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NEW GEOCHRONOLOGICAL CONSTRAINTS ON THE TIMING OF MAGMATISM FOR THE BULL ARM FORMATION, MUSGRAVETOWN GROUP, AVALON TERRANE, NORTHEASTERN NEWFOUNDLAND

A.J. Mills, G.R. Dunning[1], M. Murphy[1] and A. Langille[1]
Regional Geology Section
[1]Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, A1B 3X5

ABSTRACT

The Bull Arm Formation is one of the most areally extensive volcanic units in the Avalon Terrane of Newfoundland. Historically, the age has been interpreted from the single previous U–Pb zircon age (570 +5/-3 Ma) obtained from a rhyolite flow on Wolf Island, where no contact relations are exposed. This rhyolite was later re-interpreted as the lower part of the overlying Rocky Harbour Formation but the initial interpretation as Bull Arm Formation had by then become entrenched in the literature. New U–Pb zircon (CA-TIMS) geochronology results have been obtained for two rock samples from the volcanic-dominated Bull Arm Formation, Musgravetown Group, on the Bonavista Peninsula (Plate Cove volcanic belt) of northeastern Newfoundland, and one sample from the Isthmus that connects the Avalon Peninsula to the rest of the Island. A 40-cm-thick crystal-ash tuff near the base of the Plate Cove volcanic belt, at the roadcut east of Summerville, yielded an age of 592 ± 2.2 Ma. A lapilli tuff, located approximately 1800 m to the east, at the eastern margin of the volcanic belt, yielded an age of 591.3 ± 1.6 Ma. Quartz- and potassium feldspar-phyric, banded rhyolite from the Isthmus, approximately 95 km to the south-southwest of the two Bonavista samples, yielded an age of 605 ± 1.2 Ma.

These ages of volcanism, complemented by petrological studies, show that the Bull Arm Formation is older than 570 Ma and that the volcanic rocks assigned to the Bull Arm Formation are considerably more complex than previously known. The occurrence of similar-age pyroclastic rocks at both the western and eastern margins of the Plate Cove volcanic belt is consistent with either rapid deposition of the sequence in a few million years or stratigraphic repetition, likely owing to tight upright folding during Acadian deformation, as documented elsewhere on the Bonavista Peninsula. The 605-Ma banded rhyolite at the Isthmus is age-equivalent to tuffaceous rocks at the top of the Connecting Point Group at Bonavista Bay. The Isthmus rhyolite is overlain by diamictite, possibly correlative to the 579-Ma-glaciogenic Trinity facies and Gaskiers Formation, indicating a substantial depositional hiatus, and/or faulting, that may be related to uplift during early Avalonian orogenesis.

Geochronological results, coupled with structural observations, help to constrain the Neoproterozoic evolution of the Avalon Terrane exposed on the Bonavista Peninsula. Earliest deformation recognized in the area occurred between 605 and 600 Ma, when arc-adjacent turbidites of the Connecting Point Group underwent north-directed thrusting creating local unconformities and imbricate thrust stacks. East-side down, normal faulting along the Indian Arm fault west of the Plate Cove volcanic belt followed ca. *592 Ma transitional to weakly calc-alkaline volcanism, and culminated in deposition of a coarse, clastic wedge (the conglomeratic Plate Cove facies). A tectonically quiescent period followed, during which the 579 Ma Gaskiers-equivalent, glaciomarine Trinity diamictite and overlying grey siltstone of the Big Head Formation were deposited. North-directed thrust faulting, likely part of Avalonian orogenesis, occurred again post-565 Ma. This terminal Neoproterozoic event preceded deposition of the Early Cambrian Random Formation and possibly parts of the upper Crown Hill Formation.*

INTRODUCTION

The single previous geochronological age constraint for the mainly volcanic Bull Arm Formation (BAF), Musgravetown Group (MG), came from a rhyolite flow on Wolf Island, located in Bloody Reach, ~8 km north-northeast of Traytown (NTS map sheet 2C/12; Figure 1). This flow yielded a U–Pb (zircon) age of 570 +5/-3 Ma and was initially interpreted to represent the base of the MG (O'Brien *et al.*, 1989). It was later re-interpreted as the basal part of the overlying Rocky Harbour Formation (O'Brien and King, 2004), but by then its initial interpretation had

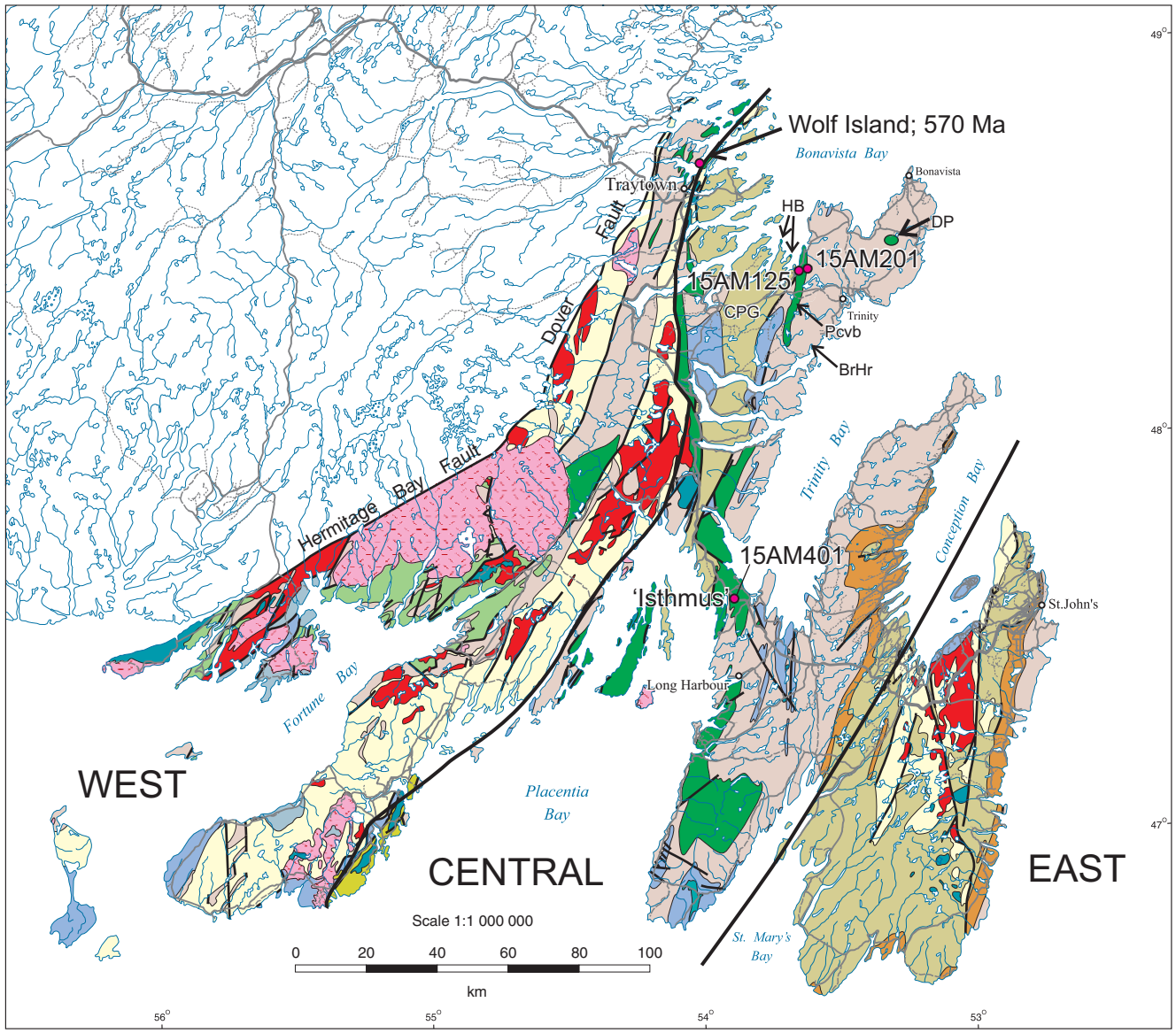
become entrenched in the literature (*e.g.*, Myrow, 1995; O'Brien *et al.*, 1996; Pisarevsky *et al.*, 2012; Pollock *et al.*, 2009; Thompson *et al.*, 2014). Certain stratigraphic correlations have also led to the interpretation that the BAF represents a late phase of Avalonian Neoproterozoic arc magmatism. In his compilation of the bedrock geology of the Avalon Peninsula, King (1988) correlates units of the (former) Hodgewater Group (Hutchinson, 1953; McCartney, 1967) to the St. John's Group and lower Signal Hill Group. He also correlates grey siltstone of the upper Hodgewater Group (McCartney, 1967) to the Big Head Formation of the MG, so that the latter broadly overlies the Signal Hill Group. Currently, there are no direct age constraints (U–Pb geochronology) on the Signal Hill Group, but the Cuckold Formation at Cape Spear contains detrital zircon possibly as young as 555 Ma (±12 Ma, 2 sigma error reported; Pollock *et al.*, 2009). Based on stratigraphy, the Signal Hill Group must be younger than the *ca.* 565 Ma Mistaken Point Formation of the Conception Group (G. Dunning, unpublished data; cited by Benus, 1988) and overlying St. John's Group (*ca.* 557 Ma; G. Dunning, unpublished data, 2007). Correlations that put MG stratigraphically above Signal Hill Group are inconsistent with new geochronological constraints from the BAF.

REGIONAL GEOLOGY

The MG stratigraphically overlies, commonly with angular discordance (*e.g.*, O'Brien, 1993), Neoproterozoic, arc-adjacent, marine basin rocks preserved as the Connecting Point Group (CPG; Dec *et al.*, 1992), and sits below the Early Cambrian, marginal-marine, Random Formation and overlying transgressive succession (Smith and Hiscott, 1984). The MG occurs mainly in the central part, but has also been mapped in the western part of the Avalon Terrane in Newfoundland (Figure 1) and extends eastward to the northwest and southwest promontories of the Avalon Peninsula (King, 1988). On the Bonavista Peninsula, the MG has been divided into (in ascending order): a basal conglomeratic Cannings Cove Formation (not everywhere present), the dominantly volcanic BAF, an unnamed middle unit, the shallow-marine to fluvial Rocky Harbour Formation, and the upper terrestrial red beds of the Crown Hill Formation (Jenness, 1963). Farther south, in the Placentia Bay area, the BAF is overlain by the Big Head Formation (McCartney, 1967), comprising basal conglomeratic to arkosic red beds that pass upward into fine-grained, grey-green siliciclastic rocks that are the dominant rock type of the Big Head Formation. At Big Head, near Long Harbour, red beds at the base of the Big Head Formation interfinger with basalt flows and breccias presumed to be part of the BAF (McCartney, 1967; Figure 1). The Big Head Formation is overlain by dominantly red arkose of the Maturin Ponds Formation, which pass upward into red and green, commonly channelized conglomerate and coarse-grained sandstone of the Trinny Formation. The latter is overlain by either the Crown Hill Formation or the Random Formation, where the Crown Hill is not recognized (McCartney, 1967). It is unclear whether the different formations of the MG reflect varying stratigraphic packages of different age, or time-equivalent lateral facies changes in a tectonically active terrane of discontinuous volcanic islands and adjacent marine basins.

Volcanic rocks traditionally assigned to the BAF (Hayes, 1948; Jenness, 1963; McCartney, 1967; O'Brien, 1993, 1994; Normore, 2010, 2012) include rhyolitic flows and ignimbrites, mafic volcanic rocks, and lesser intermediate volcanic rocks interfingered with, and overlain by, proximally derived volcanogenic sedimentary rocks (Hughes and Malpas, 1971). The BAF forms a discontinuous, north-trending volcanic belt that extends from Plate Cove southward through the Isthmus of Avalon to the southwestern part of the Avalon Peninsula between Placentia and St. Mary's bays (Figure 1). The overlying stratigraphic successions vary across the central Avalon Terrane in Newfoundland (*e.g.*, Big Head Formation in Placentia area *vis-à-vis* Rocky Harbour Formation in Bonavista area). Whereas basal red beds, which pass up into grey-green siltstone of the Big Head Formation overlie the BAF in the Placentia Bay area, BAF rocks of the Plate Cove volcanic belt (PCvb) on the Bonavista Peninsula are overlain by coarse-grained, proximally derived siliciclastic rocks of the Rocky Harbour Formation. These include flattened, volcaniclastic pebble conglomerate (Plate Cove facies; O'Brien and King, 2005) and medium- to coarse-grained, thick-bedded, light-grey sandstone having thin interbeds of maroon shale (Kings Cove Lighthouse facies; Normore, 2010). Grey siltstone, shale and fine-grained sandstone of the Kings Cove North facies (O'Brien and King, 2002; Normore, 2010) overlie and interfinger with rocks of the Kings Cove Lighthouse facies (Normore, 2010). Rocks of the Kings Cove North facies are lithologically similar to the Big Head Formation, but apparently occur stratigraphically higher in the MG (O'Brien and King, 2002; Normore, 2010).

Early studies of the BAF at the Isthmus of Avalon describe the formation there as a felsic-dominated, bimodal suite deposited in a subaerial environment (Malpas, 1971). Despite alteration of the primary chemical composition by varying degrees of metasomatism (Hughes and Malpas, 1971), Malpas (1971) suggests an original calc-alkaline affinity for the rocks based on Zr values and whole-rock analyses. These early lithogeochemical results comprise abundances for major elements and four trace elements only; no modern lithogeochemical analyses (including key elements for petrological studies, such as rare-earth elements and high-field-strength elements) have been carried out, until recently.



LEGEND

AVALON ZONE

DEVONIAN AND CARBONIFEROUS INTRUSIVE ROCKS
- Mainly granites; posttectonic relative to mid-Paleozoic orogenies

NEOPROTEROZOIC TO EARLY ORDOVICIAN STRATIFIED ROCKS
- Shallow-marine, mainly fine-grained, siliciclastic rocks, including minor limestone and volcanic rocks

NEOPROTEROZOIC
- Fluviatile and shallow-marine siliciclastic rocks (Signal Hill Group parts of Musgravetown Group)
- Marine deltaic siliciclastic rocks (St. John's Group)
- Marine turbidites (Conception and Connecting Point groups)
- Bimodal, mainly subaerial volcanic rocks (Long Harbour Group)
- Bimodal, mainly subaerial volcanic rocks (Bull Arm Formation)
- Bimodal, submarine to subaerial volcanic rocks (Harbour Main, Marystown and Love Cove groups)
- Pillow basalt, mafic volcaniclastic rocks, minor siliciclastic rocks, limestone and chert (Burin Group)

NEOPROTEROZOIC TO CAMBRIAN INTRUSIVE ROCKS
- Mafic intrusions
- Granitoid intrusions, including unseparated mafic phases

SYMBOL ● Geochronology samples and data

Figure 1. *Simplified bedrock geology map of the Avalon Terrane in Newfoundland (modified from Colman-Sadd* et al.*, 1990) showing sites of BAF geochronological samples (*this study*) and the location of the 570 Ma rhyolite of O'Brien* et al. *(1989). Also shown are approximate locations of volcanic units of the Bonavista area discussed in the text: HB – Headland basalt; PCvb – Plate Cove volcanic belt; DP – Dam Pond; BrHr – British Harbour; CPG – Connecting Point Group. West, central and east zones of the Avalon Terrane as per Myrow (1995).*

On the Bonavista Peninsula, Mills and Sandeman (2015) delineate three spatially and lithogeochemically distinct suites of mafic volcanic rocks in the area. Calc-alkaline, glomerocrystic basalt is exposed along three separate promontories on the north shore of western Bonavista Peninsula, west of the PCvb (HB, Figure 1). The Headland basalt (HB) is interbedded with mainly red pebble to cobble conglomerate, lesser sandstone and minor pyroclastic rocks. Although contacts with adjacent rocks of the CPG are generally faulted, the original contacts may have been unconformable, as preserved at Southward Head (O'Brien, 1994; Mills, 2014). The angular unconformity at Southward Head (between steeply dipping CPG rocks and overlying, shallowly dipping basal MG) has been constrained to between 605 and 600 Ma (Mills *et al.*, 2016b). Thick HB flows occur about 1 m above a 600 ± 3 Ma crystal lithic tuff (Mills *et al.*, 2016b), providing an approximate age for the HB. The north-trending, ~2-km-wide, PCvb comprises basalt, rhyolite flows and breccias, and lesser intermediate volcanic and sedimentary rocks, and occurs on the west side of the Bonavista Peninsula, east of the CPG (Figure 1). The volcanic belt is faulted on both sides and shows evidence for syn-depositional extension (Plate 1A), and at least two compressional deformation events (Plate 1B; Mills *et al.*, 2016a). Basalts of the PCvb are transitional, weakly calc-alkaline to E-MORB-like basalts (Mills and Sandeman, 2015). The OIB-like, alkaline basalts occur only locally on the eastern part of the Peninsula (Figure 1, DP–Dam Pond basalt; Mills and Sandeman, 2015).

The chemical diversity within volcanic rocks assigned to the BAF highlights the need for targeted, detailed stratigraphic, lithogeochemical and geochronological studies of the BAF and overlying sedimentary successions to better understand changes in tectonic setting throughout the latest Neoproterozoic. This paper provides the first documentation of precise U–Pb zircon (CA-ID-TIMS) constraints on the BAF within a lithological and petrological context.

SAMPLE DESCRIPTIONS AND PETROGRAPHY

15AM125 – CRYSTAL ASH TUFF (SUMMERVILLE ROADCUT; WEST SIDE OF PLATE COVE VOLCANIC BELT)

A 2 by 3 km area of the PCvb was mapped in detail (1:4000), and a cross-section through the roadcut east of Summerville was constructed as part of a B.Sc. (Hons.) thesis (Wilson, 2015; Figure 2A, B). No U–Pb age was determined during the study due to abundant common lead in poor-quality zircon, which nullified the analytical results. A greenish-yellow, fine-grained, tuffaceous rock near the base of the BAF in the Summerville area was subsequently selected as an alternate geochronological target. The 30- to 40-cm-thick tuff layer occurs within a 100-m-thick package of maroon and grey-green shale that overlies basalt near the base of the roadcut exposure. It is overlain by a >100-m-thick basalt succession, which, in turn, is overlain by >10-m-thick quartz- and potassium-feldspar-phyric rhyolite flows, including the geochronology target of Wilson's (2015) thesis.

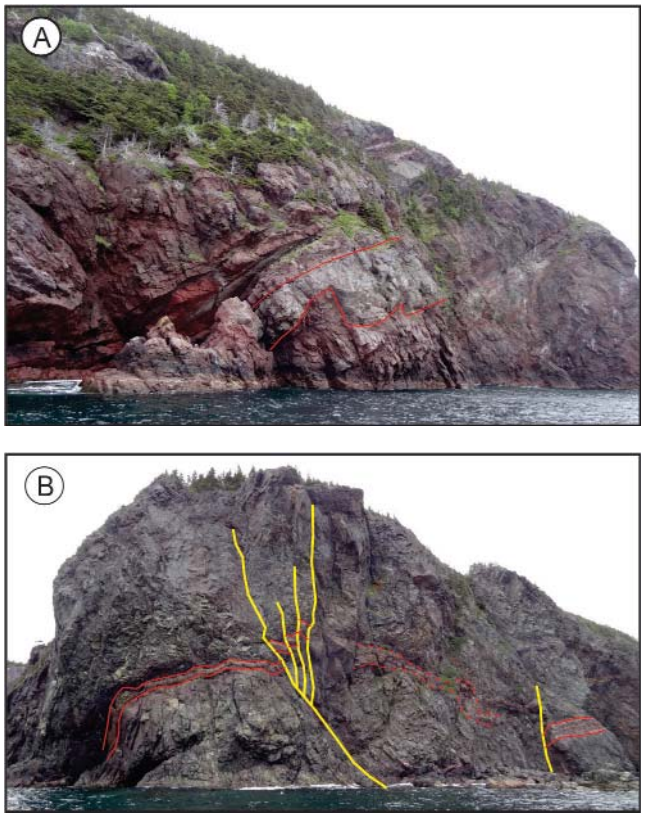


Plate 1. *Views of the Plate Cove volcanic belt. A) Half-graben fill (approximately 1 m thick at the thin neck adjacent to the graben) in a red interflow bed, indicative of syn-depositional extension (view to the southeast); B) A possible pop-up structure in mafic volcanics and red sandstone interbeds, consistent with north- to northwest-directed thrust faulting. Marker bed, outlined in red (dashed where confidence is low), is approximately 40–50 cm thick; view to the southeast.*

In thin section, the tuff is evidently weakly layered, contains very fine-grained, sub- to anhedral crystals of quartz, plagioclase, K-feldspar, and clinopyroxene (~200–400 μm), and <200 μm angular crystals and/or fragments of epidote. Locally, epidote appears to pseudomorph glass shards (Figure 2C, D).

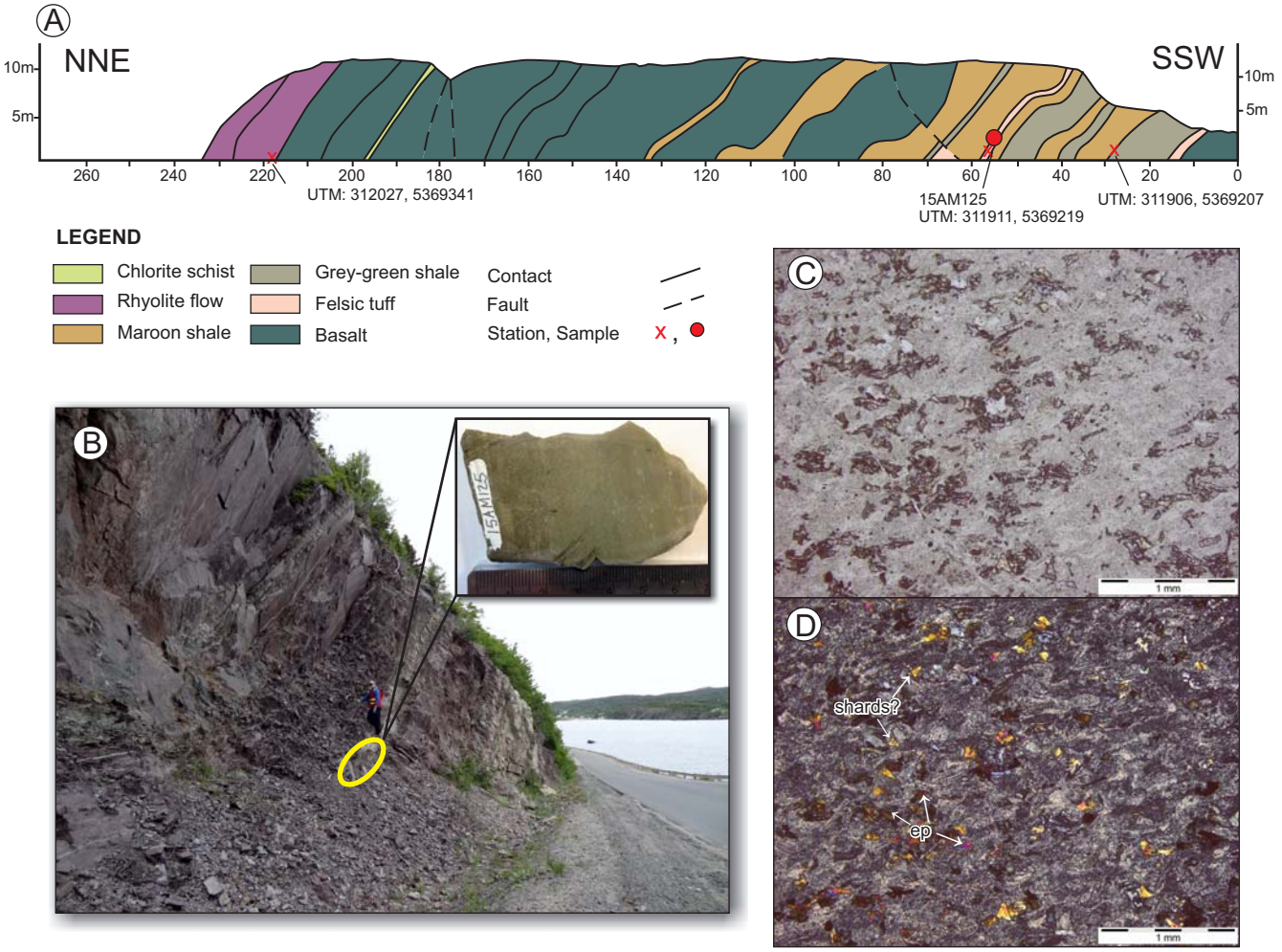


Figure 2. *Geological context for geochronology sample 15AM125. A) Cross-section of the roadcut exposure near Summerville, modified after Wilson (2015), showing location of the dated crystal tuff near the base of the section; B) Field photograph of the 30- to 40-cm-thick crystal ash tuff layer sampled for geochronological analysis (hand sample shown in inset) within a 100-m-thick shale sequence between basaltic rocks near the base of the roadcut exposure detailed in A; C) Photomicrograph of crystal ash tuff, sample 15AM125, containing possible glass shards and other crystals in a fine-grained matrix composed mainly of quartz, feldspar and white mica, shown in plane-polarized light; D) Sample 15AM125 shown in cross-polarized light; ep – epidote.*

15AM201 – CRYSTAL LITHIC LAPILLI TUFF (EAST SIDE OF PLATE COVE VOLCANIC BELT)

Crystal lithic lapilli tuff crops out near the eastern margin of the PCvb, approximately 1800 m east of the site of geochronology sample 15AM125 (Figure 1). The outcrop was exposed, in a wooded area, through mechanical stripping when the site was cleared for cabin construction. No contact relations were observed, but mapping indicates that the lapilli tuff overlies a thick succession of rhyolite flows to the west and is overlain by volcanic-clast-dominated polymictic conglomerate previously assigned to the Plate Cove facies (O'Brien and King, 2005) of the Rocky Harbour Formation. The lapilli tuff was therefore thought to occur near the top of the volcanic sequence and was sampled to provide an upper constraint on the timing of magmatism within the PCvb.

At the northernmost exposure of this site, rounded, white-weathering fragments are included within red-weathering, banded volcanic rock (Plate 2A), whereas approximately 15 m to the south, angular, red, feldspar-phyric rhyolite fragments are included within a white-weathering, tuffaceous matrix (Plate 2B). These observations are consistent with the presence of multiple eruptive units within this outcrop area.

In thin section, larger grains are identified as quartz phenocrysts, altered and rounded, brownish feldspar phenocrysts, relatively coarse crystalline volcanic rock frag-

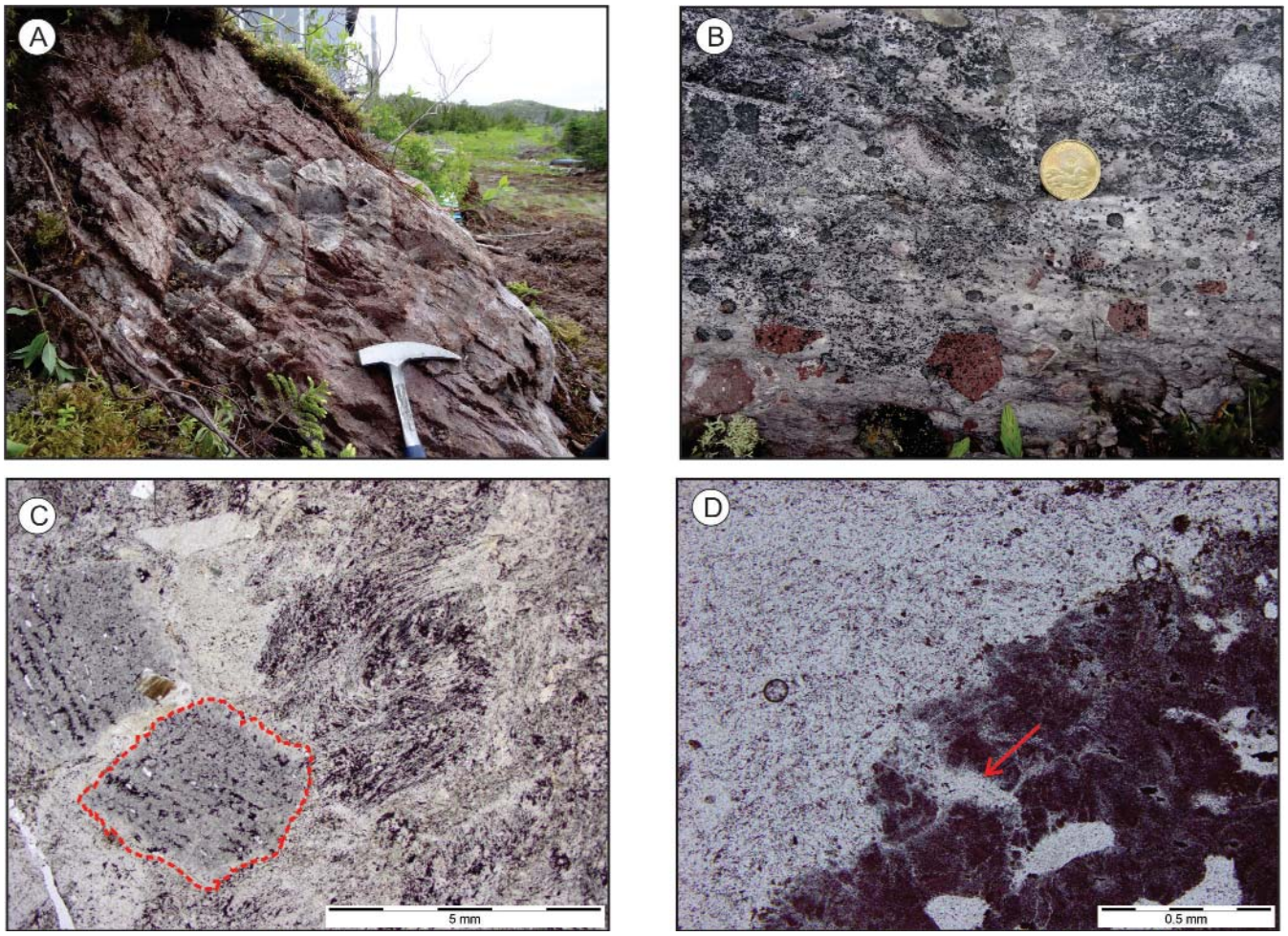


Plate 2. *Field photographs and photomicrographs of sample 15AM201. A) White, elongate clasts interpreted as lapilli incorporated in red, rhyolite flow; B) Clasts of red, feldspar-phyric rhyolite in white tuffaceous rock; C) Photomicrograph (in plane-polarized light) showing irregular, locally cuspate and lobate rims of rhyolite clasts (highlighted in red); D) Photomicrograph (in plane-polarized light) showing diffuse outer margin and deep embayment (red arrow) along the rim of a feldspar-phyric clast, consistent with incorporation of fragments into the rock while still hot.*

ments having cuspate margins and embayments, and glassy fragments, locally feathery textured. The feldspars either lack twins or exhibit simple twinning, contain thin, distinctive and resorbed rims, and common thermal cracks. Irregular (locally cuspate-lobate) margins (Plate 2C) and embayments up to 200 µm deep in quartz porphyritic volcanic clasts (Plate 2D) indicate that the fragments were likely hot when they were incorporated within the rock. It is therefore likely that eruption of the red, rhyolitic flow was coeval with ejection of the white-weathering tuffaceous rock.

15AM401 – BANDED RHYOLITE FLOW (FROM THE ROADCUT AT THE ISTHMUS OF AVALON)

Approximately 450 m of uninterrupted bedrock is exposed along the Trans-Canada Highway at the Isthmus of Avalon, 21.5 km south of Bull Arm, affording excellent access to rhyolite flows and breccias of the BAF and overlying siliciclastic rocks (Figure 3A). Pink and black, quartz- and potassium feldspar-phyric, banded rhyolite near the base of the section was sampled for geochronological analysis (Figure 3A–C). The closest roadside outcrop west of the Isthmus roadcut is a felsic to intermediate tuff, exposed in a roadcut nearly 2 km to the west. The banded rhyolite is folded about a gently south-southwest-plunging axis and is overlain to the east by grey-green siltstone and lesser tuffaceous sandstone followed by two sequences of conglomerate-dominated siliciclastic rocks (Figure 3A, B). The lower conglomeratic sequence is a green, clast-rich to clast-poor, intermediate diamictite that is mainly structureless, but locally contains rare dropstones in a finely laminated (varve-like) matrix (Figure 3D). It is overlain by pistachio

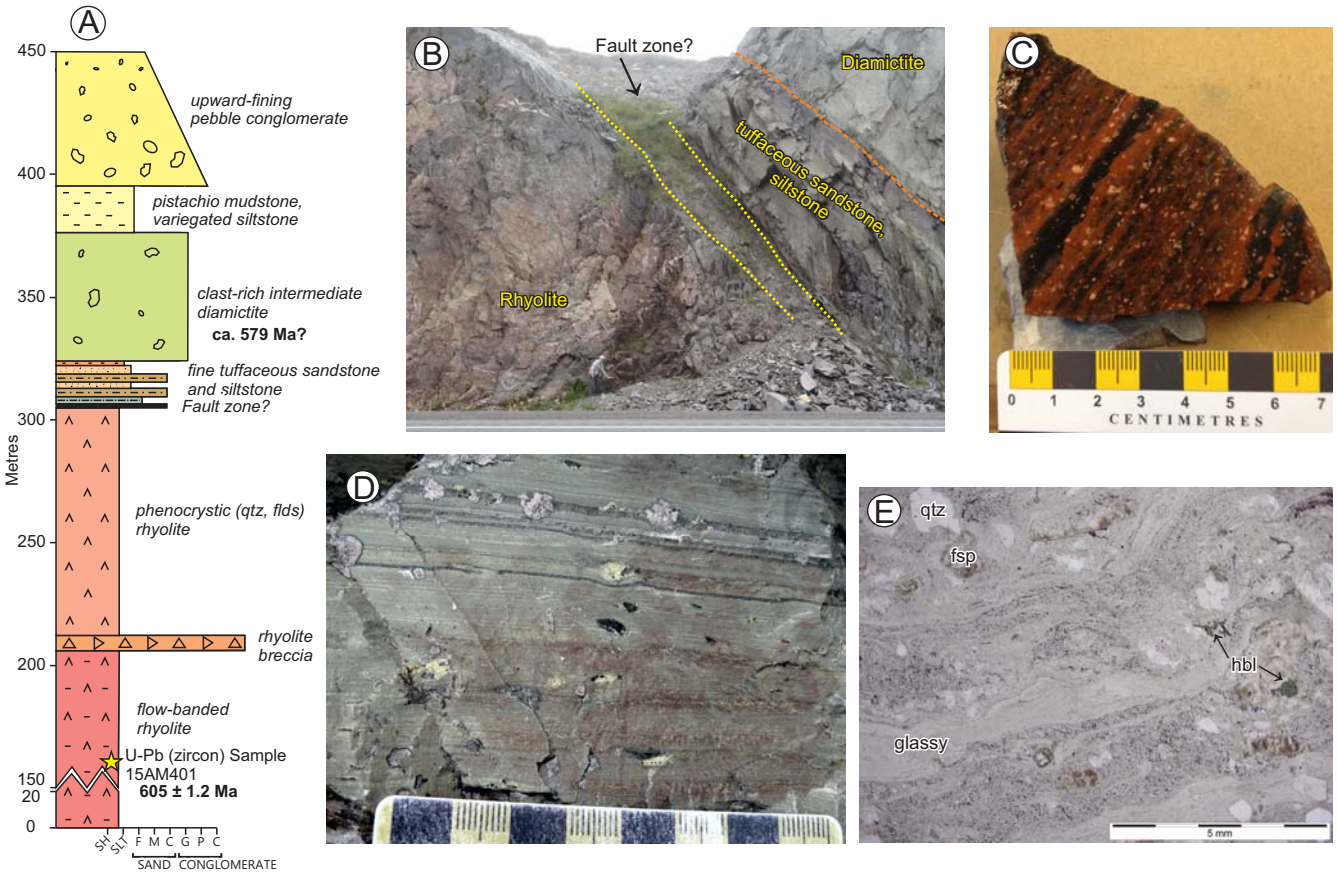


Figure 3. *Geological context for U–Pb (zircon) sample 15AM401. A) Schematic stratigraphic section of the ~450 m section exposed along the north side of the roadcut on the Trans-Canada Highway at the Isthmus of Avalon (Section represented in stratigraphic column starts at UTM coordinates 286710 m W, 5278663 m N, NAD 27, Zone 22); B) Upper contact of flow-banded rhyolite, showing possible fault contact with overlying tuffaceous siltstone and diamictite; view to the north; geologist is 154 cm; C) Rock slab of flow-banded rhyolite sampled for geochronological analysis; D) Possible dropstones in finely laminated component of the diamictite; E) Photomicrograph of 'Isthmus rhyolite' showing flow-banding and quartz and feldspar phenocrysts in plane-polarized light; qtz – quartz, fsp – feldspar, hbl – hornblende.*

green mudstone and variegated (red to green) siltstone. These pass up into cross-stratified, granule to pebble conglomerate disposed in thick, fining-upward beds containing abundant felsic and mafic volcanic clasts and mm-scale black laminations comprising detrital magnetite.

In thin section, the banding in the dated rhyolite is characterized by clear, ultra-fine-grained, feldspathic bands alternating with fine-grained, quartz-dominated bands having minor, very fine-grained magnetite and amphibole disseminated throughout (Figure 3E). The feldspathic bands are K-rich and are interpreted as devitrified glass. Reflected light microscopy reveals the presence of minor, relict magnetite, locally surrounded by hematite. Quartz crystals are rounded and embayed, indicating that they have been partially dissolved, possibly due to magma mixing. Mineral liberation analysis and back-scattered electron microscope images show that zircon is commonly spatially associated with other accessory phases, including titanite, apatite, magnetite, annite, thorite and monazite (Plate 3).

ANALYTICAL METHODS

Samples were processed using standard methods of crushing and mineral separation under clean conditions, and representative fractions of small numbers of the highest-quality euhedral zircon prisms were selected from each rock for analysis (Plate 4). Representative zircon crystals from samples 15AM125 and 15AM401 were imaged by cathodoluminescence (CL) on the scanning electron microscope prior to U–Pb isotopic analysis by CA-TIMS at the Geochronology Laboratory at Memorial University of Newfoundland. Sample 15AM201 was not imaged due to the very low yield of zircon crystals. Analytical procedures are

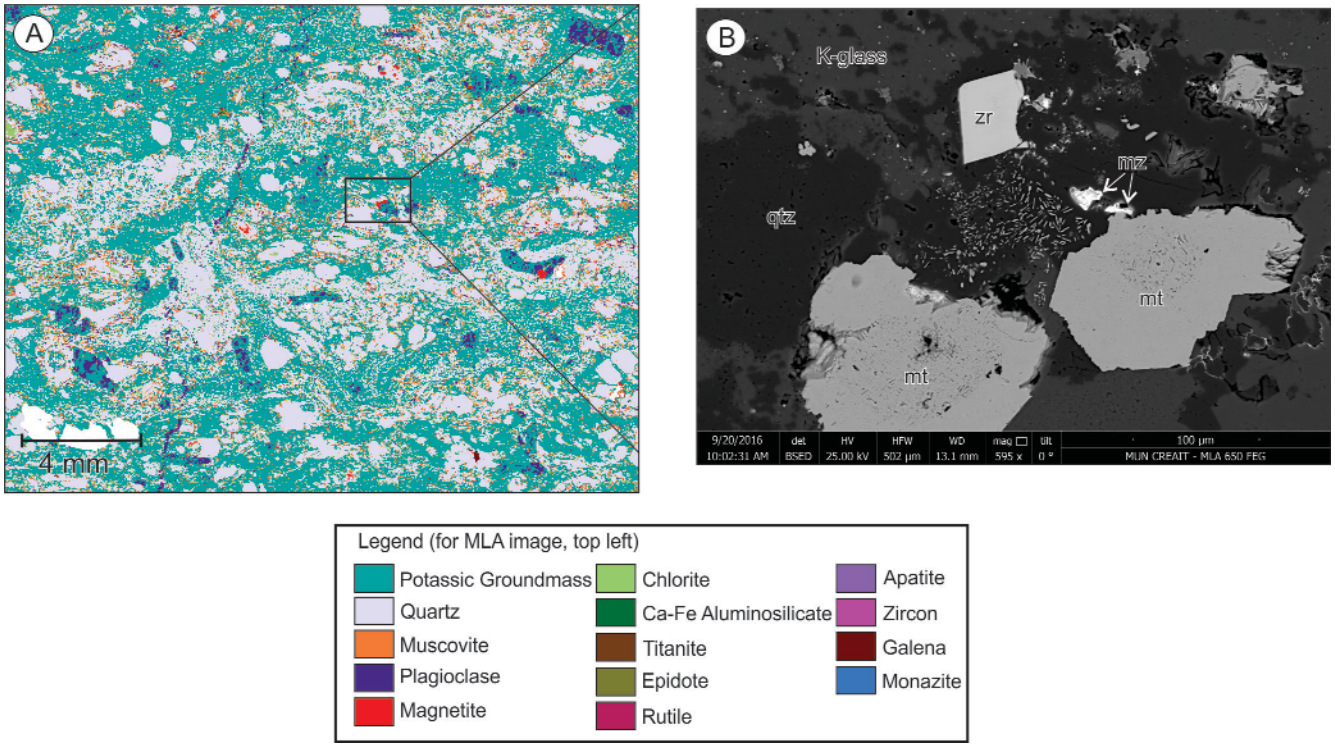


Plate 3. *A) Colour-coded image generated by mineral liberation analysis (MLA) showing mineralogy and textures in sample 15AM401; B) Back-scatter electron image showing zircon (zr) and spatially associated magnetite (mt) and monazite (mz) in groundmass of quartz (qtz) and potassic glass (K-glass). The fine laths in the centre of the photomicrograph are iron oxide, and the bright web-like lines in the bottom right are REE-rich.*

described in Krogh (1982). The chemical abrasion technique of Mattinson (2005) was used for single grain to small multi-grain analyses (up to 7 crystals) of zircon. Data are presented in Table 1 and Figure 4, with errors reported at the 2σ level. Data were plotted using unpublished in-house software. 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.

ZIRCON MORPHOLOGY AND GEOCHRONOLOGY RESULTS

Sample 15AM125 yielded a population of small, clear euhedral zircon prisms, as well as some rounded grains, likely a detrital component, which were not analyzed (Plate 4). The CL imagery reveals distinct cores in two of the zircons imaged (Figure 4A). One zircon crystal exhibits two corroded surfaces of pre-existing zircon, marked by a highly luminescent (REE-rich) margin, surrounded by new zircon growth (Figure 4A). Oscillatory zoning is evident in all imaged zircons, consistent with igneous growth. Three analyses were carried out, after chemical abrasion, on fractions containing 2, 3 and 7 grains. Two fractions give overlapping concordant points, whereas Z3, a 7-grain fraction, yields a discordant point with a $^{207}Pb/^{206}Pb$ age of 686 Ma. Z1 and Z2 yield a weighted average $^{206}Pb/^{238}U$ age of 592 ± 2.2 Ma at the 95% confidence interval (CI; Mean Square of Weighted Deviates, MSWD = 0.48; Figure 4).

Sample 15AM201 yielded a population of small, euhedral, clear prisms, having minor cracks and inclusions (Plate 4). Three analyses, of 1 or 3 grains each, were carried out after chemical abrasion, and resulted in overlapping concordant analyses with $^{206}Pb/^{238}U$ ages from 590.9 ± 2.4 to 591.6 ± 3.8 Ma (Figure 4). The weighted average $^{206}Pb/^{238}U$ age is 591.3 ± 1.6 Ma (95% CI, MSWD = 0.072).

Sample 15AM401, from the Isthmus of Avalon, yielded a population of abundant uniform, small, euhedral zircon prisms (Plate 4). Six analyses were carried out on small fractions of 1 to 5 prisms after chemical abrasion (Table 1). Some have higher common lead in the analysis, but all are

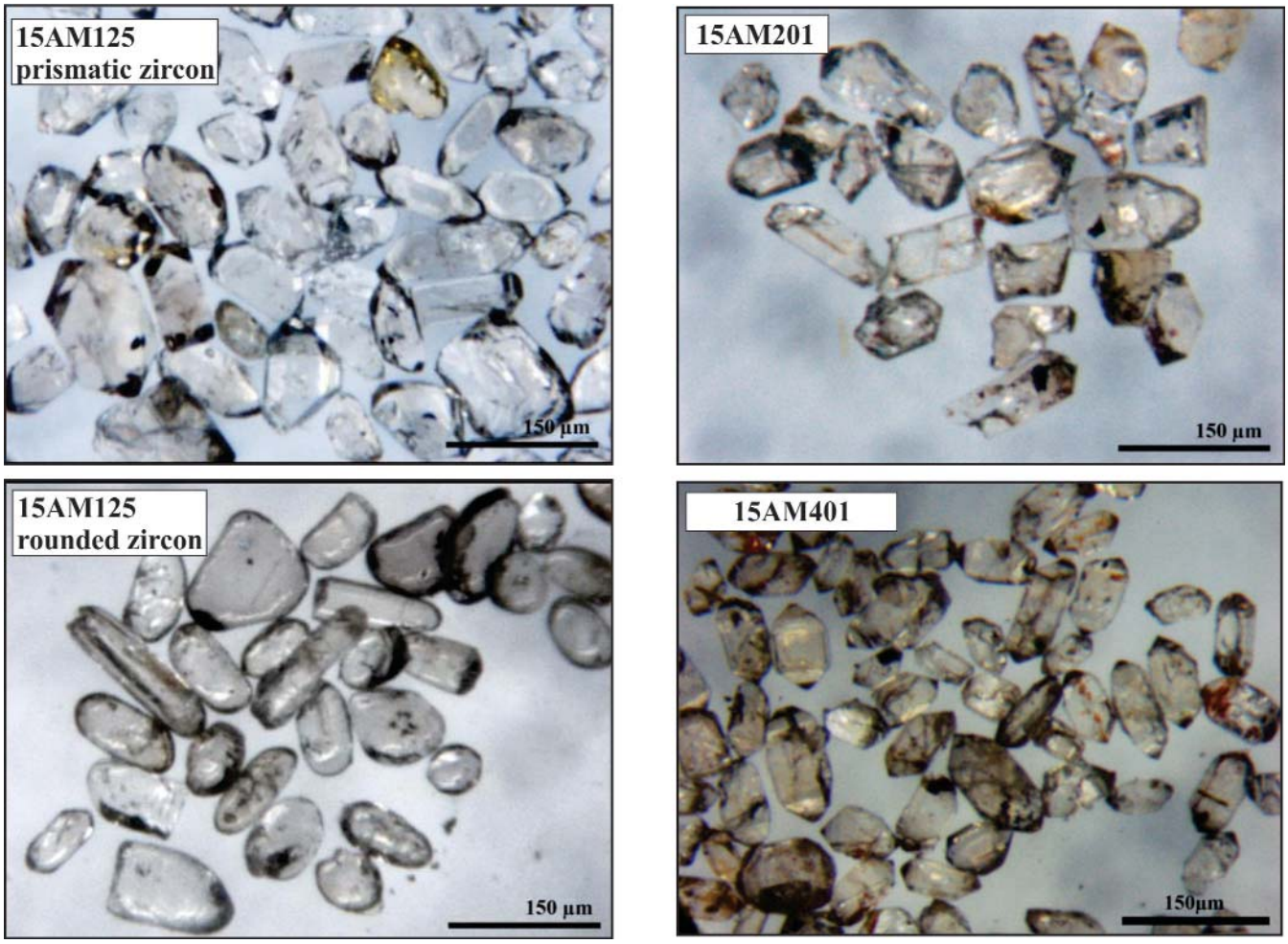


Plate 4. *Photomicrographs of zircon populations isolated from geochronology samples analysed for this study.*

concordant and overlapping, with $^{206}Pb/^{238}U$ ages ranging from 602.8 ± 3 to 607.4 ± 3.2 Ma. Together, all six analyses yield a weighted average $^{206}Pb/^{238}U$ age of 605.1 ± 1.2 Ma (95% CI, MSWD = 1.0; Figure 4).

INTERPRETATION

Two tuffaceous rocks from the west and east sides of the PCvb on the Bonavista Peninsula yielded similar $^{206}Pb/^{238}U$ ages of 592 ± 2.2 Ma and 591.3 ± 1.6 Ma, respectively. Syndepositional extension within the PCvb (Plate 1A) is inferred to have occurred at about the same time. The easternmost of the two samples was collected to provide a younger constraint on volcanism in the PCvb, but unexpectedly yielded a similar crystallization age to that of the sample from the western margin. Most of the rocks within the PCvb dip moderately to steeply to the east, but younging direction is difficult to determine within the mainly volcanic succession and the effect of Neoproterozoic Avalonian folding is not yet clearly understood (Mills *et al.*, 2016a). Coeval volcanism at the western and eastern margins of the PCvb is consistent with either rapid deposition of the volcanic sequence or moderate to tight, upright folding during Acadian deformation, as documented elsewhere on the Bonavista Peninsula (Mills *et al.*, 2016a). The age of volcanism within the PCvb, therefore, remains to be more tightly constrained but should await more detailed (1:5000 or better) structural and stratigraphic mapping complemented by petrological studies of the volcanic belt and adjacent rocks.

The stratigraphic succession at the Isthmus of Avalon (Isthmus sequence), approximately 95 km south of the dated tuffs from the PCvb, differs substantially from the stratigraphy of the PCvb. The nearest outcrop to the west of the Isthmus roadcut is a tuff located 1990 m to the northwest of the Isthmus sequence, and is presumed to be older than the banded rhyolite at the base of the measured section (Figure 3). Possible correlatives on the Avalon Peninsula include units formerly known as the Harbour Main Group: the

Table 1. U–Pb zircon data for samples from the Bull Arm Formation, central Avalon Terrane, Newfoundland

Fraction	Weight (mg)	Concentration U	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) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
15AM125 Crystal ash tuff – Summerville (311911/5369219)															
Z1 3 clr euh prm	0.004	31	3.7	5.2	179	0.4003	0.09610	46	0.7850	158	0.05924	110	591.5	588	576
Z2 2 clr euh prm	0.003	154	16.2	3.1	909	0.2088	0.09639	70	0.7937	44	0.05972	34	593.2	593	594
Z3 7 clr euh prm	0.010	165	18.8	4.2	2702	0.2175	0.10392	46	0.8935	38	0.06236	18	637.3	648	686
15AM201 Crystal lithic lapilli tuff – Summerville (313699/5369202)															
Z1 3 sml sharp prm	0.003	174	18.8	2.4	1337	0.2489	0.09600	40	0.7882	42	0.05955	26	590.9	590	587
Z2 1 clr sharp prm	0.001	310	33.1	3.6	533	0.2321	0.09610	54	0.7878	76	0.05946	48	591.5	590	584
Z3 1 clr euh prm	0.001	536	55.5	2.4	1381	0.1915	0.09612	64	0.7908	74	0.05967	48	591.6	592	592
15AM401 Flow-banded rhyolite – Isthmus of Avalon (286710/5278663)															
Z1 5 clr euh prm	0.005	370	39.0	75	169	0.1788	0.09860	56	0.8134	129	0.05983	86	606.2	604	597
Z2 1 clr euh prm	0.001	189	19.8	4.1	306	0.1745	0.09880	54	0.8104	97	0.05948	64	607.4	603	585
Z3 4 clr euh prm	0.004	142	14.8	20	191	0.1702	0.09833	70	0.7968	222	0.05877	154	604.6	595	559
Z4 3 clr euh prm	0.003	292	30.5	29	203	0.1745	0.09835	42	0.8118	60	0.05987	38	604.7	603	599
Z5 3 clr euh prm	0.003	238	24.7	6.6	682	0.1690	0.09803	50	0.8065	130	0.05967	88	602.8	600	592
Z6 2 clr euh prm	0.002	155	16.4	15	142	0.1874	0.09841	60	0.8101	146	0.05970	98	605.1	603	593

Notes: Z=zircon, 1,2,5 =number of grains, , sml=small, clr=clear, prm =prism, euh=euhedral.
All zircon was chemically abraded (Mattinson, 2005). Weights were estimated so U and Pb concentrations are approximate. * Atomic ratios corrected for fractionation, spike, laboratory blank of 2 picograms of common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 0.3 picogram U blank. Two sigma uncertainties are reported after the ratios and refer to the final digits.

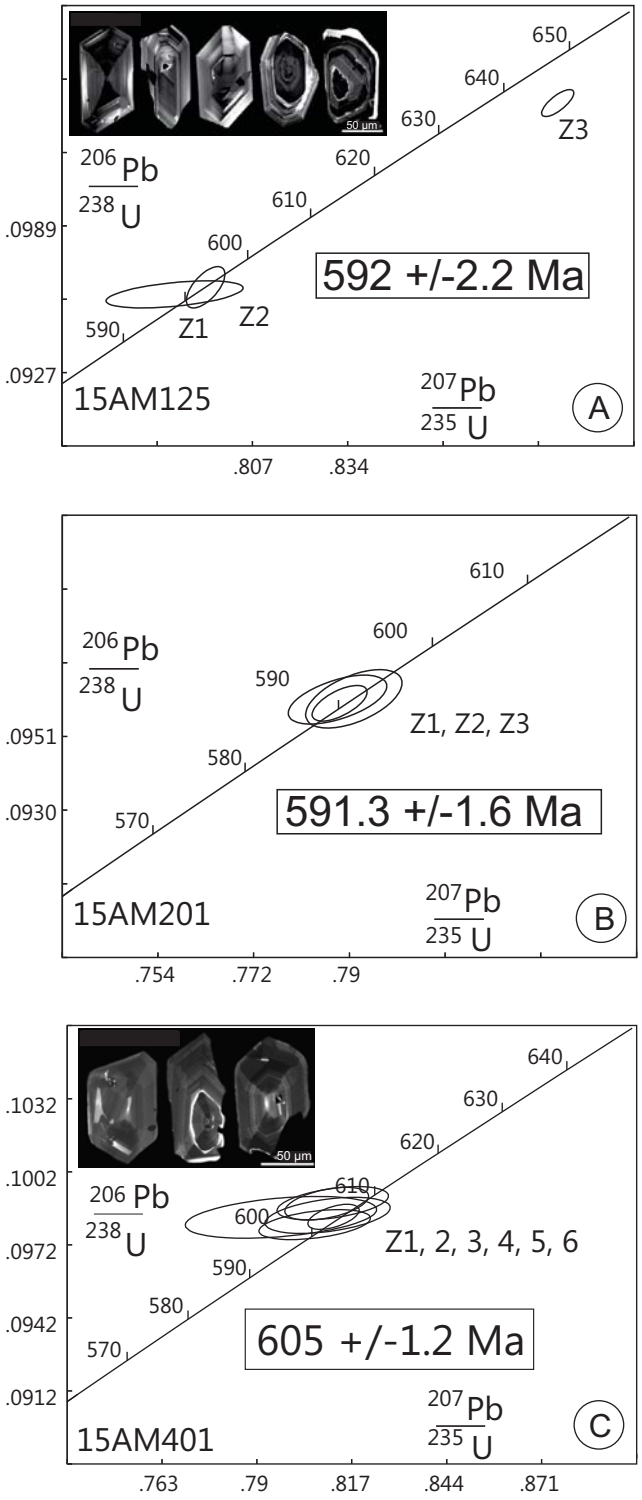


Figure 4. *Concordia plots for samples discussed in the text. A) Crystal ash tuff, sample 15AM125, from Summerville roadcut; B) Crystal lithic lapilli tuff, sample 15AM201, from eastern margin of the Plate Cove volcanic belt; C) Quartz- and potassium feldspar-phyric, banded rhyolite, sample 15AM401 from the Isthmus of Avalon.*

Hawke Hills tuff (729 ± 7 Ma; Israel, 1998), the Triangle Andesite (>640 Ma; O'Brien *et al.*, 2001), and the Peak Tuff (*ca.* 622–606 Ma; O'Brien *et al.*, 2001). The 605 ± 1.2 Ma banded rhyolite at the Isthmus could itself be correlative to the Peak Tuff, or to another tuffaceous unit formerly assigned to the Harbour Main Group and previously dated at 606 +3.7/-2.9 Ma (Krogh *et al.*, 1988).

Well-preserved igneous flow textures, and the presence of ignimbrites and red beds at the Isthmus of Avalon, are consistent with subaerial deposition of the Isthmus rhyolite (*see* Malpas, 1971). Overlying the Isthmus rhyolite, thin-bedded, fine-grained, green-grey sandstone and siltstone, and a ~50-m-thick diamictite, were likely deposited in a marine setting. Minor laminated facies within the diamictite contains rare dropstones, indicative of a glaciomarine origin (Figure 3D). Pistachio-green mudstone and variegated (red to green) siltstone that overlie the diamictite resemble rocks that overlie the Trinity diamictite on the Bonavista Peninsula (Normore, 2011; Pu *et al.*, 2016). A provisional correlation can therefore be made between the 579 Ma Gaskiers–Trinity diamictites (Pu *et al.*, 2016) and the diamictite on the Isthmus of Avalon. These new age constraints indicate a significant depositional hiatus between 605 Ma and 579 Ma, and imply either an unconformity related to (or followed by) a marine transgression, a fault relationship, or a combination of both.

On the Bonavista Peninsula, glaciogenic diamictite of the Trinity facies (Normore, 2011) overlies a thick succession of Plate Cove conglomerate. The latter is folded about open, shallowly north-northeast–south-southwest-plunging axes and is intermittently exposed over 4.1 km, across strike, along Highway 230 between the eastern edge of the PCvb and the first exposure of the Trinity diamictite to the east (*see* Normore, 2011; Mills, 2014). This thick conglomeratic sequence is apparently missing in the roadcut section exposed at the Isthmus of Avalon.

In the Sweet Bay area of western Bonavista Bay, a lithic tuff, deposited in a shallow-marine setting near the top of the CPG, yielded an age of 605 ± 2.2 Ma (Mills *et al.*, 2016b). There, the CPG is unconformably overlain by *ca.* 600 Ma interbedded red pebble conglomerate and basalt flows, characteristic of basal MG units described elsewhere on the Bonavista Peninsula (*e.g.*, Jenness, 1963; O'Brien, 1993, 1994). The >300-m-thick, 605 ± 1.2 Ma felsic volcanic succession at the Isthmus of Avalon likely formed proximal to a major felsic volcanic centre and may represent a source for zircon and volcanic detritus in shallow-marine tuffs near the top of the CPG in the Bonavista Bay area.

IMPLICATIONS FOR THE EVOLUTION OF THE BONAVISTA AREA

Geochronological results, combined with structural observations and petrogenetic studies, help to constrain the Neoproterozoic evolution of the Avalon Terrane exposed on the Bonavista Peninsula (Figure 5). The CPG is the remnant of an arc-adjacent marine basin that accumulated between *ca.* 620 (O'Brien *et al.*, 1989; Dec *et al.*, 1992) and *ca.* 605 Ma (Mills *et al.*, 2016b). Between 605 and 600 Ma, turbidite deposits of the CPG underwent north-directed thrusting that resulted in local unconformities and imbricate stacking of a fold and thrust belt (Mills *et al.*, 2016a, b; Stage 2, Figure 5). East-side down, normal faulting along the Indian Arm fault west of the PCvb (Stage 3, Figure 5) likely followed *ca.* 592 Ma transitional volcanism (weakly calc-alkaline basalts derived from a shallow, lithosphere-contaminated, enriched mid-ocean ridge basalt source; Mills and Sandeman, 2015), and culminated in deposition of the coarse, clastic wedge known as the Plate Cove conglomerate (O'Brien and King, 2005). A tectonically quiescent period followed (Stage 4, Figure 5), during which the 579 Ma Gaskiers-equivalent, glaciomarine Trinity diamictite (Pu *et al.*, 2016) and overlying grey siltstone of the Big Head Formation were deposited. North-directed thrust-faulting, likely the Avalonian orogenic event described by Anderson *et al.* (1975), occurred again at some time post-565 Ma, affecting rocks correlative to the *ca.* 565 Ma Mistaken Point Formation near the community of Trinity (Stage 5, Figure 5; Mills *et al.*, 2016a). This terminal Neoproterozoic event preceded deposition of the Early Cambrian Random Formation and possibly parts of the Crown Hill Formation.

IMPLICATIONS FOR AVALONIAN CORRELATIONS

The new age constraints facilitate correlation with tectonostratigraphic divisions from other Avalonian terranes (*e.g.*, Thompson *et al.*, 2014; Figure 6). Thompson *et al.* (*op. cit.*) correlate the conglomeratic Cannings Cove Formation and overlying BAF to Roxbury Conglomerate and 585 to 584 Ma Brighton Igneous Suite of the Boston Basin (based on former stratigraphic interpretation of the 570 +3/-2 Ma rhyolite as part of BAF). However, the new age data are more consistent with correlation of at least the 592 to 591 Ma PCvb component of BAF and overlying Plate Cove conglomerate to the 597–593 Ma Lynn-Mattapan Volcanics and overlying <595 Ma Roxbury Conglomerate (Thompson *et al.*, 2014). Deposition of the Roxbury Conglomerate is interpreted to be syndepositional with respect to Ediacaran normal faulting (Thompson, 1993). The Plate Cove conglomerate on the Bonavista Peninsula is

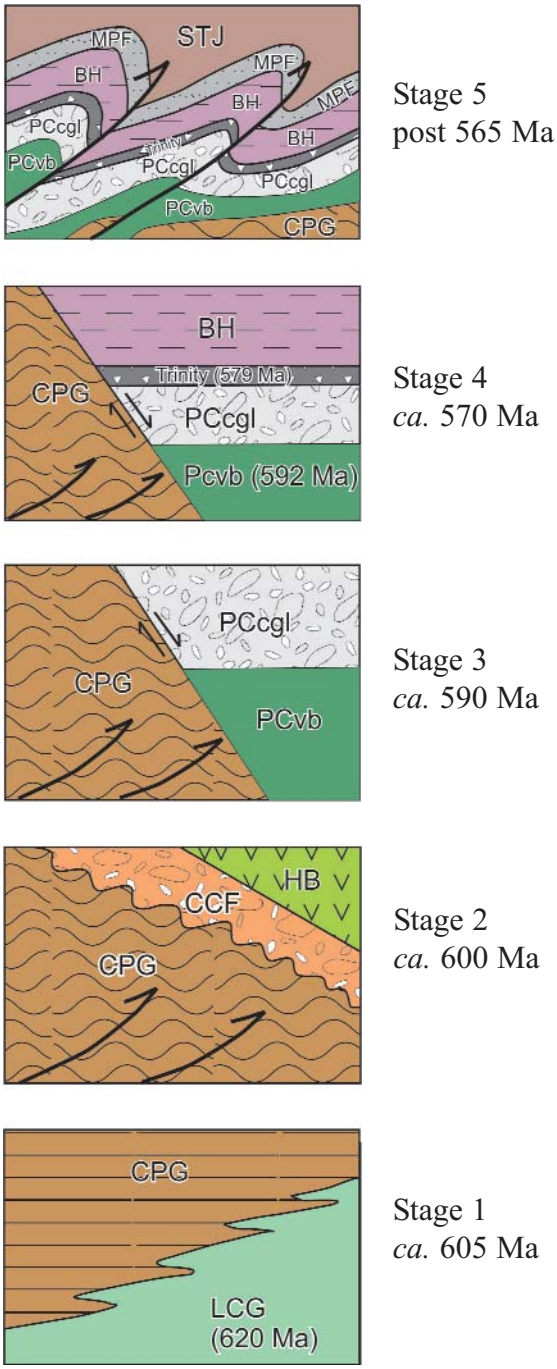


Figure 5. *Summary sketch of the evolution of the Bonavista area. CPG – Connecting Point Group; LCG – Love Cove Group; CCF – Cannings Cove Formation; HB – Headland basalt; PCvb – Plate Cove volcanic belt; PC cgl – Plate Cove conglomerate; Trinity – Gaskiers equivalent Trinity diamictite; BH – Big Head Formation; MPF – Mistaken Point Formation; STJ – St. John's Group. Geochronological constraints are from O'Brien* et al. *(1989) (620 Ma LCG); Pu* et al. *(2016) (579 Ma Gaskiers Formation and Trinity diamictite); Mills* et al. *(2016b) and* this study.

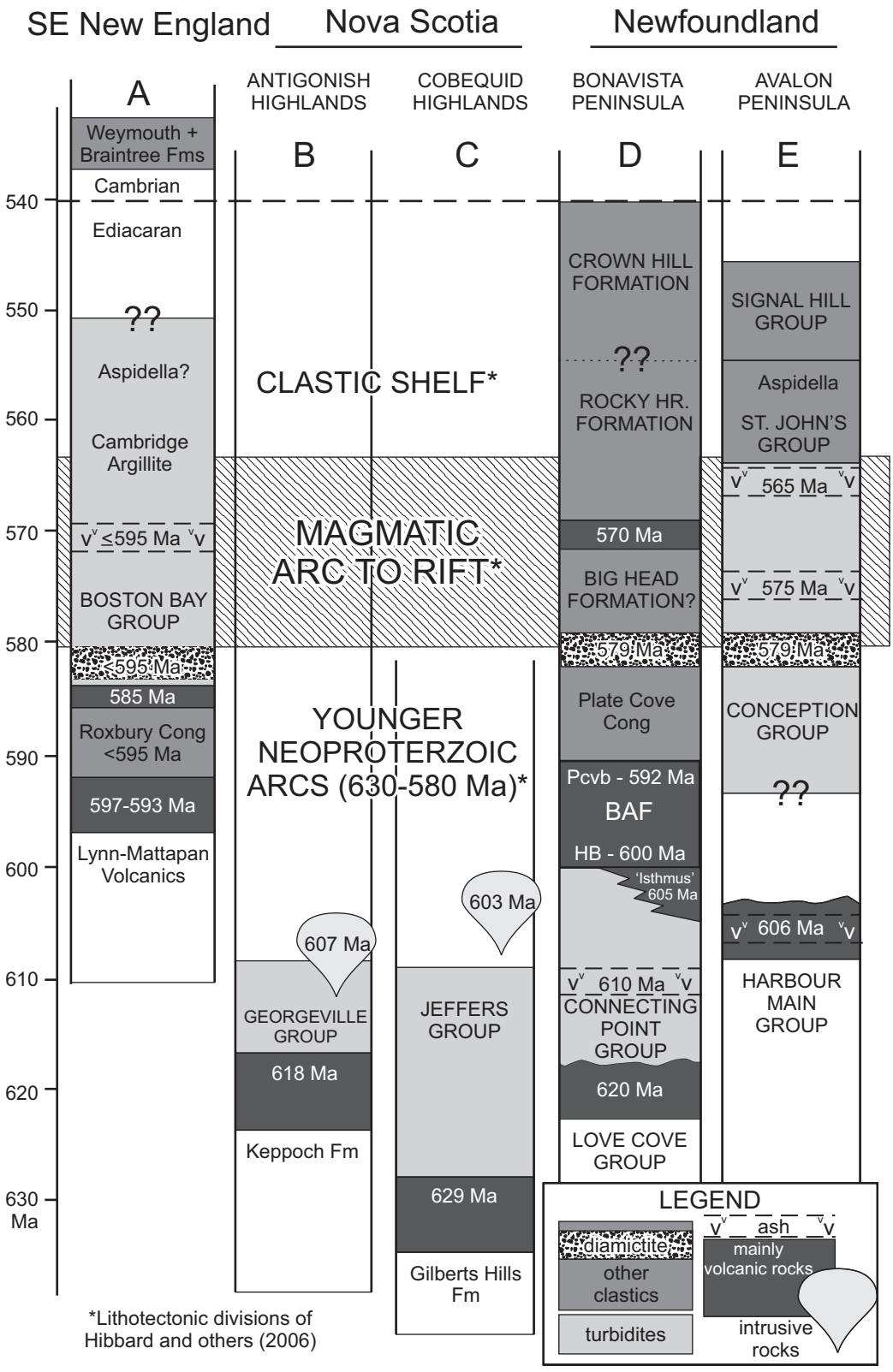


Figure 6. *Tectonostratigraphic comparison of Ediacaran sequence of Avalon Terrane in A) Southeast New England; B) Antigonish Highlands, NS; C) Cobequid Highlands, NS; D) Bonavista Peninsula, NL; E) Avalon Peninsula, NL. Age constraints from outside Newfoundland are from Thompson* et al. *(2014) and references therein. Newfoundland age constraints are from Mills* et al. *(2016b) and Pu* et al. *(2016).*

similarly inferred to have been deposited during extensional or transtensional movements.

No arc-related rocks have been identified on the Bonavista Peninsula as possible correlatives to the 585 to 584 Ma Brighton Igneous Suite from the Boston area (Thompson *et al.*, 2014). Volcanic rocks on the Bonavista Peninsula that are considered to be younger than the 592 to 591 Ma PCvb include: 1) the alkaline Dam Pond basalt (Mills and Sandeman, 2015); 2) transitional, weakly calc-alkaline to EMORB-like mafic flows and possibly correlative intrusive rocks (Series 1 of the PCvb and Type-3 dykes of Mills and Sandeman, this volume); and 3) the weakly alkaline mafic volcanic and intrusive rocks recently identified in the British Harbour area, southwestern Bonavista Peninsula (Figure 1; Mills and Sandeman, *this volume*). The youngest, clearly arc-related volcanic rocks identified on the Bonavista Peninsula are the *ca.* 600 Ma HB (Mills and Sandeman, 2015; Mills *et al.*, 2016b). Series 2 basalts of the 592 to 591 Ma PCvb exhibit a transitional to weakly calc-alkaline affinity, and are likely derived from a shallow mantle, E-MORB source (Mills and Sandeman, 2015). Thus, on the Bonavista Peninsula, rocks of the PCvb appear to herald a transition from *ca.* 600 Ma subduction-dominated tectonic processes to *ca.* 592 Ma extensional processes, with younger rocks showing more alkaline affinity. A *ca.* 590–570 Ma arc to platform transition (*e.g.*, Thompson, 1993; Nance and Murphy, 1996; Pollock *et al.*, 2009; Thompson *et al.*, 2014) has been recognized in many parts of the Avalon Terrane (*see* Figure 5), but its timing remains unclear and may be diachronous across disparate parts of the Avalon Terrane (*e.g.*, Murphy *et al.*, 1999).

SUMMARY

As currently defined, the BAF on the Bonavista and Avalon peninsulas is clearly composite, comprising rocks of different chemistries and ages. The PCvb is younger than, and therefore overlies, the CPG on the Bonavista Peninsula. In contrast, the Isthmus sequence is age-equivalent to the upper CPG and may be the source of volcanic detritus in the latter's ash layers. The original dated rhyolite sample from Wolf Island (O'Brien *et al.*, 1989) is perhaps most appropriately assigned to the Big Head Formation, which may rest unconformably on all of the above units (CPG, PCvb, and the Isthmus sequence). In light of this data, an updated formal definition of the BAF is required.

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