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NEW GEOCHRONOLOGICAL CONSTRAINTS ON THE CONNECTING POINT GROUP, BONAVISTA PENINSULA, AVALON ZONE, NEWFOUNDLAND

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ABSTRACT

The Connecting Point Group on the Bonavista Peninsula formed in one of the oldest marine basins known in the Avalon Terrane of Newfoundland. It comprises mainly resedimented pyroclastic and epiclastic rocks disposed in two turbidite-dominated sequences, separated by a regionally significant olistostrome. New U–Pb geochronological data are presented for zircon from four tuffaceous rock samples and help constrain the timing of depositional and tectonic processes. A 3-m-thick, crystal ash tuff from Eastport yielded an age of 610 ± 2 Ma, and constrains the minimum age of the stratigraphically underlying olistostrome. Approximately 32 km to the south-southeast, near Muddy Pond in the Sweet Bay area, a 1-cm-thick crystal ash tuff yielded a maximum age of 613 ± 3 Ma, which may represent the best estimate of the age of deposition of this tuff horizon. It is likely that this tuff represents the same stratigraphic unit as the tuff from Eastport. Both tuffs are concomitant with an influx of coarse volcanic debris, amalgamated sandstone and slump units, and the intrusion of synsedimentary diabase dykes and small mafic intrusions. This association is consistent with uplift of a volcanic source to the north, and associated seismicity triggering the formation of the regionally extensive olistostrome.

At Southward Head in the Sweet Bay area, possible Bull Arm Formation-equivalent basalts having calc-alkaline-arc chemical signatures are interbedded with volcaniclastic red pebble conglomerate, and overlie tuffaceous and epiclastic rocks of the upper Connecting Point Group with angular unconformity. A lithic tuff, interbedded with thin-bedded, rippled sandstone of the upper Connecting Point Group, occurs below the unconformity, on the west side of Southward Head, and its age is best represented as 605 ± 2.2 Ma. Above the angular unconformity on the east side of Southward Head, a 2-m-thick crystal tuff, interbedded with volcaniclastic red pebble conglomerate, yielded a maximum age of 600 ± 3 Ma. These new geochronological results are interpreted to constrain the timing of uplift manifested by the unconformity at Southward Head to between 605 and 600 Ma.

All three of the samples collected from the Sweet Bay area show significant inheritance, primarily of 630–610 Ma material, consistent with uplift of rocks of the underlying volcanic Love Cove Group, shedding volcanogenic and clastic material into the basin. The unconformity observed at Southward Head is interpreted to have formed in response to local uplift of a volcanic source in a dynamic and evolving, peri-continental, volcanic arc terrane.

INTRODUCTION

The Avalon Zone in Newfoundland records the development of a series of magmatic arcs that were marginal to the Gondwanan Plate in the southern hemisphere from 760 to *ca.* 550 Ma (*e.g.*, O'Brien *et al.*, 1996, 2001; Skipton *et al.*, 2013). Associated with these extensive magmatic arc sequences are marine sedimentary basins; the largest and oldest of which is represented by the Connecting Point Group (Figure 1; Hayes, 1948). These basins are filled with significant volcanic detritus and also discrete thick, m-scale volcanic crystal tuffs, and thin, cm-scale reworked ash layers. The U–Pb geochronological results from zircon from samples of four tuffaceous units are presented herein. These results help better constrain the timing of tectonic processes during the formation of the Connecting Point Group, whose age was only known approximately before this present study. The angular conformity at Southward Head has long been recognized, but the ages of the units above and below it have been interpreted differently by Jenness (1963) and O'Brien (1994).

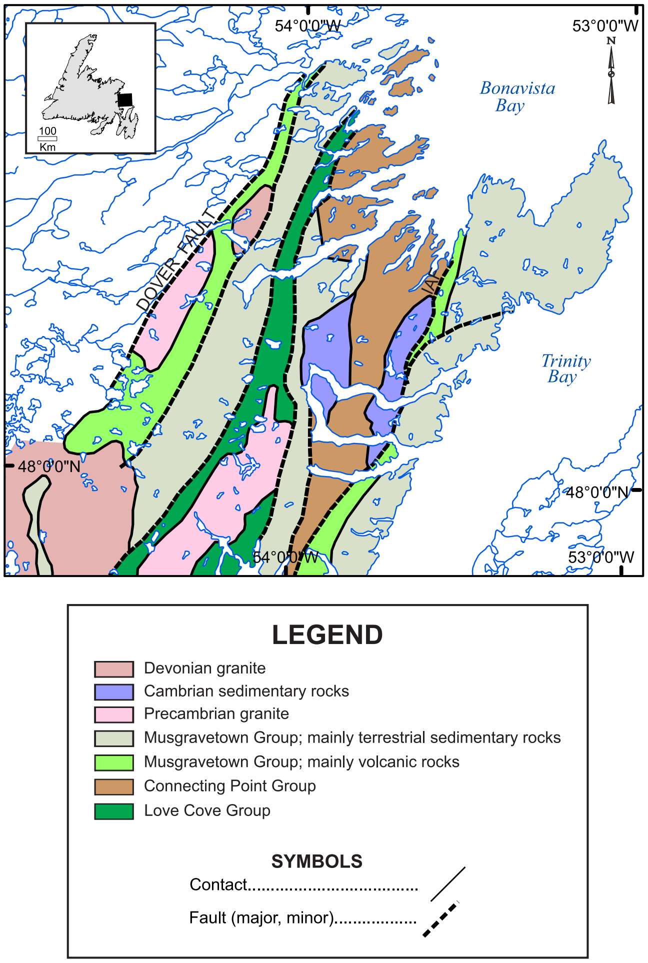

Figure 1. *Generalized geological map of the northwestern Avalon Zone showing the location of the project area (modified from O'Brien, 1993). IAF = Indian Arm fault.*

GEOLOGICAL OVERVIEW

The Connecting Point Group (Hayes, 1948) is a >3-km-thick, marine flysch succession comprising Neoproterozoic epiclastic, turbiditic sandstone, siltstone and shale that extends in the north from Cottel Island, Bonavista Bay, to Little Harbour East, located 140 km to the south in Placentia Bay. Stratigraphically, the Connecting Point Group is conformable above the *ca.* 620 Ma volcanic-rock-dominated Love Cove Group (O'Brien *et al.*, 1989), and is unconformably (Hayes, 1948; Christie, 1950; Jenness, 1963) to conformably (Younce, 1970) overlain by the subaerial volcanic and terrestrial sedimentary rocks of the latest Neoproterozoic Musgravetown Group (Figure 1). In the Sweet Bay area, Cambrian cover rocks unconformably overlie previously deformed rocks of the Connecting Point Group (Mills, 2014). These include shallow-marine rocks of the Random Formation (Smith and Hiscott, 1984) and the shale-dominated platformal succession of the overlying Adeyton and Harcourt groups (Hutchinson, 1962).

The comprehensive description of the Connecting Point Group (*see* Knight and O'Brien, 1988) for the Eastport area (NTS map area 2C/12) is summarized. Bedrock mapping was complemented by detailed measured sections on 2400 m of stratigraphy, including the upper 780 m of the Love Cove Group and the lower 1620 m of the approximately 3500-m-thick Connecting Point Group. The lower Connecting Point Group is divided into six lithostratigraphic units interpreted to have been deposited in two turbiditic basin-fill cycles, separated by a regionally significant olistostrome that likely formed when unconsolidated slope and basin sediment collapsed, and was transported farther into the basin. The lower cycle (Units C1 to C3) comprises upward-coarsening turbidites deposited on a low-efficiency, prograding deep-sea fan, typical of a volcaniclastic apron surrounding a volcanic arc. The upper cycle of coarsening- and thickening-upward sequences of silicified, more proximal turbidites (Unit C6) are inferred to be related to a second generation of submarine fans that overlapped the earlier basin fill. A thick unit of dominantly black shale, thin-bedded siltstone and chert, large- and small-scale slump deposits (Unit C5) and the above mentioned olistostrome (Unit C4) occur between the two basin-fill sequences. Notably, the olistostrome-bearing unit includes colour-banded shale and siltstone interpreted to represent pelagic and hemipelagic slope deposits having a significant terrigenous component, consistent with basin maturation. The authors 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. The deltaic and alluvial facies of the upper Connecting Point Group are not widespread in the Eastport area (NTS map area 2C/12). However, in the Sweet Bay area, they occur on the east side of Cutler Head, south of the Musgravetown Group rocks at the tip, and also west of the Plate Cove volcanic belt, stratigraphically below the Cambrian cover sequence exposed farther south (Figure 1).

In the Sweet Bay area, the Kate Harbour formation (Mills, 2014) includes those rocks that occur stratigraphically above the olistostrome (Unit C4) and black shale (Unit C5) units of Knight and O'Brien (1988). The Kate Harbour formation includes mainly coarse-grained, commonly graded and/or crosslaminated and locally remarkably convolute-bedded sandstone and lesser fine-grained siliciclastic and tuffaceous rocks, and is considered an equivalent to Knight and O'Brien's (1988) upper turbidite cycle (Unit C6). Some of the red rocks that Mills (2014) included within the Kate Harbour formation are re-interpreted as deep-marine, fine-grained sandstone to shale that has been reddened (oxidized?) near fault zones during faulting or uplift (*e.g.*, the coastal section northwest of Southward Head; *see* Figure 5 of Mills *et al.*, *this volume*).

The Muddy Pond formation (Mills, 2014) includes mainly volcaniclastic red pebble conglomerate that occurs, in the Sweet Bay area, above the Connecting Point Group, and below the Paleozoic cover rocks to the south and the Plate Cove volcanic belt to the east (Mills, 2014). The Muddy Pond formation may be stratigraphically equivalent to the Cannings Cove Formation, of the lowermost Musgravetown Group.

Petrographic analysis of the Connecting Point Group in the Eastport area indicates deep-marine resedimentation of pyroclastic and epiclastic detritus. Abundant volcanic detritus ranging from basaltic to rhyolitic, coupled with a minor component of plutonic and low-grade metamorphic detritus indicate derivation from an evolved magmatic arc developed on transitional or continental crust (Dec *et al.*, 1992). The major-element geochemistry of detrital clinopyroxenes indicates that they likely crystallized from magmas of calc-alkaline, and to a lesser extent, tholeiitic affinity, and formed in a mature volcanic-arc setting, remnants of which are preserved as the volcanic Love Cove Group (Dec *et al.*, 1992; *see* Figure 1).

Mills and Sandeman (2015) divided the mafic volcanic rocks in the Sweet Bay area into two petrochemically distinct groups. Evolved, calc-alkaline basalts having well-developed niobium anomalies occur at three prominent headlands in the Sweet Bay area (Headland basalts), whereas basalts of the Plate Cove volcanic belt (Figure 2) have transitional to weakly calc-alkaline geochemical signatures (Mills and Sandeman, 2015). At two of the three headlands, basalt flows and interbedded red conglomerate are fault-juxtaposed with rocks of the Connecting Point Group (Mills, 2014; Mills and Sandeman, 2015). At Southward Head, however, Headland basalt and red pebble conglomerate (possible Cannings Cove Formation) overlie rocks of the Connecting Point Group with angular unconformity (Plate 1). The calc-alkaline arc signatures of the Headland basalts are consistent with formation in a mature continental subduction setting (Mills and Sandeman, 2015), similar to that inferred for volcanic rocks of the Love Cove Group (*see* Figure 1) that occur stratigraphically below the western margin of the submarine Connecting Point Group basin in the Eastport area. In contrast, basalts of the northern Plate Cove volcanic belt (Figure 2) have a chemical signature that is transitional, arc-like to EMORB-like and formed stratigraphically above the eastern margin of the Connecting Point Group basin (Mills and Sandeman, 2015).

Plate 1. *Angular unconformity at Southward Head, Sweet Bay area. Thin-bedded, white-weathering turbiditic sandstone of the Connecting Point Group is overlain by red, thick-bedded, polylithic pebble to cobble conglomerate, likely correlative to the basal Cannings Cove Formation of the Musgravetown Group. View to the northwest. Location is approximately 50 m south of geochronology sample 13AM311B.*

PREVIOUS GEOCHRONOLOGICAL STUDIES

The well-exposed angular unconformity at Southward Head has long been recognized (Jenness, 1963) and was initially interpreted to separate underlying rocks of the Connecting Point Group from basal rocks of the Musgravetown Group (Jenness, 1963). More recently, O'Brien (1994) interpreted the red to green, variegated rocks below the unconformity to be upper Musgravetown Group (Crown Hill Formation), necessitating assignment of the overlying conglomerate and basalt to uppermost Neoproterozoic, or possibly, a considerably younger, Siluro-Devonian unit.

The age of the Connecting Point Group is constrained by the 620 ± 2 Ma Love Cove Group volcanic rocks on which it was deposited (O'Brien *et al.*, 1989). The only direct geochronological constraint on the age of the Connecting Point Group is from a *ca.* 610 Ma tuff in the Eastport area, estimated to occur near the stratigraphic middle of the Group (Figures 1 and 3; G. Dunning, unpublished data, 1990 *in* Dec *et al.*, 1992). Although the stratigraphic position of the tuff is well-constrained (Dec *et al.*, 1992; Knight and O'Brien, 1988) and its age has been cited in Avalonian literature (*e.g.*, Dec *et al.*, 1992; O'Brien *et al.*, 1996; Pisarevsky *et al.*, 2013; Skipton *et al.*, 2013), its geographic location was not reported. Therefore, the sample site was revisited in the fall of 2015 so that the same location and description can be included in this present study along with the geochronological data originally obtained in 1989.

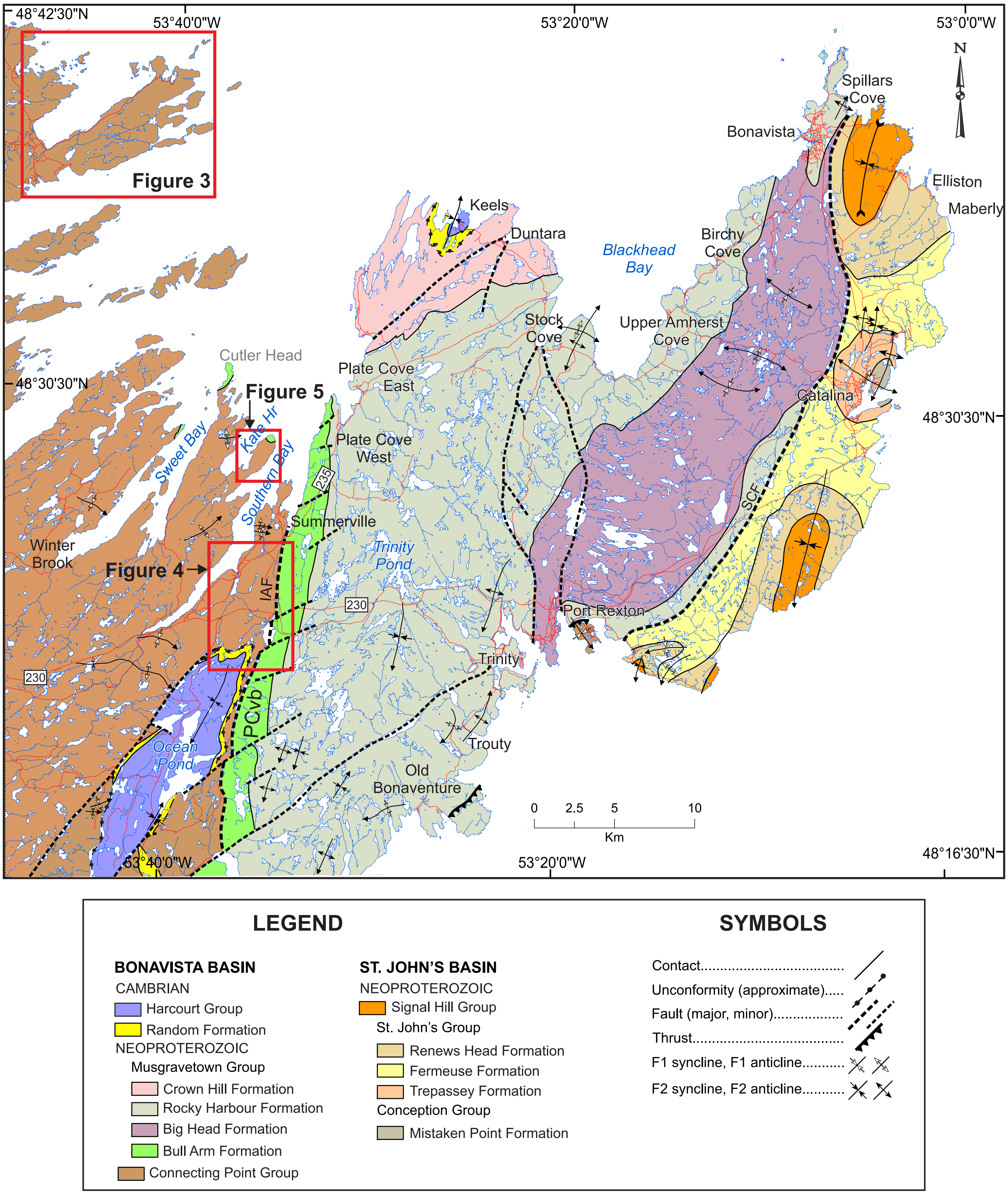

Figure 2. *Regional geology map of the Bonavista Peninsula; red boxes show the three areas for which geochronology results are presented. (IAF=Indian Arm fault; PCvb=Plate Cove volcanic belt; SCF=Spillars Cove–English Harbour fault).*

U–Pb GEOCHRONOLOGY

Three samples of tuffaceous rocks within the Sweet Bay area were collected for U–Pb zircon analysis by chemical abrasion – thermal ionization mass spectrometry (CA-TIMS). In addition, previously unpublished data for a sample of crystal ash tuff from the Eastport area (Sample TD89-01) are presented; the age and interpretation remains unchanged from the original publication (Dec *et al.*, 1992). These samples represent three distinct geographic areas within the Connecting Point Group (Figure 2): the Eastport–Salvage Peninsula (Figure 3), the washed out river that flows northwest from Muddy Pond to Seal Cove Pond, north of Highway 230 on the Bonavista Peninsula (Figure 4), and Southward Head in the Sweet Bay area (Figure 5). All sampled rocks were metamorphosed to greenschist facies.

SAMPLE AND PETROGRAPHIC DESCRIPTIONS

EASTPORT CRYSTAL ASH TUFF (SAMPLE TD89-1) – HORIZON WITHIN THE CONNECTING POINT GROUP

The olistostrome unit (C4 *of* Knight and O'Brien, 1988), the marker horizon within the Connecting Point Group separating the two turbidite cycles, is 11–17 m thick and occurs within black shale interpreted as basinal mud at both Eastport (Dec *et al.*, 1992) and in the Sweet Bay area. About 10 m stratigraphically above the olistostrome and near the base of the black shale unit (Unit C5 *of* Knight and O'Brien, 1988), a 3-m-thick tuff, herein called the Eastport tuff, occurs in the Dark Hole area, along the road between Eastport and Salvage (Figure 3). Detailed measured sections provide excellent control on the local stratigraphy (Knight and O'Brien, 1988; Dec *et al.*, 1992). The shallowly southeast-dipping tuff (S_0 = 040/20) is resistant to weathering relative to the black shale in which it occurs (Plate 2). Above the tuff, thin-bedded black shale is planar-laminated with common crosslaminations consistent with a paleocurrent at 093°. Minor white ash tuff horizons, about 1 cm thick, occur at 30 cm spacing and peter out up-section. Syn-sedimentary slumping and buckling are locally evident. Slumps and flute casts in the black shale are consistent with a paleoslope orientation of ~320° (downslope direction).

The Eastport tuff is a fine-grained, white-weathering, green-grey, crystal ash tuff containing sub-millimetre crystals (Plate 3). In thin section, the matrix appears to be mainly devitrified ash and a mix of very fine-grained euhedral grains of plagioclase, alkali feldspar, clinopyroxene and glass shards (Plate 4A, B). Chlorite and epidote infill vesicles, indicating the rock may have formed as an ignimbrite, although the presence of well-preserved glass shards indicates that it was not welded. Preservation of glass shards and the lack of lithic fragments are consistent with derivation from a single airfall event. The presence of minor chlorite indicates that the metamorphic grade is low, likely greenschist facies. A sample of the Eastport tuff (Sample TD89-1) was analyzed by TIMS in 1990 (G. Dunning, unpublished data, 1990) and detailed results are presented in this study.

MUDDY POND RIVER ASH TUFF (SAMPLE 13AM160i) – HORIZON WITHIN THE CONNECTING POINT GROUP

A sample of ash tuff was collected from along a river (referred to as Muddy Pond river on Figure 4) that flows northwest, from Muddy Pond to Seal Cove Pond, north of Highway 230 on the Bonavista Peninsula. The outcrop is described in detail in Mills (2014), including a schematic stratigraphic column of the exposure. Thin- to medium-bedded, grey-green siltstone and sandstone are overlain by thin- to medium-bedded, black shale and minor, 1-cm-thick, ash tuff horizons (Plate 5), similar to those described above the dated crystal ash tuff (Sample TD89-1) at the Eastport–Salvage section (Unit C5 *of* Knight and O'Brien, 1988). Amalgamated, slumped and convolute-bedded sandstone (Unit C6?) overlie the black shale unit with apparent conformity. Two parallel, southwest-dipping (S_0 = 130/25) tuff horizons, about 1.5 cm apart (Plate 6), were sampled using a chisel to extract only the pale ash material for geochronological analysis and the upper tuff (Sample 13AM160i) was analyzed by CA-TIMS U–Pb zircon dating.

CRYSTAL TUFF FROM SOUTHWARD HEAD EAST (SAMPLE 13AM311B) – ABOVE THE UNCONFORMITY

On the east side of Southward Head (Figure 5), shallowly northwest-dipping (S_0 = 232/30), red cobble to pebble conglomerate overlies steep northeast-dipping (S_0 = 305/75), white-weathering, green to pinkish, medium-bedded sandstone of the Connecting Point Group with notable structural discord across the unconformity (Plate 1). A 3-m-thick, red to pink crystal tuff occurs near the top of the red cobble conglomerate, 1 m below an overlying basalt flow (Plate 7; Unit HB *of* Mills and Sandeman, 2015). The locally bleached tuff (Plates 8 and 9) contains subrounded malachite blebs with bleached haloes, subhedral plagioclase feldspar crystals that commonly exceed 1 mm in length (Sample 13AM311B), and native copper, which was the most abundant mineral in the final fraction after mineral separation using the Frantz magnetic separator. In thin section, subhedral plagioclase grains typically have slightly corroded margins, although some crystals have well-preserved terminations (Plate 10A, B). The matrix is altered to

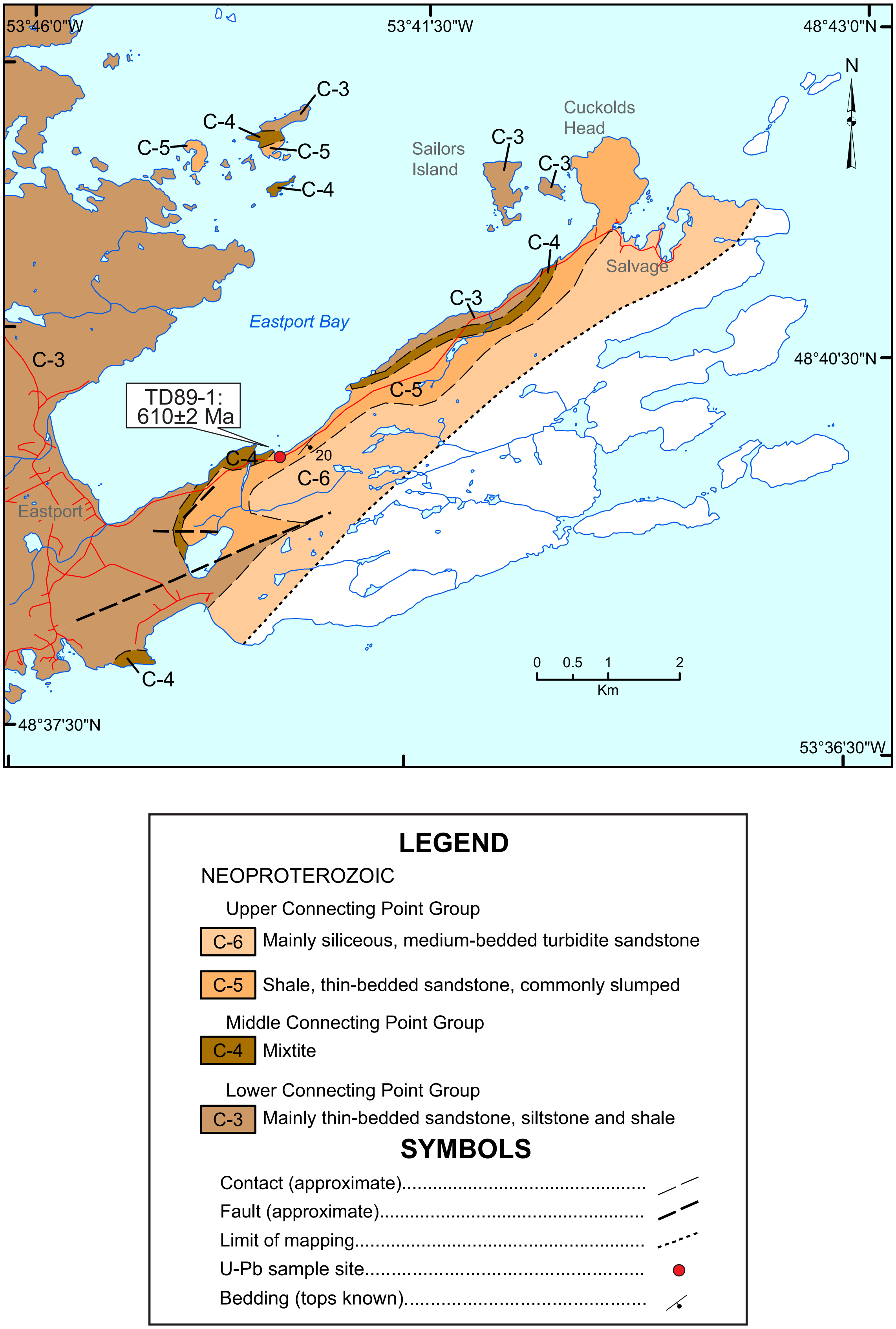

Figure 3. *Geological map for the Eastport area, site of sample TD89-1 (sample collected and analyzed in 1989).*

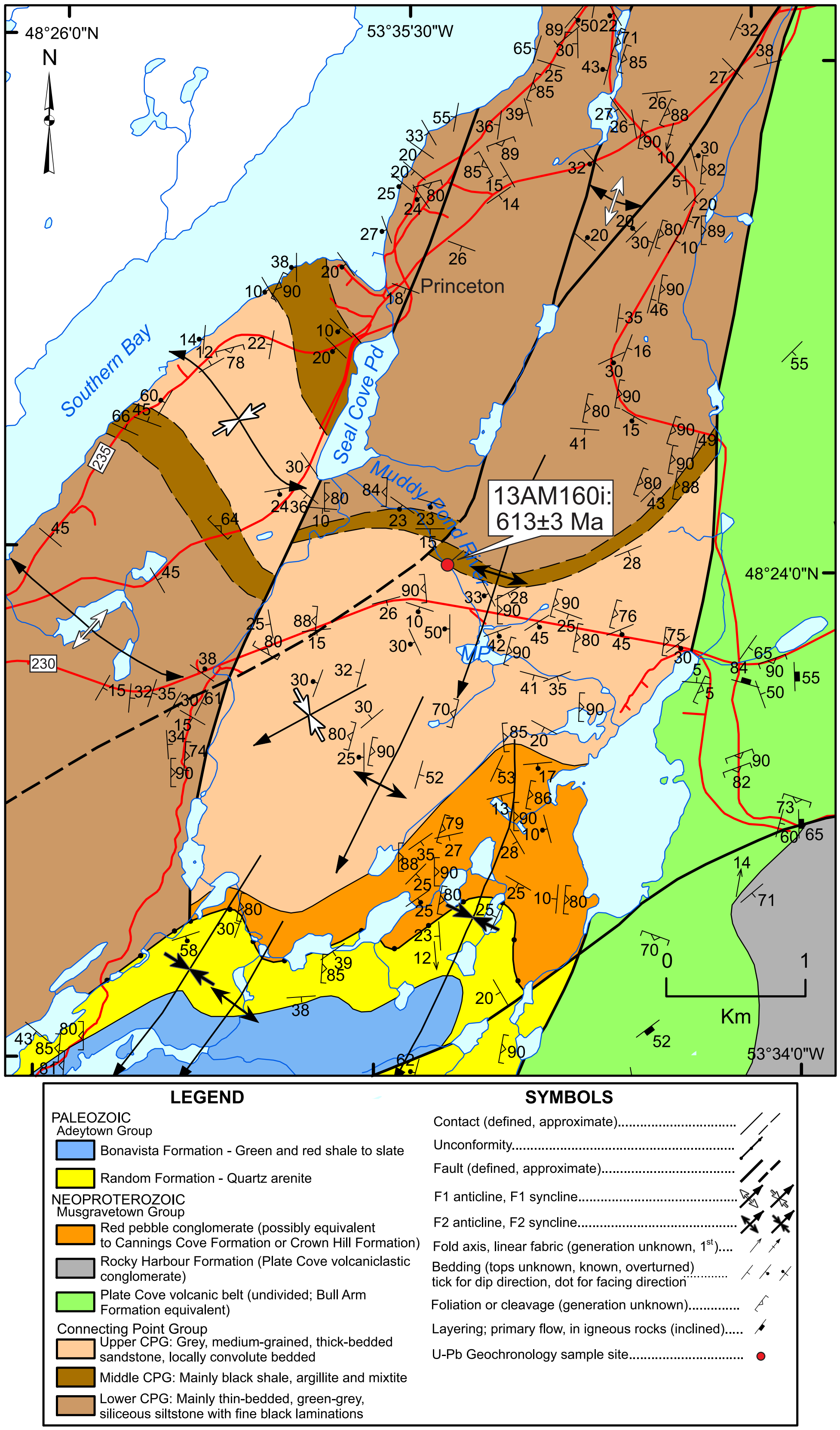

Figure 4. *Geological map for Muddy Pond river area, north of Muddy Pond (MP) along Highway 230, and approximately one kilometre southeast of Seal Cove Pond.*

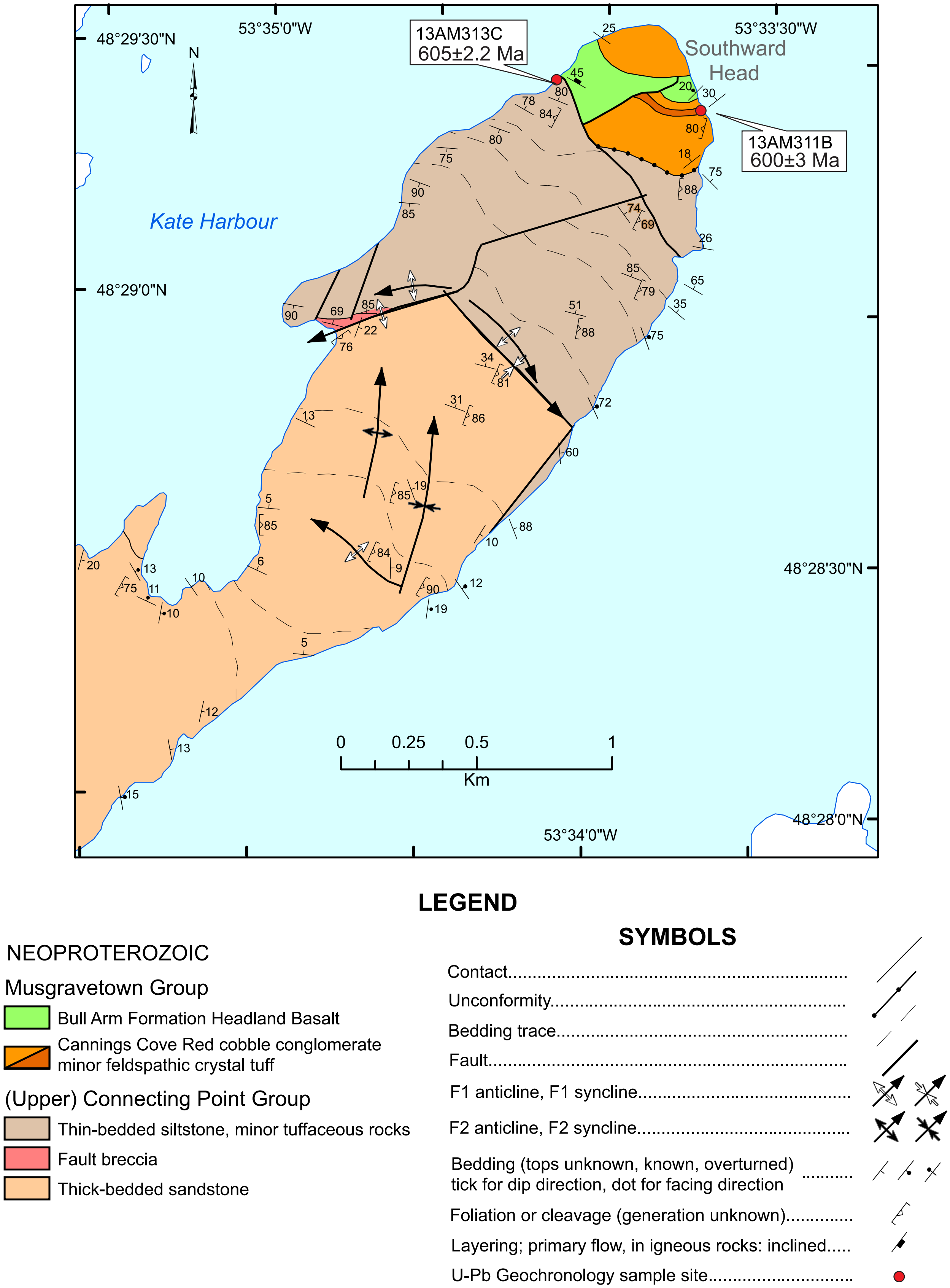

Figure 5. *Geological map for Southward Head showing locations of samples 13AM311B and 13AM313C.*

Plate 2. *Site of geochronological sample TD89-1. The 3-m-thick, siliceous tuff unit (resistant to weathering) is interbedded with thin-bedded black shale (dark, recessive beds below the thick, grey to white weathering tuff) at Dark Cove, 2 km east of Eastport. View to the south.*

Plate 3. *Photograph of siliceous crystal ash tuff from Eastport, showing sub-mm-sized fragments.*

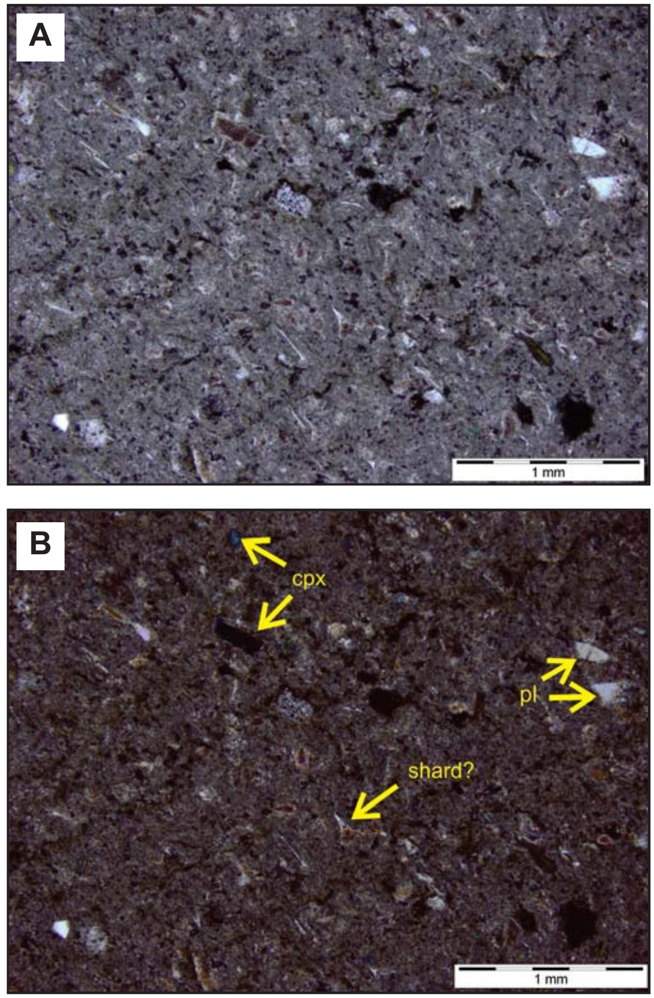

Plate 4. *Photomicrograph of Eastport tuff under A) plane-polar light and B) cross-polar light. Probable glass shard, clinopyroxene (cpx) and plagioclase (pl) crystals are evident.*

fine-grained, white mica (sericite) and minor epidote but altered glass shards are preserved with original shapes. The lithic component in the rock is <10%, and includes mainly fine-grained siltstone clasts interpreted to be locally sourced based on their lithological similarity to the underlying Connecting Point Group rocks.

LITHIC TUFF FROM SOUTHWARD HEAD WEST (SAMPLE 13AM313C) – BELOW THE UNCONFORMITY

On the west side of Southward Head (Figure 5), moderately northeast-dipping basalt (S_0 = 300/45) directly overlies steeply north-dipping (S_0 = 292/80), medium-bedded, grey sandstone and shale of the Connecting Point Group (Plate 11). The contact appears to be faulted, rather than unconformable as preserved on the east side of the headland. A 10-cm-thick, yellow-weathering lithic tuff, interbedded with fine-grained, thin- to medium-bedded sandstone and shale of the Connecting Point Group, was sampled for geochronological analysis (Sample 13AM313C; Plates 12 and 13). In hand specimen, the rock is coarse grained to granular, grey and clast-supported, with minor black angular fragments. Ripple marks in fine-grained sandstone beds immediately below the tuff (Plate 12) indicate that they are north-younging and right-way-up. These rocks are stratigraphically equivalent to the upper turbidite cycle (Unit C6) of Knight and O'Brien (1988).

In thin section, subhedral alkali feldspar is the dominant crystal phase (35 modal %); volcanic and siliciclastic clasts

Plate 5. *Thin-bedded black shale, approximately 500 m northwest of Muddy Pond river, and 1 km southeast of Seal Cove Pond, near Princeton, Bonavista Peninsula.*

comprise about 30% and 20%, respectively, and carbonate clasts comprise approximately 15% of the rock (Plate 14A, B). At least three types of volcanic clasts are recognized: plagioclase porphyritic volcanic rock, trachytic-textured volcanic rock, and possible hypabyssal fragments with plagioclase phenocrysts in a devitrified matrix of intergrown quartz and feldspar. The high proportion of lithic clasts point to an epiclastic origin for this lithic tuff, but the subhedral crystal shape and high proportion of alkali feldspars are consistent with proximity to a local felsic volcanic source. The lack of matrix material is inferred to have resulted from wave-winnowing in a shallow-marine setting.

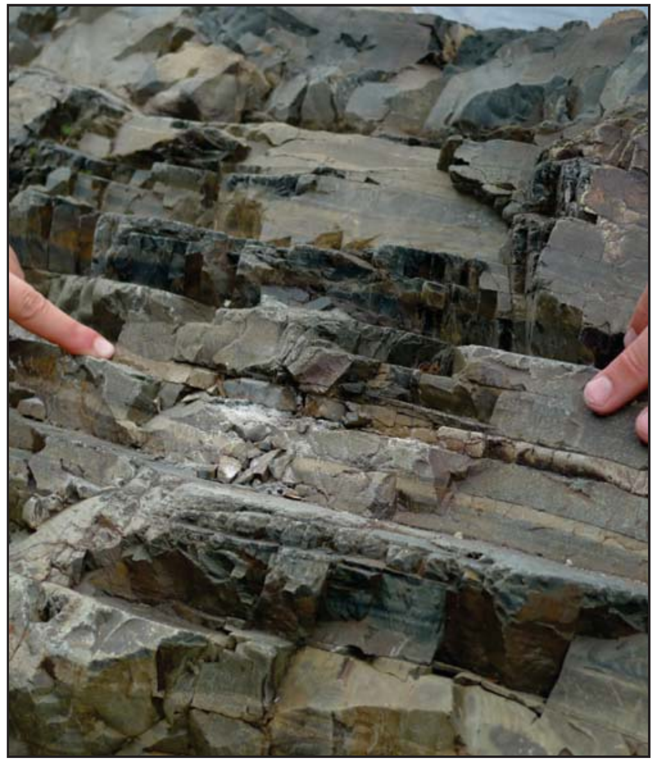

Plate 6. *Thin ash tuff horizons within black shale at Muddy Pond river. The uppermost of the two ash horizons (Sample 13AM160i) was analyzed by TIMS.*

ANALYTICAL METHODS

Samples were processed using standard methods for crushing and mineral separation under clean conditions and representative fractions of small numbers of the highest

Plate 7. *Site of U–Pb geochronology sample 13AM311B, Southward Head, Sweet Bay area. Yellowish pink-weathering, 2–3-m-thick, crystal lithic tuff, is interbedded with red pebble to cobble conglomerate. View to the northwest.*

Plate 8. *Crystal lithic tuff (sample 13AM311B) appears bleached adjacent to overlying polymictic cobble conglomerate, and locally contains subrounded blebs of malachite with bleached haloes. View northwest.*

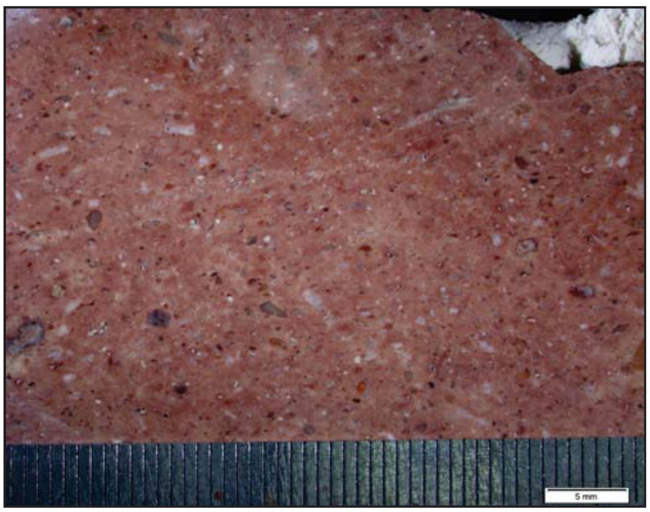

Plate 9. *Cut slab of crystal lithic tuff from the east side of Southward Head (sample 13AM311B). Note that bleaching is pervasive and forms a vague, net-like pattern. Feldspars appear euhedral and range up to 2 mm in length. Lithic fragments are subrounded to angular and also range up to 2 mm.*

quality euhedral zircon prisms were selected from each rock for analysis (Figures 6 and 7). Representative zircon crystals from each sample (except for the Eastport tuff) were imaged by cathodoluminescense (CL) on the scanning electron microscope (Figure 7), prior to U–Pb isotopic analysis by CA-TIMS, at the Geochronology Laboratory at Memorial University of Newfoundland. Analytical procedures are described in Krogh (1982). The physical abrasion technique of Krogh (1982) was used for the multigrain analyses (about 20 crystals per fraction) by isotope dilution–thermal ioniza-

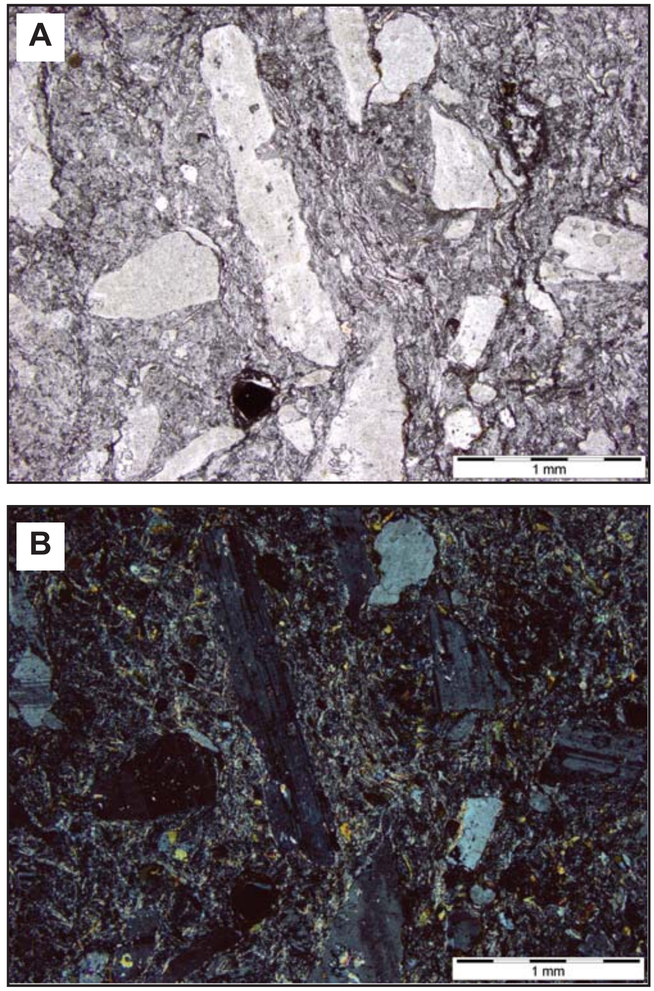

Plate 10. *Photomicrograph of crystal lithic tuff (sample 13AM311B) from east side of Southward Head; A) in plane-polar light and B) under cross-polar light. Note the slightly corroded rims of some feldspar crystals.*

tion mass spectrometry (ID–TIMS), conducted in 1990 (Sample TD89-1). The chemical abrasion technique of Mattinson (2005) was used for single grain to small multigrain analyses (up to five crystals) of zircons from samples from the Sweet Bay area. Data are presented in Table 1 and Figure 8, with errors reported at the 2σ level. Data were plotted using unpublished in-house software and weighted average $^{206}Pb/^{238}U$ ages and uncertainties at the 95% confidence interval were calculated using ISOPLOT (Ludwig, 2008). The $^{206}Pb/^{238}U$ age is used rather than the $^{207}Pb/^{206}Pb$ age because the latter depends on the precision of radiogenic ^{207}Pb measurements, which is present in very low abundances in rocks less than about 1.2 Ga (Gehrels, 2014) and its measurement is therefore less accurate and precise than the measurement of the more abundant ^{206}Pb isotope.

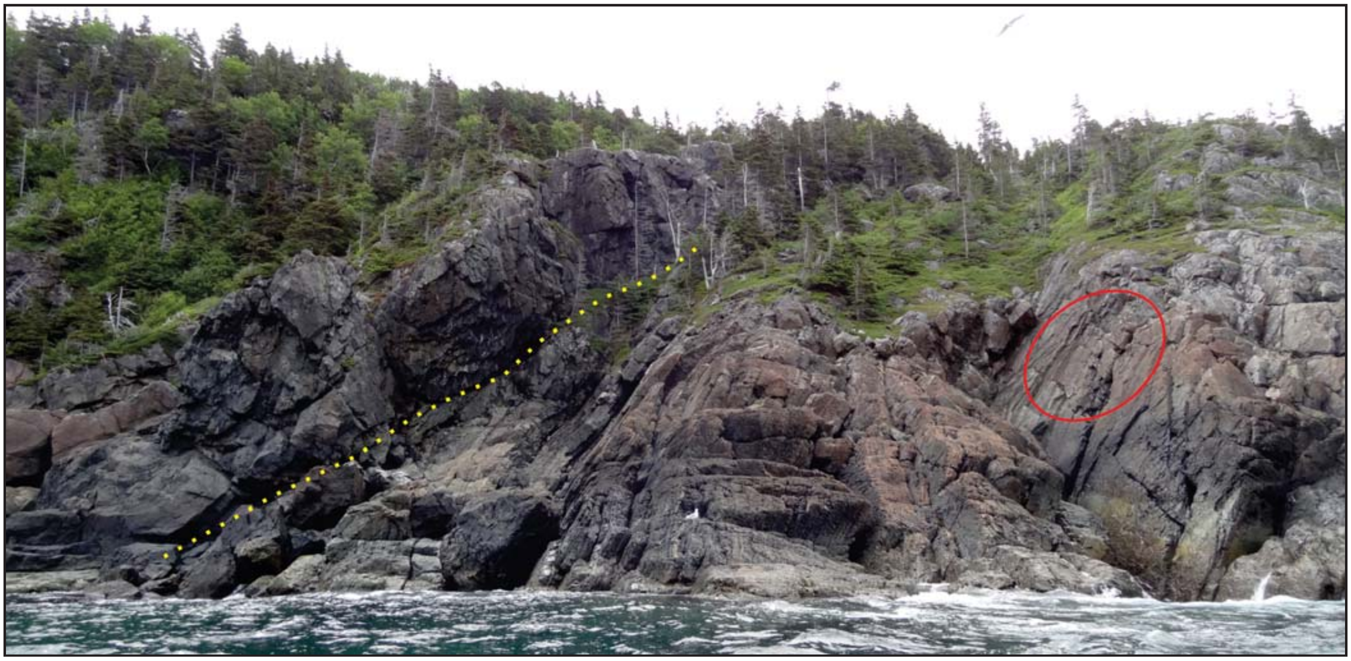

Plate 11. *Yellow dotted line separates overlying basalt from underlying thin-bedded, fine-grained sandstone–shale and minor lithic tuff of the Connecting Point Group. West side of Southward Head; view to the east-northeast. The red ellipse indicates the location of sample 13AM313C.*

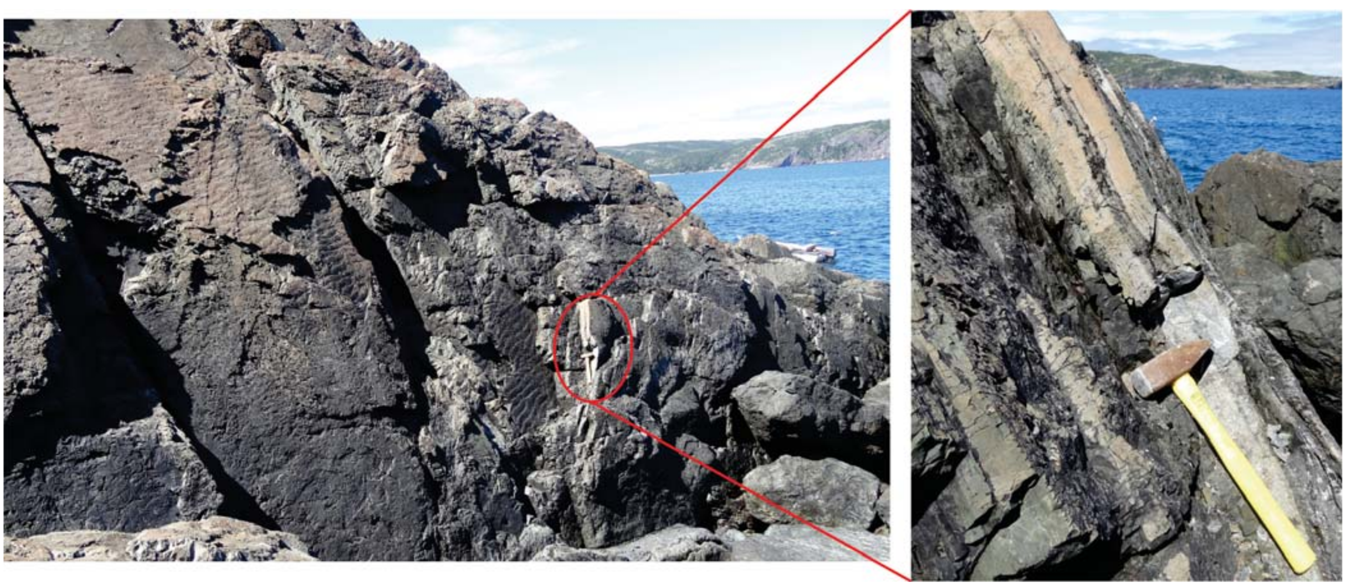

Plate 12. *Location of U–Pb geochronology sample 13AM313C. The 10-cm-thick, yellow-weathering crystal lithic tuff horizon is interbedded with fine-grained, thin-bedded turbiditic sandstone to shale. Ripple marks at the top of an underlying sandstone bed indicate that the steeply north-northeast-dipping rocks are right-way-up. View is to the southwest and west for the outcrop-scale photograph and adjacent detail, respectively.*

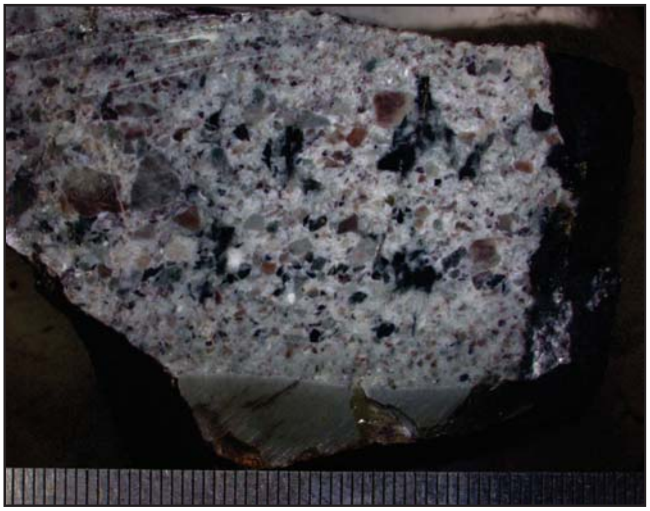

Plate 13. *Slab of the dated lithic tuff (sample 13AM313C) that occurs on the west side of Southward Head.*

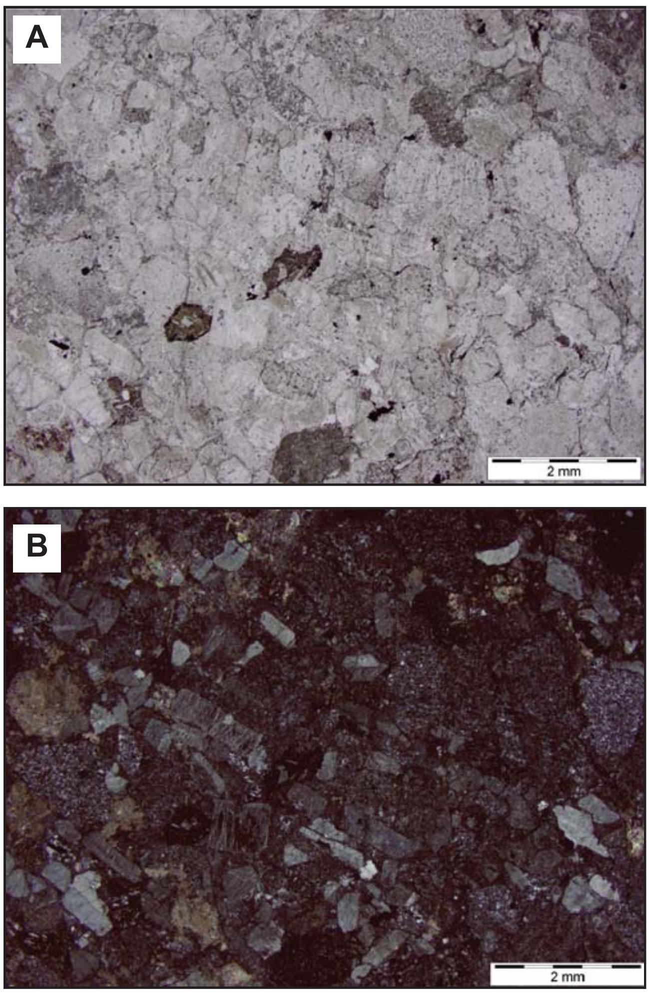

Plate 14. *Photomicrograph of the lithic tuff (sample 13AM313C) from west side of Southward Head; A) under plane-polarized light, and B) under cross-polarized light.*

ZIRCON MORPHOLOGY

Highest quality small euhedral prisms having sharp igneous growth zones were selected for analysis and representatives of the morphology types were imaged by CL microscopy (Figure 6). Zircons from the ash tuff (Sample 13AM160i) at the Muddy Pond river are stubby (aspect ratio about 1.5) to elongate (aspect ratio ~2), average about 100 µm in length, and preserve excellent oscillatory (igneous) zoning (Figure 6). Most are clear, but some show patchy red-brown staining (Figure 7). A tiny (<10 µm) core is visually apparent by CL imagery in one of the three zircons from sample 13AM160i (Figure 6, grain 2).

Zircons from sample 13AM311B range from clear to yellowish in colour (Figure 7) and are generally euhedral and either stubby (aspect ratio 1.5) or elongate (aspect ratio 2.5) prisms. One of the six representative grains imaged by CL contains an apparent core (Figure 6; row 2, grain 1). Sample 13AM313C contains both stubby (aspect ratio ~1.25) and prismatic (aspect ratio 2) zircons that are clear and colourless. One of the six representative grains from sample 13AM313C may contain an older core (Figure 6; row 1, grain 1).

RESULTS

Three small fractions were analyzed from Eastport sample TD89-1 and each contained approximately 10–20 small zircon prisms. The three fractions are concordant and overlap one another (Table 1, Figure 8A). These yield a weighted average ^{206}Pb/^{238}U age of 610 ± 2 Ma, at the 95% confidence interval (ISOPLOT, MSWD= 0.035).

Four fractions, three single zircon crystals and one fraction containing two crystals, were analyzed from the Muddy Pond river ash tuff (Sample 13AM160i). The single grain fraction, Z1, yielded the youngest ^{206}Pb/^{238}U date of 613 ± 3 Ma. Two single crystal fractions each yielded ^{206}Pb/^{238}U dates of 631 ± 8.7 Ma and 631 ± 7.4 Ma, respectively, for Z2 and Z3. A two-crystal fraction (Z4) yielded a ^{206}Pb/^{238}U date of 619 ± 4 Ma.

Six fractions, each containing two to four grains, were analyzed from the crystal tuff sample from the east side of Southward Head (Sample 13AM311B) and yielded a range of concordant ages. The youngest fraction, Z2, yielded a ^{206}Pb/^{238}U date of 600 ± 3 Ma. Four other fractions (Z3, Z4, Z5, Z6) yielded concordant ^{206}Pb/^{238}U dates of 620 ± 3.5 Ma, 618 ± 6 Ma, 610 ± 6 Ma and 608 ± 4 Ma, respectively (Table 1; Figure 8C). Fraction Z1 (Table 1; not plotted in Figure 8), yielded a concordant ^{207}Pb/^{206}Pb date of 1370 ± 4 Ma.

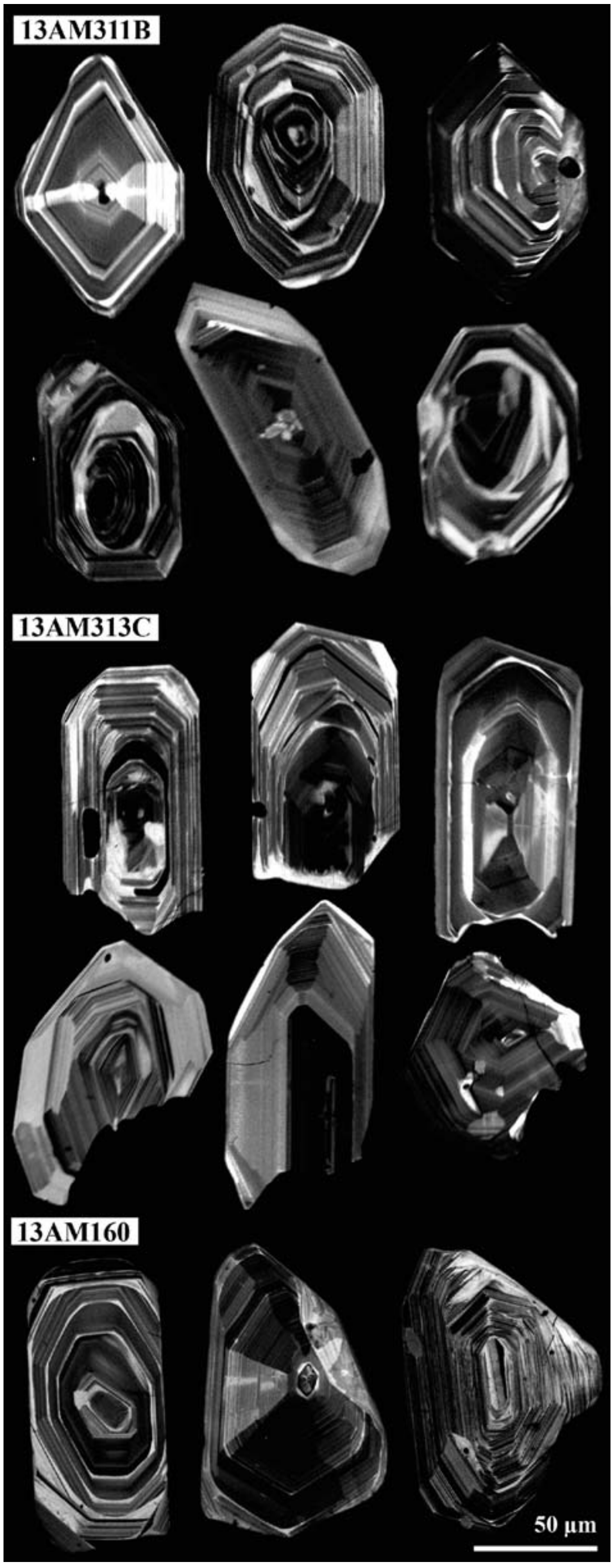

Figure 6. *Cathodoluminescence (CL) imagery showing the internal structure of zircons recovered from samples 13AM311B, 13AM313C, and 13AM160i. Most zircons show excellent magmatic growth zoning and no clear evidence of inherited cores.*

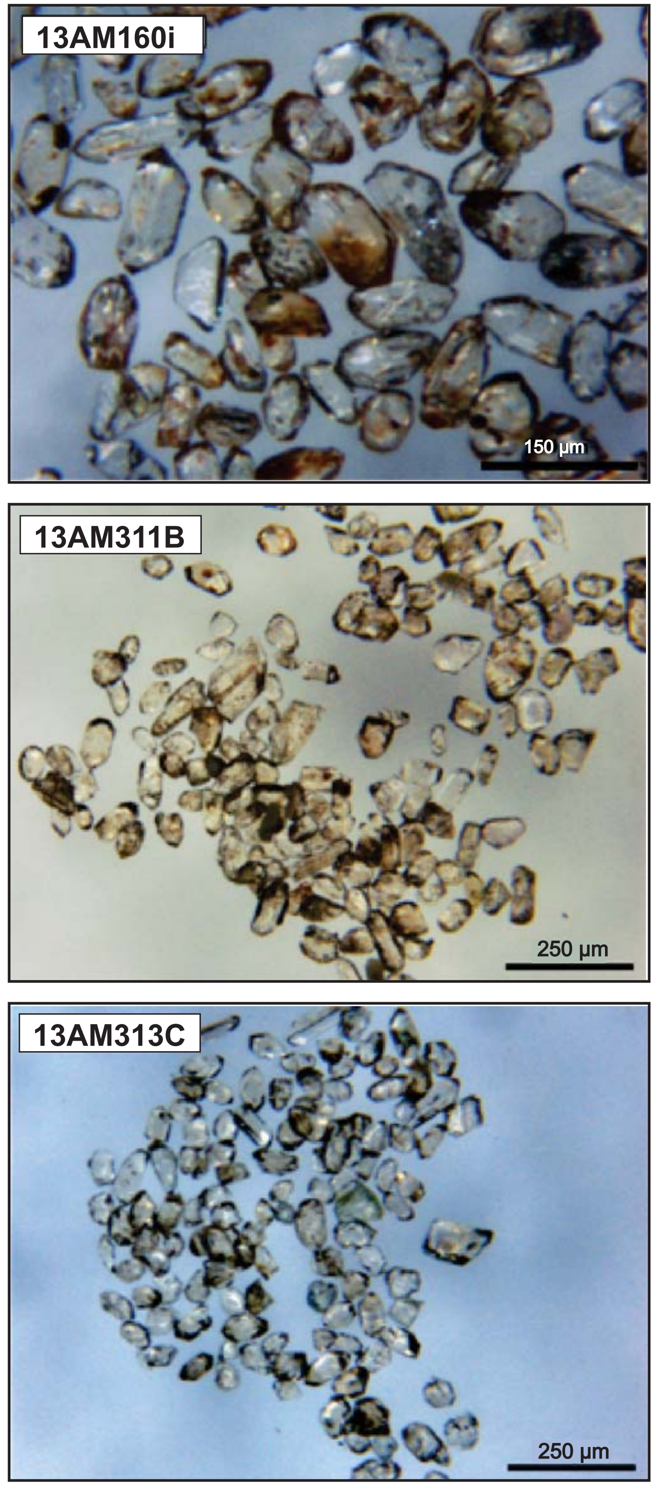

Figure 7. *Zircon microphotographs for the three geochronological samples from the Sweet Bay area.*

Table 1. U–Pb zircon data for samples from the Connecting Point Group, Bonavista Peninsula; UTM coordinates are given after the sample name and brief description (NAD 27; Zone 22)

Fraction	Weight [mg]	Concentration: U [ppm]	Concentration: Pb rad [ppm]	Measured: total common Pb [pg]	Measured: $^{206}Pb/^{204}Pb$	Corrected Atomic Ratios *: $^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	+/-	$^{207}Pb/^{235}U$	+/-	$^{207}Pb/^{206}Pb$	+/-	Age [Ma]: $^{206}Pb/^{238}U$	+/-	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
TD89-1 Crystal ash tuff – Eastport (299797/5392955)																
Z1 clr euh abr	0.080	102	10.9	7.4	6879	0.1815	0.09927	64	0.8236	56	0.06017	16	610	3.8	610	610
Z2 20 clr euh abr	0.013	217	23.0	17	1052	0.1762	0.09927	64	0.8232	64	0.06014	28	610	3.8	610	609
Z3 yellow euh abr	0.021	171	18.2	8.4	2687	0.1820	0.09937	60	0.8225	56	0.06003	16	611	3.5	609	605
13AM160i Ash tuff – Muddy Pond river (314190/5375835)																
Z1 1 sml euh prm	0.001	161	17.6	7.1	160	0.2151	0.09969	52	0.8303	242	0.06040	164	613	3.1	614	618
Z2 1 clr euh prm	0.001	111	12.0	14	69	0.1656	0.10287	148	0.8190	1044	0.05774	682	631	8.7	607	520
Z3 1 clr euh prm	0.001	48	5.1	6.8	64	0.1506	0.10284	126	0.8446	682	0.05956	446	631	7.4	622	588
Z4 2 clr euh prm	0.002	93	10.1	10	138	0.1890	0.10074	68	0.8335	126	0.06001	76	619	4.0	616	604
13AM311B Crystal tuff – Southward Head East; above unconformity (310798/5373684)																
Z1 2 sml clr prm	0.002	84	22.2	3.7	696	0.2001	0.23906	162	2.8817	248	0.08742	58	1382	9.5	1377	1370
Z2 4 sml clr prm	0.004	115	13.1	2.8	1038	0.2916	0.09760	88	0.8072	108	0.05998	68	600	5.2	601	603
Z3 2 sml clr prm	0.002	214	23.7	21	145	0.2112	0.10095	60	0.8346	166	0.05996	108	620	3.5	616	602
Z4 3 clr sml prm	0.003	183	19.5	2.2	1592	0.1664	0.10068	102	0.8356	108	0.06019	52	618	6.0	617	610
Z5 2 sml clr prm	0.002	93	10.8	3.3	373	0.3039	0.09932	102	0.8179	274	0.05973	182	610	6.0	607	594
Z6 3 sml clr prm	0.003	146	16.4	22	143	0.2595	0.09893	66	0.8193	74	0.06006	44	608	3.9	608	606
13AM313C Lithic tuff – Southward Head West; below unconformity (310286/5373808)																
Z1 3 sml clr prm	0.003	202	20.6	8.8	444	0.1435	0.09841	40	0.8154	76	0.06009	50	605	2.4	605	607
Z2 5 sml clr prm	0.005	289	30.7	29	338	0.1617	0.10092	86	0.8388	84	0.06029	42	620	5.1	619	614
Z3 4 clr sml prm	0.003	192	20.2	26	161	0.1441	0.10135	44	0.8371	52	0.05991	32	622	2.6	618	600
Z4 2 sml clr prm	0.002	124	12.9	2.2	735	0.1492	0.09990	92	0.8200	108	0.05953	76	614	5.4	608	587
Z5 1 sml clr prm	0.001	191	24.5	2.1	723	0.1415	0.12343	78	1.1464	124	0.06736	66	750	4.6	776	849
Z6 2 sml clr prm	0.002	16	1.6	2.7	90	0.1711	0.09841	130	0.8138	418	0.05998	282	605	7.6	605	603

Notes; All zircon from 13AM samples was chemically abraded (Mattinson, 2005) prior to dissolution. Z,zircon; 2,4 number of grains in analysis; prm, prism; sml, small; euh, euhedral; clr, clear, abr, physically abraded (Krogh, 1982). For 13AM samples, weights of grains were estimated, with potential uncertainties of 25-50% for these small samples.

* Atomic ratios corrected for fractionation, spike, laboratory blank of 2 picograms (pg) common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 0.3 pg U blank. Two sigma uncertainties are reported after the isotopic ratios and refer to the final digits. Two sigma uncertainties (myrs) on the $^{206}Pb/^{238}U$ ages are reported after the ages.

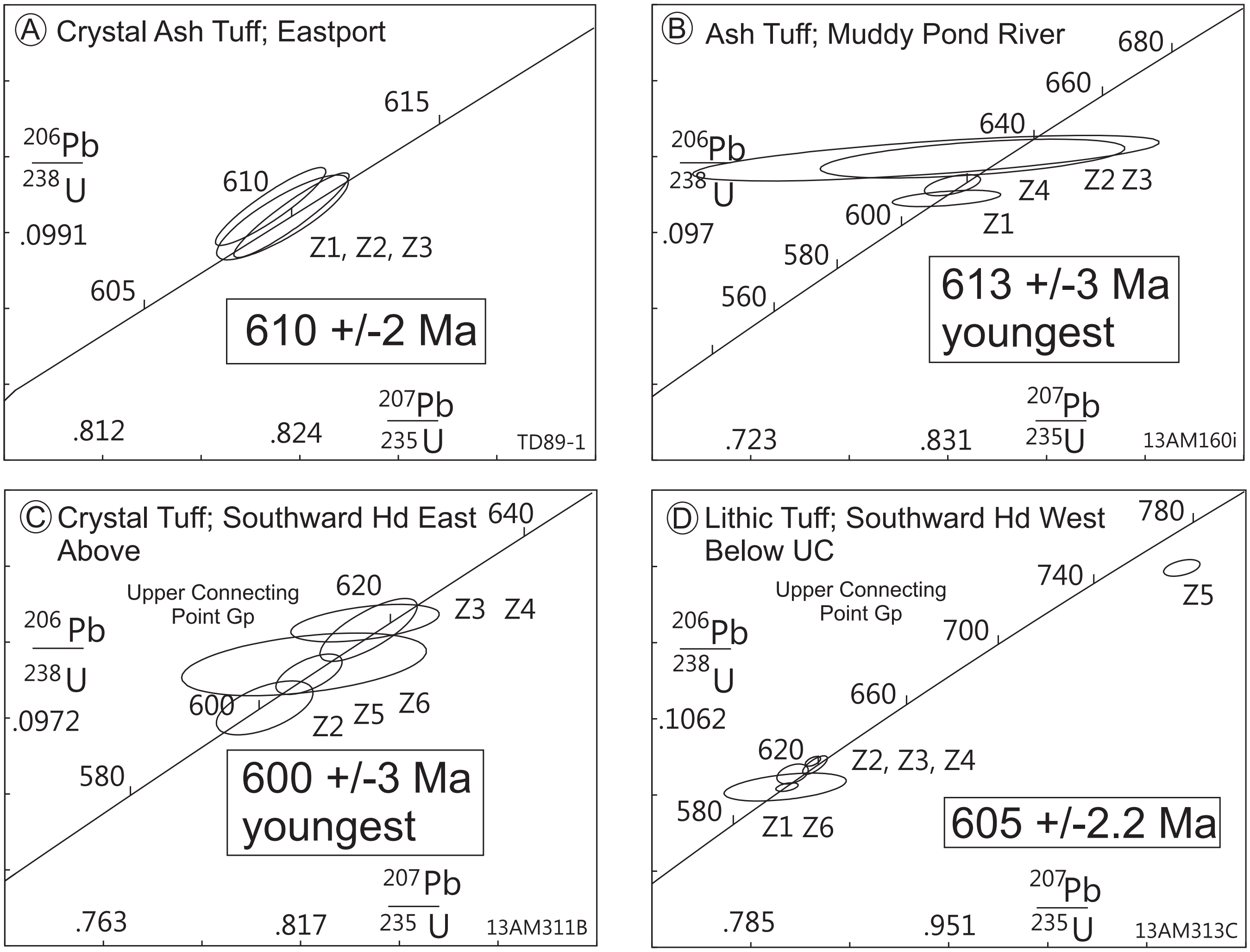

Figure 8. *Concordia plot for samples discussed in the text: A) TD89-1; B) 13AM160i; C) 13AM311B; and D) 13AM313C.*

Six zircon fractions were analyzed from the lithic tuff sampled from the west side of Southward Head (sample 13AM313C). One fraction (Z5) contained a single zircon crystal whereas the rest contained multiple zircon grains. Two analyses (fractions Z1 and Z6) overlap on the concordia line and give a weighted average $^{206}Pb/^{238}U$ age of 605 ± 2.2 Ma (95% Confidence Interval; MSWD= 0, because of perfect age agreement; Figure 8D). Z2, Z3 and Z4 yielded concordant $^{206}Pb/^{238}U$ dates of 620 ± 5 Ma, 622 ± 2.6 Ma, and 614 ± 5.4 Ma, respectively. The single-grain fraction, Z5, yielded a $^{206}Pb/^{238}U$ date of 750 ± 4.6 Ma.

DISCUSSION

The Eastport crystal ash tuff yielded a definitive age of 610 ± 2 Ma and shows no evidence of inheritance. In contrast, the geochronological data of all three tuffs from the Sweet Bay area contain a significant inherited zircon component. The 3-m-thick, crystal ash tuff from Eastport preserves glass shards, consistent with derivation from a single airfall event that has not been resedimented. The ash tuff at the Muddy Pond river occurs within the black shale unit between the upper and lower turbidite cycles of the Connecting Point Group, and is considered to represent the same stratigraphic unit as the Eastport tuff. The youngest date at Muddy Pond river of 613 ± 3 Ma can conservatively be interpreted as the maximum age of the ash layer. However, it may represent the best estimate of the age of deposition of the tuff horizon here, given the concordance and the euhedral shape of the analyzed zircon crystal, and the overlap within error of this age with the age of the Eastport tuff. This is consistent with the interpretation that both tuffs represent the same stratigraphic unit in both areas. Although the olistostrome was not observed in outcrop along the Muddy Pond river, it does outcrop along Highway 235, immediately south of Princeton, and less than one kilometre northwest of the dated sample 13AM160i, albeit across a north-northeast-trending fault of undetermined displacement (Figure 4). Both the Eastport and Muddy Pond river tuffs are overlain by slumped and variably silicified, coarsening- and thickening-upward sandstone, consistent with Knight and O'Brien's (1988) second turbidite cycle. In both areas, the olistostrome-bearing unit is associated with slumping indicative of slope instability, intrusion of synsedimentary mafic dykes (O'Brien and Knight, 1988; Mills, 2014), hypabyssal intrusions (O'Brien and Knight, 1988), and the influx of coarse mafic volcanic detritus, consistent with uplift of a nearby volcanic centre. The inherited zircon in the thin ash tuff from Muddy Pond river range from ~631 to ~619 Ma and is consistent with local derivation from the underlying, *ca.* 620 Ma volcanic Love Cove Group (O'Brien *et al.*, 1989).

The youngest date of 600 ± 3 Ma for the crystal tuff from above the angular unconformity at Southward Head (Sample 13AM311B) is interpreted to represent the best age estimate, based on concordance and the euhedral crystal habit of each zircon of the four-grain fraction; it is possible that the rock is younger. The rock contains minor lithic clasts that likely represent the incorporation of eroded local debris because the angularity of the fragments indicates minimal transport, and the pebble to cobble conglomerate with which the tuff is interbedded, indicates proximity to the erosional source. Although this crystal tuff contains less than 10% lithic fragments, the geochronology results clearly demonstrate that this rock contains a significant inherited component. These inherited, 620–608 Ma zircons are derived from a proximal, local source, consistent with the preservation of abundant glass shards (Plate 10). The source of the oldest zircon grain in this sample (1370 ± 4 Ma) is unknown but Mesoproterozoic and older detrital zircon have been reported from elsewhere in the Avalon Terrane of Newfoundland (Pollock *et al.*, 2009). Abundant Mesoproterozoic and older detrital ages from the Cambrian to Ordovician Avalonian rocks, which are absent from most Neoproterozoic sedimentary rocks of Avalonia, have been interpreted to indicate a change in provenance during the Early Cambrian to Early Ordovician (*e.g.*, Pollock *et al.*, 2009; Barr *et al.*, 2012).

The lithic tuff from below the angular unconformity was deposited in a shallow-marine setting, where some degree of reworking (winnowing) affected the sediment, likely removing any fine-grained material or ash (Plates 13 and 14). The age agreement of the youngest two fractions at 605 Ma is unlikely to be fortuitous, and is therefore interpreted to reflect the age of the lithic tuff. Inheritance could be expected for this sample, as abundant lithic fragments were observed in thin section (Plate 14). All older dates (620 ± 5 Ma, 622 ± 2.6 Ma, 614 ± 5.4 Ma, and 750 ± 4.6 Ma) of this sample therefore reflect inheritance. All three tuff samples from the Sweet Bay area contain an abundance of zircons that range from 631 to 600 Ma, consistent with derivation from the Love Cove Group. The lower Connecting Point Group is interbedded with tuffaceous rocks of the upper Love Cove Group (Knight and O'Brien, 1988) and volcanic remnants of the latter are considered to be a major contributing source to the former (Knight and O'Brien, 1988; Dec *et al.*, 1992). The single Cryogenian date of 750 ± 4.6 Ma is reminiscent of the age of the Burin Group, although it is ~10 million years younger (Krogh *et al.*, 1988; Murphy *et al.*, 2008).

The new U–Pb zircon ages constrain the timing of formation of the angular unconformity at Southward Head to between 605 and 600 Ma, consistent with the interpretation of Jenness (1963) that the angular unconformity at Southward Head marks the boundary between Connecting Point Group flysch and overlying Musgravetown Group molasse. This unconformity most likely preserves local uplift in a dynamic and evolving, peri-continental, volcanic-arc terrane possibly situated to the northeast (*see* Knight and O'Brien, 1988, page 226). This may have involved concomitant uplift of a significant part of the Connecting Point Group block, which lies west of the Indian Arm Fault (*see* Figure 2).

Uplift of the Connecting Point Group block resulted in a stratigraphic gap (omission of much of the Musgravetown Group) between Connecting Point Group rocks at the Muddy Pond river and the base of the Cambrian Random Formation, 2.5 km to the south (Figure 4), and is thought to have taken place prior to volcanism that formed the Plate Cove volcanic belt. Geochemical data presented by Mills and Sandeman (2015) is consistent with a shift from earlier, arc-like volcanism in the Headland Basalts to later, transitional, arc-like to EMORB-like volcanism in the Plate Cove volcanic belt in an overall extensional tectonic regime. Evidence for pre-Cambrian extension that predates pre-Cambrian contraction has been documented on parts of the southwestern shore of Conception Bay on the Avalon Peninsula of Newfoundland (Riveros, 1998). The transition from arc- to transitional-volcanism has to postdate the Southward Head unconformity, as basalts interbedded with conglomerate above the unconformity have continental-arc signatures (Mills and Sandeman, 2015). These may represent late arc volcanism related to the 630–600 Ma Avalonian arc, vestiges of which are now represented by the Love Cove Group (Dec *et al.*, 1992).

The basalts of the Plate Cove volcanic belt preserve a chemical signature that is transitional to weakly calc-alkaline and are derived from a lithosphere-contaminated, slightly enriched mid-ocean ridge basalt, shallow mantle source (Mills and Sandeman, 2015), consistent with lithospheric thinning in an extensional or trans-tensional tectonic setting.

Based on their structural and stratigraphic position, they likely erupted during trans-tensional movements that also accompanied uplift of the Connecting Point Group block. Correlation of the Plate Cove volcanic belt with the Bull Arm Formation, exposed in its type section 100 km to the south, is currently untenable, owing to the lack of key trace-element data for the latter. Further interpretation should be reserved until geochronological and isotopic constraints are available for both the Plate Cove volcanic belt and rocks formerly assigned to the Bull Arm Formation.

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