Current Research (2010) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 10-1, pages 77-92

THE SETTING OF OROGENIC, AURIFEROUS QUARTZ VEINS AT THE GOLDEN PROMISE PROSPECT, CENTRAL NEWFOUNDLAND AND OBSERVATIONS ON VEINING AND WALL-ROCK ALTERATION

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ABSTRACT

The Golden Promise prospect, also termed the Jaclyn Zone gold prospect, is located ca. *10 km southwest of the community of Badger in central Newfoundland in the Exploits Subzone of the Appalachian Orogen. Although the bedrock is poorly exposed, an extensive new industry and government geological database for the region indicates that the deposit comprises a series of* en-echelon-*style, east- to east-northeast-trending, auriferous quartz veins hosted near the sandstone–shale transition in the uppermost sections of the Exploits Rapids formation (also termed, Upper Stanley Waters formation) of the Victoria Lake supergroup. These veins were emplaced, roughly coplanar, and contemporaneously, with a suite of subalkaline tholeiitic basaltic dykes, into the hinge zone of a regional, 2–3 km wavelength, shallowly northeast-plunging, southeast-inclined, non-cylindrical F_1 (Salinic?) fold of volcanogenic sedimentary rocks of the Exploits Rapids formation, Lawrence Harbour formation (Caradocian shale) and the overlying Badger Group siliciclastic sedimentary rocks. Native Au occurs as blebs in vuggy cockscomb-textured quartz, but more commonly in the margins of chlorite+sericite and sulphide-rich, stylolitic quartz veins. High gold concentrations correlate with increased volumes of pyrite and arsenopyrite, but not necessarily with the rare chalcopyrite, galena and sphalerite. Alteration associated with these veins is manifest as bleached, irregular anastamosing zones in siltstones and mudstones proximal to the veins, with bleached, spotted zones occurring up to 10–15 m outward from the veins. Alteration in sandstone is more visually cryptic but largely comprises sericite–chlorite–carbonate–albite replacement of the matrix. Visual-infrared spectrometry, petrographic analysis and electron microprobe studies indicate that the alteration assemblage is dominated by Fe-chlorite+sericite+$Ca(Fe)CO_3$, whereas albite and/or Ba K-feldspar occur locally near veins.*

INTRODUCTION

The Golden Promise prospect (Jaclyn Zone gold prospect) lies within the Badger map area (NTS 12A/16; Figures 1 and 2) in central Newfoundland. It was discovered in 2002, by prospector William Mercer after a forest fire razed thick brush in heavily drift-covered areas, immediately southwest of the community of Badger. The initial discovery consisted of coarse-grained, comb-textured and stylolitic quartz boulders exposed on sub-cropping, bedrock-cored ridges. A composite sample from about 10 of these boulders assayed *ca.* 30 g/t Au. The prospect was immediately optioned by Rubicon Minerals Corporation and has since been explored under a number of joint venture projects involving Rubicon Minerals Corporation, Paragon Minerals Corporation, Placer Dome Limited and Crosshair Exploration & Mining Corporation. Since 2002, the property has been subjected to intense study, including: the completion of 8250 line-kilometres of airborne magnetic and electromagnetic surveys, a regional soil-sampling program that included *ca.* 6000 B-horizon samples, intensive prospecting and mapping and 98 near-surface (<314 m depth) NQ drillholes totalling 15 310 m. A NI-43-101F1-compliant resource calculation on the main Jaclyn Zone (Pilgrim and Giroux, 2008) outlines a total of 921 000 tonnes averaging 3.02 g Au/t (89 500 contained ounces of gold), with a cut-off grade of 1 g/t Au. The Golden Promise prospect therefore represents the first significant gold resource in this part of central Newfoundland, where low metamorphic-grade sedimentary rocks were previously considered non-prospective for mineralization. Further definition drilling and bulk sampling to test the veracity of the current resource outline is being considered (Crosshair Exploration & Mining Corporation, Press Release, September 23rd, 2009).

Publicly available Newfoundland and Labrador mineral exploration industry assessment reports and new government data contribute significant new knowledge to the geol-

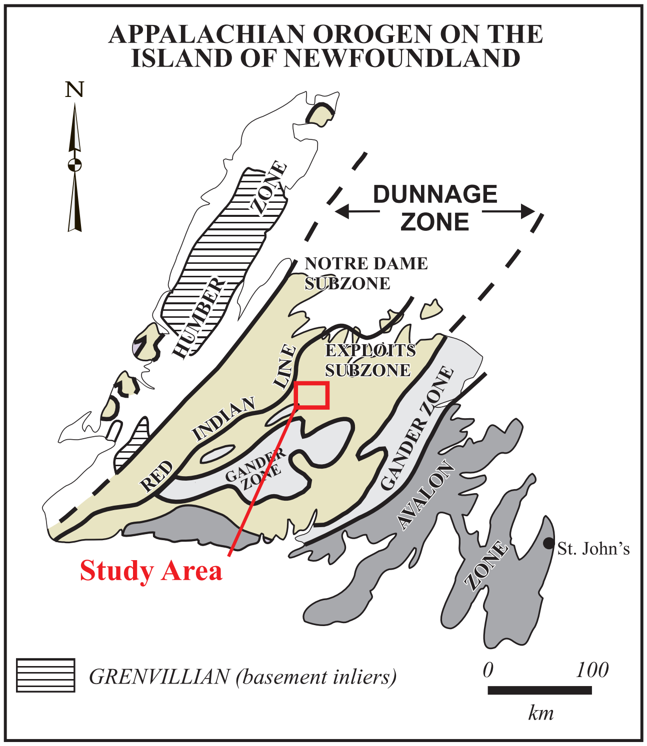

Figure 1. *Location of the Badger map area (NTS 12A/16) in the Exploits Subzone of the central Newfoundland Appalachians.*

ogy of the area and provide a basis for better focused, future mineral exploration and research. This contribution discusses the current state of knowledge of the Golden Promise prospect, and, in particular, the Jaclyn veins seven years after initial discovery. We overview the data, address some of the resultant hypotheses generated by industry during this interval and, discuss the implications for the regional setting of the Golden Promise prospect and the geology of the Badger area. We conclude with a brief overview of the ongoing research into the origin of the gold mineralization and its associated alteration.

REGIONAL SETTING AND EVOLUTION OF THE BADGER AREA

The Jaclyn Zone and larger Golden Promise property lie within the Exploits Subzone of the Dunnage Zone of the Newfoundland Appalachians (Figure 1). The Dunnage Zone comprises accreted arc and back-arc terranes that were formed in the Iapetus Ocean during the Cambro-Ordovician. A prominent feature of the Dunnage Zone is the Red Indian Line, a major crustal-scale fault zone that juxtaposes rocks of the peri-Gondwanan Exploits Subzone to the southeast, against peri-Laurentian oceanic rocks of the Notre Dame Subzone to the northwest (Williams *et al.*, 1988; Williams, 1995; Zagorevski *et al.*, 2007; van Staal *et al.*, 2009).

The Exploits Subzone is dominated by rocks of the Victoria Lake Group, a lithologically diverse and structurally imbricated series of arc-related volcanic assemblages including the Tulks Hill, Long Lake and Tally Pond belts and the sedimentary-rock-dominated Harpoon Brook belt (Evans and Kean, 2002). The structural complexity of these rocks and recognition that the assemblages are composed of petrologically distinct volcanic suites has resulted in the proposal to establish the Victoria Lake supergroup (VLS; *cf.*, Evans and Kean, 2002; Rogers and van Staal, 2002), a lithostratigraphic term that more easily accommodates all of the diverse terranes and rock types. The marine volcaniclastic sedimentary rocks of the Harpoon Brook belt consist of variably coloured shales and mudstones along with volcaniclastic sandstones and wackes considered to represent a number of Bouma cycles (Kean and Jayasinghe, 1982) that collectively demonstrate a megascopic, fining-upward sequence away from the major volcanic centres. These marine, clastic, volcanogenic sedimentary rocks dominate the VLS in the Badger map area and were recently assigned, in total, to the Stanley Waters formation (Rogers *et al.*, 2005). Following the lithostratigraphic subdivisions of Kean and Jayasinghe (1982) and Evans *et al.* (1994), these sedimentary rocks were informally subdivided by McNeill (2005; *in* Copeland and Newport, 2005) into two distinct formations and the names Badger Lookout formation and the Exploits Rapid formation were proposed. The two formations of McNeill (2005) generally correspond to units 3a and 3b of Kean and Jayasinghe (1982) and to units 4a and 4b of Evans *et al.* (1994).

Overlying the rocks of the Exploits Rapids formation, are pyritic and graphitic black mudstones of variable thickness and are Caradocian on the basis of widespread graptolite occurrences (*cf.*, Williams and O'Brien, 1991). Contacts between the Caradocian rocks and the Exploits Rapid formation are commonly sheared and complex, but have locally been reported as conformable (Kean and Jayasinghe, 1982). These graphitic mudstones are now recognized to comprise the Lawrence Harbour formation comprising the uppermost sections of the Victoria Lake supergroup (Rogers *et al.*, 2005). Possibly conformably overlying the Lawrence Harbour formation are the continentally derived, overlap rocks of the Ordovician–Silurian Badger Group. The Badger Group (Williams, 1995) is considered to have been deposited in a restricted oceanic basin during final closure of Iapetus Ocean, and in the map area, is dominated by interlayered, thick-bedded, polymictic conglomerates and medium-grained quartz arenites having sparse shale horizons.

The first modern geological map of the Badger map area (Kean and Jayasinghe, 1982) indicated that the host rocks of the Golden Promise prospect veins comprised part of their unit 5, subsequently termed the Badger Group

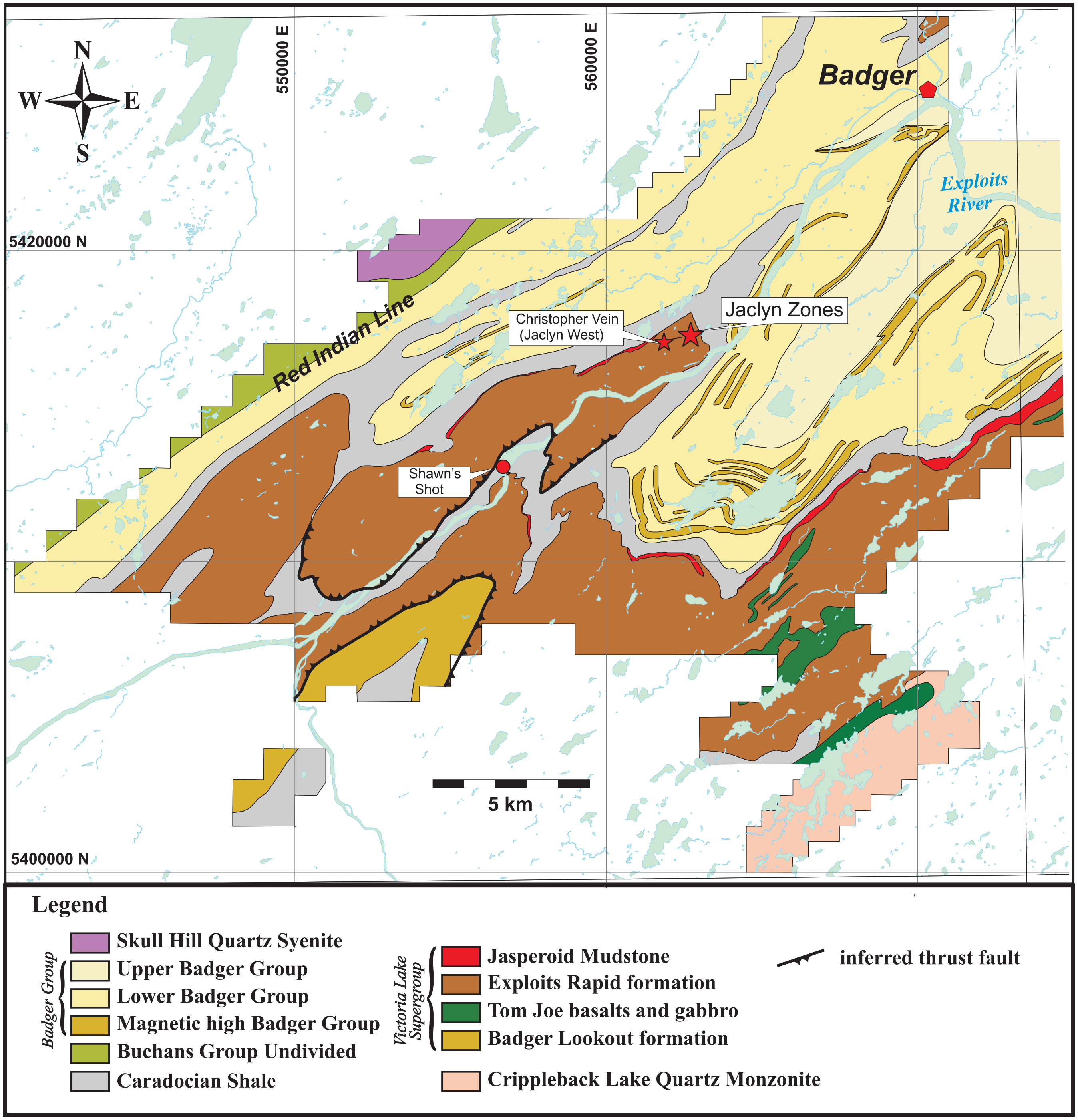

Figure 2. *Geological map of the Golden Promise prospect and the region (adapted from McNeill, 2005) showing the location of the Jaclyn Zones at the inferred top of the Exploits Rapids formation of the Victoria Lake supergroup. Also shown are the locations of the Christopher vein (Jaclyn West) and the Shawn's Shot. Note the repetition of the Exploits Rapids formation – Caradocian shale contact south of the Jaclyn vein implying a thrust contact (Tarnocai, 2004; McNeill, 2005).*

(Williams, 1995). Evans *et al.* (1994) presented a revised version of the Badger map area. Much of their revision was based on changes in the ages of some of the constituent lithostratigraphic units and they added new mineral occurrence data. The rocks of the Badger Group were also recognized to be Silurian–Ordovician rather than Ordovician (unit 10 of Evans *et al.*, 1994). Recently released, detailed airborne-magnetic and resistivity studies (Copeland and Newport, 2004) in this area of poor exposure have, however, outlined persistent and continuous magnetic and conductive *versus* poorly magnetic and non-conductive horizons within the rocks of the study area. These potential-field datasets have significantly improved our knowledge of the 3D architecture of the rocks of the region and have greatly facilitated the construction of new geological maps. One significant contribution from the detailed aeromagnetic data has been the recognition of a cryptic array of mafic dykes that were termed the Exploits dykes by McNeill (2005). These were quickly recognized to be commonly subparallel to and occupy the same fractures as major, upright quartz veins at the deposit. Sandeman and Copeland (*this volume*) describe these dykes in more detail, subdividing them into two sets, Type-1 and Type-2, and propose that at least some of the Type-1 dykes are contemporaneous with the quartz veins, whereas Type-2 dykes postdate vein emplacement.

Copeland and Newport (2005) produced a detailed map and report on the property. It included an interpretation of the geophysical surveys (Tarnocai, 2004; McNeill, 2005) and a new geological map (simplified in Figure 2). Copeland and Newport (*op. cit.*) suggested a turbidite-hosted, orogenic gold model for the Golden Promise prospect, comparable to those proposed for some of the Meguma Zone deposits in Nova Scotia (*e.g.*, Moosehead, Ovens, *etc.*, Sangster and Smith, 2007) and those of the prolific Bendigo-Ballarat region of southeastern Australia (*e.g.*, Bendigo, Ballarat; *see* Bierlein *et al.*, 2000).

Concurrent with the industry work, Rogers *et al.* (2005) conducted a regional compilation of geological data from the map area and, with the addition of their own new data combined with complementary access to the then confidential geophysical data of Rubicon Minerals Corporation, generated a new, 1:50 000-scale geological map. These collectively have led to a more sound and informed subdivision of rock types and, in particular, has led to more accurate knowledge of their distribution and has better delineated the drift-covered contacts between the Victoria Lake supergroup and the Badger Group. Although both of these map documents are somewhat similar in terms of lithological and geometrical patterns, they present significantly different structural interpretations of the map area. Discussion of the differences of interpretation, and their implications for orogenesis and deformation are beyond the scope of this contribution. It is significant to note, however, that McNeill (2005) and Rogers *et al.* (2005) indicate that the auriferous quartz veins of Golden Promise are hosted by upward-fining marine clastic sedimentary rocks of the upper Victoria Lake supergroup rather than the siliciclastic flysch sequences of the Badger Group (*see* also Williams and O'Brien, 1991; Pilgrim and Giroux, 2008 and references therein).

LITHOGEOCHEMICAL CONSTRAINTS ON THE NATURE OF THE HOST ROCKS

To unequivocally determine the affiliation of the host rocks to the deposit, and whether these rocks are classical Badger Group or Victoria Lake supergroup, new lithogeochemical data was obtained for wackes and sandstones from the Badger map area. Rocks from Golden Promise prospect were obtained from trench outcrops, angular subcrop and from drillcore at the Jaclyn and Christopher veins (Figure 2). These comprised variably altered, medium-grained, plagioclase-rich wackes, and rare arenites, locally containing abundant, small lithic fragments of plagioclase-bearing, intermediate volcanic rocks (Plate 1A and B). Clinopyroxene, and quartz in particular, are rare. Badger Group rocks were collected from widely separated exposures along the Trans-Canada Highway and from local forest-access roads. All of these outcrops are either coarse-grained, thick-bedded, polymictic conglomerates or medium-grained, lithic wackes. The lithic wackes are dominated by blue-grey quartz and less common plagioclase and detrital micas (Plate 2A and B). These locally have abundant, grey-black mudstone beds and rip-up clasts and mudstone lithic fragments.

Eighteen, comprehensive lithogeochemical analyses were obtained from wackes from the exposed bedrock, subcrop and drillcores at the Jaclyn and Christopher veins along with 7 analyses of widely separated lithic wackes from the Badger Group. A series of four variation diagrams (Figure 3) serve to illustrate some of the most significant major- and trace-element compositional differences between the rocks. Badger Group rocks have significantly higher Mg#s (47.9–59.6: molecular [$MgO/MgO+FeO^T$]*100) with corresponding elevated SiO_2 contents (Figure 3A) relative to rocks exposed at the Jaclyn Zone (Mg #s =31.0–56.3). The Al_2O_3 abundances in the Golden Promise rocks are higher than those of the Badger Group (12.13 to 14.99 wt. %), perhaps indicating their derivation from a more aluminous (feldspathic?) source (Figure 3B). This is supported by the correspondingly elevated Na_2O and K_2O abundances in wackes of the Golden Promise prospect (Figure 3C). Elevated MgO (Mg #s) and Cr_2O_3 (Figure 3D) as well as Ni and Co (not shown) are apparently at odds with the SiO_2-rich nature of the Badger Group. Badger Group wackes are typically enriched in SiO_2, MgO, K_2O, Na_2O, Cr, Ni, LREE and HFSE, relative to those obtained from the area around the Jaclyn and Christopher veins.

A plot of Th/U *vs.* Th (Figure 4A: adapted from Kasanzu *et al.*, 2008) demonstrates that the host rocks to the

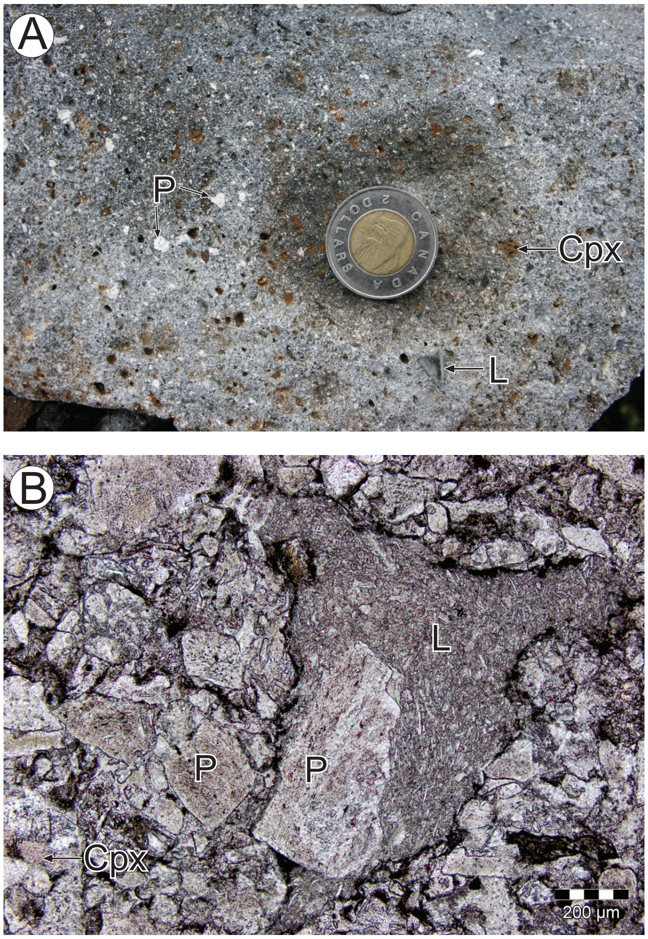

Plate 1. *A) Photograph of subcropping, plagioclase-rich sandstone (HS08-6) from the Jaclyn Main. Note the abundant plagioclase crystals and rusty, weathered-out pits inferred to be after clinopyroxene. The coin is 28 mm in diameter. B) A photomicrograph of the same sample demonstrating the plagioclase- and volcanic-fragment-rich nature of the sandstone at the Jaclyn Main area. Key: P=plagioclase; L=lithic fragment; Cpx=clinopyroxene.*

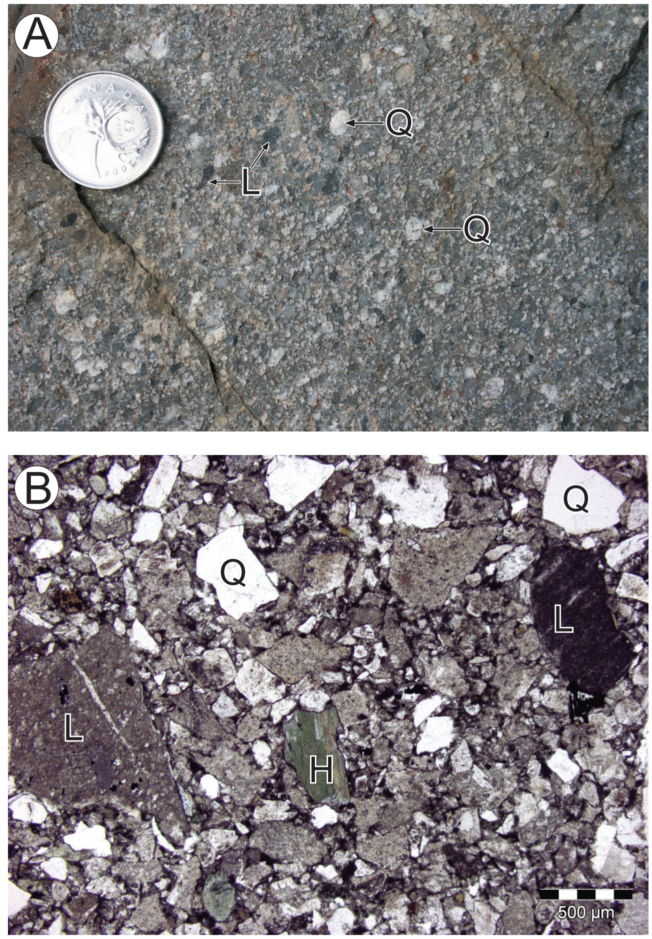

Plate 2. *A) An outcrop photograph of quartz- and lithic-fragment-rich sandstone (HS08-22) from the Badger Group. The coin is 24 mm in diameter. B) A photomicrograph of the same sample demonstrating the quartz- and mudstone-fragment-rich nature of the sandstone of the Badger Group. Key: Q=quartz; L=lithic fragment; H=hornblende.*

Golden Promise prospect are characterized by U-depleted, mantle-derived detritus, distinct from the more Th- and U-enriched, probable mixed mantle/crustal source for the Badger Group. Significantly, the Badger Group does not appear to contain detritus from highly evolved crustal sources. A plot of Th *vs.* Sc (Figure 4B; after McLennan *et al.*, 1980) emphasizes that the Badger Group is enriched in Th but contains comparable Sc concentrations relative to the host rocks of the vein systems. The Badger Group is derived from a source (or sources) collectively having an intermediate composition, in contradistinction from the dominantly mafic volcanogenic source indicated for the host rocks of the veins. Figure 4C (Th–La–Sc) further outlines a mixed mafic–felsic source for Badger Group rocks, distinct from the more Sc-enriched mafic source indicated for the wackes that host the auriferous veins. The geochemical data support the conclusions of previous investigators (McNeill, 2005; Rogers *et al.*, 2005) that the host rocks to the Golden Promise prospect are likely upper Victoria Lake supergroup or Exploits Rapids formation of McNeill (2005; *cf.*, Stanley Waters formation of Rogers *et al.*, 2005) rather than Badger Group. The host rocks to the Jaclyn and Christopher veins, were therefore derived from predominantly mafic to intermediate, feldspathic volcanogenic or volcanic rocks, whereas Badger Group wackes contain debris from mixed, both silicic crustal and mafic to ultramafic sources.

DEPOSIT-SCALE GEOLOGY AND MINERALIZATION

Four localities, Jaclyn Main and South, Christopher vein, Jaclyn north and Shawn's Shot are described below,

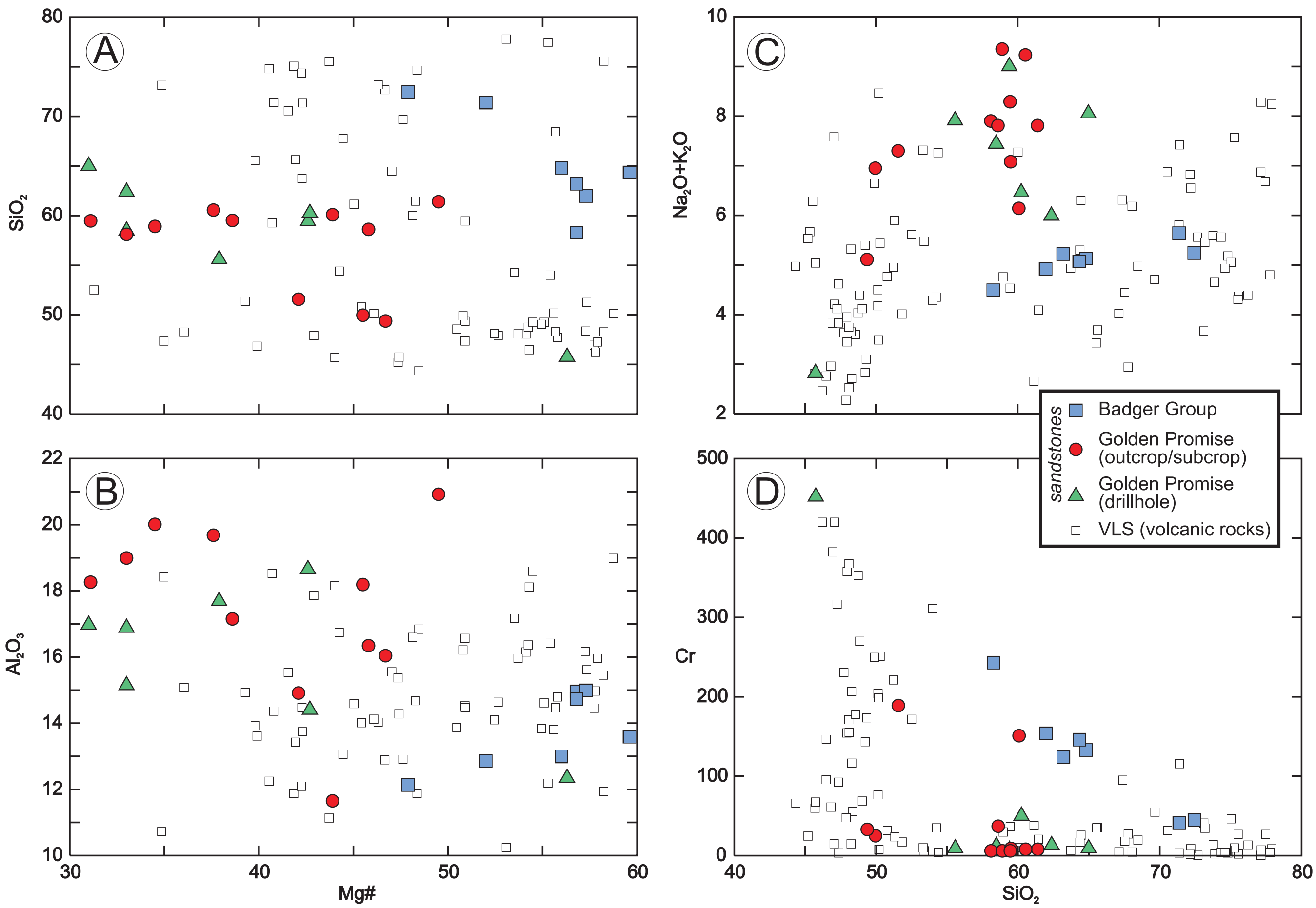

Figure 3. *Variation diagrams showing compositional variability within, and distinctions between, sandstones from the Badger Group and the Jaclyn Main, Jaclyn North and Christopher veins. Shown for comparison are volcanic rocks of the Victoria Lake supergroup from the Badger map sheet (A. Zagorevski, personal communication, 2008). Oxides in wt. % and trace elements in ppm.*

and these illustrate the local geology that hosts the Golden Promise prospect (Figures 2 and 5). The only bedrock in the first three localities was exposed by trenching and provides information on the rock types, relationships and orientations of the host sequences and the auriferous quartz veins. Shawn's Shot represents the most extensive bedrock exposure in the immediate deposit area. A detailed map of this showing is found in McNeill (2005).

The host rocks to the Jaclyn Zones, like the veins themselves, are very poorly exposed. A number of the ridge-crests in the immediate area of the Jaclyn Main Zone (Figure 5) are covered by broken, angular boulders that are inferred to represent subcrop. These comprise centimetre- to decimetre-scale, interbedded, medium-grained arkosic sandstone to wackes containing angular chert–mudstone clast-rich horizons. Bedrock in the trenches is dominated by fine- to very fine-grained cherty mudstones and siltstones and less abundant mudstone-clast-bearing wacke and plagioclase-rich, arenitic sandstone intervals. Bedding planes strike northwest and dip moderately to the northeast (Figure 5). Drillholes intersected a number of thin (≤50 cm) fining-upward sandstone beds that indicate the sedimentary package is right-way-up. The Jaclyn Main Zone contains a number of major, *ca.* east-northeast-trending sulphide and visible-gold-bearing quartz veins that have been exposed in trenches and also intersected in drillcore. A secondary set of generally thin (<4 cm thick) quartz veins have been noted in outcrop and these are moderate to steeply dipping and strike north-northeast and north-northwest. Bleaching and spotting of the host rocks, particularly in fine-grained rocks, have been noted in float and locally in the trenches. Extensive drilling reveals at least two major auriferous quartz veins cut the stratigraphy at a high angle. These veins locally contain high-grade Au intercepts (*e.g.*, GP06-52, containing 93.71 g/t gold over 1.40 m; Pilgrim and Giroux, 2008). The quartz veins commonly have pseudo-foliated, chlorite-rich stylolitic margins containing visible gold and coarser grained,

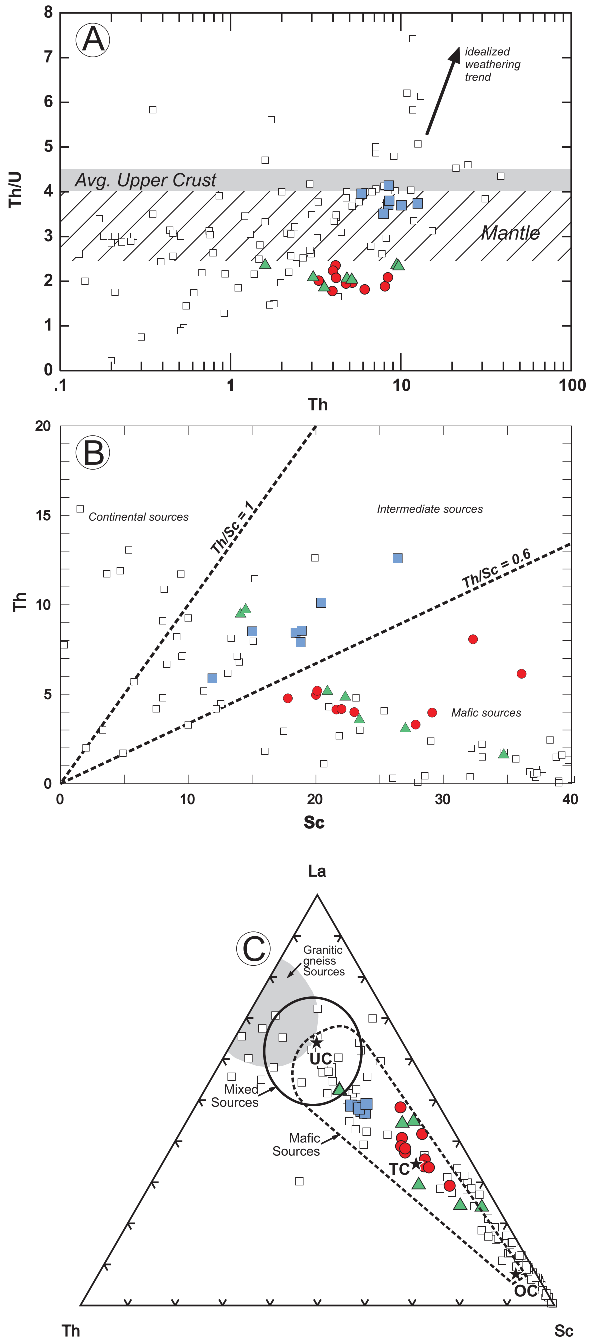

Figure 4. *Paleotectonic discrimination diagrams (elements in ppm) for sandstones of the Badger Group, Jaclyn Main, Jaclyn North and Christopher veins. A) Th/U versus Th showing the distinctly U-depleted and mildly Th-enriched character of the sandstones of the Badger Group (adapted from Kasanzu* et al.*, 2008). B) Th versus Sc plot illustrating the Sc-enriched nature of the sandstones of the Jaclyn Main, Jaclyn North and Christopher prospects (after McLennan* et al.*, 1980). C) Th–La–Sc ternary plot (after Bhatia and Crook, 1986) showing the La and Th-enriched and Sc-depleted nature of the Badger Group rocks.* See *Figure 3 for key.*

comb-textured interiors (Plate 3). The host rocks at the margins of the veins are commonly either faulted and preserve soft gouge-like material or are extensively brecciated, locally having chlorite- and sericite-altered, fine-grained sedimentary clasts (Plate 4).

Two trenches were excavated at Jaclyn North, one of which contained extensive outcrop and revealed lithological variation. Trench GP-TR-01 exposed a southwest-trending, northwest-dipping sequence (Figure 5) of metre- to tens of metres-scale interbedded clastic sedimentary rocks that varied from a few metres of arkosic sandstones in the north through *ca.* 30 m of green and black mudstones and, wacke interbeds into varicoloured mudstones in the south. Surface quartz veining at Jaclyn North exhibits two distinct orientations; a common, northwest-trending set and a less common northeast-trending set. The dips of the veins are variable, but most typically ranged from moderate to steep. In drillcore, the main quartz-vein intercepts that yielded appreciable gold concentrations (*cf.*, 5.24 g/t over 1.7 m; Pilgrim and Giroux, 2008) comprised bedding subparallel, laminated, stylolitic quartz–chlorite veins (Plate 5) having abundant brecciation textures, Fe-carbonate alteration proximal to the veins and locally, visible gold.

Approximately 500 m to the southwest of the Jaclyn Zones is the Christopher vein (Figure 2). The Christopher vein trends 085°/75°S, ranges in width from <1 to 3 m, contains abundant country-rock inclusions and has stylolitic margins, locally with a coarser grained, comb-textured interior. Visible gold is found in outcrop, however, the best outcrop assay returned a value of only 1.96 g/t Au and elevated values of As. Limited drilling similarly returned a maximum of 0.3 g/t Au over 0.7 m, accompanied by anomalous As. The Christopher (quartz) vein intercepts apparently, contain less gold than at Jaclyn (Copeland and Newport, 2005). At surface, the host rocks to quartz veins at the Christopher vein (Figure 2) are dominated by epiclastic(?) coarse-grained wackes and sandstones containing minor siltstone and mudstone intervals. Alteration of the coarse clastic sediments in the structural footwall of the vein is visually cryptic, but petrographic analysis reveals that the matrices of the rocks are extensively replaced by sericite–chlorite and carbonate. Spotting is developed in thin mudstone intervals. Rocks in the structural hanging wall are extensively hematite-Fe-carbonate-altered, medium-grained wackes.

Shawn's Shot is located at Little Indian Falls on the Exploits River, about 7 km to the southwest of the Jaclyn Zones (Figure 2). The approximately 500-m-long exposure contains a sequence of variably coloured, decimetre-scale beds of siltstone to the south, grading upward into grey and black mudstones, some of which are bioturbated, and then into black, pyritic and graphitic Caradocian shales capping

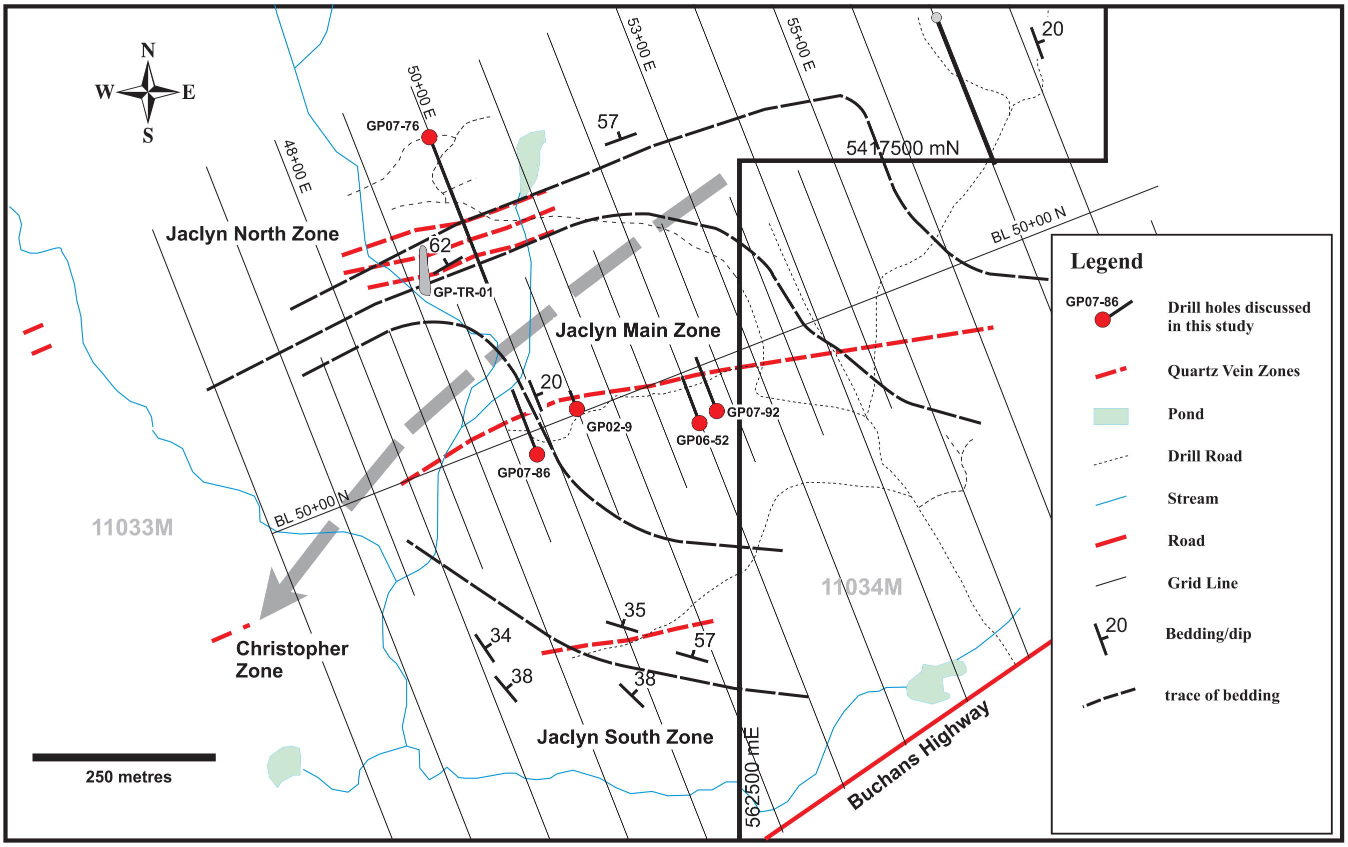

Figure 5. *Map of the Jaclyn vein area showing the location of the vein systems relative to drainage. Also shown are the locations of drillholes and trench discussed in the text, bedding measurements from trenches and the inferred trace of bedding. The large shaded arrow denotes the megascopic coarsening trend in the sedimentary rocks.*

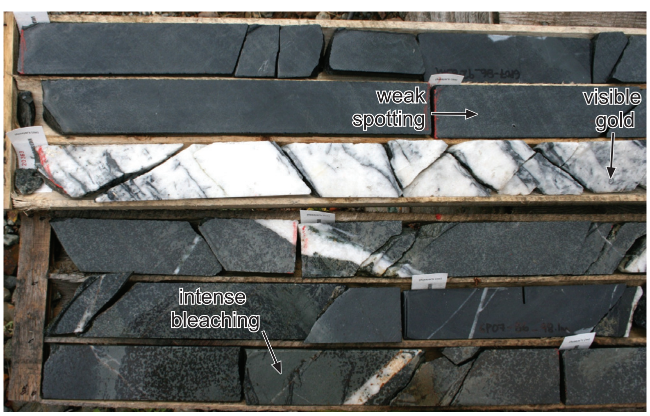

Plate 3. *Photograph of the major auriferous quartz vein and intersected in drillhole GP-07-86. Top of hole is top left of photograph and the quartz vein occurs at 94.85 to 95.45 m. This vein yielded an assay of 2.84 g/t Au and 2250 ppm As. Note the stylolitic margins with coarse-grained, comb-textured quartz intervals in the interior. Intense bleaching and spotting occurs locally in the vein footwall whereas weak spotting is prevalent in the hanging wall.*

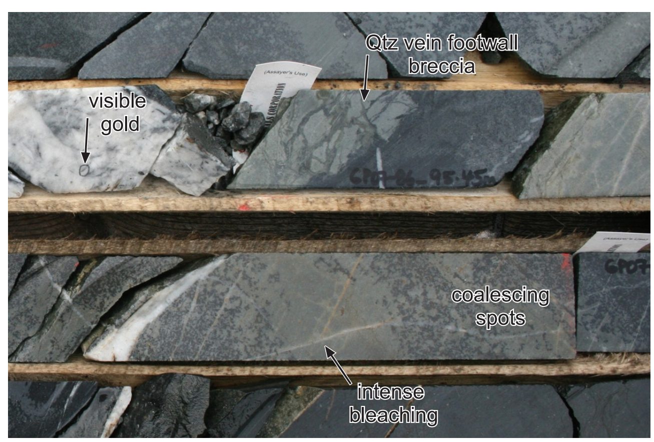

Plate 4. *Photograph showing brecciation in the immediate footwall of major auriferous quartz vein intersected in drillhole GP-07-86. Top of hole is top left of photograph and this photograph was taken immediately to the right of Plate 3. Note the strongly altered breccia fragments in the immediate footwall of the vein, the intense zone of bleaching and the adjacent area of coalescing spotting.*

Plate 5. *One of the major, bedding-parallel, auriferous quartz veins intersected by drillhole GP07-76. The vein is* ca. *25 cm in width, occurs at a depth of 123.1 m and yielded an assay of 0.51 g/t Au and 1479 ppm As. Note the stylolitic texture of the vein and, in particular, the abrupt lower margin of the quartz vein and a series of perpendicular quartz stringers in mudstone in the footwall. Top of hole is to the top left of photograph. The coin is 26 mm in diameter.*

the Victoria Lake supergroup. The rocks here are crosscut by a thin (30 cm), *ca.* 110°-trending quartz vein that contains visible gold. Two drillholes tested the exposed vein at depth and several narrow-veined zones (<15 cm) with associated altered mafic dykes (<10 cm) were intersected. Based on the core-axis angles, these composite vein–dykes zones have an east-northeast trend and steep dip, similar to that at the Jaclyn Zones. The best drillcore intercept yielded an assay of 0.60 g/t over 0.30 m (Pilgrim and Giroux, 2008) and thus the showing was deemed low priority. Despite the lack of the high gold grades encountered at surface, drilling in this area has indicated the presence of two orientations of mineralized quartz veins; *viz.*, 100° and 080° to 090°. The rocks exposed at Little Indian Falls represent the transition from the underlying Upper Stanley Waters formation (*cf.*, Rogers *et al.*, 2005) to the overlying Caradocian shale (Lawrence Harbour formation; Rogers *et al.*, 2005). The megascopic fining-upward sequence, the bed thicknesses and the rock-type associations are similar to those observed in the upper stratigraphic sections of drillcore from the Jaclyn North Zone (*e.g.*, drillhole GP-07-76: Pilgrim and Giroux, 2008), suggesting that the rocks at Jaclyn North Zone lie immediately below the Lawrence Harbour formation.

McNeill (2005) examined the regional structural geology of the Golden Promise prospect and documented the polyphase character of deformation in the area. Four generations of structures were noted and included, commonly cryptic early thrust faults containing a locally noted, related cleavage; two generations of folding and local cleavage development and; a number of late brittle faults that crosscut earlier formed structures. Folding forms the most prominent deformational feature in the area. Early formed thrusts are not easily recognized, however, repetition of folded stratigraphy that includes the Lawrence Harbour formation and the Exploits Rapids formation is exposed immediately south of the Jaclyn Zones and indicates the presence of a folded thrust surface (Figure 2). The first generation of outcrop-scale mesoscopic folds comprise upright to inclined, doubly plunging (primarily to the northeast), chevron-style folds that fold bedding and lithological contacts, have southwest-trending axial planes, and commonly exhibit broken limbs cut by small-scale faults. These folds are tight and non-cylindrical and are characterized by an interlimb angle of *ca.* 74° and generally plunge 19° toward 030° with a secondary plunge orientation of 36° toward 246° (McNeill, 2005). These are comparable to kilometre-scale folds of stratigraphy that are inferred from the regional potential-field data. Second-generation regional folds are less conspicuous, but on the basis of structural analysis of the reorientation of uncommon S_1 cleavage and the orientations of F_2 folds, McNeill (2005) suggests that these appear to be open (interlimb angle 134°) folds that have axial planes oriented 309°/73°. The dominant F_2 fold axis is oriented 45° toward 145°, however, a significant variation in the angle of plunge has been noted.

An examination of sparse outcrop in the area, the regional detailed aeromagnetic and resistivity surveys along with an extensive array of 98 drillholes provides excellent regional and downhole, 3-D control on our interpretation of the deposit-scale and regional geology. Collectively, the field, drillcore and regional data yield a number of major, first-order conclusions. The Jaclyn Zones (Figure 2) are hosted by megascopically fining-upward, right-way-up, wackes, sandstones and siltstones that are dominated by plagioclase-rich, intermediate to mafic volcanic and fine-grained pelagic sedimentary debris. These sequences are lithologically distinct from those of the Badger Group and, moreover, are also petrographically and geochemically distinct. These rocks comprise the core of a 2- to 3-km wavelength, tight, shallowly northeast-plunging and southeast-verging F_1 anticline that folds the upper Victoria Lake supergroup, the conformably overlying black, pyritic Caradocian shale and the continentally derived, turbiditic sediments of the Badger Group (*cf.*, MacNeill, 2005; Rogers *et al.*, 2005).

STYLE OF QUARTZ VEINING

Three distinct styles and orientations of major auriferous quartz veins are recognized. Discordant veins dominate Jaclyn Main, Jaclyn South, Christopher and Shawn's Shot, whereas bedding-parallel veins dominate at Jaclyn North. The upright, discordant veins crosscut bedding in the host sedimentary rocks at a high angle (trend 075–090° and dip *ca.* 70–80°S), whereas bedding-parallel veins at Jaclyn North have a similar trend (075–090°), but dip 35 to 45° N. Gold-bearing veins exposed at Shawn's Shot trend 110° and dip steeply to the southwest at 67°. A series of thinner, commonly north-northeast- and north-northwest-trending veins are also common at the Jaclyn Main, North and South areas, although these veins have yet to yield significant concentrations of gold.

The auriferous veins also exhibit two distinct textural varieties, both of which locally occur in the same vein. The first textural variant is cockscomb, coarse white quartz having local vuggy cavities that contain sparse, dispersed blebs of visible gold and trace sulphides. The second variant dominates the margins of many of the thick veins and comprises laminated, stylolitic veins with abundant chloritic septae, breccia zones and typically a greater abundance of sulphides. Both textural varieties of the larger veins have been observed to contain free gold, however, stylolitic vein margins commonly yield the highest gold assays and are invariably accompanied by pyrite along with trace arsenopyrite, sphalerite and galena. Hematite alteration of early formed sulphides is common throughout the veins and in their adjacent alteration haloes and, is particularly prevalent in the structural hanging wall of the Christopher vein (Figure 2).

Major veins at Jaclyn Main and Jaclyn South are hosted by alternating packages of graded sandstones or wackes, having thick intervals of grey, black, brown or tan siltstones and mudstones. In comparison, the Christopher vein is hosted largely by coarse volcanogenic (epiclastic?) sandstones and wackes containing fewer siltstone and mudstone horizons. The Christopher vein is inferred to have been emplaced into coarser grained, deeper portions of the host Exploits Rapids formation. These coarse-grained sedimentary rocks containing lesser mudstone possibly reflect sediment deposition more proximal to the source of the volcanogenic sedimentary detritus (volcanic arcs?). Bedding-parallel veins at Jaclyn North are almost entirely hosted by alternating, relatively thinly bedded intervals of grey, black, brown or tan siltstones and mudstones with significantly less-abundant sandstone and wacke. Drillholes at Jaclyn North are moderately inclined on an azimuth of 160° and, at depth, these penetrated a greater proportion of coarse-grained sedimentary rocks. Veins at Jaclyn North are typically narrower than those at Jaclyn Main and Christopher (≤2.15 *vs.* ≤4.05m), and moreover, more commonly comprise only stylolitic quartz–chlorite–ankerite–arsenopyrite veins.

These two distinct vein orientations have been inferred to represent cogenetic vein systems: 1) vein systems developed roughly axial planar to regional, F_1 (Salinic) anticlinal fold axes and; 2) saddle-reef, spur-reef or leg-reef-style veins developed along bedding surfaces in the limbs of the same regional folds (*cf.,* McNeill, 2005).

STYLE OF ALTERATION

Proximal (≤2 m) to the major upright auriferous quartz veins, the host siltstones typically exhibit strong bleaching in irregular patches and anastamosing channel-like zones (Plate 6). In siltstones up to 15 m from upright auriferous quartz veins, a spotted, bleached texture is very common but is not definitively in spatial association with Au-bearing quartz veins. Alteration in coarse-grained sedimentary rocks proximal to auriferous quartz veins is subtle and commonly cryptic, and is accompanied by an increase in sulphides (typically pyrite) along with chlorite + sericite (white mica) + carbonate ± hematite. Alteration associated with bedding-parallel auriferous quartz veins (Jaclyn North) is very restricted in comparison. Spotting has locally been noted, however, it is commonly minor to moderate in intensity, and is not necessarily spatially associated with quartz-veined intervals.

Thin zones of angular breccia or fault gouge occur locally throughout the stratigraphy in close proximity to quartz veins and areas of strong alteration. These commonly contain altered angular fragments of the adjacent host rocks and include sandstone and mudstone. In the core from a number of drillholes, the breccia zones contain quartz vein and mafic dyke fragments. Although these breccia zones locally exhibit strong alteration and schistose contacts, their relationship to auriferous quartz-vein emplacement is not fully understood.

VEIN AND ALTERATION MINERALOGY

Preliminary petrographic and mineral chemical analysis has been carried out on a number of samples. In drillhole GP07-86, a 60-cm-wide, major auriferous quartz vein occurs at a depth of 95 m and contains 2.84 g/t Au over 60 cm. Intense alteration and bleaching in channel-like conduits and also in spotted zones occur in the immediate hanging wall of the vein. These bleached zones and spots are characterized by intergrown chlorite + illite–sericite + ankerite + calcite + albite + Ba-potassium feldspar. Significantly, a thin veinlet that has crosscut the bleached area contains calcite and quartz rather than ankerite. Immediately below the vein is a 5-cm-wide zone of breccia comprising angular altered fragments of siltstone and fine-grained sandstone enclosed in an anastamosing network of chlorite and quartz (*see* Plate 4). The breccia fragments and their matrix contain intergrown chlorite + illite + ankerite + calcite with abundant anhedral grains of galena and sphalerite and intergrown pyrite + chalcopyrite.

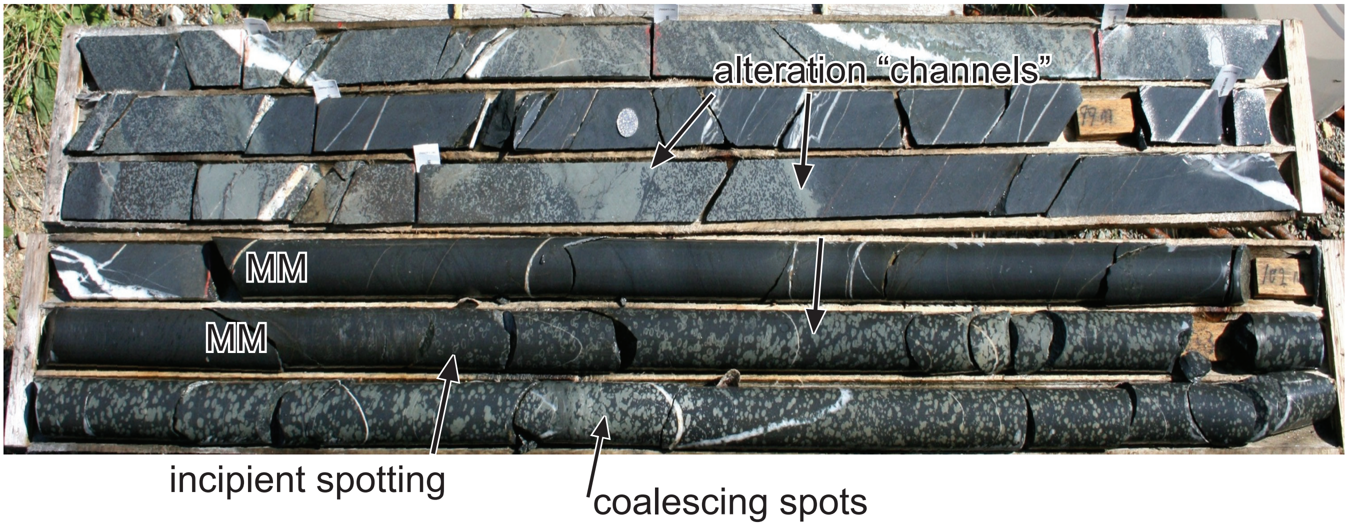

Plate 6. *Photograph showing the variability in the size, shape and distribution of bleaching and spot alteration exposed in the footwall of the main GP07-86 quartz vein (*see *Plate 4). Top of hole is top left of photograph. Note the* ca. *2-m-thick interval of massive grey-black mudstone (MM) cut by minor quartz veins, but that it lacks alteration and is less intensely veined than the remainder of the core. These cores represent the drill interval* ca. *96–105 m. The coin is 28 mm in diameter.*

Chalcopyrite has been found as euhedral grains in quartz veins. In polished thin section, however, these apparently euhedral chalcopyrite grains comprise anhedral remnant chalcopyrite surrounded by replacement mantles of bornite that is overgrown by hematite (Plate 7). Chalcopyrite also occurs in alteration patches in the adjacent wall rocks as small anhedral grains intergrown with pyrite. Locally, in some vein material, chalcopyrite occurs as fine disseminations or coatings along fractures that crosscut coarse, euhedral pyrite and arsenopyrite. Along these fractures the chalcopyrite is intergrown with hematite.

The matrix of the plagioclase-rich wacke from the immediate hanging wall of Christopher vein is intensely altered. The alteration minerals are intimately intergrown and include sericite + chlorite + carbonate + albite that are interpreted to have been overgrown by patches of hematite + sericite + illite. In one sample, the illite + sericite is apparently overgrown by a subhedral, poorly zoned *ca.* 50 µm zircon grain. Similarly, a specimen of strongly spotted mudstone, from 8 m below a major quartz-vein intercept, contains a number of monazite grains (generally <15 µm) in the alteration spots that are intergrown with chlorite + sericite + carbonate. These may prove useful for precise U–Pb geochronological dating of the timing of alteration. Intergrowths of glaucodote [(Co,Fe)AsS] and chalcopyrite have been found in spatial association with arsenopyrite. This assemblage occurs in weakly altered mudstone *ca.* 10 m above a quartz-vein intercept in Jaclyn North. The presence of glaucodote is interesting in that Co- and Cu-enriched Caradocian shale has been found in the hanging wall to the Jaclyn Zone, immediately northeast of the main showing.

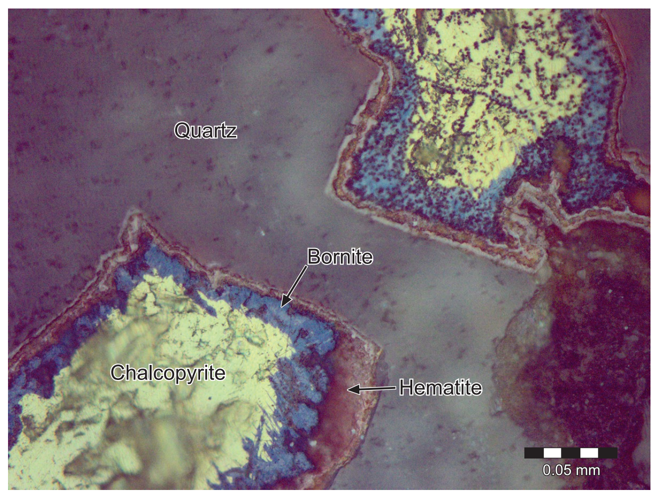

Plate 7. *Photomicrograph in reflected light of quartz-vein float (HS08-14B) from the main trench at Jaclyn South showing the oxidation of euhedral chalcopyrite to bornite and then hematite.*

The relationship between the gold mineralization and the Caradocian shales is unkown, but the Co–Cu potential in the shales may be of metallogenetic significance.

Another significant observation is that Golden Promise and the altered host rocks contain dispersed pyrite and arsenopyrite that very commonly exhibit complex dissolution-overgrowth textures. These sulphides are partly replaced by delicate-textured Fe-oxides, *e.g.*, hematite (*see* Plate 8), a relationship that appears to be particularly prevalent in late, crosscutting, fine-grained, mosaic-textured

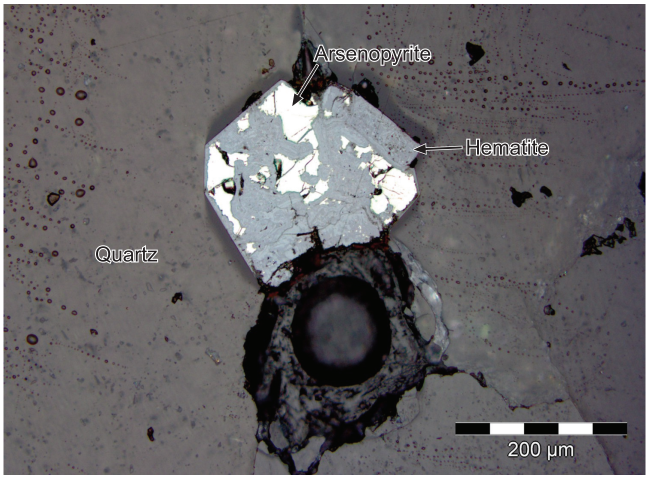

Plate 8. *Photomicrograph of quartz-vein float (HS08-11B) obtained from the discovery boulder area, showing the delicate replacement of arsenopyrite by hematite.*

quartz veins. These observations suggest that the veins and host rocks were exposed to a late pulse of oxidizing fluids. Arsenopyrite also occurs as subhedral to euhedral grains and polycrystalline masses intimately intergrown with chlorite + sericite + carbonate alteration patches. In these patches, the arsenopyrite is extensively replaced by fine-grained carbonate phases leaving remnant, anhedral cores of arsenopyrite.

To date, gold has not been observed in polished thin section, likely the result of the nugget-like nature of gold in the veins. Further sampling of the margins of quartz veins will address this problem in order to unambiguously discern the paragenetic relationships of gold with the alteration phases.

VIRS (VISUAL AND INFRARED SPECTROMETRIC ANALYSIS)

Tarnocai (2003) presented a report on 500 SWIR spectra (Short Wave Infrared Reflectance spectroscopy) collected using a Pima II spectroscope on Golden Promise rocks. In particular, a detailed investigation of drillhole GP02-9 (Figure 5) revealed distinct zonation in alteration minerals associated with quartz-vein intercepts. Alteration distal to auriferous veins is characterized by relatively iron-poor, regional metamorphic chlorite. More proximal to the veins, relatively iron-rich chlorite occurs with sericite ± carbonate in *ca.* 15-m-wide alteration haloes. Within and adjacent to the veins, the alteration assemblage is dominated by sericite + carbonate.

A range of selected drillcore and outcrop samples were examined using VIRS in conjunction with petrography. Although our database is not as extensive as that of Tarnocai (2003), our new data and observations reveal some important complexities that were not recognized by Tarnocai (*op. cit.*). Drillhole GP07-86 from the Jaclyn Main Zone was examined in detail. In GP07-86, unaltered host rocks that are distal from mineralization generally have low reflectance, whereas rocks with well-developed spotty alteration are everywhere marked by spectra indicating the presence of sericite and Fe-rich chlorite (Figure 6). With increasing depth, and in closer proximity to the main quartz-vein intercept at about 95 m (+ 3 m), there is a marked increase in the abundance of Fe-chlorite and illite. Altered host rocks (both sandstones and mudstones) adjacent to the quartz veins yield spectra that indicate strong carbonate and chlorite alteration, comparable to that observed in many of the veins. The relative VIRS response of iron-rich chlorite increases down hole toward the veins, however, only 1 m below the quartz veins, the host rocks are significantly less altered, and show little or no response in the VIRS range.

Similarly, in drillhole GP07-92, a strong VIRS response to sericite and chlorite occurs in host rocks up to 15 m structurally above a 3-m-wide quartz-vein intercept (22.2 to 25.9 m), whereas a sample of lithic wacke, 5 m below the quartz-veined zone yields no VIRS response. A sample of comparable wacke (at a depth of about 44 m) having no proximal quartz veining, however, shows a strong sericite and chlorite VIRS response comparable to that observed in rocks from immediately above the quartz veins.

These preliminary VIRS data demonstrate that, although important conclusions on the nature of the alteration phases may be obtained, alteration associated with the development of the Jaclyn Zones appears to be strongly controlled by the properties of the host rocks. Properties such as grain size and permeability are very important for the focussing of fluid flow, however, penetrative fractures and the reactivation of pre-existing fractures are also possibly very important as fluid conduits. Indeed, the widespread presence of apparently foliated, stylolitic veins that are locally brecciated, along with local breccia zones (containing altered fragments) adjacent to the veins, suggests that many of the quartz veins occupy fractures and fault zones that have experienced repeated, episodic movement. Moreover, observed crosscutting relationships between alteration (spotting) and quartz veins indicate that quartz veining must have outlasted the development of the most intense fluid-driven mineral replacement observed in host siltstones. Because there are a number of veins, and that they appear to form a subparallel array where individual veins pinch and swell, it is not always evident where breccia zones and spotty alteration occur in 3 dimensions relative to the fluid conduits. Detailed and systematic VIRS analysis of a number of representative drillholes in conjunction with mineral chemistry and lithogeochemistry is required to further clarify the nature and extent of the alteration and moreover, may pro-

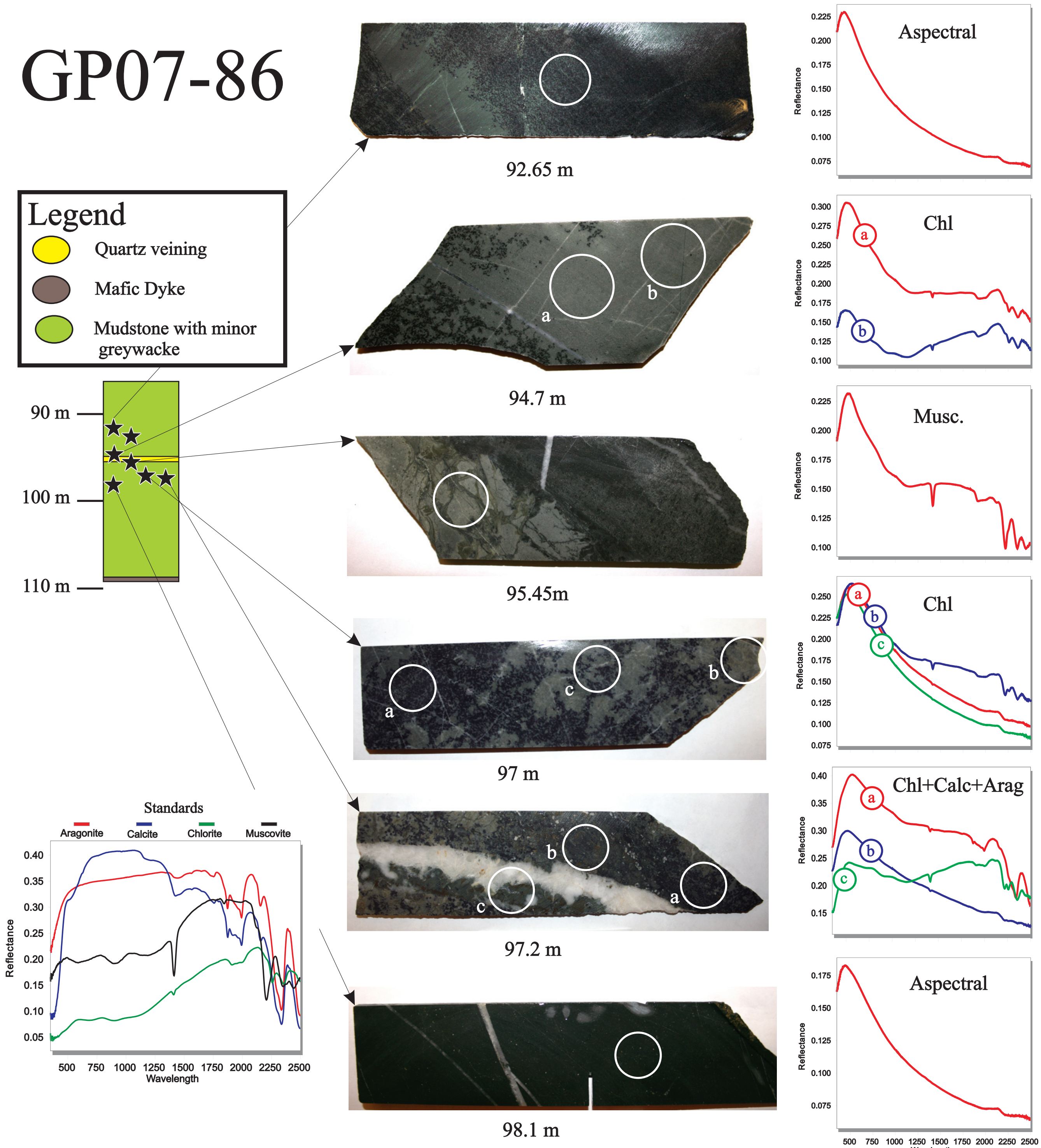

Figure 6. *Diagram showing the locations of specimens examined using petrography, VIRS and electron probe microanalysis from diamond-drill hole GP-07-86. Circled areas on the slabs show the locations of the VIRS spectra shown to the immediate right. Individual spectra are labelled according to the reflectant mineral species easily extracted from the spectrum. Reference spectra for significant mineral species are shown at the far left for comparison.*

vide a vector toward the identification of hidden quartz veins.

DISCUSSION

The extensive field, drillhole and regional geophysical investigations completed by exploration companies and the Geological Survey since 2002, along with new petrographic and mineral chemical data, provide important constraints on the setting and origin of the vein systems exposed at Golden Promise. Collectively the data are interpreted to suggest that the mineralized systems at Golden Promise are comparable to turbidite-hosted gold deposits of the Meguma Zone in Nova Scotia (*e.g.*, Moosehead, Ovens; Sangster and Smith, 2007) and those of the prolific Bendigo-Ballarat region of southeastern Australia (*e.g.*, Bendigo, Ballarat; Bierlein *et al.*, 2000). These represent orogenic quartz-vein-hosted gold systems that are developed in volcano-sedimentary fold and thrust belts during orogenesis (Groves *et al.*, 1998; Groves *et al.*, 2003). The three distinct quartz-vein orientations at Golden Promise are inferred to represent approximately cogenetic vein systems developed either roughly axial planar to regional, F_1 (Salinic) anticlinal fold axes or, they represent spur-reef, leg-reef-style veins developed along bedding surfaces in the limbs of the same regional folds (Cox, 1995; McNeill, 2005; Pilgrim and Giroux, 2008).

Such turbidite-hosted-style of mineralization involves the close interaction between progressive tectonism and an episodic flow of orogenic fluids. Indeed, the complex, multifarious relationships observed between the auriferous quartz veins, the Type-1 mafic dykes (Sandeman and Copeland, *this volume*), the numerous orientations, textural varieties and brecciation associated with the quartz veins attest to the multiphase nature of deformation, crack-conduit propagation, mafic magma injection and the infiltration of Si–CO_2–Fe–Na–K–Cl–As–Au (± others) charged fluids. The following general tectono-magmatic-hydrological scenario is proposed to explain the diverse field, structural and drillhole observations. The major northeast–southwest regional folds are inferred to be Salinic structures (MacNeill, 2005; Zagorevski *et al.*, 2007). During progressive Salinic folding and possibly thrusting, the fold systems lock up episodically as a result of fluctuation between ductile and brittle behavior of the host rocks. This fluctuation leads to periodic crack propagation and faulting roughly axial planar to the regional folds. These faults are infiltrated by early stage hydrothermal fluids, likely leading to the deposition of quartz veins. Continued variation in the regional stress field during progressive deformation, results in pulses of active faulting along pre-existing structures and similarly yields episodic veining, alteration, gold deposition and mafic magma emplacement (fault valve behaviour; Cox, 1995). Type-2 and possibly some Type-1 mafic dykes continued to be emplaced into the regional fold hinge, quartz veins and alteration envelope after faulting and quartz veining had ceased. It is not apparent if gold-mineralizing fluids were still active, however, visible gold has not been observed within the dykes, nor in quartz-vein xenoliths found within the dykes. These observations indicate that the quartz-veins and associated gold mineralization were likely emplaced during the latter stages of the Silurian Salinic orogeny. The age of mineralization is presently poorly constrained, but it is likely syn- to post-regional F_1 folding–thrusting, as the veins themselves are commonly stylolitic and locally foliated, brecciated and cospatial with fault gouge. Because emplacement of some of the quartz veins was contemporaneous with the intrusion of TYPE-1 mafic dykes, Sandeman and Copeland (*this volume*) suggest this may be constrained to the interval *ca.* 422–410 Ma.

Future work will incorporate ^{40}Ar–^{39}Ar and U–Pb geochronology, extensive regional and down-hole lithogeochemistry, mineral geochemistry as well as fluid-inclusion and stable-isotopic studies. Further lithogeochemical studies on altered host rocks and mineralized intervals will help to provide insight into the extent and nature of the alteration associated with mineralization and the metal speciation and endowments of the mineralizing fluids. Industry data indicate that, as well as having elevated Au, quartz veins and their immediate altered wall rocks are typically enriched in As, Sb, Pb and Ag relative to visually unaltered rocks. Closer integration between VIRS, petrographic and electron microprobe analysis and lithogeochemistry may help elucidate the chemical variations associated with veining and alteration and may help to distinguish auriferous *versus* barren alteration stages. This will be undertaken in a future contribution.

ACKNOWLEDGMENTS

We thank Paragon Minerals Corporation and Crosshair Exploration & Mining Corporation for access to their drill holes and databases. Lawson Dickson graciously reviewed an earlier version of this contribution.

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