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NEOPROTEROZOIC SEDIMENTARY-HOSTED 'STRATIFORM' COPPER MINERALIZATION – BONAVISTA PENINSULA, AVALON ZONE, NEWFOUNDLAND: INITIAL FIELD AND PETROGRAPHIC OBSERVATIONS

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ABSTRACT

This summary presents initial field and petrographic observations on copper mineralization in the Neoproterozoic Musgravetown Group on the Bonavista Peninsula; it focuses on observations from the Blue Point reduced horizon within the Crown Hill Formation. This represents the best example of a possible sedimentary-hosted stratiform copper-type deposit discovered in these rocks, and may be indicative of a wider potential.

Copper mineralization occurs in both, the shallow-marine sedimentary rocks of the Rocky Harbour Formation, and in the overlying terrestrial sequence of the Crown Hill Formation; but is more common in the latter. Mineralization in the Crown Hill Formation is hosted by grey reduced beds within the redbed dominated sequences, and is closely linked to the fracture systems that intersect a central core of the reduced unit, rich in synsedimentary framboidal pyrite. Oxidized fluids are interpreted to have leached metals from a previously reddened and altered underlying sedimentary sequence, with sulphide precipitation resulting from redox reactions occurring as fluids entered this sulphur-rich reduced environment. Copper sulphides are dominated by chalcocite and lesser amounts of bornite, chalcopyrite and covellite. Sulphides occur both as veinlets as well as replacements of primary framboidal pyrite and diagenetic cubic pyrite. Mineralization appears to have been introduced with silica veining, and is associated with weak propylitic alteration. Metal zonation patterns correspond with detailed stratigraphy suggesting early precipitation of V, followed by Cu, Co and Ag, followed by Pb and Zn, from upward-percolating fluids. The presence and grade of copper mineralization within the reduced horizon appears to be controlled by a combination of fluid chemistry, availability of a reductant, fracture density and permeability and porosity constraints. The metal grade variations between adjacent drillholes that contain otherwise identical rock types and stratigraphy imply that the interplay between these factors is complex, and more work is required to understand its details.

INTRODUCTION

PROJECT DESCRIPTION

This report summarizes initial work on copper mineralization hosted by late Neoproterozoic sedimentary rocks of the Musgravetown Group on the Bonavista Peninsula. The study area was explored for sedimentary-hosted stratiform copper deposits (SSC) during the late 1990s and early 2000s by Cornerstone Resources Inc. Work in 2009 focused on the Crown Hill Formation of the Musgravetown Group, which hosts the best example of SSC-style mineralization at the Blue Point prospect. Limited work was completed on copper occurrences in the lower Musgravetown Group (Rocky Harbour Formation), and in equivalent rocks elsewhere in the Avalon Zone (*e.g.*, the Long Harbour Group in the Fortune Bay area).

The report presents some initial petrographic observations and implications, and builds upon concepts previously outlined by Lane (2004) and Thorson (2004). The project is integrated with regional mapping and stratigraphic analyses in the area (Normore, *this volume*).

PREVIOUS WORK / EXPLORATION HISTORY

The earliest geological mapping in the area was conducted by Hayes and Rose (1948) who mapped the western part of the Bonavista Peninsula. This work resulted in stratigraphic correlations between the Bonavista area and the Cloud Sound area of Bonavista Bay, which defined the Musgravetown Group. The Geological Survey of Canada (GSC) published a 1:125 000-scale preliminary bedrock map of the entire Peninsula (Christie, 1950), and later completed selective follow-up work (*e.g.*, McCartney, 1958). All this work was compiled for 1:250 000-scale maps of the Terra Nova and Bonavista areas by Jenness (1963), who divided the Musgravetown Group into four formations (Cannings Cove, Bull Arm, Rocky Harbour, and Crown Hill). More recently, the Geological Survey of Newfoundland and Labrador (GSNL) mapped the area around Ocean Pond (O'Brien, 1994), and O'Brien and King (2002, 2004a, b, 2005) placed the late Neoproterozoic rocks into a revised regional stratigraphic framework.

Mineral exploration in the Bonavista area prior to 1999 was limited. A 1989 survey by Cominco Ltd. (Rennie, 1989) briefly followed up lead and zinc lake-sediment geochemical anomalies identified by earlier government surveys. In 1999, Cornerstone Resources Inc. prospectors discovered copper in the redbed successions of the Crown Hill Formation (later termed the Red Cliff property). The best prospects were drilled under a joint venture with Noranda Inc. in 2001 and 2002, and follow-up work was conducted by Cornerstone Resources Inc. (*e.g.*, Froude, 2001; Dessureault, 2002; Graves, 2003; Seymour *et al.*, 2005). Early drilling results were favourable, and defined a chalcocite-bearing reduced unit containing 0.8% Cu over 9.7 m and 1.0% Cu and 12.1 g/t Ag over 14.25 m; with a higher grade zone containing up to 2% Cu and 23.1 g/t Ag over 6 m. However, mineralization proved difficult to trace laterally. Cornerstone Resources Inc. also targeted other portions of the Crown Hill Formation in the vicinity of Random Island and around Deer Harbour (Figure 1), and portions of the underlying Rocky Harbour Formation in the vicinity of Port Rexton and Little Hearts Ease.

REGIONAL GEOLOGICAL FRAMEWORK

The following section is summarized from earlier reports by O'Brien and King (2002, 2004a, b, 2005), and also incorporates information from Normore (*this volume*).

The Bonavista Peninsula is dominated by late Neoproterozoic sedimentary rocks that are in fault contact with older volcanic (Bull Arm Formation) and intrusive rocks to the west (Figure 1). The youngest rocks occur as local synclinal outliers of Cambrian rocks.

The Neoproterozoic sedimentary rocks fall into two distinct packages. The Conception, St. John's, and Signal Hill groups are recognized only on the eastern extremity of the Bonavista Peninsula, and the remainder of the rocks are assigned to the Musgravetown Group. These packages are separated by a significant regional structure termed the Spillars Cove–English Harbour fault zone (O'Brien and King, 2002, 2004 a, b, 2005; O'Brien *et al.*, 2006; Figure 2). The Peninsula is thought to include portions of two separate sedimentary basins that overlapped in time but had uncertain original spatial affinities.

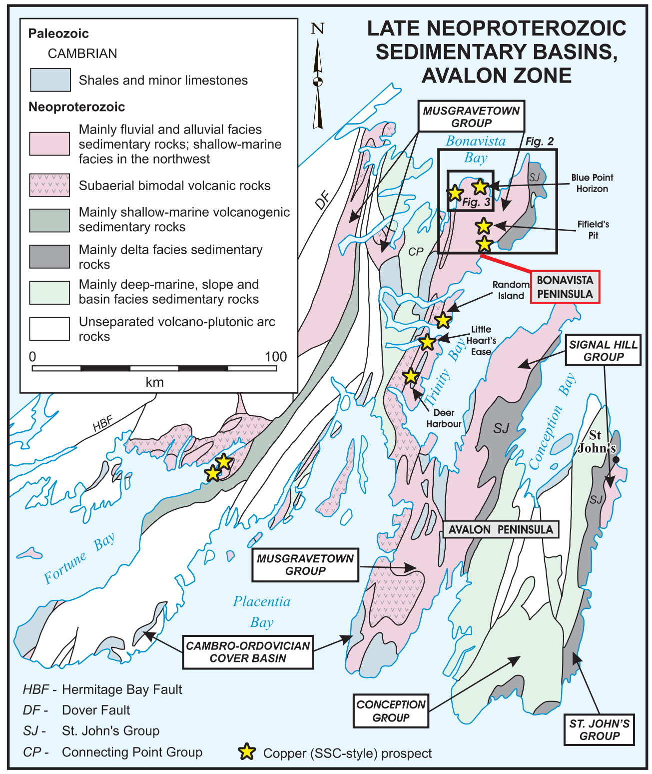

Figure 1. *Regional distribution of Neoproterozoic sedimentary rocks of the Avalon Zone showing the location of the areas studied and the location of known SSC style mineralization (modified from O'Brien and King, 2005).*

Conception Group rocks were initially suggested to occur also in the central part of the Peninsula (*e.g.*, O'Brien and King, 2002); but these were later reassigned to the base of the Rocky Harbour Formation of the Musgravetown Group (O'Brien and King 2004b); only rocks of the Musgravetown Group are discussed below.

Jenness (1963) formally subdivided the Musgravetown Group into four formations, three of which occur in the study area, including the Bull Arm, the Rocky Harbour, and the Crown Hill formations; these subdivisions were retained by O'Brien and King (2002, 2005). The various facies proposed as potential members by O'Brien and King (2005 and references therein) and Normore (*this volume*) are discussed only where they are directly related to mineralization and mineralizing processes.

The Bull Arm Formation represents the oldest part of the Musgravetown Group in the study area and occurs along the western edge of the Bonavista Peninsula (Figures 1 and 2). Normore (*this volume*) also describes pillow basalt in the middle portion of the Rocky Harbour Formation, and younger crosscutting mafic dykes. The Bull Arm Formation is bounded to the west by the Indian Arm Fault and overlain to the east by the Rocky Harbour Formation (O'Brien and

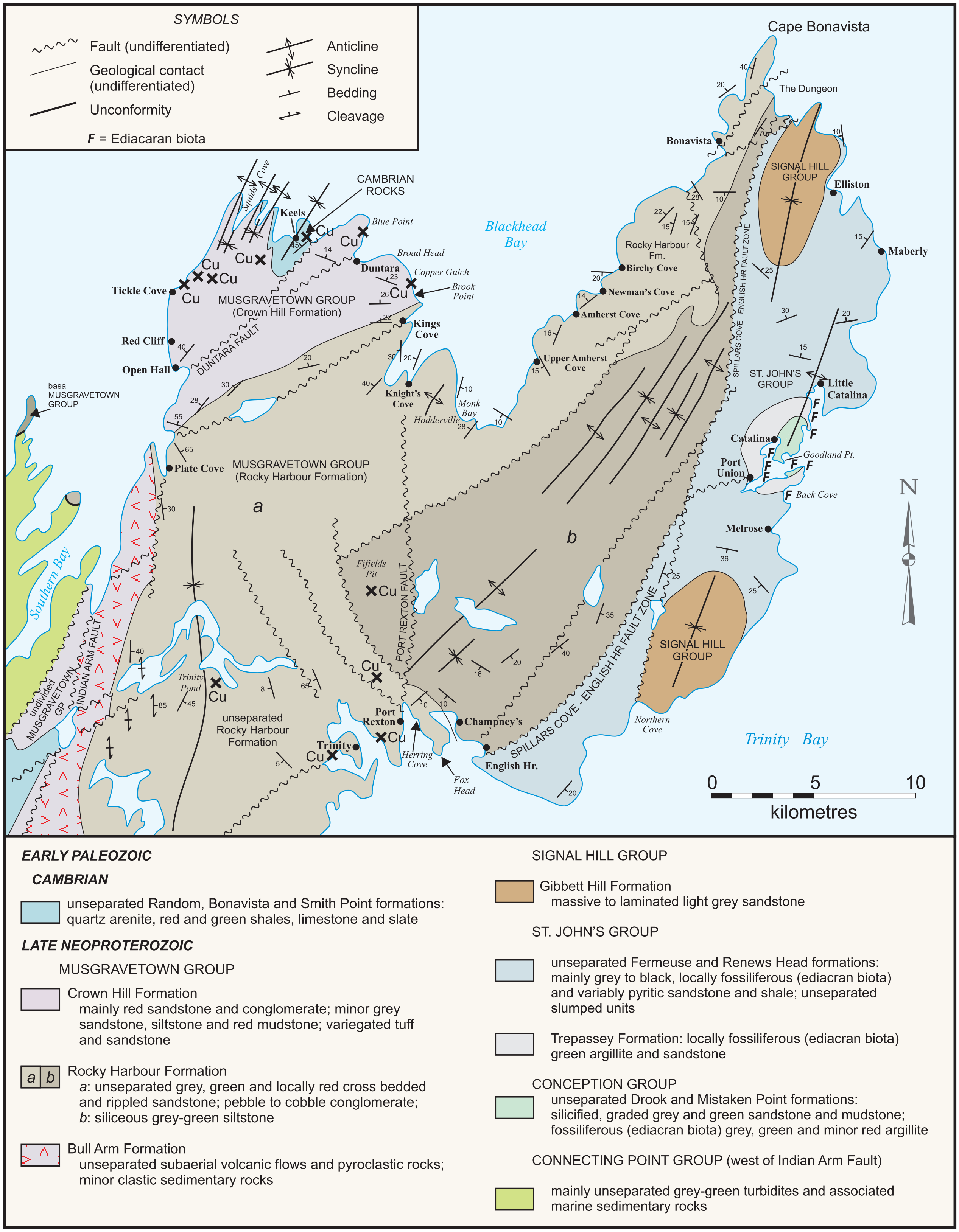

Figure 2. *Simplified map of the northern Bonavista Peninsula showing the regional distribution of rock units discussed in the text and the distribution of the main copper occurrences; see Normore (*this volume*) for a more detailed analysis of the distribution of rock units (modified from O'Brien and King, 2005).*

King, 2005). It is dominated by grey-green vesicular basaltic flows (locally columnar jointed) and red-maroon felsic flows and ash flows (O'Brien, 1994).

The Rocky Harbour Formation represents most of the Musgravetown Group in this area. O'Brien and King (2004b, 2005) divide the formation into lower and upper sections, separated by coarse-grained, well-sorted conglomerates. The lower subdivision between Bonavista and Trinity (Figure 2) is characterized by silicified and laminated fine-grained sandstones, which are variably pyritic and locally contain disseminated chalcocite mineralization (*e.g.*, Fifield's Pit prospect, Figure 2; *see* below). The upper subdivision is dominated by grey-green marine crossbedded sandstones and conglomerates, which locally have an orange to red colouration; these were partly re-interpreted as a thick, coarsening-upward, shallow-marine sequence transitional to the mainly terrestrial rocks of the overlying Crown Hill Formation (*e.g.*, O'Brien and King, 2005); this is discussed in more detail by Normore (*this volume*).

The Crown Hill Formation (Figure 3) includes the youngest Precambrian sedimentary rocks on the Bonavista Peninsula. It is a coarsening-upward redbed terrestrial succession of mudstone, sandstone and conglomerate (O'Brien and King, 2002, 2004b, 2005; Normore, *this volume*). These rocks are similar to those observed in the Signal Hill Group elsewhere in the Avalon Zone on the Bay de Verde and Avalon peninsulas (*see* King, 1988, 1990; O'Brien and King, 2002). The lower Crown Hill Formation consists of thin- to medium-bedded (~0.5–1 m) purple-grey sandstones and red mudstones. It contains distinctive, siliceous, yellow-green units interpreted to represent volcanic tuffs (*e.g.*, O'Brien and King, 2005) or remnants of dolomitic sandstones, with possible algal laminations, formed in an evaporitic tidal flat (*e.g.*, sabkha) type environment (Plate 1; O'Brien and King, 2004b; Lane, 2004; Thorson, 2004; Seymour *et al.*, 2005). The lower sandstones pass upward into red argillite, overlain by thick (10–15 m) reduced beds of grey-green-brown, laminated argillite and fine-grained sandstone. These form the Blue Point facies (O'Brien and King, 2005), which is the host to disseminated and fracture-hosted copper mineralization (Figure 3). These reduced rocks, which extend for approximately 9 km across the Duntara peninsula from Duntara to Tickle Cove, represent a return to anoxic, lacustrine, reducing environmental conditions (*see* discussion below). The mineralized, grey reduced beds are conformably overlain by coarse-grained, red pebble to cobble conglomerates.

The youngest rocks in the area are quartzites and sandstones of the Random Formation, which pass upward into red and grey mudstones and limestone of the Cambrian Bonavista Formation. More information on these rocks is given in Normore (*this volume*).

SEDIMENTARY-HOSTED 'STRATIFORM' COPPER MINERALIZATION IN THE MUSGRAVETOWN GROUP

INTRODUCTION

Since 1999, exploration by Cornerstone Resources Inc. and joint venture partner Noranda Inc. led to the discovery of numerous copper showings in the Crown Hill Formation, and also in the underlying Rocky Harbour Formation (Figures 1, 2 and 3). All of these discoveries had characteristics suggesting affinities to the currently accepted models for sediment-hosted stratiform copper (SSC) deposits (*e.g.*, Brown, 1993, 1997; Kirkham, 1996; Hitzman *et al.*, 2005).

The most significant discovery is the Blue Point prospect (Plate 2), which occurs in reduced rocks of the Blue Point facies, in the upper Crown Hill Formation near Duntara (Figure 3). This variably mineralized, reduced grey bed horizon, and a lower, barren, reduced horizon, are remarkably continuous between Duntara and Tickle Cove (Figure 3). The Blue Point prospect is the main focus of this report, although other showings were investigated. Mineral occurrences were also investigated in the Crown Hill Formation near Random Island and Deer Harbour in the southern portion of Bonavista Peninsula (Figure 1).

SEDIMENTARY-HOSTED STRATIFIED COPPER DEPOSITS: OVERVIEW OF DEPOSIT MODELS

This section is largely derived from reviews by Brown (1993, 1997), Kirkham (1996) and Hitzman *et al.* (2005), to which the reader is directed for more detailed information on this deposit type.

Sedimentary-hosted stratified copper deposits are interpreted as the product of diagenetic to epigenetic deposition of copper (with variable amounts of other metals) from evolving basin- or sub-basin-scale fluid-flow systems through the host sedimentary rocks. Deposit models call for a source of metals and sulphur, sources of fluids capable of transporting metals, thermal and or hydraulic driving mechanisms to facilitate fluid transport, and finally chemical and physical mechanisms to allow sulphides to precipitate (*e.g.*, Hitzman *et al.*, 2005). The deposits typically occur as relatively thin (<30 m), peneconcordant sulphide-bearing zones in reduced horizons that overly thick sequences of oxidized continental redbeds, or occur in reduced units within continental redbed sequences. The reduced host rocks are commonly interpreted as a basin-scale marine or lacustrine transgression into a terrestrial environment, although they may also be 'discordant' reduced zones formed in post-depositional settings (*e.g.*, Brown, 1997).

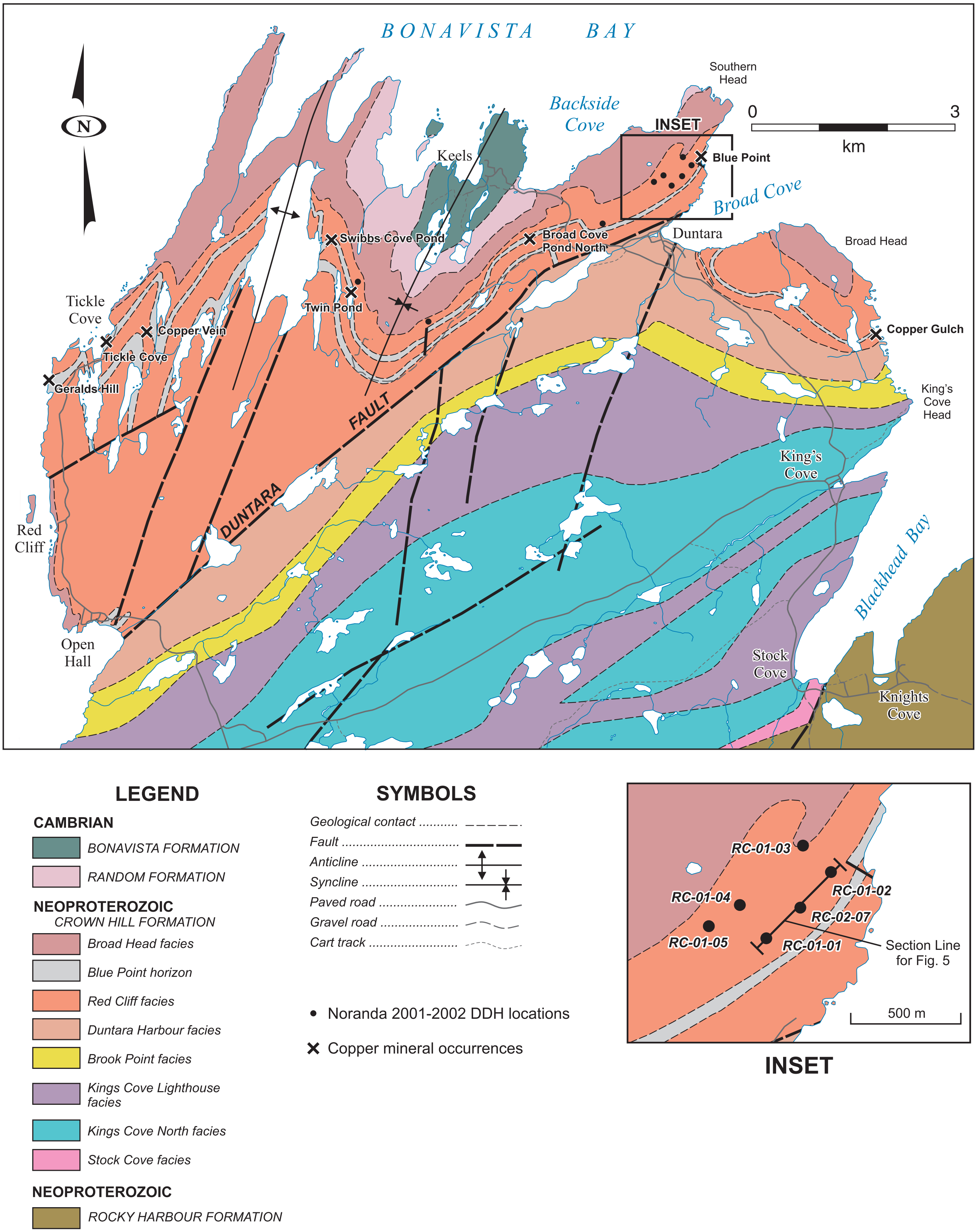

Figure 3. *Local geology of the Crown Hill Formation illustrating the location of the reduced horizons and the locations of diamond-drill holes (from Normore,* this volume*).*

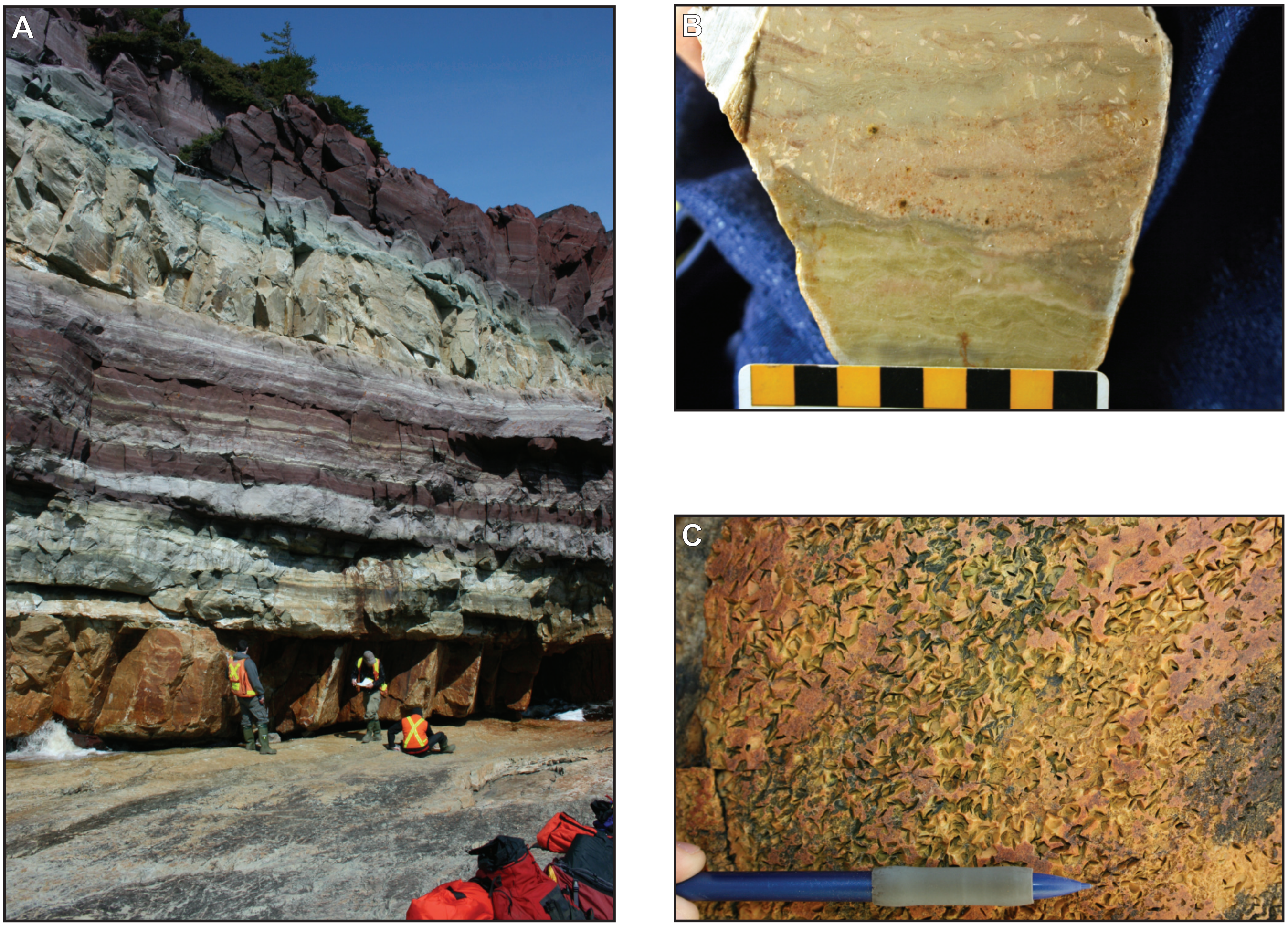

Plate 1. *A) Outcrop illustrating possible sabkha or evaporite beds in the Crown Hill Formation; B) possible examples of carbonate replaced gypsum crystals and algal mats; C) possible gypsum pseudomorphs at Brook Point.*

The source of metals in SSC deposits is largely attributed to the terrestrial redbed sequences that typically occur stratigraphically below the deposits (*e.g.*, Kirkham, 1989; Brown, 1993, 1997, 2003; Hitzman *et al.*, 2005). Redbed sequences act as permeable reservoirs interpreted to contain significant metal contents loosely held in, oxidized, first-cycle labile clastic material (*e.g.*, Zielinski *et al.*, 1983; Walker, 1989; Brown, 2003, 2005, 2006). However, the basin fill is not deposited in an oxidized 'redbed' form, rather the basin fill is subject to an evolving, early diagenetic reddening process (*e.g.*, Walker, 1967, 1989; Zielinski *et al.*, 1983; Brown, 2003, 2005, 2006). The sediment is converted to an oxidized state, from which metals can be leached and mobilized from amorphous to poorly crystalline goethitic iron oxide and clay particles by an oxidizing, low-temperature chloride brine (Zielinski *et al.*, 1983; Rose and Bianchi-Mosquera, 1993; Brown, 2005). As such, there is a close spatial and temporal relationship between the diagenetic reddening process, metal solubility, and the transport of metalliferous brines to sites of potential deposition. This process has importance when determining the validity of compaction-driven circulation models for SSC deposits, in which there is vigorous brine circulation during maximum basin compaction and fluid exsolution (*e.g.*, *see* Garven and Raffensperger, 1997 and Swenson *et al.*, 2004). These models, typically, do not recognize that the basin infill was not initially deposited as red sediments, and as such, they do not invoke the processing that is required to prepare the basin infill sediments to allow easy leaching of metals from labile minerals.

Sulphur needed to form the copper sulphides in SSC deposits can be derived from numerous sources including marine or lacustrine sulphates, or brines formed by the evaporation of these sulphates, pre-existing diagenetic sulphides (pyrite), or hydrogen sulphides in petroleum (Hitzman *et al.*, 2005). Thick, sulphate-bearing marine evaporates exist in the stratigraphy hosting the Kupferschiefer deposit in Poland and Germany (*e.g.*, Glennie, 1989), and may also have been present in the Central African Copperbelt (*e.g.*, Jackson *et al.*, 2003). This led Hitzman *et al.* (2005) to suggest that evaporates are important as sulphur sources, as

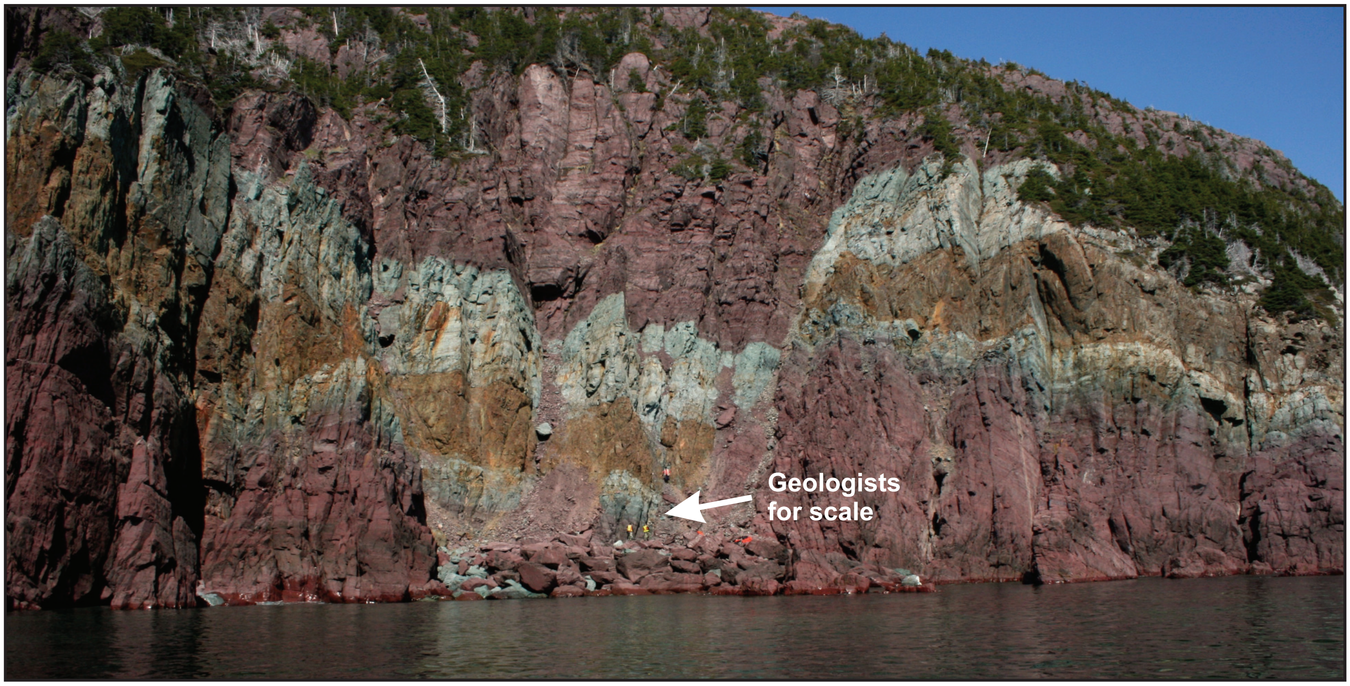

Plate 2. *Blue Point (SSC) prospect. Copper mineralization is associated with the brown-weathering, framboidal pyrite-rich core portion of the larger grey reduced horizon within the dominant redbeds. The reduced grey-brown rocks are approximately 14 m thick. Late fracturing has occurred on numerous scales. Note people for scale highlighted by the arrow.* See *text for further discussion.*

well as providing high-salinity fluids capable of leaching metals from the redbeds (*see* also Kirkham, 1989). Pre-existing diagenetic sulphides are commonly present in the host reduced sediments, where they are typically formed by bacterial sulphate reduction.

The fluids responsible for metal leaching, transport and eventual precipitation are commonly described as oxidized, low-temperature chloride brines. These brines are interpreted to permeate through the redbed sedimentary pile, to eventually encounter a reduced horizon that facilitates sulphide precipitation and formation of a SSC deposit. Brine circulation can be driven by several processes including meteoric recharge, sediment compaction, or local anomalous heat flow; the first process is preferred by recent deposit models (*e.g.*, Brown, 2003, 2005, 2006) that favour a relatively closed system model of fluid flow (*e.g.*, Hitzman *et al.*, 2005). However, it should be noted that all of these processes may play a role. Compaction-driven fluid flow occurs at an early stage, and may enhance cross-strata permeability through fluid-escape structures. Later, fluid flow may be driven through local meteoric recharge, seawater flooding or other processes. As discussed by Brown (2003, 2005, 2006), and alluded to above, conditions for metal leaching and transport would not be met until the basin had been sequentially oxidized across the basin fill. The mineralizing fluids become focused at specific depositional sites, and in some cases this is likely controlled by syn- or post-depositional faults.

Sulphide precipitation occurs through redox reactions whereby the metalliferous chloride brine interacts with reductants in the reduced grey bed host horizons (Hitzman *et al.*, 2005). Mineralization is dominated by copper sulphides (chalcocite, bornite, chalcopyrite and digenite) and lesser amounts of other base-metal sulphides, such as galena and sphalerite. The metals are typically zoned relative to the interface of the oxidized footwall redbed rocks and the reduced host rock (*i.e.*, the redoxcline of Brown, 1997). The metal zonation is distributed outward from the interface from the least soluble to the most soluble sulphides with chalcocite followed by bornite and finally by chalcopyrite. Other base metals are typically found farther from the redoxcline or farther downstream (*e.g.*, *see* Kirkham, 1996; Brown, 2003).

SEDIMENTARY ENVIRONMENTS OF MINERALIZED FACIES

Oxidized versus Reduced Environments

As discussed above, current models for SSC-type deposits all recognize the close association of mineralization with sediments deposited in localized transitional zones representing marine or lacustrine transgressive environments (*e.g.*, reduced conditions) into continental redbed (*e.g.*, oxidized) type sediments (*e.g.*, Brown, 2003, 2005, 2006; Hitzman *et al.*, 2005).

The Musgravetown Group on the Bonavista Peninsula is composed of a lower component of submarine, deltaic to shallow-marine sedimentary rocks (Rocky Harbour Formation), and an upper terrestrial redbed sequence (Crown Hill Formation). The latter is dominated by sedimentary redbed facies interpreted to have formed in continental terrestrial fluvial and/or alluvial fan environments and progressively oxidized to redbeds (Plate 3), but also contains localized, fine-grained grey reduced sedimentary rocks that are semi-concordant to concordant with bedding and are interpreted to have formed in a lacustrine-type (playa lake(?)) environment (Plate 2). Such facies could also form during episodic marine trangressions, but the predominance of the terrestrial redbed facies in the Crown Hill Formation suggests a lacustrine, rather than submarine environment.

Plate 3. *Photograph illustrating the redbed dominated nature of the Crown Hill Formation. Note the local yellow- to buff-weathering horizons, one of which represents the Brook Point facies. Photo looking north from Kings Point Lighthouse.*

The Blue Point reduced facies in the Crown Hill Formation is the best known example of a lacustrine environment (Figure 3). This facies occurs as two, 10–15-m-thick distinct horizons, consisting of very finely laminated, grey argillite to sandstone, locally with a central core containing disseminated, fine-grained framboidal pyrite (Plates 2, 4A, B, C). Coarse-grained, diagenetic cubic pyrite also occurs within the reduced horizons (Plate 5A, B). The very fine-grained nature of the reduced sedimentary rocks, in contrast to the surrounding coarse-grained, locally conglomeratic redbeds, suggests that this was a low-energy environment. Micro-laminations (Plate 4A) are perhaps indicative of algal activity. Although most contacts with the surrounding

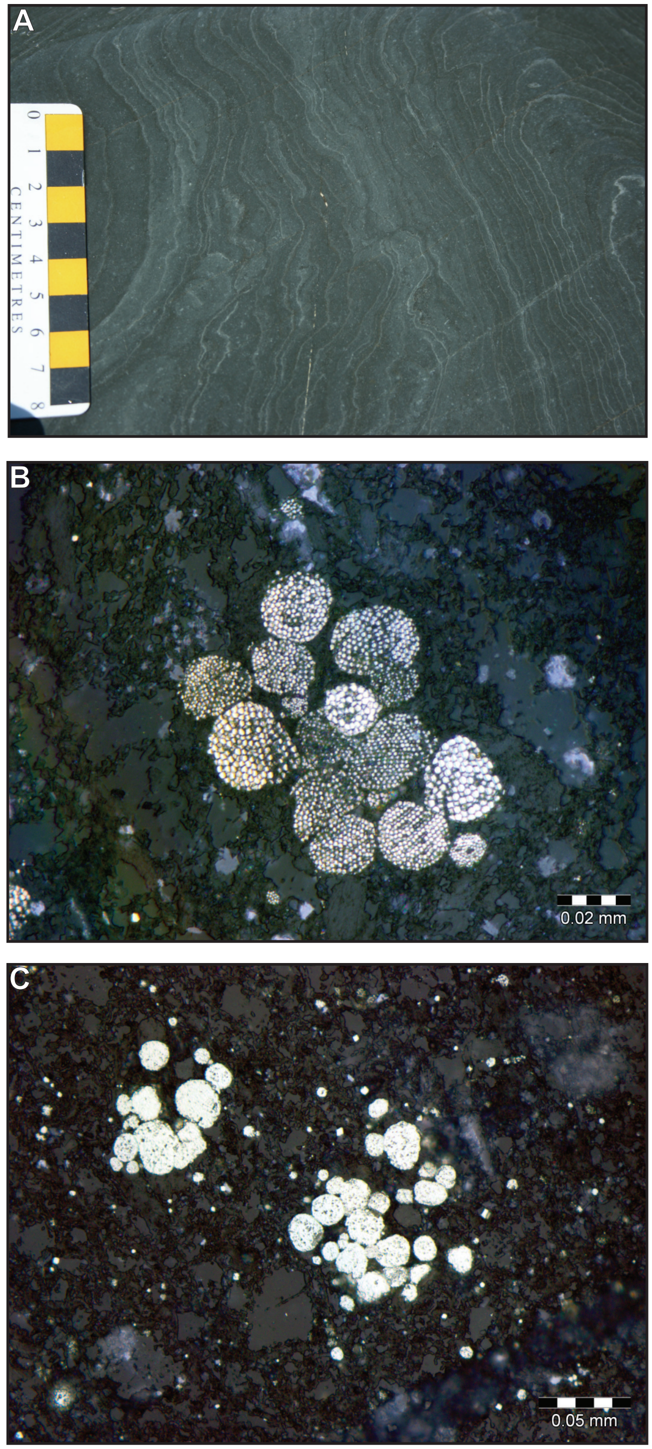

Plate 4. *A) Finely laminated grey argillite to siltstone outcrop; B) reflected light photomicrograph of well-preserved pyrite framboids in the grey fine-grained rocks that have high copper grades; C) reflected light photomicrograph of compacted pyrite framboids in the grey fine-grained rocks that have very low copper grades.*

Plate 5. *A) Outcrop south of Tickle Cove illustrating a stratigraphically controlled horizon with abundant (now weathered-out) pyrite cubes; B) analogous stratigraphic horizon with preserved cubic diagenetic pyrite from drillcore in the Blue Point mineralized horizon.*

redbeds appear gradational or transitional and subparallel to parallel to bedding (Plate 6A, B), there also are numerous examples of strongly discordant reduction–oxidation boundaries (Plate 6C). South of Tickle Cove, the reduced horizon is strongly discordant and preserves evidence supporting the idea that the fine-grained sediments were initially deposited in a reduced state, were then partially oxidized, and then returned to anoxic conditions (Plate 7). In drillcore from the Blue Point reduced horizon (Plate 8A, B and C), framboidal pyrite localized along sedimentary bedding planes (interpreted to have been produced by bacterial sulphate reduction) is replaced by titanium oxide near discordant reduction–oxidation boundaries. If the framboidal pyrite is syndepositional, the observed relationships dictate that some grey reduced beds at Blue Point were never oxidized, and that oxidation–reduction boundaries observed in the Crown Hill Formation are oxidation fronts rather than reduction fronts. Similar oxidation–reduction facies variations within the Crown Hill Formation were observed elsewhere, particularly at Random Island, Little Hearts Ease, and Deer Harbour (Figure 1). Although the stratigraphic context is not as well defined as at Blue Point, copper mineralization is similarly associated with localized, fine-grained reduced facies within surrounding redbed sequences. The distinction between the Crown Hill and the Rocky Harbour formations in these areas is more difficult, and these redbeds may not be directly correlative with those of the Duntara area. They may, instead, locally represent lower portions of the stratigraphy than the Rocky Harbour Formation, perhaps equivalent to the Trinny Cove and Maturin Head formations defined by King (1988) in the Trinity Bay area.

Copper mineralization is also documented in the Rocky Harbour Formation at the Fifields Pit, Trinity, and Trinity Pond occurrences (Figure 2), where it is hosted by grey-green, fine-grained argillites and siltstones. Although there are no redbeds in the immediate vicinity of the copper occurrences, similar rocks between Champneys and Fox Head include redbeds and also possible sabkha evaporate beds representing shoreline environments (*see* below; *see* also Thorson, 2004; Seymour *et al.*, 2005). These observations suggest that the base of the Rocky Harbour Formation was deposited in shallow-marine to exposed terrestrial environments; somewhat analogous to the proposed environment of deposition for the Crown Hill Formation. The Fifields Pit occurrence is enriched in copper mineralization compared to much of the Blue Point horizon, distal to the main showing, and there may be potential for the Rocky Harbour Formation to host SSC-style copper mineralization elsewhere.

Periods of High Evaporation Rates and Rapid Burial

The Crown Hill Formation, which hosts most of the copper occurrences on the Bonavista Peninsula, records periods of desiccation, and also rapid burial and compaction. Both of these processes are relevant to the mineralizing processes as they could serve to provide increased fluid salinities (increased potential to mobilize metals) and increased cross-stratigraphic permeability, respectively.

Desiccation or mud cracks are found within the fine-grained rocks (Plate 9A, B); and there are some very large desiccation cracks (~40 cm long) indicative of long periods of intense desiccation (Plate 9B). In the overall depositional setting inferred for the Crown Hill Formation, involving periodic flooding into an arid, terrestrial environment, such high evaporation rates could precipitate sulphate minerals such as gypsum. The salinity of the basinal waters would increase dramatically, which could promote metal mobility in basinal fluids (Warren, 2000; Thorson, 2004). Even if the process did not result in evaporite deposits being formed,

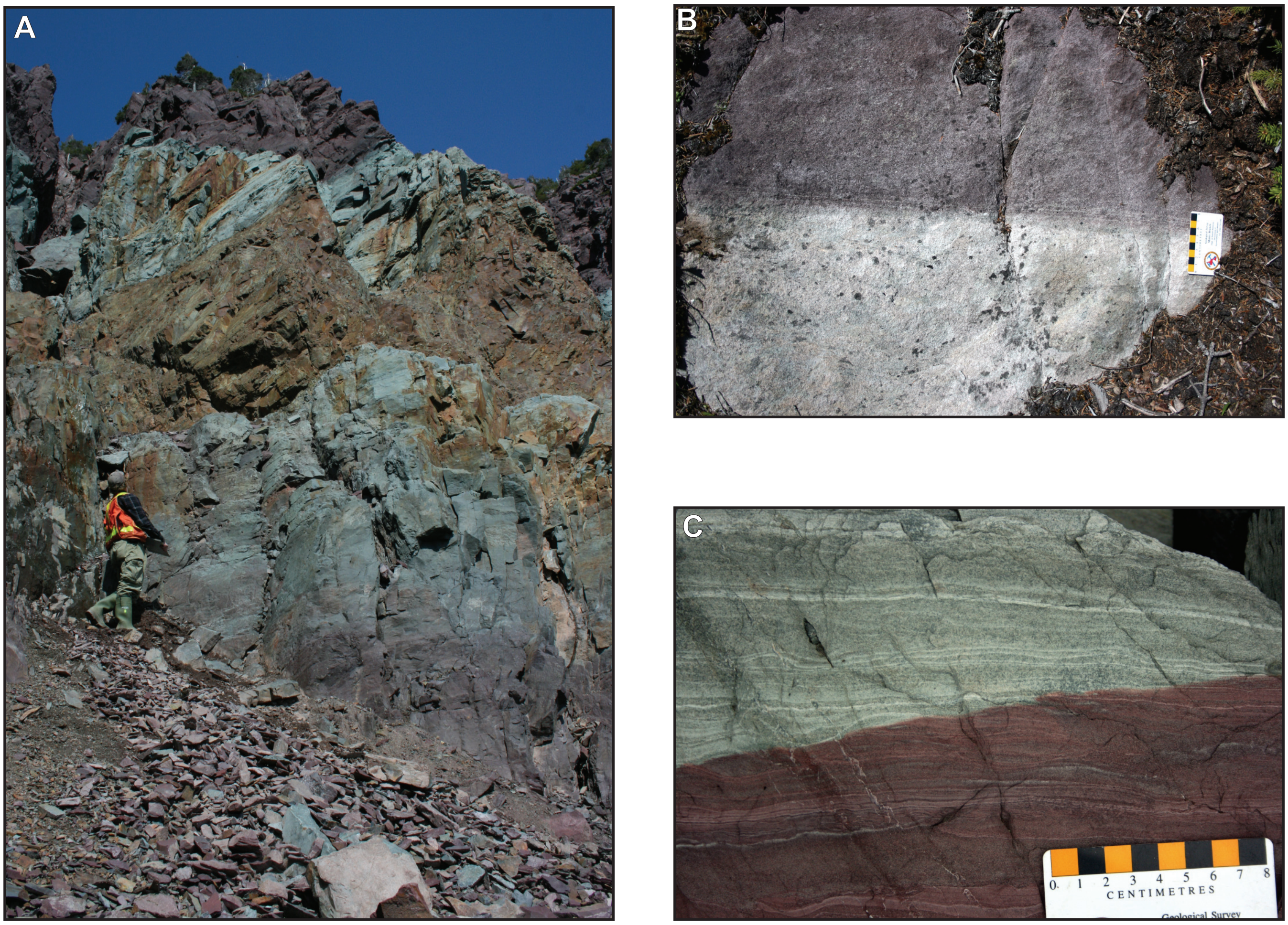

Plate 6. *A) Semi-concordant, transitional boundary between redbed sediments to grey reduced sediments with a maroon transitional zone (bottom right of photograph) at the Blue Point prospect; B) sharp, bedding-parallel contact between lower reduced rocks and above oxidized rocks; C) discordant redox boundary, south of Tickle Cove.*

salinities would still increase through the evaporation process.

Thorson (2004) suggested evaporite-bearing strata in the form of sabkha beds, a shoreline facies that is deposited along low-energy margins of lagoonal or lacustrine settings. Possible examples of sabkha-type strata occur in the area of Brook Point, in the lower part of the Crown Hill Formation (Plate 1), as well as in the Herring Cove area, in the basal part of the Rocky Harbour Formation in the vicinity of Port Rexton. These rocks contain teepee structures, and mineral casts that may be pseudomorphs of gypsum, all of which could support the sabkha-environment interpretation (Plate 1B, C). Desiccation cracks also occur in the same horizon as the possible sabkha beds at Brook Point.

There is also some evidence for rapid sediment burial and fluid over-pressuring in the Crown Hill Formation. These include loading and flame structures (Plate 10), and abundant examples of fluid-escape structures formed as over pressured fluids forced their way through laminated sediments, producing brecciation textures (Plate 11). Such processes would produce increased cross-strata permeability, which could aid in later circulation of mineralized fluids. The absence of bleached plume tracks surrounding the water escape structures in the terrestrial redbeds suggests the over pressurized fluids were in an oxidized state (Plate 11). However, local examples of reduction spheres surrounding single pyrite crystals in redbed sequences (Plate 12) as well as local examples of reduced, relatively coarser grained rocks within the redbed sequences, suggest that either some component of the basinal fluids were in a reduced state or that sufficient reductant material was locally present to cause reduction of the predominantly oxidized basin fluids.

Copper Mineralization

Copper that was eventually precipitated in the reduced horizons of the Crown Hill Formation was probably liberated from the redbeds that dominate the formation. This pro-

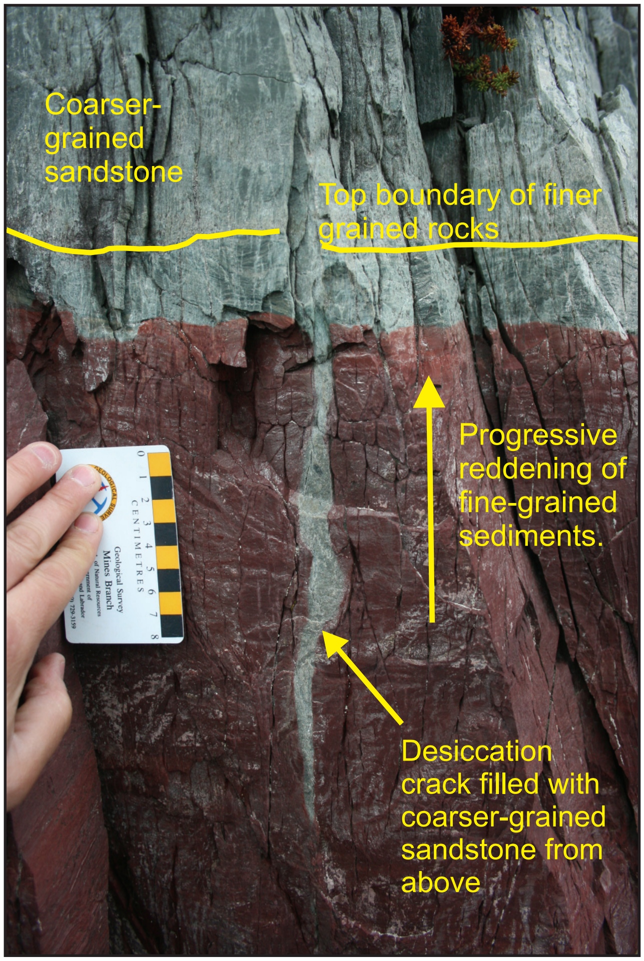

Plate 7. *Oxidation–reduction relationship that is suggestive of an incomplete oxidation front that was shut down by rapid emplacement of reduced sandstone.*

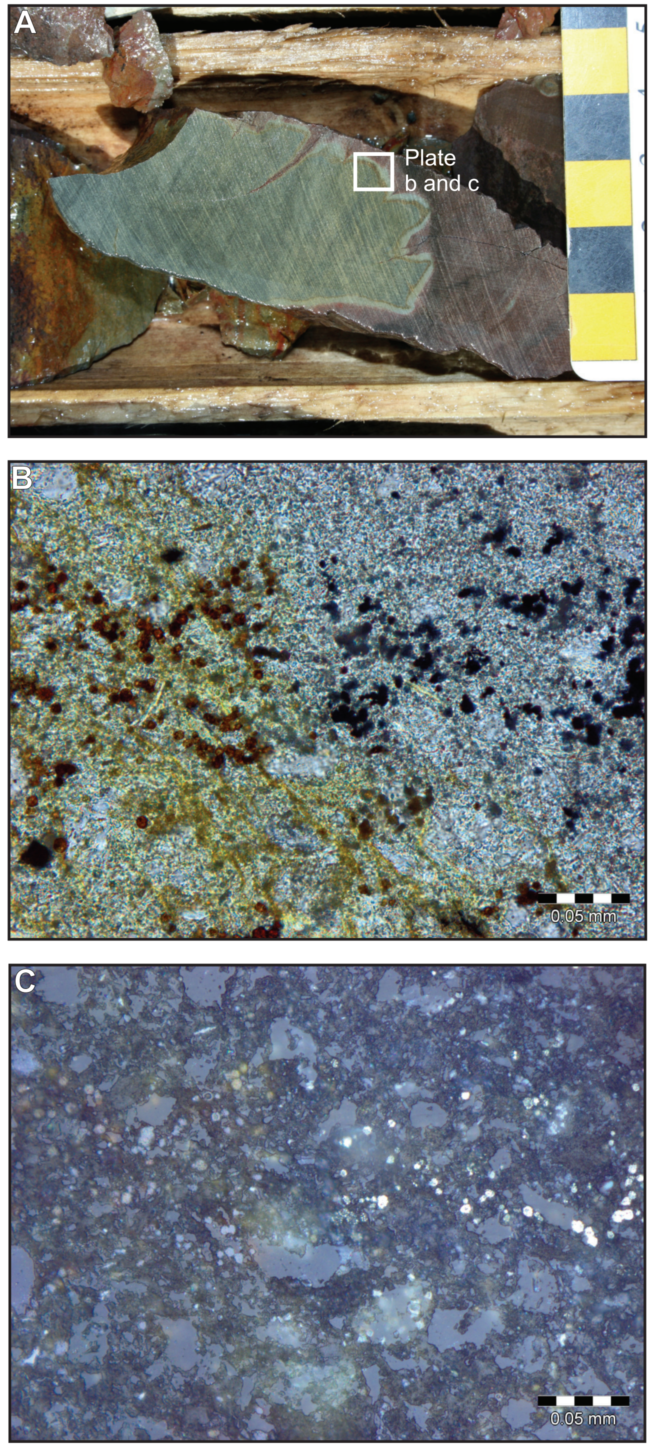

Plate 8. *A) Strongly discordant and convolute redox boundary from the Blue Point drillcore (RC-02-07), note location of Plates B and C; B) transmitted photomicrograph illustrating replacement of framboidal pyrite by titanium dioxide (rutile?); C) same as in B except using reflected microscopy.*

gressive and pervasive diagenetic reddening commonly results in the leaching and alteration of many primary mineral phases. Leaching of iron from titano-magnetite leaves pseudomorphs of titanium dioxides (ilmenite and rutile) and leuxocene (Plate 13A, B), and along with the alteration of feldspars to clay minerals (*see* Brown, 2005), would have facilitated the leaching of metals by oxidized saline fluids.

Based upon the observations made, copper sulphides occurring in the reduced horizons in the Crown Hill and the lower Rocky Harbour formations were precipitated after partial cementation and lithification of the host sediment occurred. The highest concentrations of copper are associated with siliceous veinlets that typically crosscut bedding but also locally veer into the plane of bedding lamella (Plate 14), and are associated with weak silica, epidote, chlorite, sericite, and albite alteration. These veins vary from being straight, en-echelon style veins to slightly contorted veins that were later exposed to some degree of compaction (Plate 14). Locally, mutual (?) crosscutting relationships between silica-dominated veinlets and chalcocite–bornite-dominated veinlets suggest that the copper mineralization occurred synchronously with a generation of silica-rich veining (Plate

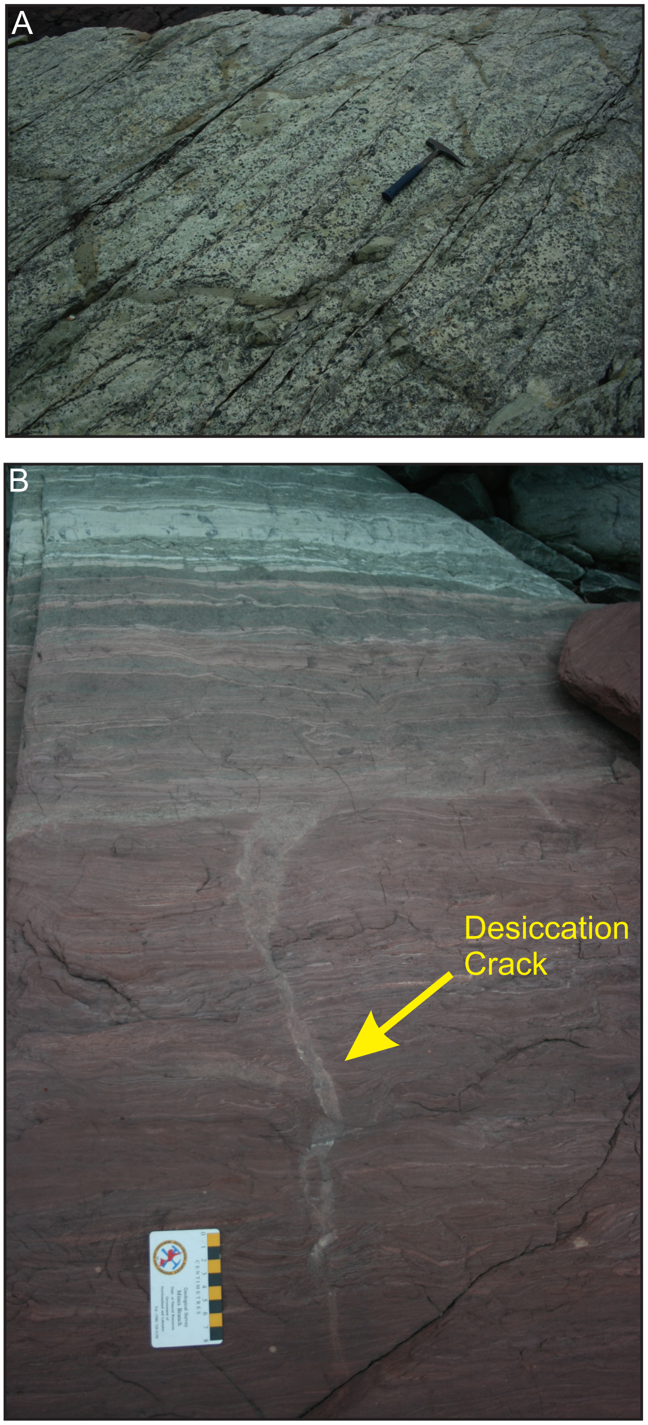

Plate 9. *A) Polygonal mud cracks above the Brook Point outcrop; B) very large (~40 cm long) desiccation crack in the Tickle Cove area.*

14). However, the crenulated, and locally fault offset, silica vein on the right of Plate 14C, indicates that there was also an earlier episode of silica veining. Discordant (bedding-perpendicular) veins locally offset bedding-parallel mineralized veins or horizons (Plate 14D). Observations so far are

Plate 10. *Flame structure in fine-grained sedimentary rocks resulting from lithostatic pressure related to sediment loading during rapid burial.*

not conclusive as to whether such offsets indicate two generations of mineralized veinlets, or if they record the influence of variable permeability and porosity or reductant phase constraints. The proportion of silica, relative to base-metal sulphides in the veinlets, directly controls the grade of the mineralization. The variation in the proportions of copper sulphide to silica within the veinlets throughout the reduced horizons could be related to different fluid compositions or fluid salinities, differences in the availability of reductants in the reduced horizons, or different generations of veining. A fluid inclusion study is currently ongoing, as part of a B.Sc. thesis through this project, on the Blue Point mineralization by M. Crocker at Memorial University, and will hopefully contribute further information.

Copper sulphides were predominantly precipitated in sections of the reduced horizons where there were abundant pre-existing iron sulphides. The pre-existing sulphides are dominated by diagenetic framboidal pyrite (perhaps indicative of organic material as well), but also occur as larger diagenetic pyrite cubes (Plates 4B, 5A, B). Locally abundant, very fine-grained, black translucent material in the reduced sedimentary rocks may be relict organic material.

The copper mineralization occurs in various forms and textures. These include linear to locally contorted copper sulphide (chalcocite–bornite and local covellite and chalcopyrite) siliceous veinlets of varied orientation with respect to bedding (Plate 14), as discussed above. Also, copper sulphides variably replace primary diagenetic framboidal pyrite (Plate 15), and form rims and replacements of larger pyrite cubes (Plate 16). All forms of copper mineralization appear to be associated with low-grade propylitic alteration (epidote–chlorite–sericite–albite ± carbonate), identified on the basis of visual and visible near-infrared spectrometry.

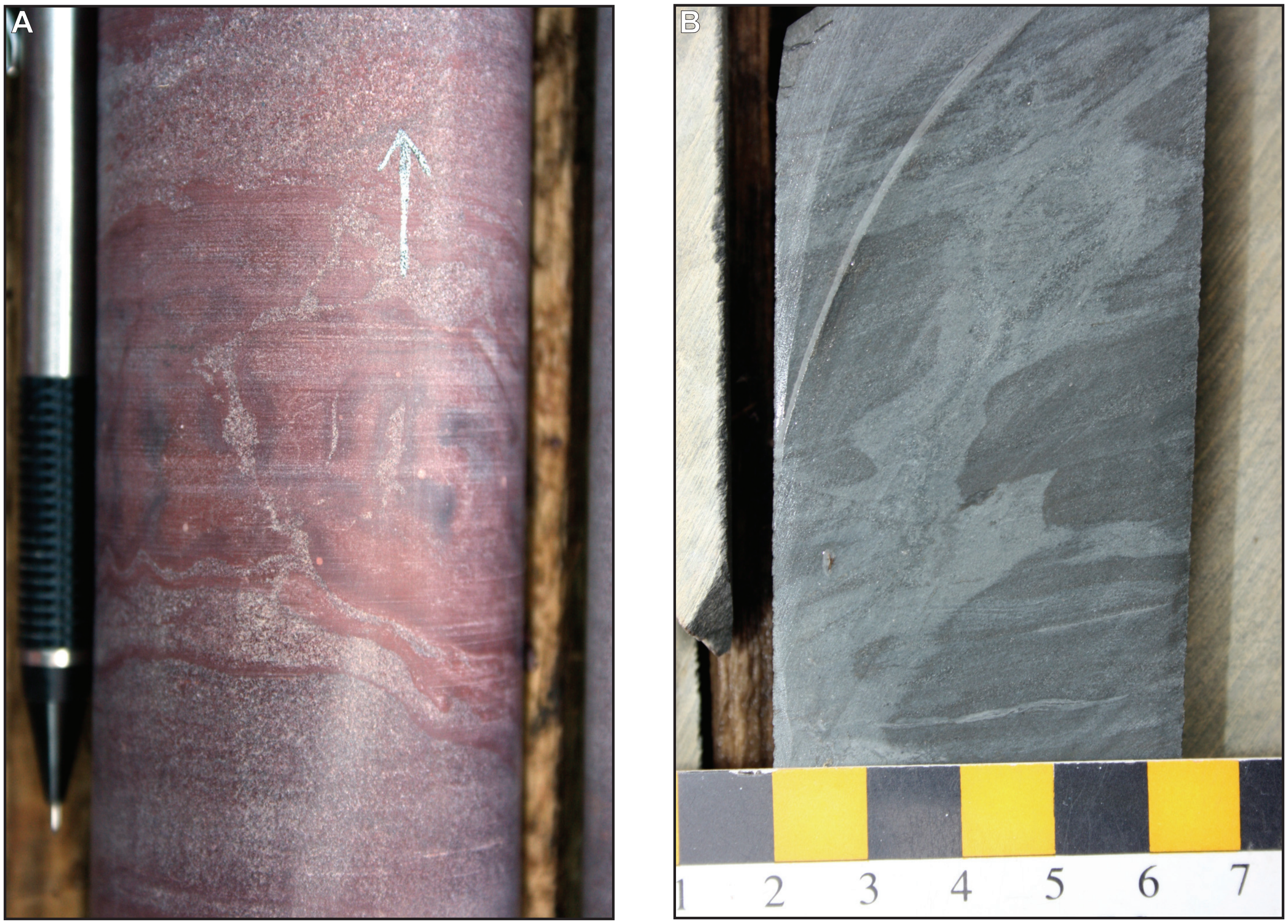

Plate 11. *Fluid escape structures in both redbeds (A) and greybeds (B).*

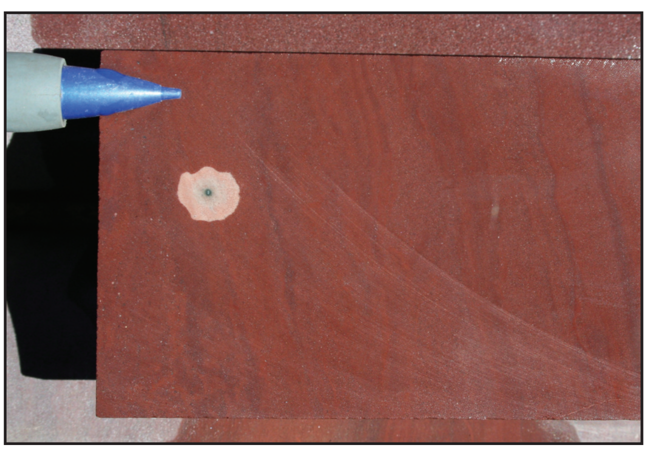

Plate 12. *Reduction sphere surrounding small pyrite crystal in redbed sedimentary rocks.*

Copper Sulphide and Siliceous Veinlets

Copper sulphide and silica veinlets are associated with the highest grades of mineralization in the reduced horizons in both the Crown Hill Formation (*e.g.*, Blue Point reduced horizon) as well as in the Rocky Harbour Formation (*e.g.*, Fifields Pit prospect). The veinlets vary from being linear, en-echelon style, to slightly contorted veinlets; indicative of semi-solid conditions in the host rocks. The *en-echelon* nature of some of the veinlets (Plate 14) could be related to progressive vein nucleation and propagation associated with sediment loading and fluid over-pressuring and subsequent release phenomena, or alternatively they could be related to larger, basin-scale growth and evolution processes. Vein compositions range from being completely composed of copper sulphides, through to completely siliceous, to combinations of both (Plate 14). The *en-echelon* veinlets commonly display terminations with stepwise links to further propagating veinlets (Plate 14). There appears to be small-scale sulphide zonations, with chalcocite as the dominant sulphide phase, and increased proportions of bornite and chalcopyrite in the 'downstream' termination points of the veinlets (Plate 14).

As veining and fracturing are observed in both mineralized and unmineralized portions of reduced horizons, albeit

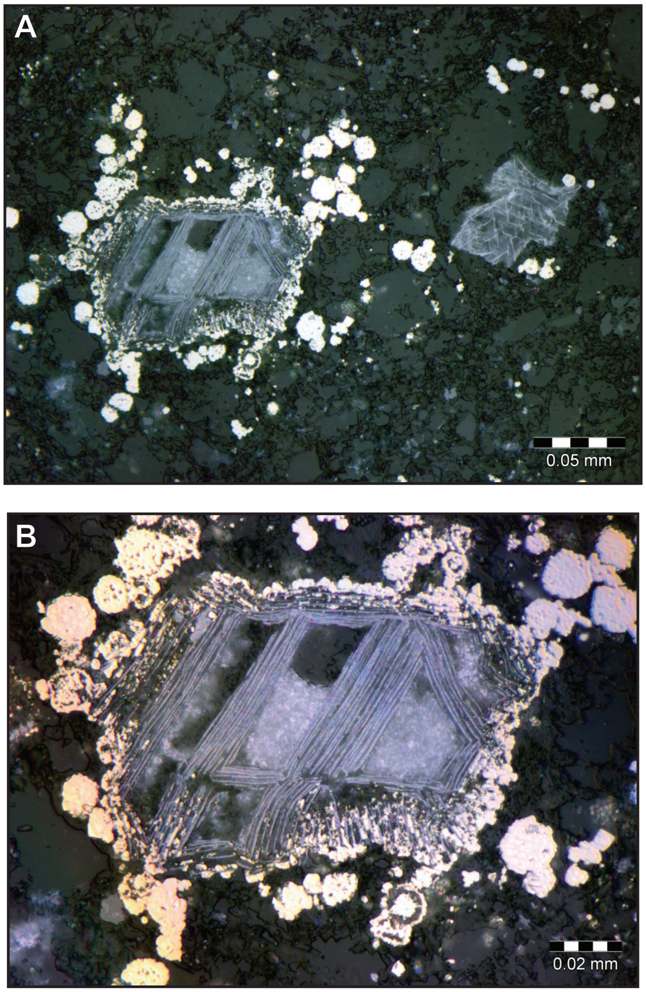

Plate 13A and B. *Leaching of iron from a detrital titanomagnetite crystal resulting in titanium dioxide remnants. Note local scavenging of the iron by bacterial processes to form framboidal pyrite.*

with different proportions of sulphide and silica, the process that was responsible for the fracturing must have operated over a large area, and potentially over a protracted period of time. As such, the copper content of the reduced rocks is not solely related to the pre-existence of fracturing. Likewise, both mineralized and non-mineralized veinlets occur in reduced rocks with similar proportions of pre-existing sulphides (diagenetic framboidal pyrite and cubic pyrite), suggesting that the presence or quantity of pre-existing reductants alone did not control copper grades. Barren siliceous veinlets are commonly observed in the light-grey reduced horizons that directly overlie the main pyrite- bearing mineralized horizon at Blue Point, indicating that the fluids were either stripped of their metals as they passed through the lower pyrite-rich zone, or that the fluids require very specific conditions to drive sulphide precipitation. Variations in the copper content of the veins would be linked to copper content of the fluids and would be related to the composition of the basinal fluids and the associated ability to leach and mobilize metals.

Copper Sulphide Replacement of Diagenetic Framboidal Pyrite

The highest grade of mineralized intervals occurs in horizons with abundant pre-existing reductant; predominantly in the form of framboidal pyrite. However, as alluded to above, the mere presence of abundant framboidal pyrite and veining does not guarantee high copper grades.

The degree of copper sulphide replacement of pre-existing framboidal pyrite varies throughout the reduced horizons, and has obvious impacts on the overall copper grade of a particular interval. Variable porosity and permeability, in otherwise identical facies of the reduced host rocks, may have controlled the movement of the copper-bearing fluid through the rocks, and hence the degree of replacement of the pre-existing framboidal pyrite (Plate 15). There are local examples of perfectly preserved and pristine framboidal pyrite directly adjacent to copper sulphide veinlets; perhaps suggesting that the host sedimentary rocks were too compacted and lithified to allow enough fluid ingression along strata to replace framboidal pyrite. However, in other nearby locations, framboidal pyrite is variably replaced by copper sulphides in areas adjacent to copper sulphide-bearing veinlets (Plate 15). These discrepancies suggest that there are some variable permeability boundaries at the macroscopic scale; potentially related to porosity occlusion associated with early episodes of sediment leaching.

Copper Sulphide Replacement of Diagenetic Cubic Pyrite

Copper mineralization is also commonly observed to partially replace larger (up to cm-scale) diagenetic pyrite cubes in the grey reduced horizons that typically occur directly above and below the central, framboidal pyrite-rich core of the reduced horizons (Plate 16). Although not as significant from an economic perspective, this is important to the modelling of the mineralizing process, as it is not directly associated with sulphide-silica veinlets. There may have been a metal-enriched fluid flux that was independent of that related to the sulphide–silica veining. Alternatively, the fluids responsible for the replacement of diagenetic pyrite may simply represent the same fluid phase permeating through the slightly coarser grained and presumably more permeable sediments that contain the larger pyrite cubes. As with the sulphide–silica veinlets, replacement of larger diagenetic pyrite grains is associated with weak silica–epidote–chlorite alteration.

Metal Correlations

Preliminary examination of diamond-drill hole litho-

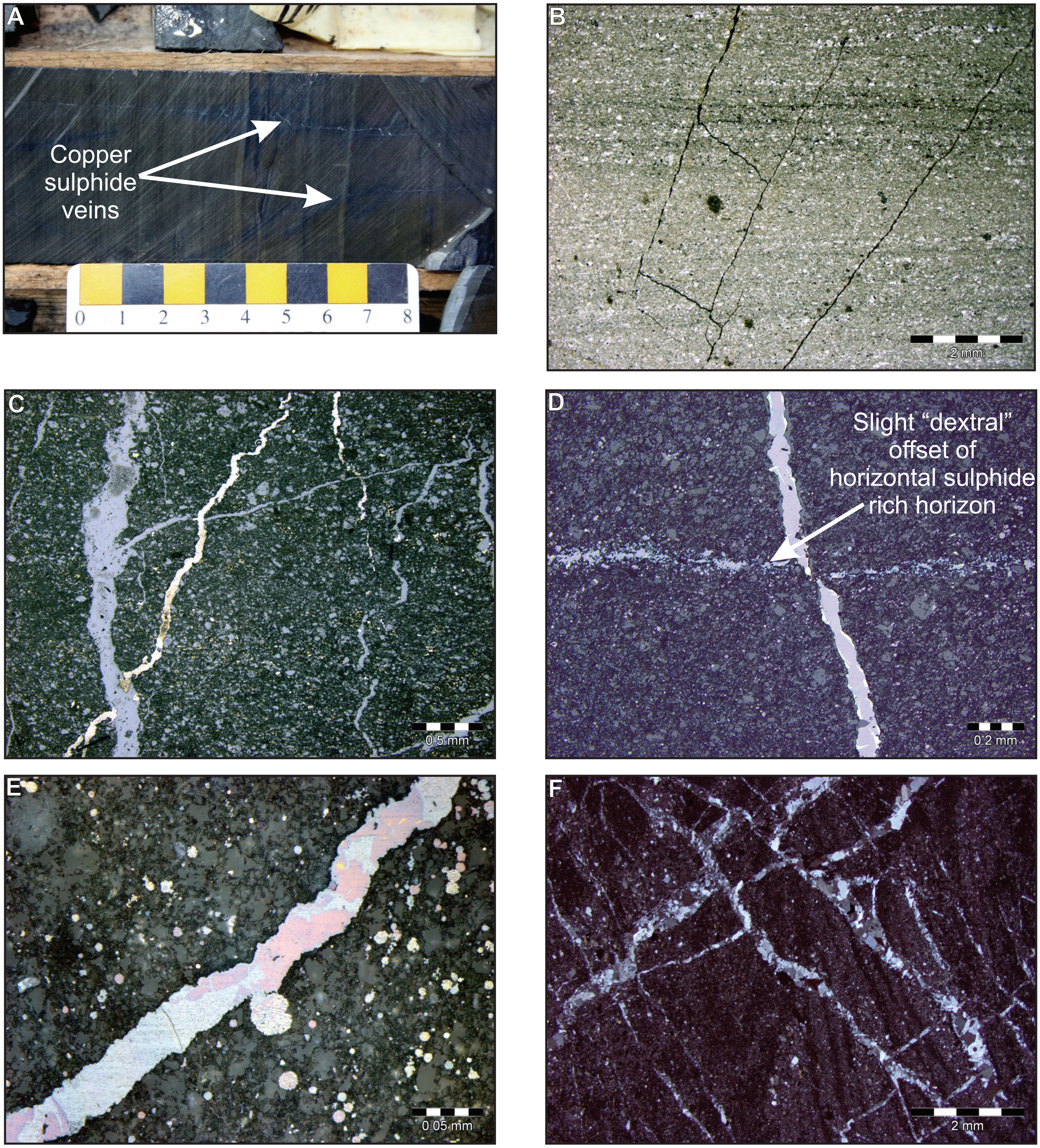

Plate 14. *Copper sulphide and silica veins from the Blue Point (SSC) prospect. A) Drillcore illustrating chalcocite veins perpendicular to, as well as parallel to, bedding; B)* en-echelon *nature of the sulphide veins; C) contradicting crosscutting relationships suggesting that the base-metal rich veinlets are synchronous with at least one episode of silica veining; D) bornite and chalcopyrite veinlet occurring perpendicular to bedding that either offsets an earlier vein of mineralization or preferentially veers into a specific (earlier offset) permeable horizon; E) chalcocite and bornite vein; F) veinlets comprised predominantly of silica. See text for discussion.*

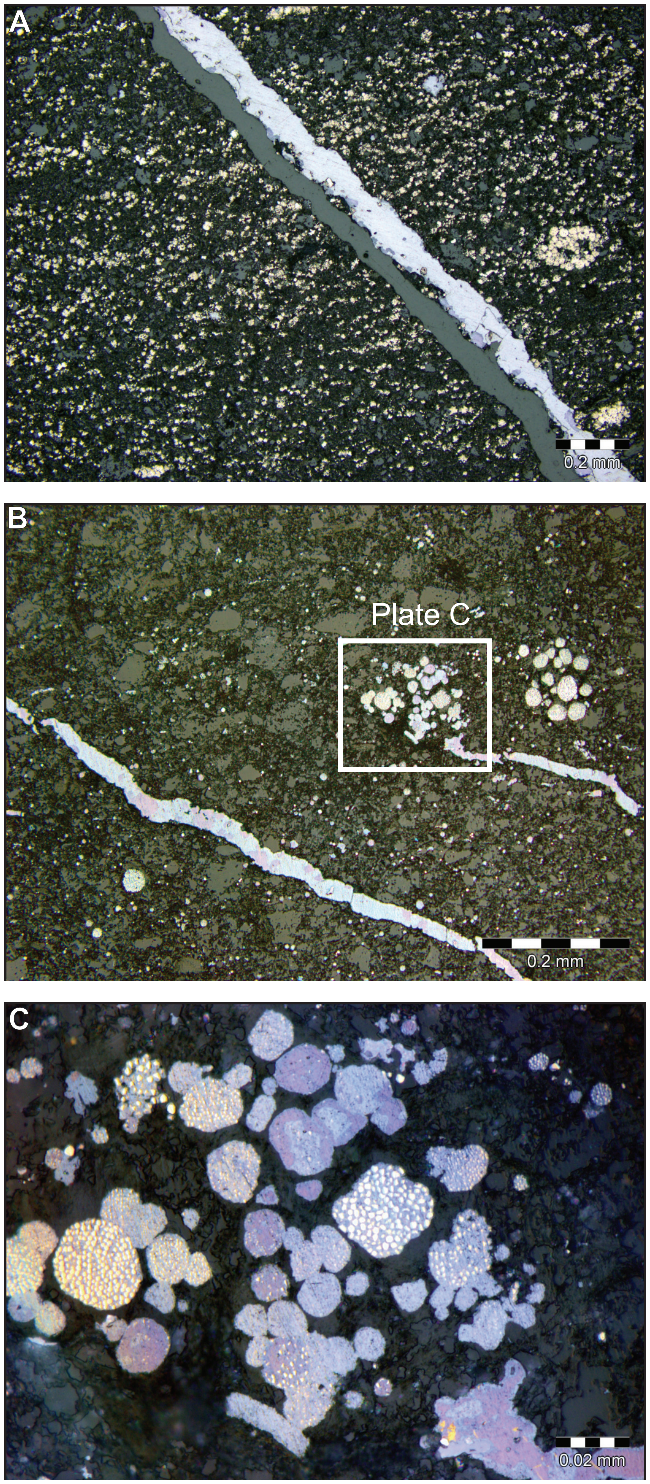

Plate 15. *A) Preserved framboidal pyrite directly adjacent to a chalcocite veinlet, note the silica vein paralleling the sulphide vein; B) chalcocite and bornite veinlets with partially replaced adjacent framboidal pyrite; C) blow-up area from Plate B illustrating the variable degrees of framboidal pyrite replacement by copper sulphides (chalcocite and bornite).*

geochemical data obtained by Cornerstone Resources Inc. (Seymour *et al.*, 2005) illustrate some common correlations between copper concentrations and other metals. Profiles of copper concentrations are closely matched by the profiles of other metals such as Ag, Co, Bi, and to a lesser degree As (Figure 4), most likely indicating similar chemical properties such as redox sensitivity and solubility. Vanadium has a different distribution, as it is concentrated at lower stratigraphic levels (Figure 4). This may be because it precipitated earlier than other metals, likely because it can occur in three different oxidation states (V^{4+}, V^{5+}, and V^{6+}) and would be particularly susceptible to changes in redox states. Lead is mostly present at stratigraphic levels equivalent to and above Cu and Co, and the pattern for Zn is indistinct, although the highest Zn contents are in the upper section of the interval (Figure 4). This suggests that the Pb and Zn precipitated slightly later, in a 'downstream' position, consistent with their higher relative solubilities. Further analysis of such metal correlations awaits lithogeochemical results from the 2009 season.

Controls on Copper Grades: Unresolved Questions

There are some unresolved questions regarding controls on the distribution and grade of copper mineralization throughout the reduced horizon at the Blue Point prospect. The highest-grade mineralization is commonly associated with base-metal and silica-rich veinlets that permeate through reduced horizons rich in framboidal pyrite, and variably replace this material. However, the precise controls on copper sulphide precipitation and copper grades remain uncertain. The cross-section in Figure 5 shows the initial two drillholes at the Blue Point prospect (RC-01-01 and RC-01-02) as well as a subsequent infill drillhole between the initial holes (RC-02-07). The central hole had very low copper grades compared to those on either side (*see* Figure 3 for the locations of diamond-drill holes), and this is difficult to explain. All three drillholes intersected identical strata and facies including the reduced horizon with an inner core rich in framboidal pyrite. Although the same sedimentary facies were observed, some textural differences were noted that may partially explain the much lower copper grades in DDH RC-02-07. This drillhole has a much lower proportion of fracturing and veining compared to the drillholes with the higher grades. This observation suggests that fluid percolation was not as efficient and that the metal-rich oxidized fluid was not present to the same extent. Additionally, the relict framboidal pyrite in DDH RC-02-07 is devoid of detailed textural features compared to the framboids in the other two drillholes (Plate 4B, C). It is possible that this indicates a higher degree of compaction associated with lithostatic loading in this location, which reduced its local permeability.

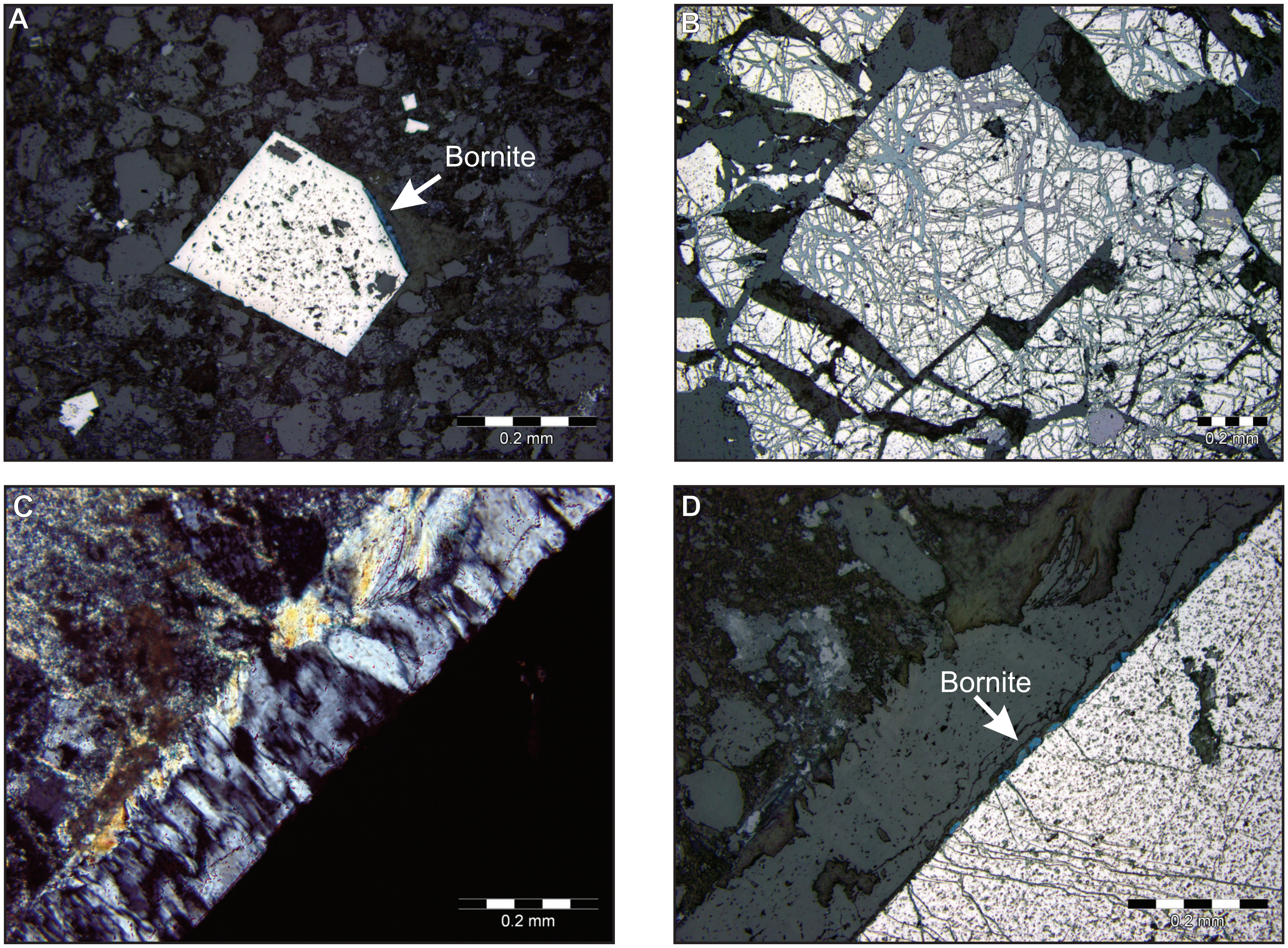

Plate 16. *A) Bornite replacing diagenetic pyrite cube; B) more pervasive replacement of diagenetic pyrite by copper sulphides; C) quartz and chlorite alteration surrounding diagenetic pyrite cube; D) same view as C but in reflected light illustrating bornite replacing diagenetic pyrite.*

Diamond-drill holes RC-01-03 and RC-01-05 (*see* Figure 3), which were drilled directly down-dip and underneath the previously described drillholes with the highest grades, contain identical stratigraphy with the framboidal pyrite-rich horizon and also contain similar crosscutting veinlets. However, these contain only minor copper mineralization (<0.2% Cu). This would suggest that local conditions had a strong influence on the passage of mineralized fluids, and on the precipitation of metals from them, and a better understanding of this is of great importance for future exploration, and the definition of any resource.

SUMMARY AND FUTURE WORK

This report presents preliminary observations and interpretations on the style(s) and setting(s) of copper mineralization hosted within rocks of the Neoproterozoic Musgravetown Group on the Bonavista Peninsula. Most copper mineralization, interpreted to have affinities with the SSC-deposit type, occurs in lacustrine, grey reduced beds within the terrestrial redbed-dominated Crown Hill Formation, but it is also present within fine-grained grey-green shallow-marine sedimentary rocks of the underlying Rocky Harbour Formation.

Initial results support the idea that metals were leached from thick successions of redbeds subsequent to an initial phase of diagenetic reddening and preliminary leaching of the initially grey to brown sediments. Disseminated and fracture-controlled copper mineralization is associated with laterally continuous reduced facies; the best example of which is the Blue Point prospect in the Crown Hill Formation. Copper sulphide precipitation was most efficient within a central core portion of the Blue Point reduced horizon where abundant framboidal pyrite and possible organic material acted as reductants. Cross-strata permeability, both

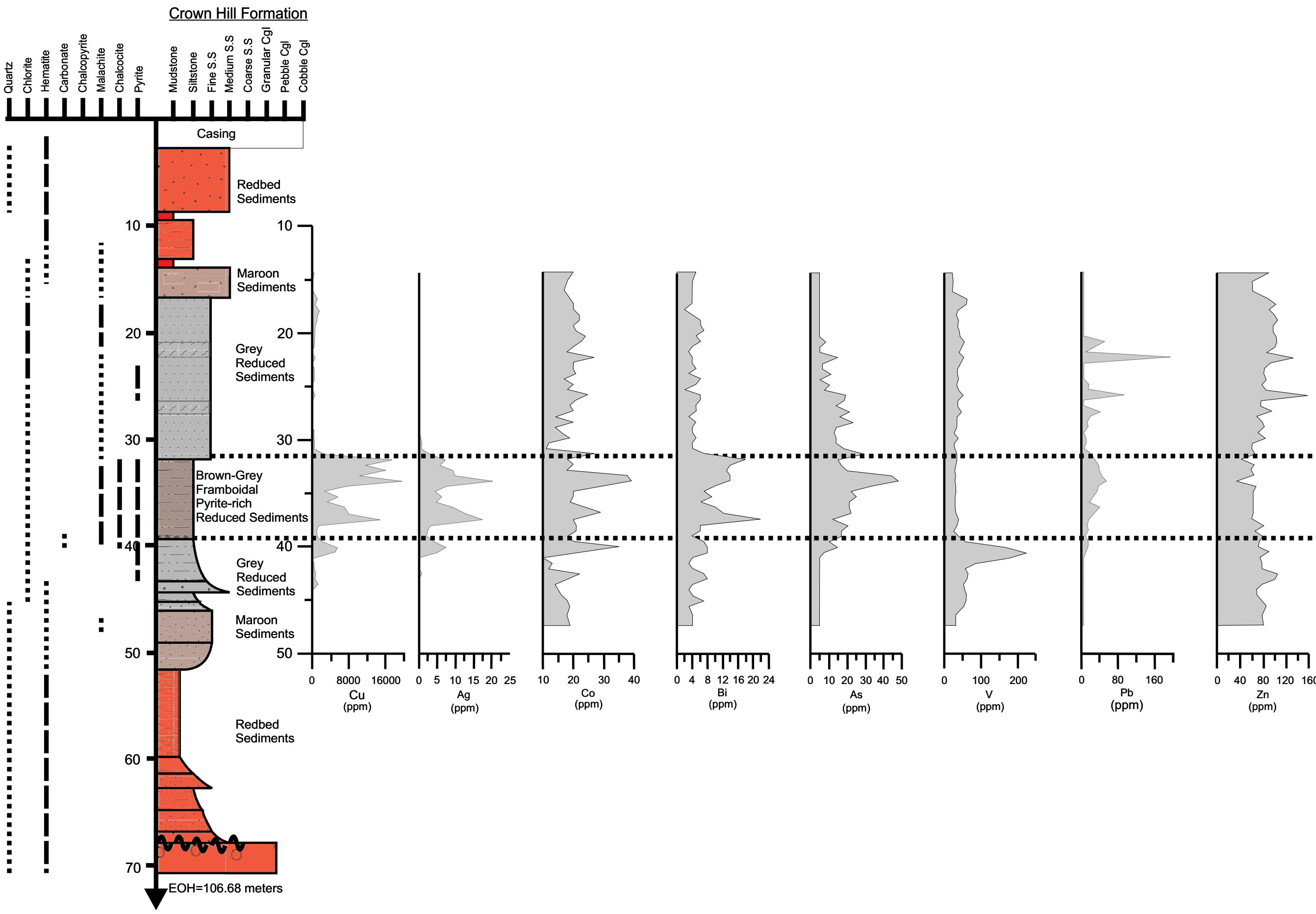

Figure 4. *Detailed diamond-drill hole log with corresponding metal correlations for Blue Point drillhole RC-01-01. Note that the base-metal mineralization is associated with a fine-grained inner framboidal pyrite-rich core zone of a larger reduced sequence within the Crown Hill Formation redbeds. Note also the close correlation between copper, silver, cobalt, bismuth and to a lesser degree arsenic, whereas vanadium, lead and zinc are concentrated on the peripheries of the main copper mineralized zone. Lithogeochemical data is from Noranda Inc. and Cornerstone Resources Inc. public data. The dotted and dashed lines in the left hand portion of the diagram represent weak and moderate amounts of minerals or alteration, respectively.*

in the redbed successions and in the reduced host rocks, was likely increased by water escape structures associated with earlier basin compaction processes and fluid release.

Mineralization in the Rocky Harbour Formation is best exemplified by the Fifields Pit prospect where disseminated and fracture-controlled copper mineralization occurs within fine-grained, finely laminated, grey-green sedimentary rocks interpreted to be submarine in origin. Although there are no redbed sedimentary rocks in the immediate vicinity of this occurrence, local redbed oxidized horizons are present in nearby stratigraphic successions and similar models of mineralization may apply.

Future work will continue on the study of copper occurrences on the Bonavista Peninsula to better understand the origins and controls on mineralization, and assess the potential of these sequences. Several other areas of similar Neoproterozoic sedimentary rocks on the Avalon Peninsula may be prospective for SSC-style mineralization (*e.g.*, *see* O'Brien and King, 2002), and these will be investigated to compare and contrast sedimentary environments and mineralizing styles with those observed on the Bonavista Peninsula.

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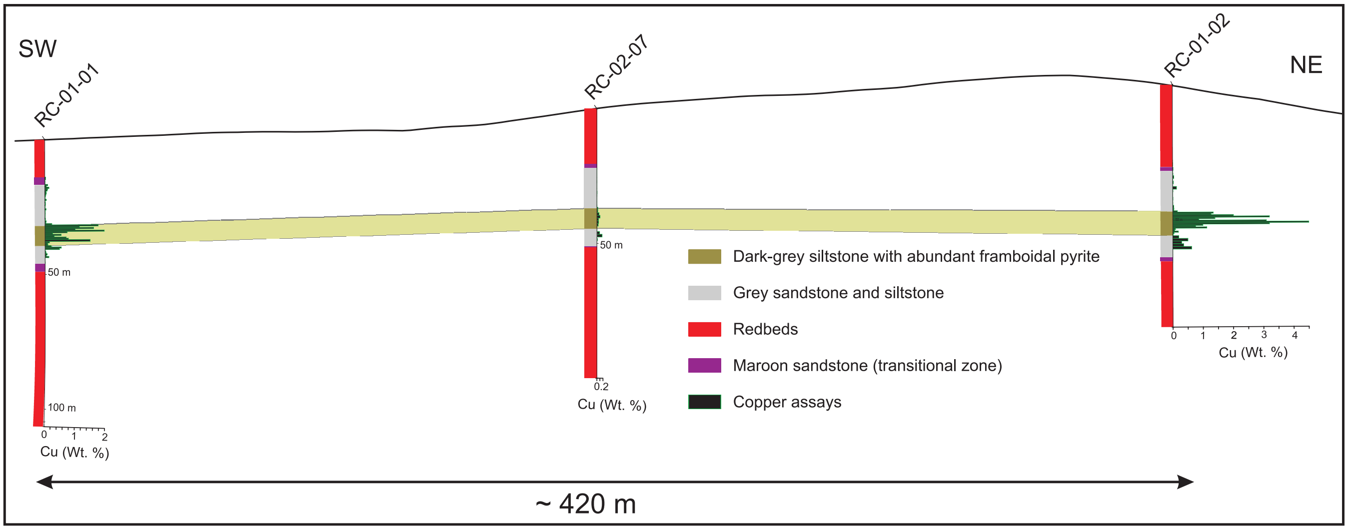

Figure 5. *Diamond-drill hole long section illustrating the along strike variation in copper grades within the same facies rocks.* See *Figure 3 for section location. Copper assays are from Noranda Inc. and Cornerstone Resources Inc. public data.*

studies. This report was reviewed by Andy Kerr and Tim van Nostrand who are thanked for improving the conciseness and readability of this paper.

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