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NEOPROTEROZOIC STRATIGRAPHY OF THE BONAVISTA PENINSULA: PRELIMINARY RESULTS, REGIONAL CORRELATIONS AND IMPLICATIONS FOR SEDIMENT-HOSTED STRATIFORM COPPER EXPLORATION IN THE NEWFOUNDLAND AVALON ZONE

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Regional Mapping Section

ABSTRACT

Existing regional bedrock maps of the Bonavista Peninsula of eastern Newfoundland assign all Neoproterozoic strata to the Musgravetown Group, a unit that has been characterized in much of the geological literature as a thick, and widespread succession of slightly deformed continental red beds. Mapping described below, however, has instead shown that significant parts of the Bonavista Peninsula consist of silicified and non-silicified marine and deltaic, clastic sedimentary rocks, correlative with several of the principal late Neoproterozoic units of the Avalon Peninsula to the southeast: viz., the Conception Group (including the Mistaken Point Formation), the Trepassey, Fermeuse and Renews Head formations of the overlying St. John's Group, and the Gibbett Hill Formation of the Signal Hill Group.

The lithologically contrasting Musgravetown Group is widely developed west of the Conception and St. John's groups, and is typified by openly folded and in many areas, gently dipping to sub-horizontal, shallow-marine to fluvial siliciclastic rocks of the Rocky Harbour and overlying Crown Hill formations, respectively. The Rocky Harbour Formation has been tentatively divided into six component facies of potential member status. One of the most extensive of these is a purple to grey-green conglomerate facies that overlies subaerial volcanic rocks (Bull Arm Formation of the Musgravetown Group) in the west and folded and silicified marine sedimentary rocks (Conception Group) in the east. Chalcocite mineralization within the Musgravetown Group occurs in grey beds within the red bed dominated Crown Hill Formation and in grey and green gritty sandstones of the underlying Rocky Harbour Formation.

Preliminary findings allow the Neoproterozoic stratigraphic record for the Bonavista Peninsula to be correlated, at varying levels of detail, with large parts of the Avalon Peninsula, and the western Bonavista Bay and northern Fortune Bay regions. This correlation, coupled with the nature of the Neoproterozoic basins and the lithofacies of basin-fills, have significant ramifications for exploration for sediment-hosted stratiform copper and Sedex-style base metals in eastern Newfoundland.

INTRODUCTION

This report summarizes the results of a limited program of bedrock mapping carried out along six regional transects across the Bonavista Peninsula of eastern Newfoundland (Figure 1). This work is part of a larger effort by the authors to develop a comprehensive and regionally unified stratigraphic framework for the late Neoproterozoic sedimentary rocks in the Avalon Zone, currently the focus of exploration programs targeting large-tonnage, sediment-hosted, stratiform, copper (SSC) deposits. The results of these 2001 investigations, coupled with unpublished mapping between Bonavista and New Bonaventure by King, and earlier work by O'Brien and Knight (1988) and O'Brien (1993, 1994) in adjoining areas in Bonavista Bay, have led to new insights on the regional stratigraphy and tectonic history of this little-known part of the Avalon Zone. The newly proposed stratigraphic framework for the Bonavista Peninsula aids in identification and regional correlation of copper-mineralized lithostratigraphic units throughout eastern Newfoundland, and in doing so, points to other unexplored areas having SSC potential.

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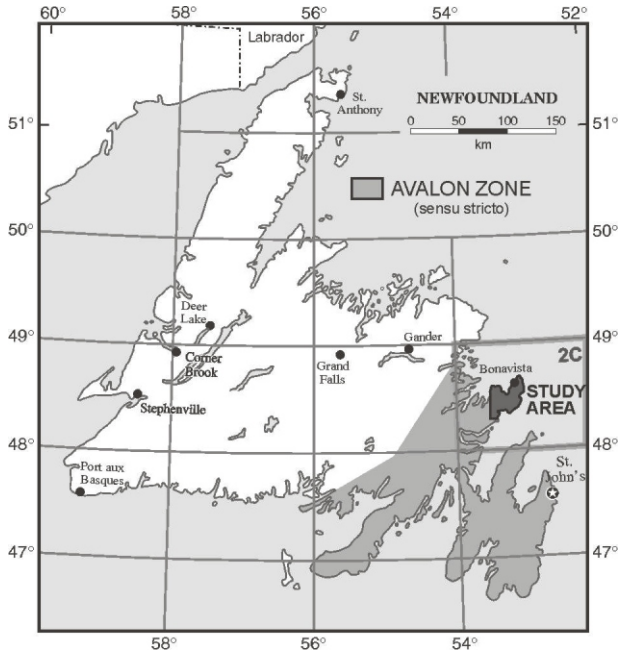

Figure 1. *Map of Newfoundland, showing the location of the Bonavista Peninsula study area and outlining the area of Figure 2.*

PREVIOUS INVESTIGATIONS

The first recorded geological investigations in this region were made during Sir Martin Frobisher's late sixteenth century expeditions. Frobisher documented the widespread occurrence of coarse-grained metallic mineralization (initially identified as gold and copper) in slates on the coastline near Catalina, on the eastern Bonavista Peninsula. The same exposures were later visited by members of one of Sir Humphrey Gilbert's expeditions; samples were collected and sent for assay in England, where the mineralization was correctly identified as pyrite. Despite the early interest in its geology and minerals, the Bonavista Peninsula has remained, until recently, one of the least-prospected and, geologically, poorly known parts of Newfoundland.

Hayes and Rose (1948) mapped the westernmost part of the Bonavista Peninsula (west of 53° 30') during a larger survey of the area between Trinity and Placentia bays by the Geological Survey of Newfoundland. They correlated rocks in the westernmost Bonavista Peninsula with those in the Clode Sound area of Bonavista Bay; all were assigned to their newly defined Musgravetown Group. The Geological Survey of Canada (GSC) completed a broad reconnaissance survey of the larger NTS 2C (Bonavista) map area in the summer of 1949. This work was published as a 1:125 000 preliminary map (Christie, 1950) and remains the most detailed published geological map of the Bonavista Peninsula. Select parts of the NTS 2C map area, including the Bonavista Peninsula, were re-examined by the GSC during a 2½ month period in 1957. These results were integrated with those of Christie (1950) and included in the 1:250 000 maps of the Terra Nova and Bonavista map areas (Jenness, 1963). The maps of Hayes and Rose (1948), Christie (1950) and Jenness (1963) are alike in depicting almost the entire area of the Bonavista Peninsula as Musgravetown Group; the only exception is a small syncline of Cambrian strata at Keels. These maps designate more than 90 percent of the Musgravetown Group rocks on the peninsula as undivided.

The Geological Survey of Newfoundland and Labrador carried out a regional lake-sediment geochemical survey of the Bonavista Peninsula in 1981 (Butler and Davenport, 1981), and undertook follow-up stream sediment and soil geochemical surveys targeting cobalt and lead anomalies in the lake-sediment data (Butler and Davenport, 1985). Most recently, the Bonavista Peninsula was included within a regional till-geochemistry survey of NTS 2C map area (Batterson and Taylor, 2001).

Other than investigations by local area prospectors, one of the only exploration programs for base metals, prior to the late 1990s, was carried out by Cominco, who briefly investigated select geochemical anomalies for lead and zinc that had been identified in earlier government surveys. In the mid-1990s, variegated slates that occur in tightly folded Cambrian rocks at Keels were test quarried on a small scale. Slate deposits in correlative rocks occur south of the area studied, at Nut Cove, in Smith Sound, Trinity Bay, where the Hurley Slateworks Company is currently producing purple and green roofing slate from rocks first quarried commercially between 1850 and 1907.

In 1999, prospectors with Cornerstone Resources Inc. discovered significant chalcocite mineralization in the uppermost Proterozoic red bed succession in the northwestern Bonavista Peninsula (Red Cliff Property). Recent drilling on the property (near Duntara) by joint venture partners, Cornerstone Resources Inc. and Noranda Inc., intersected a chalcocite-bearing, pyritic grey sandstone–siltstone unit within the red beds, which returned assays of 1% Cu and 12.1 g/t Ag over 14.25 m including 2% Cu and 23.1 g/t over 6 m (*see* Cornerstone Resources Inc. press releases 01-10, and below).

CURRENT INVESTIGATION

The study reported here was initiated in response to recently heightened interest in exploration for SSC deposits within the late Neoproterozoic Musgravetown Group of the northwest Avalon Zone. The investigation is aimed at establishing a regional stratigraphy for the large area of undivided Musgravetown Group rocks previously identified on the

Bonavista Peninsula and western Trinity Bay, and placing known SSC-style copper mineralization and published geochemical data into that stratigraphic framework. The 2001 field program was designed to examine the most complete section of late Neoproterozoic rocks as possible in the short time available, and to allow ready integration of this work with earlier independent mapping by each of the authors. This approach was developed to target areas that have the greatest potential to return maximum results from future sedimentologic, stratigraphic and metallogenic studies. The authors' 2001 field study was carried out mainly over a two-week period in July, and as principally restricted to that part of the Bonavista Peninsula east of 53° 30' and north of 48° 15'. The work was primarily a reconnaissance stratigraphic study and did not involve detailed examination of the sediment-hosted mineralization in the field. Descriptions of the latter mineralization including assay results, are available on Cornerstone Resources Inc. web-site.

The data presented in the following account are inconsistent with two widely held views, *viz.* i) that all of the Proterozoic rocks of the Bonavista Peninsula belong to a single group (the mainly undivided Musgravetown Group), and ii) that the Musgravetown Group in the Bonavista Peninsula can be characterized as "slightly-deformed, continental red beds" (Jenness, 1963). Mapping by the authors has shown that the Musgravetown Group is only one of four Neoproterozoic groups that constitute the Bonavista Peninsula; red beds are amongst the least extensive of several component lithofacies. Red beds occur primarily in the Crown Hill Formation, at and near the top of the Musgravetown Group, and also in the upper part of the underlying Rocky Harbour Formation. Evidence of stratiform sediment-hosted style of copper mineralization occurs in both the Crown Hill and Rocky Harbour formations. Preliminary findings allow the Neoproterozoic stratigraphic record for the Bonavista Peninsula to be correlated, at varying levels of detail, with large parts of the Avalon Peninsula, and with the western Bonavista Bay and northern Fortune Bay regions. This correlation may have significant ramifications for exploration for stratiform sediment-hosted copper and Sedex-style base metals in eastern Newfoundland.

LITHOSTRATIGRAPHY OF THE NEOPROTEROZOIC ROCKS

The Neoproterozoic rocks of the Bonavista Peninsula can be assigned to one or another of four lithostratigraphic units of group rank: Conception Group, St. John's Group, Signal Hill Group and Musgravetown Group (Figure 2).

Much of the eastern half of the Bonavista Peninsula is composed of rocks atypical of the Musgravetown Group, as described or defined by earlier workers (Jenness, 1963; McCartney, 1967). The geology of that area can be readily correlated with the late Neoproterozoic stratified succession of the Avalon Peninsula (King, 1988, 1990) and includes, i) a thick sequence of variously silicified, grey marine sandstone–mudstone turbidite facies rocks, ii) an overlying unit of black shale–sandstone, shallow-marine to delta facies rocks, and iii) an upper unit of massive grey sandstone, of similar shallow-marine and deltaic facies. Lithofacies and internal stratigraphic divisions that have been identified, allow detailed correlation of these rocks with the Neoproterozoic Conception Group (including the Mistaken Point Formation), the Trepassey, Renews Head and Fermeuse formations of the overlying St. John's Group, and the Gibbett Hill Formation of the Signal Hill Group, respectively.

The Musgravetown Group occurs to the west of the Conception Group, and is disposed in a well-exposed, in many places gently dipping to subhorizontal, openly folded section that extends almost the entire length of the northern coast of the peninsula, southward and westward at least as far as the Trinity and Trinity Pond areas. The broadest stratigraphic framework for these rocks is, in part, consistent with that described elsewhere in the western Avalon Zone by Jenness (1963). Most of the rocks here included with the Musgravetown Group can be assigned to the Rocky Harbour Formation (Jenness, 1963), on the basis of their stratigraphic position above subaerial bimodal volcanic rocks (Bull Arm Formation) and below red beds (Crown Hill Formation) that are overlain by fossiliferous Cambrian rocks. No equivalent of the group's basal sedimentary formation (Cannings Cove) was identified during this investigation.

The nature of the original relationship between the eastern, Conception–St. John's–Signal Hill succession, and the Musgravetown Group in the west remains equivocal. Available data cannot rule out the possibility that the lithologically contrasting successions are, in part, time-stratigraphically equivalent, and parts of two distinct basins separated by some fundamental structure. The apparent truncation of regional folds in the Conception and St. John's groups by the Musgravetown Group, however, argues for an unconformable relationship. Also, an unconformity in this area is consistent with observations elsewhere in Bonavista Bay, where a similar Musgravetown Group succession unconformably overlies Neoproterozoic marine rocks of the Connecting Point Group (*see* Jenness, 1963; O'Brien, 1994; Figure 2). The exact nature of this boundary is the focus of future work by the authors in this area.

PRE-MUSGRAVETOWN GROUP ROCKS

The Conception, St. John's and Signal Hill groups mainly occur east of a boundary that extends from the Dungeon, near Bonavista, south and southwest toward Trinity. The contact with the adjacent Musgravetown Group to the west is mainly unexposed but locally defined by pronounced

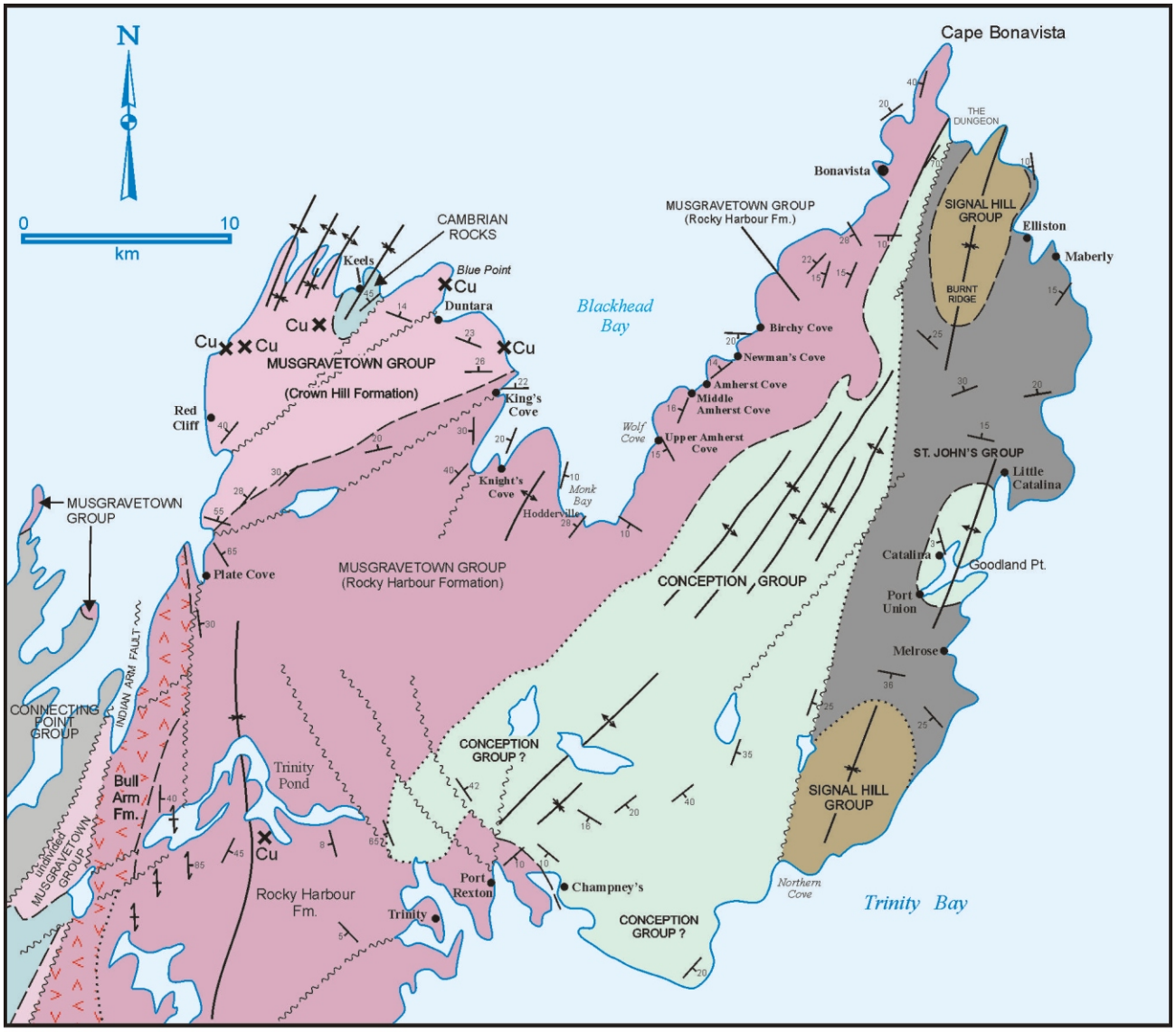

Figure 2. *A preliminary and simplified map showing distribution of principal geological units on the Bonavista Peninsula, northeast Avalon Zone, Newfoundland (compiled, in part, from Christie, 1950 and O'Brien, 1993). Locations of copper showings provided by Cornerstone Resources Inc.*

linears and coincident, steep brittle fault zones. The original boundary may have been unconformable (*see below*). The pre-Musgravetown Group rocks are coincident, on a regional scale, with areas of anomalously high concentrations of lead in regional lake-sediment data and zinc in till-geochemical data (Davenport *et al.*,1993; Batterson and Taylor, 2001), and appear to contain prospective areas for Sedex-style base-metal mineralization.

Conception Group

Rocks that are here assigned to the Conception Group were mapped in two separate areas. Strata that are most readily identifiable as Conception Group – in terms of both lithology and stratigraphic position – are well exposed in coastal outcrops around Goodland Point, in Catalina (Figure 2). There, reddish-purple, green and grey, medium-bedded and graded siliceous turbidites (Plate 1) are exposed in a periclinal dome. These rocks are typical of the Middle Cove Member (King, 1990) of the lower Mistaken Point Formation on the Avalon Peninsula. The siliceous turbidites are surrounded and sharply overlain by distinctive green and reddish-purple argillaceous siltstones and shales that are comparable with the Hibbs Cove Member (King, 1990) of the upper Mistaken Point Formation on the Avalon Peninsula. The Mistaken Point Formation equivalents around Catalina are conformably overlain by dark-grey shales, siltstones and sandstones of the St. John's Group.

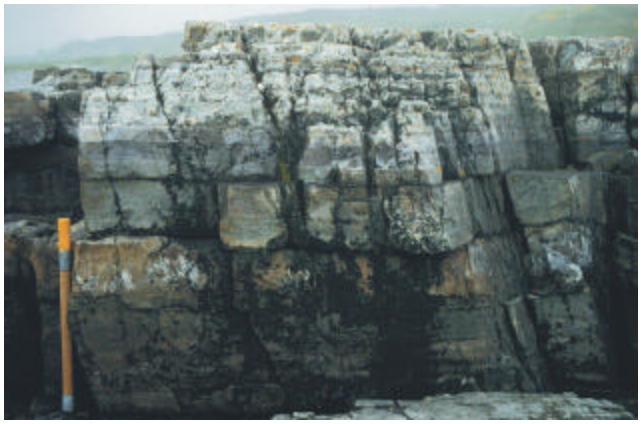

Plate 1. *Silicified turbidites, Mistaken Point Formation of the Conception Group, at Catalina.*

Other siliciclastic rocks assigned to the Conception Group are exposed in the central part of the peninsula (east of Trinity), extending to the pronounced linear that coincides with the faulted boundary with the St. John's Group to the east (Figure 2). These rocks form a northward-narrowing belt that has been traced from Bonavista, at least as far south as Route 230, northeast of Champneys. They typically display weak to moderate silicification, and are folded into open to tight syncline–anticline pairs, parasitic on a regional-scale anticline. Most of the west limb of this structure, including the upper Conception Group and the overlying St. John's Group, appears to have been truncated by boulder conglomerate of the Musgravetown Group in the region around Champneys, in what may prove to be an unconformable relationship. Conception Group rocks are, in almost all cases, more pervasively folded, cleaved and silicified than adjacent Musgravetown Group strata.

Two silicified facies other than those at Catalina have been identified within the Conception Group. The first has the characteristic white- to yellow- and green-weathering beds of dark-green and grey siliceous sandstone, characteristic of the Drook Formation throughout the Avalon Peninsula (Williams and King, 1979; King 1990; O'Brien *et al.*, 2001). Common sedimentary features found in this turbidite facies include graded bedding, convolute and ripple lamination, rip-up clasts, slump folds and other small-scale thixotrophic deformation features. The siliceous sandstones are locally associated with graded beds of coarse-grained gritty sandstone; comparable facies are found in the Briscal Formation of the Conception Group on the southern Avalon Peninsula, where it underlies the Mistaken Point Formation (Williams and King, 1979).

A second, more widespread thinly laminated sandstone facies locally overlies and is interlayered with the more massive siliceous sandstones. This facies is characterized by the presence of grey, siliceous, finely laminated sandstone having thin, parallel laminae, locally affected by micro-faults. These sediments contain localized areas of intense silicification with finely disseminate pyrite and in places, pyrrhotite; these are locally coincident with zinc and lead anomalies in lake sediment, soil and till. One such zone, located several kilometres north of the road from Catalina to Amherst Cove, was the focus of limited exploration by Cominco in the mid-1980s (Rennie, 1989).

St. John's Group

Facies that are typical of each of the three constituent formations of the St. John's Group in the Avalon Peninsula type area have been identified in the eastern Bonavista Peninsula. These correspond to the basal Trepassey, the intermediate Fermeuse and the upper Renews Head formations of that group. The formations have not been mapped in detail, and are not separated on the accompanying map. Their boundaries appear to be gradational, and coincide with an overall increase in the proportion of sandstone, stratigraphically upward. The basal boundary with underlying Mistaken Point Formation is either conformable, as in the domal structure at Catalina, or a fault. The Trepassey Formation may be missing along much of the faulted St.

John's – Conception group boundary between the Dungeon (near Bonavista) and Northern Cove (ca. 10 km southwest of Melrose).

The Trepassey Formation in the eastern Bonavista Peninsula is represented by grey and green (and rarely, pale pink) very fine-grained sandstone and grey-black shale having characteristic parallel-sided beds and laminae; thin to medium beds predominate. The Fermeuse Formation in this area consists of three main lithofacies: i) black shales having very thin laminae of siltstone and very fine-grained sandstone, ii) very thin-bedded to medium-bedded, dark-grey siltstone to fine-grained sandstone, containing thin layers of rusty-brown-weathering, commonly pyritic, grey sandstone (Plate 2) and iii) slumped beds of sandstone within black shale. Slump folds are common within the Fermeuse Formation and vary in height from less than 1 cm to as much as 1 m. Within the Fermeuse Formation, sandstone typically comprises less than 50 percent of the rock. The overlying Renews Head Formation is characterized by rusty-weathering, lenticular- and wavy-bedded grey sandstone, interbedded with minor dark-grey shale and siltstone. Where sand content exceeds 60 percent, some of the sandstones show flaser bedding characterized by thin streaks, laminae and rip-up clasts and flasers of dark-grey mudstone within ripple troughs.

Microfossils were discovered by the second author in 1978 in the black shales of the St. John's Group, one kilometre northwest of Melrose (*see* Hoffman *et al.,* 1979). Poorly preserved, flattened fragments of simple, nonseptate algal filaments (*Taeniatum sp.*) were interpreted to be the remains of tubular sheaths of cyanophytes. Although the filaments can not provide a precise age, it is noteworthy that comparable species have been reported from Neoproterozoic marine sediments throughout Eurasia.

Extensive rusty zones are exposed within the St. John's Group in the area between Elliston and Maberly, where pyrite is disseminated in thin, discontinuous sandy layers in dark-grey siltstone. Coarse-grained pyrite occurs locally in dark-grey shale and grey sandstone of the uppermost Conception Group and basal St. John's Group around Catalina and Little Catalina. These pyritic units, known locally as 'Catalina-stone' (Jukes, 1843) are historically significant as one of the earliest documented mineral discoveries in Newfoundland. Jenness (1963) described the presence of galena in fracture-fill, crystalline quartz-calcite veins in St. John's Group rocks at Little Catalina (*see also* Butler and Davenport, 1985). Hematite and manganese staining of dark-grey shales of the Fermeuse Formation is extensively developed in roadside exposures along Route 230, southeast of Melrose.

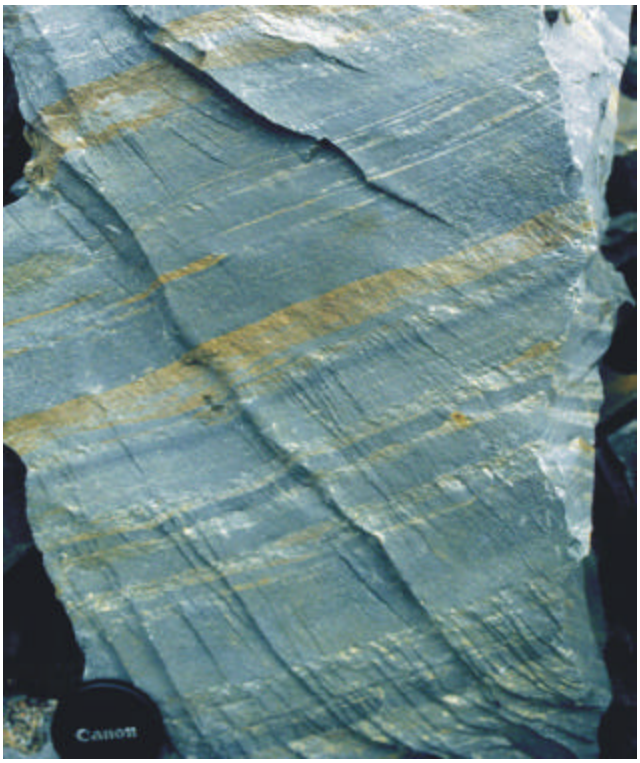

Plate 2. *Wavy-bedded grey siltstone and sandstone of the Fermeuse Formation, St. John's Group, near Melrose.*

The presence of sulphide-rich rocks within the dark-grey to black shale- and silt-dominated St. John's Group, coupled with till- and lake-sediment geochemical anomalies for zinc and lead in till and lake sediment, and the presence of remobilized lead mineralization may point to the possibility of Sedex-style base-metal mineralization in the eastern Bonavista Peninsula. Evidence of a similar style of mineralization has been identified in correlative rocks in the Carbonear–Hearts Content area, east of Trinity Bay (Butt, 1993), which are likewise coincident with anomalously high base-metal concentrations in lake sediment (Figure 3).

Signal Hill Group

The youngest rocks in the pre-Musgravetown Group succession of the eastern Bonavista Peninsula are the medium to thick and laterally persistent beds of grey sandstones that overlie the St. John's Group in a north-plunging syncline at Burnt Ridge, west of Elliston. Preliminary observations indicate that the same rocks may occupy much or all of the core of an open, south-plunging syncline in the area between Melrose and Northern Cove. These grey sandstones are typically featureless in outcrop, having a massive appearance, but contain rip-up clasts and an indistinct or weakly developed wavy to planar lamination. These rocks are comparable in terms of both facies and lithostratigraph-

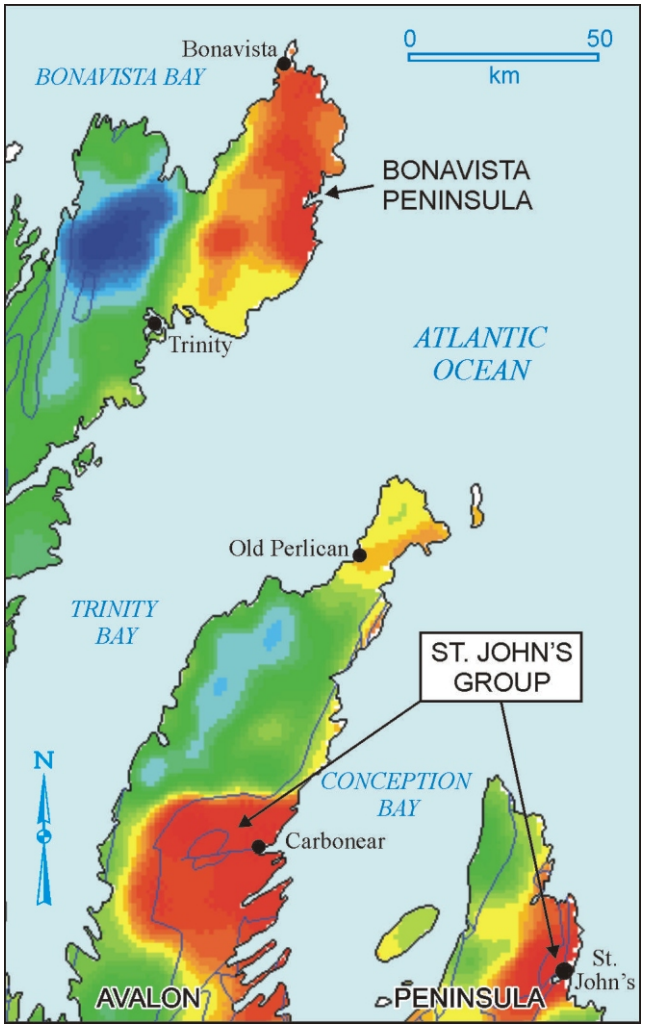

Figure 3. *Colour-contoured map depicting relative concentrations of lead (blue is lowest, red is highest) in lake-sediment from the northeastern Avalon Zone. Geochemical data, colour contours and 1:1 million scale geological linework from Davenport* et al.*, 1996).*

ic position to the Gibbett Hill Formation of the Signal Hill Group of the Avalon Peninsula.

MUSGRAVETOWN GROUP

The formalized stratigraphic nomenclature used by Jenness (1963) to denote the Musgravetown Group is retained in this report. The Musgravetown Group within the sections studied consists of i) a basal formation of subaerial bimodal volcanic rocks (Bull Arm Formation) that is only found west of Trinity Pond, ii) a complex, composite and widely distributed middle unit of grey and green sandstones and conglomerates (Rocky Harbour Formation), and iii) an upper unit of red beds, capped by red conglomerate (Crown Hill Formation). The exact location and nature of the base of the Musgravetown Group on the Bonavista Peninsula remains uncertain, although current investigation points to an unconformable contact with the (underlying) Conception and St. John's groups. A similar unconformable relationship with underlying marine turbidites (Connecting Point Group) has been described elsewhere in Bonavista Bay (Jenness, 1963; O'Brien, 1994; Figure 2). The upper boundary of the Musgravetown Group is drawn at the base of the Random Formation, a quartz arenite unit that is disconformably overlain by shale-rich early Cambrian platformal facies rocks exposed at Keels.

Bull Arm Formation

Subaerial volcanic rocks belonging to the Bull Arm Formation comprise the lowest stratigraphic division of the Musgravetown Group in the area mapped. They occur in a 2-km-wide, steep to moderately west-dipping and west-younging belt that extends north–south from Plate Cove to the area east of Ocean Pond (*see* O'Brien, 1993, 1994). It is bounded to the west by the Indian Arm Fault, a major structure that separates the volcanic rocks from Crown Hill Formation and Cambrian sedimentary rocks, and overlain, to the east, by grey and green to locally purple conglomerate and coarse-grained sandstone of the Rocky Harbour Formation. The principal facies within the Bull Arm Formation are grey–green vesicular basalt and red to purple and maroon felsic flows and rheomorphic ash flows (*see* O'Brien, 1994). The basalt flows are rich in hematite, chlorite, epidote and carbonate, and are locally intercalated with breccia of apparently similar composition. Columnar-jointed flows are locally preserved. Inter-flow material includes poorly sorted to crossbedded red and maroon volcanogenic sandstone and variegated yellow–green sandstones and siltstones. Both flow material and interlayered clastics are locally malachite-stained near the Indian Arm Fault. The felsic volcanic units include sparsely porphyritic, mottled grey–maroon flows that are sampled by overlying Rocky Harbour Formation conglomerates, and constitute a prominent element of the detrital assemblage of those rocks.

Rocky Harbour Formation

The Rocky Harbour Formation mapped on the Bonavista Peninsula is characterized by light grey-green to dark-grey, terrigenous conglomerates and coarse-grained sandstones. Minor units of volcanic rocks occur within the formation elsewhere in the Bonavista Bay area, but none were encountered in the area studied. Thickness changes and lateral variability of facies are typical in this weakly metamorphosed, gently dipping and openly folded succession. In the west part of the peninsula, coarse-grained facies of the Rocky Harbour Formation are either faulted with, or in erosional contact with, the underlying Bull Arm Formation. Preliminary data may imply that in the area northeast of

Trinity, the Bull Arm Formation is absent and Rocky Harbour conglomerates have been deposited directly on the Conception Group, overstepping the western limb of a large regional fold. The absence of the St. John's Group rocks and truncation of the regional fold is consistent with an unconformity in this area. This postulated unconformity may extend northward to the general area of Bonavista, where the same conglomerates are exposed. The Rocky Harbour Formation in the area around Trinity Pond is affected by broad open folds that may be related to structures affecting Cambrian rocks in the north of the peninsula, around Keels.

The Rocky Harbour Formation is best exposed along the north shore of the Bonavista Peninsula between Cape Bonavista and Knights Cove, where at least six lithostratigraphically distinctive facies of potential member status have been identified. From north to south, these are the: i) Cape Bonavista facies, ii) Jones Pond facies, iii) Birchy Cove–Newmans Cove facies, iv) Middle Amherst Cove–Wolf Cove facies, v) Monk Bay–Hodderville facies, and vi) King's Cove North facies. Facies associations, as well as vertical and lateral variations have yet to be determined; facies ii) to vi) appear to be in ascending stratigraphic order.

Cape Bonavista Facies

The Rocky Harbour Formation exposed around Cape Bonavista is typified by an openly folded succession of well-bedded and thickly bedded, olive green, buff-yellow-weathering sandstones having ubiquitous well-developed, large-scale crossbeds (Plate 3); distinctive, thin units of pebble conglomerate locally accentuate the foresets. In a number of instances, the green sandstones have a distinctively mottled pale-pink to pale-green surface coloration.

The same facies also occurs more than 20 km southwest of Bonavista, in the Trinity Pond area, where the mottled sandstones are interstratified as thin to thick units within conglomerate (*see below* Jones Pond facies). Southeast of Cape Bonavista, these crossbedded sandstones are in fault contact with thin- to medium-bedded siliceous turbidites of the Conception Group and black shale of the St. John's Group. The Cape Bonavista facies sandstones are typical of much of the Rocky Harbour Formation exposed in western Bonavista Bay and southwestern Trinity Bay (O'Brien and Knight, 1988; King, 1988, unpublished data).

Plate 3. *Crossbedded sandstones of the Cape Bonavista facies of the Rocky Harbour Formation, Cape Bonavista.*

Jones Pond Facies

The Jones Pond facies is mainly developed near the base of the Rocky Harbour Formation, and is characterized by pebble to cobble conglomerate, having a grey–green matrix. It is one of the most extensive developed facies within the formation, extending from the Trinity Pond area, east toward Port Rexton and thence northwest toward the region east of Upper Amherst Cove. From there it forms a continuous band of variable ($\leq$1 to 3 km) width extending north to a point about 3 km south of Bonavista. Examples of the conglomerate are well exposed in a large quarry at Jones Pond, near Bonavista (Plate 4, top). The conglomerate typically occurs in very thick tabular units, that are crudely to moderately sorted, and locally interstratified with planar to cross-stratified immature sandstones and granule conglomerate. The clasts are typically oval-shaped, well-rounded and matrix-supported. In the region from Bonavista south to Upper Amherst Cove, the conglomerate locally overlies fine-grained, planar-bedded grey sandstone and siltstone.

Conglomerates similar to those of the Jones Pond facies have also been mapped in a wide area extending from Trinity Pond east to Port Rexton, in the southwestern part of the peninsula. In the area around Trinity Pond, the conglomerate is interbedded with lithic-rich, crossbedded sandstones similar to those found in the Cape Bonavista facies (*see below*). Also near Trinity Pond, the pebble-rich conglomerate is interlayered with a distinctive matrix-rich mixtite unit, containing isolated volcanic, plutonic and sedimentary clasts in a massive to locally laminated fine-grained sandstone and siltstone matrix (Plate 4, bottom). Comparable mixtite units within the late Neoproterozoic Big Head Formation (Musgravetown Group) at Long Harbour (on the Isthmus of Avalon) have been interpreted as being either volcanogenic or glaciogenic in origin (King, 1988). Throughout much of that area, the Rocky Harbour Formation is, typically, little deformed and subhorizontal or gently folded. However, in a broad, 1- to 2-km-wide zone adjacent to the underlying Bull Arm Formation, west of Trinity Pond, a steep and in many cases penetrative cleavage is developed in pebble to small cobble conglomerate.

The conglomerates in most of these localities are composed of up to 75 percent subaerial volcanic detritus, which

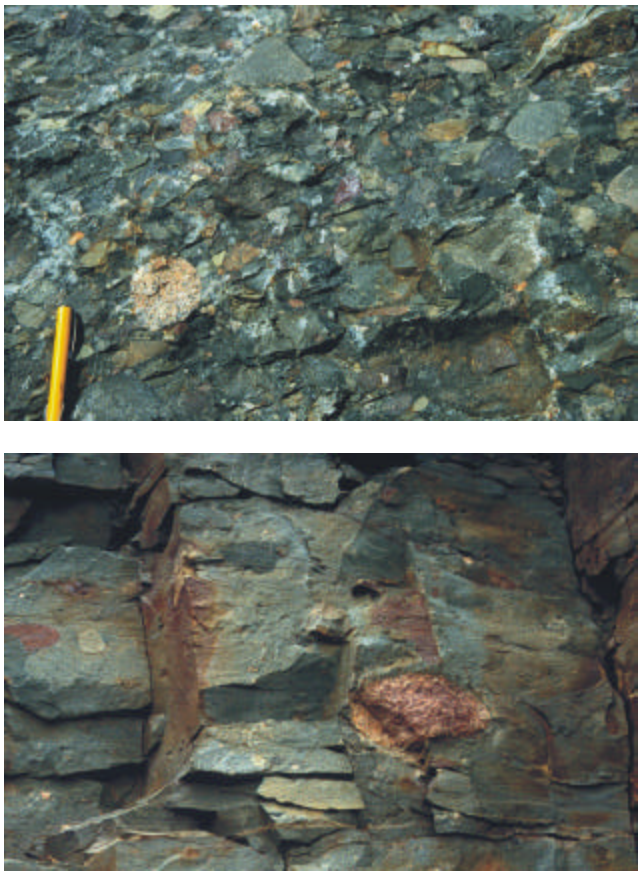

Plate 4. *Conglomerates of the Jones Pond facies of the Rocky Harbour Formation: top) typical Jones Pond facies at Jones Pond, containing rounded clasts of pink granite in conglomerate; bottom) mixtite at Trinity Pond.*

typically includes variegated red to purple rhyolite and vesicular green basalt. Less common detritus includes pink to orange felsite and fine-grained granite, white vein quartz, red "chert", and granules of pink feldspar. The type and amount of intrabasinal sedimentary detritus is variable. At one site, there may be an abundance of small pebbles of siltstone, whereas at another site, nearby, there may be many large clasts of well-bedded and slumped sandstone. The overall colour of the conglomerates is variable and predicated by the proportion and nature of included volcanic clasts. The most typical colours are grey, green, grey–purple and bluish-grey. The purple colouration typical of the facies in the west part of the peninsula is largely related to the colour of volcanic material predominant in the detrital assemblage, which in that area is rich in clasts of purple to maroon, subaerial volcanic rocks from the underlying and adjacent Bull Arm Formation.

The matrix of the granule conglomerates and interstratified coarse-grained sandstones locally contain disseminated chalcocite (e.g., at Trinity Pond; Figure 2).

Birchy Cove–Newmans Cove Facies

Rippled to streaky-laminated grey–green sandstone and siltstone of the Birchy Cove–Newmans Cove facies overlie the crossbedded sandstones of the Cape Bonavista facies, and are well exposed in coastal cliffs between Birchy Cove and Amherst Cove. The predominance of impoverished or isolated sand ripples results in a distinctive wispy or discontinuous, lenticular bedding in these rocks (Plate 5). The streaky laminae are isolated, 1- to 2-cm-thick lenses and ribbons of sand. The coarser grained sand is red–brown to pale orange, whereas the silt and finer sand is grey–green to olive green; silt and sand occur in approximately equal proportions. Thin layers of grey laminated calcareous material occurs as discontinuous layers in the wispy-bedded units. Facies variants in the lower part of this unit include a more continuously bedded, silty and slightly siliceous sandstone.

Plate 5. *Characteristic lenticular bedding in sandstone and siltstone of the Birchy Cove–Newmans Cove facies, Rocky Harbour Formation, near Birchy Cove.*

Middle Amherst Cove–Wolf Cove Facies

The thick-bedded, rippled and slumped grey sandstones that define this facies are well exposed in coastal cliffs around the communities of Amherst Cove and Upper Amherst Cove, above cross-bedded sandstones of the Birchy Cove–Newman's Cove facies and gradationally below red sandstone beds at the base of the Monk Bay–Hodderville facies. The lower part of this facies includes thick, convoluted sandy beds that are locally slumped and typically lack interlayered silty material. These pass upward into thin-bedded to laminated and, in places, lenticular-bedded, grey sandstones, having impoverished and isolated ripples. Bedding is more-or-less regular and continuous. The top of the facies is likewise sand-rich and is slumped throughout. These grey sandstones exhibit superbly preserved ripple marks, crossbeds and well-developed, centimetre- to metre-scale slump folds (Plate 6).

Plate 6. *Bedding surface with exceptionally well-preserved ripple marks in sandstone of the Middle Amherst Cove–Wolf Cove facies, Rocky Harbour Formation, between Black Bay and Wolf Cove.*

Monk Bay–Hodderville Facies

This facies is well exposed in the low coastal cliffs at Monk Bay and Hodderville; the most complete section is exposed between Knights Cove and King's Cove. It is characterized by thick-bedded, coarse-grained, pale red to buff sandstone, with large-scale symmetrical and asymmetrical ripples or dunes, having rounded crests and troughs, and wavelengths up to one metre. Large-scale and small-scale trough crossbeds are well developed (Plate 7), and display a generally northerly direction of transport. Tabular beds of red mudstone, from 2 to 10 cm thick, infill ripple troughs. A minor component of this facies is granule to small pebble conglomerate, containing rounded clasts (1 to 3 cm) of pink felsite and purple, intermediate to mafic volcanic rocks.

Plate 7. *Large-scale ripples and crossbeds in sandstone of the Hodderville–Monk Bay facies of the Rocky Harbour Formation, at Monk Bay; paleoflow to the left (northwest).*

Detrital magnetite is locally preserved in narrow discontinuous bands.

In the Monk Bay section, its lower boundary is drawn at a thin unit of fine-grained pale green siltstone at the top of the Amherst Cove facies, which overlies slumped and well-rippled, rusty- to buff-weathering, grey coarse-grained sandstone. The top of the Monk Bay–Hodderville facies is drawn at the occurrence of thinly laminated, pale green siltstone of the King's Cove North facies.

King's Cove North Facies

This distinctive, light grey siltstone and shale facies occurs at the top of the Rocky Harbour Formation, overlying coarse-grained purple to red sandstone of the Monk Bay facies. Its typical lithology is white-weathering, finely laminated, fissile siltstone, which is well exposed on the north

side of King's Cove, including outcrops adjacent to the Roman Catholic church. This facies forms a mappable unit that extends along the highway from King's Cove, southwest to the area around Plate Cove, where it is truncated by either the Indian Arm Fault or northeast-trending splays from that major structure.

Crown Hill Formation

Red bed units occur mainly (although not exclusively) in the upper Musgravetown Group. Red and maroon terrigenous sandstones and conglomerates, assigned to the Crown Hill Formation by Jenness (1963), overlie a thin unit of parallel-laminated, thin-bedded green siltstone (King's Cove North facies) at the top of the Rocky Harbour Formation. The main area of red beds in the area studied by the authors lies above this unit, northwest of a boundary extending from King's Cove southwest toward Plate Cove East. Jenness (1963) estimated the thickness of Crown Hill rocks in this area as between 1 and 1.5 km. Less extensive purple to maroon sandstones are locally developed at the top of the underlying Rocky Harbour Formation, and are described above (*see* Monk Bay–Hodderville facies).

Most of the Crown Hill Formation red beds are sandstones, similar to sandy facies in the Quidi Vidi Formation and Blackhead Formation (Maddox Cove Member) of the Signal Hill Group of the eastern Avalon Peninsula (King, 1990), and to sandy facies west of Old Perlican (Old Perlican Member, Bay de Verde Formation of the Signal Hill Group). Red conglomerate facies that are typical of the Crown Hill Formation around the type area in Trinity Bay, appear to be restricted primarily to the uppermost part of the Crown Hill Formation. Maddox Cove-like rocks occur in the section between King's Cove and Duntara. The lower part of this section includes coarse-grained, red to reddish-purple sandstones interbedded with thin units of red mudstone; sand and mud layers are disrupted by sandstone dykes formed by quicksand injection of deep-red, fine-grained sand. These are locally associated with granule conglomerate units that are, on average, 1 m thick. Elsewhere, the sandstones consist of alternating bands of laminated, red and buff to greyish-red, fine-grained sandstone and siltstone. Coastal exposures east of Duntara include thin to locally thick amalgamated beds of red to maroon sandstone, siltstone and mudstone. The section west of Duntara includes bright red sandstones that are comparable to the Quidi Vidi Formation of the Signal Hill Group on the Avalon Peninsula (King, 1990). The thickest accumulations of red conglomerate appear to be restricted to the uppermost part of the Crown Hill Formation, and are well exposed around Keels. These are well-cleaved rocks of red, rather than red–purple or maroon colouration. The conglomerates contain moderately flattened red shale pebbles, together with 1 cm pebbles of porphyritic volcanic rocks, orange felsite and vein quartz.

The red beds are reportedly overlain unconformably by folded succession of Cambrian quartz arenite, shale and limestone, exposed around the community of Keels (Jenness, 1963). The contact at the coast at Keels is tectonic, although there is no obvious regional discordance in bedding within rocks above and below the contact. The cleavage in the conglomerate appears to be co-planar with that of the overlying Cambrian rocks.

At Blue Point, near the community of Duntara, the red beds contain a laterally extensive, thin- to wavy-bedded, fine-grained light and dark-grey fine-grained sandstone unit, up to 40 m thick, which hosts the Cornerstone–Noranda SSC-style copper prospect (Cornerstone Resources Inc., press release 01-03; Plate 8). The copper mineralization (chalcocite) occurs in a brown-weathering, gossanous, finely pyritic grey bed (Plate 9). Mineralization occurs as discreet, very thin, chalcocite-rich laminae, as a replacement of disseminated pyrite in sandy layers, and in fractures normal to bedding. A continuous chip sample collected across the pyritic bed returned assays of 0.54% Cu and 7.2 g/t Ag over 25.50 m, including 0.93% Cu and 13.02 g/t Ag over 13.50 m and 1.38% Cu and 19.35 g/t Ag over 4.50 m (Cornerstone Resources Inc., press release 01-03). Subsequent drilling undertaken by Cornerstone Resources Inc. and its joint venture partner, Noranda Inc., intersected the mineralized unit along strike, 1.8 km to the west. Published results include values of 1% Cu and 12.1g/t Ag over 14.25 m, including 2% Cu and 23.1 g/t Ag over 6 m (Cornerstone Resources Inc., press release 01-10).

Plate 8. *Brown and grey mineralized zone (0.92%Cu, 13.02 g/t Ag over 13.5 m) in Crown Hill Formation red beds of the Musgravetown Group at Blue Point. Photo courtesy of Cornerstone Resources Inc.*

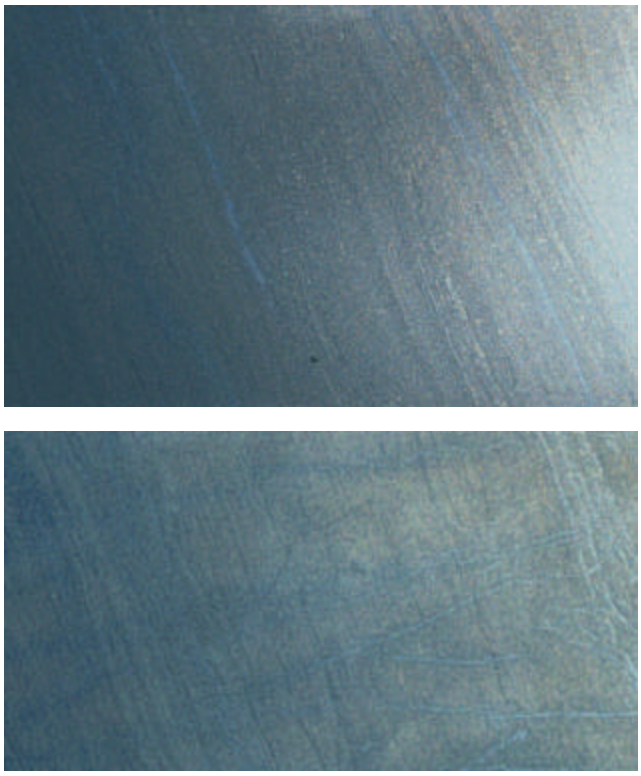

Plate 9. *Mineralized drill-core (4.5% Cu) from the Duntara Prospect (sample provided by Cornerstone Resources Inc.); (top) thin-bedded, light and dark grey, fine-grained sandstone contains disseminations and laminae of fine-grained chalcocite replacing pyrite; (bottom) same as above, but with additional chalcocite-filled fractures normal to bedding. (NQ core; core axis perpendicular to bedding)*

DISCUSSION

REGIONAL CORRELATION AND DISTRIBUTION OF THE COPPER-MINERALIZED UNITS

Volcanic and sedimentary rocks of similar age, facies and stratigraphic order to those in the Musgravetown Group on the Bonavista Peninsula have been mapped throughout much of the west-central Avalon Zone (e.g., Jenness, 1963; McCartney, 1967; O'Brien and Knight, 1988; King 1990; Figure 4). Lithostratigraphic correlatives of the copper-mineralized units described above, continue southward from the area studied, to Smith Sound and onto the Isthmus of Avalon. Facies similar to those described from the Bonavista Peninsula (including parts of the Crown Hill and Rocky Harbour formations) have also been identified within an extensive belt of Musgravetown Group rocks that reappears along the west side of Trinity Bay, extending south along the length of the peninsula between St. Mary's and Placentia bays (King, 1990). In the last area, sedimentary rocks overlie a basal bimodal volcanic unit, equivalent to the Bull Arm Formation. In the section exposed east of Trinity Bay, however, the volcanic rocks are missing, and Musgravetown strata lie directly on the St. John's Group and the Gibbett Hill Formation of the Signal Hill Group (King, 1990). The principal facies in the late Neoproterozoic successions in these areas are outlined in a simplified fashion in Figure 4. In each case, the Neoproterozoic successions contain red beds that are correlative with part of all of the Crown Hill Formation. The uppermost red beds are in turn overlain by the same quartz arenite–shale–limestone sequence of Cambrian age that occurs on the Bonavista Peninsula at Keels.

Openly folded rocks of the Crown Hill, Rocky Harbour and underlying Bull Arm formations also crop out in western Bonavista Bay, west of the belt of 620 to 610 Ma marine turbidites that separate east and west belts of the Musgravetown Group in the northwestern Avalon Zone (O'Brien and Knight, 1988; Figure 4). They occupy a narrow but laterally extensive, fault-bounded belt extending southward for about 100 km to the Devonian Ackley Granite. A number of volcanic- and sediment-hosted chalcocite and/or native copper prospects occur in these rocks (e.g., West Princess property of Cornerstone Resources Inc.). A smaller outlier of Musgravetown Group red beds and subaerial volcanic rocks are exposed between the eastern and western belts, in southern Bonavista Bay, unconformably overlying the Connecting Point Group (O'Brien, 1993); these rocks host volcanic red bed copper (VRC) style mineralization in the Stag Brook and related chalcocite showings of Cornerstone Resources Inc.

Rocks coeval with the Musgravetown Group reappear south of the Ackley Granite, in the Long Harbour Group and its equivalents around northern Fortune Bay (Williams, 1971; O'Brien *et al.*, 1984). The shallow-marine and terrestrial sedimentary formations in this area – Andersons Cove and Rencontre formations, respectively – include facies similar to those found in parts of the Rocky Harbour and Crown Hill formations. A number of significant examples of stratiform sediment-hosted copper mineralization have recently been described in red beds and grey–green beds in the Long Harbour Group: viz., the Fortune Bay Property of Altius Minerals, and the Merlin (1.84% Cu over 3.8 m, continuous chip) and related prospects in the Bay L'Argent property of Celtic Minerals Ltd. (*see* Altius Minerals Corporation press release 01-02 and Celtic Minerals press release 08-16-01). In that part of the western Avalon Zone, however, preserved remnants of sedimentary basins are areally less extensive than associated subaerial volcanic successions; as well, the red beds are interlayered with subaerial peralkaine volcanic units (e.g., Mooring Cove Formation, O'Brien *et al.*, 1984) similar to those in the Musgravetown Group in southern Bonavista Bay. Available geochronological data indicate that basin evolution associated with deposition of the Mus-

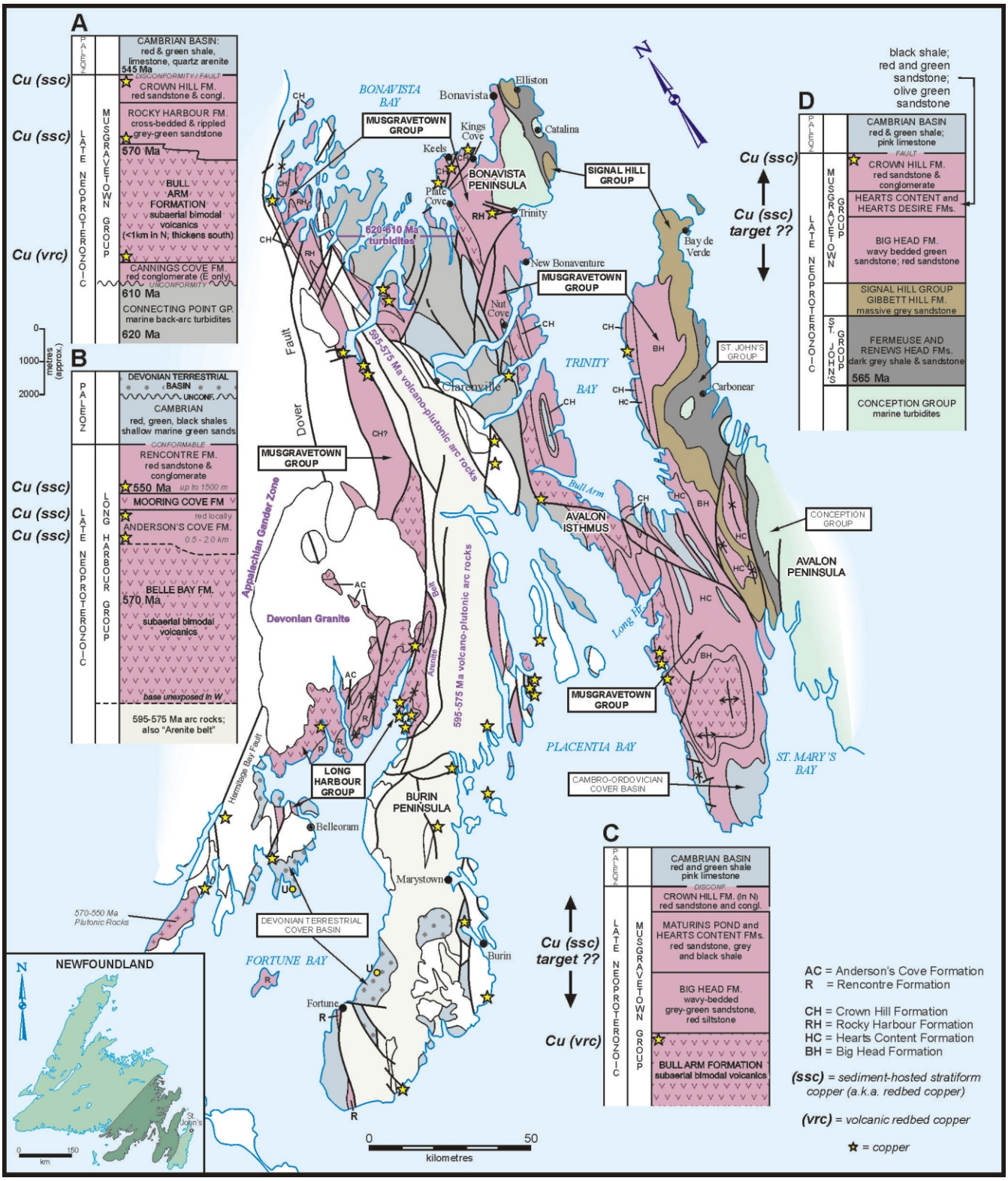

Figure 4. *Distribution and correlation of principal Late Neoproterozoic and Paleozoic siliciclastic sedimentary rocks in the west-central Avalon Zone, Newfoundland, showing select copper occurrences. Schematic composite sections are from: A = Bonavista Bay, B = Northern Fortune Bay, C = Avalon Isthmus-western Placentia Bay, and D = eastern Trinity Bay.*

gravetown Group sedimentary rocks is coeval with that of the Long Harbour Group and is bracketed between about 570 Ma and 550 Ma (O'Brien, 1998; O'Brien and Dunning, unpublished data).

REGIONAL SETTING AND AGE OF THE COPPER-MINERALIZED SEDIMENTARY BASINS IN THE AVALON ZONE

The Neoproterozoic rocks of the Avalon Zone in southeastern Newfoundland chronicle several contrasting stages of the complex and protracted (≥200 Ma) evolution of magmatic arcs and marine to terrestrial basins along a plate margin peripheral to the ancient continent of Gondwana, coeval with, and linked to, late-stage evolution of the Pan African orogenic belt (O'Brien *et al.*, 1983, 1990, 1996). Final accretion of this Neoproterozoic orogenic system to the Paleozoic Appalachian occurred in the Siluro-Devonian. The same Neoproterozoic "Avalonian" rocks form a tectonically disrupted belt that continues along strike for approximately 3000 km in North America, reappearing in the Caledonides south of Torquist Suture. Rocks of an age, setting, lithology and stratigraphic framework similar to those of the Appalachian Avalonian belt also occur in North Africa (O'Brien *et al.*, 1983; King and O'Brien, 1989).

In much of the Newfoundland Avalon Zone, the geological record prior to deposition of the Musgravetown Group and coeval rocks is characterized by arc-related calc-alkaline volcanism, plutonism and back-arc sedimentation, within a compressional tectonic regime, active from about 640 Ma (*see* review in O'Brien *et al.*, 1996). The character of post-570 Ma Neoproterozoic successions is fundamentally different, however, and appears to reflect a change in tectonic style that may be related to extension and the transpressional dispersal of the larger Avalonian belt (Gibbons, 1990). The stratigraphic record of the western Avalon Zone in the approximate interval 570 Ma to 545 Ma records the widespread development of terrestrial volcano-sedimentary basins (e.g., King, 1980; O'Brien *et al.*, 1990, 1996) during a period of global rifting at the end of the Proterozoic (Bond *et al.*, 1984).

Volcanic rocks of this age in the western Avalon Zone include rift-related bimodal lavas and pyroclastic deposits of moderate to strongly alkaline and peralkaline affinity (e.g., O'Brien *et al.*, 1984, 1990). Importantly, vesicular basalts erupted at this time contain elevated copper, and locally host volcanic-red bed-copper-style copper mineralization. The 570 Ma to 545 Ma basin-fills are stratigraphically complex, but regional-scale similarities in age and style of facies support correlations that suggest the basins were once of significant aerial extent; thus it is possible that the late Neoproterozoic SSC-style copper-mineralizing systems may have been of a large scale. These late Neoproterozoic basins include deltaic and shallow-marine facies in some areas, and are everywhere characterized – in their upper stratigraphic levels – by thick successions of red beds that accumulated in fluvial, alluvial and lacustrine environments. Each preserve facies that record conditions suitable for formation of SSC-style copper mineralization.

The 570 Ma to 545 Ma sedimentary successions developed above or adjacent to the copper-bearing, syn-basinal volcanic pile, but locally onlapped unconformably onto earlier (680 to 620 Ma) volcano-plutonic complexes and 620 to 610 Ma turbidite basins. The Neoproterozoic basins rocks were affected by characteristically weak and mainly inhomogeneous brittle deformation during and subsequent to basin development. The late Neoproterozoic sediments pass upward (conformably and disconformably) into shallow-marine, shale-dominated successions that accumulated in relatively shallow but extensive basins of Cambrian to earliest Ordovician age. Both the Neoproterozoic and early Paleozoic basins were disrupted by folding and faulted related to Siluro-Devonian deformation linked to final accretion of the Avalon Zone to the inboard Appalachian-cycle rocks (O'Brien *et al.*, 1990, 1996).

EXPLORATION IMPLICATIONS

Exploration industry descriptions of recently discovered sediment-hosted copper mineralization in the late Neoproterozoic basins of the Avalon Zone indicate that at least some of these showings appear to share a number of characteristics with red bed copper or SSC deposits. These include the overall nature, lithofacies and regional setting of the host basins, the stratigraphic linkage with copper-mineralized subaerial mafic lavas, and the apparent spatial association of chalcocite with reduced (pyritic) beds, primarily within red bed sequences. The latter facies associations are developed in the upper parts of these basins across much of the western Avalon Zone; regional stratigraphic studies indicate the same association is preserved in a number of other parts of the Avalon Zone, within the 570 Ma and later Musgravetown, Long Harbour and Signal Hill groups. Importantly, however, fine-grained and coarse-grained grey and green clastic facies, in places pyritic, are developed in other, lower stratigraphic levels within the basin-fills (e.g., Rocky Harbour Formation of the Musgravetown Group and Anderson's Cove Formation of the Long Harbour Group), and also contain stratiform-style chalcocite mineralization (*see above*). Available age controls and overall facies similarities in the latest Neoproterozoic and overlying Cambrian sediments in the Avalon Zone are consistent with the possibility that these basins, which are now physically separate and locally fault-bounded, may have been linked, as a single entity, in the Neoproterozoic. The combination of detailed mapping and

related analysis of sedimentary facies, coupled with prospecting and lake-sediment geochemistry appear to be effective means of assessing areas of future exploration for SSC deposits in the Newfoundland Avalon Zone.

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