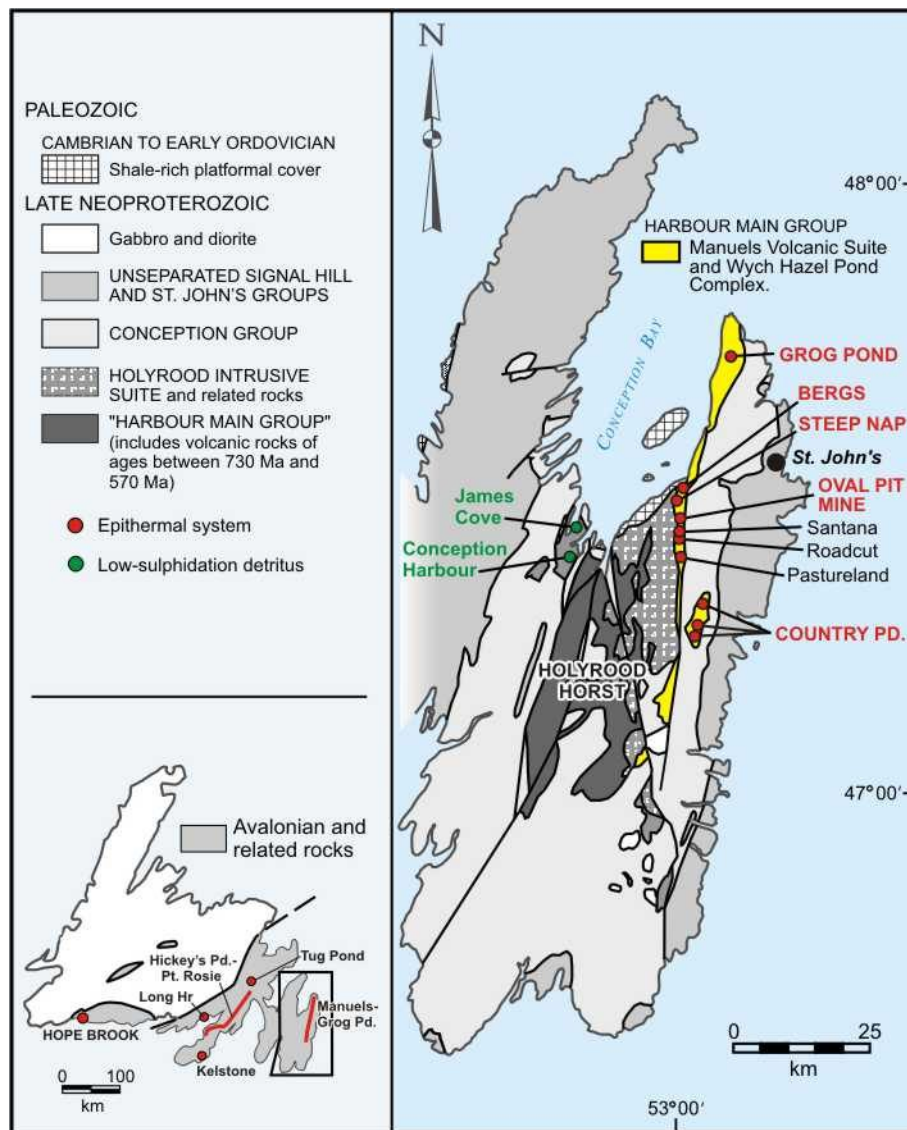
also the timing and relationships between spatially associated low- and high-sulphidation systems, which have been derived from chemically distinctive hydrothermal fluids at contrasting shallow crustal levels. The following account includes new data bearing on the genesis, timing and relationship of the contrasting low- and high-sulphidation systems, as well as the timing and nature of disparate pre- and syn-mineral magmatic events within and adjoining the alteration belt. This paper presents new and existing geochemical and geochronological data in the framework of both previously described and newly defined field relationships. These data augment the results of the authors' earlier work in this belt, presented elsewhere (O'Brien *et al*., 1998,

2001a,b; Mills *et al.*, 1999; Dubé *et al.*, 2001; Sparkes, 2002; O'Brien and Sparkes, 2004).

REGIONAL SETTING

The eastern part of the Avalon Peninsula is cored by a broad, north–south elongated, south-plunging uplift, the Holyrood Horst (McCartney, 1969; Figure 1). It is composed of late Neoproterozoic, primarily subaerial volcanic and supposedly co-genetic plutonic rocks that have historically been assigned to the Harbour Main Group and the Holyrood Intrusive Suite, respectively (McCartney, 1967; King, 1988a, 1990; Hayes and O'Driscoll, 1989, 1990; O'Brien and O'Driscoll, 1996; O'Brien *et al.*, 1997). These low-grade rocks, which characteristically lack penetrative deformation, have previously yielded a variety of late Neoproterozoic U–Pb zircon ages (Krogh *et al.*, 1988) between ca. 630 and 580 Ma. This volcano-plutonic core contains outliers of marine siliciclastic rocks and is flanked by a younger, shoaling-upward succession of marine, deltaic and fluviatile siliciclastic rocks (Conception, St. John's and Signal Hill groups, respectively; e.g., King, 1988a), concentrically disposed around the older succession. Tuff beds in the upper parts of this marine succession are dated at 565 Ma (G.R. Dunning, *in* King, 1988b). The oldest of the marine sedimentary rocks are locally intruded by felsic porphyry and dioritic to gabbroic plutons, spatially associated with the horst-bounding Topsail Fault. The late Neoproterozoic volcanic, plutonic and sedimentary rocks are overlain unconformably by a fossiliferous, primarily shale-rich, Cambrian to earliest Ordovician cover sequence.

EVOLUTION OF IDEAS AND HYPOTHESES

Early studies in this region attributed the regionally developed hydrothermal alteration to the emplacement of the Holyrood Intrusive Suite into the Harbour Main Group, where the latter was viewed as the coeval, lithologically diverse volcanic carapace to the former intrusions (e.g., Rose, 1952; McCartney, 1967, 1969; Hughes and Bruckner, 1971). More recent regional mapping and geochronological studies of the volcano-plutonic elements of the Holyrood Horst, however, have demonstrated the composite nature of the Harbour Main Group (*see* O'Brien *et al.*, 2001b). This work identified disparate volcanic successions, the formation of which was punctuated by both marine and terrestrial sedimentation, and by the emplacement, uplift and erosion of discrete intrusive suites of differing age and composition. The Neoproterozoic rocks are now described in a framework of seven lithostratigraphically and chrono-stratigraphically discrete units, that formed over a period of 160 million years (O'Brien *et al.*, 2001b).

Three of several fundamental points bearing on the timing and setting of mineralization were learned from the initial stages of our investigations (*see* O'Brien *et al.*, 1998, 2001b). The first showed that most of the magmatism recorded by the widespread granitic plutons and felsic volcanic rocks occurred between 625 and 620 Ma. The second was that the volcanic host to the high-sulphidation style alteration postdated the emplacement of these magmas by ca. 40 Ma. The third was that the high-sulphidation system was formed, then uplifted and eroded prior to the deposition of a younger Proterozoic mixed sequence of subaqeous sedimentary rocks and associated volcanic rocks of mainly mafic composition. Deformation occurred subsequent to this sedimentation, but prior to deposition of the Early Cambrian succession (cf. O'Brien, 2002).

These data precluded a direct genetic link between magmatism of the Holyrood Intrusive Suite and the epithermal alteration systems. In doing so, they highlighted our need to identify, 1) a stratigraphic or tectonic discontinuity between older plutons and younger volcanic rocks, 2) a stratigraphic or tectonic discontinuity between older and younger volcanic rocks, and 3) a heat source for the epithermal systems. The recognition of an unconformable relationship between the altered rocks and overlying, unaltered sedimentary succession (Wych Hazel Pond Complex), the presence of advanced argillic alteration as detritus in the cover, and the recognition of tuff beds within that succession, together provided a unique opportunity to establish the timing of the high-sulphidation system using U–Pb geochronology. As well, the presence of an extensively altered suite of monzonites, granites and porphyries along the margin of the alteration zone (lithologically different from the adjoining Holyrood Intrusive Suite) provided a hypothetical heat source for the younger epithermal alteration – and a hypothesis that can be tested by U–Pb geochronology. The discovery of exposures of low-sulphidation, vein-bearing, crystal-rich ash-flow tuff of felsic composition (Bergs Prospect; O'Brien, 2002) provided the first suitable mineralized rock unit for a U–Pb geochronological test of the maximum age of the low-sulphidation system. Finally, the recognition of the spatial association of syn-sedimentary porphyry intrusions within the Wych Hazel Pond Complex provided an opportunity to establish the timing of this magmatism and the age of the syn-plutonic sedimentary host rock.

PRINCIPAL DATED ELEMENTS OF THE EASTERN HOLYROOD HORST

The western part of the study area (Figure 2) is underlain by unaltered to extensively propylitized granite of the late Neoproterozoic Holyrood Intrusive Suite (King, 1990;
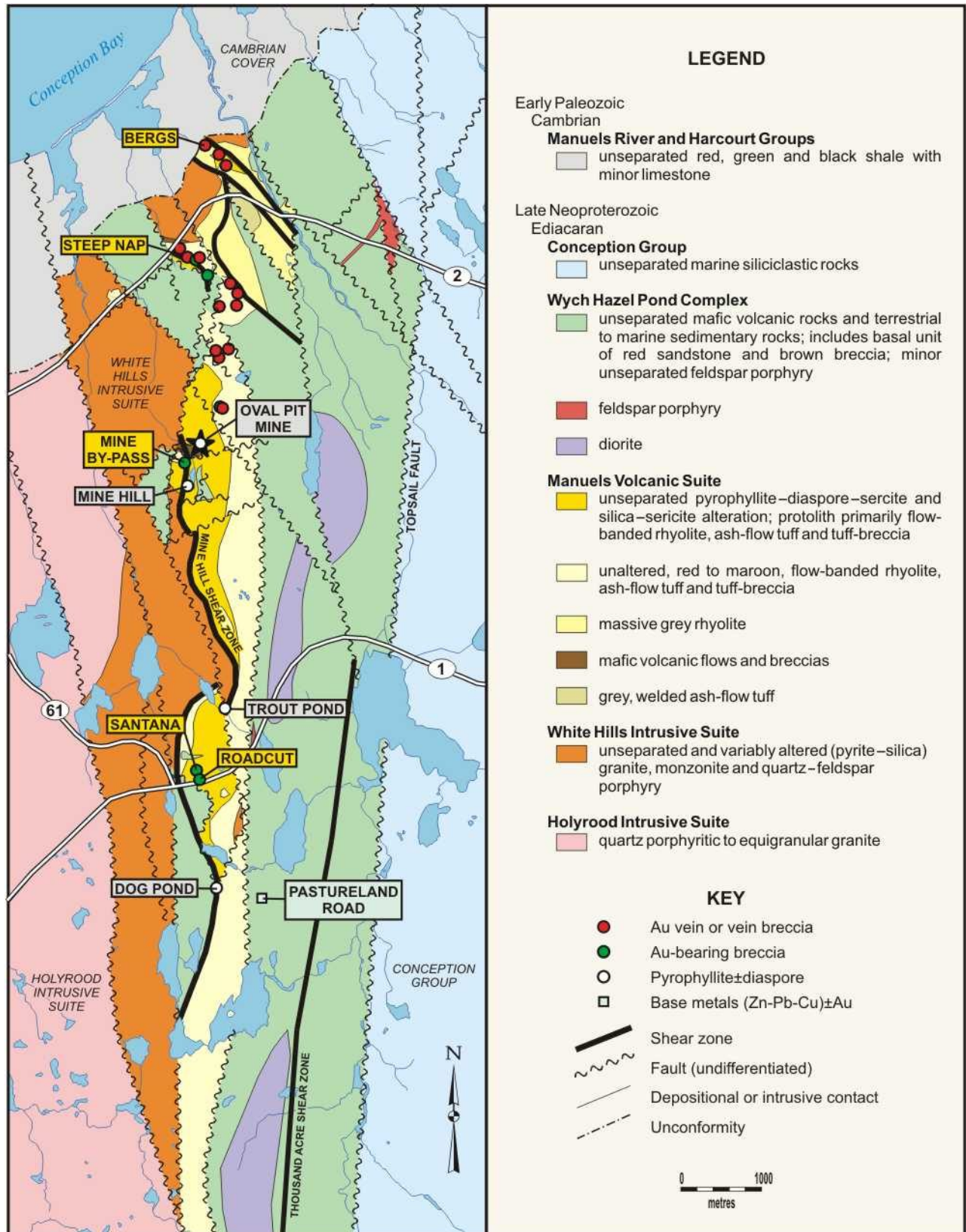
Figure 2. *Regional geology of the eastern side of the Holyrood Horst in the area between Conception Bay and the Thousand Acre Marsh.*

O'Brien *et al.,* 1997). Here, the granite is typically quartz porphyritic, locally has distinctive pink, white and green colouration due to pervasive chlorite–sericite–epidote alteration, and in many places is affected by tuffisite brecciation (O'Brien *et al.,* 2001b). The granite intrudes the Hawke Hills Tuff (O'Brien *et al.,* 2001b) to the west and south; its contact with the White Hills Intrusive Suite (Sparkes *et al.,* 2004) to the east is either a fault or an inferred intrusive contact. The White Hills Intrusive Suite is a composite suite of monzonite, porphyry and silica-altered pyritic granite, that displays significantly more lithologic diversity than the Holyrood Intrusive Suite. Plutonic rocks of similar texture and compositional range reappear on the opposing, western margin of the Holyrood Horst, where they are separable from the main 620-Ma granite lobe of the Holyrood Intrusive Suite (O'Brien *et al.,* 2001b).

Samples of granite and quartz–feldspar porphyry from the Holyrood and White Hills intrusive suites, respectively, have been selected for the geochronological study. The quartz–feldspar porphyry phase of the White Hills Intrusive Suite is intrusive into flow-banded rhyolite and lithic-rich volcaniclastic sequences that comprise a separate unit in what was earlier included in the previously unseparated Manuels Volcanic Suite (O'Brien *et al.,* 2001b). This volcanic unit is the oldest known host of the low-sulphidation auriferous, colloform–crustiform chalcedonic silica ± adularia veins.

The unseparated and variably altered Manuels Volcanic Suite (O'Brien *et al.,* 2001b) forms a north–south-trending belt between the White Hills Intrusive Suite to the west and the younger Wych Hazel Pond Complex to the east. It is characterized by aphyric and porphyritic rhyolite flows, lithic-rich tuffs and tuff breccias, and less extensive ash-flow tuffs. Two distinctive units from the suite have been selected for the geochronological study. The first is the flow-banded rhyolite that is host to the high-sulphidation alteration system (Oval Pit Mine); the second is unaltered dark red crystal-rich ash-flow tuff that is host to low-sulphidation stockwork style colloform–crustiform chalcedonic silica ± adularia veins (Bergs prospect).

Felsic volcanic rocks of the Manuels Volcanic Suite are unconformably overlain by subaerial to mainly subaqueous siliciclastic sedimentary rocks of the Wych Hazel Pond Complex (O'Brien *et al.,* 2001b). Conglomerate units near the base of the Wych Hazel Pond Complex contain clasts of pyrophyllite–diaspore-bearing advanced argillic alteration; boulder conglomerate at the contact is locally affected by silica–sericite–pyrite alteration (O'Brien *et al.,* 2001b). The basal conglomerate is in turn overlain by unaltered, interbedded red siltstone and sandstone that locally contain minor pumiceous tuff beds at several levels within the sequence; the lowest tuff bed has been selected for this geochronological study. The lower redbeds pass upward into green siliciclastic sedimentary rocks and subaqueous mafic flows and breccias.

In the eastern portion of the area, sedimentary rocks correlated with those unconformably overlying the Oval Pit Mine, are intruded by feldspar porphyry. Along its margins, the porphyry is brecciated; angular porphyry fragments are surrounded and supported by thermally metamorphosed sedimentary rocks that form the breccia matrix. This relationship implies the breccia formed as a result of porphyry emplacement into unconsolidated sediments. This intrusion represents the youngest dated intrusive event exposed within the area. Their relation to poorly exposed diorite intrusions emplaced into the Wych Hazel Pond Complex is unknown. Throughout most of the area, the Topsail Fault separates the Wych Hazel Pond Complex from the easterly adjacent Conception Group marine siliciclastic sedimentary rocks.

The Holyrood Intrusive Suite, the White Hills Intrusive Suite and the Manuels Volcanic Suite are all unconformably overlain by Lower and Middle Cambrian shales and minor limestones. Basal conglomerates of the Cambrian succession locally overlie the foliated Manuels Volcanic Suite and contain foliated clasts of advanced argillic alteration and clasts of banded chalcedonic silica that are readily matched with rocks found in the nearby high- and low-sulphidation systems, respectively (O'Brien, 2002). The same conglomerate unconformably overlies one of a series of major, early post-mineral structures that affects both the low- and high-sulphidation systems (O'Brien, 2002).

ALTERATION AND GOLD MINERALIZATION

Elements of the Manuels Volcanic Suite host well-preserved examples of both high-sulphidation and low-sulphidation hydrothermal systems (O'Brien *et al.,* 1998; Mills *et al.,* 1999; O'Brien, 2002). The presence of both styles of epithermal systems as detritus in unconformably overlying fossiliferous Lower Cambrian cover demonstrates their Proterozoic age.

Significant amounts of pyrophyllite–diaspore-bearing advanced argillic alteration occur in a number of areas, most notably Mine Hill, Oval Pit, Dog Pond and Trout Pond (Figure 2). The most extensive of these occurrences is the Oval Pit pyrophyllite mine, where approximately 1.5 mt of pyrophyllite-bearing ore have been produced; approximate reserve figures are in the order of 2.5 to 3 mt (*see* O'Brien *et al.,* 1998 and references therein). The best exposed sec-

tion through the advanced argillic zone is exposed in the Oval Pit Mine (Papezik and Keats, 1976; Hayes and O'Driscoll, 1990; Hayes, 1997; O'Brien *et al.*, 1998, 2001a). There, discrete subzones of argillic, advanced argillic and massive silica alteration have been identified, and are variably affected by weak- to medium-strain, inhomogeneous, post-alteration deformation (O'Brien *et al.*, 1998). In areas of lowest strain, well-preserved flow-banding and eutaxitic textures are preserved (O'Brien *et al.*, 1998). The advanced argillic alteration related to the high-sulphidation system at the Oval Pit Mine is characterized by the relatively high-temperature (250 to 300°C) assemblage pyrophyllite–sericite–diaspore–barite–rutile ± kaolinite.

Samples of altered ash flow and flow-banded rhyolite were collected from the open pit in order to establish a maximum or lower limit to the age of this alteration. The areas of argillic, advanced argillic and silica zones are typically barren at surface, except where are cut by at least two styles of gold-bearing breccia (<2g/t) of uncertain affinity (O'Brien *et al.*, 1998; Sparkes, 2002). Narrow, banded and massive chalcedonic silica veinlets locally cut the alteration and contain anomalous gold (≤1g/t).

The low-sulphidation system in the region includes colloform–crustiform vein and breccia complexes of variable strike lengths (up to 1500 m), having anomalous precious-metal contents and discrete zones of bonanza-grade gold at surface. Hematite, chlorite and illite are common alteration phases. Prospective, boiling-zone levels of the system are clearly preserved at both the Bergs (O'Brien, 2001) and Steep Nap (Mills *et al.*, 1999) prospects where auriferous veins contain crustiform- and colloform-banded chalcedonic silica, adularia, and bladed calcite pseudomorphed by silica. Multiple generations of hydrothermal breccia (pre-, syn- and post-mineral) are developed and contain variable gold grades. Locally, breccias are coincident with and related to veining; similar-style breccias occur south of Steep Nap where they cut silica-altered rhyolites on the margin of the advanced argillic alteration. Very fine-grained visible gold, in chalcedonic silica-white adularia bonanza-grade veins at the Bergs prospect, are crosscut by specular-hematite-breccia zones (O'Brien and Sparks, 2004). A sample of tuff that hosts gold-bearing, banded silica–adularia–hematite veins was collected at the Bergs prospect to test the maximum or older age limit of the low-sulphidation system.

At surface, Steep Nap veins are wider and more tightly constrained to steep northwest-trending structures than is the case at the Bergs prospect; in the latter case, the veins are significantly narrower and display multi-directional stockwork pattern. The absence of hematite-stained orange adularia (ubiquitous in banded Steep Nap veins) may imply slightly contrasting fluid compositions at Bergs, relative to

Steep Nap. Perhaps the most significantly unique aspect of the Bergs system is the presence of hydrothermal eruption breccias suggesting the preservation of paleo-surficial features (O'Brien and Sparkes, 2004). The existing data are insufficient to demonstrate whether or not the Steep Nap and Bergs veins systems are coeval.

U–Pb GEOCHRONOLOGY

INTRODUCTION

The following section draws together results derived from several separate stages of the geochronological investigations in the eastern side of the Holyrood Horst. Taken together, and integrated with field relationships from the authors' detailed- and regional-scale mapping, the data presented help bracket the age of both the high- and low-sulphidation systems and identify the existence (and distribution) of disparate ca. 625 to 620 Ma and ca. 580 Ma volcanic and intrusive rock successions within the region. The data includes that from the felsic volcanic succession that hosts the high-sulphidation style Oval Pit pyrophyllite mine, initially established by Ketchum (1998), and herein further refined. Also presented are hitherto unpublished data from the Holyrood Intrusive Suite granitic rocks near its contact with the White Hills Intrusive Suite. New ages, generated as part of the senior author's M.Sc. dissertation, include quartz–feldspar porphyry of the White Hills Intrusive Suite; crystal-rich ash-flow tuff (containing low-sulphidation veins) from the Manuels Volcanic Suite; pumiceous tuff from the base of the Wych Hazel Pond Complex; and feldspar porphyry that is intrusive into the complex.

All zircon samples were abraded prior to dissolution to reduce the effects of secondary lead loss. Samples were processed and analyzed at Memorial University using a Finnigan MAT 262V TI-mass spectrometer. The following discussion presents concordia diagrams only; full data tables are available from G.W. Sparkes (G.W. Sparkes, 2005, Memorial University of Newfoundland).

625 to 620 Ma MAGMATIC EVENT

Holyrood Intrusive Suite: Pink, White and Green Granite

The dated sample is a type example of the pink, white and green, propylitized eastern side of the main granitic lobe of the Holyrood Intrusive Suite. This part of the granite intrudes the Hawke Hills Tuff (O'Brien *et al.*, 2001b) to the west and south; its boundary with the White Hills Intrusive Suite to the east is a fault or inferred intrusive contact. The dated sample is a medium-grained, quartz-phyric, biotite–hornblende granite having extensive epidotized and sericit-

ized plagioclase; the sample was collected about 5.5 km southwest of the Oval Pit Mine.

Three multiple-grain zircon fractions of abraded, clear, euhedral prisms were analyzed. These fractions produced three points that are between 0.7% and 1.1% discordant. The weighted average of the $^{207}Pb/^{206}Pb$ ages of the three analyses is 622.5 ± 1.3 Ma at the 95% confidence interval (MSWD = 0.75; Figure 3). This age of 622.5 ± 1.3 Ma is coeval with other dated samples from within the Holyrood Intrusive Suite (Krogh *et al.*, 1988; Sparkes *et al.*, 2002).
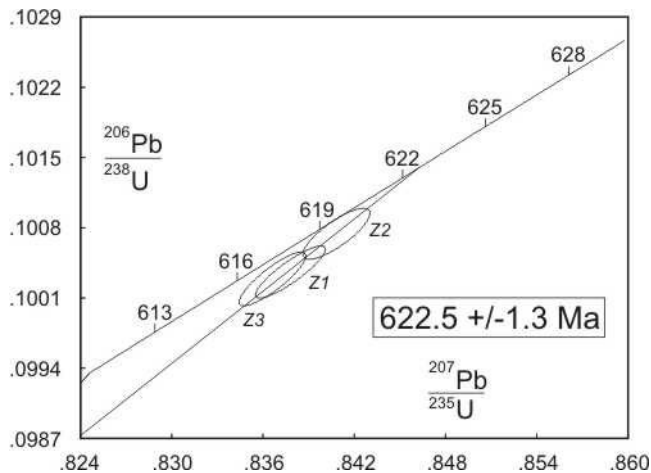
Figure 3. *Concordia diagram for the pink, white and green granite phase of the Holyrood Intrusive Suite.*

White Hills Intrusive Suite: Quartz–Feldspar Porphyry

The dated quartz–feldspar porphyry phase is the youngest of all component units of the White Hills Intrusive Suite. It contains 2- to 4-mm pale white plagioclase and pale pink K-feldspar crystals and 3- to 4-mm subrounded quartz crystals within a light purple aphanitic groundmass; the rock typically consists of 40 to 60 percent phenocrysts. The dated unit is intrusive into a volcaniclastic unit that contains fragments of earlier granitic and felsic porphyritic rocks, and that locally hosts banded, low-sulphidation, chalcedonic silica ± adularia veins.

The porphyry unit yielded abundant, predominantly clear, euhedral zircons, and a second more magnetic fraction of fractured, semi-clear prisms. Six analyses were carried out on clear, euhedral, abraded zircons; two analyses consisted of single grains (Z_1 and Z_2), three analyses consisted of two clear, euhedral, abraded grains (Z_3, Z_5 and Z_6) and one analysis consisted of four clear, euhedral abraded grains (Z_4). The resultant six analyses (between 2.3 to 5.7% discordant, Z_6 and Z_3 respectively) define a linear trend (Figure 4); analysis Z_1 is closest to concordia and analysis Z_3 is most
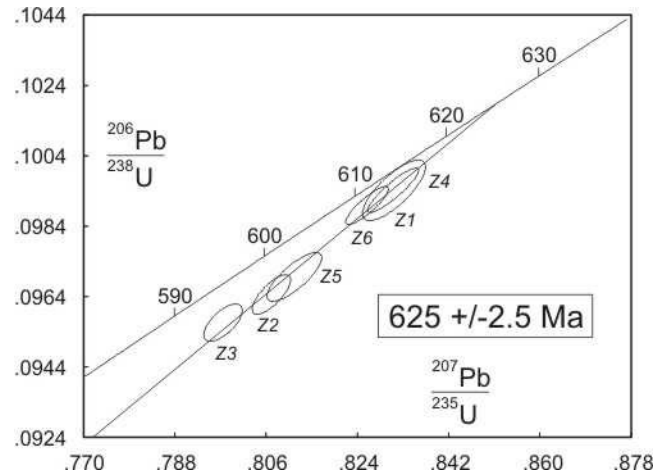

Figure 4. *Concordia diagram for the quartz–feldspar porphyry of the White Hills Intrusive Suite.*

discordant. The age of the porphyry is 625 ± 2.5 Ma, which is the weighted average of the $^{207}Pb/^{206}Pb$ ages of all six analyses (95% confidence interval, MSWD=1.0).

585 Ma AND YOUNGER MAGMATIC EVENTS

Oval Pit Mine: Felsic Volcanic Succession

The dated felsic volcanic rock, part of the Manuels Volcanic Suite, was collected from the core of an advanced argillic (pyrophyllite–diaspore) alteration zone associated with the high-sulphidation system in the Oval Pit Mine. Two samples were collected for dating from the open pit: the first was collected from a zone of pyrophyllite–diaspore alteration (SJOB-97-GC-1). The second sample was representative of low-strain and less altered material in which relic flow banding and pumice fragments are well preserved (SJOB-GC-97-2).

Sample SJOB-97-GC-1 contained abundant small to large clear, euhedral prisms that have minor cracks and inclusions. Three multiple-grain zircon fractions were analyzed for sample SJOB-97-GC-1. The most recent fraction, Z_3, analyzed in 2002, consisted of 6 large clear, euhedral prisms and produced a concordant point at 582 Ma (Figure 5). The two remaining fractions Z_1 and Z_2 (analyzed in 1998) both consisted of 16 abraded, clear, euhedral zircons, and produced points that are displaced to the right of Z_3, due to their higher proportion of common lead. Also plotted are two analyses from SJOB-97-GC-2, which contained zircons of similar morphology to those in SJOB-97-GC-1. Two fractions, Z_{1-2} and Z_{2-2}, consisting of 24 and 23 grains respectively, produced two concordant points. All five analyses have $^{206}Pb/^{238}U$ ages in the range of 582 to 585 Ma, and the weighted average of these yields an age of 584 ± 1Ma at the 95% confidence interval (Figure 5). This age provides the lower age limit to the high-sulphidation alteration.
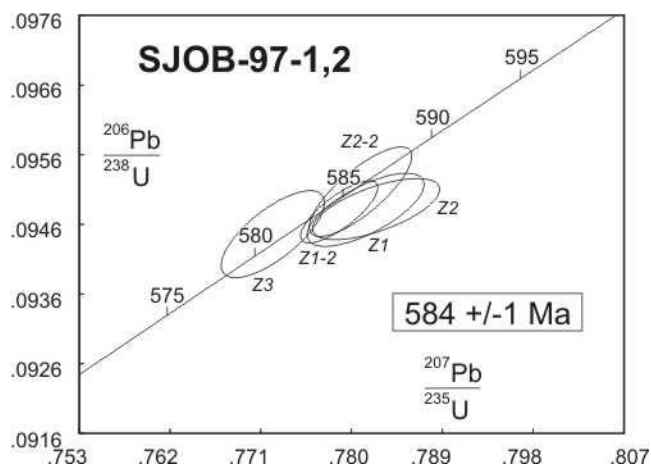
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Figure 5. *Concordia diagram for felsic volcanic rocks that host the Oval Pit Mine advanced argillic alteration. The diagram includes two samples of the Manuels Volcanic Suite, both of which were collected within the open pit of the Oval Pit Mine.*

Figure 6. *Concordia diagram for the Bergs crystal-rich ash-flow tuff, Manuels Volcanic Suite. The 582 ± 4 Ma age is from the weighted average (95% C.I.) of Z_5 ($^{206}Pb/^{238}U$ age: 583 ± 5 Ma), Z_6 ($^{206}Pb/^{238}U$ age: 582.5 ± 8 Ma) and Z_7 ($^{206}Pb/^{238}U$ age: 575.5 ± 11 Ma).*

Bergs Prospect: Crystal-rich Ash-flow Tuff

The dated crystal-rich ash-flow tuff is an areally restricted unit in the northeastern portion of Figure 2, which is host to abundant stockwork type, banded chalcedonic silica ± adularia veins and associated hydrothermal brecciation. This ash-flow tuff contains pale white 1- to 2-mm crystals and crystal fragments within a dark red hematite-rich groundmass.

The unit provided a very poor zircon yield with euhedral to subrounded grains, indicative of a potentially mixed-age population, resulting from the presence of detrital zircon. In total, seven fractions were analyzed. Three analyses of the largest, clear, euhedral single grains (Z_5, Z_6, Z_7) provide the maximum age and possibly the eruption age of the ash-flow tuff, at 582 ± 4 Ma (Figure 6). Z_5 and Z_6 have very low concentrations of ^{207}Pb, which accounts for the wide ellipses along the $^{207}Pb/^{235}U$ axis, and Z_7 has a higher concentration of common Pb, accounting for the larger ellipse. This age is calculated from the weighted average of the $^{206}Pb/^{238}U$ ages of Z_5, Z_6 and Z_7 and either represents the youngest age of detrital zircon present within the sample, or the actual eruption age of the ash-flow unit. Another concordant analysis consists of two large, clear, euhedral, abraded zircons, which produces a point with a $^{207}Pb/^{206}Pb$ age of 568 Ma, and a $^{206}Pb/^{238}U$ age of 562 Ma (Z_1: 1.1% discordant). This analysis potentially reflects the eruption age of the ash-flow tuff, however it has not been reproduced, and thus is currently not incorporated into the age determination for this unit. Analyses Z_2, Z_3 and Z_4, which consist of two small grains, four small grains and three small grains
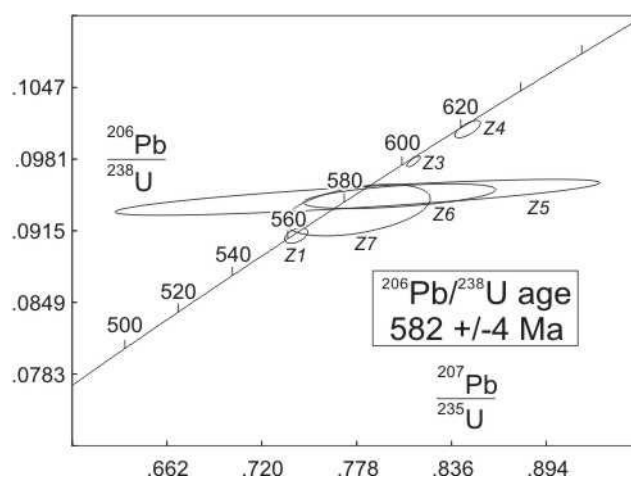
respectively, are 1.7 to 7.5% discordant. As these analyses did not contain any visible cores they are presumed to represent a detrital component within the ash-flow.

Post-alteration Pumiceous Tuff

The dated pumiceous tuff is interbedded with siltstone and pebble conglomerates of the lower Wych Hazel Pond Complex (containing eroded detritus of advanced argillic alteration associated with the high-sulphidation system) and overlies a boulder conglomerate at the base of the sedimentary succession. This boulder conglomerate has undergone silica–sericite alteration associated with what is assumed to be late-stage advanced argillic alteration.

This unit produced two distinct zircon populations, one consisting of moderately abundant, large, clear euhedral zircons, and a second population of abundant, small, clear, euhedral zircon prisms. Four fractions consisting of 8, 10, 16 and 14 abraded zircons respectively, from the second, more abundant population, produced a cluster of points near concordia at 583 Ma. The weighted average of $^{206}Pb/^{238}U$ ages for Z_5, Z_6 and Z_7 gives an age of 582 ± 1.5 Ma (95% C.I., MSWD = 0.20; Figure 7). This is interpreted to be the age of eruption of this tuff unit. The remaining analyses (Z_1, Z_2, Z_3), which are discordant, are single grains from the larger, less abundant zircon population. These grains, as indicated by the older ages, likely represent a detrital component contained within the tuff bed. Analysis Z_8 is a multiple-grain analysis from the second population; this point is slightly displaced to the right, which may imply that the analysis also included an older grain with the younger zircon population.
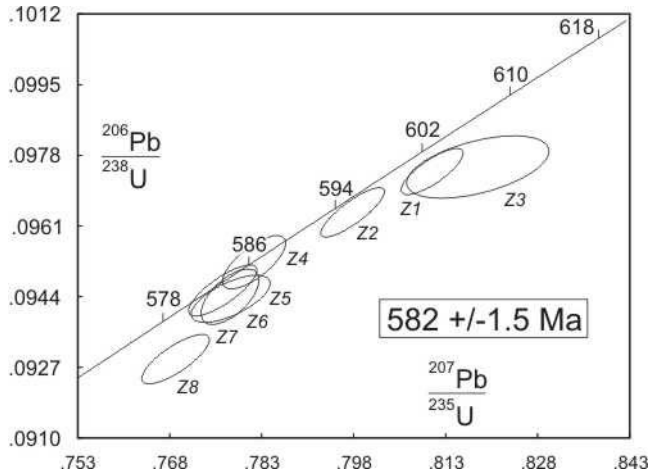
Figure 7. *Concordia diagram for unaltered pumiceous tuff (Wych Hazel Pond Complex), unconformably above high-sulphidation-style advanced argillic alteration.*

Figure 8. *Concordia diagram for feldspar porphyry of the Wych Hazel Pond Complex.*

Wych Hazel Pond Complex: Feldspar Porphyry

The dated feldspar porphyry is predominantly confined to the northeastern portion of the map area, in the area east of Manuels River (Figure 2). The porphyry contains subhedral to euhedral white plagioclase phenocrysts (1 to 2 mm in length), within a fine-grained, dark purple to pale grey groundmass. This unit intrudes and brecciates into thin- to medium-bedded, fine-grained, green siltstone of the Wych Hazel Pond Complex.

The sample produced abundant, clear, euhedral zircons from which three fractions were analyzed. One analysis consisted of two large, clear, euhedral grains (Z_3), while the other two samples consisted of four clear, euhedral grains (Z_1 and Z_2; Figure 8). Analyses Z_1 through Z_3 define a line, with Z_1 being most discordant (4%) and Z_2 being the least (2.4%). The weighted average of the ^{207}Pb/^{206}Pb ages at the 95% confidence level gives a preliminary age of 589 ± 7 Ma (MSWD = 0.72).

DISCUSSION

TIMING OF ALTERATION AND MINERALIZATION

The maximum age of the pyrophyllite–diaspore-bearing advanced argillic alteration of the high-sulphidation epithermal system is provided by the 584 ± 1 Ma U–Pb age of the host rhyolite and ash-flow succession. Clear field relationships in the Oval Pit area prove that overlying late Neoproterozoic sedimentary rocks of the Wych Hazel Pond Complex unconformably overlie and erode the main high-sulphidation alteration zone. The new 582 ± 1.5 Ma U–Pb age of pumiceous tuff beds near the base of the overlying sedimentary succession in the Oval Pit Mine provides a min-
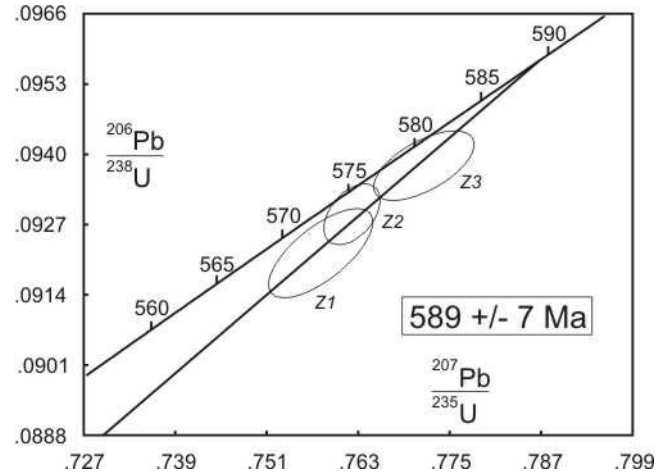
imum age for the high-sulphidation system. Furthermore, it indicates that volcanism, advanced argillic alteration and sedimentation occur within a narrow time frame between approximately 585 and 580.5 Ma (within analytical error). The mineralogy of the alteration (pyrophyllite–diaspore) typically implies depths of formation of approximately 1 to 1.5 km, thus the data require rapid uplift and erosion. Subsequent sedimentation records the collapse and rapid submersion of the alteration system, immediately after uplift (O'Brien *et al.*, 2001b). This extension is also recorded by the emplacement of alkalic to weakly subalkalic dykes at this time (G.W. Sparkes, unpublished data, 2004).

The youngest precisely defined lower limit for the timing of low-sulphidation veining and brecciation is the 582 ± 4 Ma age of red, crystal-rich ash-flow tuff at the Bergs prospect. The upper limit for the age of the low-sulphidation system is provided by the Early Cambrian fossils from the early Paleozoic, platformal sedimentary cover that contains clasts of the underlying low-sulphidation vein material. Results of ^{40}Ar–^{40}Ar dating of adularia from the Steep Nap vein system are pending and may yet provide a younger limit for the low-sulphidation system in that area.

TIMING OF MAGMATIC EVENTS

The new geochronological data indicate that remnants of the 584 Ma volcanic field are less extensive in this area than first envisaged. Rhyolitic rocks previously assigned to the 584 Ma sequence are intruded by quartz–feldspar porphyry, monzonite and granite of the White Hills Intrusive Suite along the western margin of the 15-km-long alteration belt. The new U–Pb data now bracket the emplacement of this suite between ca. 625 and 620 Ma. The field relationship and geochronological data thus demonstrate the pre-620 Ma age of much of the volcanic succession in this area,

including the host rocks to some or all of the Steep Nap vein system. Therefore, the Manuels Volcanic Suite (as shown on Figure 2) is a composite unit, having an age range of at least 40 Ma. These data also argue for correlation of the White Hills Intrusive Suite with the principal granite phases of the Holyrood Intrusive Suite that occupy the central core of the Holyrood Horst to the west (*see below*) and also require an alternate magmatic heat source for the ca. 585 Ma alteration.

The data from the Wych Hazel Pond Complex porphyry place an absolute age on younger plutons that have been emplaced into sediments correlated with those overlying the high-sulphidation system at Manuels. At least some of the intrusions related to this younger magmatic event are, on the regional scale of the eastern Holyrood Horst, focused along zones of late Neoproterozoic strain that locally merge with the younger, post-Cambrian Topsail Fault. This younger magmatism is coeval with the eruption of the Bergs tuff and potentially linked to the development of the low-sulphidation system.

GEOCHEMICAL SEPARATION OF THE 620 AND 580 Ma INTRUSIVE ROCKS

Representative geochemical data from intrusive rocks along the eastern side of the Holyrood Horst reveal distinct chemical similarities and differences that support the corre-lation and separation of magmatic events as defined by map-ping and geochronology. The following discussion is restricted to the presentation of some diagnostic features that may be used to identify similar, undated rocks else-where. A presentation and discussion of the full major- and trace-element geochemical dataset is available from the sen-ior author.

The 589 ± 7 Ma porphyry in the Wych Hazel Pond Complex is characterized by depletion in Sr and enrich-ments in Nb, Zr, Dy and Y in comparison to the older quartz–feldspar porphyry of the White Hills Intrusive Suite (Figure 9). The separation of younger and older intrusions is clear on the tectonic plot of Pearce *et al.* (1984; Figure 10), which further points to their contrasting origins in separate tectonic environments. This contrast is also supported by field evidence. The White Hills Intrusive Suite clearly intrudes subaerial volcanic rocks of the previously unsepa-rated Manuels Volcanic Suite (Harbour Main Group), but it has not intruded sediments overlying that suite. The 589 ± 7 Ma porphyry, in contrast, intrudes much younger siliciclas-tic sedimentary rocks of the Wych Hazel Pond Complex that were deposited in subaqueous conditions, and unconsolidat-ed at the time of intrusion. In addition, the sedimentary rocks contain eroded clasts of earlier granitic rocks similar to those in the White Hills and Holyrood intrusive suites.

The correlation of the coeval White Hills and Holyrood intrusive suites is further supported by the geochemical data. The similar geochemical nature of the two is reflected in the Nb–Y plot of Pearce *et al.*, 1984 (Figure 11), which displays an overall tight and overlapping grouping of the data from both intrusive suites. Furthermore, the granitic rocks of both intrusive suites are subalkalic and calcalkalic, and fall with-in the peraluminous field of Maniar and Piccoli (1989; Fig-ure 12).

FURTHER LOCAL AND REGIONAL IMPLICA-TIONS

At the Bergs and Steep Nap prospects, banded low-sul-phidation veins occur in proximity to, 1) a hybrid suite of variably silica-altered and pyritic granites, 2) the base of overlying late Neoproterozoic cover successions, and 3) zones of relatively high strain in sericite–silica alteration. New data suggest that the spatially associated granites of the White Hill Intrusive Suite are significantly older (ca. 40 Ma) than the established lower limit of the low-sulphidation veins. The presence of the older magmatic rocks as a base-ment feature along the margin of the Holyrood Horst may influence siting of not only the high-sulphidation system and later Neoproterozoic strain, but also the low-sulphida-tion veins. Similar granites have been mapped up to and beyond (east of) the Topsail Fault, where they can be readi-ly separated from a regionally extensive composite suite of younger mafic to intermediate intrusions (G.W. Sparks and S.J. O'Brien, unpublished data, 2004).

The Mine Hill shear zone (Figure 2) is one of several important regional Neoproterozoic structures in this area (Figure 2). Along much of its length, it defines the tectonic boundary between the 584 Ma volcanic suite and the older (625 to 620 Ma or earlier) volcano-plutonic arc succession. This broad shear zone has been mapped regionally, and affects several of the unseparated elements of the Manuels Volcanic Suite as well as the overlying Wych Hazel Pond Complex. The shear zone also marks the eastern limit of the older volcanic and plutonic rocks in the area west of the Topsail Fault, and thus coincides with a boundary that may have played a role in siting the epithermal systems. Defor-mation along this structure affects sedimentary rocks that overlie (and erode) the high-sulphidation alteration, sug-gesting more than one episode of Proterozoic fault move-ment. Similar shear zones located to the north of this are preserved unconformably beneath fossiliferous Cambrian cover, and shed detritus into the basal conglomerate of the cover sequence (O'Brien, 2002).

Volcanic rocks of broadly similar age to those hosting both the Bergs and Steep Nap systems, reappear on the west-
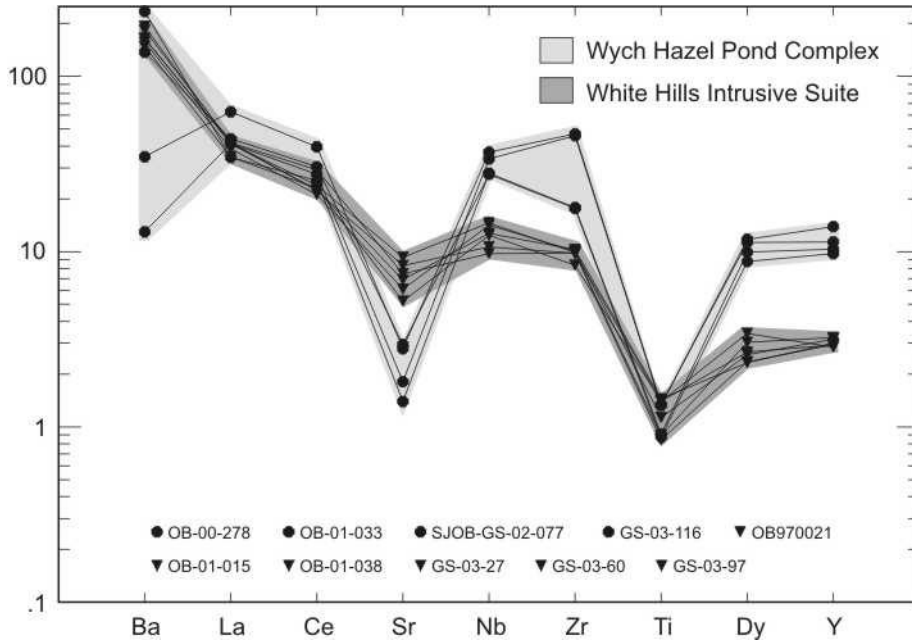
Figure 9. *Chondrite-normalized multi-element geochemical plots for the feldspar porphyry of the Wych Hazel Pond Complex and older quartz–feldspar porphyries of the White Hills Intrusive Suite.*
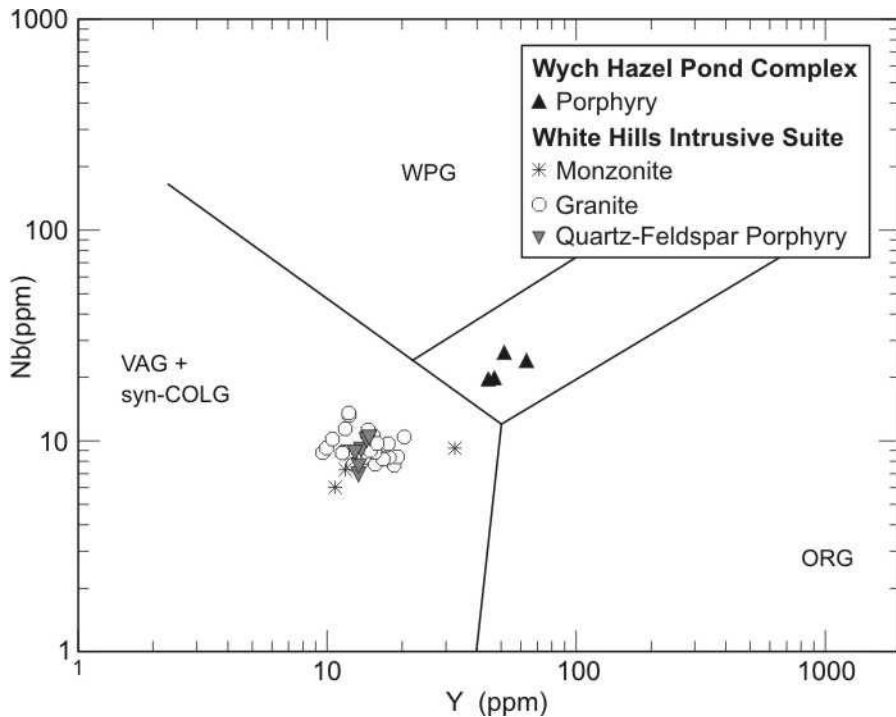

Figure 10. *Nb–Y tectonic discrimination diagram of Pearce* et al. *(1984) for intrusive rocks described in the text. WPG - within-plate granite; ORG - ocean-ridge granite; VAG - volcanic-arc granite; syn-COLG - syn-collisional granite.*

ern side of the Holyrood Horst, where they are locally affected by zones of relatively high-strain sericite–silica alteration. New and previously presented data from that area record late Neoproterozoic unroofing of chalcedonic-silica vein-lets (±adularia) and breccias of possible low-sulphidation affinity (O'Brien, 2001; Sparks *et al.*, 2004; Figure 1) having anomalous gold values up to 1.5 g/t. This material occurs as a small but significant component of the detritus in boulder conglomerates overlying (and possibly interbedded with) red rhyolites and ash flows along a major portion of the strike length of the 590 ± 2 Ma Peak Pond Tuff (O'Brien *et al.*, 2001b; G. Dunning, unpublished data, 2001). Significantly, this material is spatially associated with syn-sedimentary porphyry intrusions of the ca. 590 Ma Kitchuses porphyrites (O'Brien *et al.*, 2001b). The exact relationship of these units to low-sulphidation systems in the Manuels area is unclear at this time but the presence of such material could have significant regional implications, not only for exploration, but also for the number and timing of epithermal systems around the Holyrood Horst.

SUMMARY AND CONCLUSIONS

1) Both eastern and western margins of the Holyrood Horst have significant potential to host extensive, auriferous low-sulphidation epithermal vein systems. In both cases, the most prospective regions host major structural boundaries and/or locally preserved post-620 Ma Neoproterozoic porphyry intrusions.

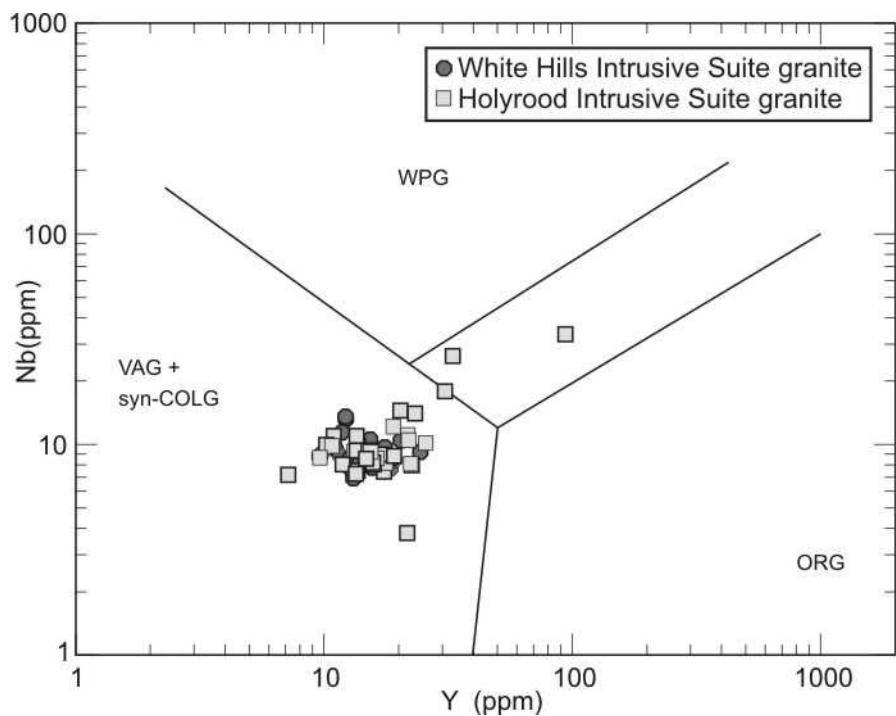2) The age of 622.5 ± 1.3 Ma for propylitically altered pink, white and green granite of the Holyrood Intru-

Figure 11. *Nb–Y tectonic discrimination diagram of Pearce* et al. *(1984), for granitic rocks of the Holyrood and White Hills intrusive suites. WPG - within-plate granite; ORG - ocean-ridge granite; VAG - volcanic-arc granite; syn-COLG - syn-collisional granite.*
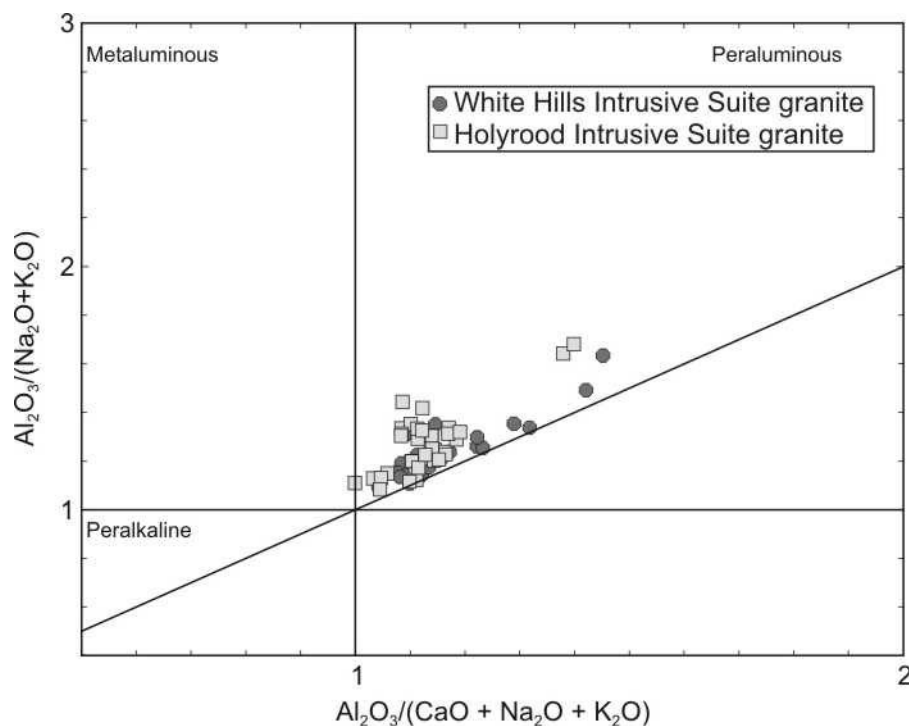

Figure 12. *Alumina saturation diagram of Maniar and Piccoli (1989) for granitic rocks of the Holyrood and White Hills intrusive suites, with limits for metaluminous, peraluminous and peralkaline fields.*

sive Suite is the same as that of granite phases elsewhere in the Holyrood Intrusive Suite, previously reported as 622 ± 2 Ma (B. Sparks *et al.*, 2002) and 620 ± 2 Ma (Krogh *et al.*, 1988). It represents the time of the principal episode of magmatism in that suite.

3)   The age of the White Hills Intrusive Suite has been determined as 625 ± 2.5 Ma. This suite is geochemically similar to, and coeval in age with the Holyrood Intrusive Suite, and hence correlated with it. Even though the White Hills Intrusive Suite is affected by extensive silica–pyrite–sericite alteration near the high- and low-sulphidation systems in nearby volcanic successions, its emplacement is not directly related to the development of either.

4)   The 584 ± 1 Ma U–Pb crystallization age for the Manuels Volcanic Suite in the area of the Oval Pit Mine provides a precise older limit for the timing of advanced argillic alteration associated with the regional high-sulphidation system. The intrusive relationships between newly dated 625 Ma White Hills Intrusive Suite and other parts of the Manuels Volcanic Suite, coupled with this 584 ± 1 Ma age, demonstrates the composite nature of the volcanic suite. This point is further demonstrated by the data from the unaltered Bergs tuff (582 ± 4 Ma).

5)   Termination of the high-sulphidation-style alteration is recorded by the deposition of subaerial to mainly subaqueous siliciclastic sedimentary rocks of the Wych Hazel Pond Complex, which unconformably overlie (and contain only undeformed clasts of) immediately underlying pyrophyllite–diaspore-bearing, advanced argillic alteration. The basal conglomerate of the complex is overlain by unaltered pumiceous tuff, herein dated at 582 ± 1.5 Ma. This age provides the lower age limit of the overlying sedimentary succession, and constrains the

formation, uplift and erosion of the high-sulphidation system to a period between 585 and 580.5 Ma. The age also provides an older limit for the regional (cleavage-forming) Neoproterozoic deformation.

6) The U–Pb data broadly constrains the time of formation of the low-sulphidation system between 586 and 541 Ma. Whether there were single or multiple pulses is unclear. The current interpretation of the geochronological data from the Bergs tuff places the crystallization age of the tuff at 582 ± 4 Ma, based on the weighted average of three analyses of single euhedral zircons, thus providing the youngest lower age limit for the low-sulphidation vein system. A single, slightly discordant point with a $^{206}Pb/^{238}U$ age of 562 Ma was not reproduced during subsequent analyses, but nonetheless remains problematic, and could potentially reflect a younger limit for the development of the low-sulphidation veins having significant regional ramifications.

7) Sedimentary rocks correlated with those overlying the high-sulphidation-style alteration are intruded by feldspar porphyry dated at 589 ± 7 Ma, representing the youngest dated intrusion within the region. These younger porphyries are chemically distinct from older, dated porphyries from the White Hills Intrusive Suite.

8) At this juncture, it is unclear what part, if any, of the alteration affecting the 625 to 620 Ma plutons along the eastern margin of the Holyrood Horst is related to the younger ca. 580 Ma hydrothermal event. The possibility cannot be ruled out that the alteration may be exclusively syn-magmatic and potentially related to the 620 Ma porphyry-style Cu–Au mineralization in the same age granite–porphyry at Butlers Pond, approximately 25 km farther south in the Holyrood Horst (Sparks *et al.*, 2002).

9) Both the high- and low-sulphidation systems occur in volcanic rocks that are broadly coeval with the epithermal systems. They also occur in significantly older volcanic and plutonic rocks that formed during or prior to the 625 to 620 Ma magmatic events. Thus, the presence of altered intrusive rocks within either of the epithermal systems need not imply deep erosion into that system.

10) The 585 to 580.5 Ma age bracket for the pyrophyllite–diaspore-bearing advanced argillic alteration requires a source of fluid and heat that is significantly younger than magmatic rocks (such as the White Hills and Holyrood intrusive suites) now occupying the eastern margin of the Holyrood Horst. Intrusions in the

Wych Hazel Pond Complex may represent the waning stages of such a magmatic event, although specific porphyries such as the one dated in this study, postdate uplift of the system. A source of heat and fluids has yet to be identified.

11) Available data are consistent with a model where the high-sulphidation system has been focused along (and above) a pre-existing structure coincident with the contact between the 625 to 620 Ma plutonic rocks and younger (ca. 580 Ma) volcanic suite. The boundary is now marked by the Mine Hill shear zone.

12) Current modeling for high- and low-sulphidation epithermal systems (e.g., Hedenquist *et al.*, 2000) would imply that the Oval Pit pyrophyllite–diaspore deposit and the Bergs–Steep Nap veins (adularia–calcite–chalcedonic silica) formed in contrasting environments at contrasting crustal levels. Thus, the observed proximity (1.5 km lateral distance) of these two types of systems in the eastern Holyrood Horst would require their original separation either in space or in time. Existing field and U–Pb geochronological data do not provide an accurate enough age separation to adequately explain the observed proximity of such contrasting low- and high-sulphidation epithermal systems. The possibility remains that the low-sulphidation colliform–crustiform veins and breccias represent a slightly younger (<1 Ma) telescoped, near-surface epithermal system overprinting a relatively deeper high-sulphidation system.

ACKNOWLEDGMENTS

REFERENCES

Buddington, A.F.
1916: Pyrophyllitization, pinitization and silicification of rocks around Conception Bay, Newfoundland. Journal of Geology, Volume 24, pages 130-152.

Dubé, B., Dunning, G. and Lauzière, K.
1998: Geology of the Hope Brook Mine, Newfoundland, Canada: a preserved Late Proterozoic high-sulphidation epithermal gold deposit and its implications for exploration. Economic Geology, Volume 93, pages 405-436.

Dubé, B., O'Brien, S.J., and Dunning, G.
2001: Gold deposits in deformed terranes: Examples of epithermal and quartz–carbonate shear zone-related gold systems in the Newfoundland Appalachians and their implications for exploration. North Atlantic Minerals Symposium 2001, Extended Abstract Volume, pages 31-35.

Finch, C.J.
1998: Inductively coupled plasma-emission spectrometry (ICP-ES) at the geochemical laboratory. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 98-1, pages 179-193.

Hayes, J.P.
1997: Geological setting and genesis of the eastern Avalon high-alumina belt. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, 172 pages.

Hayes, J.P. and O'Driscoll, C.F.
1989: The geology of the eastern Avalon high-alumina belt, Avalon Peninsula, Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey, Map 89-149.

1990: Regional setting and alteration within the eastern Avalon high-alumina belt, Avalon Peninsula, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 90-1, pages 145-155.

Hedenquist, J.W., Arribas, A.R. and Gonzales-Urien, E.
2000: Exploration for epithermal gold deposits. *In* Gold in 2000. *Edited by* S.G. Hagemann and P.E. Brown. Reviews in Economic Geology, Volume 13, 245-277.

Hughes, C.J. and Bruckner, W.D.
1971: Late Precambrian rocks of eastern Avalon Peninsula, Newfoundland - a volcanic island complex. Canadian Journal of Earth Sciences, Volume 8, pages 899-915.

Ketchum, J.
1998: Report on U–Pb geochronology of hydrothermally altered volcanic and plutonic rocks on the Burin and central Avalon peninsulas, Newfoundland. Unpublished report on geochronology contract for the Newfoundland Department of Mines and Energy, Geological Survey, 4 pages.

King, A.F.
1988a: Geology of the Avalon Peninsula, Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey, Map 88-01, scale 1:250 000.

1988b: Late Precambrian sedimentation and related orogenesis of the Avalon Peninsula, Eastern Avalon Zone. Geological Association of Canada–Mineralogical Association of Canada–Canadian Society of Petroleum Geologists, Annual Meeting, Trip A-4, Guidebook, St. John's, Newfoundland, 84 pages.

1990: Geology of the St. John's area. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-2, 88 pages.

Krogh, T.E., Strong, D.F., O'Brien, S.J. and Papezik, V.S.
1988: Precise U–Pb zircon dates from the Avalon Terrane in Newfoundland. Canadian Journal of Earth Sciences, Volume 25, pages 442-453.

Maniar, P.D. and Piccoli, P.M.
1989: Tectonic discrimination of granitoids, Geological Survey of America Bulletin, Volume 101, pages 635-643.

McCartney, W.D.
1967: Whitbourne map-area, Newfoundland. Geological Survey of Canada Memoir 341, 133 pages.

1969: Geology of Avalon Peninsula, southeast Newfoundland. American Association of Petroleum Geologists, Memoir 12, pages 115-129.

Mills, J., O'Brien, S.J., Dubé , B., Mason, R. and O'Driscoll, C.F.
1999: The Steep Nap Prospect: A low-sulphidation, gold-bearing epithermal vein system of Late Neoproterozoic age, Avalon Zone, Newfoundland Appalachians. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 99-1, pages 255-274.

O'Brien, S.J.
2001: Bedrock mapping and related studies of the central Avalon Peninsula (Avalon Zone) eastern Newfoundland. *In* Report of Activities for 2001. Newfoundland Department of Mines and Energy, Mines Branch, pages 20-22.

2002: A note on Neoproterozoic gold, early Paleozoic copper and basement–cover relationships on the margins of the Holyrood Horst, southeastern Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 02-1, pages 219-228.

O'Brien, S.J., Dubé, B., O'Driscoll, C.F.
1999a: Neoproterozoic epithermal gold–silver mineralization in the Newfoundland Avalonian belt. Geological Association of Canada, Mineral Deposits Section: Gangue Newsletter, Issue 62, pages 1-11.

1999b: High-sulphidation, epithermal-style hydrothermal systems in late Neoproterozoic Avalonian rocks on the Burin Peninsula, Newfoundland: Implications for gold exploration. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 99-1, pages 275-296.

2001a: Epithermal style hydrothermal systems in Late Neoproterozoic Avalonian rocks on the Avalon Peninsula, Newfoundland: Implications for Gold Exploration. Field Trip A-6 Guidebook, St. John's 2001 Joint Geological Association of Canada–Mineralogical Association of Canada Annual Meeting, 29 pages.

O'Brien, S.J., Dubé, B., O'Driscoll, C.F. and Mills, J.
1998: Geological setting of gold mineralization and related hydrothermal alteration in late Neoproterozoic (post-640Ma) Avalonian rocks of Newfoundland, with a review of coeval gold deposits elsewhere in the Appalachian Avalonian belt. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 98-1, pages 93-124.

O'Brien, S.J., Dunning, G., Dubé, B., O'Driscoll, C.F., Sparks, B., Israel, S. and Ketchum, J.
2001b: New insights into the Neoproterozoic geology of the central Avalon Peninsula (NTS map areas 1N/6, 1N/7 and 1N/3), eastern Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 01-1, pages 169-189.

O'Brien, S.J., King, A.F. and O'Driscoll, C.F.
1997: Late Neoproterozoic geology of the central Avalon Peninsula, Newfoundland, with an overview of mineralization and hydrothermal alteration. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 97-1, pages 257-282.

O'Brien, S.J. and O'Driscoll, C.F.
1996: Preliminary investigation of Neoproterozoic (Avalonian) rocks, northeastern Holyrood (NTS 1N/6) map area: notes on geology, mineralization and mineral exploration potential. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 97-1, pages 311-327.

O'Brien, S. and Sparks, G.
2004: Bonanza-grade gold from Neoproterozoic low-sulphidation epithermal veins and breccias, Bergs Prospect, Avalon Zone, eastern Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey, Open File 001N/10/0742.

Papezik, V.S. and Keats, H.F.
1976: Diaspore in a pyrophyllite deposit on the Avalon Peninsula, Newfoundland. Canadian Mineralogist, Volume 14, pages 442-449.

Papezik, V. S., Keats, H.F. and Vahtra, J.
1978: Geology of the Foxtrap pyrophyllite deposit, Avalon Peninsula, Newfoundland. Canadian Institute of Mining and Metallurgy Bulletin, Volume 71, pages 152-160.

Pearce, J.A., Harris, N.B.W. and Tindle, A.G.
1984: Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology, Volume 25, pages 956-983.

Rose, E.R.
1952: Torbay map area, Newfoundland. Geological Survey of Canada, Memoir 265, 64 pages.

Saunders, P.
1986: Geological and rock geochemical surveys on the Foxtrap claims, Newfoundland, licence 2551, 2557, October 1985 to January 1986. Apex Geological Consultants Ltd, unpublished report [001N/07/468].

Sparkes, B.A., O'Brien, S.J., Wilson, M.R. and Dunning, G.R.
2002: The geological setting, geochemistry and age of late Proterozoic intrusive rocks at the Butlers Pond Cu–Au prospect (NTS 1N/3), Avalon Peninsula, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 02-1, pages 245-264.

Sparkes, G.
  2002: A comparison of the Mine By-Pass and Roadcut prospects: two areas of breccia-hosted gold mineralization, Eastern Avalon Zone, Newfoundland. Unpublished B.Sc. (Honours) thesis, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, 90 pages and 2 appendices.

Sparkes, G., O'Brien, S.J. and Dunning, G.R.
  2004: The setting and timing of epithermal alteration and gold mineralization in the eastern Avalon Zone: an update. *In* Report of Activities for 2004. Newfoundland Department of Natural Resources, Mines Branch, pages 24-26.

Sun, S.S. and McDonough, W.F.
  1989: Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *In* Magmatism in the Ocean Basins. Geological Society, Special Publication 42, pages 313-345.

Vhay, J.S.
  1937: Pyrophyllite deposits of Manuels, Conception Bay, Newfoundland. Department of Natural Resources, Geological Section, Bulletin Number 7, 33 pages.