Current Research (2010) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 10-1, pages 281-301

GEOLOGY OF THE BONAVISTA MAP AREA (NTS 2C/11), NEWFOUNDLAND

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ABSTRACT

The Bonavista Peninsula, located within the Avalon Zone, eastern Newfoundland, is divided into two sedimentary domains (east and west) characterizing unique Neoproterozoic depositional basin settings. The eastern domain is the westernmost extent of the fossiliferous Neoproterozoic Conception, St. John's and Signal Hill groups (St. John's basin) and is located along the eastern edge of the Bonavista Peninsula; depositional environments are turbiditic, deep marine and fluvial, respectively. The western domain comprises Neoproterozoic sedimentary rocks (and rare volcanic rocks) of the Musgravetown Group, corresponding to the shallow-marine and fluvial depositional environments of the Bonavista basin. These two basins are separated by the Spillars Cove–English Harbour fault. Unconformably overlying the western domain are rocks that form a remnant of the strata deposited during the Early Cambrian global sea-level rise. The Cambrian Random Formation outcrops in the Keels area and was formed during a marine transgression across the Avalon Zone. The youngest sedimentary rocks are the Early Cambrian Bonavista Formation slates disconformably deposited above the Random Formation.

The 2009 field survey located a radial dyke swarm, oriented toward the newly discovered mafic volcanic rocks of the Bull Arm Formation, in the south central part of the map area. Results indicate the St. John's and Bonavista basins formed in distinctly different depositional regimes, although they have comparable basin architecture and are now juxtaposed.

INTRODUCTION

Detailed bedrock mapping of NTS map area 2C/11 (Bonavista) was completed during the 2009 summer field season (Figure 1). This report summarizes the initial findings of a new, 1:50 000-scale mapping project on the Bonavista Peninsula. The 180 km of coastline in the map area was surveyed by boat, and the interior was accessed *via* foot, ATV trails and resource roads. A regional metallogenic study was also carried out in conjunction with this mapping project (*see* J. Hinchey, *this volume*).

Field work concentrated on the mapping (Figure 2) and stratigraphic correlations of the Rocky Harbour and Crown Hill formations, Musgravetown Group (Figure 3a) and their relationships to the Conception, St. John's and Signal Hill groups (Figure 3b), located to the east, across the Spillars Cove–English Harbour (SC–EH) fault.

LOCATION, ACCESS AND PHYSIOGRAPHY

The Bonavista Peninsula is located in eastern Newfoundland between Bonavista Bay, to the west, and Trinity Bay, to the east. The peninsula lies within the Avalon

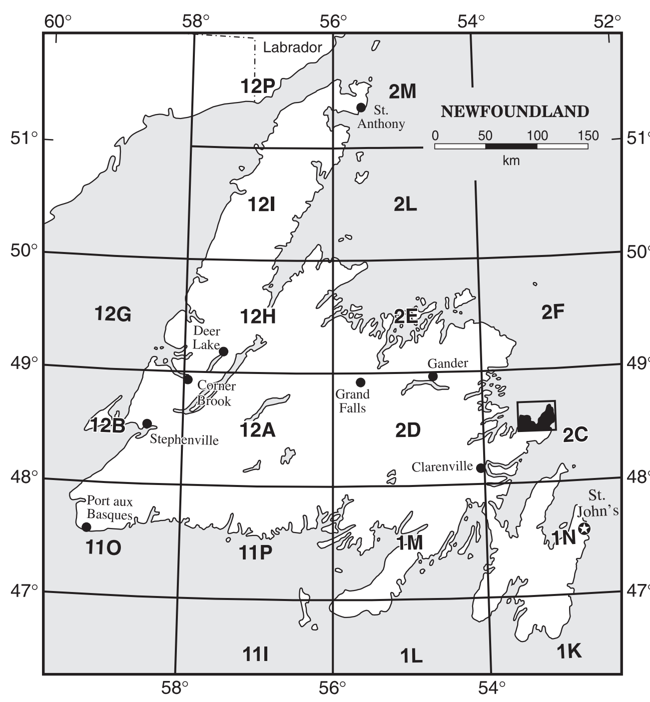

Figure 1. *Location map of the study area (NTS map area 2C/11).*

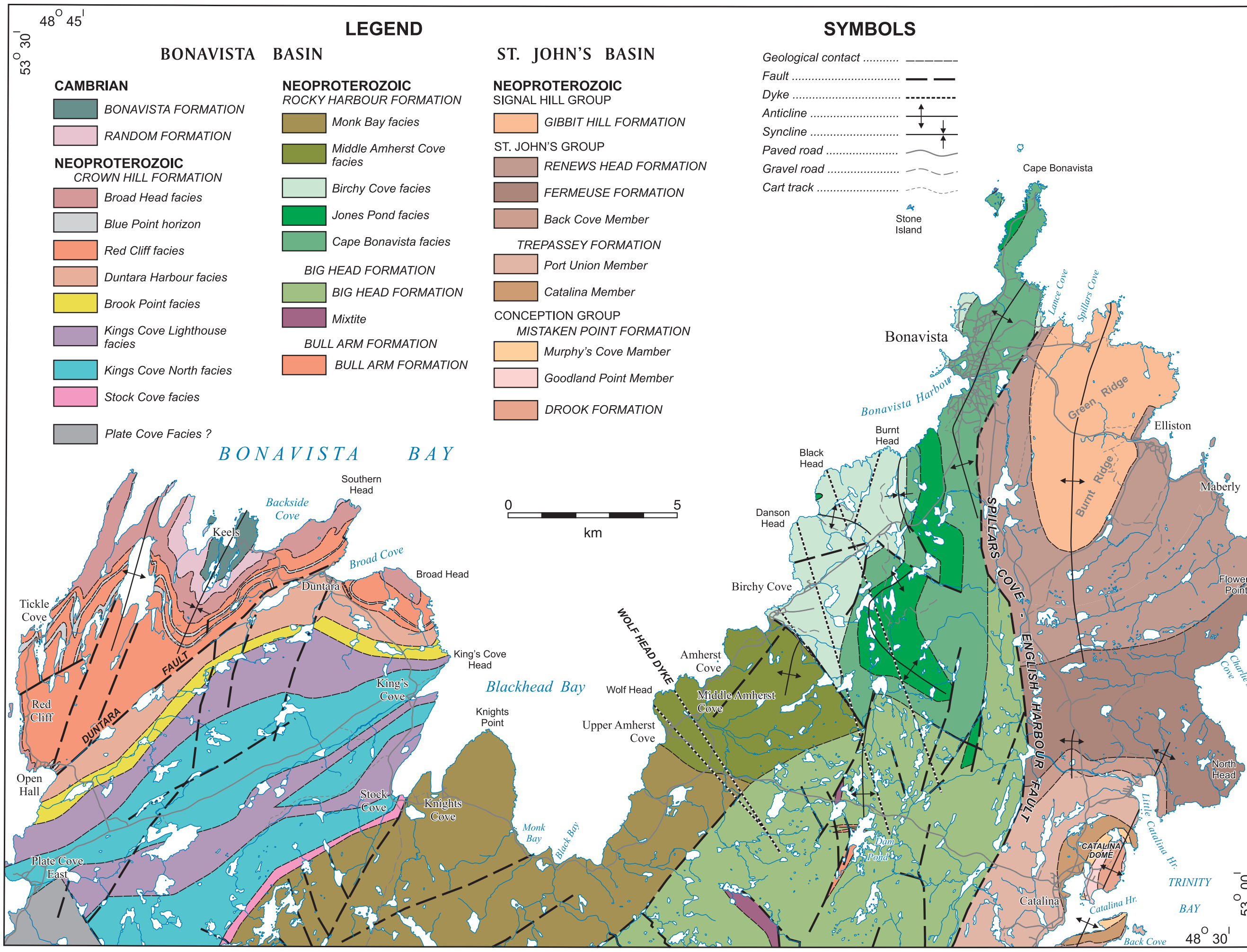

Figure 2. *Geology of the Bonavista map sheet (NTS map area 2C/11) based on field work and previous compilation (*see *Previous Studies, this page).*

(tectonostratigraphic) Zone of Williams (1979). The southwest corner of NTS map area 2C/11 is approximately 62 km northeast of Clarenville via Routes 230 and 235. The area has a good network of paved roads, two resource roads (Birchy Cove and Stock Cove resource roads), an abandoned railway line, and several ATV trails. The topographic relief is mostly gentle with a maximum elevation of 200 m. Bog and barrens dominate the area west of Route 230.

PREVIOUS STUDIES

Geological studies of the Bonavista Peninsula are summarized in O'Brien and King (2002). The entire Bonavista Peninsula was designated Musgravetown Group sedimentary rocks (Hayes, 1948) and subdivided into the Bull Arm, Rocky Harbour and Crown Hill formations by Jenness (1963). Discovery of Ediacaran fossils were used to correlate the stratigraphy of the eastern Bonavista Peninsula (O'Brien and King, 2004a; O'Brien *et al.*, 2006; Hofmann *et al.*, 2008) with that of earlier studies of the Conception, St. John's and Signal Hill groups of the eastern Avalon Peninsula (King, 1988). Mineral exploration for sediment-hosted copper resulted in extensive geological studies of the Bonavista Peninsula (*see* Froude, 2001; Dessureault, 2002; Graves, 2003; Seymour *et al.*, 2005).

REGIONAL SETTING

The Island of Newfoundland forms the northeast extension of the Appalachian orogenic system in eastern North America. The volcanic, plutonic and sedimentary rocks of the Avalon Zone in southeast Newfoundland are part of an exotic terrane that records the accretion and break up of a proto-Gondwana supercontinent (Williams, 1979; Nance *et al.*, 1991). The evolution of multiple volcanic island arcs and their associated deep-marine basins form several, thick volcano-sedimentary successions, prior to the docking of the Avalon Zone with inboard terranes of the Appalachians in mid-Paleozoic times (O'Brien *et al.*, 1983).

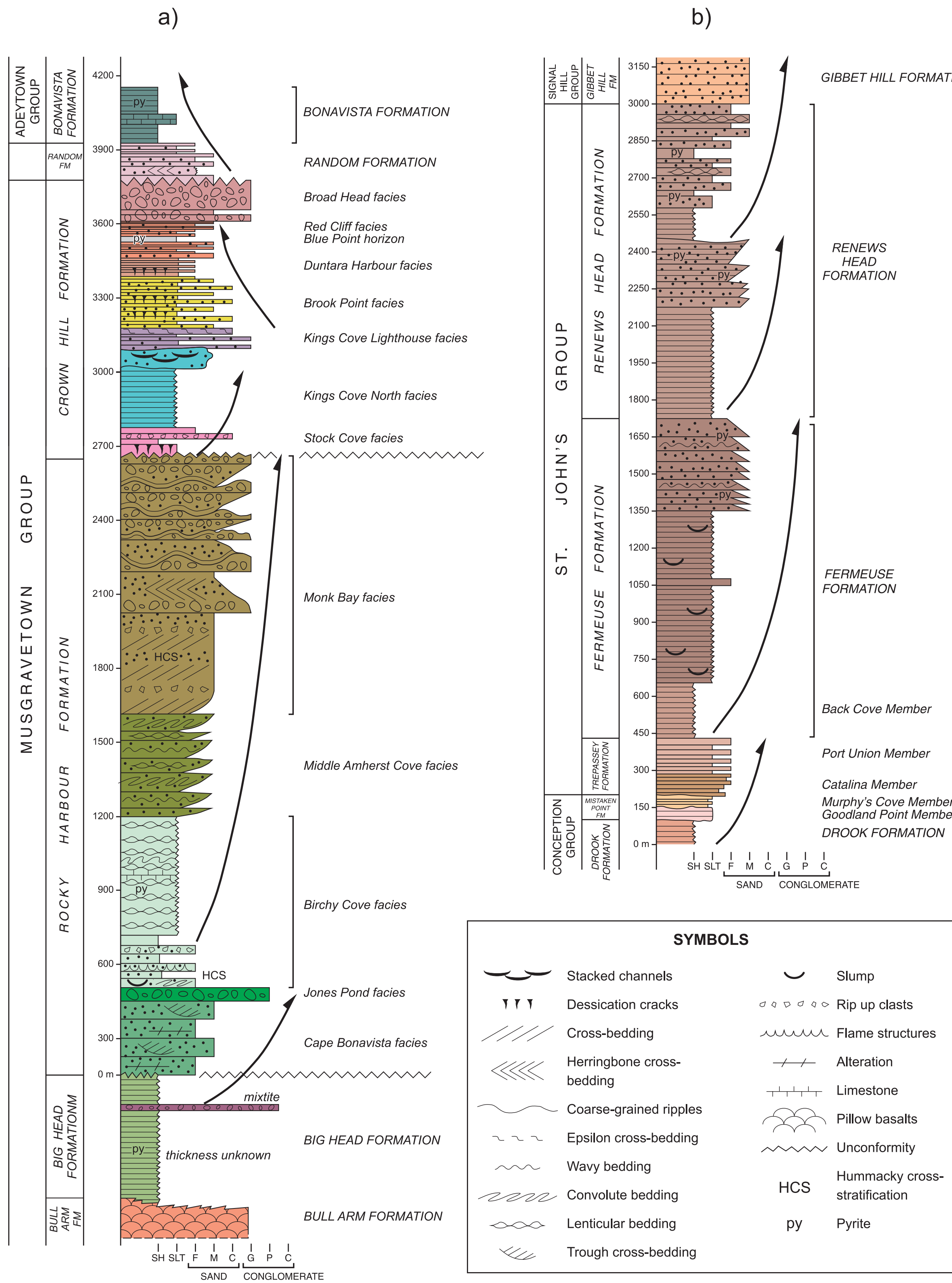

Figure 3. *Stratigraphic logs of a) the Bonavista basin (Musgravetown Group, Random and Bonavista formations) and b) the St. John's basin (Conception, St. John's and Signal Hill groups), on the Bonavista Peninsula.*

The Avalon Zone rocks on the Bonavista Peninsula are divided into two sedimentary basins, separated by the SC–EH fault. Late Neoproterozoic sedimentary rocks and minor volcanic rocks of the Musgravetown Group and Early Cambrian marine sedimentary rocks of the Random and Bonavista formations on the western part of the Bonavista Peninsula, comprise the Bonavista basin (Figure 2). To the east of the SC–EH fault, the St. John's basin consists of the late Neoproterozoic Conception, St. John's and Signal Hill group sedimentary rocks (Figure 2). This report briefly discusses the St. John's basin, followed by a more detailed account of the Bonavista basin. Finally, the newly discovered radially oriented dykes are discussed with their potential implications on the time-stratigraphic-equivalent basin architecture of the Bonavista and St. John's basins.

FIELD RESULTS

NEOPROTEROZOIC ST. JOHN'S BASIN

The part of the St. John's basin found on the Bonavista Peninsula (Figure 3b), like its correlative on the Avalon Peninsula, consists of the Conception, St. John's and Signal Hill groups (O'Brien and King, 2002; O'Brien *et al.*, 2006). Since the discovery of Ediacaran fossils in the Port Union area (O'Brien and King, 2002), subsequent work has produced detailed maps of this part of the Bonavista Peninsula with precise correlation of the St. John's basin stratigraphy (King and Williams, 1979; O'Brien and King, 2005; Hofmann *et al.*, 2008). As a result, only the upper St. John's and overlying Signal Hill groups were mapped during this study, to help determine their relationship with the juxtaposed Rocky Harbour and Big Head formations (Figure 2).

St. John's Group

The St. John's Group is over 2500 m thick on the Bonavista Peninsula (Figure 3b), outcropping from Little Catalina to Elliston. It gradationally overlies the Conception Group and is made up of, in ascending stratigraphic order; the Trepassey, Fermeuse and Renews Head formations. In the Little Catalina area, turbiditic, medium-bedded, fine-grained sandstones and siltstones are found in the upper Trepassey Formation and are transitionally overlain by black shale, siltstones and fine- to medium-grained sandstones of the Fermeuse Formation. The lowermost Renews Head Formation is in transitional contact with the Fermeuse Formation and consists of thin lenticular-bedded sandstones and siltstones deposited during a shallowing-upward succession (King, 1990).

Trepassey Formation

The Trepassey Formation is located along the north-plunging axis of the Catalina Dome on the west side of Little Catalina Harbour, as well as in Port Union Harbour and the north coast of Back Cove (Figure 2). The Trepassey Formation had previously been subdivided into the lower mud- and silt-rich Catalina member and the sand-rich Port Union member (Figure 3b) by O'Brien and King (2005).

Fermeuse Formation

The Fermeuse Formation outcrops from Little Catalina to Flowers Point, on the coast of Trinity Bay (Figure 2). It conformably overlies the Trepassey Formation and displays a general coarsening-upward trend, which is divided into three facies (Figure 3b). The lowermost shale-rich facies has been named the Back Cove member (O'Brien and King, 2005) and has been eroded away to form Little Catalina Harbour. This member is dark grey to black, weathers to brown shale and siltstone. It is interbedded with fine-grained, disrupted and brecciated, grey sandstone horizons, and rare thin- to medium-bedded, sand-rich breccia and minor tuff. The middle facies is characterized by large slumped units within interbedded siltstone–sandstone beds and outcrops from North Head to Charlies Cove (Figure 2). Siltstones are dark grey and thinly bedded while the sandstones are light grey and range from thin to thick bedded. The grain size increases to the uppermost facies of the Fermeuse Formation from Charlies Cove to Flowers Point. Here the succession contains grey, pyritic, thin- to medium-bedded, wavy to parallel-bedded, medium-grained sandstone.

Renews Head Formation

Gradationally overlying the Fermeuse Formation is the Renews Head Formation (Figure 3b). It outcrops between Flowers Point to Elliston on the coast of Trinity Bay and also occurs as a tectonic sliver to the west at Lance Cove (Figure 2). The Renews Head Formation contains a wider variety of rock types than the underlying Fermeuse Formation, and distinctive sedimentary structures, such as lenticular bedding, starved current ripples, concretions, water-escape structures and small sand dykes are clearly in evidence. On the Bonavista Peninsula, the Renews Head Formation consists of two coarsening-upward successions. The lower succession varies from a dark-grey, thin-bedded siltstone facies to a grey, thin- to thick-bedded, fine-grained, pyritic sandstone facies. The upper succession has a pyritic, rusty brown, shale-rich facies overlain by dark-grey, interbedded shale and siltstone with sporadic lenticular, medium-grained, brown-grey sandstone. Olistostromes, noted at Lance Cove within the upper Renews Head Formation, are commonly products of submarine slides within slope settings.

Signal Hill Group

Grey, thick-bedded sandstones outcrop along the coastline from Elliston to Spillars Cove forming a large synclinal structure over the Green Ridge and Burnt Ridge areas (Figure 2). This sequence conformably overlies the Renews Head Formation (Figure 3b) and comprises the youngest sedimentary rocks that are directly correlated with the St. John's basin on the Bonavista Peninsula. They are interpreted to be deposited in a deltaic depositional environment and correlated with the Gibbet Hill Formation of the lowermost Signal Hill Group (King, 1990; O'Brien and King, 2004b).

NEOPROTEROZOIC–CAMBRIAN BONAVISTA BASIN

Rocks of the Bonavista basin are well exposed in the area between Lance Cove and Plate Cove East (Figure 2). The sequence contains an incomplete succession of Musgravetown Group volcanic and sedimentary rocks unconformably overlain by quartz arenites of the Early Cambrian Random Formation. The Random Formation is unconformably overlain by slate, sandstone and limestone of the Early Cambrian Bonavista Formation; this succession is over 4000 m thick (Figure 3a).

Musgravetown Group

The Musgravetown Group of Hayes (1948) was divided into five formations in the Bonavista Bay area (Jenness, 1963). The five formations of Jenness, in ascending order, are the Cannings Cove, Bull Arm, Middle Undifferentiated, Rocky Harbour and Crown Hill. These divisions were carried to the south into the Isthmus of Avalon (McCartney, 1967), resulting in the addition of the Big Head, Maturins Pond and Trinny Cove formations, and the replacement of Jenness' Middle Undifferentiated and Rocky Harbour formations. Only the Rocky Harbour and Crown Hill formations were recognized on the Bonavista map sheet (NTS 2C/11) by Jenness (1963). A well-defined unconformity has been observed between the Musgravetown Group and the underlying Connecting Point Group (Hayes, 1948; Jenness, 1963). Considerable debate surrounds the upper contact of the Musgravetown Group (*see* below Random Formation and Hiscott, 1982).

Bull Arm Formation

First described by Jukes (1843), the Bull Arm Formation was added to the Musgravetown Group by Jenness (1963), overlying the Cannings Cove Formation and intercalated with the Big Head Formation. Newly discovered subaerial volcanic rocks were located in outcrop in the central part of NTS map area 2C/11 (Figure 2), corresponding to an aeromagnetic high (Figure 4) and are assigned to the Bull Arm Formation. Dark-brown to black, vesicular pillow lavas and dark green-black volcaniclastic breccias have epidote alteration. Subsequent hematite and quartz precipitation occurs within the vesicles of the pillow lavas and the matrix of the breccias. A sharp, irregular contact separates the top of the Bull Arm Formation from the overlying Big Head Formation in the map area (Plate 1). These volcanic rocks are correlatives of a 2-km-wide belt of bimodal volcanic rocks, identified 2.5 km to the west of the Bonavista map area (O'Brien, 1994).

Big Head Formation

In the south central part of the map area and along the boundary of the SC–EH fault (Figure 2), thinly laminated, grey-green and blue-grey siliceous siltstones outcrop around the domal structure cored by the underlying Bull Arm Formation. These siltstones are now assigned to the Big Head Formation of McCartney (1967); they were previously assigned to the Conception Group (O'Brien and King, 2002) and later to the siliceous grey-green siltstones of the lower Rocky Harbour Formation (O'Brien and King, 2005). The Big Head Formation outcrops in the Placentia Bay, Bay de Verde and Cape St. Mary's regions (*see* King, 1988; Fletcher, 2006) and was placed stratigraphically between the Bull Arm and Maturin Pond formations by McCartney (1967). On the Bonavista Peninsula, the Big Head Formation is unconformably onlapped by the Rocky Harbour Formation (Figure 2). The absence of redbeds, correlative to the Maturin Pond Formation on the Bonavista Peninsula, indicates that they were never deposited in this region or were eroded by the overlying Rocky Harbour Formation. The thickness of the Big Head Formation has not been established on the Bonavista Peninsula.

Mixtite Unit

Dark green-grey to dark-purple, matrix-supported, poorly sorted, angular to subrounded granule to cobble polymictic conglomerate (Plate 2) forms isolated outcrops within the Big Head Formation (Figure 2). Volcanic clasts floating in a very fine-grained matrix are sometimes surrounded by hematite or chlorite rims. No contact relationships were found with adjacent units. The mixtite facies is comparable with the mixtite located near Trinity Pond, representing sporadic contemporaneous volcanism of the Bull Arm Formation during deposition of the Big Head Formation (O'Brien and King, 2002). The fact that similar volcanic or glaciogenic mixtite units are found within the Big Head Formation at Long Harbour, on the Isthmus of Avalon (King, 1988), help corroborate the presence of the Big Head Formation on the Bonavista Peninsula.

Rocky Harbour Formation

The Rocky Harbour Formation comprises a succession

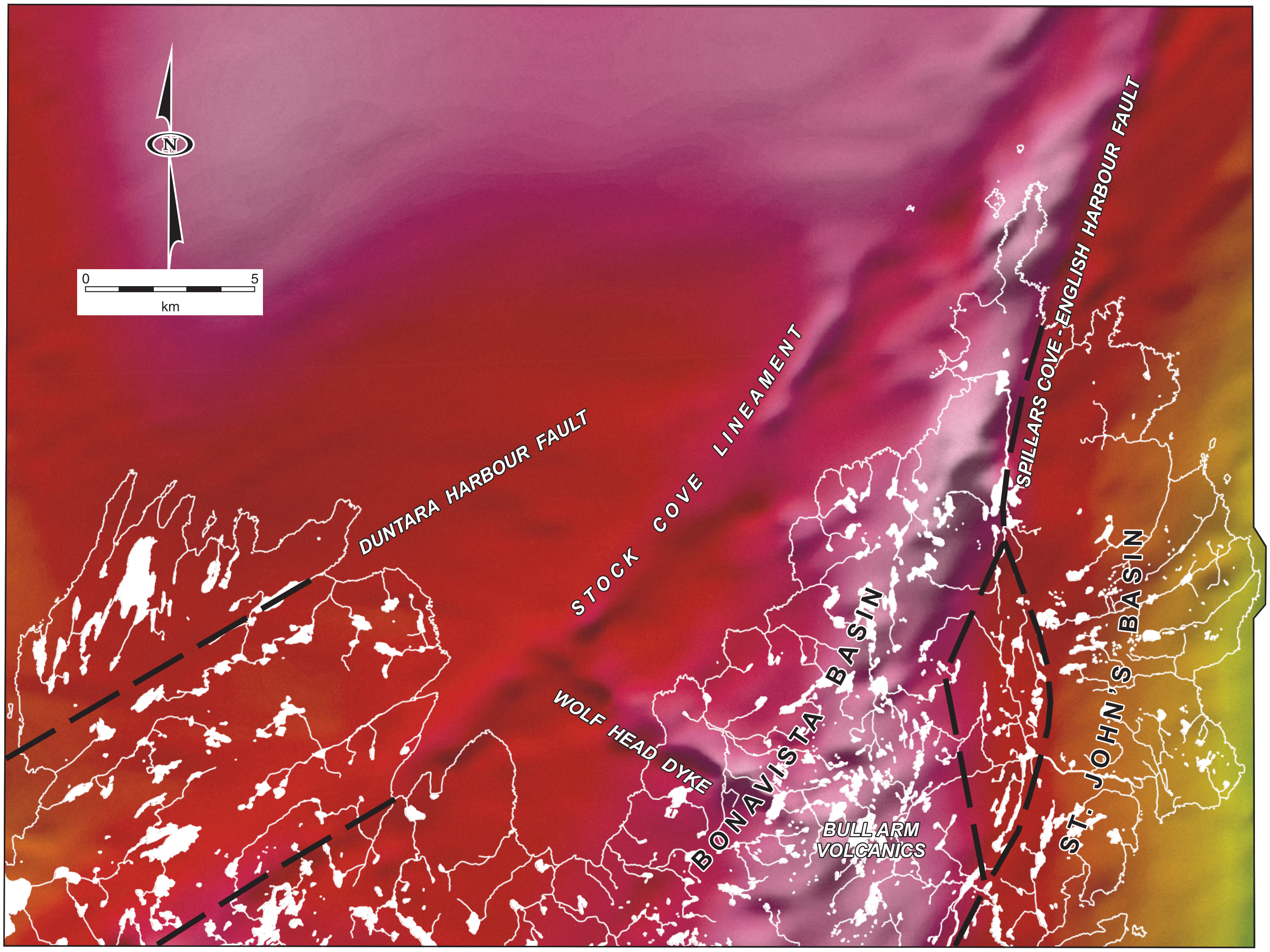

Figure 4. *Aeromagnetic map of the Bonavista Peninsula. Note the anomalous values separating the Bonavista basin and the St. John's basin along the Spillars Cove–English Harbour fault and truncation of the anomalous Wolf Head dyke by the Stock Cove lineation. The creation of a pull-apart basin along the Spillars Cove–English Harbour fault indicates compressional tectonics with the associated sinistral strike slip.*

of generally west-dipping, sedimentary rocks exposed between Cape Bonavista and Stock Cove, Bonavista Bay (Figure 2). This report retains the previously described lithostratigraphic subdivision of the Rocky Harbour Formation on the Bonavista Peninsula (O'Brien and King, 2002), with the exception of the Kings Cove North, and the Plate Cove facies, which have been reassigned to the Crown Hill Formation (*see* below Kings Cove North facies). In stratigraphic order from oldest to youngest, the facies are Cape Bonavista, Jones Pond, Birchy Cove, Middle Amherst Cove, and Monk Bay (Figure 3a).

The base of the Rocky Harbour Formation is structurally complex, juxtaposed against the Renews Head Formation to the north by the SC–EH fault and unconformably against the Big Head Formation to the south (Figure 2). The upper contact is disconformable with the Crown Hill Formation. The Rocky Harbour Formation can be correlated with the Hearts Content Formation in Trinity, Placentia and St. Mary's bays (King, 1990; Fletcher, 2006) and the Trinny Cove Formation in western Trinity Bay (King, 1990) and eastern Placentia Bay (McCartney, 1967). Depositional environments for the Rocky Harbour Formation are shallow marine with evidence for a river-dominated delta-front and pro-delta settings as well as wave and tidally influenced shoreface settings.

Cape Bonavista Facies

The Cape Bonavista facies is the lowermost subdivision of the Rocky Harbour Formation. It forms a broad anticlinal structure at Bonavista (Figure 2). The anticlinal axis curves from north-northeast to south-southeast and is truncated by a combination of thrusting and sinistral strike-slip move-

Plate 1. *Sharp irregular contact of the dark-brown, grey-weathering vesicular pillow basalts of the Bull Arm Formation and the overlying light-grey, yellow-pink-weathering, thinly laminated, siliceous siltstone of the Big Head Formation; located at Dam pond, off Route 237.*

Plate 2. *Dark-green, matrix-supported, poorly sorted, angular to subrounded, granule to cobble mixtite within the Big Head Formation, Bonavista Peninsula; volcanogenic or glaciogenic affinity.*

ment of the SC–EH Fault (*see* below Structure). The most easily recognizable lithology of this facies is the diagenetically altered, dark green-grey to light pink-grey, crossbedded, medium- to coarse-grained arkosic sandstones (Plate 3). Sandstone beds are interbedded with black, well-rounded, well-sorted, medium-bedded, granule conglomerate with rare detrital magnetite matrix.

Alteration of these rocks along high-permeability corridors such as faulting or subtle lithology variations has produced a mottled texture (Plate 3). The light-coloured alteration contains plagioclase and epidote cement whereas the dark-coloured rocks have chloritic alteration (Seymour et al, 2004).

Plate 3. *Typical Cape Bonavista facies having a mottled texture, following relatively high permeability corridors along existing fracture systems and subtle variations, located near Bonavista, Bonavista Bay.*

Jones Pond Facies

The Jones Pond facies is transitional to, and intercalated with, the Cape Bonavista facies. It outcrops on the west side of Cape Bonavista and south-southwest of the town of Bonavista (Figure 2). These detrital magnetite-bearing polymictic granule to pebble conglomerate beds have erosive lower boundaries grading into fining-upward successions. The conglomerates are very hard, dark-grey to black, locally dark-purple, well-rounded, clast-supported, and moderately sorted. The sandstones are dark-grey, thin- to medium-bedded, and fine-grained, and are capped by green-grey, thinly laminated siltstone. The intercalated nature and lensiodal geometry of this facies, in association with the large size, sphericity, and well rounding of the clasts, indicate a beach shoreline depositional environment.

Birchy Cove Facies

Siltstones and sandstones of the Birchy Cove facies outcrop from Burnt Head to Newman's Cove, Bonavista Bay (Figure 2), and can be divided into upper and lower sub-facies. The lower sub-facies (of the Birchy Cove facies) contain a wide variety of rock types including sandstones, siltstones and mudstones. Dark grey-green to brown, thin- to medium-bedded, fine-grained sandstone is the dominant lithology and is interbedded with light green-brown, thick-laminated siltstone and distinctive light yellow-green, thick-bedded, siliceous mudstones. The upper sub-facies is dark- to light-grey, thinly laminated to medium lenticular-bedded, fine- to medium-grained sandstone and siltstone, locally containing minor disseminated pyrite and convolute bedding. The relationship of the basal contact with the Cape Bonavista facies is unknown as it was not observed in the field. The upper contact with the overlying Middle Amherst Cove facies is faulted.

Sedimentary structures found in this facies include flame structures (Plate 4), intrabasinal, grey, angular to tabular siltstone clasts displaying alteration haloes (Plate 5), large-scale crossbedding, hummocky cross-stratification (Plate 6), and convolute bedding (Plate 7). Fining-upward successions containing very angular to locally subrounded, dark-brown cobble-size rip-up clasts, near the base of coarse grain beds, are also found locally. A rare occurrence of an intrabasinal pebble- to cobble-conglomerate channel or slump scar (Plate 8) that has eroded into dark-grey, coarse-grained sandstone containing angular to tabular siltstone clasts is found within the lower section of the Birchy Cove facies.

The wide variety of sedimentary structures found in the lower Birchy Cove sub-facies, indicates a rapidly deposited, wave-dominated upper shoreface environment. Hummocky cross-stratification is most common in fine- to medium-grained sandstone of shallow-marine or nearshore origin as the product of strong and complex wave activity below the fair-weather base (Collinson *et al.*, 2006). The upper Birchy Cove sub-facies is interpreted as a pro-delta slope. Slumps generally occur on slope settings at much greater depths but they will occur on any steep slope such as is created in a progradation deltaic environment. Flame structures and convolute bedding is evidence of rapid deposition characteristic of river-dominated deltas (Mail, 1984).

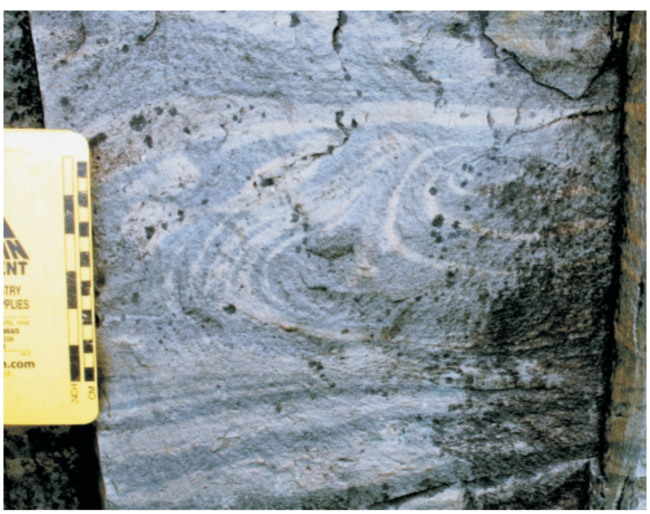

Plate 4. *Flame structure within the Birchy Cove facies with paleo-slope to the right, located between Black Head and Burnt Head, Bonavista Bay.*

Plate 5. *Intrabasinal grey angular siltstone clasts with alteration haloes in the Birchy Cove facies, located near Black Head, Bonavista Bay.*

Plate 6. *Hummocky cross-stratification (at base of student's feet), characteristic of deposition between storm and fair weather base, located within the Birchy Cove facies, near Black Head, Bonavista Bay.*

Plate 7. *Convolute bedding within the Birchy Cove facies, located near Danson Head, Bonavista Bay.*

Plate 8. *Intrabasinal well-rounded pebble to cobble conglomerate channel or slump scar eroding into underlying coarse-grained sandstone, Birchy Cove facies, located near Danson Head, Bonavista Bay.*

Limestone Bed within the Birchy Cove Facies

A distinctive component of the upper Birchy Cove subfacies is a light-pink to locally dark-grey, thinly laminated to thin-bedded, locally wavy-bedded, micritic limestone bed (Plate 9), located near Danson Head, Bonavista Bay. The limestone sequence pinches and swells from approximately 20 to 40 cm thick, with a distance of 2–3 m between crests. The limestone bed is truncated to the north by a 5-m-wide mafic dyke, thus preventing a determination of the unit's lateral continuity or geometry.

This limestone bed is the only carbonate unit found in the entire Musgravetown Group. The only other comparable Neoproterozoic limestone is overlying the Gaskiers Formation in Harbour Main, Conception Bay (Myrow and Kaufman, 1999). The Gaskiers Formation is located in the lower

Plate 9. *Light-pink and grey, thinly laminated to thinly bedded, micritic limestone within the Birchy Cove facies, located at Danson Head, Bonavista Bay. Designation as cap carbonate requires carbon and oxygen isotope, and palynomorph studies.*

Conception Group between the turbiditic Mall Bay and Drook formations (*see* King and Williams, 1979) and has been interpreted to be a Neoproterozoic glacial deposit by Myrow and Kaufman (1999). Widespread glaciations in the Neoproterozoic have deposited tillites with associated cap carbonates on all continents (Hambrey and Harland, 1981), stratigraphically below all known Ediacaran faunal assemblages (Knoll and Walter, 1992). Correlation of the limestone beds from the St. John's and Bonavista basins would indicate a much older age for the lower Rocky Harbour Formation than previously assumed.

Middle Amherst Cove Facies

The Middle Amherst Cove facies outcrops along the coast of Bonavista Bay from Newmans Cove to Upper Amherst Cove (Figure 2). Dark-grey to light-pink, fine- to medium-grained, lenticular to wavy sandstone beds are interbedded with siltstone. Diagnostic sedimentary structures include very thick convolute bedding (Plate 10), bedding confined slumping (Plate 11) and coarsening-upward successions.

The presence of coarsening-upward successions indicates classic deltaic cycles as coarser grained sediments prograde over finer grained sediments. A constant shifting of delta lobes results in stacked coarsening-upward successions with additional smaller scale coarsening-upward successions created during the infilling of interdistributary bays. The undisturbed nature of the bedding above or below, which surrounds slump units, indicates that slumping was syn-depositional on the leading edge of a steeply dipping delta-front.

Plate 10. *Very thick convolute bedding in the Middle Amherst Cove facies, near Wolf Head, Bonavista Bay.*

Monk Bay Facies

The Monk Bay facies outcrops along Bonavista Bay from Upper Amherst Cove to Knights Cove (Figure 2). The main rock type is dark-grey, thick-bedded, fine- to coarse-grained, poorly sorted, low-angle crossbedded sandstone (Plate 12). The diagnostic feature of this facies is poorly sorted, subrounded, trough crossbedded, coarse-grained ripples (Plate 13). Fining-upward successions occur at the base of the facies and coarsening-upward succession occur in the upper section. Other sedimentary structures include hummocky cross-stratification, imbricated, angular rip-up clasts (Plate 14), mud drapes (Plate 15), and rare herring-bone (Plate 16) and bi-direction crossbedding.

Wave-formed, coarse-grained ripples (formerly termed megaripples; *see* Leckie, 1988), with a crest spacing of less than 3 m and amplitudes of less than 35 cm are typically deposited in wave-influenced, upper and lower shoreface environments in water depths ranging from 3 to 160 m (Leckie, 1988). The coarse-grained ripples in conjunction with the hummocky cross-stratification indicate a wave-

Plate 11. *Bedding confined slumping in the Middle Amherst Cove facies, near Upper Amherst Cove, Bonavista Bay.*

Plate 12. *Low-angle, metre-scale crossbedding within dark-grey, thick-bedded, poorly sorted, medium- to very coarse-grained sandstone, near Knight's Cove, Bonavista Bay.*

Plate 13. *Symmetric, clast-supported, well-rounded, coarse-grained ripples, Knights Point, Bonavista Bay.*

Plate 14. *Imbricated angular, tabular grey siltstone rip-up clasts within symmetrical coarse-grained ripples; the unidirectional nature of the imbrication contrasts with the bi-direction nature of the symmetric wave form, Knights Point, Bonavista Bay.*

influenced upper shoreface with significant tidal action as demonstrated by the herring bone crossbedding and mud drapes.

A distinctive upper unit of the Monk Bay facies has been identified in Black Bay. This unit is a light-pink to dark grey-green, brown-weathered, locally mottled, medium-grained, thick-bedded, siliceous sandstone. This sandstone unit contains sinuous, round bifurcating ripples and, in places, is interbedded with dark-grey, thick-laminated siltstone. The lower contact of the Monk Bay facies is transitional with the underlying Middle Amherst Cove facies and the upper contact is disconformable (*see* below; Plate 17) with the overlying Stock Cove facies of the Crown Hill Formation.

Crown Hill Formation

The Crown Hill Formation introduced by Jenness (1963) was subdivided on the Bonavista Peninsula by O'Brien and King (2005) into a series of facies. In ascending stratigraphic order, the original sequence was the Duntara Harbour, Brook Point (contained within Duntara Harbour), Pigeon Gulch, Broad Head, Red Cliff, Blue Point, Tickle Cove and Western Head facies. The sections below will provide a basis for the following stratigraphic revision of the Crown Hill Formation: in ascending stratigraphic order; the Stock Cove (new), Kings Cove North (previously in Rocky Harbour Formation), Kings Cove Lighthouse (new), Brook Point, Duntara Harbour, Red Cliff, Blue Point (contained within Red Cliff) and Broad Head facies (Figure 3a). (The nature of the Place Cove facies is poorly understood and will be an important objective of subsequent field work.)

This years mapping has established the same stratigraphic succession on the east and west sides of the Duntara Fault. This negates the use of the Pigeon Gulch facies in favour of the Red Cliff facies and removes the Western Head

Plate 15. *Mud drapes overlying coarse-grained ripples; alternation of high- and low-energy environments. Also note light-pink alteration associated with the dark-grey mudstones. Monk Cove facies, Blackhead Bay.*

Plate 16. *Herring bone crossbedding within grey-green, trough crossbedded medium-grained sandstone, near Knight's Point, Bonavista Bay.*

Plate 17. *Disconformable surface with large desiccation cracks and angular rip-up clasts indicating long period of subaerial exposure, base of Stock Cove facies.*

and Tickle Cove conglomeratic facies, leaving the Broad Head as the uppermost conglomeratic unit in the Crown Hill Formation. The Blue Point horizon aids in establishing the new stratigraphy as it acts as a marker bed where it is picked up on the east side of the Duntara Fault. The fact that this horizon is unmineralized does not exclude it from Blue Point designation (*see* Figure 5 of J. Hinchey, *this volume*).

Stock Cove Facies

The newly introduced Stock Cove facies is the lowermost facies of the Crown Hill Formation and the type section is located in Stock Cove, Blackhead Bay (Figure 2). This distinct facies is the first occurrence of redbeds within the Musgravetown Group on the Bonavista Peninsula. The dominant rock types include light grey-green, locally brick-red, thin- to thick-laminated, interbedded siltstone and fine-grained sandstone. Light-pink, moderately sorted, matrix-supported, polymictic, well-rounded, granule conglomerate containing large, angular cobble- to boulder-size, red siltstone rip-up clasts are much rarer. The base of the Stock Cove facies is taken as the first occurrence of prolonged subaerial exposure, as indicated by the large desiccation cracks within the underlying red siltstone (Plate 17).

The boundary between the Crown Hill and Rocky Harbour formations has been modified from the previous interpretation of O'Brien and King (2005). It has been lowered to include all terrestrial sedimentary rocks and is located at the base of the Stock Cove facies (Figure 3a). This will bring previously defined Kings Cove North facies and the newly defined Kings Cove Lighthouse facies (*see* below) up-section into the Crown Hill Formation to maintain a completely terrestrial depositional environment for the Crown Hill Formation and a completely marine depositional environment for the Rocky Harbour Formation.

The lower boundary of the Stock Cove facies is disconformable and faulted, and coincides with a linear aeromagnetic anomaly (Stock Cove lineament) that continues to Stone Island (Figures 2 and 4), to the northwest of Cape Bonavista, where rocks typical of the Kings Cove Lighthouse facies outcrop. It is important to note that the Stock Cove aeromagnetic anomaly truncates the aeromagnetic signature of the largest mafic dyke to the west, indicating the mafic dykes were emplaced prior to deposition of the Crown Hill Formation.

Kings Cove North Facies

The Kings Cove North facies is described by O'Brien and King (2002) as white-weathering, finely laminated, light-grey, fissile siltstone occurring at the top of the Rocky Harbour Formation. As noted above, this unit is now placed near the base of the Crown Hill Formation, above the Stock Cove facies, within the terrestrial component of the Musgravetown Group. Sedimentary structures within the Kings Cove North facies and the relationship with the overlying and intercalated Kings Cove Lighthouse facies indicate a continued terrestrial depositional environment. The reduced nature of the Kings Cove North facies is possibly indicative of a lacustrine depositional environment

The Kings Cove North facies is intercalated with the Kings Cove Lighthouse facies and outcrops in three separate successions from Stock Cove to Kings Cove and west to Plate Cove East (Figure 2). This facies has an upper sand-rich unit, which marks the transition into the overlying

Kings Cove Lighthouse facies. This upper unit consists of light grey-green, rusty-weathering, trough crossbedded, fine-grained sandstone. Interbedded with the sandstones are dark-grey, wavy, thinly laminated siltstone and locally, poorly sorted, granular conglomerate. Distinct channel-fill lenses, up to 2.5 m thick, composed of granule to pebble conglomerate, have eroded into the sandstone and contain large angular boulders of collapsed overbank siltstone. This setting is diagnostic of meandering river channels overlying a flood-plain to lacustrine depositional environment of the lower Kings Cove North facies and is a correlative of the Hearts Desire Formation in the south and east of Trinity Bay, eastern Placentia Bay and western St. Mary's Bay (King, 1990).

Kings Cove Lighthouse Facies

The newly named Kings Cove Lighthouse facies was created to recognize a distinction between the Duntara Harbour facies found above and below the Brook Point facies as defined by O'Brien and King, 2005 (*see* Figure 4 of O'Brien and King, 2005). This facies is best exposed below Kings Cove Lighthouse, on Stone Island, and at Plate Cove East (Figure 2) and the type section was chosen at the Kings Cove Lighthouse due to the accessibility. The dominant rock types include interbedded sandstone and siltstone. Medium- to coarse-grained sandstones are dark grey-purple to light grey-pink, thin- to medium-bedded, with large-scale epsilon crossbedding (Plate 18). Siltstones are grey to dark-purple, wavy laminated with dark-purple mud drapes. The large-scale epsilon crossbedding represents Gilbert type deltas, characterized by close-to-angle-of repose foreset beds (Bhattacharya, 2006). The repetition of the Kings Cove Lighthouse facies and the underlying Kings Cove North facies demonstrates the cyclicity of stacked successions in a meandering fluvial to lacustrine system. The lower boundary of the Kings Cove Lighthouse facies is commonly erosional into the underlying Kings Cove North facies and the upper boundary is transitional with the Brook Point facies (Figure 3a).

Plate 18. *Large-scale epsilon crossbedding characteristic of Gilbert type deltas deposited in lacustrine settings, Kings Cove Lighthouse facies, south of Kings Cove, Bonavista Bay. Note the sigmoid nature (red line) of the crossbedding surfaces, illustrating the threefold cross-sectional subdivision into topset, foreset and bottomset strata.*

Brook Point Facies

The Brook Point facies is an easily recognizable succession of light yellow to buff, thinly laminated siltstones interbedded with red and grey, thin- to medium-bedded, fine- to medium-grained sandstones. It was previously identified as a pinching-out unit within the Duntara Harbour facies by O'Brien and King (2005). Recent field mapping identified the Brook Point facies on the coastline south of Open Hall, on the west coast of the Bonavista Peninsula, extending the facies across the peninsula from north of Kings Cove (Figure 2). The Brook Point facies has transitional upper and lower boundaries with the Duntara Harbour and Kings Cove Lighthouse facies', respectively (Figure 3a). Abundant polygonal desiccation cracks and gypsum molds (Plate 19) indicate a depositional environment of alternating wet and arid conditions with extensive evaporation of shallow standing water.

Duntara Harbour Facies

The Duntara Harbour facies outcrops in Duntara Harbour, Pigeon Gulch and Open Hall on the Bonavista Peninsula (Figure 2). Dark-purple to red, thin-bedded siltstone interbedded with light-grey wavy-bedded to discontinuous fine-grained sandstone are the main rock types of the Duntara Harbour facies. The facies contains a wide variety of sedimentary structures including excellent polygonal desiccation cracks (Plate 20), gutter casts, flutes (Plate 21), and asymmetric ripples (Plate 22). The Duntara Harbour facies is transitional with both the overlying Red Cliff facies and the underlying Brook Point facies (Figure 3a). Abundant

Plate 19. *Bladed gypsum molds in the Brook Point facies, north of Kings Cove Head, Bonavista Bay.*

Plate 20. *Polygonal desiccation cracks within the Duntara Harbour facies, Broad Cove, Bonavista Bay.*

unidirectional sedimentary structures such as, asymmetric ripples, gutter casts and flutes, indicate the Duntara Harbour facies was deposited in a fluvial system that had regular extended periods of drought, demonstrated by the polygonal desiccation cracks.

Red Cliff Facies

The Red Cliff facies outcrops on the coast near Red Cliff, the north side of Duntara Harbour and both sides of Broad Head (Figure 2). It consists of dark purple-red, thin- to medium-bedded, fine- to medium-grained sandstone containing bright-red, thinly laminated to disrupted siltstone beds (Plate 23) and sand dykes. The Red Cliff facies has a transitional upper boundary with the overlying Broad Head facies and contains the copper-mineralized Blue Point horizon (Figure 3a). The sedimentary structures found in the Red Cliff facies indicate rapid burial creating over-pressure conditions in the subsurface with the resulting sand dykes and disrupted bedding occurring as equilibrium is achieved.

Plate 21. *Erosional scours within the Duntara Harbour facies with paleoflow to the right, Broad Cove, Bonavista Bay.*

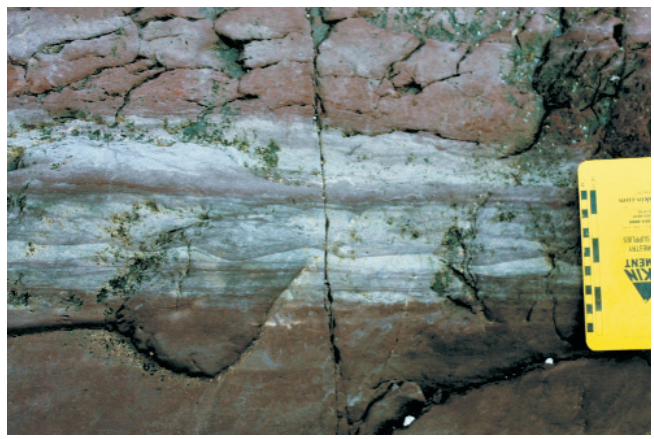

Plate 22. *Asymmetric ripples within the Duntara Harbour facies with paleoflow to the right, south of Broad Head, Bonavista Bay.*

Plate 23. *Disrupted bedding in the Red Cliff facies caused by rapid deposition of sediments and failure of partially consolidated sediments during water escape, near Red Cliff, Bonavista Bay.*

The Red Cliff facies is correlated with the Hurricane Brook member, Crown Hill Formation of Fletcher (2006).

Blue Point Horizon

The Blue Point horizon is a grey-reduced unit completely contained within the Red Cliff facies and is the primary target for sediment-hosted copper on the Bonavista Peninsula (*e.g.*, Froude, 2001; Seymour *et al.*, 2005; J. Hinchey, *this volume*). The Blue Point horizon outcrops on the north side of Duntara Harbour and can be traced through intense folding to the west at Tickle Cove (Figure 2). It occurs as two discreet units, 10 to 15 m thick, and consists of finely laminated, grey to green (locally brown where copper and pyrite mineralization occur) siltstone, mudstone and fine- to locally coarse-grained, sandstone. Truncation of the basal component of the Red Cliff facies by the Duntara fault has resulted in the presence of only one reduced horizon at the type section.

Broad Head Facies

The Broad Head facies outcrops at Broad Head, Southern Head, Western Head, north of Tickle Cove and near Open Hall (Figure 2). It is a coarse-grained conglomeratic unit that transitionally overlies the Red Cliff facies, and is the uppermost unit of the Crown Hill Formation (Figure 3a). It consists primarily of dark-red to pink, pebble conglomerate interbedded with purple-pink, sandstone. The thick-bedded, large-scale trough crossbedded, coarse-grained sandstone contains dark purple-red mudstone rip-up clasts and locally displays irregular erosional boundaries with pebble lags at the basal contact. The conglomerates are thick bedded, subrounded, poorly sorted, and crudely stratified. The thickness of this facies varies, due to the extent of erosion by the overlying Random Formation. The Broad Head facies is correlated with the Cross Point member, Crown Hill Formation of Fletcher (2006).

CAMBRIAN

The only confirmed Cambrian rocks in the Bonavista map area are found in an intensely folded region at Keels (Figure 2). The Early Cambrian Random Formation unconformably overlies the Crown Hill Formation and is overlain by the Early Cambrian Bonavista Formation (Figure 3a). The Random Formation was originally defined by Walcott (1900) and redefined by Christie (1950) and Greene and Williams (1974). The Bonavista Formation (van Ingen, 1914; Hutchinson, 1962) is the basal unit of the Adeyton Group (Jenness, 1963). The Cambrian section at Keels has been studied in detail by various authors including Butler and Greene (1976), Hiscott (1982) and Landing and Benus (1987).

Random Formation

Most of the headlands from Tickle Cove to Duntara on the western side of the Bonavista Peninsula are composed of the erosion-resistant beds of the Random Formation (Figure 2). The Random Formation is a very distinct unit of white crossbedded quartz arenite interbedded with green-grey, coarse-grained sandstone and grey siltstone, deposited in a storm-influenced macro-tidal setting (Hiscott, 1982), during a globally recorded transgressive event (Vail *et al.*, 1977). The contact with the underlying Musgravetown Group has varying interpretations: disconformable at Keels, Random Island, Smith Sound and the eastern shore of Trinity Bay (Hutchinson, 1953; McCartney, 1967; Anderson, 1981; Hiscott, 1982), unconformable at Cape St. Mary's (Fletcher, 2006) or conformable (Butler and Greene, 1976) at Keels (O'Brien and King, 2004b) and Fortune Bay (Hiscott, 1982). An angular unconformity at the base of the Random Formation has been observed on the east side of Southern Head (Plate 24) on the Bonavista map sheet. This unconformable contact is also demonstrated by the variable thicknesses found in the uppermost Broad Head facies of the Crown Hill Formation, as well as the absence of the Rencontre and Chapel Island formations below the Random Formation in this area.

Plate 24. A*ngular unconformity at the base of the Random Formation, Southern Head, Bonavista Bay.*

The Random Formation has a reported thicknesses of 87 m (Butler and Greene, 1976) and has been subdivided into four facies by Butler and Greene (1976) and Hiscott (1982). These facies are: 1) mineralogically and texturally mature, herring bone crossbedded quartz arenite deposited in an open-marine sub-tidal setting or as intertidal sand shoals in protected embayments (Plate 25); 2) thin-bedded sandstone and mudstone displaying shrinkage cracks indicative of high-intertidal ponds on mud flats; 3) mudstones containing graded glauconitic sandstone beds deposited on muddy shelf deposits; and 4) fine-grained red, micaceous

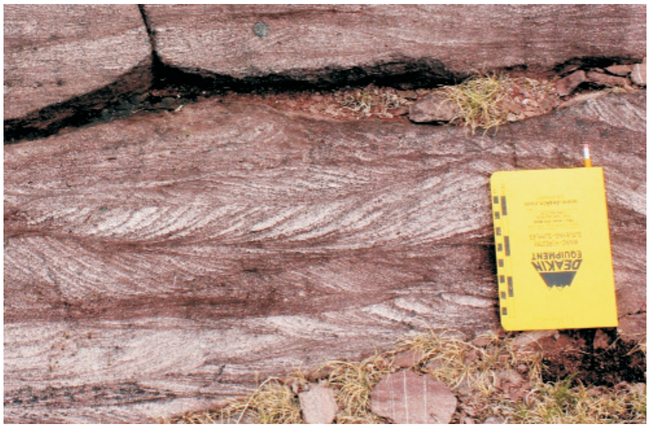

Plate 25. *Herring bone crossbedding within the Random Formation, Keels, Bonavista Peninsula.*

sandstone associated with crossbedded quartz arenite formed in lower shoreface rip-current channels.

ADEYTON GROUP

Red, green and grey mudstone and slate, interbedded with thin-bedded pink, green and grey limestone are the main rock types of the Adeytown Group. It includes the Bonavista, Smith Point, Brigus and Chamberlains Brook formations (Jenness, 1963). Only the Bonavista Formation of the Adeyton Group is found at Keels (Landing and Benus, 1987).

Bonavista Formation

The members of the Bonavista Formation described below will follow the stratigraphic model of Fletcher (2006), as modified from the stratigraphic section of Landing and Benus (1987). Fletcher (2006) did not accept the Bonavista Group model of Landing and Benus (1987) because it divides a prominent mappable limestone unit (Smith Point Limestone) into two groups, *viz.*, their Adeyton and Bonavista groups. Instead, Fletcher (2006) kept the Petley, West Centre Cove and Cuslett as members of the Bonavista Formation and retained Hutchinson's (1962) definition of the Bonavista and Smith Point formations.

Petley Member

The Petley member is a crossbedded, fine- to medium-grained, quartz arenite interbedded with green to red, silty mudstone containing calcareous nodules and lenticular pebble conglomerate at the base. It has a disconformable contact with the underlying Random Formation (Figure 3a; Landing and Benus, 1987; O'Brien and King, 2004b).

West Centre Cove Member

Variegated structureless mudstone containing scattered limestone nodules and capped by a distinctive limestone bed (correlative to the St. Bride's Limestone Bed at Cape St. Mary's; Fletcher, 2006 and Landing and Benus, 1987), comprising the West Centre Cove member are found on each side of Keels (Figure 2). The pink and red stromatolitic, hyolith-rich, algal-mud-mound limestone marks the boundary between the West Centre Cove and overlying Cuslett members (Figure 3a).

Cuslett Member

The Cuslett member is the youngest of the Bonavista Formation members found on the Bonavista Peninsula (Landing and Benus, 1987). It conformably overlies the West Centre Cove member (Figure 3a) and consists of variegated, medium- to thick-bedded slate that exhibit clearly defined redox boundaries, crosscutting stratigraphy (Plate 26). Spherical limestone nodules occur locally, and in places, are concentrated along bedding planes along with abundant euhedral pyrite crystals associated with the reduced green-grey zones. The tightly folded north-plunging syncline containing the Cuslett Member at Keels has been quarried for slate.

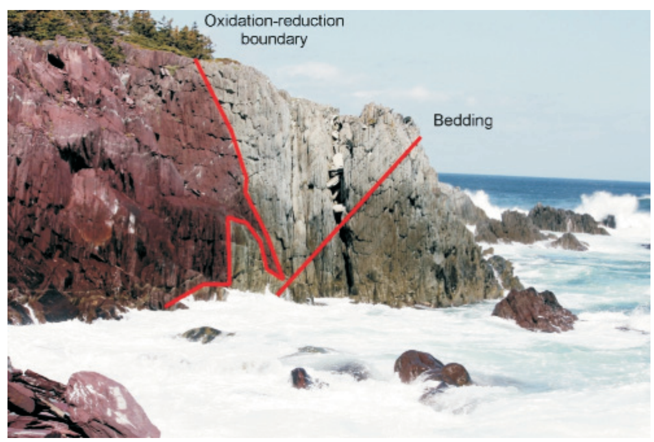

Plate 26. *Redox boundary crosscutting stratigraphy within the Cuslett member, Bonavista Formation, Keels, Bonavista Bay.*

DYKES

Several mafic dykes have been located during this summer's field work, all contained within the Rocky Harbour Formation on the north coast of the Bonavista Peninsula (Figure 2). The dykes form a radial pattern, changing from an easterly orientation for the western most dyke to a northerly orientation for the easternmost dyke. They radiate from a point centred on the Bull Arm Formation volcanic rocks located in the south central part of the map area. A study of the geochemical relationship between the Bull Arm Formation volcanics and the dykes is ongoing and results are expected later in the year. The mineralogy of the Bull Arm Formation basaltic lavas is similar to the mafic dykes within the Connecting Point Group, leading to suggestions of a common origin (McCartney, 1958). Mafic dykes are widespread in the Connecting Point and Love Cove groups but occur only rarely in the Musgravetown Group (O'Brien, 1987).

The dykes are only found in the Rocky Harbour Formation, and as such establish a timeline for formation of the rocks on the Bonavista Peninsula. The absence of these dykes in the St. John's basin indicates a diachronous timing can be implied for the accumulation of sediments in both the St. John's and Bonavista basins, with subsequent docking along the SC–EH fault occurring after dyke emplacement. As noted previously, the truncation of the Wolf Head dyke (Plate 27) by the Stock Cove lineament (Figure 4) constrains dyke formation prior to deposition of the Crown Hill Formation. Samples from the Wolf Head dyke were analyzed and did not contain zircon (G. Dunning, personal communication, 2009). Additional samples from the other dykes will be taken in the future for age dating, to assist with the timing of juxtaposition of the St. John's and Bonavista basins on the Bonavista Peninsula.

Plate 27. *The Wolf Head dyke is the largest dyke in the map area, measuring over 15 m in thickness and is clearly defined on the regional aeromagnetic data (Figure 4). Note person on right boundary of dyke for scale.*

Based on dyke boundaries and structures within the adjacent sedimentary rocks, the age of dyke emplacement appears to be variable from syn-sedimentation with the oldest rocks of the Rocky Harbour Formation to post lithification with the upper Rocky Harbour Formation. Soft-sediment deformation and alteration of sedimentary rocks occur adjacent to the most northerly dyke (north of Bonavista) where as most dykes have sharp boundaries with the adjacent sedimentary rocks and locally entrain angular clasts of the host rock (Plate 28) or have brecciated boundaries. Post-lithification emplacement is also supported by the location of the dykes within antiformal crests that have acted as traps for gas-magma accumulation and controlled the emplacement of the dyke (Platten, 1984).

Plate 28. *Mafic dyke crosscutting the sedimentary rocks of the Birchy Cove facies, near Burnt Head, Bonavista Bay. Note large rafted angular clast of siltstone within the dyke.*

STRUCTURE AND RELATIONSHIPS BETWEEN THE BONAVISTA AND ST. JOHN'S BASINS

The structural history of the Bonavista Peninsula is complex with regional folding occurring in both the Bonavista and St. John's basins. While deformation within the St. John's basin is fairly uniform, the intensity of deformation in the Bonavista basin increases to the west toward the Indian Arm fault (west of current map sheet) and also up section near the top of the Crown Hill Formation and overlying Cambrian rocks. Three major structures are present on the Bonavista Peninsula. The Duntara fault extends northeast from Open Hall in the west to Duntara Harbour in the east (Figure 2). It separates the Duntara Harbour and Red Cliff facies' of the Crown Hill Formation creating different deformation zones. The mild deformation below the Duntara fault contrasts with the intense deformation above, demonstrated by the very tight northerly plunging folds between Keels and Tickle Cove. The Stock Cove lineament separates the Rocky Harbour and Crown Hill formations with an arcuate trend from north-northeast at the base of the map area to east-northeast at Stock Cove (Figure 2). The Stock Cove lineament is clearly seen in the aeromagnetic signature (Figure 4) where it parallels the coast of Blackhead Bay and truncates the Wolf Head dyke. The SC–EH fault is a basin-bounding fault and is the dominant structural element in the map area separating the Bonavista and St. John's basins (Figure 2).

The equivocal nature of the SC–EH fault has been documented in the past (O'Brien and King, 2002; O'Brien *et al.*, 2006). An unconformable relationship between the Bonavista and St. John's basins was originally based on the truncation of regional folds in the St. John's basin by the Bonavista basin and similar relationships located to the northeast in Bonavista Bay, where Musgravetown Group rocks unconformably overlie the Neoproterozoic Connecting Point Group (Jenness, 1963; O'Brien, 1994; O'Brien and King, 2002). Subsequent interpretations indicate a stratigraphic continuity across the SC–EH fault based on outcrop south of Maberly with rock types characteristic of Cape Bonavista and Birchy Cove facies (O'Brien *et al.*, 2006). A conformable contact of the Bonavista basin and the St. John's basin is also consistent with the Big Head Formation of the Musgravetown Group conformably overlying the Gibbet Hill Formation of the Signal Hill Group on the east side of Trinity Bay (King, 1988; O'Brien *et al.*, 2006).

The complete history of the SC–EH fault is still unclear but several lines of evidence suggest a prolonged structural history of the SC–EH fault. The apparent truncation of the lowermost Rocky Harbour Formation by upper St. John's Group sedimentary rocks (Figure 2) indicates thrusting of the St. John's basin onto the time-equivalent or younger Bonavista basin, although the fault appears to be vertical along the coast. The thickness of the shale units in the Fermeuse and Renews Head formations provide an excellent surface for prolonged thrust and strike-slip movement along the SC–EH fault. The change in orientation of the SC–EH fault northwest of Port Union, from north-northeast to north-northwest, corresponds to a pull-apart structure indicative of sinistral strike-slip movement (Figure 4). The presence of Bull Arm and Big Head formations on the Bonavista Peninsula indicate a thicker succession for the Bonavista basin.

FUTURE WORK

Further field work on the Trinity map area, to the south, should provide additional evidence of the relationships between the St. John's and Bonavista basins on the Bonavista Peninsula. More regional mapping is needed to thoroughly understand the stratigraphy and relationship of the Bonavista and St. John's basins. The coincidence of the Stock Cove lineament and the Rocky Harbour–Crown Hill boundary is not completely understood and requires more detailed mapping in conjunction with a new aeromagnetic survey. Confirmed correlation of the Danson Head and Gaskiers cap carbonates require additional work and will provide a timeframe for Rocky Harbour Formation deposition. Carbon and oxygen isotopic data would provide useful information for correlation of the strongly negative carbon isotope signature accompanying Neoproterozoic glaciations worldwide (Kaufman and Knoll, 1995). Local aeromagnetic surveys would be beneficial for highlighting additional volcanic and intrusive rocks in the area.

ACKNOWLEDGMENTS

The author acknowledges the superb boat-handling skills of Mr. Barry Wheaton and the very capable field assistance of Mr. Nathan Corcoran. Gerry Kilfoil is acknowledged for his geophysical interpretations and Gerry Hickey is acknowledged for field logistics. The author also acknowledges the thought-provoking discussions with Dr. John Hinchey while in the field. For discussions and review of the original manuscript, the author thanks Brian O'Brien, Ian Knight, Lawson Dickson and Nicola Tonkin.

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