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NEW INSIGHTS INTO THE NEOPROTEROZOIC GEOLOGY OF THE CENTRAL AVALON PENINSULA (PARTS OF NTS MAP AREAS 1N/6, 1N/7 and 1N/3), EASTERN NEWFOUNDLAND

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ABSTRACT

New mapping and geochronological studies of the central Avalon Peninsula reveal a geological record of protracted and episodic volcanicity, having varied composition, lithofacies, and depositional environments, spanning a period of 160 Ma in the late Neoproterozoic. Deposition of these disparate volcanic successions was punctuated by both marine and terrestrial sedimentation, and by the emplacement, uplift and erosion of intrusive suites of differing age and composition. The new data clearly demonstrate, for the first time, that volcanic rocks previously included within the Harbour Main Group cannot be categorized as a single lithostratigraphic unit of group status. These Neoproterozoic rocks are described below in a framework of six lithostratigraphically and chrono-stratigraphically discrete units that can be mapped on a regional scale. A seventh volcanic unit occurs east of the Topsail Fault and is in part coeval with the youngest (ca. 585 Ma) subaerial volcanism west of this structure. Several contrasting ages, settings and styles of volcanic-hosted mineralization are preserved; these include volcanic-redbed copper, VMS-style zinc–lead–copper, and high- and low-sulphidation styles of precious metals.

The new data also document a plutonic history that is complex, protracted and metallogenically important, especially vis-a-vis *porphyry-style copper–gold mineralization. Several chronologically disparate, lithologically distinctive plutons have been mapped within the Holyrood Intrusive Suite. Additional subdivision and reassignment of rocks historically grouped within this suite likely will be required, as further geochemical and geochronological information becomes available.*

Three separate ages of Neoproterozoic marine sedimentation have been identified. The oldest siliciclastic rocks lie unconformably on pre-640 Ma volcanic successions in the central Holyrood Horst, and contain ca. 620 Ma tuff beds. The earlier of two periods of post-585-Ma marine sedimentation records the initial submergence of the epithermally altered rocks along the east side of the Holyrood Horst, and was accompanied by submarine mafic volcanicity, the emplacement of intermediate hypabyssal intrusions, and the formation of VMS-style mineralization. Younger marine siliciclastic sequences, such as those found east of the Topsail Fault, typically lack intercalated volcanic rocks, and lie in stratigraphic continuity with the 565 Ma, Ediacaran-bearing strata of the upper Conception Group.

INTRODUCTION

Most published syntheses of the Avalonian rocks of the Appalachian–Caledonide system regard the Avalon Peninsula of southeastern Newfoundland as the type area for this orogen-scale Neoproterozoic belt. The geological evolution of the well-exposed central core of the peninsula has typically been described within the context of a regionally tripartite, late Neoproterozoic stratigraphic framework, comprising:

i) at the base, a lithologically complex but stratigraphically coherent sequence of volcanic rocks, intruded by
ii) a coeval plutonic suite, occurring with the volcanic rocks in the core of a central, fault-bounded horst, which is flanked by
iii) a younger, shoaling-upward sedimentary succession of marine turbidites, deltatic shales and terrestrial siliciclastic sedimentary rocks (e.g., McCartney, 1969; Williams and King, 1979; King, 1988a, 1990; O'Brien *et al.*, 1990).

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This relatively simple framework contrasts with that documented farther west in the Newfoundland Avalon Zone, where recent stratigraphic and geochronological studies demonstrate protracted geological histories, marked by multiple cycles of magmatism and sedimentation in the late Proterozoic (e.g., O'Brien *et al.*, 1995, 1996). The apparent west-to-east contrast impacts not only on stratigraphic and metallogenic correlations across the Avalon Zone but also on models of the overall polarity of Avalonian magmatic arcs, and the tectonic development of the larger Avalonian belt.

PREVIOUS INTERPRETATIONS

In previous accounts, all Proterozoic volcanic rocks in the east-central Avalon Peninsula region, irrespective of age, facies or external contacts, are historically grouped together and designated as a single stratigraphic unit, the Harbour Main Group of Rose (1952). In a similar way, marine sedimentary strata flanking the Holyrood Horst[6], together with those in folded outliers within the horst, have been correlated and assigned to the Conception Group (Rose, 1952). Plutonic rocks are likewise bundled into an expansive unit of primarily felsic composition, variously designated as the Holyrood Batholith (Rose, 1952), Holyrood Plutonic Series (McCartney, 1967) or Holyrood Intrusive Suite (King, 1988a). Previously published U–Pb geochronology has been used to argue that much or most of this volcanic and plutonic activity is broadly coeval, at about 620 Ma (e.g., Krogh *et al.*, 1988), despite the existence within the Holyrood Horst of Proterozoic ages as young as ca. 585 Ma. The only previously available age of the marine sedimentary rocks comes from tuff layers overlying fossiliferous Ediacaran-bearing beds near the top of the Conception Group. These have yielded U-Pb zircon ages of 565 ± 3 Ma (G. Dunning, unpublished data; *in* King, 1988b).

Earlier studies in various parts of the Avalon Peninsula – including the area currently under consideration – have uncovered a wide and, in some cases conflicting, spectrum of relationships amongst rocks that have been assigned to these three principal units. As an example, the Conception–Harbour Main group boundary has been variably described as either a conformable contact (Williams and King, 1979), an angular unconformity (McCartney, 1967, 1969), or an interfingering contact between wholly or partly contemporaneous units (Hughes and Brückner, 1971; King, 1990). Additionally, rocks typically designated as Holyrood Intrusive Suite are reported not only to intrude the Conception Group (e.g., Rose, 1952; Mullins, 1970; O'Brien *et al.*, 1997) but also to be present as detritus in lower or basal Conception strata, both in the northern (Rose, 1952; O'Brien *et al.*, 1997) and southern (Williams and King, 1979) Avalon Peninsula. The existence of these and other, apparently contradictory relationships – given their validity – points to the possibility of multiple, protracted and widely spaced stages of volcanism, sedimentation and plutonism within the late Neoproterozoic pile. This premise, first speculated upon by Rose (1952), is currently being tested by ongoing mapping and geochronology sponsored by the Geological Survey of Newfoundland and Labrador. Results obtained thus far clearly point to the validity of this hypothesis.

CURRENT STUDY

In 2000, the Geological Survey of Newfoundland and Labrador (GSNL) carried out a program of 1:50 000 bedrock geological mapping in the east-central Avalon Peninsula, in parts of NTS map areas 1N/3, 6, 7 and 11 (Figure 1). This ongoing work is the continuation of regional mapping undertaken in 1997, and incorporates mapping carried out during joint GSNL-Geological Survey of Canada gold metallogeny studies in 1997 and 1998 (O'Brien *et al.*,1997, 1998, 1999a,b). Both the regional mapping and metallogenic investigations have been supported by integrated U–Pb geochronological studies. Preliminary results from some of this work are incorporated in this paper. The new mapping and geochronological data, when combined with earlier published and unpublished information, necessitate major revision of existing concepts of the volcano-stratigraphic development and plutonic history of this region. A sampling of preliminary results is presented below.

Field relationships and age-dates point to the shortcomings of published stratigraphic nomenclature for this region, in particular for the volcanic rocks. Although this work has identified units of potential formation and group status, formal stratigraphic nomenclature will be proposed only after the ongoing program of mapping and geochronology is complete. Several informal names for the principal volcanic units are employed here in order to help facilitate ready description of the region's complex and protracted geological history[7].

[6] The term Holyrood Horst, first used by McCartney (1969), denotes the volcano-plutonic core of the Avalon Peninsula, bounded by the Topsail and Peak Pond faults.

[7] Names are capitalized to ensure future consistency.

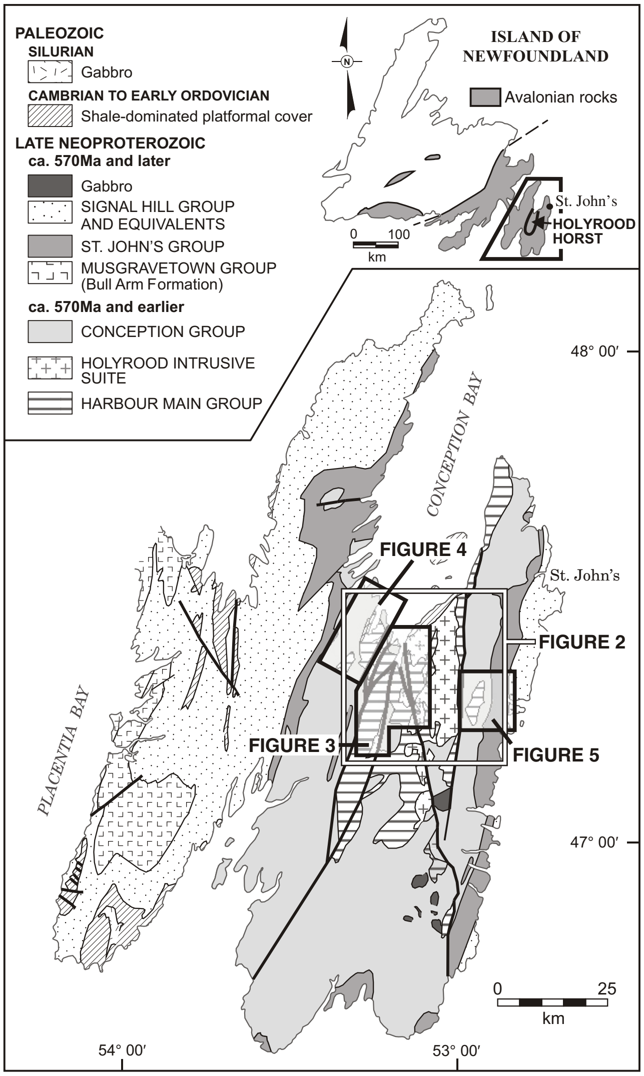

Figure 1. *Simplified geological map of the Avalon Peninsula showing the location of the study area.*

THE "HARBOUR MAIN GROUP" REVISITED

PREVIOUS INTERPRETATIONS

Most maps of the central Avalon Peninsula depict the Neoproterozoic Harbour Main Group as a stratigraphically coherent, albeit lithologically complex, subaerial volcanic succession, divisible into broad litholologic subdivisions of limited stratigraphic significance (e.g., Rose, 1952; McCartney, 1954; Mullins, 1970; Hsu, 1975). Papezik (1969, 1970) recognized regional lithic variation within the group and invoked a general three-fold subdivision, that outlined lithologically distinctive eastern, central and western blocks, delineated in an approximate fashion by the Topsail and Peak Pond–North Arm faults. These were interpreted to share a common stratigraphic position below the base of the Conception Group and, for that reason, were interpreted as coeval and assigned to the same group, regardless of distinctively disparate lithofacies, and differing depositional relationships with overlying Conception strata.

The only formal lithostratigraphic division of the Harbour Main Group is that proposed by King (1990) for the area east of Conception Bay (east of the Topsail Fault). Three distinctive formations were identified (*viz*. St. Phillips, Princes Lookout, and Portugal Cove), which included rocks formerly assigned to the Conception Group by Rose (1952). King (1990) emphasized the unique lithofacies development in this area, as compared to that farther west in the Harbour Main type area. These formations were viewed, in part, as penecontemporaneous lithofacies within a deep-water marine volcanic succession that interdigitates with the overlying Conception Group.

A REVISED NEOPROTEROZOIC VOLCANIC STRATIGRAPHY FOR THE CENTRAL AVALON PENINSULA

The authors' studies of the volcanic succession of the central Avalon Peninsula (e.g., "Harbour Main Group") have identified major lithostratigraphically and chronostratigraphically disparate units, whose range in absolute age is approximately 160 Ma. That part of the sequence that lies west of the Topsail Fault can be separated into at least six regionally mappable divisions, here referred to by the informal names (in order of decreasing age): Hawke Hill Tuff, Triangle Andesite, Peak Tuff, Blue Hills Basalt, Manuels Volcanic Suite, and Wych Hazel Pond Complex (Figure 2). In the northernmost part of the study area, rocks equivalent to the Wych Hazel Pond Complex reappear east of the Topsail Fault (King, 1990). A seventh division, Country Pond Rhyolite, underlies the Conception Group in periclinal domes east of the Topsail Fault, and is presumed to be equivalent to the Manuels Volcanic Suite. It includes a thin, uppermost unit of mafic volcanic rocks, that may be equivalent in part to the Wych Hazel Pond Complex.

External relationships and absolute ages of these units, summarized below, substantiate earlier calls for revision of the concept of the Harbour Main volcanic pile as a single group (e.g., Krogh *et al.*, 1988; King, 1990; O'Brien *et al.*, 1996). Our data clearly demonstrate, for the first time, that these units cannot be part of a single stratigraphic unit of group status.

A brief account of each unit is presented below. These include thumbnail descriptions of salient lithologic and metallogenic features, absolute or relative ages, and external contact relationships. More extensive descriptions are given of units not hitherto described in other reports. Further

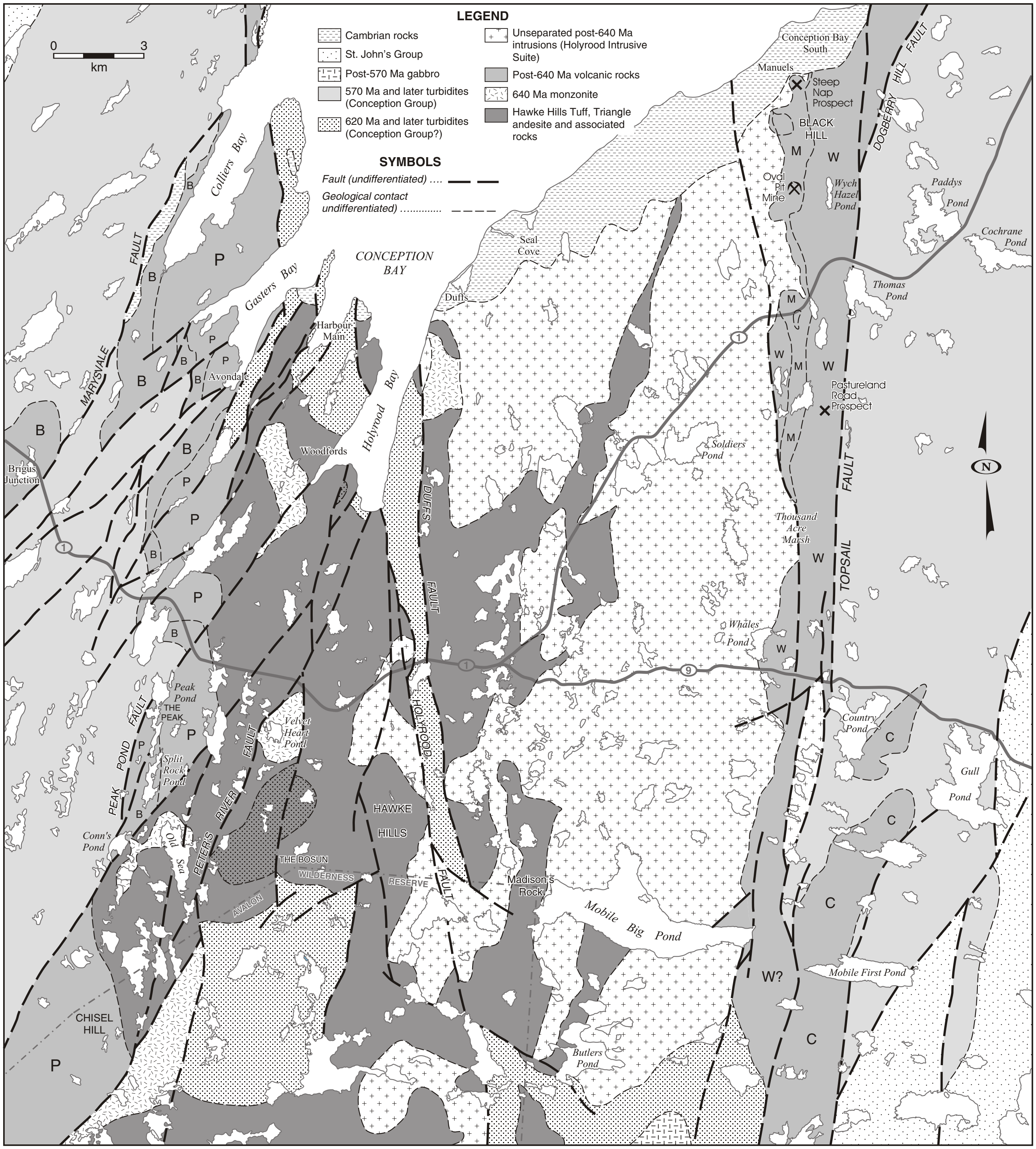

Figure 2. *Simplified map showing distribution of stratigraphic units for the central Avalon Peninsula, based on the stratigraphic framework described in this paper. M = Manuels Volcanic Suite, W = Wych Hazel Pond Complex, C = Country Pond Rhyolite, P = Peak Tuff, B = Blue Hills Basalt*

details of the region's geology, with references to previous mapping and mineral exploration, are available from several sources (e.g., Rose, 1952; McCartney, 1967; Mullins, 1970; O'Brien and O'Driscoll, 1996 and O'Brien *et al.*, 1997). The geology of adjoining areas is described in Hutchinson (1953), King (1990) and Williams and King (1979).

Hawke Hills Tuff

The oldest rocks in the region occur within an internally composite, felsic to intermediate volcanic sequence that occupies the central core of the Holyrood Horst. The Hawke Hills Tuff, an informal usage employed here to designate these volcanic rocks, is bounded to the east by younger Proterozoic intrusive rocks, and to the west by the Peter's River Fault (King, 1988a). The bounding intrusions include elements of a 640-Ma monzonite suite (*see below*), and a series of quartz-feldspar porphyry sheets and plugs, locally dated at 631 ± 2 Ma (Krogh *et al.,* 1988). Erosional unconformities separate the unit from at least two cover sequences. The older cover is composed of Proterozoic marine siliciclastic beds previously assigned to the Conception Group (McCartney, 1967; O'Brien *et al.,* 1997; *see below*); the younger is early to middle Cambrian in age, part of the shale-rich Adeyton and Harcourt groups. The basal beds of both cover sequences are marked by boulder and cobble conglomerates that sample the underlying volcanic and plutonic rocks. The Hawke Hills Tuff corresponds, in large part, to units 2 and 3 on the regional geological map (Figure 2 *in* O'Brien *et al.,* 1997).

Much of the Hawke Hills Tuff is characterized by grey and grey-green, crystal-rich, intermediate (rhyodacite–dacite) and less extensive felsic pyroclastic flows that are intimately associated with breccia and related hypabyssal rocks. Notable within the unit are a large number of metre-scale, gossanous zones of silica–pyrite alteration. This facies is best exposed in the northern part of the area, around Holyrood Bay. The Hawke Hills Tuff immediately below the sub-Conception Group unconformity in that area has been dated at 729 ± 7 Ma (Israel, 1998).

The Hawke Hills Tuff also includes a much more extensive, regionally mappable subdivision of grey and locally red-grey plagioclase-rich crystal tuff, and a less extensive coarse-grained volcanic breccia. The grey tuff is best exposed along the Hawke Hills range (NTS map area 1N/6), southward into the Avalon Wilderness Area (NTS map areas 1N/6, 1N/3); the red-grey facies, is best seen northwest of Butlers Pond toward the area around Madisons Rock, west of Mobile Big Pond (NTS map area 1N/6). Although both stratigraphic and intrusive controls demonstrate these are part of the larger pre-620 Ma volcanic succession, their absolute age and their relationship to the 730 Ma volcanic pile remain unresolved.

Triangle Andesite

Mapping to date allows tentative subdivision of the volcanic rocks west of the Peter's River Fault into three major litho- and chrono-stratigraphically separate divisions (Figure 3). The oldest of these is the Triangle Andesite, a succession of andesite flows and pyroclastic deposits, which occupies much of the heavily forested lowlands immediately west of the Hawke Hills. The base of the Triangle Andesite is unexposed; its contact with the Hawke Hills Tuff is faulted. Its top can be drawn either at the boulder and cobble conglomerate at the base of the overlying Peak Tuff or at pebble to cobble conglomerate at the base of Proterozoic marine siliciclastic rocks in and around Holyrood Bay, and in the region between Old Sea and the Hawke Hills (NTS map area 1N/3). The absolute age of the Triangle Andesite is unknown. The best minimum age limit for these rocks is provided by the 640 ± 2 Ma U–Pb age on one of a homogeneous suite of monzonitic plutons, intrusive into the Triangle Andesite in the northern part of the study area (*see below*).

The Triangle Andesite is characterized by fine- to medium-grained, grey-green and locally reddened, plagiophyric andesitic flows and volcanic breccia. The porphyritic andesite flows are associated with lesser amounts of trachytic textured rocks and crudely layered tuffaceous deposits. Locally, scoriaceous andesite flows intertongue with mafic breccia. Fine-grained mafic to intermediate hypabyssal rocks occur as sheets and sill-like bodies, but are rare. Flows and tuffs are locally interlayered, on an outcrop scale, with red tuffaceous sandstone and red thin-bedded siltstone. The eastern part of the Triangle Andesite belt is characterized by the predominance of medium- to coarse-grained mafic to heterolithic, intermediate breccia (Plate 1). The breccias are widely affected by syn-volcanic hematite–epidote alteration; variably intense chloritic alteration of andesite flows is also widespread. Intense network quartz veining and local silica flooding of the andesite is developed near the monzonite intrusions (*see below*).

Both the Triangle Andesite and the monzonites emplaced into it are metallogenically significant, *vis-à-vis*, copper and gold, particularly near the monzonite–andesite contacts. Rocks both sides of these contacts are the site of silica alteration in several areas extending southward from the Woodfords–Harbour Main area, through Triangle Pond to the till-covered region between Velvet Heart Pond and Conns Pond (NTS map area 1N/7; *see* O'Brien *et al.,* 1997; *see* the section 640 Ma Monzonites, below). In addition, chalcocite, bornite and chacopyrite occur in narrow (typically 2 cm) quartz-carbonate breccia veins and narrow stringer-like veinlets, associated with elevated silver and gold. Minor copper mineralization is also associated with the contact between the breccias and epidote-rich, syn-volcanic siltstones.

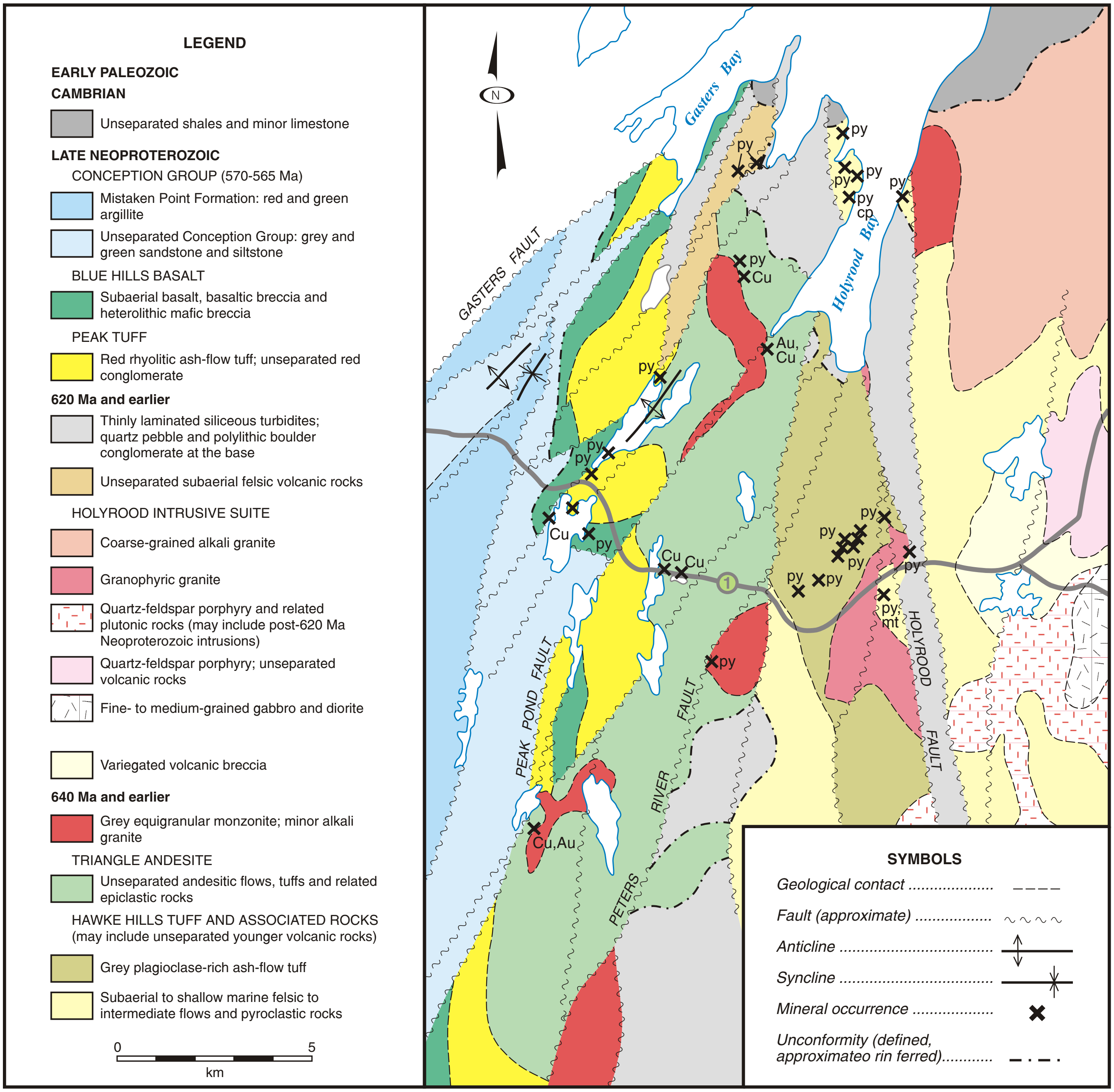

Figure 3. *Geological map showing distribution of major geological units in the eastern half of the Holyrood (NTS map area 1N/6), east of the Gasters Fault, central Avalon Peninsula (modified in part from O'Brien* et al., *1997).*

Peak Tuff

The Triangle Andesite is disconformably overlain by a subaerial succession composed of red, pink and maroon tuffs and interlayered, red siliciclastic sandstone and conglomerate, herein informally designated as the Peak Tuff. The unit has been mapped from Avondale (NTS map area 1N/7) southward to Chisel Hill (NTS map area 1N/3); its resistant ash-flows are well exposed in isolated monadnocks that occur along the length of the belt (Figure 3). Presumably equivalent rocks occur northwest of the Gasters Fault, on the peninsula between Gasters and Colliers bays. The section around Colliers consists of three composite ash-flow sequences, from 250 to 500 m thickness, separated by terrestrial sedimentary rocks; all are intruded by subvolcanic plagioclase porphyries. The section in this area has been described in detail by Nixon (1974) and Ford (1977).

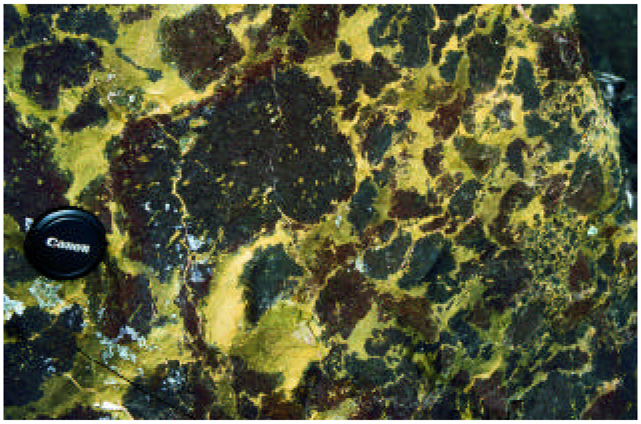

Plate 1. *Heterolithic, intermediate volcanic breccia, Triangle Andesite.*

The same unit has an estimated minimum thickness of 500 m in the area around The Peak (NTS map area 1N/6). In that area, southward to Chisel Hill (NTS map area 1N/3), the succession is characterized by red and pink, quartz-rich and quartz-poor plagiophyric varieties of ash-flow and air-fall tuff. Compositionally, these rocks are typically rhyolitic and rhyodacitic; texturally, they are characteristically granular rather than glassy. Both welded and non-welded varieties are present, and eutaxitic textures can be identified on suitably weathered surfaces. The tuffs are locally intruded by narrow sheets of quartz-feldspar porphyry, and granophyre. Coarser grained facies are locally well-developed, and include both tuff-breccia and agglomerate, in which red rhyolite and felsite clasts predominate, in a crystal-rich, quartzofeldspathic matrix. The coarse- and fine-grained pyroclastic facies are interlayered with red sandstone, siltstone and conglomerate, both in outcrop and as more regional, map-scale units. The finer grained red rocks are thick and medium bedded, internally laminated, crudely graded and crossbedded. Typical conglomerate units are thick bedded to massive, locally imbricated, and poorly sorted. Clasts are subrounded to well rounded, and are derived from interlayered pyroclastic units, as well as from unrelated monzonite, andesite, and hydrothermally altered siliceous rocks (Plate 2).

Narrow zones of hydrothermally altered (silica–sericite–pyrite±iron carbonate) felsic volcanic rocks are found within or adjacent to the Peak Tuff, and are distributed discontinuously along the belt, from the Harbour Main area, southward to the Split Rock Pond area (O'Brien and O'Driscoll, 1996; O'Brien *et al.*, 1997). In some cases, alteration is sited in narrow ($\leq$ 10m) rectilinear zones that crosscut stratigraphy, and are likely synchronous with late faulting. In other areas, alteration appears stratabound and is presumably syn-volcanic.

Plate 2. *Rounded clasts of monzonite in conglomerate near the base of the Peak Tuff.*

Krogh *et al.* (1988) report a U–Pb zircon age of 606 ± 3 Ma for felsic volcanic rocks that are here interpreted to represent extension of the Peak Tuff, northwest of the Gasters Fault. Hydrothermally altered volcanic rocks between Avondale and Harbour Main, dated at 622 ± 2 Ma by Krogh *et al*. (1988), may be either part of the same felsic package, or a separate unrelated unit.

The 640 ± 2 Ma minimum age provided by monzonite emplaced into the underlying Triangle Andesite, represents evidence of a major hiatus – potentially as much as 30 Ma – at the unconformity at the base of the Peak Tuff. It should be noted that there is no absolute age for the underlying andesite, and that existing geochronology includes data from rocks 10 km apart, and from opposing sides of the Gasters Fault. Further detailed mapping and U–Pb dating is planned to better define unit boundaries and establish the duration of this hiatus.

Blue Hills Basalt

The name Blue Hills Basalt designates those basaltic rocks and spatially related heterolithic breccias that overlie the Peak Tuff along the western side of the Holyrood Horst (Figure 4). The contact with underlying rocks is concordant and assumed to be conformable. The Blue Hills Basalt is well exposed around Colliers Bay, southward to Route 1, and reappears in an anticlinal inlier, surrounded by Conception Group, near Brigus Junction (NTS map area 1N/6). The characteristic lithology is grey and green subaerial, vesicular alkali basalt. The uppermost part of the unit between Avondale and Southwest Pond (NTS map area 1N/7) is defined by a well-rounded, coarse- to very-coarse-grained, mixed mafic breccia. In both areas, the basalts are locally associated with mafic sills, and are interstratified with red

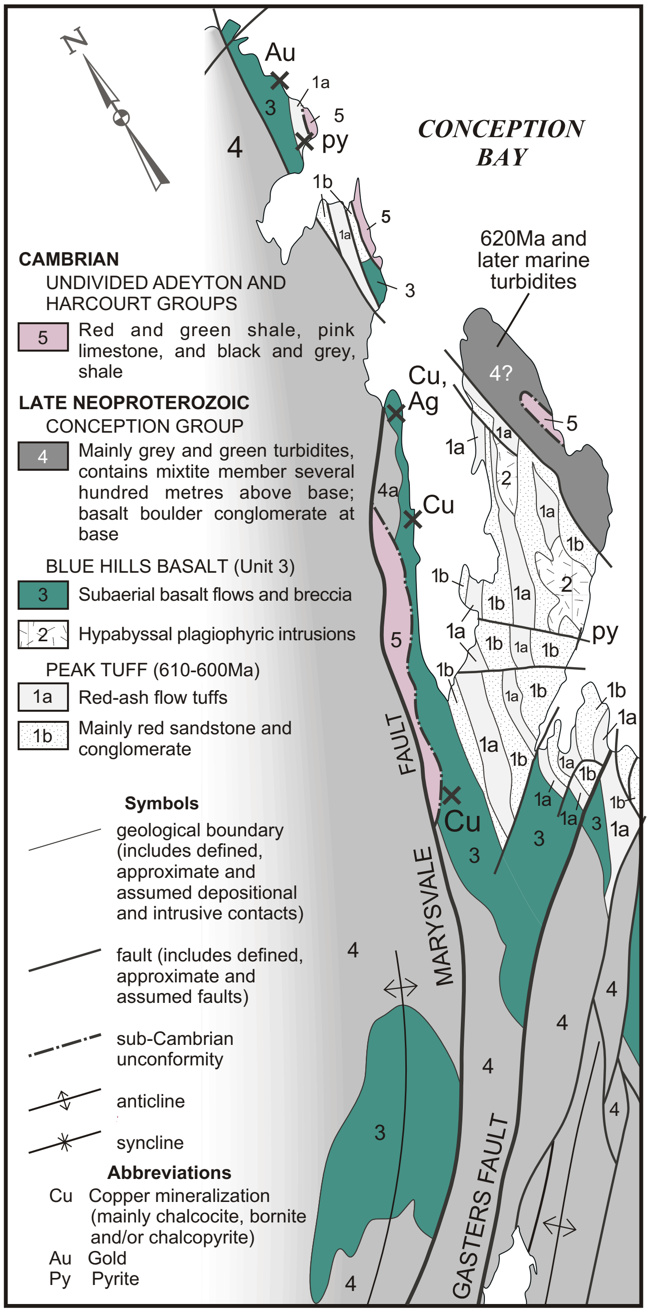

Figure 4. *Distribution of the Blue Hills Basalt and adjacent units in the area west of the Gasters Fault, Avalon Peninsula (with modification, after O'Brien* et al., *1997 and Nixon, 1974).*

sandstone and thin discontinuous units of mafic breccia. The basalt sequence, which reaches thicknesses up to 600 m around Colliers Bay, has been described in detail by Cameron (1986). The unit contains Cu–Ag mineralization in several areas; the best known of these are Colliers River and Turks Gut Ridge, where chlorite–epidote–silica-altered basalt flows contain narrow stringers, breccia-veins and fractures containing bornite, chalcopyrite, chalcocite and pyrite (*see* O'Brien *et al.*, 1997).

The Blue Hills Basalt lies unconformably below both the Conception Group and lower Cambrian shales. Its absolute age is unknown; the lower age limit is provided by the 606 ± 3 Ma on rhyolite ash-flow of the underlying Peak Tuff, on the east side of Colliers Bay (Krogh *et al.*, 1988).

Manuels Volcanic Suite

The term Manuels Volcanic Suite is used here to denote those subaerial volcanic successions along the eastern margin of the Holyrood Horst, immediately east of the Holyrood Intrusive Suite. Included in this unit are subaerial successions affected by widespread high-sulphidation style, pyrophyllite–diaspore–silica alteration and low-sulphidation style Au–Ag mineralization (*see* O'Brien *et al.*, 1998 and references therein). The Manuels Volcanic Suite can be traced southward from the Manuels–Foxtrap area (Conception Bay South) to the Thousand Acre Marsh (NTS map area 1N/7). The youngest dated volcanic rocks in this unit are 584 ± 2 Ma ash-flow tuffs that host the Oval Pit pyrophyllite deposit. The base of the complex is not defined and the age of its oldest rocks are currently unconstrained. Its western margin is either a tectonic or intrusive contact with porphyry, diorite and hydrothermally altered granite, previously included with the Holyrood Intrusive Suite. The top of the Manuels Volcanic Suite is drawn at the unconformity with the overlying marine volcano-sedimentary Wych Hazel Pond Complex (*see below*). The northern, on-land extent of the Manuels Volcanic Suite, west of the Topsail Fault, is obscured by a cover sequence of fossiliferous Cambrian shales.

Geological details of various parts of the Manuels Volcanic Suite are available from a number of sources (e.g., Vhay, 1937; Dawson, 1963; Keats, 1970; Hayes and O'Driscoll, 1990; Hayes, 1997; O'Brien *et al.*, 1997, 1998, 1999a,b). The complex has a characteristic three-fold volcanic lithofacies association: i) rhyolite (and rhyodacite), ii) ash-flow tuff and rheoignimbrite, and, iii) breccias. The rocks most characteristic of the complex are red, purple-grey and grey (buff and white, where altered) flow-banded and autobrecciated rhyolite and laminar rheoignimbrite, in which lithophysae and spherulites are well developed (Plate 3). These are spatially associated with a several-hundred-metre thick pile of grey, variably flattened and welded, pumice-rich ash-flow tuff. Breccias include both hydrothermal and primary volcanic varieties. Amongst the primary volcanic breccias is a distinctive unit of unsorted to very crudely stratified heterolithic tuff-breccia and agglomerate that hosts low-sulphidation style, crustiform banded silica–adularia veins at the Steep Nap prospect (Mills *et al.*, 1999). These breccias contain potassic-altered rhyolite

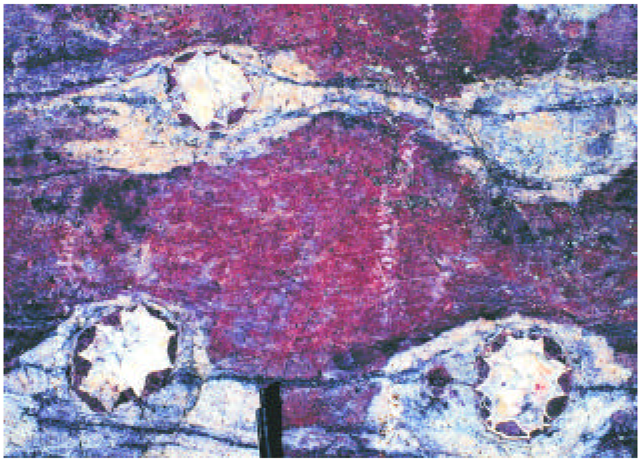

Plate 3. *Lithophysae in hematite-rich banded rhyolite of the Manuels Volcanic Suite, adjacent to the Oval Pit pyrophyllite Mine, Manuels.*

clasts and granite that are either comagmatic with the breccias or derived from earlier basement granite. A wide variety of hydrothermal breccias are preserved within the high- and low-sulphidation alteration systems (*see* O'Brien *et al.*, 1998, 1999a,b).

Hydrothermally altered rocks of subaerial volcanic protolith are widely developed along the length of the unit, and have been described in detail by a number of authors (*see* review by O'Brien *et al.*, 1997 and maps by Hayes and O'Driscoll, 1989). At least locally there is a strong spatial relationship between hydrothermal alteration and porous zones, such as those affected by vapour-phase recrystallization. The high-sulphidation alteration system includes massive silica, silica–sericite–pyrite and pyrophyllite–diaspore alteration lithofacies. In zones of high strain, these rocks are variable schistose and carry a distinctive anastomosing fabric ("ellipsoidal schists" of Vhey, 1937). The low-sulphidation system is also associated with a facies of massive, silica-rich rocks.

Basaltic rocks occur either stratigraphically within or tectonically juxtaposed with the Manuels Volcanic Suite, but are rarely exposed. Fine-grained and coarsely vesicular basaltic rocks are in fault contact with tuff-breccias that host the Steep Nap prospect (Mills *et al.*, 1999). Hematized vesicular flows have been encountered in drill core (Lewis, 1999), and uncovered in road excavations; in both cases the basalt lies along the western margin of the complex.

Wych Hazel Pond Complex

The informal name Wych Hazel Pond Complex is used here to denote the mixed volcano-sedimentary sequence of late Neoproterozoic age that overlies the Manuels Volcanic Suite. These submarine mafic volcanic rocks, shallow-marine sedimentary rocks and unseparated hypabysal feldspar porphyries, form a 1- to 2-km-wide belt that occupies much of the area between the Manuels Volcanic Suite and the Topsail Fault. The same or similar rocks reappear east of the Topsail Fault, where they continue along strike into the St. Phillips Formation of the Harbour Main Group (King, 1990), along the east side of the St. John's Peninsula. The complex can be traced southward to the Thousand Acre Marsh; it is exposed along strike in the area of Route 13 (Witless Bay Line), whence it extends to the southern limit of the study area. The Wych Hazel Pond Complex, which includes the Black Hill sequence or "mis-Conception" beds of Dawson (1963), is separated from "classic" Conception Group strata (*viz.*, those in stratigraphic continuity with the St. John's and overlying Signal Hill groups) by the Topsail Fault.

The Wych Hazel Pond Complex is characterized by three major lithofacies. The stratigraphically lowest of these is a thin-bedded, internally laminated and slumped shallow-marine sequence of green and grey siltstones, sandstones and feldspathic grits. These rocks mainly occur west of the Manuels Volcanic Suite, but are also preserved in several outliers, unconformable upon the latter complex. The unconformity at the base of the sequence is exposed at Black Hill and in the nearby Oval Pit Mine (Plate 4), and has also been intersected in drilling at the Santana Prospect, near Route 1 (*see* Lewis, 1999). The basal conglomerate units contain detritus derived from the underlying high-sulphidation alteration system, together with unaltered volcanic detritus and in rare instances, clasts of granite. In the Oval Pit Mine, basal red conglomerate gives way upwards to extensively slumped beds of green siltstone and thin and medium beds of grey, coarse-grained feldspathic grit. The

Plate 4. *Oblique aerial view showing hydrothermally altered Manuels Volcanic Suite (light coloured and rusty areas) overlain by red conglomerate and green, slumped siliciclastic sediments at the base of the Wych Hazel Pond Complex (Oval Pit Mine).*

latter occur as planar beds, as internally slumped interlayers in siltstone and bounded by planar beds, or as totally disrupted and discontinuous layers affected by soft-sediment folding. Here and elsewhere in the complex, the green siltstones contain distinctive laminae of grey and black shale, that show fine-scale slump features and associated syn-sedimentary micro-faults. In the northernmost part of the study area, the dark-grey grits form thick- to very-thick-bedded or massive sheets, interlayered with mafic breccia. There, the grits are associated with i) rare green and very locally red chert, and ii) green granule conglomerate containing rip-ups of slumped green siltstone and chert.

The second and most distinctive lithofacies is characterized by several types of submarine volcanic breccias of mafic, and more rarely, mixed mafic–felsic composition. Those interbedded with the sediments include fine- to coarse-grained, fluidized hyaloclastites containing irregularly shaped bombs of brown-weathering, finely vesicular mafic material. Another breccia type contains 1- to 10-cm chilled fragments of purple–grey, vesicular, mafic to intermediate material in a green heavily chloritized matrix. Other breccias are true agglomerates, having chilled "plastic" basalt fragments in an epidote-rich matrix. Pillow breccias containing well-developed pillow selvages are locally preserved. Other monolithic breccias form from in-situ disruption of calcite–epidote-vesicular basalt. Massive and pillowed basalt flows are less common; the massive flows show evidence of incipient brecciation that has been the focus of extensive epidote alteration.

The volcanic and sedimentary rocks are spatially associated with hypabyssal porphyry, that represents the third principal lithofacies. The porphyry occurs as small plugs or intrusive sheets that occur primarily within the volcanic breccias, but that also are emplaced into sedimentary rocks. The porphyry is typically grey, and massive or featureless; it contains light-grey or grey-green euhedral plagioclase set in a fine-grained or glassy matrix. Some of the earliest porphyry sheets may have been injected prior to lithification of the host sediments. In other cases, porphyry intrudes clast-bearing breccia but appears to have been unroofed into the same (or similar) breccia. The porphyry is in places hematitized, pyritic, and silica-altered, and is locally associated with VMS-style base-metal mineralization (see below). The sedimentary units are locally intruded by syn-sedimentary mafic dykes and sills that have highly irregular margins, marked by zones of intermixed pillow-like fragments of diabase, slumped sediment, and hyaloclastite.

Within the study area, the Wych Hazel Pond Complex contains several zones of pyritic alteration and at least one significant example of VMS-style sphalerite, galena and chalcopyrite mineralization (Pastureland Road prospect). The latter prospect was originally noted by Hayes and O'Driscoll (1990) and extended by trenching, first by Fort Knox Gold Inc. (Lewis, 1999), and most recently by the current license-holders (T. Gosine and A. Turpin). The prospect occurs in deformed, fine-grained mafic breccias associated with a coarser grained, chlorite-rich, dark-green to purple-grey mafic–felsic agglomerate. Mineralization is developed in fine-grained silicified fragmental rocks of presumed mafic protolith, within a zone that is several tens of metres wide, adjacent to a plug or folded sheet of fine-grained (2 to 3 mm) plagioclase porphyry. Sphalerite, galena and chalcopyrite occur together with pyrite as disseminations, as network fractures, and in early mineralized fragments within the fine-grained, grey, fragmental rocks. The entire zone is weakly anomalous in gold (ca. 20 to 100 ppb), and in some silicified zones has yielded values up to 2.1 g/t Au; barium, silver and cadmium are highly anomalous throughout. High-grade sulphide-rich zones at surface (up to 8.9 percent Zn and 5.2 percent Pb in grab samples; A. Turpin, personal communication, 2000) have a semi-massive appearance, and form discontinuous pods or strain augen (Plate 5). The largest of several pods has approximate surface dimensions of 1 by 0.5 m. A short vertical drillhole, recently collared in one such pod, shows these are more extensive in the immediate subsurface; this hole intersected mineralized rocks that include a zone of 3.1 percent Zn and 1.35 percent Pb over 6 m (A. Turpin and T. Gosine, written communication, 2000). The mineralized rocks are affected by part of a major regional high-strain zone, but mineralization, in large part, is pretectonic. These rocks are the site of a major vertical or near-vertical zone of high-strain developed on a regional scale, immediately west of and parallel to the Topsail Fault.

The shear zone that overprints the mineralization has been traced from north to south across most of the study area. It varies in width from several tens of metres to sever-

Plate 5. *Zinc-rich pods of semi-massive sulphide and sulphide-bearing breccia, Pastureland Road Prospect.*

al hundreds of metres, and may encompass more than one simple or single high-strain zone. It is characterized by an intense and penetrative chloritic fabric and the development of a down-dip stretching lineation, primarily in mafic volcanic rocks, but also in siliceous marine sedimentary rocks. The northern extension of the zone may be in part truncated by later displacements that define the Topsail Fault.

The absolute age of the Wych Hazel Pond Complex is currently unknown. Its age is bracketed by 584 ± 2 Ma rhyolite from the top of the underlying Manuels Volcanic Suite and by 565 ± 3 Ma tuff near the top of the overlying Conception Group.

Country Pond Rhyolite

A sequence of subaerial felsic volcanic rocks of similar facies to the Manuels Volcanic Suite is exposed in periclinal domes east of the Topsail Fault, immediately south of Route 13. That succession is here given the informal designation, Country Pond Rhyolite. This unit is characterized by red and maroon flow-banded rhyolites and rhyolite autobreccia, with substantially lesser amounts of pink to red rheoignimbrite and pyroclastic breccia and contains several zones of sericitic and silica-rich alteration and related hematite-rich hydrothermal breccia (Plate 6), similar to that seen west of the Topsail Fault, in the Manuels Volcanic Suite (e.g., Santana and related prospects, O'Brien *et al.*, 1998). The rhyolite succession around Country Pond is capped by a thin unit of basalt and basalt breccia, that may be in part equivalent to mafic volcanic units in the Wych Hazel Pond Complex.

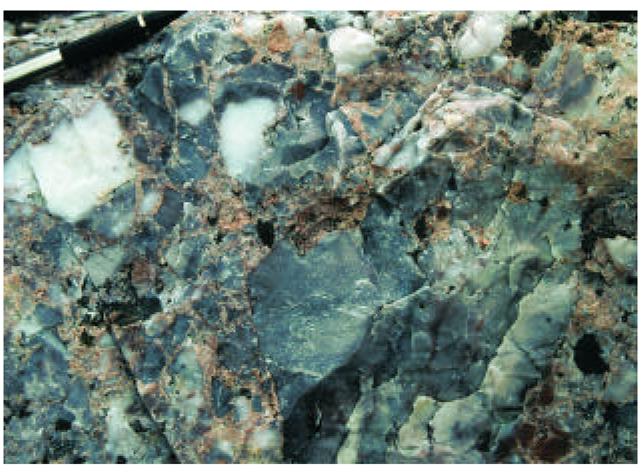

Plate 6. *Hematite–silica hydrothermal breccia in flow-banded rhyolite, County Pond Rhyolite.*

A pronounced erosional unconformity separates the mafic rocks from boulder conglomerate developed at the base of the overlying Conception Group succession (Plate 7). Much of the Conception Group stratigraphy immediately north of the Country Pond Rhyolite can be readily matched to that mapped by King (1988a) in the St. John's Peninsula.

Plate 7. *Basal Conception Group conglomerate unconformable on Country Pond Rhyolite near Mobile First Pond.*

NEOPROTEROZOIC PLUTONISM IN THE HOLYROOD HORST

INTRODUCTION

A great volume and wide diversity of felsic, and lesser intermediate and mafic intrusive rocks occur within the study area. Previously, most or all have been grouped together, either within the Holyrood Batholith by Rose (1952), the Holyrood Granite by McCartney (1967) or the Holyrood Intrusive Suite by King (1988a). These rocks can be separated into several spatially separate plutons: some are temporally and genetically unrelated, whereas others are lithologically distinct but cogenetic. Current data demonstrate that most of the intrusive rocks were emplaced in several discrete intervals between about 640 Ma and 580 Ma. The oldest dated plutons were intruded almost 60 million years before onset of the latest volcanism in the Holyrood Horst. The youngest plutons are emplaced into the 585 Ma volcanic successions and younger Proterozoic volcanic and sedimentary rocks, postdating earliest volcanism by more than 150 million years. Some of the intrusions are coeval with and likely cogenetic with respect to adjacent volcanic rocks. The felsic intrusions are restricted to the volcanic terrane between the Topsail and Peter's River faults. Intermediate intrusions are most widespread west of the Peter's River Fault, where typically they are spatially associated with the Triangle Andesite.

Stratigraphic nomenclature currently used to designate the region's plutonic rocks – like that of its volcanic rocks – requires modification, in light of the emerging database. Final revision of pluton boundaries and, where necessary, proposal of new nomenclature, await further results from ongoing geochemical, petrographic and geochronological studies. What follows is a brief geological update, incorporating some recent results. Further details from earlier mapping of the plutonic rocks by ourselves and others is summarized in O'Brien and O'Driscoll (1996) and O'Brien *et al.* (1997).

AGE, LITHOLOGY AND MINERALIZING EVENTS

640 Ma Monzonites

The oldest isotopically dated intrusions that occur on a mappable scale are a lithologically homogeneous suite of equigranular monzonite plutons[8]. A new U-Pb age from the largest of these, exposed near Woodfords, establishes the timing of magmatism at 640 ± 2Ma. This pluton is the northernmost of a suite of monzonites that extend southwards to the Conns Pond – Old Sea area (*see* descriptions in McCartney, 1967; O'Brien and O'Driscoll, 1996 and O'Brien *et al.*, 1997). In all cases, these plutons are composed of chloritized, equigranular, pyroxene-bearing monzonite to quartz monzonite, associated with only very minor amounts of red granite, which typically occurs as narrow veinlets. The monzonites intrude the Hawke Hills Tuff and the Triangle Andesite and occur as clasts in conglomerates in the overlying Peak Tuff.

These monzonites are of important metallogenic significance *viz-a-viz* copper and gold. Zones of semi-massive silica and moderate to intense network-silica veining, which are associated with elevated copper and gold, occur in several areas along this belt. Significant zones of hydrothermally altered monzonite containing elevated copper and gold values were encountered in drilling in the Conns Pond area (Ace Minerals, 1995 press releases; *see also* O'Brien *et al.*, 1997). More detailed descriptions and reference to other assessment work in the Conns Pond area have been previously presented in O'Brien and O'Driscoll (1996) and O'Brien *et al.* (1997).

A pluton of similar monzonite intrudes the Hawke Hills Tuff east of Holyrood; a small plug of the same rocks also intrudes the Hawke Hills Tuff immediately below the Cambrian cover sequence north of Chapels Cove. Rocks mapped as part of the same monzonite suite by McCartney (1967) in the area between Route 13 and Mobile Big Pond, are texturally and compositionally different (mainly coarse-grained gabbro and diorite) and unrelated to the rocks described above. Mullins (1970) described several areas of monzonite in the St. Catherines map area, but preliminary observations indicate that these rocks are largely granitic or, in places, dioritic in composition, and much different from the 640 Ma intrusions described here.

Quartz–Feldspar Porphyries (635 to 630Ma) and Spatially Associated High-level Intrusions

Several irregularly shaped plugs and sheets of red to pink, fine- to coarse-grained quartz–feldspar-porphyry are exposed in the low ground east of the Hawke Hills. These have typically sharp intrusive contacts with several different facies of volcanic country rock. Those in the area around the Route 13 contain some evidence of silica–pyrite alteration and are locally coincident with lake sediment anomalies (up to 18 ppb) for gold. A larger body of porphyry to the west and southwest of Mobile Big Pond (within the Avalon Wilderness Reserve) contains extensive zones of gossanous silica–pyrite-bearing hydrothermally altered rocks; the largest of these is exposed discontinuously along strike for approximately two hundred metres. One of the larger porphyry intrusions near Butter Pot Park has been dated at 631 ± 2 Ma (Krogh *et al.*, 1988); its relation to the others in the general area is unclear.

A several-square-kilometre body of mainly fine-grained, pink granite, miarolitic granophyre and felsite is exposed in the Hawke Hills immediate south of the Trans-Canada Highway, west of the porphyries described above.

[8] Smaller, outcrop-scale sheets of sub-volcanic porphyry and grey felsite have an intimate spatial association with dated ca. 730 Ma volcanic rocks in the northern part of the Hawke Hills Tuff, and are assumed coeval with this volcanism.

Extensive zones of silica–pyrite alteration occur in country rocks adjacent to this irregularly shaped intrusion. Narrow fractures containing magnetite were noted in one area. The age of this intrusion is unconstrained.

625 to 620 Ma Quartz-rich Granites and Spatially Associated Intrusions

The most extensive pluton in the area is an elongate (north–south) intrusion of porphyritic to subporphyritic quartz-rich hornblende–biotite granite, that extends from Conception Bay southward to the Mobile Big Pond area. The pluton corresponds in large part to the main body of Holyrood Granite as outlined by McCartney (1967), including large parts – but not all – of Rose's (1952) Holyrood Batholith. It is bounded to the west, the south and the east by volcanic rocks or other plutons, and is intruded by one or more suites of equigranular intrusions, that may be in part cogenetic. In a number of areas, intrusive contacts with surrounding volcanic rocks are exposed. In at least two instances, granites that are included within this pluton have sharp and unequivocal intrusive contacts with both outcrop-scale inclusions and larger roof pendants of thin-bedded marine sedimentary rock, not unlike that assigned to the Conception Group elsewhere within the Holyrood Horst. Parts of this intrusion were previously dated by Krogh *et al.* (1988) as 620 ± 2Ma.

The principal quartz-porphyritic granite phase is typically grey-weathering, biotite–hornblende-bearing, and readily identified by the ubiquitous occurrence of knobby-weathering, euhedral quartz. Grain size is variable, and in places, separate areas of fine-, medium- and coarse-grained "quartz-knobby" granite can be identified on a regional scale. Plagioclase and K-feldspar typically occur in near equal proportion. A texturally similar variant of the medium-grained granite is well developed in the northeastern part of the intrusion, primarily north of Route 13. This phase, dated at 623 ± 3 Ma, has a distinctive pink, white and green coloration due to chlorite–sericite–epidote alteration (Plate 8). This and other northern parts of the granite exhibit well-developed areas of fine-grained tuffisite breccia. The granite locally contains centimetre- to metre-scale, variably resorbed, cognate xenoliths of dioritic composition. The quartz-rich granite contains some areas of intense silica–pyrite hydrothermal alteration and brecciation (e.g., near the entrance to Butterpot Park; O'Brien and O'Driscoll, 1996) but is more typically unaltered, particularly in the north of the area, away from younger intrusions. The southern and southeastern parts of the granite pluton contain extensive zones in which chlorite-rich propylitic-style assemblages occur, most notably along its eastern margin.

A separate and aerially extensive pluton of coarse-grained alkali-granite and K-feldspar-rich granite occurs in the area northwest of Butterpot Provincial Park, northward to the Seal Cove area. The pluton locally contains small discontinuous zones of pink graphic granite and granophyre. The granitic rocks hosting spectacular granophyric textures at Duffs, on the shore of Conception Bay (*see* Hughes, 1971; O'Brien and O'Driscoll, 1996) present the northwesternmost extent of this pluton. Its relationship to the dated 620 ± 2 Ma granite is unclear, but it is likely that the two are related.

Plate 8. *Pink, white and green granite, a 623 ± 3 Ma pluton in the Holyrood Intrusive Suite.*

Younger plutons of pale pink to pale orange granite (or adamellite) and spatially associated, grey and pale pink equigranular granodiorite intrudes the quartz-rich porphyritic phase in a number of areas. The equigranular rocks have been mapped as regional-scale bodies in some areas (e.g., north of Mobile Big Pond; Figure 5). In many cases they form irregular shaped, narrow or elongate sheets or dyke-like features, within larger areas of quartz-rich porphyritic rocks. Porphyritic granite adjacent to these equigranular phases locally shows evidence of secondary K-feldspar growth, presumably representing a form of potassic alteration. Several narrow molybdenite-bearing quartz veins occur in this general area (Rose, 1952). The absolute age of this equigranular granite and its genetic relationship to the 620 ± 2 Ma quartz–porphyritic granites are presently uncertain.

Both the pink, white and green granite and the coarse-grained alkali granite phases represent interesting dimension-stone exploration targets.

Post-620 Ma Intrusions

Hydrothermally altered felsic intrusions that are spatially associated with, and locally intrusive into the Manuels Volcanic Suite, are amongst the youngest intrusions yet documented in the study area. They form a discontinuous, 2- to 3-km-wide belt of granite, granodiorite, diorite, quartz–

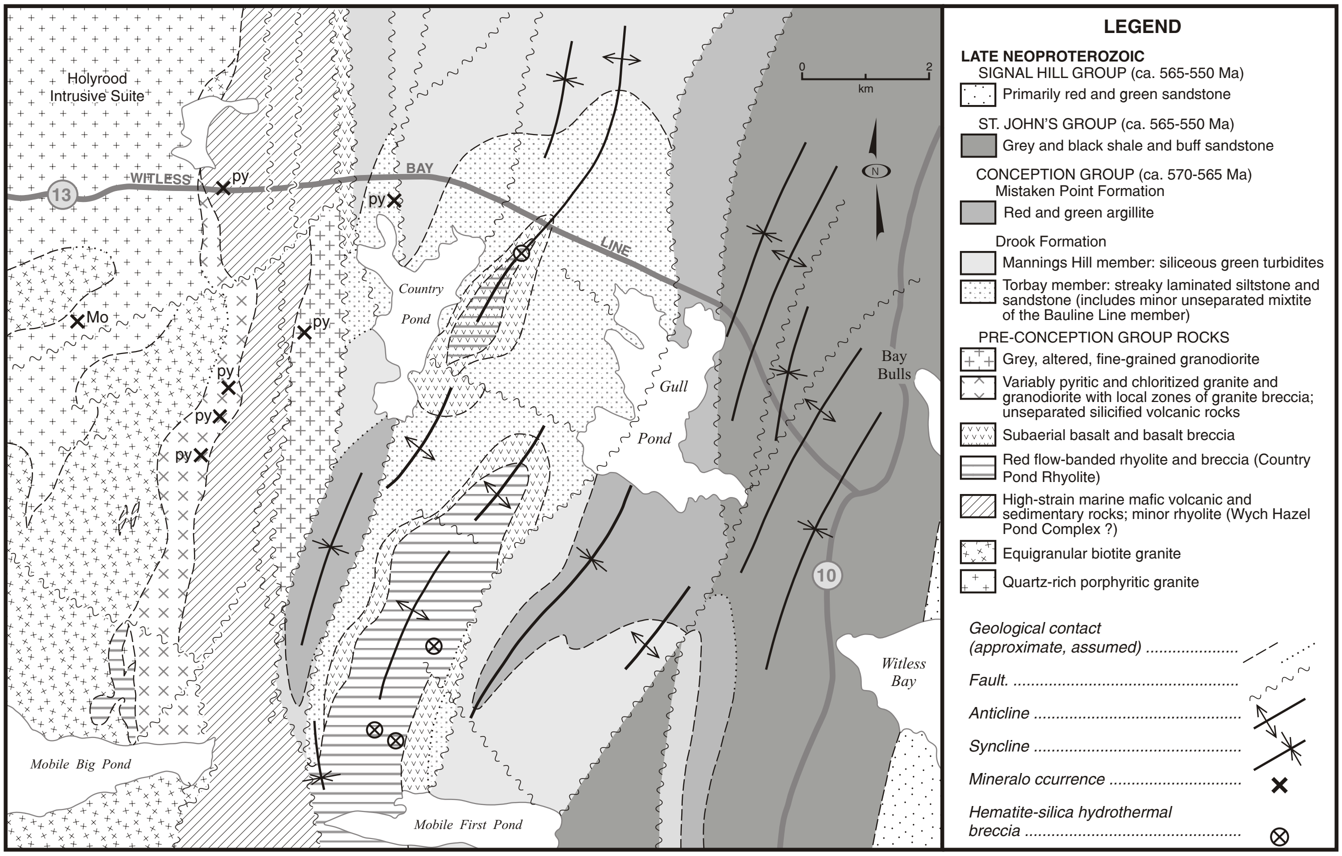

Figure 5. *Preliminary geological map of the region between Mobile First Pond and the Thousand Acre Marsh (geology by S. O'Brien and B. Sparkes, 2000).*

feldspar porphyry and hybrid rocks, which is sited along the east side of the Holyrood Horst. It includes plutons significantly younger than, and unrelated to, adjacent 620 Ma granite. These intrusions are weakly to intensely silicified and in places hydrothermally brecciated and pyritic. Some are intruded into the Manuels Volcanic Suite and have been hydrothermally altered at the same time as the development of epithermal systems in the 585 Ma volcanic rocks. Other post-620 Ma granites in this belt may have been emplaced during earlier volcanism preserved within the adjacent volcanic complex.

Silica–pyrite alteration of malachite-stained, fractured granite is developed adjacent to the Oval Pit pyrophyllite deposit; similar pyrite–silica alteration occurs extensively in granite around the smaller Trout Pond pyrophyllite prospect. Silica-altered granite with moderately disseminated pyrite and traces of chalcopyrite and molybdenite are associated with granite near the north end of the Manuels Volcanic Suite. Hydrothermally brecciated, silicified and, locally, potassic-altered granite was encountered in drilling near this area, under the Steep Nap gold–silver prospect (Lewis, 1999). Similarly brecciated and hematitized granite was intersected in drilling adjacent to the Santana Au–Ag prospect (Lewis, 1999); these granites contain pyrite and specular hematite associated with possible traces of bornite.

Hydrothermally altered granites reappear in a similar position along the east side of the Holyrood Horst, in poorly exposed areas south of the Witless Bay Line (Route 13). One such narrow belt of granite extends from Whales Pond south to Mobile Big Pond (Figure 5); its relation to adjacent equigranular granites is unclear. Granite and country-rock rhyolite are silicified and pyritic, and in at least one area, the granite contains outcrop-scale and smaller areas of finely milled, pyritic hydrothermal breccia. A second, nearby belt of altered intrusions includes fine-grained, silicified dioritic rocks, which are extensively pyritized. These rocks are physically separated from other intrusions by the Wych Hazel Pond Complex. It is possible that these rocks were intruded into this post-585 Ma succession.

Elements of an extensive suite of pretectonic gabbroic intrusions, that may be part of the larger Whalesback Gabbro (Williams and King, 1979), are emplaced into undated Conception Group strata in the area around Butlers Pond.

Their absolute age is unknown. Similar rocks reappear farther south in the Horsechops Road area (NTS map area 1N/3), and are described by O'Brien *et al.*, 1997.

A cogenetic relationship between intermediate feldspar porphyry and subaerial volcano-sedimentary successions in the Peak Tuff is reported from from the west side of the Holyrood Horst (Nixon, 1974; O'Brien and O'Driscoll, 1996). The age of tuff beds in the cogenetic volcanic package places these intrusions ("Kitchuses porphyrites" of O'Brien and O'Driscoll, 1996) in the range of 610 to 600 Ma.

Sheets and plugs of feldspar porphyry that are intrusive into the Wych Hazel Pond Complex, (and included as units within it) may represent some of the youngest intrusions in the area. These rocks, which are described elsewhere in this report (*see* Wych Hazel Pond Complex, above) are interpreted to be cogenetic with rocks that stratigraphically overlie 585 Ma rhyolite. These porphyries are more extensive to the north of the present study area (*see* Hsu, 1975).

Intrusions in the Butlers Pond Area

Intrusive rocks around Butlers Pond form a separate, magmatically mixed suite characterized by feldspar-quartz porphyry, quartz monzonite and quartz diorite, and by extensive hydrothermal alteration (e.g., pyrite–biotite–chlorite–sericite ± hematite ± magnetite ± silica) and by both hydrothermal and magmatic brecciation. These rocks form a discrete irregularly shaped pluton, intrusive into surrounding volcanic rocks, but readily separate from adjacent quartz-rich intrusions that form the southwards extension of 620 ± 2 Ma quartz porphyritic granite (Figure 5). Their relation with marine sedimentary rocks in the area is less certain. Granite–sediment relationships preserved in drill core from the area are largely enigmatic (Pickett, 1996). It is notable, however, that some of the sedimentary rocks at surface are disconformable on mafic volcanic rocks that, elsewhere in the immediate area, are intruded by the granite. Equally noteworthy is the presence of 2- to 3-m angular boulders of hematite-rich boulder conglomerate containing rounded clasts ($\leq$50cm) of hematitized granite, similar to that which outcrops nearby. Both observations are consistent with a depositional granite–sediment contact.

The Butlers Pond area is well known because of the presence of a number of unsourced boulders of hydrothermally altered granite breccia and volcanic rocks. These include hydrothermally altered (silica–sericite with minor biotite, chlorite and magnetite) intrusive breccia, containing chalcopyrite, pyrite and minor magnetite (Plate 9). One such boulder has returned assays up to 12.2g/t Au and 6 percent Cu (Crocker, 1993). Other hydrothermally altered boulders,

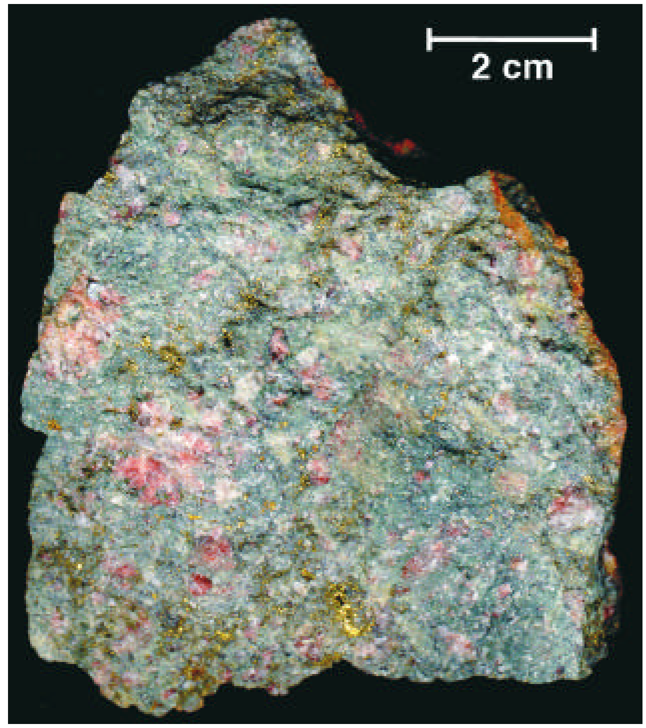

Plate 9. *Hydrothermally brecciated granite float from Butlers Pond, containing chalcopyrite, pyrite and magnetite in a silica–sericite–chlorite–magnetite matrix.*

of apparent volcanic origin, contain hydrothermal magnetite, as well as silica, sericite, minor pyrite and traces of biotite (B. Sparkes, unpublished data). Intensely altered volcanic boulders containing up to 15 percent pyrite are characterized by sericite and silica alteration. Bedrock exposures of similarly altered and mineralized felsic volcanic breccia occur in the area, and contain locally anomalous gold and silver concentrations (Crocker and Dalton, 1994).

The new data from the area around Butlers Pond demonstrate that hydrothermal alteration is widespread, and a common feature of a lithologically distinct, metallogenically important pluton (or suite of plutons). However, the age of the Butlers Pond intrusive rocks is as yet undetermined, and their genetic relation to the main (620 Ma) granite pluton of the Holyrood Intrusive Suite remains unknown. The brecciation associated with mineralization in boulders at Butlers Pond share some similarities with that seen in exposures in the immediate area. The lithofacies being brecciated, however, is a weakly altered, medium-grained equigranular granite most readily comparable with phases found in a number of areas, most notably north of Mobile Big Pond. Available data dispense with previous notions of the Butlers Pond area as a small, anomalous example of alteration and mineralization, unrepresentative of a very much larger granite batholith.

NEOPROTEROZOIC SILICICLASTIC ROCKS

DISTRIBUTION

The stratigraphy of the late Neoproterozoic, siliciclastic sedimentary succession of the central Avalon Peninsula (Conception, St. John's and Signal Hill groups) is well documented, particularly in the region east of the Topsail Fault (Williams and King, 1979; King, 1990). Less well known, however, is the nature of marine clastic successions assigned to the Conception Group within the Holyrood Horst and the manner in which they may correlate with marine clastic rocks elsewhere on the peninsula (*cf.* King, 1988a).

The member-level subdivision of the Conception Group proposed by King (1990) for the St. John's area is readily applicable to much of the marine siliciclastic succession found east of the Topsail Fault in the present study area, and allows correlation of both successions. However, our mapping and geochronological data do not support an equally exact correlation of Conception Group east of the Topsail Fault with marine siliciclastic units that outcrop farther west, as outliers within the Holyrood Horst. The data demonstrate that deposition of these two sequences – hitherto depicted as coeval – was separated in time by subaerial felsic volcanism and coeval plutonism, and by submarine mafic volcanism.

A third area of marine sedimentary rocks, assigned here to the Wych Hazel Pond Complex (and described above), includes rocks previously denoted as Conception Group on some maps (*see,* for example, King, 1988a). These strata record a discrete period of sedimentation coeval with the aforementioned submarine volcanism.

Finally, Conception Group rocks are widely developed west of the Holyrood Horst. The regional stratigraphy of the group in that area is shown in King (1988a) and details of parts of the succession are given in O'Brien *et al.* (1997). The stratigraphy and correlation of these rocks with marine siliciclastic rocks farther east are not part of the work reported on in this paper. There are a number of lines of evidence, however, that support correlation of these rocks with Conception strata east of the Topsail Fault (O'Brien *et al.,* 1997; O'Brien and King, unpublished data).

CONCEPTION GROUP EAST OF THE TOPSAIL FAULT

Of the sedimentary rocks traditionally assigned to the Conception Group in the study area, only those east of the Topsail Fault and west of the Peak Pond Fault unequivocally postdate all Neoproterozoic volcanism within the Holyrood Horst. These strata pass gradationally upward into the 565 ± 3 Ma Mistaken Point Formation, which is in turn overlain by the St. John's Group; the latter is conformably overlain by the terrestrial siliciclastic Signal Hill Group (e.g., King, 1988a).

Internal divisions of the Conception Group defined by King (1990) in the St. John's area can be traced from the Cochrane Pond region, southwards to the area around Mobile First Pond (NTS map area 1N/7). These include (in ascending stratigraphic order) the Broad Cove River, Bauline Line, Torbay and Mannings Hill members of the Drook Formation, and the overlying Mistaken Point Formation (*cf.* King, 1988a). Detailed lithological descriptions of each of these units are given in King (1990) and only brief summaries are presented here. The Mistaken Point Formation remains largely undivided in the study area. The Broad Cove River member is best developed in the northern part of the study area. Farther south, near Route 13 (Witless Bay Line), it is either thin or absent. There the Torbay Member lies unconformably on basaltic rocks at the top of the Country Pond Rhyolite. The Bauline Line Member is only exposed on or adjacent to Route 13; its boundaries are tectonic and its stratigraphic position has yet to be confirmed from data in this area.

The distribution of units in most of the study area is controlled by open regional-scale fold-pairs and periclinal domes and basins. In the area around Mobile First Pond, Conception Group subdivisions are repeated by faults. Similar structures locally (e.g., Mobile River) have caused interleaving and repetition of the upper Conception strata with the overlying St. John's Group. The Signal Hill Group is not exposed in the area surveyed.

The Broad Cove River Member typically consists of medium- to thick-bedded, graded siliceous grey-green sandstone with dark-grey shaley interbeds. The graded, planar-bedded sandstones locally contain distinctive, millimetre-scale calcareous vug-like features. The member contains rare, thick beds of grey cherty sandstone. The Bauline Line Member comprises a thin unit of primarily red to maroon, and locally green, unsorted, boulder-rich "mixtite" (*cf.* King, 1990). In exposures on and around Route 13, the mixtite is faulted with and locally underlain by distinctive units of thinly laminated grey siliceous siltstone and massive to thixotrophically deformed grey chert. The mixtite unit appears to have planar boundaries but lacks internal stratification. Detritus in the mixtite includes a variety of intrabasinal sedimentary rocks, in addition to mafic volcanic rocks, silica-flooded and sericitic felsic volcanic rocks, and several types of granite. The latter include distinctive "pink-, white-, and green"-weathering, epidote–sericite–chlorite–altered granites, similar to that dated at 623 ± 3 Ma elsewhere in the study area.

The Torbay Member is best exposed in the area around Country Pond, where it is characterized by homogeneous units of streaky-laminated, grey-green and yellow-green, massive to thick-bedded sandstone. The sandstone locally contains discontinuous pyritic laminae, and rarely, pyrite nodules (≤10 cm). The basal part of the conformably overlying Mannings Hill Member is marked by several beds of red siliceous siltstone. This basal red unit passes upward into a well-bedded succession of medium- to thick-bedded siliceous sandstone and chert, characterized by distinctive white to yellow-green weathering. Sandstones are graded and display parallel laminae and small-scale crosslaminae. Thin disrupted beds of chert are a distinctive feature of the Mannings Hill Member.

The boundary of the Drook Formation with the overlying Mistaken Point Formation is gradational and drawn at the appearance of red argillite in the succession. Typical facies of the Mistaken Point Formation in this region are reddish-purple argillaceous siltstone, and well-cleaved, red and green argillite. In the north of the study area, these rocks lie mainly to the east of the underlying Drook Formation. Farther south they are infolded with and/or tectonically interleaved with both the Mannings Hill and Torbay members of the Drook Formation. In the area south of Country Pond, the Mistaken Point Group is juxtaposed with pre-Conception Group intrusions along a splay of the Topsail Fault. The upper boundary of the Mistaken Point Formation with the overlying St. John's Group appears to be sharp and conformable.

CONCEPTION GROUP IN THE HOLYROOD HORST

A narrow synclinal keel of grey and green, marine sedimentary rocks, designated as Conception Group on most maps, occurs within the Holyrood Horst, immediately east of the Hawke Hills, and extending northwestward across the major headlands in southern Conception Bay. These strata lie with pronounced unconformity on several of the Neoproterozoic volcanic units, including the Hawke Hills Tuff and Triangle Andesite, and contain detritus derived from one or more granitoid suites (O'Brien and O'Driscoll, 1996; Israel, 1998).

The succession is well-exposed on the east shore of Holyrood Bay, where a thick, basal unit of granite-clast-bearing conglomerate is developed. Several rhyolite tuff beds are interlayered with fine-grained strata in the lower part of the succession immediately above the basal conglomerate unit (*see below*). Northwest of Conception Bay, a thin unit of laminated red tillite, capped by a distinctive limestone bed, lies near the base of the marine sediments. There, the base of the succession is defined by quartz–pebble and cobble conglomerate, which lies with profound angular discordance on underlying units (McCartney, 1967; O'Brien, 1972). The succession in this area is described by O'Brien and O'Driscoll (1996), O'Brien *et al.* (1997) and Israel (1998).

Similar sedimentary rocks lie unconformably on the Hawke Hills Tuff, within a broader outlier located west and south of the Hawke Hills and the Bosun. Well-bedded marine sedimentary rocks are also exposed within and adjacent to the Avalon Wilderness Reserve (Rose, 1952; Mullins, 1970), where they are intruded by large gabbroic and dioritic plutons of presumed late Neoproterozoic age (e.g., Whalesback Gabbro, Williams and King, 1979). Further details of the geology of these sedimentary successions, including descriptions of basal relationships, are presented in Rose (1952), McCartney (1967), Mullins (1970), O'Brien and O'Driscoll (1996), O'Brien *et al.* (1997) and Israel (1998).

Several general observations can made regarding the marine sedimentary outliers within the Holyrood Horst. In all areas, the basal contact, are either unconformable or faulted; upper contact relationships are either unexposed or tectonic; boundaries with major plutonic units are both unconformable and intrusive. Nowhere do these successions lie in stratigraphic continuity with the uppermost Neoproterozoic deltaic and alluvial facies rocks (St. John's and Signal Hill groups). Nowhere do they include rocks that might be correlated with the Mistaken Point Formation. Correlation at member-level with Drook Formation east of the Topsail Fault is not possible. The local presence of red laminated tillite near the base of these sections, however, does support correlation with the glaciogenic Gaskiers Formation of the southwestern Avalon Peninsula (Williams and King, 1979).

An absolute age for the marine succession exposed either side of Conception Bay is provided by a 621+5/-4 Ma U–Pb age on one of the felsic tuff beds near the basal unconformity on the eastern shore of Holyrood Bay (Israel, 1998). When coupled with the known stratigraphy and external contact relationships elsewhere, this date provides strong evidence for the existence a marine sedimentary succession that predates not only the Manuels Volcanic Suite and the Wych Hazel Pond Complex, but also the Conception Group strata (east of the Topsail Fault) that lie above the latter complexes. The age (or ages) of the other sedimentary outliers remains largely unconstrained at this stage.

ST. JOHN'S GROUP

Very little of the area shown as St. John's Group on King's (1988a) map of the Avalon Peninsula was included in the mapping reported upon here. The most typical facies encountered in the study area is comparable to that described as typical of the Fermeuse Formation, and possibly of the lower Renews Head Formation, east and northeast of the study area (*see* King, 1990). The St. John's Group rocks encountered in this study are typically well-cleaved, openly and tightly folded, and fault imbricated, both on regional and outcrop scales. In some instances, imbrication occurs entirely within St. John's Group units; elsewhere (e.g., Mobile First Pond area), Conception Group and pre-Conception units are involved. The outcrop pattern and distribution of the St. John's Group contrasts with that preserved elsewhere on the eastern Avalon Peninsula, and reflects the apparent increase in intensity of tectonism encountered closer to the Holyrood Horst.

The St. John's Group in the study area is characterized by black to dark-grey shale and siltstone containing thin, continuous laminae and discontinuous, wispy laminae of grey–brown sandstone. The shales also contain nodules and lenses of brown calcareous sandstone. Thin and medium beds of slumped and disrupted sandstone are locally developed but are rare, and mainly developed within sandier, thin- and medium-bedded siltstone and sandstone units. These are found in the lowest stratigraphic parts of the section exposed east of Mobile First Pond. These may represent the base of the Fermeuse Formation or the top of the underlying Trepassey Formation (*see* King, 1990).

The St. John's Group elsewhere on the Avalon Peninsula contains stratiform-style occurrences of pyrrhotite with minor base-metal sulphides, the best known of which share some similarities with Sedex-style mineralization (e.g., Carbonear prospect; Butt, 1993). However, neither pyrite nor other sulphide minerals appear to be widely developed in the areas of St. John's Group studied here. Pyrite is the principal sulphide phase encountered, and it is associated with calcareous nodules or, more typically, within and adjacent to extensional quartz veins near fault zones. Multi-element base-metal anomalies in lake bottom sediment are coincident with the St. John's Group south of the study area (Dean and Meyer, 1983), and these may indicate a favourable prospective environment *vis-a-vis* shale-hosted mineralization.

CONCLUSIONS

1) The concept of the Harbour Main Group as a single lithostratigraphic and chronostratigraphic entity recording the late Neoproterozoic evolution of a broadly coeval volcanic field is largely incongruous with field relationships and geochronological data. The expanding and evolving geological database, only part of which is incorporated in the preceding account, necessitates revision of existing concepts of the volcano-stratigraphic development and plutonic history of the region. The data demonstrate the future need for formal revision of stratigraphic nomenclature[9].

2) The Hawke Hills Tuff, itself a composite unit, includes the oldest rocks yet documented on the Avalon Peninsula. These represent the earliest period of felsic volcanism known within the Appalachian Avalonian belt. A similar 734 ± 2 Ma protolith age has been reported on orthogneiss from the Cobequid Highlands sector of the Nova Scotia Avalon Zone (Doig *et al.*, 1991). The Cobequid rocks are spatially associated with 620 Ma volcanic successions, which are correlated with those in Newfoundland. It is possible that the correlation may extend to the earlier magmatism also, although such a linkage is highly speculative at this stage.

3) The volcanic rocks west of the Peter's River Fault fall into two major litho- and chrono-stratigraphically separate packages. The older of these consists almost entirely of calc-alkaline andesitic and rhyodacitic flows and pyroclastic rocks, which are intruded by a 640 Ma suite of metallogenically important monzonite plutons. The younger succession is dominated by red rhyolitic ash-flows, locally dated at 606 ± 3 Ma, and capped by basalt and basalt breccia. Boulder conglomerates, containing clasts of the underlying monzonites, occur at different levels within the younger succession, and at its base.

4) Rocks previously assigned to the Holyrood Granite (McCartney, 1967) or Holyrood Intrusive Suite (King, 1988a) can be separated into spatially and lithologically separate, and in some cases, temporally and genetically unrelated plutons.

5) Observations made in the Butlers Pond area point to the presence in that area of a lithologically unique, composite pluton, that has been affected by extensive and locally intense hydrothermal alteration and brecciation. Glacially dispersed granite boulders in this area have porphyry-copper-style alteration and copper–gold mineralization; these boulders have features found not only in this pluton but also in others farther to the north.

[9] New nomenclature will be formally proposed following completion of mapping and related geochemical and geochronological work in 2001.

6) The volcanic complex that hosts the high- and low-sulphidation-style alteration systems found along the east side of the Holyrood Horst (Manuels Volcanic Suite) include some of the youngest volcanic rocks in the area (ca. 585 Ma). These same or similar rocks reappear east of the Topsail Fault, in large-scale periclinal anticlines immediately south of the Witless Bay Line, where they host zones of silica alteration similar to that in the Manuels region.

7) The Manuels Volcanic Suite and the overlying Wych Hazel Pond Complex record the transition from mineralized (Au–Ag) subaerial epithermal conditions to mineralized (Zn–Pb–Cu) submarine conditions. These successions record the collapse and submergence of the metallogenically important ca. 585 Ma volcanic arc, characterized by widespread hydrothermal activity. The upper marine volcano-sedimentary succession has significant, largely untested potential for both conventional and Au-rich VMS-style mineralization, such as that preserved in the Pastureland Road prospect. This unit has significant aerial extent, most notably to the north-northeast, where it can be traced onto the St. John's Peninsula.

8) Marine sedimentary rocks preserved in synclinal keels within the Holyrood Horst (either side of the Hawke Hills) pre-date the Wych Hazel Pond Complex and Manuels Volcanic Suite by as much as 40 Ma. The existence of siliciclastic basins that pre-date Neoproterozoic volcanic complexes is also well documented in the western Avalon Zone, where deposition of marine turbidites from 620 to 610 Ma (Connecting Point Group) and between 570 and 555 Ma (Anderson's Cove Formation) bracket the 590 to 575 Ma evolution of a major volcanic arc (Marystown Group; O'Brien *et al.*, 1996).

9) Of the marine sedimentary rocks traditionally assigned to the Conception Group in the study area, only those east of the Topsail Fault and west of the Peak Pond Fault unequivocally postdate all Neoproterozoic volcanism within the Holyrood Horst. Within the study area, these sedimentary rocks clearly pass gradationally upward through 565 ± 3 Ma Mistaken Point Formation into the overlying St. John's Group; these same sections have been mapped by King (1990) to continue upwards (to the east) into the latest Neoproterozoic Signal Hill Group.

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