GEOLOGICAL ASSOCIATION of CANADA
NEWFOUNDLAND and LABRADOR SECTION

2017 FALL FIELD TRIP
September 29 – October 1

DEPOSITIONAL SETTINGS AND TECTONIC EVOLUTION OF ROCKS OF THE BONAVISTA PENINSULA: NEW CONSTRAINTS AND QUERIES FOR AVALONIA

Andrea Mills
Logistics Coordinators: Stephanie Lode and Anne Westhues

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Note
This field-trip guide is an updated adaptation of the GAC NL 2008 Fall Field Trip Guidebook. Bonavista: Stratigraphy, Palaeongology, and Economic Geology along this historic Discovery Trail by A. Kerr

CONTENTS

Page

FIGURES

Page

PLATES

SAFETY INFORMATION

GENERAL INFORMATION

The Geological Association of Canada (GAC) recognizes that its field trips may involve hazards to the leaders and participants. It is the policy of the Geological Association of Canada to provide for the safety of participants during field trips, and to take every reasonable precaution to ensure that field trips are run with due regard for the safety of leaders and participants. GAC recommends steel-toed safety boots when working around road cuts, cliffs, or other locations where there is a potential hazard from falling objects. GAC will not supply safety boots to participants. Some field trip stops require sturdy hiking boots for safety. Field trip leaders are responsible for identifying any such stops, making participants aware well in advance that such footwear is required for the stop, and ensuring that participants do not go into areas for which their footwear is inadequate for safety. Field trip leaders should notify participants if some stops will require waterproof footwear.

Field trip participants are responsible for acting in a manner that is safe for themselves and their co-participants. This responsibility includes using personal protective equipment (PPE) when necessary (when recommended by the field trip leader or upon personal identification of a hazard requiring PPE use). It also includes informing the field trip leaders of any matters of which they have knowledge that may affect their health and safety or that of co-participants. Field Trip participants should pay close attention to instructions from the trip leaders and GAC representatives at all field trip stops. Specific dangers and precautions will be reiterated at individual localities.

SPECIFIC HAZARDS

Many of the stops on this field trip are in coastal localities. Access to the coastal sections normally requires short hikes, in some cases over rough, stony, steep, or wet terrain. This field trip involves some moderate hikes, of which the longest is about 3 km. Participants should be in good physical condition and accustomed to exercise. The coastal sections contain saltwater pools, seaweed, mud and other wet areas; in some cases it may be necessary to cross brooks or rivers. There is a strong possibility that participants will get their feet wet, and we recommend waterproof footwear. We also recommend footwear that provides sturdy ankle support, as localities may also involve traversing across beach boulders or uneven rock surfaces. On some of the coastal sections that have bouldery or weed-covered sections, participants may find a hiking stick a useful aid in walking safely.

Coastal localities present some specific hazards, and participants MUST behave appropriately for the safety of all. High sea cliffs, such as those at Kings Cove lighthouse, are extremely dangerous, and falls at these localities would almost certainly be fatal. Participants must stay clear of the cliff edges at all times, stay with the field trip group, and follow instructions from leaders. Coastal sections elsewhere may lie below cliff faces, and participants must be aware of the constant danger from falling debris. Please stay away from any overhanging cliffs or steep faces, and do not hammer any locations immediately beneath the cliffs. In all coastal localities, participants must keep a safe distance from the ocean, and be aware of the magnitude and reach of ocean waves. Participants should be aware that unusually large "freak" waves present a very real hazard in some areas. If you are swept off the rocks into the ocean, your chances of survival are negligible. Stay on dry sections of outcrops that lack any seaweed or algal deposits, and stay well back from the open water. Remember that wave-washed surfaces may be slippery and treacherous, and avoid any area where there is even a slight possibility of falling into the water. If it is necessary to ascend from the shoreline, avoid unconsolidated material, and be aware that other participants may be below you. Take care descending to the shoreline from above.

A small number of field trip stops are located on or adjacent to roads. In these areas, participants should make sure that they stay off the roads, and pay careful attention to traffic, which may be distracted by the field trip group. Roadcut outcrops present hazards from loose material, and should be treated with the same caution as coastal cliffs.

Weather is unpredictable in this area and participants should be prepared for a wide range of temperatures and conditions. Always take suitable clothing. A rain suit, sweater, and sturdy footwear are essential at almost any time of the year.

The hammering of rock outcrops, which is in most cases completely unnecessary, represents a significant "flying debris" hazard to the perpetrator and other participants. For this reason, we ask that outcrops not be assaulted in this way; if you have a genuine reason to collect a sample, inform the leaders, and then make sure that you do so safely and with concern for others. In this context, all participants should note that the fossil locality visited on this excursion is protected by Provincial legislation, and any damage or attempts at sampling or collecting material are against the law. Our preference is that you leave hammers at home or in the field trip vans.

Subsequent sections of this guidebook contain the stop descriptions and outcrop information for the field trip. In addition to the general precautions and hazards noted above, the introductions for specific localities make note of specific safety concerns such as traffic, water, cliffs or loose ground. Field trip participants should read these cautions carefully and take appropriate precautions for their own safety and the safety of others.

INTRODUCTION

The Bonavista Peninsula is well known as an historic and scenic region of eastern Newfoundland, and it attracts growing numbers of visitors and seasonal residents. The first and most famous Transatlantic visitor was Giovanni Caboto, or John Cabot, who reputedly landed in 1497 near Cape Bonavista. Legend has it that his first words upon seeing this new world rise above the horizon were "Buena Vista!" (beautiful sight). Today, tourists are drawn by the beauty of landscapes and seascapes, by historic communities such as Bonavista, Trinity and Kings Cove, outdoor activities such as hiking and kayaking, and by a growing summertime cultural scene of theatre and music. More recently, the Discovery Aspiring Geopark Inc. initiative is working towards the recognition of the Bonavista Peninsula as an UNESCO Global Geopark to highlight the geological and paleontological importance of the area. Geologically, the peninsula had been poorly understood for many years, compared to the neighbouring Avalon Peninsula. The only systematic mapping prior to 2002 was by the Geological Survey of Canada in the 1950s, who assigned virtually the entire Bonavista Peninsula to a single unit known as the Musgravetown Group (Jenness, 1963). Over the years, mineral exploration largely bypassed the region, aside from some small-scale industrial minerals operations. There was a general perception that the region held little mineral potential, and this provided a disincentive for the more systematic geological investigation enjoyed by some other parts of eastern Newfoundland.

This situation began to change with the new millennium. Regional mapping initiated by the Geological Survey of Newfoundland and Labrador (GSNL) showed that the sedimentary rocks of the area are more varied than previously supposed, including at least two subareas with distinct stratigraphy and structure (O'Brien and King, 2002, 2004a, b, 2005; O'Brien *et al.*, 2006). A fledgling junior exploration company, later to become Cornerstone Resources, became interested in the potential of certain units for stratiform sediment-hosted copper (SSC) deposits. Their prospecting efforts located several new showings and occurrences, which eventually led to a joint venture with Noranda Mining, and limited drilling (*e.g.*, Graves, 2002; Seymour *et al.*, 2005). Although these mineral discoveries were not of economic grades or dimensions, they sparked wider interest in the copper potential of late Precambrian sedimentary rocks in the Avalon Zone, and led to exploration elsewhere. In 2003, well-preserved soft-bodied fossils of the latest Precambrian Ediacaran biota were discovered in the Catalina area, confirming that host rocks are correlatives of the famous Mistaken Point Formation (O'Brien and King, 2004b). Subsequent detailed investigations showed that Ediacaran fossils are widely distributed, and over 40 sites are currently known. These fascinating organisms are now well documented (Hofmann *et al.*, 2008; Mason *et al.*, 2013; Liu *et al.*, 2014). Clearly, there is much more to the Bonavista Peninsula than early mapping had indicated.

The field trip is in three parts. The Day 1 drive to the Port Rexton area includes stops that illustrate rock types on the western part of the peninsula, including cross-sections through roadcuts to maximize exposure of stratigraphic units. Day 2 focuses on the stratigraphy, structure and paleontology of the region between Old/New Bonaventure and Cape Bonavista, including one of the more accessible Ediacaran fossil localities, and the northern expression of the Spillars Cove–English Bay fault zone. It will end at the community of Bonavista (just south of Cape Bonavista, the site of John Cabot's landfall in 1497). Day 3 is a tour of the scenic coastline along Blackhead Bay, the broad bay on the northern side of the Bonavista Peninsula between the Cape Bonavista to the east and Keels to the west. In addition to aspects related to bedrock geology, the field trip will also highlight several interesting aspects of coastal geomorphology that illustrate the active processes that work to create dramatic scenery throughout the peninsula.

Revisions to the ordering of stops may be necessary, depending on weather conditions, tidal schedules and other factors. The Brook Point coastal section near Kings Cove requires a round trip hike of some 3 km.

The material in this guidebook is drawn from Kerr (2008) and references therein, with additional details provided from ongoing work by Mills (2014, 2017; Mills *et al.*, 2016a, b). Several figures were drawn directly from referenced sources, with some minor updates. Although this guidebook was written and assembled by the trip leader, the underlying geological information has been attributed to original sources. Additional references relevant to specific units and topics are given in the appropriate sections. Development of this guidebook would not have been possible without the contributions made by those individuals who conducted work in this area since 2000: Leon Normore, Sean O'Brien and Dr. Arthur King. Anne Westhues and Stephanie Lode are thanked for providing logistical support for the Field Trip.

REGIONAL GEOLOGICAL SETTING

The Bonavista Peninsula is located on the northwest side of Trinity Bay and the southeast side of Bonavista Bay, and lies entirely with the Avalon Terrane of the Appalachian Orogen in Newfoundland (Figure 1). The Avalon Terrane is dominated by a complex assemblage of Neoproterozoic sedimentary, volcanic and plutonic rocks developed between 760 and 540 Ma; these are overlain by Cambrian and locally Ordovician sedimentary rocks of shallow-water setting (Smith and Hiscott, 1984; Figure 1). The rocks of the Avalon Terrane (*sensu stricto*) are thought to have been unaffected by the Ordovician and Silurian orogenic events that formed the Appalachian Orogen, and were probably accreted to Laurentia during the Devonian, prior to emplacement of *ca.* 380 to 375 Ma granites (Dallmeyer *et al.*, 1981, 1983). The later Paleozoic history of the type Avalon Terrane is expressed by regional folding and the emplacement of these granites, notably along its western boundary (Figure 1). Several small areas of Neoproterozoic rocks occur within the central portion of the Newfoundland Appalachians, representing either extensions of Avalonian crust or a separate block, now generally termed Ganderia (*e.g.*, van Staal, 2005). The wider context of Avalonia and Ganderia within the tectonic evolution of the Appalachians is beyond the scope of this guidebook, but they, along with similar rocks in Europe, North Africa and South America, are generally considered to be microcontinental block(s) representing part of the Gondwanan margin of the Early Paleozoic Iapetus Ocean. On a wider scale, they are part of the so-called "Pan African" orogenic belts, which weld older cratonic nucleii throughout the southern continents. The Pan-African Orogeny was essentially the event that assembled the supercontinent of Gondwanaland, which would later be joined with other continental blocks at the end of the Paleozoic to form Pangaea.

Figure 1. *Simplified bedrock geology map of the Avalon Terrane in Newfoundland (modified from Colman-Sadd* et al.*, 1990). Delineation of West, Central and East domains of the Avalon Terrane are from Myrow (1995). Bedrock ages are compiled from [1]Swindon and Hunt, 1991; [2]Krogh* et al. *(1988); [3]Murphy* et al. *(2008); [4]Israel (1998); [5]O'Brien* et al. *(2001); [6]Bowring* et al. *(2003); [7]Pu* et al. *(2016); [8]O'Brien* et al. *(1989); [9]O'Brien* et al. *(1995); [10]Hinchey (2001); [11]Skipton* et al. *(2013); [12]Mills* et al. *(2016b); [13]Mills* et al. *(2017); [14]Rabu* et al. *(1996); [15]Sparkes and Dunning (2014); [16]Sparkes* et al. *(2005); [17]Sparkes* et al.*, (2002); [18]O'Brien* et al. *(1998); [19]Ferguson* et al. *(2016); [20]Kellett* et al. *(2014).*

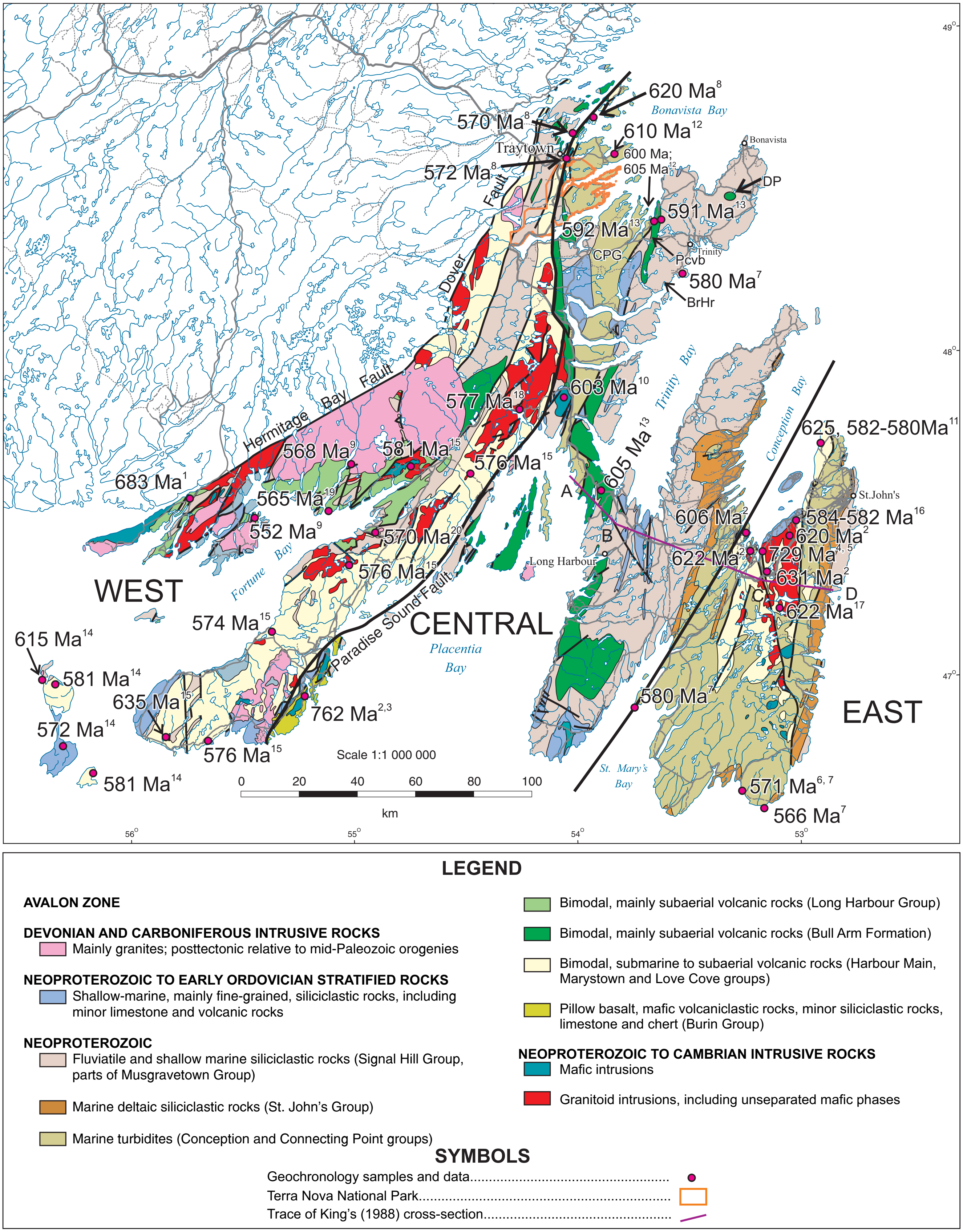

Figure 1. *Caption on page 2.*

The regional stratigraphy and structure of the Avalon Terrane in Newfoundland is an intricate topic, not easily summarized in a paragraph, but there is a widely accepted general framework from the mapping and compilation of King (1988), adapted from earlier work by the GSC. The evolution of the Avalon Terrane is reviewed by O'Brien *et al.* (1996), and the regional correlations of units within it, as proposed by King (1988) and Brückner (1977), are indicated in Figure 2. Note that the stratigraphic terminology for volcanic and sedimentary rocks varies from east to west, and the correlation of some units has not been fully resolved. Early development of the Avalon Terrane is dominated by volcanism and plutonism considered to be of broadly arc-related character. The assembly of these individual arcs into a composite terrane was followed by the development of sedimentary basins during the time period now termed the Ediacaran (~630 Ma to 542 Ma). In a general sense, Ediacaran sedimentary rocks of the Connecting Point and Musgravetown groups (western Avalon zone) and the Conception, St. John's and Signal Hill groups (eastern Avalon zone) constitute shallowing-upward sequences that progress from deep marine to shallow water and then to terrestrial and alluvial environments. However, the western and eastern sequences differ in lithology and depositional environments. At the top of these (both eastern and western) sequences, a marine transgression indicates a return to marine conditions in Cambrian times, and the base of the Cambrian sequence ranges from a local disconformity with respect to the terrestrial Crown Hill Formation (upper Musgravetown Group) to an angular unconformity with older Connecting Point Group rocks (Mills *et al.*, 2016b). The Ediacaran in the western Avalon Terrane was also marked by extensive bimodal volcanism of the Bull Arm Formation (Malpas *et al.*, 1972), which sits near the base of the Musgravetown Group in the central part of the Avalon Terrane (Figure 1). For further discussion of the complex Precambrian history of the region, readers are referred to O'Brien *et al.* (1996) and the relevant chapters in the Decade of North American Geology (DNAG) volume (Williams, 1995), and to the abundant references therein.

The Bonavista Peninsula forms part of a region dominated by Ediacaran sedimentary rocks juxtaposed with older volcanic and plutonic rocks to the west, by a series of faults extending from Terra Nova National Park to Paradise Sound (*see* Figure 1). Volcanic rocks of the Bull Arm Formation occur on the western part of the peninsula (the Plate Cove volcanic belt; Figure 3), and Cambrian rocks are preserved as synclinal outliers in two main areas (Ocean Pond and Keels areas; Figure 3). The sedimentary rocks of the peninsula were traditionally assigned in their entirety to the Musgravetown Group (*e.g.*, Jenness, 1963). O'Brien and King (2002) correlated the eastern extremity of the peninsula, which is demarcated by an important fault zone called the Spillars Cove – English Harbour fault zone (SCF; Figure 3; O'Brien and King, 2004b; Normore, 2010), with time-equivalent sequences of the Conception, St. John's and Signal Hill groups, for which the type areas are in the eastern Avalon Peninsula (Williams and King, 1979; O'Brien and King, 2002, 2004a, 2005; O'Brien *et al.*, 2006). Initial reconnaissance work led O'Brien and King (2002) to assign much of the bedrock on the eastern side of the Bonavista Peninsula to the Conception Group, but they later re-assigned rocks west of the SCF to a lower marine sequence (Rocky Harbour Formation) within the Musgravetown Group (O'Brien and King, 2004a). The Bonavista Peninsula thus preserves portions of two discrete sedimentary basins that are separated by the SCF.

GEOLOGY

Field work by A. F. King in the 1980s in the area between Trinity and Bonavista led him to suggest that some of these rocks resemble those of the eastern Avalon Peninsula (St. John's area) rather than the typical strata of the Musgravetown Group. Mapping by O'Brien and King (2002, 2004a, 2005) confirmed

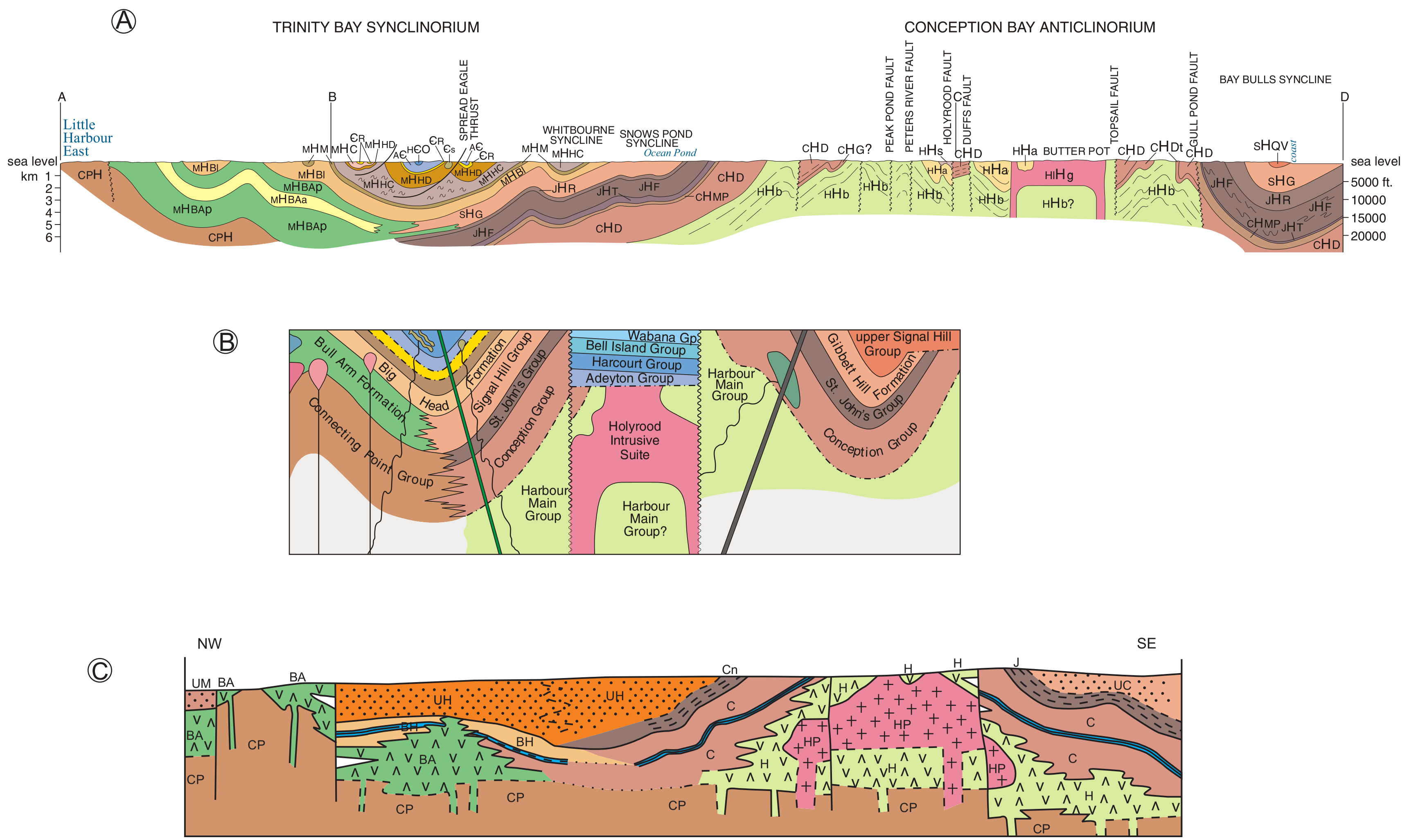

Figure 2. *Suggested stratigraphic nomenclature and correlation of units within the Avalon Terrane; A) Cross-section across Avalon Terrane, after King (1988); B) Simplified cross-section of King (1988) as key to abbreviations for stratigraphic units, after King (1988); C) Schematic cross-section across Avalon Terrane, after Brückner (1977); CP = Connecting Point Group; BA = Bull Arm Formation; UM = Upper Musgravetown Group; BH = Big Head Formation. UH = Upper Hodgewater Group; Cn = Carbonear Formation; C = Conception Group; H = Harbour Main Group; HP = Holyrood plutonic series; J = St. John's Group; UC = Upper Cabot Group (now Signal Hill Group). The tillite units (*i.e., *Trinity facies and Gaskiers Formation) are depicted in bright blue.*

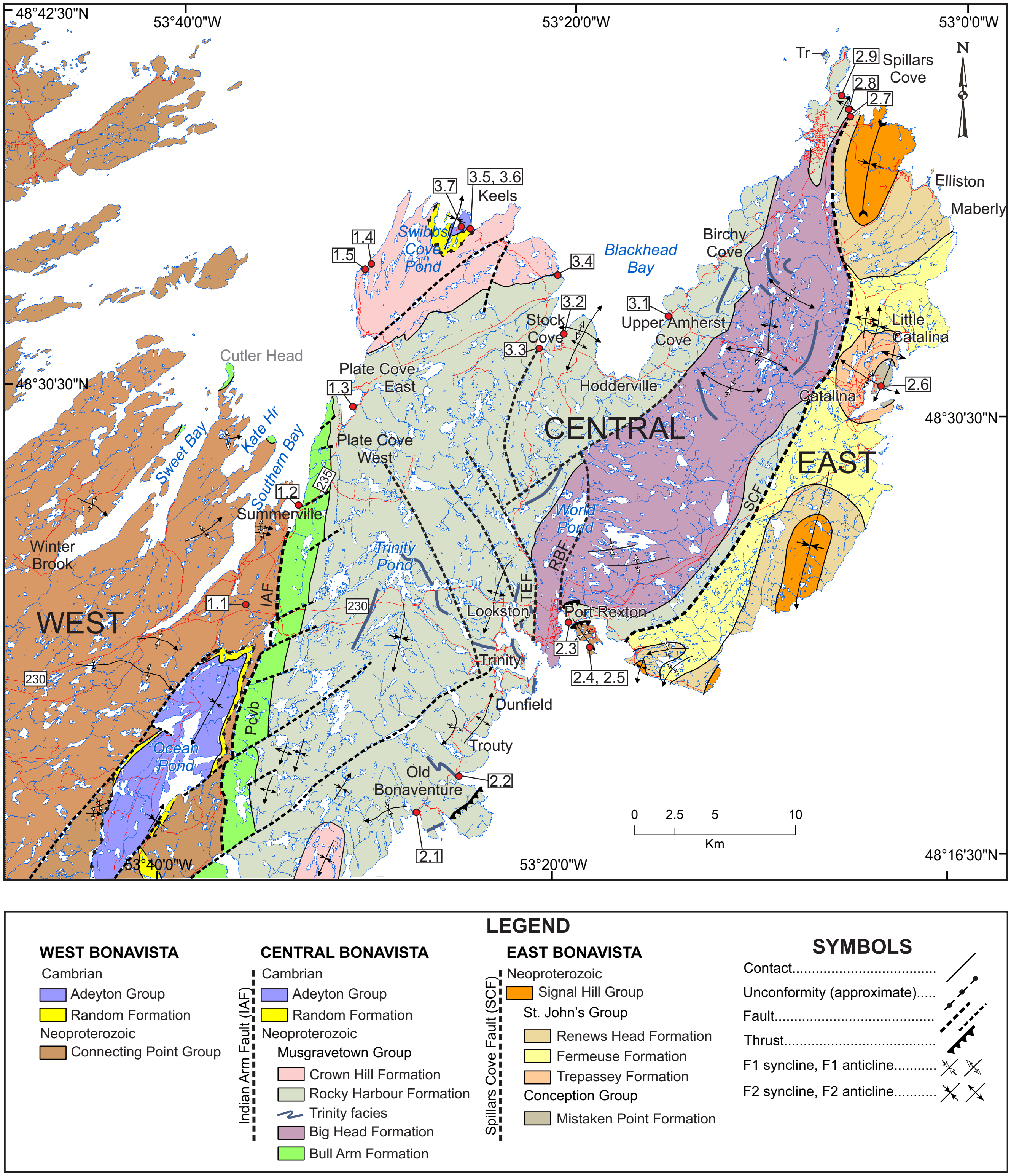

Figure 3. *Simplified geology of the Bonavista Peninsula including Stop Locations (modified from O'Brien and King, 2005). IAF = Indian Arm Fault; PCvb = Plate Cove volcanic belt; TEF = Trinity East fault zone; RBF = Robinhood Bay fault zone; SCF = Spillars Cove–English Harbour fault zone.*

this correlation and identified an important regional structure that defines the western limit of these rocks. This is termed the Spillars Cove–English Harbour fault zone (SCF), and it divides the bulk of the Peninsula into two contrasting areas (Figure 3). The sedimentary rocks across the entire region are all affected by Paleozoic folding, but in general the intensity of such effects is greater west of the SCF, where the rocks are interpreted to be older. Rocks west of the SCF also show bedding reversals indicative of folding about an east-west axis, whereas this effect is highly subdued east of the SCF. However, the lithological monotony of parts of the Musgravetown Group and lack of exposure away from the coastline combine to impede detailed analysis of the regional structure. Cambrian rocks in the Keels area are restricted to a tight regional synclinal structure, which is flanked by numerous parallel structures in the underlying Precambrian rocks. Subvertical rocks in the Trinity–Port Rexton area contrast with gently-dipping rocks elsewhere, and indicate structural complications related to regional folding and/or block faulting. In contrast, to the east of the SCF, Ediacaran strata of the St. John's and Signal Hill groups dip gently around open dome-and-basin structures, and the Conception Group occurs only in the core of a broad domal culmination at Catalina. The regional pattern is attributed to the interference between late Neoproterozoic, thrust-related, Avalonian folding and Paleozoic (possibly Devonian/Acadian) folding (Mills *et al.*, 2016a). Further, recent structural studies in the Bay Bulls area on the Avalon Peninsula have identified growth strata in the upper Conception, St. John's and lower Signal Hill groups (Peddle, 2017). It is therefore likely that time-equivalent units on the Bonavista Peninsula were also deposited during regional (Avalonian) deformation.

The sedimentary rocks on either side of the SCF were formerly thought to be partly time-equivalent, and to mainly differ in terms of lithology and depositional setting (O'Brien and King, 2004a, 2005). However, new age constraints suggest that rocks west of the SCF are markedly older than those to the east. The Trinity facies (Normore, 2010) is a 580 Ma glacigenic diamictite (Pu *et al.*, 2016) that provides an excellent marker horizon within the Musgravetown Group. Although its geometry remains elusive, its sporadic occurrence between the Plate Cove volcanic belt and the SCF indicates that much of the middle Musgravetown Group in this area (Rocky Harbour and Big Head formations) is as old as 580 Ma. The oldest rocks east of the SCF are nominally older than *ca.* 565 Ma, based on correlation between Ediacaran fauna-bearing strata at Catalina with upper Conception Group units on the Avalon Peninsula (O'Brien and King, 2002; 2004a; 2005; Benus, 1988). The exact nature and magnitude of movements across the structure remain an open question, as does the course of its continuation offshore to the south in the Trinity Bay region.

Parts of the Musgravetown Group were formerly interpreted to be younger than parts of the Signal Hill Group (King, 1988; Figure 2). The Bull Arm Formation was considered to be coeval with and the source for deposition of the Signal Hill Group. This was based, in part, on the lack of (proximal) volcanic debris in the underlying Conception and St. John's groups. In addition, the Signal Hill Group is overlain by grey siltstone and sandstone interpreted as Big Head Formation of the Musgravetown Group on the Bay de Verde peninsula (King, 1988). Furthermore, the age of the Bull Arm Formation had been only poorly constrained by a single U–Pb (TIMS) age from a rhyolite flow on an island north of Terra Nova National Park (O'Brien *et al.*, 1989) where no contact relations are exposed. This 570 +5/-3 Ma flow was later reinterpreted as the basal part of the overlying Rocky Harbour Formation (O'Brien and King, 2004), but by then the initial interpretation had become entrenched in the literature. Recent geochronological constraints show that the bulk of Bull Arm Formation volcanism is older than the 570 Ma rhyolite. Rhyolite from the Isthmus of Avalon yielded a U–Pb (TIMS) age of 605 ± 1.2 Ma (Mills *et al.*, 2017) and is apparently overlain by both calc-alkaline and rift-related basalts (Murphy, 2017). Tuffaceous rocks near the top of the Connecting Point Group north of Summerville also gave an age of 605 Ma (Mills *et al.*, 2016b). There, the Connecting Point Group is unconformably overlain by *ca.* 600 Ma interbedded red pebble conglomerate and calc-alkaline basalt flows. It is, therefore, possible that the 605 Ma felsic volcanic centre was located near the Isthmus and was the source for volcanic detritus near the top of the Connecting Point Group in the Bonavista Bay area. Tuffs near the western and eastern margins of the Plate Cove volcanic belt yielded concordant U–Pb (TIMS) ages of 592 ± 2.2 and 591 ± 1.6 Ma, respectively, and this may mark the onset of rifting of the *ca.* 630-600 volcanic arc terrane (Mills *et al.*, 2017).

The new geochronology constraints (Mills *et al.*, 2016b, 2017; Pu *et al.*, 2016), coupled with litho-geochemistry results, highlight the need for revision of Avalonian stratigraphy in Newfoundland (*see* Figure 2). Brückner (1977) suggested that tillites in the eastern (Gaskiers Formation) and western (Trinity facies) parts of the Avalon Terrane likely formed contemporaneously. Recent dating of pre-, syn-, and postglacial tuffs associated with both the Gaskiers Formation and the Trinity facies (Pu *et al.*, 2016) confirms Brucker's (1977) hypothesis (Figure 2). Therefore, the tillites represent time markers that can be used for east-west correlation (Figure 2). Efforts to recompile the geology and stratigraphy of the Avalon Terrane in Newfoundland should include interpretation of tectonic setting based on lithogeochemical results combined with detailed studies of the stratigraphy that overlies the volcanic successions. Structural studies are also critical, as one possible explanation for the position of Big Head Formation above Signal Hill Group rocks on the northwestern Avalon Peninsula is thrust-emplacement during either Avalonian or Acadian orogenesis.

PRECAMBRIAN (EDIACARAN) ROCKS EAST OF THE SCF

Conception Group

The oldest rocks in the area are assigned to the Conception Group, and occur only in a small area around Catalina and Port Union, where they are exposed in the core of a gentle doubly plunging anticlinal structure, termed the "Catalina Dome" (Figures 3 and 4; O'Brien *et al.*, 2004a, 2005). The base of the Conception Group is not exposed on the Bonavista Peninsula, and the sequence in the Catalina Dome represents the upper part of the group, namely the Drook Formation and the Mistaken Point Formation (Figure 5). The Conception Group on the Bonavista Peninsula represents a deep-water marine environment, as in its type area, and most of the rocks represent turbidites, separated by thin tuffs and intervals of pelagic sedimentation. O'Brien and King (2005) provide detailed information on these rocks and their contained sedimentary structures, which is summarized below.

Drook Formation

The Drook Formation is dominated by laminated siltstone and sandstone, typically grey-green, and interbedded with subordinate mudstone. Essentially all are of turbiditic origin. The base of the formation is not seen in the Catalina area, where its constituent rocks are named the Shepherd Point Member (O'Brien and King, 2005).

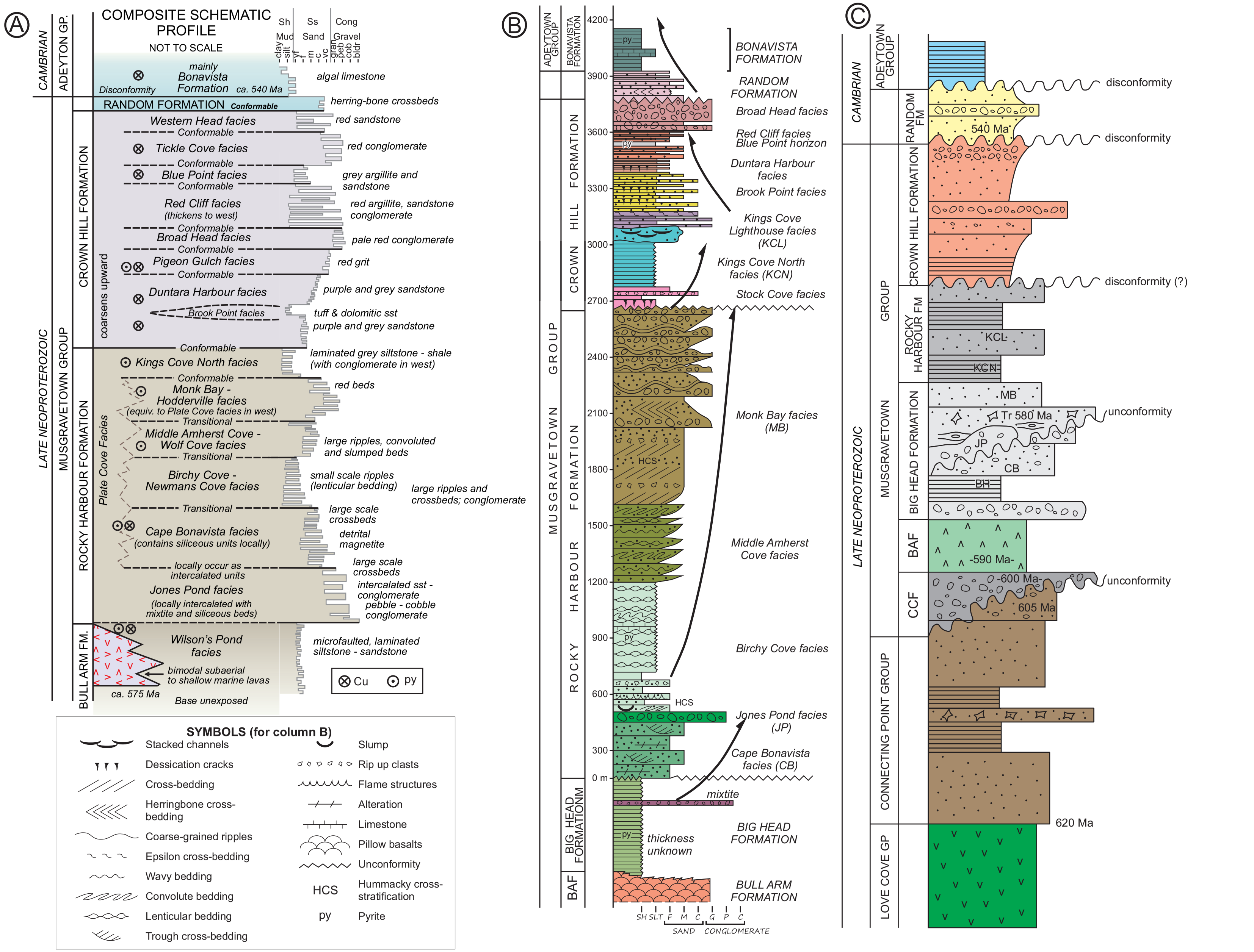

Figure 4. *Comparison of suggested stratigraphic profiles of the Bonavista basin. A) Stratigraphic profile, after O'Brien and King (2005); B) Stratigraphic log of Bonavista basin, after Normore (2010); C) Revised schematic stratigraphic section for Bonavista basin based on current geochronological constraints (Mills* et al.*, 2016b, 2017; Pu* et al.*, 2016).*

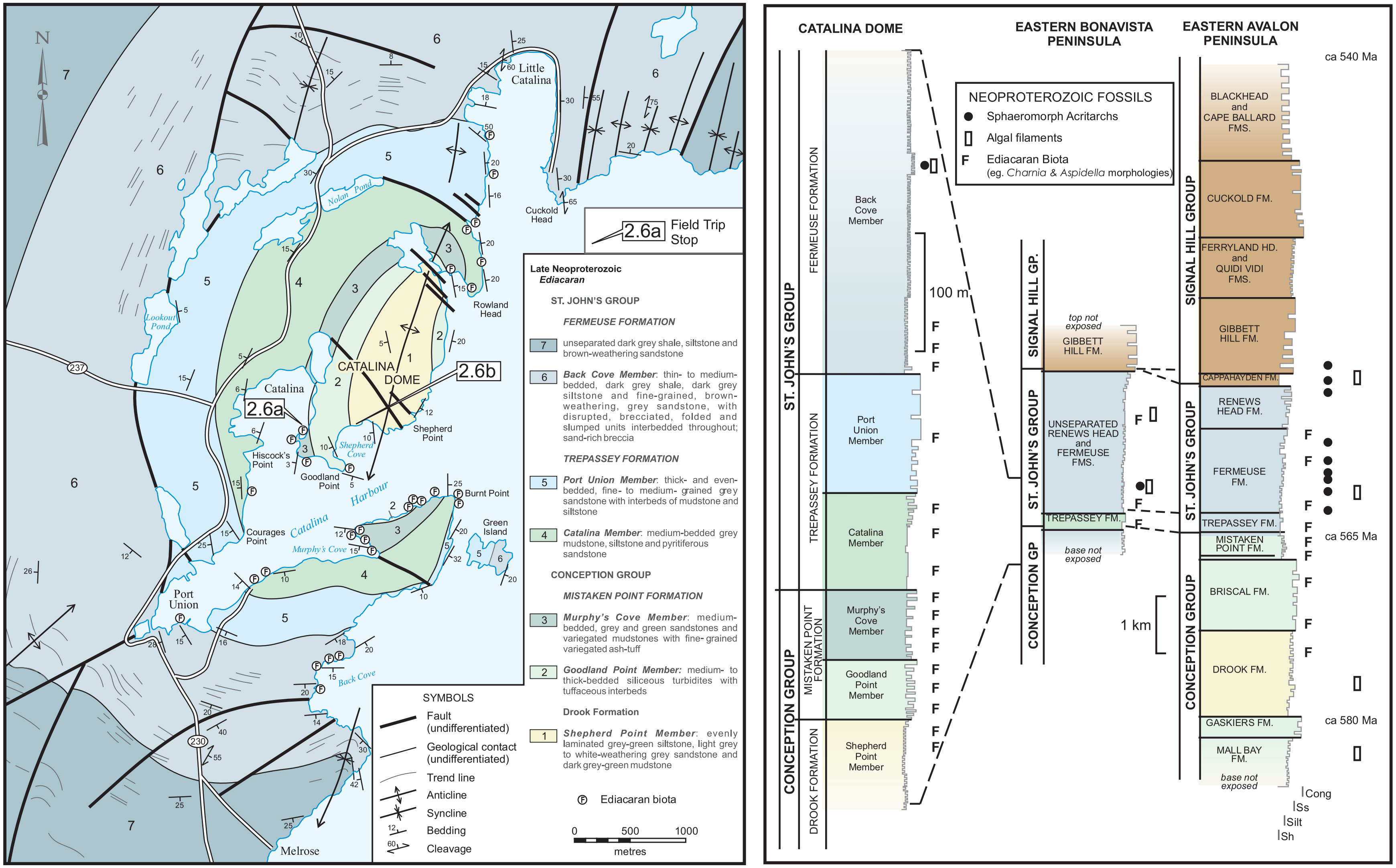

Figure 5. *Geological map of the Catalina–Port Union area, showing member-level subdivisions of the Conception and St. John's groups in their wider stratigraphic context. The map shows most (but not all) fossil localities, and the site visited on this field trip. Modified from O'Brien and King (2005).*

Mistaken Point Formation

The Mistaken Point formation consists of a lower sequence of siltstone and sandstone, and an upper sequence of more argillaceous character, including mudstone and shale. These are termed the Goodland Point and Murphy's Cove members, respectively (O'Brien and King, 2005), and are also dominated by turbidites. The Mistaken Point Formation also includes numerous thin units of pale yellow-green siliceous material interpreted to be of volcanic origin, *i.e.*, fine-grained aquagene tuff from distant explosive eruptions. These tuffaceous intervals are critically important in the context of Ediacaran fossil preservation.

St. John's Group

Around the Catalina Dome, the rocks of the Conception Group pass conformably into those of the St. John's Group, which occupy much of the area east of the Spillars Cove–English Harbour fault zone (Figure 3). In its type area, the St. John's Group is divided into the Trepassey, Fermeuse and Renews Head formations (Williams and King, 1979) and all three divisions are recognized in the field trip area, although the total thickness of the group is considerably less than in its type area (Figure 4). The rocks of the St. John's Group are well exposed along the coastal section northeast of English Harbour (Figure 3), and they are described in considerable detail by O'Brien and King (2005), and summarized below.

Trepassey Formation

The Trepassey Formation includes a lower sequence dominated by siltstone and mudstone, and an upper sequence of more thickly bedded sandstone; these are termed the Catalina and Port Union members, respectively (O'Brien and King, 2005). As a whole, the formation represents a coarsening-upward and thickening-upward cycle. The Catalina Member includes some thin tuffaceous units, associated with Ediacaran fossils. The Trepassey Formation also includes spectacular slumped units that attest to periodic slope instability.

Fermeuse Formation

The Fermeuse Formation consists mostly of dark shale, with lesser mudstone, siltstone and sandstone, marking a return to deeper-water conditions. Like the underlying Trepassey Formation, it contains slumped units, and thin tuff units that are associated with Ediacaran fossils.

Renews Head Formation

The Renews Head Formation is a coarsening-upward and thickening -upward sequence of siltstone, sandstone and granule conglomerate that preserve sedimentary structures indicative of a gradual transition from basinal into deltaic conditions. It contains very few Ediacaran fossils of note.

Signal Hill Group

The youngest rocks in the area east of the Spillars Cove–English Harbour fault zone are assigned to the Signal Hill Group (O'Brien and King, 2002), specifically the lowermost Gibbet Hill Formation (Williams and King, 1979). These rocks are preserved in the cores of two gentle synclinal structures that complement the anticlinal culmination of the Catalina Dome (Figure 3). In the field trip area, the Gibbet Hill Formation consists mostly of thick-bedded sandstone interpreted to be of largely deltaic origin (O'Brien and King, 2005). Younger formations of the Signal Hill Group are not exposed on the Bonavista Peninsula.

PRECAMBRIAN (EDIACARAN) ROCKS WEST OF THE SCF

Connecting Point Group (CPG)

The oldest rocks on the Bonavista Peninsula form a southward-narrowing siliciclastic sedimentary belt that extends from central Bonavista Bay in the north to Placentia Bay in the south (Figure 1) called the Connecting Point Group (CPG). The >3500-m-thick sequence conformably overlies the volcanic-rock-dominated Love Cove Group (Knight and O'Brien, 1988; Dec *et al.*, 1992; Myrow, 1995), exposed 15 km to the west, near Clarenville. Geochronological constraints on the CPG include an age from a tuff near the top of the underlying Love Cove Group, dated at 620 ± 2 Ma (O'Brien *et al.*, 1989), and a tuff unit from the middle of the CPG succession, dated at 610 ± 1 Ma (In Dec *et al.*, 1992; Mills *et al.*, 2016b). The top of the CPG is constrained at Southward Head (the head of Southern Bay), where *ca.* 605 Ma tuffaceous rocks and fine-grained, thin-bedded, locally ripple-marked sandstone is unconformably overlain by *ca.* 600 Ma crystal tuff and red pebble to cobble conglomerate presumed to be lowermost rocks of the overlying Musgravetown Group (Mills *et al.*, 2016b; Figure 1).

Upper contacts of the CPG vary regionally. It is an angular unconformity overlain by conglomerates of the Cannings Cove Formation at Milner Cove, at Charlottetown on Clode Sound (Hayes, 1948; *see* also O'Brien, 1987), as well as at Southward Head. However, the top of the CPG is described as a conformable or disconformable contact with the volcanic-dominated Bull Arm Formation of the MG at Newman Sound, south and east of the Louil Hills, and west of Traytown (Younce, 1970) and also two miles west of Rantem Cove (McCartney, 1967). Differences in the nature of the upper CPG contact likely resulted from variable expressions of north-directed thrust deformation across the basin (Mills *et al.*, 2016a). While continuous sedimentation and punctuated volcanism occurred within parts of the basin, other parts were thrust-stacked, uplifted and eroded during the 605-600 Ma interval (Mills *et al.*, 2017).

Knight and O'Brien (1988) divided CPG rocks of the Eastport area into six lithostratigraphic units interpreted to have been deposited in two turbiditic basin-fill events, separated by an olistostrome that resulted from basin collapse. The lower package comprises upward-coarsening turbidites deposited on a low-efficiency, prograding deep-sea fan typical of a volcaniclastic apron surrounding a volcanic arc. The upper package is characterized by a well-developed, high efficiency, levee-channel sequence consistent with basin enlargement. A thick unit of dominantly black shale, thin-bedded siltstone and chert, large- and small-scale slump deposits and a regional-scale olistostrome occur between the two basin-fill sequences (Knight and O'Brien, 1988; Mills *et al.*, 2016b). Knight and O'Brien (1988) suggest that the upward transition to more classical turbidites indicates that basin maturation was interrupted by extension and renewed uplift of a source terrane that provided the sediment deposited in the upper turbidite cycle. The upper cycle of Connecting Point Group deposition is thought to have culminated in a shallowing upward sequence of deltaic and fluvial sediments as the basin again matured.

Musgravetown Group

All Precambrian rocks in the field trip area west of the Spillars Cove–English Harbour fault zone were assigned to the Musgravetown Group (Jenness, 1963; O'Brien and King, 2005), which, in the Bonavista Peninsula, was subdivided into (in ascending order): the basal, conglomeratic Cannings Cove Formation (not present everywhere), the mainly volcanic Bull Arm Formation, the marine siliciclastic Rocky Harbour Formation, and the terrestrial red bed-dominated Crown Hill Formation (Jenness, 1963). Volcanic rocks of the Bull Arm Formation occur along the western edge of the field trip area (Plate Cove volcanic belt; Figure 3), and are likely the source for much of the coarse clastic rocks of the Rocky Harbour Formation. The most aerially extensive subdivision is the Rocky Harbour Formation (Jenness, 1963), dominated by marine siltstone and sandstone, punctuated by conglomerate units. The formation is not formally subdivided, as its internal stratigraphy is complicated by lateral and vertical facies variations, abundant brittle faults, and poor exposure in the interior of the peninsula. Normore (2011) subdivided rocks above the Bull Arm Formation and below the Crown Hill Formation into a lower unit dominated by grey-green and blue-grey siltstone and fine-grained sandstone (Big Head Formation) and an upper unit comprising mainly coarse-grained siliciclastic rocks (Rocky Harbour Formation). Normore (2010) recognized a mixtite unit within the siltstone-dominated Big Head Formation and subsequently established its glaciogenic origin by the presence of common dropstones and rare faceted and striated clasts (Normore, 2011). He named this ancient tillite unit, or glacial diamictite, the Trinity facies and reassigned it to the Rocky Harbour Formation due to its stratigraphic position above coarse clastic rocks on the southwest part of the Bonavista Peninsula. Association of the Trinity facies with fine-grained siltstone in the northeast part of the Bonavista Peninsula and with coarse-grained rocks of the Rocky Harbour Formation in the southwest part of the peninsula is likely due to different depositional environments: the former may be a continental slope to rise setting, consistent with the presence of common convolute beds suggesting slope instability. The coarse-grained rocks of the Rocky Harbour Formation, however, were likely deposited in a foreshore or shelf setting as indicated by the presence of mega-ripples consistent with deposition above storm wave base. The overlying Crown Hill Formation is a very different sequence dominated by redbeds and terrestrial sedimentary rocks, and occurs in the area around Duntara and Tickle Cove, where it hosts copper mineralization, and in the British Harbour area on the southwestern part of the peninsula (Figure 3). Overall, the Musgravetown Group exhibits considerable lateral facies variations, described in detail by O'Brien and King (2004a, 2005) and by Normore (2010, 2011), and the correlation of individual sequences to define member-level subdivisions is not an easy matter. The present stratigraphic framework for the group in the field trip area is shown in Figure 4C. For simplicity, the various "facies" proposed as potential members by these authors are not described below.

Cannings Cove Formation

The Cannings Cove Formation is a conglomeratic unit that overlies the Connecting Point Group, with angular unconformity, in the area north of Musgravetown (O'Brien, 1987) and at Southward Head in the eastern Sweet Bay area (Mills, 2014; Mills *et al.*, 2016b). It is considered to be the basal unit of the group, although its lateral extent may be limited, as volcanic rocks of the Bull Arm Formation directly overlie the Connecting Point Group at Newman Sound, south and east the Louil Hills, west of Traytown (Younce, 1970) and west of Rantem Cove (McCartney, 1967).

Bull Arm Formation

The Bull Arm Formation occurs at or near the base of the Musgravetown Group and is best known in the area of the isthmus of Avalon (Figure 1). The formation is more than 2 km thick, is lithologically and geochemically variable, but essentially bimodal in composition (*e.g.,* Malpas, 1972). The dominant rock types are subaerial basalts, rhyolite flows, felsic ash-flow tuffs, and assorted pyroclastic rocks and breccias. Chemically, the oldest mafic flows on the Bonavista Peninsula (*ca.* 600 Ma; Mills *et al.*, 2016b) are calc-alkaline (Mills and Sandeman, 2015) whereas the younger (possibly *ca.* 592-591 Ma; Mills *et al.*, 2017) mafic flows within the Plate Cove volcanic belt are transitional (weakly calc-alkaline to enriched mid-ocean ridge basalt EMORB-like), and are derived from a lithosphere-contaminated, slightly enriched (E-MORB), shallow mantle source (Mills and Sandeman, 2015). Basalts at Dam Pond (half-way between Catalina and Upper Amherst Cove) have ocean island basalt (OIB)-like chemistry, indicating a deeper source that may be related to late-stage Neoproterozoic rifting. The felsic rocks are reported to locally have alkaline (Malpas, 1972) to peralkaline compositions (O'Brien *et al.*, 1990, Williams, 1995).

Rocky Harbour Formation

O'Brien and King (2002, 2004a, 2005) divide the Rocky Harbour Formation into two broad sequences, interpreted to represent its lower and upper subdivisions, separated by a distinctive marker unit of well-sorted conglomerates and coarse-grained sandstones. This coarse clastic sequence is exposed in the area west of Port Rexton and includes the glacigenic Trinity facies of Normore (2011). The lower subdivision is found mostly in the area between Bonavista and east of Port Rexton, immediately west of the Spillars Cove–English Harbour fault zone, whereas the upper subdivision extends from Cape Bonavista to the area around Kings Cove and Plate Cove (Figure 3). The lower subdivision (Big Head Formation of Normore, 2010) is dominated by fine-grained siliciclastic rocks of generally monotonous character. Locally, these resemble some of the turbiditic rocks typical of the Conception Group, and were initially correlated with the strata exposed around Catalina (O'Brien and King, 2002). However, thin arkosic units, which are atypical of the Conception Group, were subsequently recognized by O'Brien and King (2004a), prompting these workers to suggest that this area should remain within the Musgravetown Group. The upper subdivision of the Rocky Harbour Formation is dominated by crossbedded sandstone and conglomerate; O'Brien and King (2004a, 2005) define several facies that appear to have broad stratigraphic continuity and may thus form a basis for member-level subdivision. Some of the units in this part of the formation have a red or orange cast, but they are not red beds in the sense of the overlying Crown Hill Formation (*see* below). The uppermost rocks of the Rocky Harbour Formation (Kings Cove North facies, O'Brien and King, 2005) are grey shale and siltstone, and these are interbedded at regional scale with medium- to thick-bedded sandstone having common maroon (locally grey) shaley laminations and/or mud drapes (King's Cove Lighthouse facies of Normore, 2010). These pass abruptly but conformably into redbeds of the Crown Hill Formation. In the western part of the field trip area, a thick sequence of conglomerate marks the general boundary region between sedimentary rocks of the Rocky Harbour Formation and the underlying Bull Arm Formation, here referred to as the Plate Cove volcanic belt (Mills and Sandeman, 2015; Figure 3); these conglomerates are lithologically similar to the Cannings Cove Formation, but occur stratigraphically above the tilted volcanic succession.

It is notable that the middle, mainly conglomeratic unit (Monk Bay–Hodderville facies of O'Brien and King, 2002, 2004a, 2005) contains interbeds of green-grey siltstone to mudstone, which are locally scoured by overlying coarse-grained pebbly sandstone beds. Interbedding of fine-grained and coarse-grained siliciclastic rocks is consistent with the interpretation of these sediments as paralic deposits, or interfingered marine and terrestrial deposits. The erosive nature of coarse clastic rocks in to fine-grained rocks is suggestive of a possible unconformity within the Rocky Harbour Formation. Alternatively, given the abundance and thickness of clay-rich rock locally having conglomeratic lenses, a glaciolacustrine origin cannot be ruled out.

Crown Hill Formation

The Crown Hill Formation includes the youngest Precambrian rocks in the area and has broadly been considered to be a time-equivalent of the upper part of the Signal Hill Group in the eastern Avalon Peninsula (*i.e.*, the Quidi Vidi, Cuckold, and Bay de Verde formations). These latter units have presumably been removed by erosion in the area east of the Spillars Cove–English Harbour fault zone (Figure 3), so that only the stratigraphically lowest unit, the Gibbet Hill Formation, is preserved there. The Crown Hill Formation is a spectacular sequence dominated by red and purple sandstone and conglomerate that exhibit a wide range of sedimentary structures, coupled with evidence of algal activity and perhaps bioturbation. In the lower section of the formation, distinctive yellow-green units have been interpreted as tuffs (O'Brien and King, 2005) or as possible dolomitic sandstone representing an evaporitic tidal-flat setting, *i.e.*, a "sabhka" (Lane, 2004; Thorson, 2004). Alternatively, the distinctive, commonly cryptocrystalline marker unit known as the Brook Point facies (O'Brien and King, 2005) may be the product of diagenetic, deuteric, or subsequent hydrothermal alteration. Evidence of alteration includes incomplete obliteration of primary layering that is locally discernible within the unit. The stratigraphy is summarized in Figure 4, and Figure 6 shows the preliminary bedrock map of the Tickle Cove– Duntara area. Although the bulk of the Crown Hill Formation is red and oxidized, there are intermittent but stratigraphically persistent "grey beds" that represent a transient return to reducing conditions. Some of these grey silty units are important as hosts to disseminated copper mineralization (Figure 6). They are described in detail by Lane (2004), who mapped their distribution and divided the Crown Hill Formation into several map units that appear to have stratigraphic continuity. The reduced "grey beds" occur mainly within two parallel units, and have been interpreted to have formed in a lacustrine environment (Hinchey, 2010, 2012). Subdivisions of the Crown Hill Formation on the northwest promontory of the Bonavista Peninsula (Keels/Duntara block) are shown in the detailed map of Figure 6, with more detailed stratigraphic columns for the Crown Hill Formation that indicate contrasts from east to west.

LATEST EDIACARAN AND CAMBRIAN ROCKS

Random Formation

The Random Formation is a laterally persistent marker in the Avalon Zone that represents the globally recognized earliest Cambrian marine transgression that marks the beginning of the Paleozoic Era (Vail *et al.*, 1977; Hiscott, 1982). It is exposed in the Keels area, where it forms the base of Cambrian strata in a regional synclinorium (Figures 3 and 6). The Random Formation is only about 100 m thick (Jenness, 1963), and consists of quartz arenite and quartz-pebble conglomerates, typically showing excellent cross-bedding. The boundary between the Musgravetown Group and the Random Formation is interpreted to be a conformable transition, although it is locally complicated by faulting. These rocks and their contact relationships are described by O'Brien and King (2004a, 2005) and Normore (2010).

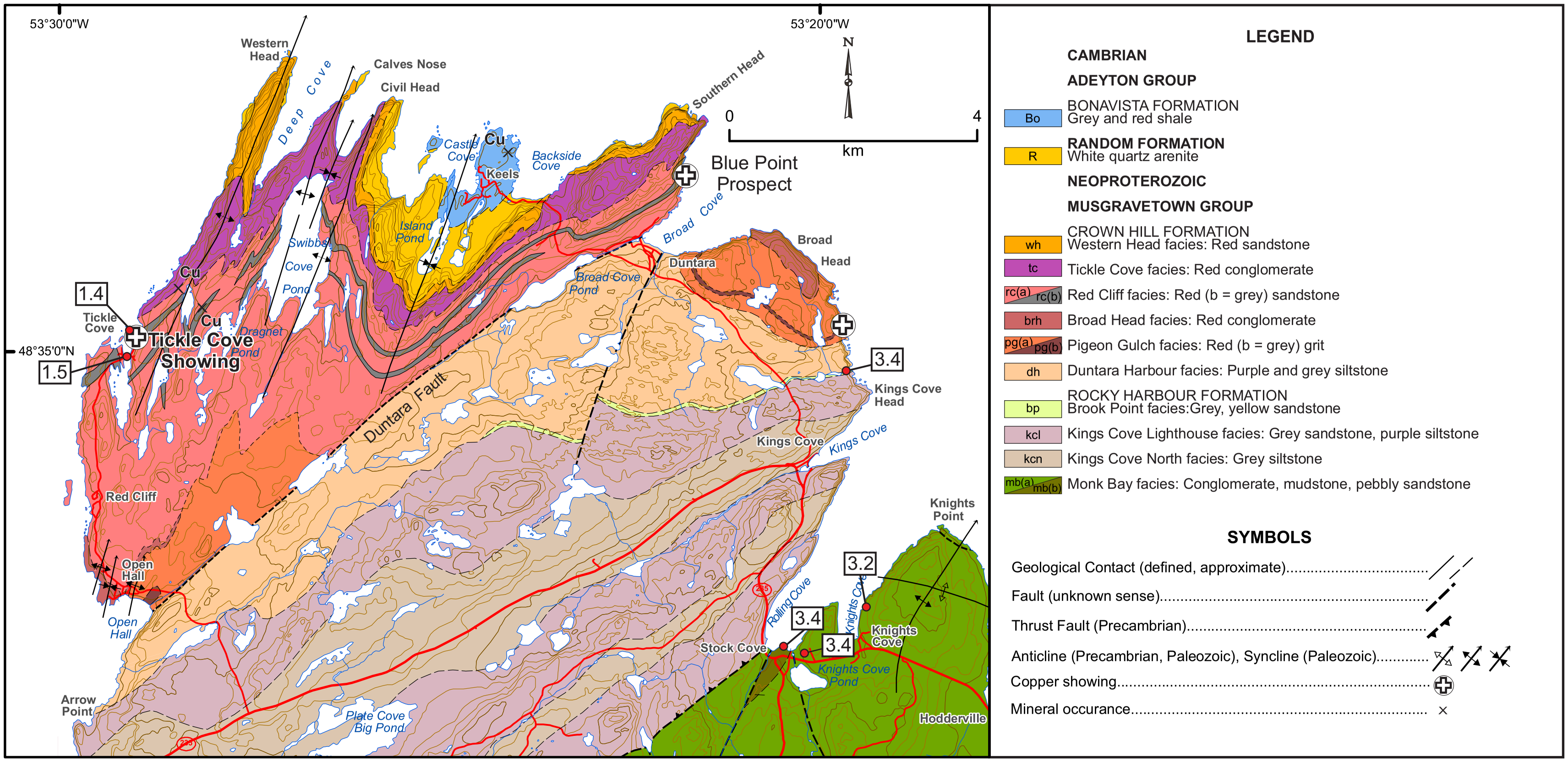

Figure 6. *Geological map of the Red Cliff copper property (Keels–Duntara area). Locations of field trip stops are shown. Adapted from Normore (2010).*

Adeytown Group

Green and red mudstones and shales of Cambrian age overlie the Random Formation in the Keels area (Figures 3, and 6). O'Brien and King (2004a, 2005) assign these mostly to the Bonavista Formation (Hutchison, 1962), and also recognize the distinctive pink algal limestones characteristic of the Smith Point Formation, although they recognized the possibility that these might represent other carbonate units lower in the sequence. Thus, the presence of other Cambrian formations that normally underlie the Smith Point marker unit cannot be established with certainty. The Cambrian rocks exhibit wide colour variation due to differential oxidation and reduction, which transgresses bedding and is clearly late relative to deposition. They are well-cleaved in the central part of the synclinal structure, where they are true slates, locally of high quality and with attractive colour variations. Minor copper mineralization is reported in Cambrian rocks of the Keels area, and also in the area around Ocean Pond, south of Summerville (Lane, 2004; Seymour *et al.*, 2005).

PALEONTOLOGY

THE DISCOVERY OF EDIACARAN FOSSILS

Prior to 2003, the only fossils known on the Bonavista Peninsula were of Cambrian age recovered from the Keels area, Cambrian trilobites reported in fragments of black shale in Ocean Pond area south of Southern Bay (O'Brien, 1994), and poorly preserved acritarchs and filamentous structures in the Catalina area (Hofmann *et al.*, 1979). However, the recognition that the structural culmination of the Catalina Dome includes rocks of the Mistaken Point Formation suggested that the area had potential for well-preserved Ediacaran fossils akin to those at the famous type locality of this unit. Ediacaran fossils are also known from parts of the St. John's Group, although they are rarely as spectacular as those of the Mistaken Point Formation.

Well-preserved body fossils of Ediacaran animals were discovered in the Murphy's Cove Member of the Mistaken Point Formation (Figure 5) in 2003, and have subsequently been discovered at many other sites in this unit and the overlying Trepassey and Fermeuse formations of the St. John's Group (O'Brien and King, 2004b; Hofmann *et al.*, 2008). Although the numbers of preserved organisms pale in comparison to the famous Mistaken Point sites, their preservation is exceptional, and the associations between different forms and species lend new insight into the nature of the Ediacaran biota and its ecosystem (Hofmann *et al.*, 2008; Mason *et al.*, 2013; *see* below). This section of the guide is divided into two parts. The first provides some general information about Ediacaran fossils and organisms, drawn from various published sources. The second provides a simplified account of the Ediacaran fossils described in the Catalina area, summarized from Hofmann *et al.* (2008).

THE EDIACARAN BIOTA AND ITS SIGNIFICANCE

Narbonne (1998) provides a short article that outlines the history of Ediacaran fossil research and the significance of these forms to paleontologists. There are many more detailed accounts in the paleontological literature, which are not referenced here for the sake of brevity. However, the introduction to the paper by Hofmann *et al.* (2008) provides a thorough review of work that is relevant specifically to Newfoundland examples, and Narbonne (2005) provides a wider detailed discussion of what is known about Ediacaran biology and what is intensely debated.

The extremely rare fossils of soft-bodied Neoproterozoic life forms known as the Ediacaran biota offer a tantalizing window into the origins of the earliest complex, multicellular organisms on our planet. The Ediacaran is the newest time period to be added to the accepted International Geological Time Scale (Knoll *et al.*, 2006), and it is partly defined by these creatures. These rare fossils occur in scattered locations around the globe, and eastern Newfoundland contains some of the best-known occurrences, including the famous site at Mistaken Point, first described by Misra (1969). Newfoundland was the first place where fossils of this age range were described, as the fossil *Aspidella terranovica* occurs commonly in and around downtown St. John's. It was first described by Elkanah Billings from behind the original post office on Water Street, and Boyce and Reynolds (2008) present a more recent inventory of urban *Aspidella* occurrences. This curious, disk-like fossil spent many years demoted to a mere pseudofossil, but its biological origins were recently restored with the recognition that it is probably a component of frond-like fossils termed *Charnia* and *Charniodiscus*, first described from Charnwood Forest in England. Gehling *et al.* (2000) suggest that *Aspidella* represents the "holdfast" that tethered the frond-like organism safely to its substrate. It was evidently not the most effective attachment, for *Aspidella* is more commonly preserved than the fronds themselves in Newfoundland, where it seems that the latter were more often swept away to their doom by turbidity currents. The Ediacaran fossils occur on all continents except Antarctica, and there are presently over 100 species known, most of which are visibly more complex than lowly *Aspidella*. Most of the occurrences are in sedimentary rocks of shallow-water character, but the sites in Newfoundland and England are of special interest, because they are hosted by deep-water turbidites. This is of particular importance, because it implies that these organisms lived in a lightless environment, indicating that they did not survive by photosynthesis, and were probably the earliest animals to develop on Earth. Ediacaran fossils in Newfoundland are also unique in that they represent localized extinctions of entire ecosystems; the organisms were killed by ash from distant eruptions, which buried and protected them until they were preserved as epireliefs upon lithification.

The biological affinities of the Ediacaran organisms are a topic of fierce debate, although most researchers agree that they have little in common with the familiar animal phyla that dominate the Phanerozoic. It has even been suggested that they represent an entirely distinct kingdom that was neither plant nor animal in the true sense of the word, termed *Vendozoa* or *Vendobionta* (Seilacher, 1989, 1992). Affinities to fungi have also been proposed, and others still maintain that they were early plants or colonial organisms. The abrupt disappearance of the Ediacaran organisms from the geological record has been attributed to the development of predation; these sessile, defenseless organisms are perhaps a remnant of an Earth that was very different to that of today. Predation is believed to have been the driving force of the "evolutionary arms race" that led to the development of defensive exoskeletons and increasingly more complex organisms in the Cambrian. It remains possible that a few Ediacaran organisms were actually the source of the first predatory organisms, which eventually gave rise to modern life forms, but these progenitors have yet to be identified with any confidence (*e.g.*, Narbonne, 2005).

EDIACARAN FOSSILS IN THE FIELD TRIP AREA

Much has been written about the famous fossil site at Mistaken Point (*e.g.*, Narbonne *et al.*, 2002), and much of this is applicable to the sites of the Bonavista Peninsula. The mode of preservation appears to be identical, and many of the species described from Mistaken Point also occur around Catalina. Figure 7, adapted from Clapham and Narbonne (2002) and Hofmann *et al.* (2008), illustrates the interpreted form of Ediacaran organisms preserved in the Mistaken Point and Bonavista areas. Many Ediacaran fossils

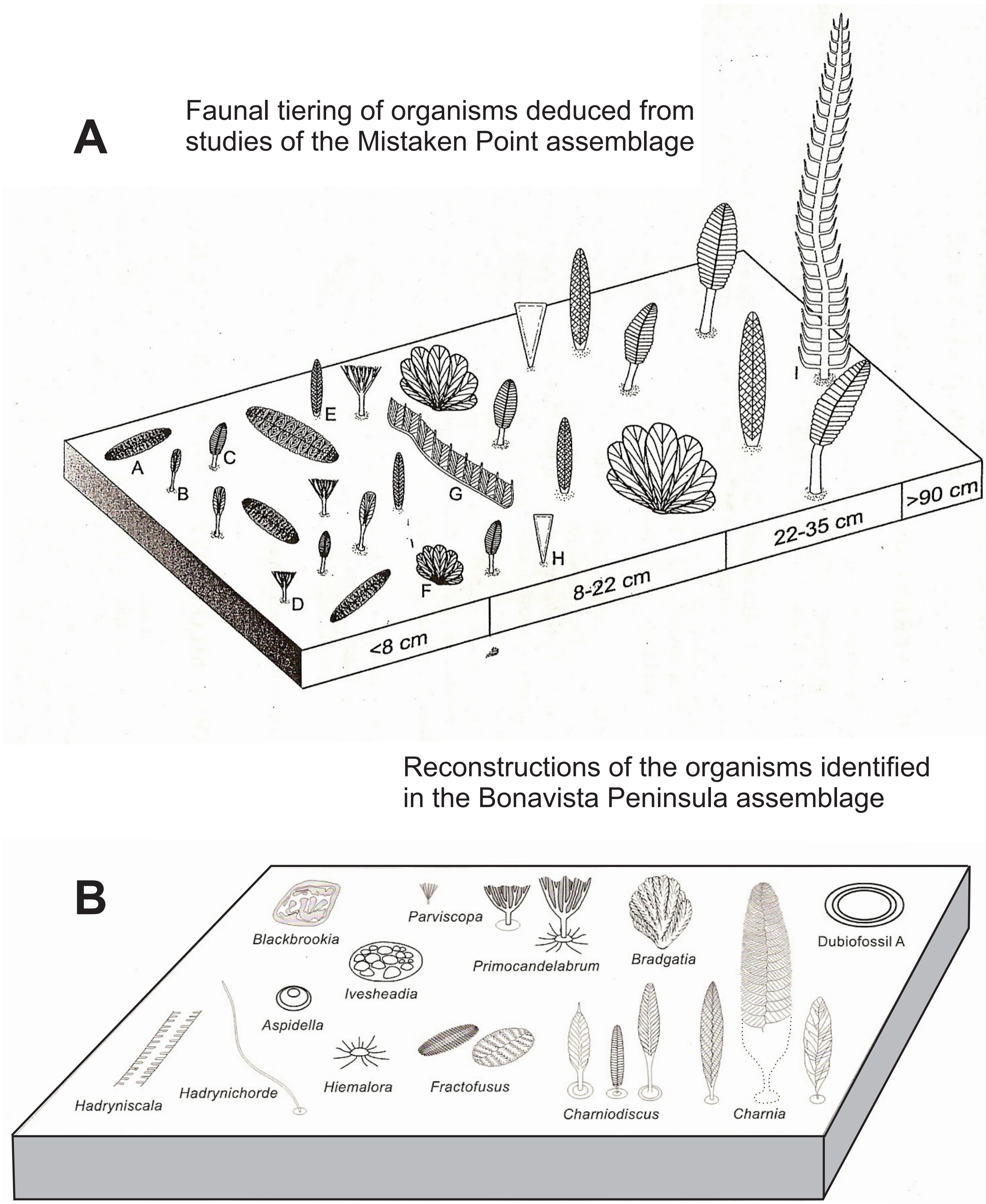

Figure 7. *Reconstructions of Ediacaran organisms. A) Diorama showing the suggested forms, sizes and ecological "tiering" of organisms at Mistaken Point, taken from Clapham and Narbonne (2002); B) Diorama showing the suggested forms of organisms in the Catalina area, taken from Hofmann* et al. *(2008).*

lacked formal names for many years, and were known by fanciful comparisons such as "spindles", "pizza disks" and "christmas trees". The preservation of Ediacaran fossils in Newfoundland is exceptional, because the sedimentary rocks in which they occur are fine-grained. However, they are mostly very low-relief positive impressions (epireliefs) and they can be exceptionally difficult to locate if the light conditions are less than ideal. Compared to Mistaken Point, the bedding planes in most areas are sparsely and sporadically fossiliferous, and it is very easy to miss the fossils completely in walking the sedimentary sections.

The fossils known in the Catalina area were described initially by O'Brien and King (2004b) with tentative identifications at a generic level, and are formally described and documented by Hofmann *et al.* (2008). In this guidebook, the formal species names are avoided as much as possible in the text, but they are listed in Figure 7b. Note that two of these genera, namely *Hadryniscala* and *Hadrynichorde*, are new genera that are presently endemic to the Bonavista occurrences (Hofmann *et al.*, 2008). Their names are derived from the time period "Hadrynian", which was part of the original Precambrian time scale developed for the Canadian Shield by C. H. Stockwell in 1964. *Parviscopa* and *Primocandelabrum* are also new species genera by Hofmann *et al.* (2008). Most recently, the macrofossil *Haootia quadriformis*, also endemic to the Bonavista Peninsula, has been discovered at Back Cove, Port Union area (Liu *et al.*, 2014). This fossil is distinct from contemporaneous Ediacaran fossils, and could present the oldest evidence for muscular tissue. The specimen is now located at the Rooms Provincial Museum in St. John's. Liu *et al.* (2016) describe a newly discovered fossil surface with excellent exposure at Burnt Point, Port Union area, with implications for the taxonomy of Ediacaran fossils.

The Bonavista Peninsula sites are notable for their exceptional preservation of an organism termed *Hiemalora* (Figure 7b), which is less common at Mistaken Point. The morphology of this fossil resembles that of a modern jellyfish, and many researchers have thought of it as an early colenterate-like animal that could have been mobile. At several sites there is an association between this fossil and a newly-recognized bush-like fossil (*Primocandelabrum* in Figure 7b), and in rare cases it appears that the two are intimately attached, with the disk-like portion acting as a holdfast. Thus, *Hiemalora* may be more akin to the humble *Aspidella*, and the "tentacles" might have been more like roots that provided greater security of attachment (Hofmann *et al.*, 2008). The Bonavista fossils also reveal several other inferences about Ediacaran ecology, including an indication that many species extend to higher stratigraphic levels than previously supposed within the St. John's Group. Near Mistaken Point, the oldest fossils lie within the Drook Formation, but no localities are presently known in this unit on the Bonavista Peninsula. However, the basal portion of the Mistaken Point Formation (Goodland Point Member; O'Brien and King, 2005) contains a curious dubiofossil (*i.e.*, a structure of uncertain but potential biological origin) that might represent a large holdfast to a potentially huge organism that has yet to be documented (Hofmann *et al.*, 2008). The new species *Hadryniscala* and *Hadrynichorde* are also interesting, because they superficially resemble trace fossils from younger rocks; if this is the case, it implies mobility, which is a new concept for Ediacaran organisms (Liu *et al.*, 2010).

The absolute age of the fossil horizons on the Bonavista Peninsula remains unknown, but the association of these faunas with tuffaceous units indicates potential for U–Pb zircon dating. The main fossil-bearing plane at Mistaken Point was previously dated by G.R. Dunning at 565 ± 3 Ma (unpublished, reported by Benus, 1988). Tuffs in the sequence at Catalina have been sampled for geochronological analyses.

ECONOMIC GEOLOGY

GENERAL INFORMATION

The Avalon Zone has a diverse metallogeny, including gold mineralization (mostly epithermal in character), lead and zinc (typically vein-hosted, but locally of VMS affinity), several styles of copper mineralization, stratabound iron ore and manganese, barite, fluorite, molybdenite and a wide range of industrial minerals commodities including slate, building stone and pyrophyllite. Although some deposit types are demonstrably linked to mid-Paleozoic granites, and others are interpreted to be so linked, many examples of mineralization are connected to the Precambrian and earliest Paleozoic history of the region.

The Bonavista Peninsula is historically very significant in the context of economic minerals in Newfoundland, because it gave rise to the first suggestions of mineral potential in the nascent colony. Sir Martin Frobisher's expeditions of the late 1500s documented coarse grained "gold and copper" in the "slates" of the Catalina area, and these sites were also visited by Sir Humphrey Gilbert, who collected samples and took them back across the ocean for identification and assay. Neither Frobisher nor Gilbert possessed geological knowledge, and were perhaps disappointed when the "gold and copper" turned out to be large cubes of common pyrite. Despite its lack of value, diagenetic pyrite cubes are spectacular in their own right, and are locally termed "Catalina stone".

The Bonavista Peninsula contained very few known mineral occurrences prior to 2000, and it still remains poorly endowed compared to other parts of Newfoundland. The area saw little or no systematic exploration during the 20th century. However, several interesting copper showings and prospects have been unearthed by exploration in the early 2000s. This section contains a brief summary of copper mineralization and potential host environments. There has to date been limited public-domain information on these deposits, although some general descriptive information is present in regional geology reports (*e.g.*, O'Brien and King, 2005). Assessment reports, mostly prepared for Cornerstone Resources and/or Noranda (*e.g.*, Graves, 2002; Seymour *et al.*, 2005), are now in public documents, and these provide significantly more information. The report by Lane (2004) provides a comprehensive account, and several useful maps and sections.

AN OVERVIEW OF STRATIFORM SEDIMENT-HOSTED COPPER (SSC) DEPOSITS

In the early 2000s, mineral exploration in the Bonavista area focused on the search for sediment-hosted stratiform copper (SSC) deposits within the Musgravetown Group. This section provides some general information about SSC deposits, as summarized by Kerr (2008) and drawn, in large part, from reviews by Brown (1993) and Hitzman *et al.* (2005).

SSC deposits of major economic significance are rare, but this group includes some of the world's largest copper deposits, and is second only to porphyry deposits as a global copper source, accounting for almost 25% of world Cu production. The best-known examples are the Kupferschiefer deposits of central Europe, the Central African copperbelt of Congo and Zambia, and the White Pine deposits in Michigan. Other SSC deposits occur in central Asia and Australia, although not all of these are currently exploited. In addition to copper, deposits of this type are significant sources of cobalt, silver, and locally gold, uranium and rare-earth elements (Brown, 1998, Hitzman *et al.*, 2005). Some of these deposit clusters are enormous; for example, the reserves and resources in central Africa are estimated at close to 5 billion tonnes at 3.4% Cu (165 Mt of metal). Many such deposits have high grades and exhibit remarkable stratigraphic continuity, making them very attractive mining targets.

SSC deposits are viewed as metal concentrations of diagenetic to epigenetic timing linked to the basin-scale movement of low temperature, metal-bearing hydrothermal solutions through the host sedimentary sequences. Like all ore deposit types, they require sources for metals, sources for fluids, thermal and hydraulic processes to drive fluid flows and – above all – an effective mechanism for precipitation of metals (Hitzman *et al.*, 2005). The host sequences to these deposits commonly include reduced (*i.e.*, grey or green) sedimentary units within sequences dominated by rocks of oxidized, terrestrial character (*i.e.*, redbeds). The immediate reduced host units are in some cases stratigraphic members representing marine transgressions, or the local development of anoxic conditions in restricted basins. However, they may also be discordant reduced zones that result from post-depositional but pre-mineralization processes (Brown, 1993). The reduced units, which commonly contain abundant syngenetic or diagenetic pyrite (on a regional scale), likely formed chemical traps for metalliferous brines, reflecting the low solubility of copper under reducing conditions compared to its high solubility in oxidized fluids.

SSC deposits are typically located above thick footwall redbed sequences, which are viewed as permeable aquifers, and also as the most likely sources of the copper, originally held in Fe-oxides and hydroxides. The interface between these oxidized footwall and the reduced host, also known as the redoxcline (Brown, 1993) is commonly regionally enriched in copper (and other metals) and forms the most obvious exploration target. The sulphur associated with the metals could have a variety of sources including marine or lacustrine evaporites, HS-bearing organic matter, or reduced seawater. Hitzman *et al.* (2005) emphasize the potential importance of evaporites in generating high-salinity fluids. The metalliferous fluids were focused at depositional sites controlled by the basin architecture, and possibly also by syndepositional faults associated with basin development. Precipitation of metals was likely a function of reduction, through syngenetic sulphides and/or organic matter in the host “grey bed” units (Brown, 1993; Hitzman *et al.*, 2005). Mineralization consists of copper sulphides (chalcocite, chalcopyrite, digenite and bornite), other base-metal sulphides (*e.g.*, galena and sphalerite), and native copper and silver may also be present. The deposits are commonly zoned, with chalcocite and digenite closest to the redoxcline, and chalcopyrite and bornite in more distal settings; such zonation reflects differing solubilities of these sulphides as the oxidized solutions become progressively reduced. Other base-metal sulphides also tend to be located “downstream” of the redoxcline, because they have higher solubilities than the copper sulphides (Figure 8).

The stratiform character of these deposits, and their commonly bedded appearance, has led to considerable discussion of their origins. Early models suggested magmatic-hydrothermal models in which the host sediments were “replaced”, but these ideas were replaced between the 1940s and 1960s by syngenetic concepts. These models held that copper and other metals were deposited with their host rocks in sedimentary environments where metal-rich waters discharged into anoxic basins. However, this model encountered problems in explaining the transport of metals in fresh waters that lacked suitable complexing agents such as chloride. The most widely accepted model today involves diagenetic or epigenetic processes that are related to basin development and dewatering, without the requirement for magmatic involvement. However, the fact that many SSC deposits are in rift-type basins may indicate elevated heat flow. The sources of the metals are considered to be the footwall redbed sequences and/or deeper marine

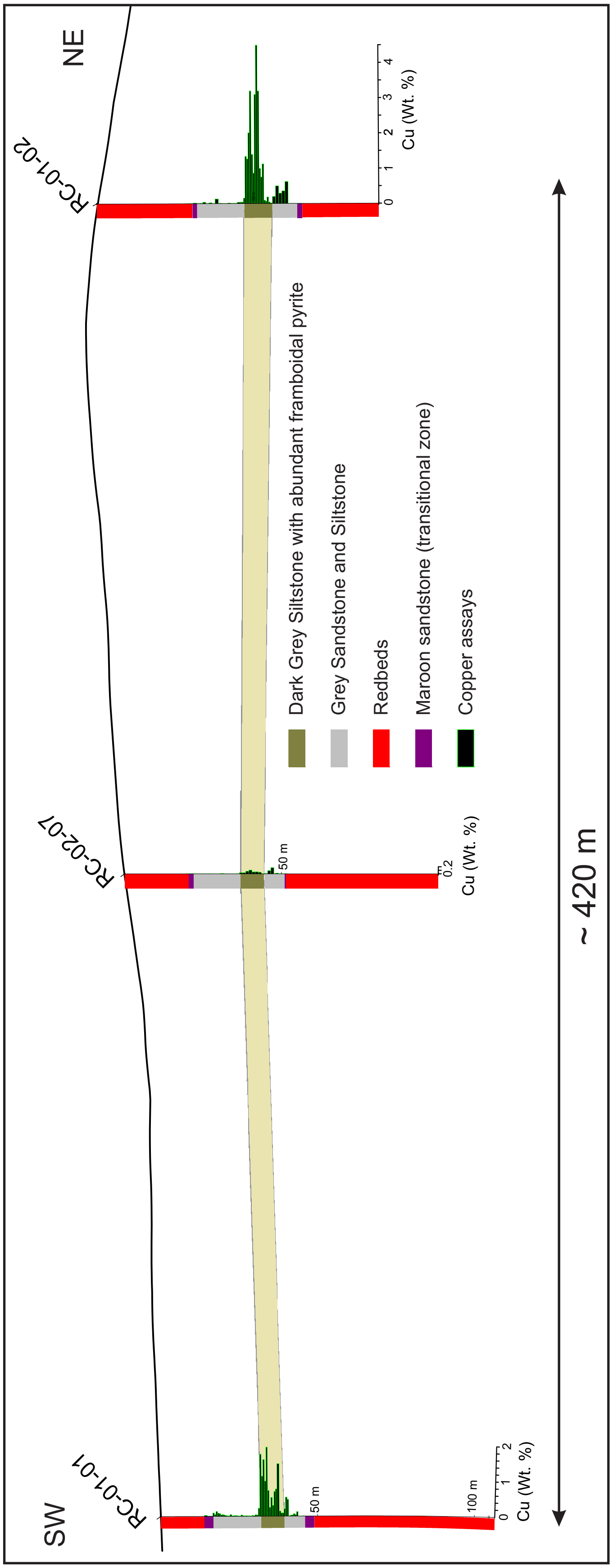

Figure 8. *Long-section through Crown Hill Formation rocks (including the Blue Point horizon) based on diamond-drill hole data for area north of Duntara (after Hinchey, 2010).*

sedimentary rocks, and the fluids are believed to focus along fault systems around basin margins, which were likely active during sedimentation. In some cases, fluids flowed laterally along permeable units. The timing of mineralization is epigenetic, but in some cases may occur prior to complete consolidation and lithification of their host strata. Replacement of early syngenetic or diagenetic pyrite by copper sulphides may represent an important control on the formation of such deposits. Hitzman *et al.* (2005) suggest that deposits of this type can form at several stages in basin evolution, ranging from early diagenesis to much later deformation and metamorphism. Thus, the temperatures of fluids involved may vary significantly, and the characteristics of the deposits so formed are variable, rather than unique. This is supported by the differences in metal associations and depositional controls reported between major SSC deposit provinces such as the North American midcontinent, central Europe, south-central Africa and Siberia.

COPPER MINERALIZATION ON THE BONAVISTA PENINSULA

This section provides a brief review of copper mineralization known on the Bonavista Peninsula, including one site that will be visited on this field trip. It is based to a large extent of assessment reports submitted by exploration companies that are now in the public domain (notably Graves, 2002; Seymour *et al.*, 2005, and Lane, 2004), coupled with observations and insight provided by the Geological Survey (*e.g.*, O'Brien and King, 2002, 2005; Hinchey, 2010, 2012).

Prior to the late 1990s, the only exploration in the area was by Cominco, who followed up Pb and Zn anomalies in regional lake sediment data, and by Radex Minerals, who conducted a regional reconnaissance for uranium in the sedimentary sequences. In the late 1990s, prospectors working with Cornerstone Resources discovered copper mineralization in the form of a chalcocite-rich unit within the Crown Hill Formation, which is exposed on the coast in a steep cliff northeast of Duntara (the Blue Point prospect). Similar mineralization was discovered in the Tickle Cove area. These discoveries prompted a systematic investigation of the Crown Hill Formation as a potential host to SSC mineralization, through a joint venture with Noranda, and a wider reconnaissance of equivalent rocks elsewhere in the Avalon Terrane. Several other copper showings were discovered in the Crown Hill and Rocky Harbour formationa within the field trip area (Hinchey, 2010).

Systematic sampling of the Blue Point prospect (not an easy task in view of its precipitous location) indicated 0.93% Cu over a 13.5 m channel, mostly in the form of finely disseminated and fracture-hosted chalcocite and bornite, with abundant disseminated pyrite. The characteristics of the mineralization broadly fit the SSC model, with precipitation of copper within a reduced, pyritiferous unit within a thick oxidized redbed sequence (*cf.* Brown, 1998; Hitzman *et al.*, 2005). A drilling program in 2001 tested the continuity of the host unit away from the coastal exposures, and proved that it extends for a distance of at least 600 m. The best results were similar to those of the initial discovery, with intersections of 0.8% Cu over 9.7 m and 1.0% Cu over 14.25 m (Graves *et al.*, 2002; Seymour *et al.*, 2005). The highest grade interval returned about 2% Cu over 6.2 m. Extensions of the prospective horizon are less well-defined, and mineralization and grades vary significantly along strike (Figure 8; Hinchey, 2010). Follow-up work in 2010 included rock and soil sampling and the drilling of six diamond drill holes, one of which intersected low-grade copper mineralization (0.27% Cu over 10.9 m; Hicks, 2011).

Work elsewhere on the peninsula identified both surficial and bedrock copper enrichment, and some systematic work was completed in the Rocky Harbour Formation in the Port Rexton area, where drilling was completed on low-grade disseminated mineralization at the Fifield's Pit and World Pond showings. The results from work in this area were not as encouraging as those from Duntara. The applicability of the SSC model in this area is not as obvious, although local redbed oxidized horizons are present in nearby successions indicating that similar models of mineralization may apply (Hinchey, 2010).

The Joint Venture with Noranda expired in 2003, and Cornerstone initiated some regional geological studies through a consultant, Jon Thorson, and some systematic mapping and evaluation under the direction of Tom Lane. The results of this work are reported by Thorson (2004) and Lane (2004), although some of the data and synthesis in the former source remains preliminary in nature. Work on the Bonavista Peninsula and elsewhere in the Avalon Zone identified low-grade Cu mineralization and potential SSC environments in several areas, but subsequent investigations have been limited.

During the same general time period, Cornerstone Resources also explored the Peninsula northeast of Musgravetown (the Princess property), where prospectors discovered low-grade copper mineralization. Mineralization in this area is hosted by mafic volcanic rocks of the Bull Arm Formation, and also by quartz-carbonate vein systems in Musgravetown Group sedimentary rocks; the stratiform controls on mineralization there are less evident (Hutchings, 1998; Froude, 2002). The style of mineralization in this area has been compared broadly to "Volcanic Redbed Copper" (VRC) as defined by Kirkham (1996). Hitzman *et al.* (2005) consider VRC mineralization to be broadly similar to SSC mineralization in that it is driven by fluid migration and redox precipitation mechanisms; in many regions, the two are associated, and perhaps both are indirectly linked to high heat flow expressed by the associated volcanism. Drilling results in this area, at the Stag Brook prospect, indicated that mineralization was discontinuous and low in grade, and no work has occurred in recent years.

OTHER TYPES OF MINERALIZATION

There has long been an interest in the potential of the Cambrian rocks for slate production, driven in part by the attractive red, purple and green colours of this material, which yield better prices in the slate market than the dull greys generally associated with the stone. Slates developed on the east side of the synclinal structure at Keels contain a well-developed cleavage, and a small quarry was developed here in the 1990s. However, this did not prove to be economically viable.

Other indications of mineralization include laterally extensive pyritiferous zones of stratiform aspect in the sedimentary rocks of the St. John's Group, notably at Sandy Cove, between Elliston and Maberly. Although these are not known to contain anomalous metal contents, they indicate the possibility for sediment-hosted base metal mineralization. Equivalent rocks in the Heart's Content–Carbonear area do contain some Pb and Zn mineralization, and both areas are associated with Pb enrichment in lake sediments. The Pb-enriched area in the northeastern Bonavista Peninsula is bounded to the west by the trace of the Spillars Cove–English Harbour fault zone, independently supporting conclusions drawn on the basis of regional geology and paleontology (O'Brien and King, 2002, 2005). A small galena showing was reported in the Little Catalina area by Jenness (1963) but this occurrence has not been visited by the author.

ANCIENT GLACIAL PRODUCTS

Recognition of ancient glacial events is not an easy task due to their lateral and vertical variability in the sedimentary record (Arnaud and Etienne, 2011; Figure 9), the limited diagnostic features that can be used to unequivocally demonstrate glacial influence (Chumakov, 2015) and subsequent reworking and redeposition of glacial debris. The only broadly accepted criteria that are considered diagnostic of glacial processes, and therefore acceptable proof that a rock is a glacial product, are dropstones (isolated, extra-basinal rock fragments that occur within finer-grained water-deposited sedimentary rocks), striated and faceted clasts, and glacial pavements. Conglomerate, sandstone, siltstone and mudstone are common in lithofacies of glacial origin, but, as they are not unique to glacial deposition, they can be easily overlooked as pre-, post-, or non-glacial products. In contrast to recent glacial deposits, glaciogenic landforms tend not to be preserved or are poorly preserved in ancient glaciogenic successions (Arnaud and Etienne, 2011).

There are three main Neoproterozoic glacial events that are globally recognized: the Sturtian, the Marinoan and the Ediacaran events (which, as per Hoffman and Li (2009), includes the Gaskiers event). Sturtian glaciation has been recognized on 14 paleocontinents and may have lasted from *ca.* 726 Ma to *ca.* 660 Ma (Hoffman and Li, 2009). Marinoan (younger Cryogenian) glacial deposits occur on at least 15 paleocontinents and are broadly constrained to between *ca.* 655 Ma and 635 Ma (Hoffman and Li, 2009). The Gaskiers glaciation in Newfoundland had been constrained to 580 Ma (Bowring *et al.*, 2003) and is considered too short in duration to create a Snowball Earth as per Hoffman *et al.* (1998).

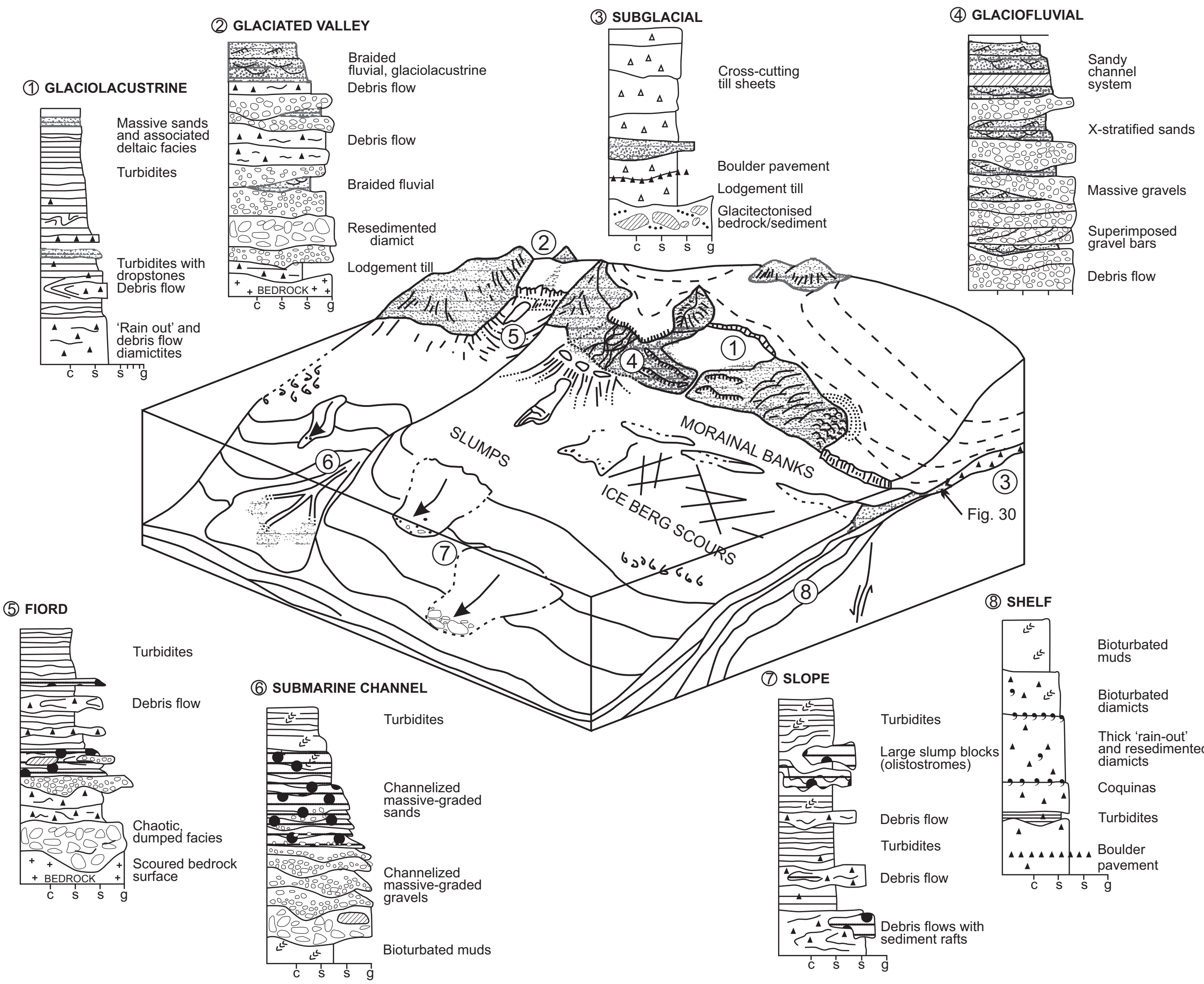

Figure 9. *Conceptual model for fjordal glacial systems (after Eyles and Eyles, 1992) showing the dynamic setting associated with glacial systems.*

Tillites of the Gaskiers Formation were first described by Brückner (1969) and the discovery of glacial striae on pebble and cobble-size clasts provided confirmatory evidence of their glacial origin (Brückner and Anderson, 1971), which was further substantiated by the presence of chatter-marked garnets (Gravenor, 1980). Tillites were described from many locations within the Avalon Terrane of Newfoundland including Portugal Cove, Flat Rock, localities between Holyrood and Brigus bays, Great and Little Colinet islands, the east shore of St. Mary's Bay (including Gaskiers) and Virgin Rocks Shoal, about 200 km southeast of St. John's on the Grand Banks (Brückner and Anderson, 1971 and references therein). Williams and King (1979) subdivided the Conception Group, which had been viewed as a thick monotonous sequence, into five formations. These include the pre-glacial Mall Bay Formation, the glacial Gaskiers Formation, the post-glacial Drook and Briscal formations, and the uppermost Mistaken Point Formation. It is notable that Brückner and Anderson (1971) report two tillite units in Flat Rock, with a "small thickness of … normal Conception strata indicating that there were two glacial advances within the major ice age…". No measured stratigraphic section of the two tillite units has yet been documented;

possibly no uninterrupted section comprising the two units and amenable to detailed measurement and analysis has been found. The ~300 m section exposed at Double Road Point in St. Mary's Bay has been measured and examined in detail (Anderson and King, 1981; Anderson, 1987; Eyles and Eyles, 1989) and contains a single thick (~280 m) glacial section with no intervening turbidite sequence as described between the two glacial units in the Flat Rock area.

Deposition of the Gaskiers diamictite on the Avalon Peninsula has recently been constrained to between 580.4 ± 0.40 and 579 ± 0.44 Ma and the Trinity diamictite on the southern Bonavista Peninsula has been constrained to between 579.63 ± 0.15 and 579.24 ± 0.17 Ma (Pu *et al.*, 2016). These age dates allow for correlation between the Gaskiers Formation (Conception Group on Avalon Peninsula) and the Trinity facies (Musgravetown Group on Bonavista Peninsula) and validate Brückner's (1977) use of tillite units as a stratigraphic marker horizon (Figure 2C). The age data have been used to infer a maximum duration of ≤340 k.y. for deposition of the Trinity diamictite (Pu *et al.*, 2016). However, it is possible that these results constrain an "event bed" within a stratigraphic sequence that includes additional glacial products not yet recognized as such. The currently recognized glacial diamictites include deep (Gaskiers Formation) to shallow (Trinity facies) marine strata; nowhere in the Avalon Terrane of Newfoundland have products of terrestrial glacial deposition been documented.

Possible glacial products located on the Bonavista Peninsula include:

- Laminated, dropstone-diamictite (New Bonaventure)
- Extensively slumped and disrupted interbedded sandstone-shale sequences with common sandstone dykes, other water-escape features and rare outsized clasts (Middle Amherst Cove)
- Iron-rich sandstone containing lone stones (near Dungeon Provincial Park)
- Cryptocrystalline Brook Point facies with possible carbonate pseudomorphs at top (Knight's Cove and Brook Point)
- Possible Tepee-like structures in "pistachio" unit overlying Trinity facies (Trinity area, along Highway 230 near Trinity Pond and possible at Spaniards Cove
- Outsized extra-basinal clasts in interbedded mudstone–sandstone and internal (non-tectonic) disruption of bedded layers (Spaniards Cove)
- Deeply scouring cross-stratification with small wavelength (possible "frozen" crossbeds; near Dungeon Provincial Park)

FIELD TRIP STOP DESCRIPTIONS

Field trip stop descriptions are located below using kilometerage distances measurable by vehicle odometer, description of local landmarks, and (for most stops) by GPS coordinates. The latter has not been provided for potentially sensitive Ediacaran fossil sites. In using the location information provided, readers should be aware that vehicle odometers vary in accuracy by as much as ± 5% to 10%, and we recommend calibration against information in this guide – you may have to correct for your vehicle. To minimize this source of confusion, the kilometerage quoted is measured from the nearest possible reference point. It is also possible that landmarks may have changed (*e.g.*, houses may have been repainted), and road conditions may have altered from those described here.

DAY ONE – WESTERN BONAVISTA PENINSULA

Stop 1.1: Cross-section through marine turbidites and black argillite of the upper Connecting Point Group at Muddy Pond River (48.39669, -53.58222)

From St. John's (or wherever you start from) take the TCH to Georges Pond, about 10 km west of Clarenville, and then turn onto on the Discovery Trail (Route 230) signposted for Trinity and Bonavista. Continue about 45 km, or until about 3.5 km west of the Irving Midway Gas Station at Southern Bay. A power plant can be seen on the south (right hand) side of the highway, and parking is available just east of the guard rail on the north side.

> *Exercise caution while descending over the embankment of boulder-sized fill and talus. The river level is highly variable and while hiking boots may be the best choice for descent over the bank, rubber boots may be more practical when the water level is high. To see the best exposures, you will need to cross the river at various localities.*

The excellent exposure here resulted from forceful flooding that displaced the culvert and washed out the river banks during Hurricane Igor in 2010. The old culvert can be seen some ~100+ m downstream from its original position under the highway.

The top of the section here includes variegated (reddish to green) turbidite sandstone containing microfaults that locally offset primary banding. On the northwest side of the river, the beds are green and locally contain euhedral pyrite cubes up to 1 cm; presumably, these beds were once red and their present green colour (and presence of pyrite) is interpreted to have resulted from reducing fluids. Farther downstream, metre-thick, reddish sandstone beds display excellent convolute folds indicating deposition on an unstable slope that was likely subject to seismicity resulting in slumping (Plate 1). Subsequent beds scour into underlying beds and mud chips and ball-and-pillar structures

Plate 1. *Coarse-grained, thick-bedded, red (and green) sandstone showing well-developed convolute bedding with scoured tops, consistent with deposition on an unstable slope.*

can be seen locally. Several dykes crosscut the sandstone at a high angle. While some dykes appear to have cuspate margins, indicating nearly syndepositional intrusion, other dykes may be post-depositional.

Continue another 100 m down-section from the red and green sandstone to the black argillite. These thin-bedded argillites are typical of the mid-Connecting Point Group stratigraphy, and separate the two turbidite-dominated successions of the lower and upper Connecting Point Group (Knight and O'Brien, 1988). Ash tuff horizons, ~1 cm thick, occur locally within the black argillite, and this stop is the site of a geochronological sample that yielded an age of 613 ± 3 Ma, interpreted to represent the approximate age of deposition (Mills *et al.*, 2016b). This age overlaps within error with the age of 610 ± 2 Ma for a 3 m-thick tuff that occurs within black shale above a regional olistostrome near Eastport, where measured sections of the stratigraphy clearly demonstrate its position between the lower and upper turbidite successions (Dec *et al.*, 1992; Knight and O'Brien, 1988; Mills *et al.*, 2016b).

In the Sweet Bay region, to the northwest of this Field Stop, Connecting Point Group turbidites comprise an imbricate thrust stack formed by north-directed thrust tectonics, and are locally overlain, with angular unconformity, by 600 ± 3 Ma crystal tuff, red cobble conglomerate and calc-alkaline basalt flows (Mills and Sandeman, 2015; Mills *et al.*, 2016b). This provides evidence of a pre-Avalonian tectonic event, as much of the strata affected by Avalonian deformation on the Avalon Peninsula had not yet been deposited at this time (*see* Calon, 2001).

Stop 1.2: Plate Cove volcanic belt (Bull Arm Formation) mafic and felsic flows, pyroclastic and epiclastic rocks – Summerville Roadcut. (48.44661, -53.54439)

From Stop 1.1, return to Southern Bay, and turn right onto Highway 235. Continue about 2 km north of the turn-off to Summerville. The stop is the long roadcut on the east side of the road.

> *Vehicles should park on the shoulder near the base of the hill. Be attentive to traffic, as the shoulder is narrow and folks on the driver's side must be aware of traffic travelling north before opening doors!*

This stop was the focus of a B.Sc. (Hons.) thesis by Wilson (2015), who completed a 2 x 3 km bedrock map, including a detailed cross-section through the roadcut, and geochemical, petrographic and geochronological work on rocks in the area. Due to high common lead content in zircon separated from the rhyolite flow near the top of the section, the geochronological sample did not yield an age date. Subsequent geochronological analysis of a yellow-green crystal ash tuff, near the base of the section, yielded an age of 592 ± 2 Ma (Mills *et al.*, 2017; Plate 2). Basaltic rocks from the Plate Cove volcanic belt have a transitional geochemical signature (calc-alkaline to enriched mid ocean ridge basalt (E-MORB) source), and considered along with syn-depositional half-graben structures observed locally within the belt, have been interpreted to indicate an arc-rift tectonic setting that may have initiated shortly after arc volcanism ceased (Mills *et al.*, 2017). The rhyolitic rocks near the top of the roadcut sequence have alkaline chemistry (Wilson, 2015).

Several structural elements may be observed along the roadcut. These include evidence of early (Avalonian) folding. The strong cleavage developed pervasively throughout the pyroclastic and epiclastic rocks is subvertical and north-northeast-striking – typical of the Acadian cleavage developed in the

Plate 2. *Field photograph of the crystal ash tuff layer dated at 592 ± 2 Ma at Summerville roadcut, yellow oval marks sample location and inset shows rock slab.*

Cambrian rocks at Ocean Pond (to the south) and at Keels (to the northeast). On some of these S2 cleavage surfaces, a bedding intersection lineation can clearly be seen to vary from subhorizontal to steeply plunging. This indicates that the bedding here was folded prior to S_2 cleavage development. Micro-kinks of the S_2 cleavage are visible near the top of the section. These may have formed due to gravity loading during D_2 (Acadian) deformation (Mills *et al.*, 2016a).

Stop 1.3: Plate Cove conglomerate and overlying sandstones and siltstones (Rocky Harbour Formation) – Plate Cove roadcut. (48.49872, -53.50171)

From Stop 1.2, continue north ~7 km toward Plate Cove East. Park at St. Patrick's Church on the right hand side of the road. The stop is the roadcut outcrop that extends through the bottom of Plate Cove.

This long roadcut outcrop provides excellent exposures of the Plate Cove conglomerate, which forms a thick and coarse clastic wedge above the Plate Cove volcanic belt, at the base of the Rocky Harbour Formation. The conglomerate is strongly foliated at the southern end of the roadcut, but the strain state evidently decreases to the northeast. Detailed bedding and cleavage measurements along the roadcut allow demarcation of the axial trace of pre-S_2 folds (Figure 10). These asymmetric folds are interpreted to be Avalonian in age (Mills *et al.*, 2016a).

Conglomeratic rocks of the Plate Cove facies are commonly thick bedded, poorly to moderately sorted, and only locally contain sandy lenses or grading that allow bedding to be measured. The conglomerates fine upward, and the transition to coarse-grained, immature sandstone interbedded with maroon mudstone and lenses is gradational. These sandstones were included in the upper Monk Bay–Hodderville facies of O'Brien and King (2002, 2004, 2005), but were re-assigned to a new facies, the King's Cove Lighthouse facies, by Normore (2010). The depositional environment for the facies is interpreted to be a meandering fluvial system (Normore, 2010).

Stop 1.4: Redbeds and "grey beds" of the Crown Hill Formation at Tickle Cove

From Stop 1.3, continue north on Highway 235 and turn left to head north toward Open Hall, Redcliff and Tickle Cove. This is a very pretty road, with lovely vistas and many red outcrops. Continue through

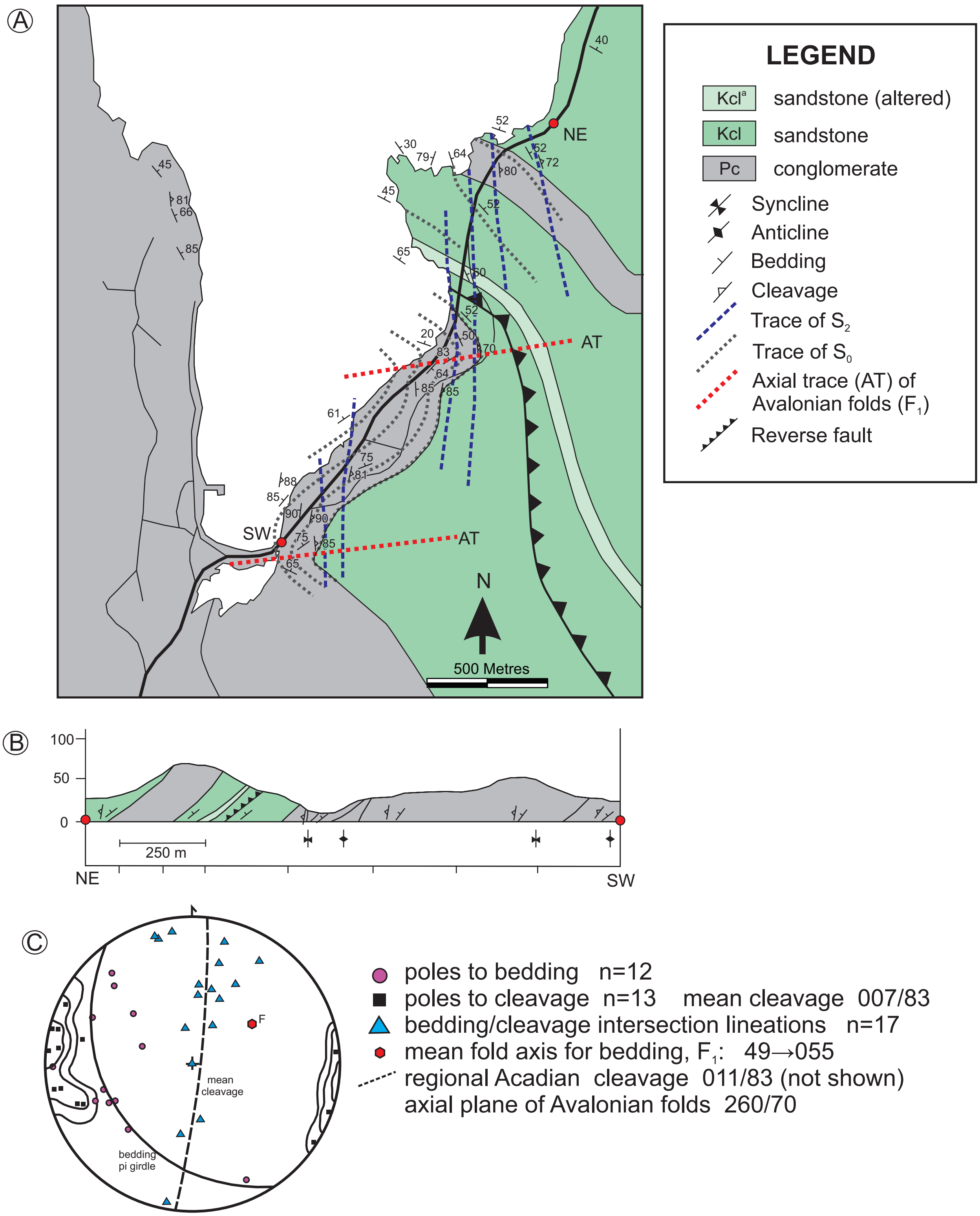

Figure 10. *A) Map of the Plate Cove area showing the trace of bedding folded by Avalonian deformation and clearly overprinted by a north-striking Acadian cleavage resulting in highly variable bedding/cleavage intersection lineations; B) Schematic cross-section along Highway 235 at Plate Cove East; C) Stereoplot for structural elements in the Plate Cove area, including: bedding, Acadian cleavage, bedding/cleavage intersection lineations, and calculated Avalonian fold axis (from Mills* et al., *2016a).*

the village of Tickle Cove and park at the end of the road, about 8 km from Route 235, and a few hundred metres past the end of the pavement. Walk down to the shore, and go north for 50 to 100 m; the rusty outcrops should be obvious!

The rocks exposed enroute to Tickle Cove mostly form part of the Red Cliff facies of the Crown Hill Formation, which consists of red siltstone, argillite and sandstone, interbedded with conglomerate. However, the Tickle Cove showing is hosted by a reduced unit of grey, laminated siltstone and sandstone that is correlated with the Blue Point Horizon, site of the most significant copper showing outlined to date in this area (Figure 6; Lane, 2004). The reduced unit is up to 20 m thick. The main part of the showing consists of a prominent rusty-weathering bed, and it generally lacks the malachite staining that one would expect in association with copper. The host rock is a fine-grained pyritic siltstone to mudstone, which also contains finely disseminated chalcocite; native copper has also been reported locally. In several areas, pyrite cubes of presumed diagenetic origin have been partially replaced by copper-bearing minerals (Lane, 2004; MODS file 2C/11/Cu006). The best results from surface sampling were 0.89% Cu and 2.1 g/t Ag (Froude, 2001); systematic sampling of the outcrop gave 0.18% Cu over approximately 3 m (Lane, 2004). The same unit extends eastward from here, and another similar showing in an inland location contains 0.35% Cu (Lane, 2004). Follow-up drilling in 2010 included six diamond drill holes, one of which intersected low-grade copper mineralization (0.27% Cu over 10.9 m) at the Blue Point prospect (Hicks, 2011).

The grey argillitic rock that forms the host to most of the mineralization here can be examined closely in loose blocks near the beach; some of these display superb lamination, and possible algal structures.

Stop 1.5: The Arch Hole (optional)

From Stop 1.4, drive back into Tickle Cove and park at the signposts for the Arch Hole. Turn right at the white house with Newfoundland flag (just past the large, presumably abandoned, building) to find designated parking for the Arch Hole trail. The short trail to this interesting feature is easy to find and follow.

The cliffs at the viewpoint are steep and dangerous; stay away from the edge at all times!

The Arch Hole is an interesting example of coastal erosional processes; it is a large sea-arch preserved in a small offshore island. The outcrops consist of red argillite, sandstone and conglomerate of the Red Cliff facies of O'Brien and King (2005). These dip gently towards the east, but contain a strong subvertical cleavage, likely related to the parasitic folds developed on the flanks of the regional anticlinal structure that underlies the western part of the Keels Peninsula (Figure 6). This combination of bedding and cleavage provides many thin slabs that show superb lamination and sedimentary structures; the load structures where conglomerate units overlie siltstone or mudstone are particularly notable, and they locally scour into the underlying bed. On the trail to the Arch Hole, the view over Tickle Cove Harbour reveals the grey, reduced unit that correlates with the mineralized rocks at Stop 1.4. The islands in the harbour form part of a paired anticline and syncline.

It has been suggested by some that Tickle Cove has the largest Arch Hole in Newfoundland, or that it could be termed the Arch Hole capital of Newfoundland. Fortunately, neither of these options has yet been adopted as a tourist slogan. Tickle Cove is also famous as the inspiration for the famous folk song Tickle Cove Pond, which refers to the lake immediately inland from the community.

DAY TWO : NEW BONAVENTURE–FOX ISLAND–CATALINA AREA

Stop 2.1: New Bonaventure–Trinity facies glacial diamictite of the Musgravetown Group (Rocky Harbour Formation). (48.283269, -53.443178)

From Port Rexton, drive west on Route 230 and turn left onto Highway 239 signposted for Trinity and Old Bonaventure. Drive south to New Bonaventure. As you enter the community, veer left to go down the hill toward the wharf. You will pass "Joe's Bar" on your right (which is not really a bar, but was used as part of the set in the filming of The Grand Seduction, filmed in 2012 and released the following year). Continue along the road past Aunt Hattie's Vacation Home. Park along the side of the red storehouse where the road bends, or wherever space permits so as not to impede local traffic. Walk down to the beach and turn right to walk along the shoreline toward the wharf.

The outcrops consist of internally laminated, light green- to tan-weathering, matrix-supported, poorly sorted glacial diamictite containing abundant dropstones (Plate 3). Glacially striated clasts occur locally (Normore, 2011). Recent TIMS dating of tuffaceous rocks below and above the Trinity facies at Old Bonaventure confirm first-order synchroneity with deposition of the well-known, glacigenic, Gaskiers Formation of the Conception Group on the Avalon Peninsula at 580-579 Ma (Pu *et al.*, 2016). Since the Gaskiers and Trinity units yielded slightly different ages, it is possible that the glacial event lasted longer than the depositional duration of either one of these two marker units. Also, the overlying sandstone units (Monk Bay facies and possibly King's Cove Lighthouse facies) may be products of glacial outwash, but this hypothesis remains to be tested.

Stop 2.2: Spaniards Cove – Pebbly sandstone, mudstone and conglomerate of the Monk Bay facies (48.30881, -53.41354)

Head back north, 4 km, along Highway 239 and stop at the small sign that marks the trail to Spaniards Cove. Park on the shoulder and walk down the trail, veering left toward the bottom of the trail. The trail is wet in places due to small seasonal creeks and run-off. Veer to the left to see small cliff exposures (48.307612, -53.410079).

The lowermost beds in this area are thick, coarse-grained sandstones that commonly coarsen up to granule to pebble conglomerate topped by mud drapes. These are overlain by thinly interbedded maroon mudstone and sandstone that preserves disrupted and slumped beds, and minor outsized clasts. These characteristics are consistent with either deposition on an unstable slope, ice-rafting or both. The mudstone-sandstone lithofacies is overlain by a distinctive, pale yellowish-green, very fine-grained unit that is ~3 m thick. A markedly similar unit commonly occurs above the glacigenic Trinity facies in the Trinity Pond area, where it is typically 30-50 cm in thickness, and also at Brook Point (Stop 3.4), where it has been designated as the marker unit between underlying shallow-marine rocks of the Rocky Harbour Formation and overlying terrestrial red beds of the Crown Hill Formation. Laminations within the "Brook Point-like" horizon are readily evident locally, but are commonly only vaguely discernible to absent. The unit appears to be altered, but whether by early diagenetic processes or by post-depositional (hydrothermal?) processes remains unclear.

Plate 3. *A) Boulder-sized dropstone clast within the Trinity facies at New Bonaventure, showing penetration of dropstone through underlying laminations; B) Purple matrix-supported well-rounded, poorly sorted diamictite of Trinity facies at Northwest Trinity Arm; C) Photomicrograph of igneous dropstone penetrating thin sandstone laminations; D) Two distinct striation orientations on a clast recovered from the Trinity facies from Northwest Pond Resource Road (west of Trinity); E) Dropstones in Trinity facies at New Bonaventure. Photographs are from Normore (2011).*

Some of the lithofacies at Spaniards Cove may be glacigenic and correlative to the Trinity facies (Plate 4). However, the laminated diamictite lithofacies with abundant dropstones is absent here, making interpretation and correlation somewhat tenuous. The presence of striated clasts, if discovered here, would provide excellent evidence in support of a glacial depositional setting – keep your eyes peeled and notify the trip leader if you think you've found a striated clast!

Plate 4. *Outsized, extra-basinal, rhyolite clast in disrupted shale-sandstone facies at Spaniards Cove.*

Stops 2.3 West Champney's – peperite, granite sill, and siltstone above thick-bedded sandstone (48.38966, -53.31887)

Return to Route 230 and turn right toward Bonavista/Catalina. After about 4 km, take a right into Champney's West. Continue on for about 750 m and park on the right side of road, close to the white house. Take the quad trail toward coast and examine outcrop (48.388297, -53.320254).

The coastal rocks here include thick-bedded, coarse-grained sandstone with pebble lag at the top, a transitional unit of interbedded and/or flaser-bedded sandstone and siltstone, green-grey siltstone and peperite. A peperite is a mixed rock developed where a felsic extrusion or near-surface intrusion has interacted with unconsolidated, wet, sediment (Plate 5). The dark glassy material represents quickly chilled material, and the lack of vesiculation indicates significant water depth (Kerr, 2008).

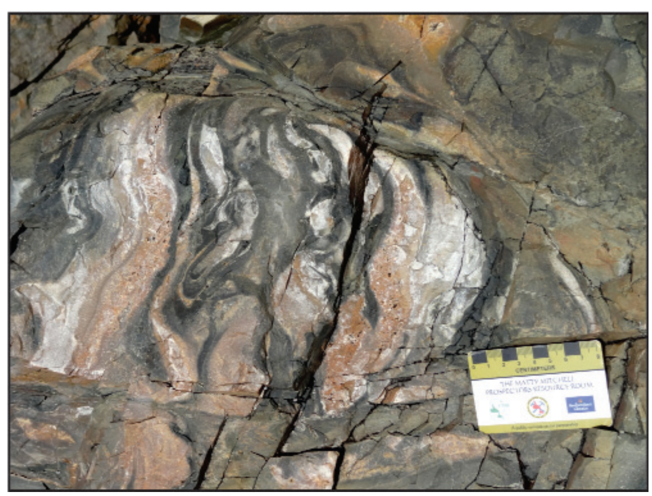

Plate 5. *Peperite from West Champney's area.*

The sill beneath the peperite has a preliminary age of 576 ± 1.7 Ma (L. Normore and G. Dunning, unpublished data 2012).

The sequence is repeated to the immediate south, likely due to north-directed thrusting.

Stop 2.4: Fox Island North Area – folds and thrust faults in Ediacaran mudstone–siltstone (48.387698, -53.309384)

Drive south and across the causeway to Fox Island and park at the white church. As you walk down the hill, note the subtle folds in the exposure on the north side of the road here. The folds here range from open to tight and overturned and plunge shallowly to the south-southwest and northeast (Figure 11). Bedding-parallel shearing and small thrusts present here are consistent with intraformational folding and thrusting in an overall west-directed, contractional regime (Mills *et al.*, 2016a).

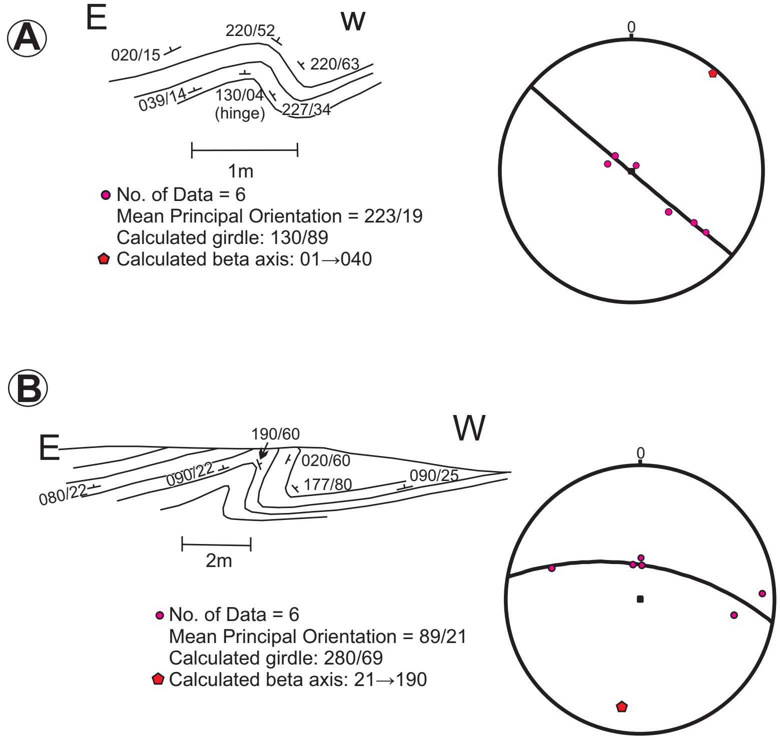

Figure 11. *Sketches and lower hemisphere, equal area plots illustrating fold geometry along roadside, northern Fox Island. A) Asymmetric open fold with calculated fold axis of 1° toward 040°; B) asymmetric, overturned, tight fold with calculated fold axis plunging 21° toward 190°. The sketches are viewed to the south and show measured bedding geometry along the folds (from Mills* et al.*, 2016a).*

Continue farther west until you reach the causeway, and descend down the cliff to view rocks to the immediate south (48.387683, -53.314805). A spectacularly exposed thrust fault displays hanging-wall and footwall-ramp geometry (Plate 6). South-dipping siltstone and mudstone with local convolute beds is folded and thrust-faulted to the north above siltstone. Similar rocks occur in both the hanging wall and footwall, indicating only minor stratigraphic separation.

Stop 2.5a: Fox Island: pyrite and jasper occurrence (48.37982, -53.30049)

Continue south on Fox Island for another 1.3 km until you reach the small parking area for the Fox Island walking trail. Ensure that vehicles are parked off the main road, so as not to impede local traffic. Walk west-southwest along the trail until you reach the shoreline, then carry on to the north to the first cliff exposure (48.376459, -53.303408).

Notice the bright red fragments that occur locally throughout the rock. This is jasper, and appears to occur in disrupted veins here. Jasper is not a mineral, but a mixture of microcrystalline quartz and impurities of other mineral compositions. Jasper typically occurs in veins and cracks, as it does here, but is per-

Plate 6. *North-directed thrust fault at northwest tip of Fox Island.*

haps more common in volcanic rocks. The sandstone adjacent to the disrupted and veined rocks also locally contains pyrite cubes up to 2 cm. These occasionally get physically separated from the rock and several near-perfect cubes have been found in the vicinity.

Stop 2.5b: Fox Island: ramp anticline

Walk ~300 m south along the shoreline toward the high cliffs. Continue past the red shales with common thin, grey, reduced horizons until you pass up-section into grey laminated siltstone. At the top of the cliff, notice the ramp anticline with a small leading syncline. The thrust surface may be difficult to recognize, and is illustrated in Plate 7. The ramp anticline plunges ~25° to the west-southwest and, while this orientation is consistent with Acadian deformation structures, the thrust faults at Fox Island are folded and may be older structures that have been re-oriented during Acadian deformation. The imbricate thrust stack in the Fox Island area shows overall north-directed transport, likely overprinted by Acadian deformation.

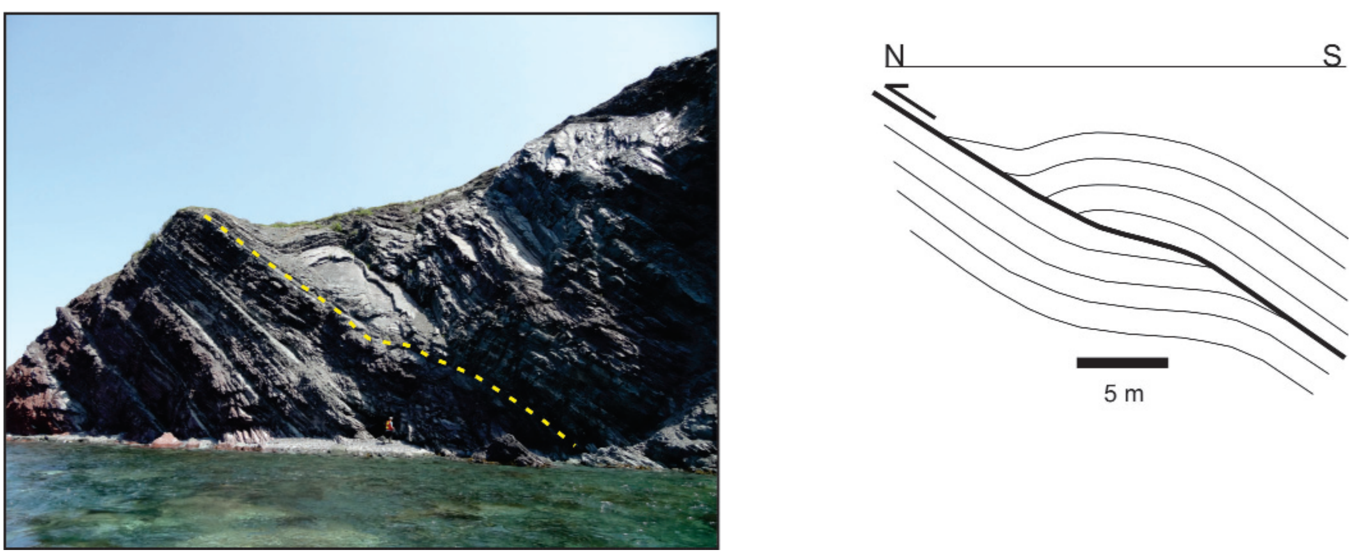

Plate 7. *Ramp anticline plunging to the southwest (view northeast; west coast of Fox Island).*

Stop 2.5c: Fox Island – *Aspidella* holdfast and site of 566 Ma tuff (optional)

Head east along the path south of the small pond and north of the cliff exposures of the last Stop. Continue ~50 m south of the red shales. A single *Aspidella* holdfast has been identified on the east side of Fox Island (Plate 8), near the site of an unpublished TIMS age of 566 ± 1.5 Ma from a tuff within the siltstone succession (L. Normore and G. Dunning, Unpublished data, 2012).

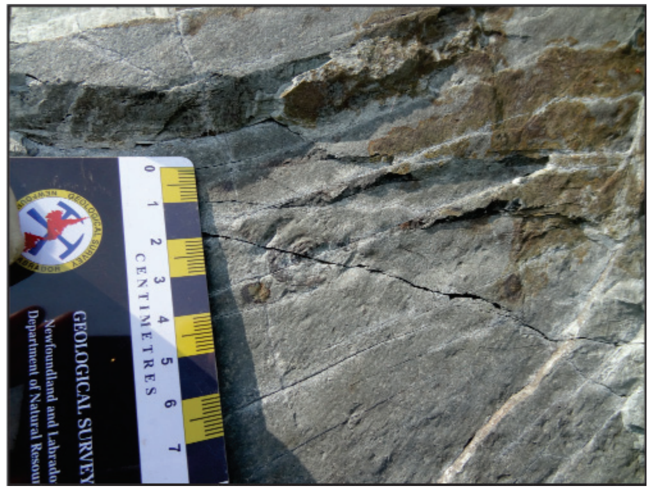

Plate 8. Aspidella *holdfast from Fox Island.*

Both the *Aspidella* fossil and the 566 Ma tuff are somewhat discreet and difficult to locate. The tuff horizon is <10 cm thick and similar in colour (grey) to the siltstones with which it is interbedded. It is slightly paler grey and more crumbly and fissile than the siltstone. The tuff horizon is folded and an upright antiform is visible, but the overall structural geology here is difficult to unravel owing to the obliquity of bedding with respect to the exposed section (a cross-sectional view is preferred!).

Stop 2.6a: Catalina area – Ediacaran fossils at Sandy Point (48.51383, -53.06512)

From Fox Island, return to Route 230 and drive north to Catalina. Continue through the town of Catalina, and then turn right at the Western Petroleum gas station onto Main Street. Turn left onto East Point Road and continue around the northern side of the harbour (there was a shortcut across a small wooden bridge, but this has fallen in disrepair and was closed on our last visit (2017) to Catalina). Follow the road south towards Goodland Point, and turn right on Sandy Point Road to the shore. Walk a short distance north to examine outcrops on the shore, located near the remains of two wharves. The outcrops are best viewed at low tide, and under morning or evening light.

> *Note that the tide-washed outcrops are very smooth and may be slippery. The fossils are protected by legislation and it is illegal to damage them or attempt any collection. Hammering is not permitted!*

The outcrops here lie at the base of the Murphy's Cove Member of the Mistaken Point Formation. The fossil assemblage here is diverse, and it is easy to see a variety of forms. There are numerous specimens of *Aspidella* here, as well as several speciments of the genus *Hiemalora.* The holotype of the new genus Hadrynichorde (Hofmann *et al.*, 2008) is also present at this Stop.

Stop 2.6b: Catalina; Shepherd Cove area – Subtle deformation features of Avalonian and Acadian events

From Stop 2.6a, walk east to Shepherd Cove. These outcrops of well-laminated grey to green siltstones are the oldest rocks exposed in this part of the Bonavista Peninsula, and are assigned to the Drook Formation of the Conception Group, which underlies the fossiliferous Mistaken Point Formation. At this spot, the beds dip about 10° to the west, but they are essentially horizontal to the east of here, and then dip in the opposite direction at shallow angles. This is the core of the gentle antiformal structure named the Catalina Dome (O'Brien and King, 2005). The Drook Formation is fossiliferous in the type Mistaken Point area, and in fact contains the oldest complex fossil yet known on Earth, which is a large frond-like organism. However, in the Bonavista area, the Drook Formation has not yet yielded fossils.

Two variably developed cleavages are present in the rocks here. The dominant one is north-trending and subvertical and is presumed to be Acadian, as it is well-developed in Cambrian rocks in the Keels and Ocean Pond areas (and therefore cannot be Neoproterozoic). A variably developed spaced cleavage or joint set oriented at 110°/55° may be Avalonian.

Walk north along the cove ~200 m to where the shoreline bends round to the east (48.51457, -53.0638). Look back to the south to see the subtle interference fold pattern between an open, upright Avalonian F_1 syncline and an open, upright Acadian syncline-anticline pair (Plate 9). The folds are all very low amplitude buckle folds, but the Acadian folds can be distinguished based on their axial surfaces which are parallel to the main regional S_2 cleavage orientation. The F_1 Avalonian fold is a doubly plunging syncline having shallow west-southwest–east-northeast axes and is refolded by open and upright, gently south-southwest-plunging F_2 folds.

Further evidence of the style of the early folds is evident <50 m farther north where a steeply inclined, asymmetric, shallowly southwest-plunging anticline occurs (Plate 10). The forelimb dips moderately to steeply to the northwest, whereas the backlimb dips gently to the southeast and is associated with gentle, open, mesoscopic folds. Minor parasitic folds also occur locally on the forelimb of the F_1 fold. At the hinge of the Avalonian anticline, a weakly developed cleavage obliquely transects the core of the fold (Plate 10). Since the orientation of the cleavage there is broadly consistent with the orientation of the regional S_2 cleavage, it is interpreted as Acadian S_2 cleavage overprinting a pre-existing F_1 anticline, rather than as an early, transecting S_1 cleavage.

Plate 9. *Interference fold pattern at Catalina dome. View to the south. (Plate 11 from Mills* et al.*, 2016a.)*

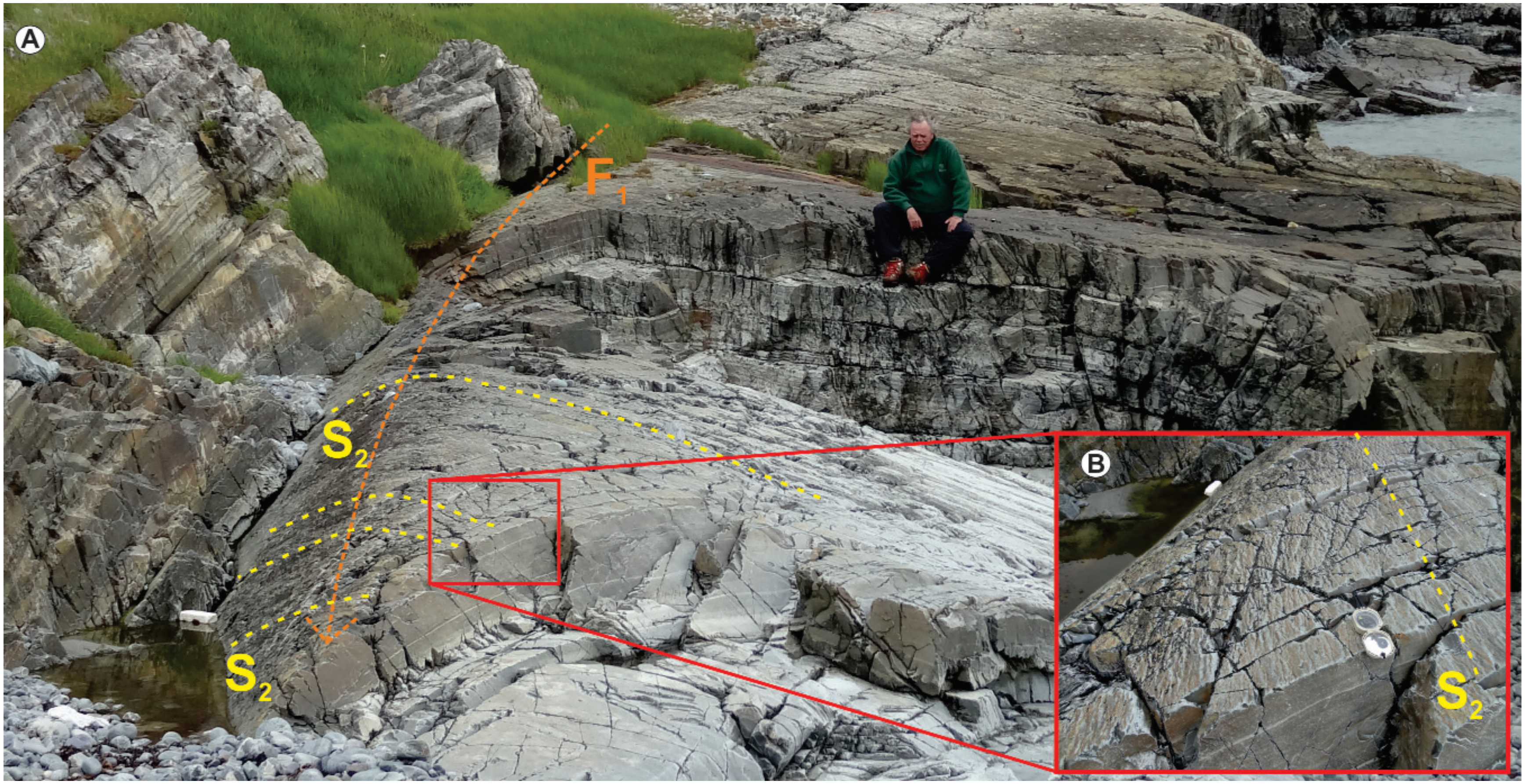

Plate 10. *A) Gently southwest-plunging, asymmetric Avalonian anticline (F_1) overprinted by steep Acadian cleavage (S_2; 035/56). Note steep northwest forelimb, shallow southeast backlimb. View to the east-northeast; B) Close-up of weakly developed Acadian S_2 cleavage (seen mainly as bedding – S_2 cleavage intersection lineations) overprinting the gently southwest-plunging, Avalonian anticline. View to northeast. UTM coordinates: 347700 m W, 5375410 m N; NAD27, Zone 22 (from Mills* et al.*, 2016a).*

Stop 2.7: Lance Cove; Trace of the Spillars Cove–English Harbour Fault Zone (48.66483 N; -53.08454 W)

From Stop 2.6, return to Route 230 through Catalina, and drive north towards Bonavista for about 16 km. There are two routes; the quicker follows Route 230 directly to the outskirts of Bonavista, but the scenic diversion through Elliston is worth considering. From Bonavista, take the right turn for Spillars Cove and Elliston, and then take the left turn that veers towards the community of Spillars Cove. Turn left again towards Lance Cove and Dungeon Provincial Park. Follow the road for about 800 m to stop at Lance Cove.

The embankment leading to the cove is steep but a small trail can be used for safest access. The trail may be wet and slippery so exercise caution on your descent!

Spillars Cove is a zone of structural complexity related to the Spillars Cove–English Harbour Fault Zone, which is an important regional structure. The rocks on the east side of the cove are amongst the youngest in this area, and include possible slivers of St. John's Group rocks overlain by sandstones of the Gibbett Hill Formation (Signal Hill Group). The west side of the fault zone is underlain by unseparated rocks of the Musgravetown Group. The effects of strong brittle deformation are clearly visible in these outcrops.

Slump folding is common in the grey, thinly laminated siltstone and mudstone of the St. John's Group. Tops indicators give younging to the east in most beds, although west-younging beds are also present in the cove, indicating tight to isoclinal folding. One subvertical, north-northeast-trending fault cuts obliquely through subvertical beds (Plate 11), but no slip-direction indicators were found. The lack of unambiguous younging indicators also obstructs the overall structural interpretation at the Lance Cove area. These outcrops remain enigmatic because the brittle deformation and tectonic brecciation obscure their original nature.

Plate 11. *Steeply east-dipping fault truncating bedding in thinly laminated siltstone of St. John's Group at Lance Cove, part of the Spillars Cove–English Harbour fault zone. View to south.*

Stop 2.8: "The Dungeon" (48.66508, -53.08416)

From Stop 2.7, continue 200 m north to Dungeon Provincial Park. The Dungeon itself is easily located by the wooden viewing platform and interpretation signboards.

The cliffs around the Dungeon are steep and should not be approached too closely. If you were to fall, this particular Dungeon would be very difficult to get escape from.

The Dungeon is a collapsed sea cave developed in steeply dipping grey sandstones and siltstones, presumed to be part of the Musgravetown Group (Rocky Harbour Formation). It now forms a large cavity with sheer walls and a small beach, connected to the open ocean by two archways. The beds dip steeply towards the water, although there is some local variation in attitude. The coastal outcrops above the arches are easily accessible, and have a well-developed cleavage developed essentially at right angles to strike; this is perhaps the reason for the preferential erosion of this zone. The Dungeon also appears to be controlled by a high-angle fault zone that is clearly visible in its internal cliffs, and runs essentially north-south, parallel to the coast and the Spillars Cove Fault Zone. The fault is marked by intense fracturing and some rusting, and there are signs that bedding is locally deflected against it. Gently-dipping white quartz veins also seem to record crenulation possibly related to motions on this fault.

In a wider sense, the Dungeon can be viewed as sea-stacks in the process of formation. The surrounding coastline of Lance Cove contains many examples of sea-stacks that attest to the operation of this process over long periods of time.

Stop 2.9: Cape Bonavista sandstone and their "strange" cross-stratification (48.67603, -53.08831)

From Stop 2.8, continue northward on the dirt road ~800 m and take the smaller dirt road that veers off to the right. Follow the road ~350 m and park off the road to avoid hampering local or tourist traffic.

Rocks north of Bonavista were assigned to the Cape Bonavista facies (O'Brien and King, 2002, 2004, 2005; Normore, 2010). The lithofacies consists primarily of streaky, dark green-grey and light pink-grey, medium to thick bedded, cross-stratified, medium-grained to pebbly sandstone that may be diagenetically altered locally (Normore, 2010). Swaley to hummocky cross-stratification is common and quite striking in these rocks, as overlying beds scour sharply and deeply into underlying beds (Plate 12). Dark-grey to black feldspathic sandstone commonly containing detrital magnetite along foresets, and locally containing lonestones of granite and porphyritic felsic volcanic rock overlies the gravelly sandstone to the east. Rarely, the base of the black sandstone is marked by a thin, basal pebble lag containing red, feldspar-porphyritic volcanic clasts. These rocks display a unique cross-stratification marked by common, erosive surfaces that scour deeply into the underlying strata.

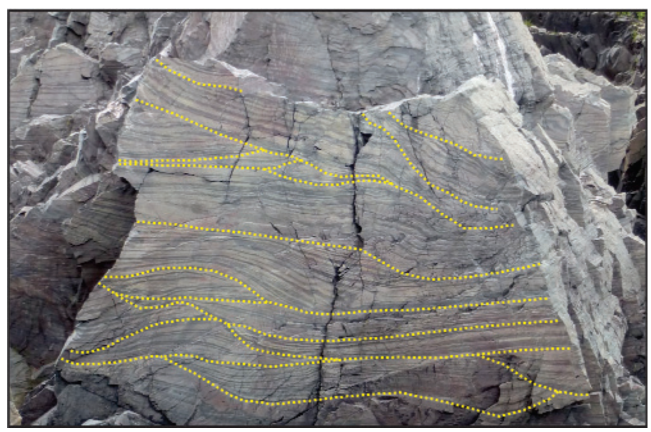

Plate 12. *Peculiar crossbedding in sandstone of the Cape Bonavista facies. Note the depth and short wavelength associated with the scours.*

DAY THREE: BONAVISTA TO KINGS COVE

Stop 3.1: Interbedded mudstone and sandstone of the Middle Amherst Cove–Wolf Cove facies at Upper Amherst Cove

From Bonavista, drive south on Route 235 for about 15 km, then turn right into Upper Amherst Cove (home of the famous Bonavista Social Club). Drive down the hill toward the bay. The stop includes coastal exposure from the north side of the remains of a small wharf to the south side. Park along the side of the road, but leave ample space for local traffic.

This lithofacies comprises thick-bedded, rippled and slumped grey sandstone and thinly interbedded to lenticular-bedded dark grey siltstone to mudstone and sandstone. The unit is commonly slumped and convolute, and contains abundant water-escape structures including pervasive sandstone dykes. Wave-induced ripples and combined ripples are also common in this lithofacies. Subdued hummocky cross-stratification is common in the lower part of the sequence. The upper sequence exhibits major slumping, convolute bedding, synsedimentary under-thrusting and several types of ripple marks including wave-induced and combined flow ripples.

Near the south end of the coastal exposure, locate the "giant pincer-fold" (Plate 13), a large-scale slump fold created as the semi-consolidated sand and silt was squeezed up and out laterally above underlying beds. This structure indicates intense synsedimentary disruption. Westward thickening of beds further indicates westward flattening of the paleoslope. Locally, the geometry of synsedimentary recumbent and convolute folds is consistent with a paleoslope dipping to the west and northwest. Many of these features can be found along the shoreline here at Wolf Cove.

Plate 13. *Giant "pincer" slump-fold in shale-sandstone of the Middle Amherst Cove facies.*

Stop 3.2: Monk Bay facies pebbly sandstone, mudstone and conglomerate at Knights Cove

Return to Highway 235 and continue south for 12 km to Knights Cove. Take the first right turn at Knights Cove (just after the light brown house) and drive to the end of the road. Park near the last house on the road. Walk north along the ATV trail until you approach the wooded area, then descend down the bank onto the rocky shoreline.

Note that the bank is made of loose gravel and is unstable; take care going down!

The rocks exposed here comprise mainly pebbly sandstone of the Monk Bay–Hodderville facies (O'Brien and Knight, 2002). The sandstone contains abundant, rounded salmon-pink pebbles, similar to those seen at Spaniards Cove (Stop 2.2). The foresets are accentuated by the presence of detrital magnetite and indicate paleoflow to the north and northeast. The rocks dip shallowly to the west or northwest, so walk back to the south to see the underlying beds. Note the presence of mega ripples draped by a thin veneer of mudstone. The mudstone is commonly eroded off the crests of the ripples and is thicker within the troughs. Thicker units of mudstone are also present and locally resemble the pistachio coloured mudstone unit at Spaniards Cove. Note the convolute inclusions, locally, within the mudstone. Some of these are concave-up, and appear to have "fallen" into the mudstone from above. Some inclusions have voids where carbonate may have weathered out or dissolved. Similar rocks occur above the Trinity facies diamictite, and suggest the possibility that a poorly developed cap carbonate may have been destroyed by diagenetic (or subsequent?) alteration.

Stop 3.3: Green-grey-maroon-red shales at Stock Cove – marine regression followed by transgression?

Return to Route 235 and continue west for 1.2 km to Stock Cove. Take the dirt road that leads to the remains of an old wharf. The Stop includes the coastal outcrops to the left (west side) of the former wharf.

The distinct lithofacies here is the first (lowest) occurrence of redbeds within the Musgravetown Group on the Bonavista Peninsula. The shale beds here transition gradationally from grey-green to maroon to brick-red. Sandstone interbedded with the brick-red shale forms dykes that locally disrupt the red shale. The vibrant red colour can be interpreted to suggest prolonged subaerial exposure (Normore, 2010) and may reflect a significant marine regression. These rocks are reminiscent of the grey to red shales at Fox Island (Stop 2.5b) and may, therefore, be correlative to the Mistaken Point Formation; this correlation, however, remains to be proven.

White-weathering granular conglomerate appears to form a disconformable surface within the red shale unit and the sandstone dykes have been interpreted to infill desiccation cracks (Normore, 2010). Farther west along the shoreline here, the shale is overlain by a thick bed of brown-weathering, coarse-grained sandstone which, in turn, is overlain by grey-green, wavy-laminated to lenticular sandstone and shale with a cobble to pebble lag at its base (Plate 14). This transition appears to mark a return to anoxic (possibly marine) conditions and would seem to suggest that the marine regression was relatively short-lived prior to a subsequent transgression. [However, the interpretation is somewhat tenuous due to gaps in the exposed section and evidence of faulting in the area].

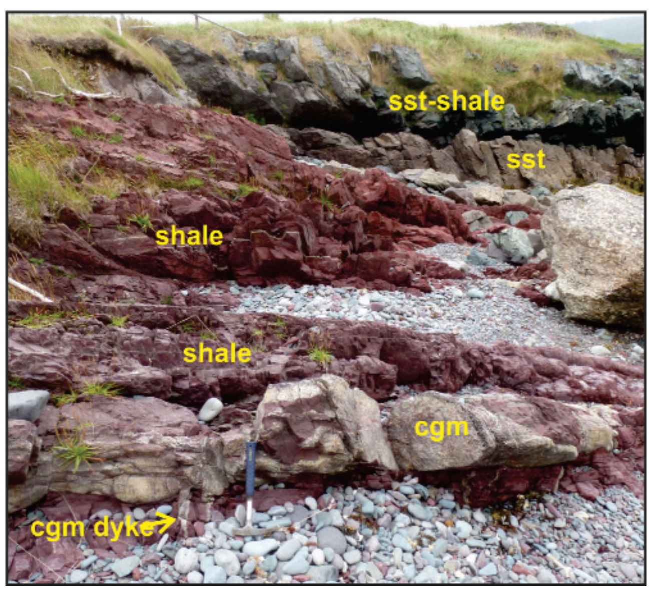

Plate 14. *Maroon to red shale having lenticles and dykes of conglomerate (cgm), overlain by structureless brown sandstone, in turn overlain by sandstone-shale facies having distinct pebble lag at its base; possible unconformities above and below brown sandstone. View west at Stock Cove.*

Stop 3.4: Kings Cove Lighthouse Section (Brook Point) (48.56968, -53.33208)

From Stop 3.3, continue northward on Route 235 for 4 km to Kings Cove. Kings Cove is one of the more picturesque towns in the field trip area, and appears to have retained a larger number of old buildings than many communities. In the town, take the Top Road for 500 m and park at the church. The trail to the lighthouse is sign-posted. From here, hike northeastward along the well-defined trail, which is an old road, through the meadows, and then through coastal woodlands for about 1 km, to the Kings Cove lighthouse. The meadows are known as "Pat Murphy's meadows", and were the inspiration for the famous folk song of that name. From the lighthouse, continue along the loop for about 600 m and follow the second trail on the right to Brook Point. A sign along the trail indicates where the "lookout" is and leads to the Brook Point outcrop (48.579600, -53.325361).

> *Note that the cliffs are locally steep here, and it is dangerous to approach them too closely; also, do not venture into any areas where the rocks are wet or seaweed-covered – keep a safe distance from the water at all times! The southeast edge of the bedding surface at the first part of the stop is formed by a vertical drop to deep and rough water, so do not approach it too closely!*

The trail to the lighthouse is mostly within rocks of the upper part of the Rocky Harbour Formation (Kings Cove North facies of O'Brien and King, 2005); several small outcrops reveal these rocks enroute. Vertically below the lighthouse, these grey to greenish-grey very fine-grained sandstones (which are inaccessible) pass into light grey to buff, medium-grained sandstone interbedded with maroon siltstone. This latter lithofacies, called the King's Cove Lighthouse facies, was separated from the King's Cove North facies and the two are apparently interbedded at a regional scale (Normore, 2010). This location is known locally as Brook Point, and is the type area for the Brook Point Facies of O'Brien and King (2005), which here forms the lowermost portion of the Crown Hill Formation. There is no mineralization of note, but there are superb sedimentary structures and some enigmatic rock types. It is also a very scenic locality that makes a good spot for lunch.

Descend with care along the prominent bedding surface that leads towards the water; the surface is rough and provides good traction. Be careful of the drop on the water side (south side) of this surface. The lowermost bedding surface here faces a spectacular vertical cliff showing well-developed cyclic bedding. The grey rocks of the uppermost Rocky Harbour Formation can be seen below, close to the bottom of the cliff. The basal Crown Hill Formation is dominated by arkosic sandstone and conglomerate, typically of red to purple colour, interbedded with white to pale yellow fine-grained sandstone and siltstone. Sedimentary structures are abundant in these rocks, and the finer-grained rocks have a finely-banded to locally contorted appearance suggestive of algal laminations. Some units appear blotchy and are perhaps bioturbated (Kerr, 2008).

From this surface, return to the bedding surface that leads to the lighthouse, and continue up section. There is a zone of prominent low-angle quartz veining, which is followed by a sequence of sandstones and fine-grained conglomerates that show well-developed crossbedding and some spectacular sand-dyke structures generated by loading at the bases of conglomeratic units. Beyond here, it is more difficult to proceed up section, and it may be necessary to move inland towards the trees, and then return to the shore on the next prominent bedding surface. The next part of the section shows some distinctive, well-laminated, yellow-green units that are of controversial origin. These have been suggested to represent rocks that were originally dolomitic sandstones developed in a tidal-flat (sabhka) environment where algal activity was important (Thorson, 2004; Lane, 2004). However, these units also have the general appearance of tuffaceous sandstones and siltstones seen elsewhere in the Avalon Zone (O'Brien and King, 2005), and may thus be of volcanogenic origin. These yellow-green units are reported to be anomalous in copper (O'Brien and King, 2004a; Lane, 2004). Similar cryptocrystalline rocks commonly overlie the Trinity facies along Highway 230, near Trinity Pond, leading to a possible alternative, glacigenic origin for the rock.

It is possible to proceed farther up section from these outcrops, but it requires climbing some rather steep rock faces, and is therefore not advised. The overlying rocks are mostly red sandstones of the Duntara Harbour Facies (O'Brien and King, 2005). The Brook Point Facies, as seen at this stop, appears to be laterally discontinuous, as it is not observed on the other side of the Keels Peninsula (O'Brien and King, 2004a; Lane, 2004).

Stop 3.5: Uppermost section of the Crown Hill Formation (optional)

From Stop 3.4, continue northward to Keels. The road winds through the hills and then descends a steep grade above the ocean towards the community, passing some prominent red outcrops which form this stop. There is only limited parking space here, but there is virtually no traffic.

> *The roadcut outcrops are high and steep; be aware that debris could fall, and avoid any overhanging sections.*

There is an excellent view northwestwards across the synclinal structure of the Keels area; the prominent white cliffs in the distance represent the Random Formation (on the far side of the syncline; these are bedding planes dipping towards you), and the red and green slates at the quarry are the Cambrian sedimentary rocks. These outcrops are red conglomerates that form the upper section of the Crown Hill Formation, which eventually passes up into the Random Formation (Stop 3.6). The conglomerates contain pebbles of felsic volcanic rocks, white to grey quartz, and other rock types, including orange felsite and porphyry. There are well-developed but discontinuous red argillitic lenses, and this material is also present as prominent and locally spectacular rip-up clasts.

The lower section of this long outcrop appears white, because it is riddled with quartz veins. However, the amount of quartz is deceptive because the outcrop surfaces have developed along the veins themselves. The veining in this location, and at Stop 3.6, may be related to some faults that in part define the Crown Hill–Random formational contact in this area, although it is considered to be an originally conformable stratigraphic transition.

Stop 3.6: Random Formation quartzites

From Stop 3.5, continue down the hill past the beach, and turn right on the road to the slate quarry. Park at the turnoff (there is plenty of space) and descend to the outcrops on the northwest side of this small but beautiful sandy beach. The second part of the stop, if time permits, is located on the southeast side of the beach, about 2 minutes walk from here.

The outcrops by the beach here are white to pale-yellow quartzite, with some interbedded conglomerates dominated by granule to pebble quartz clasts. They display superb cross-bedding and lamination, including herringbone structures indicative of frequent current reversals. The rocks here are closely similar to some of those on the other side of the beach, but generally lack any red, argillitic interbeds; however, there is one small purplish siltstone unit amongst the quartzite. On the other side of the beach, there appears to be a downsection transition from pure quartzite into reddish and purple sandstone and conglomerate, which again display well-developed cross-lamination. It is not entirely clear how much of this apparent contrast is related to the fact that these outcrops are not as well wave-washed, but the rocks here contain several red argillitic interbeds, which are more characteristic of the Crown Hill Formation. Thus, although there is a clear contrast in sedimentary environment between the two formations, the shift from terrestrial to shallow marine conditions was not a sudden event, but a progression over time.

Stop 3.7: Cambrian slates, redox boundaries and minor copper mineralization

From Stop 3.6, continue to the slate quarry. There is a locked gate, and it will likely be necessary to walk the last few hundred metres to the site.

> *This is an abandoned quarry operation and there are numerous steep drops on the edges of the pits, which are not marked or protected. Equipment and other industrial debris (e.g., cables and wires) also present specific hazards. There is a hazard from falling debris beneath some of these faces, and there is deep water in at least one of the pits. Parts of the stop also lie close to the ocean, from which there is a wave hazard. Please be cautious everywhere in this area!*

This quarry was developed in the 1990s to exploit attractive but not particularly high quality red and green slates developed within Cambrian rocks on the southeast flank of the Keels syncline, where there is a well-developed subvertical axial planar cleavage. The red and green here reflects oxidation–reduction effects in the original mudstones and shales; some of these were likely syngenetic or diagenetic, but much of the colour variation has been superimposed and transgresses primary bedding. There is also some minor sulphide mineralization, which is reported to be locally Cu-enriched (Lane, 2004).

The large face adjacent to the flooded pit illustrates the attitude of primary bedding, which is here defined by units that contain prominent grey, nodular reduction zones, some of which likely contain minor carbonate. These dip at about 45o to the northwest. The reduction zones can be seen in many of the large blocks littered around the pit edge, and they have very sharp boundaries against their red host rock. At the north end of the quarry, in the area of the small metal building that looks like a privy but was perhaps more likely an explosives store, the boundary between the predominantly red unit of the quarry and adjacent green slates is well exposed. This is a high angle boundary that obviously truncates the bedding in adjacent outcrops, and is also discordant to the well-developed cleavage. The exact timing of the reduction (or oxidation?) process is not clear, but it is obviously post-depositional.

Sulphide mineralization occurs in the northwest wall of the quarry site at several spots, where it is in general terms associated with another redox front transition into a grey green, poorly-cleaved unit. Disseminated pyrite is present in the latter rocks, and is in most cases associated with fractures, but there are also nodule and vein-like pods of massive pyrite. There is no visible malachite staining in any of these zones, but samples from the quarry area reportedly contained up to 0.5% Cu, although such values are likely not representative. It has been argued that the presence of this Cu-rich mineralization in the Cambrian indicates that potentially more significant SSC-type mineralization in the underlying Crown Hill Formation (*e.g.*, Blue Point, Tickle Cove) may have formed during the Cambrian (Lane, 2004).

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