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VOLCANIC ARC TO ARC-RIFT TRANSITION AT CUTLER HEAD, SWEET BAY AREA, BONAVISTA PENINSULA

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ABSTRACT

Cutler Head is one of three headlands or promontories in the Sweet Bay area, Bonavista Peninsula, where terrestrial siliciclastic and volcanic rocks of the Musgravetown Group, which overlie upper parts of the marine Connecting Point Group, are exposed. The contact is not exposed at Cutler Head and faulted at Maiden Hair Cove head, whereas at Southward Head, the easternmost of these three headlands, the contact is preserved as an angular unconformity on the east side, but faulted on the west side. Previous geochronological constraints bracket the unconformity at Southward Head to be between 605 and 600 Ma. Basaltic flows above the unconformity at Southward Head and at Maiden Hair Cove head ("Headland basalts") are calc-alkaline. At Cutler Head, the stratigraphically lowest basalt flow is calc-alkaline, whereas the upper flows are andesitic and transitional (weakly calc-alkaline to tholeiitic) rocks that originated from a shallow asthenospheric source, similar to basalts of the Plate Cove volcanic belt (Series 2; PCvb2). Although no direct age constraint is available for this tectonomagmatic transition, it must postdate 600 Ma, the age of the basal Musgravetown Group tuff dated at Southward Head, one metre above which lies a calc-alkaline basalt flow. The intervening sedimentary section at Cutler Head reflects depositional changes in response to this magmatic shift. Rocks below and above the lower, calc-alkaline basalt comprise a shoaling-upward, shallow-marine to terrestrial sequence, including thick, commonly red, volcaniclastic boulder to cobble conglomerate, possibly deposited in response to extensional tectonics. This redbed-dominated succession, referred to as the Kate Harbour formation, marks the transition from deep marine sedimentation, typical of the Connecting Point Group, to a shallow marine-to-terrestrial depositional environment. In parts of the Sweet Bay area, this transition is gradational within Connecting Point Group strata, but elsewhere the transition is abrupt and occurs at the base of the Musgravetown Group (basal, conglomeratic Cannings Cove Formation) where faulting, depositional hiatus (unconformity), or both, control the stratigraphy.

REGIONAL SETTING

The Connecting Point Group (CPG; Hayes, 1948) comprises a southward-narrowing belt of Neoproterozoic, epiclastic, marine turbiditic rocks that extends from Bonavista Bay in the north to Placentia Bay, some 20 km south of Goobies, in the south (Figure 1). These deep-marine basin rocks formed adjacent to a volcanic arc, remnants of which are preserved as the *ca.* 620 Ma Love Cove Group (Widmer, 1949; Jenness, 1963; Dec *et al.*, 1992). The CPG is unconformably overlain by latest Neoproterozoic, terrestrial- to shallow-marine sedimentary and volcanic rocks of the Musgravetown Group (MG; Hayes, 1948; Christie, 1950). Jenness (1963) subdivided the MG into four formations, with undivided rocks occupying the middle, between the lower two and upper two formations. In ascending order, these are the conglomeratic Cannings Cove Formation, the volcanic-dominated Bull Arm Formation (BAF), the shallow-marine Rocky Harbour Formation, and terrestrial redbeds of the Crown Hill Formation. The MG is succeeded by Lower Cambrian rocks of the Random Formation, a quartz-arenite-dominated, marine-shelf succession (Hiscott, 1982) which, along with other Cambro-Ordovician strata, formed a shallow-marine blanket over a peneplanated Precambrian surface (Smith and Hiscott, 1984).

LOCAL SETTING

In the Sweet Bay area, turbiditic sandstone of the upper CPG is conformably and gradationally overlain by arkosic sandstone and granular to pebbly, variegated (red to green) conglomerate (O'Brien, 1994; Mills, 2014; Plate 1A). Early workers (Hayes, 1948; Christie, 1950) assigned these rocks to the MG; whereas Jenness (1963) included them in the CPG, based primarily on the assumption that the base of the MG should be drawn at the unconformity at Southward Head. On the east side of Southward Head, an angular unconformity clearly separates steeply dipping, medium-bedded, pinkish-grey tuffaceous sandstone from overlying, shallowly north-dipping, red cobble conglomerate and basalt. The unconformity is faulted on the west side where steeply north-dipping tuffaceous sandstone is overlain by

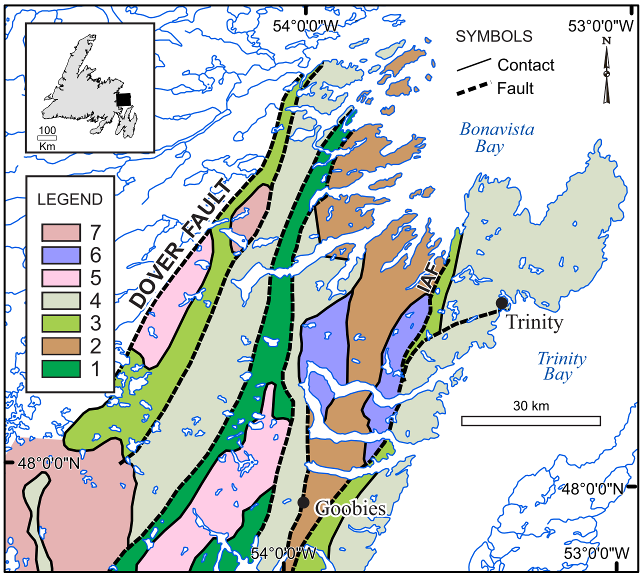

Figure 1. *Simplified geology map of the northwestern Avalon Terrane in Newfoundland, including the Bonavista Peninsula, showing regional fault zones and broad lithostratigraphic units (modified from O'Brien, 1993). Key: 1 = Love Cove Group; 2 = Connecting Point Group; 3 = Musgravetown Group (mainly volcanic rocks); 4 = Musgravetown Group (mainly sedimentary rocks); 5 = Precambrian granite; 6 = Cambrian sedimentary rocks; 7 = Devonian granite; IAF = Indian Arm fault.*

basalt without intervening conglomerate (Mills *et al.*, 2016b). The same conglomerate–basalt sequence occurs at two other headlands in the Sweet Bay area: Cutler Head and Maiden Hair Cove head (Figure 2). The contact between overlying conglomerate–basalt and underlying CPG rocks is unexposed at Cutler Head and appears faulted at Maiden Hair Cove (O'Brien, 1994; Mills, 2014).

REDBEDS OF THE UPPER CONNECTING POINT GROUP – LOWER MUSGRAVETOWN GROUP

O'Brien (1994) challenged Jenness' (1963) assignment of red sedimentary successions north of Southern Bay to the Connecting Point Group, assigning them instead, as earlier workers had, to the Musgravetown Group (Hayes, 1948; Christie, 1950). He noted that these "Unnamed Red Beds" occur in the northern Sweet Bay area and also south of Summerville, where he noted that they pass upward, without angular discordance, through the Crown Hill Formation, into the Random Formation. Assignment of the redbeds, both in the Sweet Bay area and in the area south of Summerville (Figure 2), to the MG was based on their shared basal relationship above upper CPG rocks (O'Brien, 1994), and the assumption that this unit, south of Summerville, passes conformably through uppermost MG rocks (Crown Hill Formation), into Lower Cambrian rocks of the Random Formation. O'Brien (1994) further speculated that if the correlation of redbeds in the northern Sweet Bay area to those south of Summerville, and their assignment to the MG, are correct, then the conglomerate–basalt sequences above the unconformity at Southward Head may be post-Cambrian.

Mills (2014) assigned O'Brien's (1994) "Unnamed Red Beds" to the Kate Harbour formation, a unit proposed to include commonly pebbly, arkosic sandstone and conglomerate that sit conformably and gradationally above thin- to medium-bedded, turbiditic rocks characteristic of the CPG. Rocks of the Kate Harbour formation vary from channelized

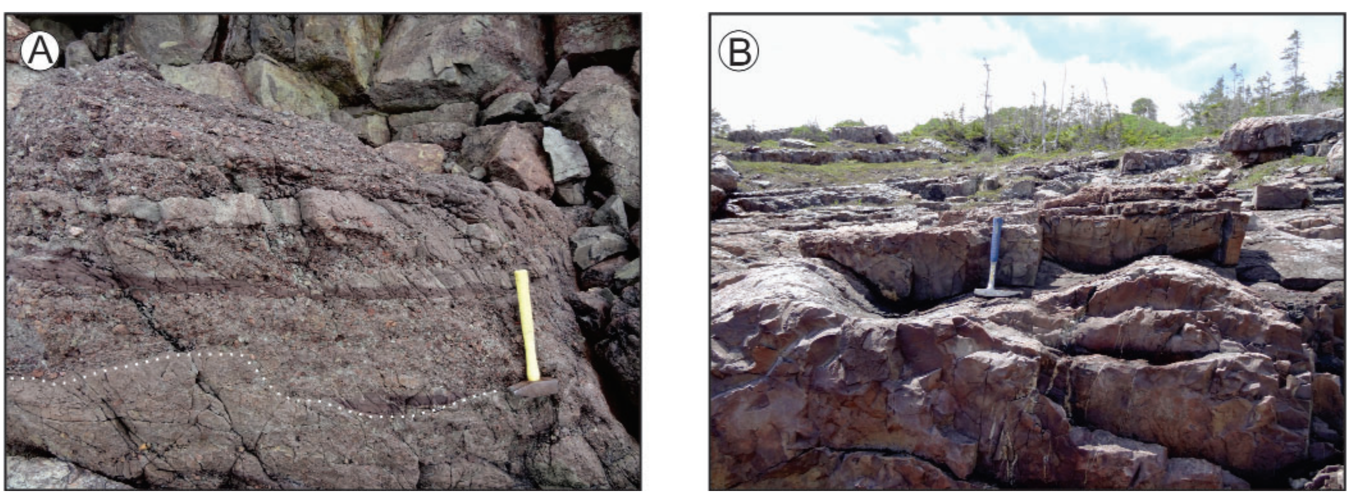

Plate 1. *Rocks of the Kate Harbour formation. A) Interbedded, red-grey pebble conglomerate and sandstone. Note conglomeratic channel with maroon sandstone lens at the base (UTMs: 307409m W, 5375645m N; NAD 27, Zone 22); B) Very coarse (metre-scale), wave ripples in thick- and wavy-bedded red sandstone (UTMs: 308730m W; 5371975m N; NAD 27, Zone 22).*

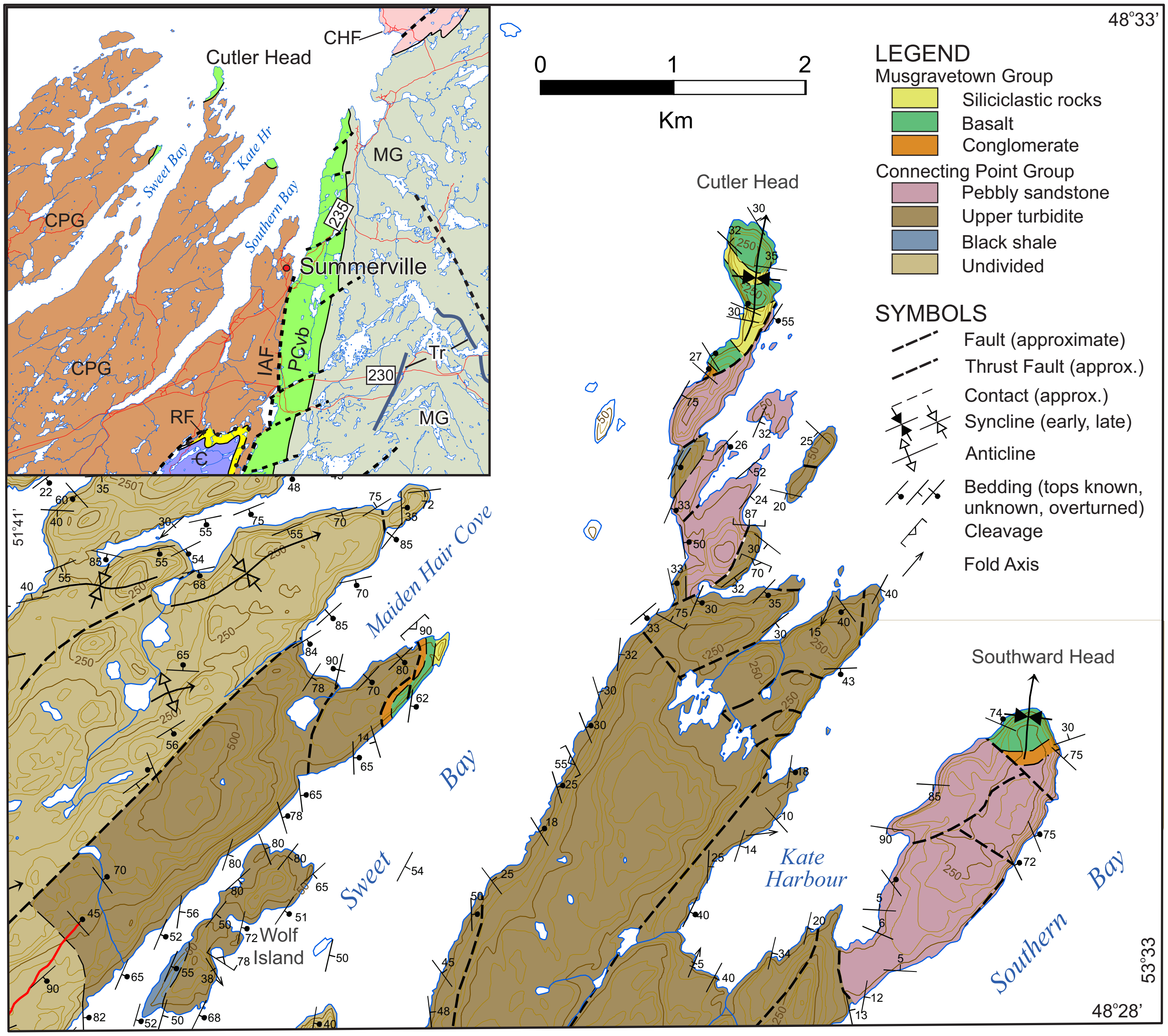

Figure 2. *Preliminary bedrock geology map of the northern Sweet Bay area (NTS 2C/5 and 12) showing the location of Musgravetown Group rocks on the headlands at Maiden Hair Cove, Cutler Head and Southward Head. Inset map shows the position of the headlands relative to Plate Cove volcanic belt (PCvb), Indian Arm fault (IAF), Random Formation (RF) and overlying Cambrian rocks, and units of the Musgravetown Group (MG) including the Crown Hill Formation (CHF) and the glacial Trinity facies (Tr) and Connecting Point Group (CPG).*

gravels (Plate 1A) to wavy-bedded sandstones locally preserving coarse wave-ripples (Plate 1B). These rocks likely reflect a shallow-marine to alluvial depositional environment, consistent with shoaling-up of the basin near its margin. Rocks assigned to the Kate Harbour formation are lithologically similar to the lower sedimentary sequences within the conglomerate–basalt successions at Cutler Head. This suggests that the depositional hiatus represented by the unconformity at Southward Head need not have been long and protracted. Indeed, tuffs above and below the unconformity at Southward Head yielded depositional ages of 600 ± 3 Ma and 605 ± 2.2 Ma, respectively (Mills *et al.*, 2016b), consistent with a relatively short depositional hiatus, and demonstrating that the conglomerate–basalt sequences exposed on the three headlands in the northern Sweet Bay area are basal MG rocks.

PREVIOUS LITHOGEOCHEMICAL INVESTIGATIONS

Mills and Sandeman (2015) investigated the lithogeochemistry of volcanic rocks on the Bonavista Peninsula, all of which had been previously assigned to the BAF (Jenness, 1963; O'Brien, 1994; Normore, 2010). These include basal MG basalts from the headlands of three promontories in Bonavista Bay (the Headland basalts: HB), the north-trending Plate Cove volcanic belt (PCvb) that outcrops east of the Indian Arm fault (*cf.* O'Brien, 1994; Figure 1 and Figure 2 - Inset), and basalts at Dam Pond (DP), east-central Bonavista Peninsula that occur within thin-bedded siliceous siltstones mapped as the Big Head Formation of the MG (Normore, 2010). The HB consist mainly of basaltic rocks having calc-alkaline characteristics that reflect a mature, continental arc (Mills and Sandeman, 2015). In contrast, basalts of the PCvb are transitional to weakly calc-alkaline, and are derived from a lithosphere-contaminated, enriched mid-ocean ridge basalt source, likely at shallower depths relative to the HB source. The DP basalts have distinct ocean island basalt (OIB) chemistry and have not been recognized in the current study area (Sweet Bay area; 2C/5; Figure 2).

CUTLER HEAD

Three headlands/promontories in the Sweet Bay area (Figure 2) preserve basal successions of the terrestrial siliciclastic and volcanic rocks of the MG. The stratigraphic succession exposed along the west side of the central promontory, Cutler Head, comprises a north-younging progression from pebbly sandstone and conglomerate overlain by basalt, through a coarse siliciclastic sequence, to andesitic flows at the northernmost tip of the Head. As the Headland basalts are separated from rocks of the PCvb by open ocean, through which passes the Indian Arm fault (Figure 2; O'Brien, 1994; Mills, 2014), the andesitic rocks at the northern tip of Cutler Head may provide some insight into the nature of the tectono-magmatic transition between Headland basalts and PCvb.

FIELD OBSERVATIONS

The west side of the Cutler Head promontory offers a nearly continuous section through the stratigraphy of the lower MG. There, the lowermost pebbly sandstone and granule to pebble conglomerate exhibit a variegated, red to green colour. As these coarse clastic rocks here are separated from the CPG by a fault, and are directly overlain by inferred BAF basalt, they should be assigned to the Cannings Cove Formation (Jenness, 1963). However, lithologically similar rocks (Kate Harbour formation; Mills, 2014) occur on the east side of the promontory, where they gradationally overlie thin-bedded, turbiditic and locally tuffaceous sandstone typical of the CPG. The red to green pebbly sandstones, on both the west (Cannings Cove Formation) and east (Kate Harbour formation) sides of Cutler Head contain common conglomeratic lenses and channels, consistent with a terrestrial (alluvial) depositional environment. Overall, rocks of the CPG have been interpreted to young to the south and east, but the distribution of Kate Harbour formation rocks, and their upward coarsening and thickening in the northern Sweet Bay area are consistent with the basin shoaling up to the east or northeast.

O'Brien (1994) provides a brief but relatively detailed summary of the stratigraphy exposed on the west side of Cutler Head. Lowermost red, grey and green sandstone, pebbly sandstone (Plate 2A) and conglomerate pass upward (to the north) into a 10-m-thick, reddish, coarsening-upward, followed by fining-upward, boulder- to pebble-conglomerate (Plate 2B, C) overlain by aphyric and then vesicular, subaerial basalt flows (Plate 2D, E). These flows are overlain by a red tuff-breccia, succeeded by red sandstone and conglomerate, in turn, overlain by volcaniclastic rocks, including a 30–50-cm-thick agglomerate unit (Plate 3B). Volcanic bombs within the agglomerate range from tear-shaped to fusiform, with vesicles elongated parallel to the long axis of the bomb, consistent with a projectile, pyroclastic origin (Plate 3C). The agglomerate is overlain by several metres of variegated, red to pale-green sandstone, succeeded by a <5-m-thick, matrix-supported boulder conglomerate (Plate 3D, E). This last unit was referred to by O'Brien (1994) as a mafic volcanic breccia, likely owing to the predominance of mafic volcanic boulders and patchy epidote alteration. However, the unit is polymictic, as it contains subordinate red and dark-grey sandstone cobbles. This mafic volcanic-dominated, matrix-supported, boulder conglomerate is overlain by thin-bedded, fine-grained red shale at the southern extent of its exposure. To the north, it is overlain by a 1.5-m-thick, white-weathering, highly siliceous conglomerate that is resistant to weathering relative to the underlying mafic-boulder conglomerate (Plate 3E). It is unclear whether the lack of continuity of the siliceous conglomerate is primary (facies variation) or secondary (fault-controlled). Two to three metres of thin-bedded red shale overlie the siliceous conglomerate, followed by 2–3-m-thick, siliceous, salmon-pink conglomerate (Plate 4). Massive andesitic flows cap the sequence.

PETROGRAPHY

The lowermost mafic volcanic flow (from the HB unit; 13AM335; Figure 3) appears highly altered in thin section (Plate 5). Plagioclase phenocrysts are up to 5 mm in length and are highly resorbed and saussuritized. Locally, clear, inclusion-free rims are preserved, indicating that the original cores may have been sieve-textured. Fine-grained matrix

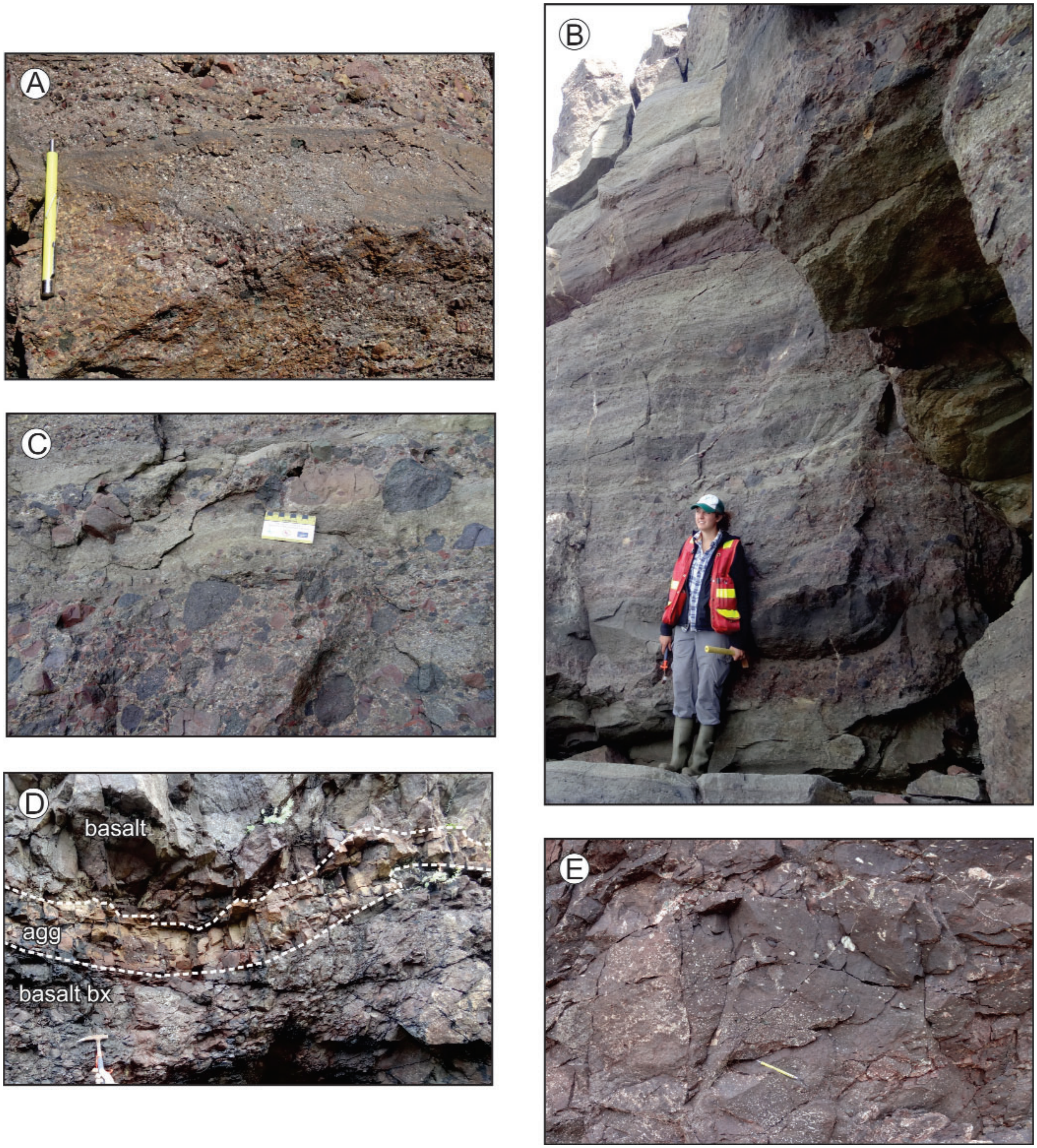

Plate 2. *Rocks from southern Cutler Head. A) Immature, volcaniclastic, pebbly sandstone with black laminations and distinctive foresets; B) Volcaniclastic, polymictic, cobble conglomerate; C) Detail of the cobble conglomerate shown in B; D) Basaltic breccia, overlain by thin, agglomerate containing bombs of amygdaloidal basalt, in turn overlain by basalt flow; E) Amygdaloidal basalt. (UTMs for A, B and C: 307782m W, 5377284m N; NAD 27, Zone 22; UTMs for D and E: 30802m W, 5377465m N; NAD 27, Zone 22).*

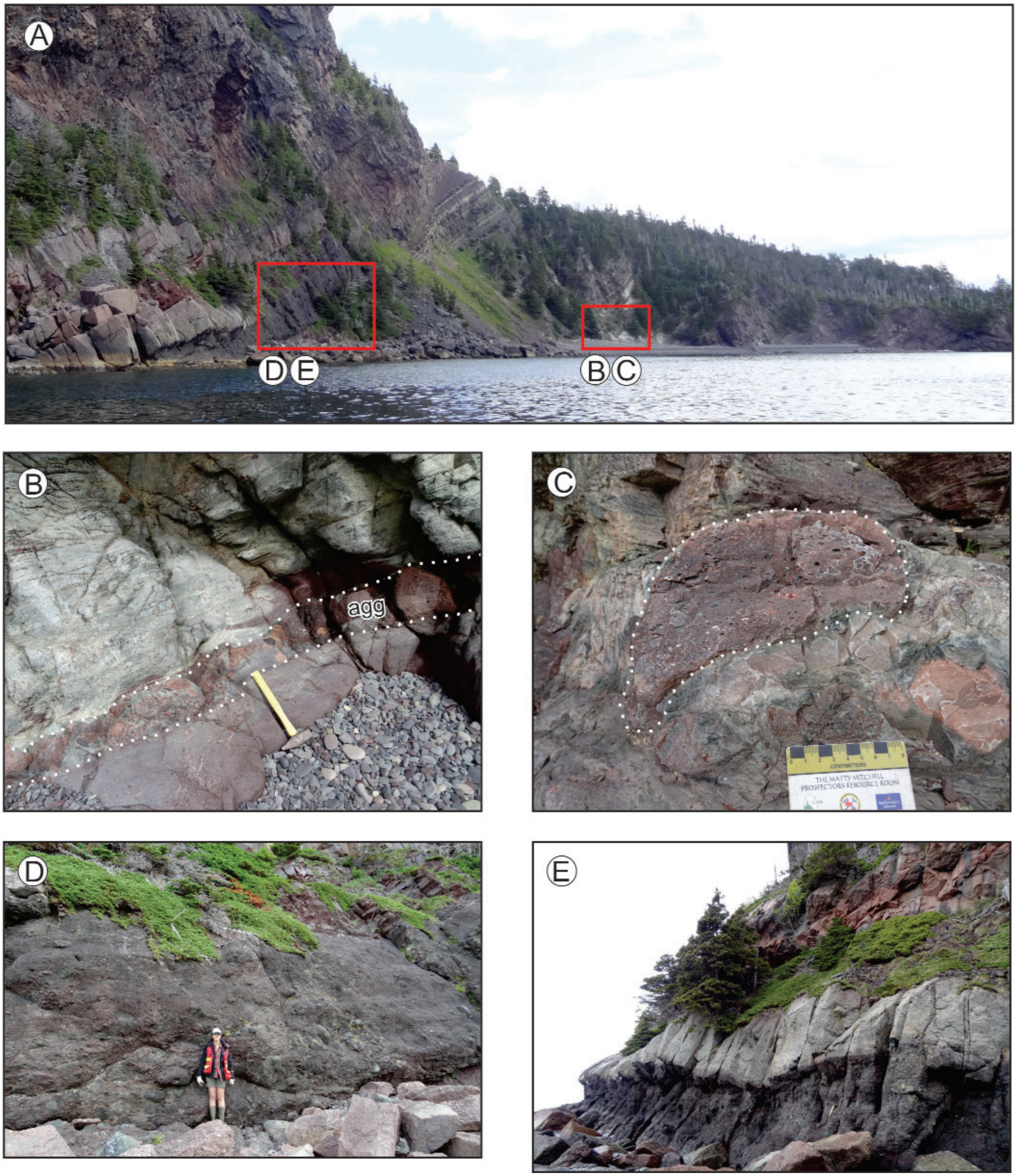

Plate 3. *A) Northern section of Cutler Head, viewed to the southeast; B) Agglomerate (agg) overlying red pebbly sandstone, and overlain by pale-green, tuffaceous sandstone. (UTMs: 308101m W, 5377710m N; NAD 27, Zone 22); C) Fusiform volcanic bomb within the agglomerate; D) Matrix-supported, basalt-rich, boulder conglomerate; E) Recessive-weathering, matrix-supported, boulder conglomerate overlain by siliceous, white-weathering conglomerate and red-brown shale.*

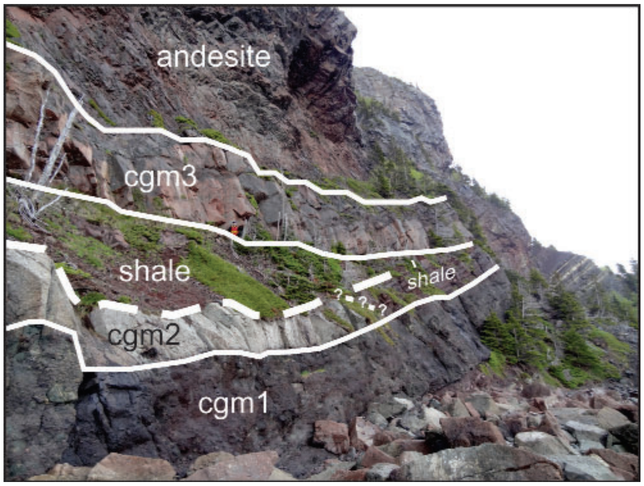

Plate 4. *Northern Cutler Head section, viewed to the south-east. Matrix-supported, basaltic-boulder-rich conglomerate overlain by siliceous, clast-supported conglomerate, shale and andesite. Key: cgm1 = matrix-supported, basalt-rich, boulder conglomerate; cgm2 = white-weathering, siliceous, clast-supported conglomerate; shale = sandstone and shale; cgm3 = pink, siliceous, clast-supported conglomerate.*

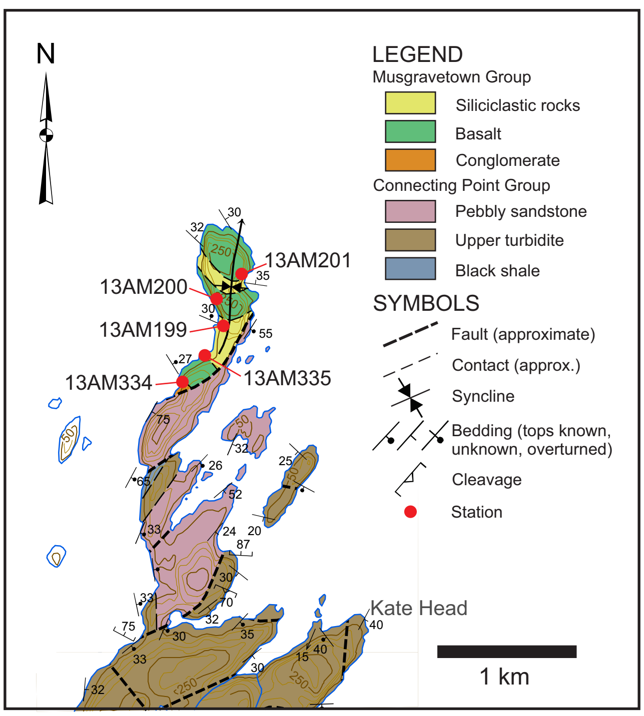

Figure 3. *Detail of geology at Cutler Head, showing the locations of samples discussed in the text. Note that samples 13AM199C02, 13AM199C05 and 13AM199C07 were all collected at site 13AM199.*

plagioclase laths are randomly oriented, with no evidence of flow-texture. Fine-grained (10–20 µm), equant magnetite grains occur interstitial to matrix plagioclase laths, and locally these exhibit ilmenite exsolution lamellae. Minor carbonate veinlets crosscut the basalt.

The dark-grey, amygdaloidal basalt bomb (from the agglomerate unit; 13AM199C02; Figure 3) locally exhibits well-developed trachytic flow texture. Phenocrysts are absent. Amygdales are irregular in shape and mainly quartz-filled. Some amygdales show radiating quartz, but more commonly contain relatively coarse quartz grains that are rimmed by very fine-grained quartz. Dark, essentially isotropic, patches are locally visible where the matrix may have been glassy. Rare opaque minerals are mainly ≤10 µm in diameter, equant ilmenite grains mantled by magnetite.

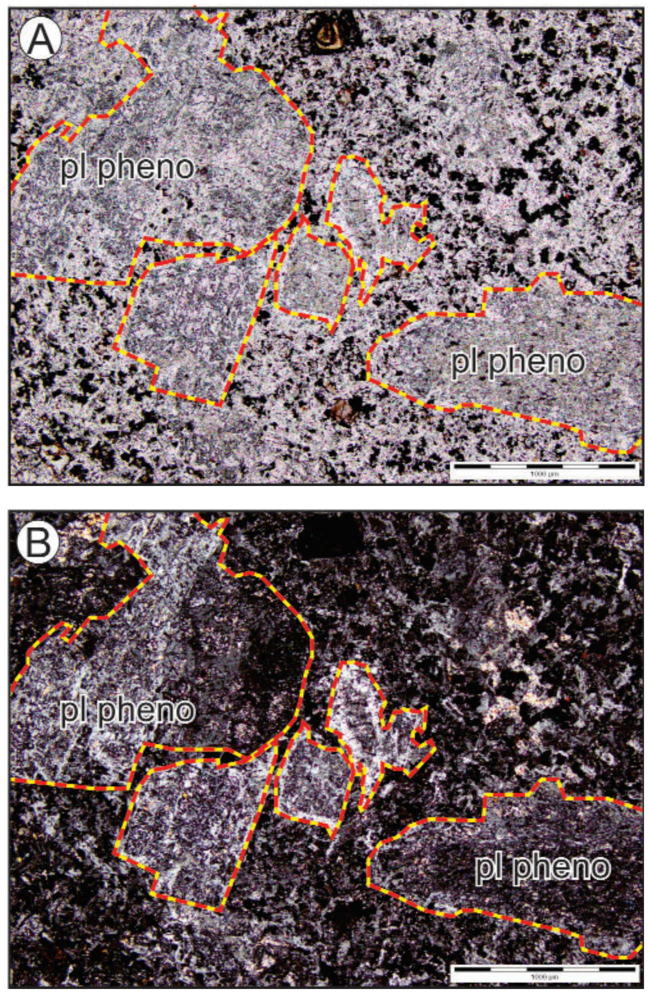

Plate 5. *Photomicrographs of plagioclase-phyric, basalt flow from southern Cutler Head (13AM335) viewed at 5X magnification. A) Under plane-polar light; B) Under crossed-polar light. Red-yellow dotted lines outline plagioclase phenocrysts (pl pheno).*

The pink, amygdaloidal basaltic andesite (agglomerate unit; 13AM199C05; Figure 3) contains local plagioclase phenocrysts that are strongly altered. Although their tabular shape is preserved, the rims are ragged and resorbed and twinning appears diffuse. The matrix consists of fine-grained plagioclase laths that are commonly randomly oriented, although trachytic texture is locally preserved. Accessory apatite is abundant and coarse grained (up to 800 µm). Amygdales are variably filled with quartz and epidote, and less commonly, chlorite and iron oxides are noted.

The pale-green, tuffaceous matrix within which the volcanic bombs are enveloped (13AM199C07; Figure 3) appears altered to saussurite and/or sericite. Rare examples of possible glass shards are embedded in a very fine-grained matrix comprising altered plagioclase, opaque grains and possible lithic fragments.

The andesite from the west side of Cutler Head (13AM200; Figure 3) contains minor, small (<100 µm) phenocrysts in a very fine-grained, mainly randomly oriented, plagioclase lath-rich matrix (Plate 6). The matrix also contains minor devitrified glass and fine ilmenite. The andesite from the east side of Cutler Head (13AM201; Figure 3) exhibits well-developed flow texture, rare 250–350 µm sieve-textured plagioclase phenocrysts, rare euhedral titanite, and trace interstitial, fine-grained (<50 µm) magnetite.

LITHOGEOCHEMISTRY

Four samples from Cutler Head are examined and compared to previously studied basaltic rocks from the greater Sweet Bay area (Mills and Sandeman, 2015). Basalts from the Sweet Bay area were previously divided into calc-alkaline basalts from the Headland basalts (HB), and transitional, (weakly) calc-alkaline to enriched mid-ocean ridge basalts (Mills and Sandeman, 2015). The latter are from the Plate Cove volcanic belt, east of the Indian Arm fault (Figure 2) and are subdivided into two groups: PCvb2 rocks (pink dots; Figure 4) have lower Nb/Y and Zr/Ti ratios than PCvb1 (blue dots; Figure 4).

In terms of their major-element composition, volcanic rocks at the south end of the Cutler Head section are basaltic, whereas those at the northern tip are andesitic (Figure 4A). Sample 13AM200, from the west side of Cutler Head, plots in the andesite field, whereas sample 13AM201, from the east side of Cutler Head, plots in the trachyandesite field on the total alkalies *vs.* SiO_2 diagram (LeMaitre *et al.*, 1989; Figure 4A). The pink volcanic bomb from the agglomerate (13AM199C04) has high silica and alkalies, low iron and Mg, and plots as a rhyolite. Based upon immobile elements, however, all three samples plot in

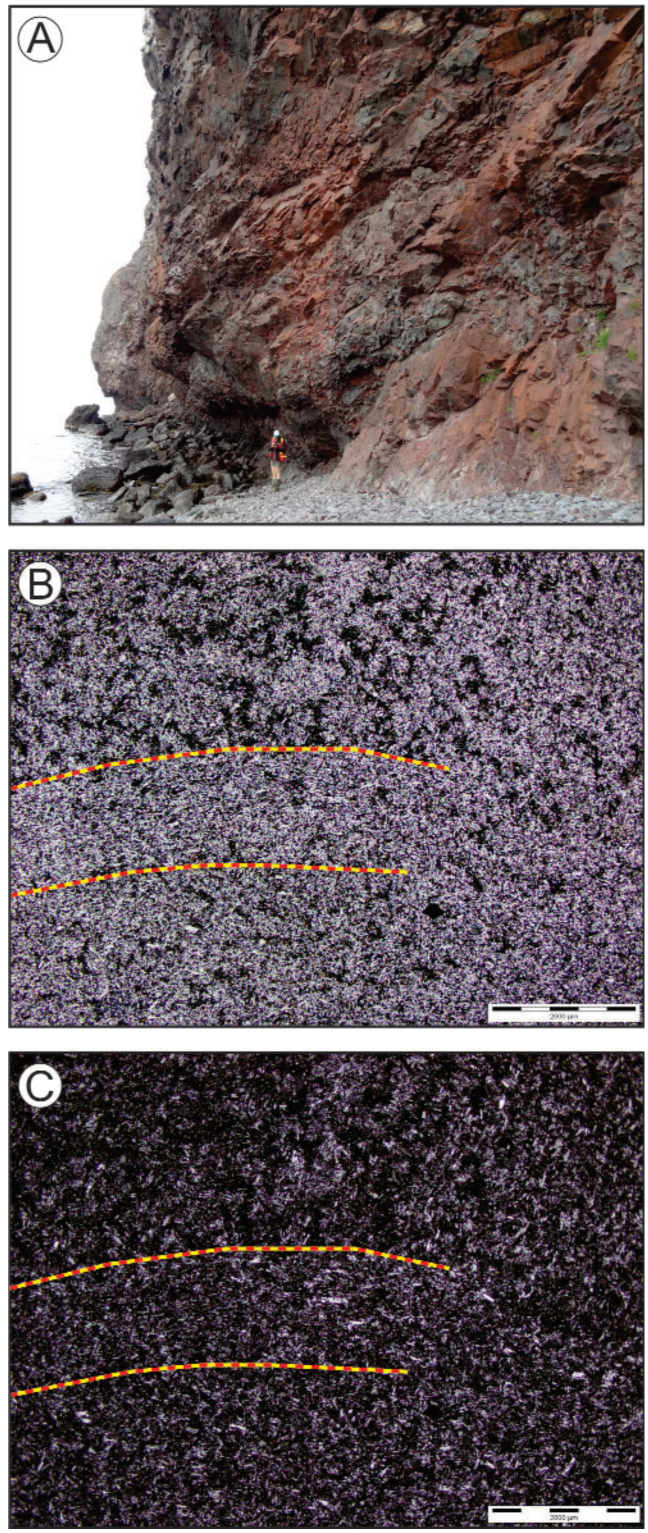

Plate 6. *A) Massive, andesite flow at the north end of Cutler Head (sample site 13AM200; UTMs: 308024m W, 5378015m N, NAD 27, Zone 22), and photomicrographs of same viewed at 2.5X magnification; B) Under plane-polar light; C) Under crossed-polar light. Red-yellow dotted lines trace weak flow fabric.*

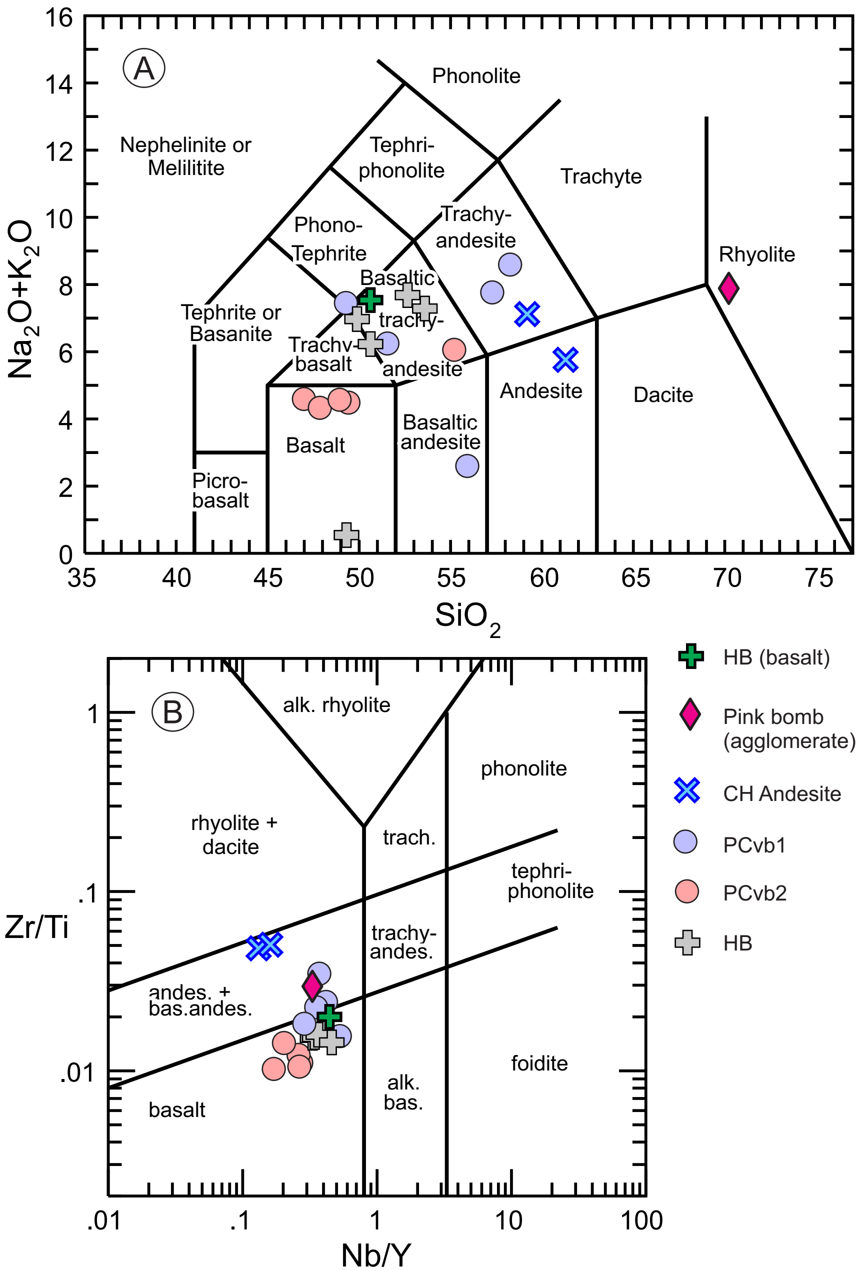

Figure 4. *A) Total alkalis* vs. *silica diagram (after Le Maitre* et al.*, 1989), showing the compositions of: basalt from southern part of Cutler Head section (13AM335A); a pink volcanic bomb from the agglomerate (13AM199C), and andesite flows from the northern part of Cutler Head (CH andesite: 13AM200, 13AM201); B) The data plotted in Zr/Ti* vs. *Nb/Y space (Pearce, 1996). Rocks of the PCvb1, PCvb2 and HB units (Mills and Sandeman, 2015) are shown in muted blue, red and grey, respectively.*

the andesite to basaltic andesite field of Pearce (1996; Figure 4B). The pink volcanic bomb likely originated as an andesite but has since been silicified and/or altered. Both the HB and PCvb2 plot as basalts and PCvb1 rocks straddle the basalt–basaltic andesite field.

The lowermost basalt (13AM335) plots consistently near other samples of HB (Figures 5 and 6). It contains high Al_2O_3 and Th, low TiO_2 and Nb, and high incompatible trace-element ratios (La/Nb, La/Yb, Th/Nb, Gd/Yb). Its REE and multi-element patterns are steep, and exhibit distinct negative troughs for the high field strength elements (Nb, Zr, Hf, Ti; Figure 7). Similar to other samples of HB, sample 13AM335 plots in the calc-alkaline and arc-basalt fields of Cabanis and Lecolle (1989) and Wood (1980), respectively (Figure 8). The rock is LREE-enriched, with a pronounced negative Nb anomaly, and high Th content (Figure 7), consistent with a volcanic-arc source.

Relative to the HB, the andesites from Cutler Head contain higher SiO_2, Zr, and lower Al_2O_3 and Th (Figure 5). They also have lower La/Yb, Th/Nb, La/Nb and Gd/Yb ratios (Figure 6). Relative to PCvb1 and PCvb2, the andesites contain lower abundances of TiO_2 and Cr, higher abundances of SiO_2 and Zr (Figure 5), and similar incompatible trace-element ratios to both the PCvb 1 and PCvb2 basalts with some minor differences. The andesites contain comparable Nb abundances and La/Nb ratios to PCvb2 basalts (Figures 5 and 6), however, they have lower Nb and higher La/Nb than the PCvb1 basalts.

Multi-element patterns of the Cutler Head andesites are notably similar to PCvb1 and PCvb2 basalts (Figure 7). Owing to their lower Th and Nb compositions, these andesites are more similar to PCvb2 rather than PCvb1 basalts. The pink volcanic bomb from the agglomerate, however, is markedly similar to the southern, lowermost basalt and other samples of the HB. On the Cabanis and Lecolle (1989) ternary plot, the pink bomb plots near-coincident with HB, whereas the andesites plot close to PCvb2 rocks, and near the back-arc basin basalt end member (BABB; Figure 8A). In Nb/Yb *vs.* Th/Yb space, the andesites also plot closer to PCvb2 than PCvb1 rocks (Figure 8C), albeit with slightly lower Nb/Yb ratios. In Nb/Yb *vs.* TiO_2/Yb space, however, the andesites plot below

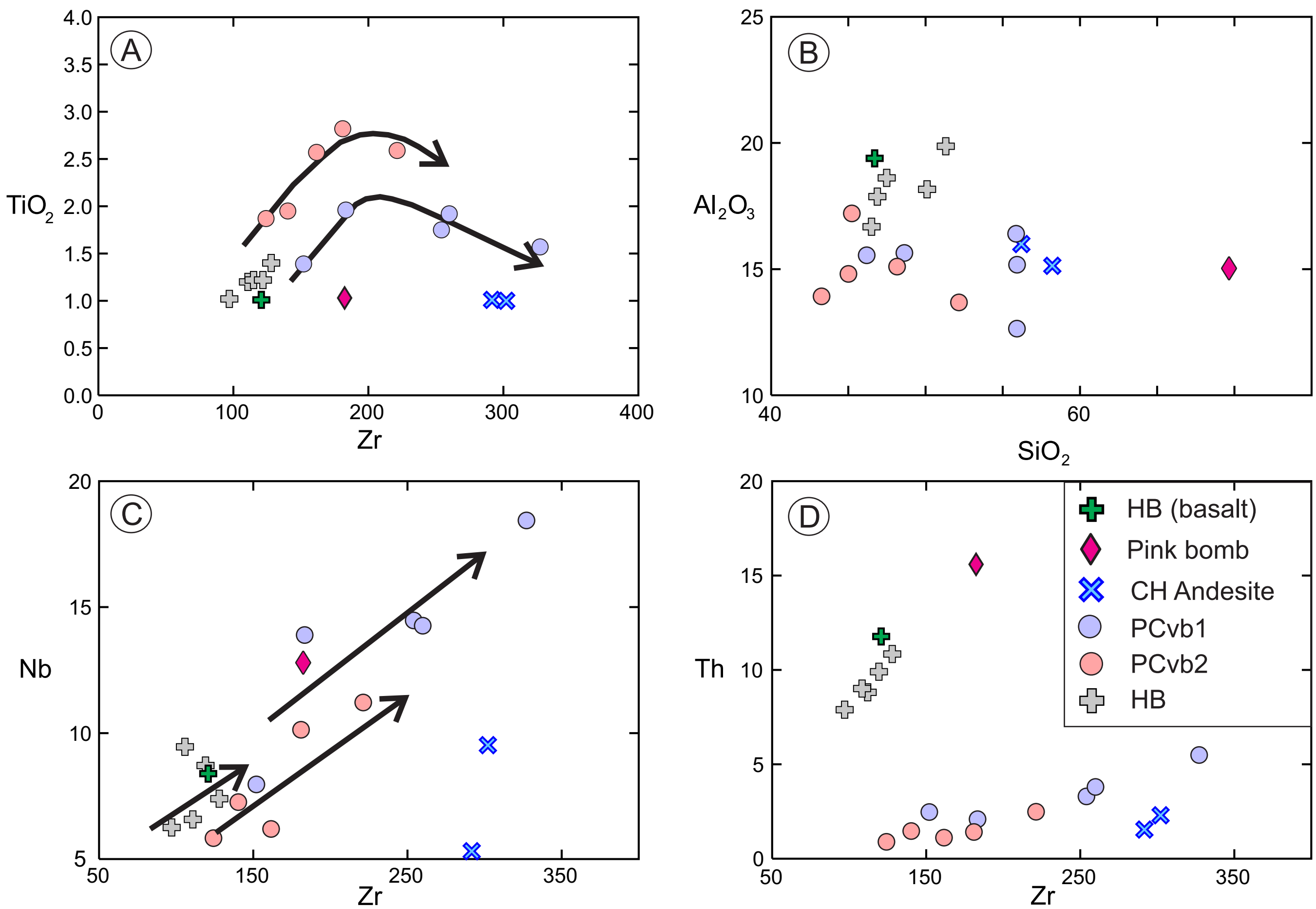

Figure 5. *Binary plots of A) TiO_2* vs. *Zr; B) Al_2O_3* vs. *SiO_2; C) Nb* vs. *Zr; D) Th* vs. *Zr, for rocks from Cutler Head.*

the mantle array, owing to their low TiO_2/Yb ratios (Figure 8D), consistent with their more fractionated compositions.

DISCUSSION AND IMPLICATIONS

STRATIGRAPHIC POSITION OF THE KATE HARBOUR FORMATION

Contrary to O'Brien's (1994) interpretation that the red sandstones and conglomerates in the Sweet Bay area are equivalent to upper MG rocks of the Crown Hill Formation, Mills (2014) proposed that these redbeds are part of the CPG sequence (Kate Harbour formation), and indicate shoaling-up toward the Connecting Point basin margin. Some of the redbeds in the Kate Harbour area are medium-bedded turbidites of the CPG that have been variably reddened, perhaps due to oxidation upon uplift that resulted from north-directed thrusting (Mills *et al.*, 2016a), which may also have resulted in the angular unconformity at Southward Head. Rocks of the Kate Harbour formation were deposited between *ca.* 605 and 600 Ma (Mills *et al.*, 2016b) and are broadly penecontemporaneous with the conglomeratic Cannings Cove Formation of the lowermost MG. It is therefore clear that some redbeds in the western Avalon Terrane in Newfoundland belong to a considerably older (*ca.* 600 Ma) sequence rather than only the terminal Neoproterozoic Crown Hill Formation. Although there are currently no direct age constraints on the Crown Hill Formation, in the northern Bonavista (Keels) area, it must be younger than the stratigraphically lower, *ca.* 580 Ma Trinity facies (*see* Pu *et al.*, 2016; Figure 2).

IMPLICATIONS OF COARSE SILICICLASTIC ROCKS

Basaltic rocks associated with variegated, red to green, conglomerates at the south end of the Cutler Head section are calc-alkaline rocks (HB) inferred to have formed in a mature continental volcanic arc setting. The sandstone to boulder conglomerate-dominated sequence that overlies the HB at Cutler Head may reflect initial deposition in an extensional regime. The predominance of coarse clastic material,

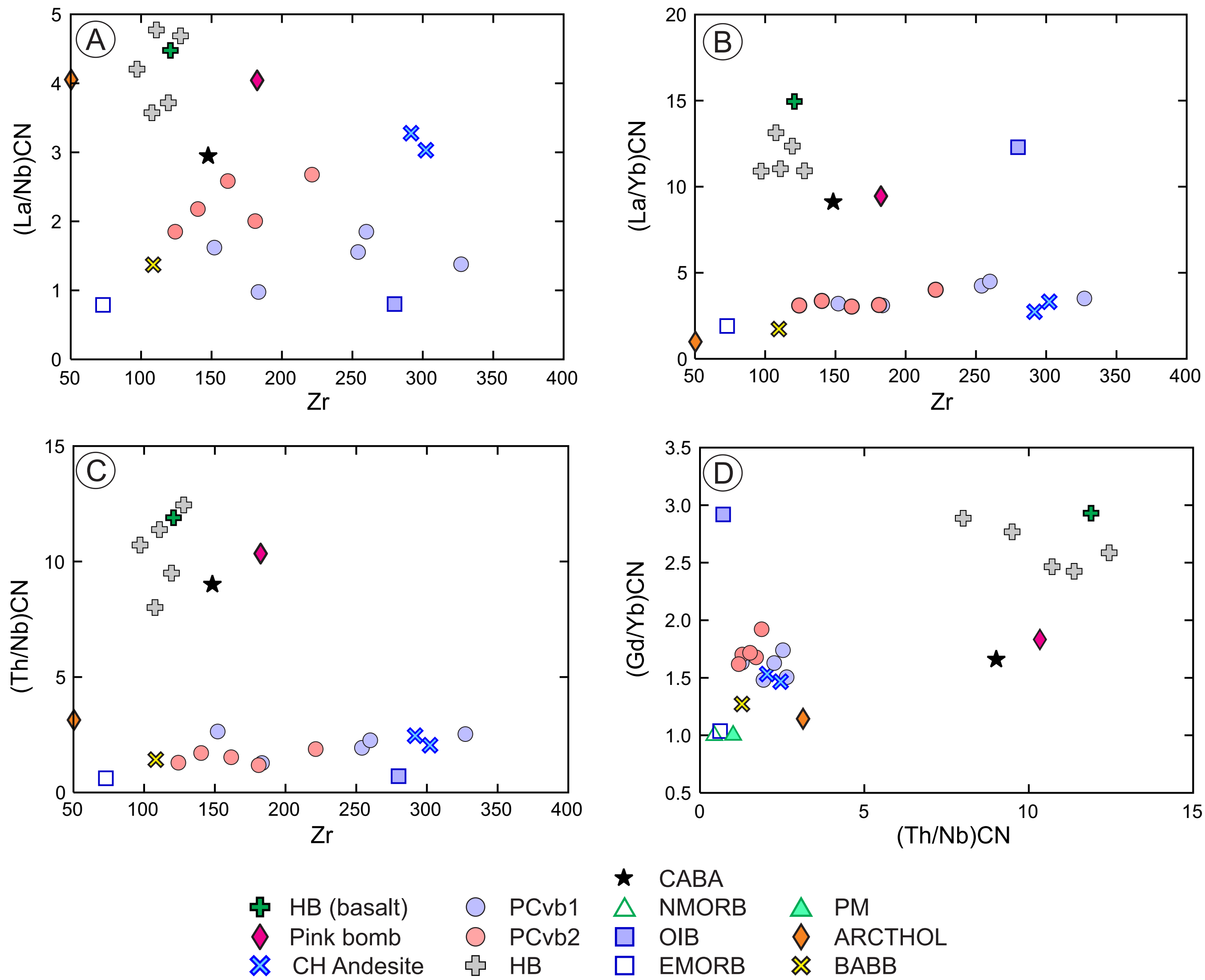

Figure 6. *Binary plots of incompatible-element ratios in rocks from Cutler Head, compared to basaltic rocks from HB, PCvb1 and PCvb2. A) La/Nb* vs. *Zr; B) La/Yb* vs. *Zr; C) Th/Nb* vs. *Zr; D) Gd/Yb* vs. *Th/Nb. CN denotes chondrite-normalized (normalizing values from Sun and McDonough, 1989). Key: CH = Cutler Head; ARCTHOL = Mariana arc tholeiite (GUG6; Elliott* et al.*, 1997); BABB = East Scotia Ridge back-arc basin basalt (wx47; Fretzdorff* et al.*, 2002); CABA = Calc-alkaline basaltic andesite (CA 172; Giuseppe* et al.*, 2018); PM, NMORB, EMORB, OIB = primitive mantle, normal mid-ocean ridge basalt, enriched mid-ocean ridge basalt, and ocean-island basalt, respectively (Sun and McDonough, 1989).*

and lateral discontinuity of some units (Plate 4) are consistent with extensional faulting. However, rapid horizontal and vertical facies changes, sedimentological features such as outsized clasts (Plate 7) and the predominance of diverse conglomerates, including a matrix-supported, boulder conglomerate (Plate 3B, C), are also consistent with, but not diagnostic of, a periglacial setting. Whereas Pu *et al.* (2016) argue that the duration of the Gaskiers glacial event was ≤340 k.y., it is equally possible that this constrains only a major deglaciation event, as no evidence constraining the onset of glaciation has been documented.

Magmatic Shift: Volcanic Arc-to-Extensional Magmatism

The agglomerate at Cutler Head sits stratigraphically above HB flows and below the andesite flows documented herein. It is, therefore, a strategic geochronological target to better constrain the timing of the tectonomagmatic shift from arc-related volcanism to extensional volcanism. Its tuffaceous matrix contains poorly preserved lithic fragments, feldspar crystals and rare glass shards, consistent with a pyroclastic origin. The pink volcanic bomb from the agglom-

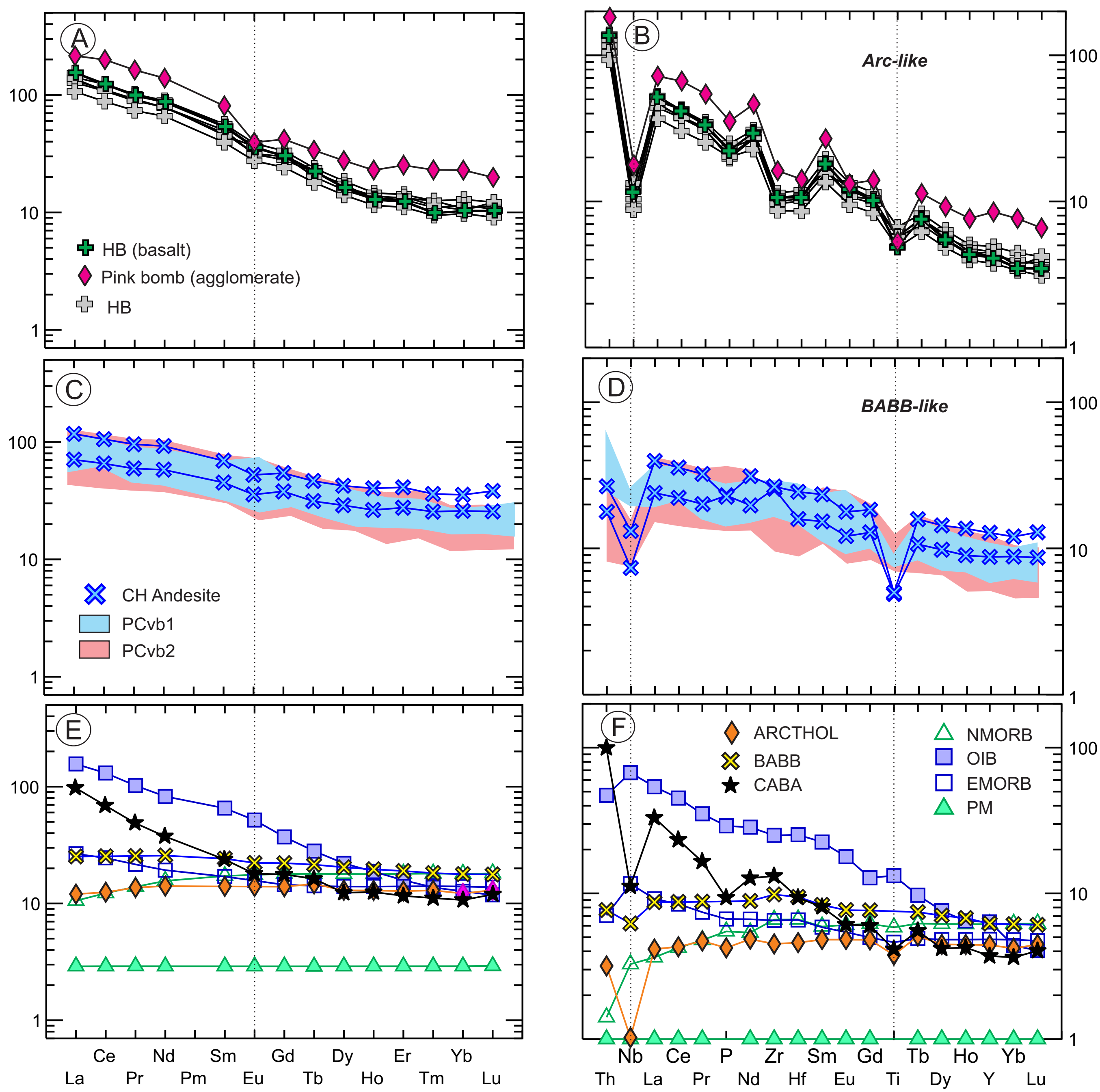

Figure 7. *Chondrite-normalized (A, C, E) and primitive mantle-normalized (B, D, F) multi-element plots for rocks from the Cutler Head section (normalizing values from Sun and McDonough, 1989). Symbols as in Figure 6.*

erate unit is lithogeochemically similar to the HB flows. The rock is LREE-enriched having a steeply inclined multi-element pattern, a pronounced negative Nb anomaly, and high Th content (Figure 7), consistent with a volcanic arc source. The sample also plots in the calc-alkaline field on most tectonic discrimination diagrams (Figure 8A, B). Its stratigraphic position, <50 m below the first andesite flow, suggests that calc-alkaline magmatism prevailed at least up until deposition of the agglomerate. The transition to extensional tectonics likely postdates eruption of this pyroclastic rock.

The andesites from the northern tip of Cutler Head are geochemically similar to basalts of the PCvb2 (Figures 7 and 8). Their relatively flat REE and multi-element patterns

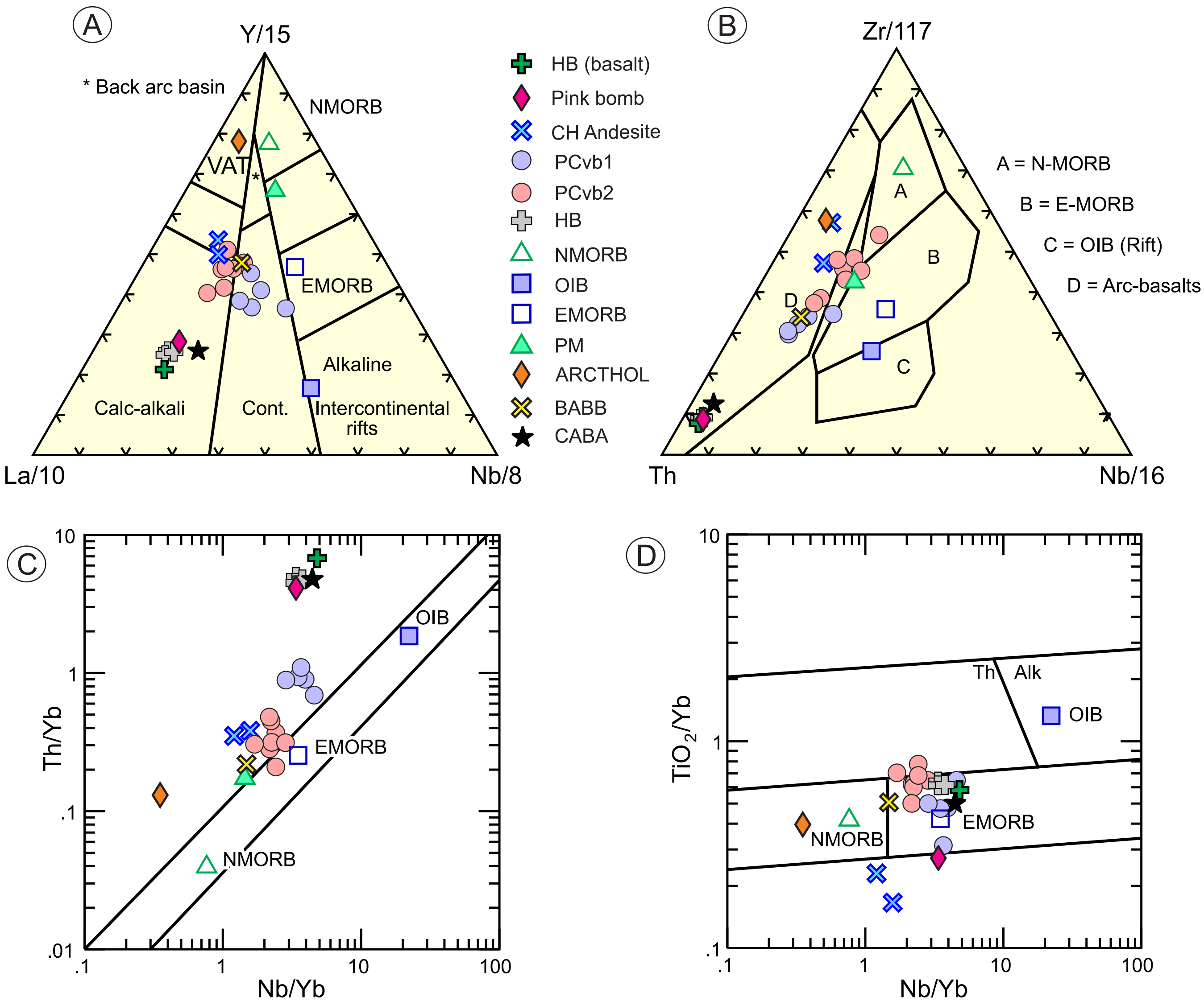

Figure 8. *Tectonic discrimination diagrams showing rocks from Cutler Head, with rocks from Bonavista Peninsula reproduced (after Mills and Sandeman, 2015) for comparison. A) La-Y-Nb diagram (Cabanis and Lecolle, 1989); B) Th-Zr-Nb plot (Wood, 1980); C) Th/Yb* vs. *Nb/Yb (Pearce, 2008); D) TiO_2/Yb* vs. *Nb/Yb (Pearce, 2008). Symbols as in Figure 6.*

are characteristic of an EMORB-like source. The andesites exhibit modest negative Nb and Ti troughs, but do not appear to represent products of mature continental arc magmatism. Interpretation of arc magmatism based solely on the presence of negative Nb anomalies is an erroneous assumption, and inconsistent with the flat REE and multi-element patterns and the high TiO_2 content of the PCvb2 rocks, the latter of which is suggestive of a shallow mantle source. More likely, the small Nb troughs resulted from incorporation of older lithospheric material through assimilation and contamination of the parental magmas, either in their mantle source, or during ascent through the lithosphere.

The new data indicate that a major tectonomagmatic shift occurred within rocks previously assigned to the Bull Arm Formation. Earliest magmatism in the Sweet Bay–Bonavista area was calc-alkaline and formed in a mature, continental volcanic arc (Mills and Sandeman, 2015) at about 600 Ma (Mills *et al.*, 2016b). Although no direct age constraint is available for PCvb1 and PCvb2, a tuff located above a PCvb2 flow and below a PCvb1 flow at Summerville (Wilson, 2015) yielded an age of 592 ± 2.2 Ma (Mills *et al.*, 2017). Based on lithogeochemistry and stratigraphic position, combined with available geochronological constraints, the andesites are likely younger than *ca.* 600 Ma

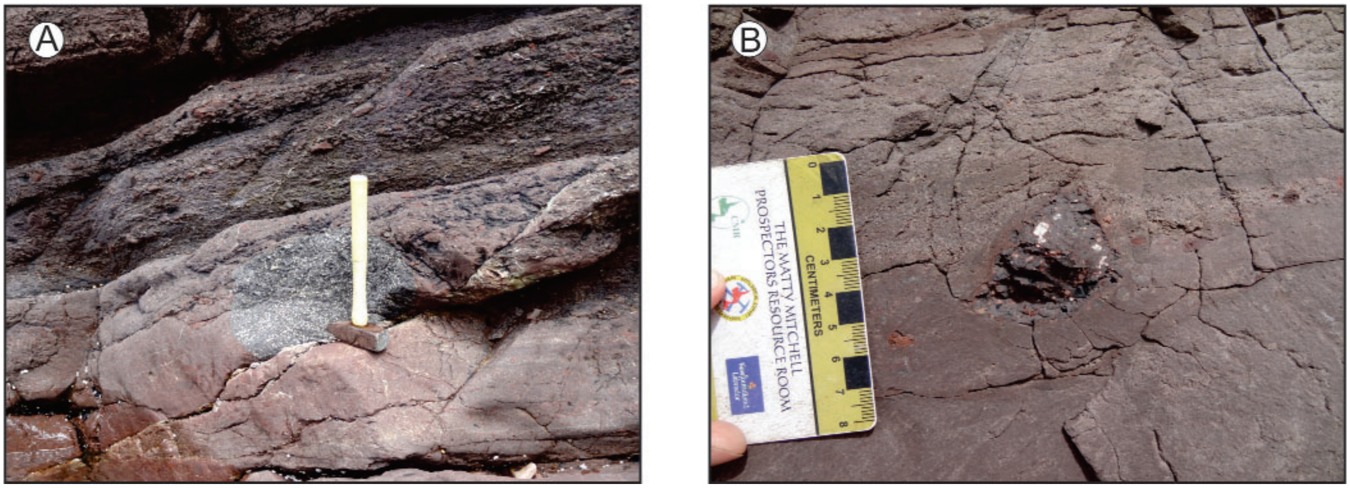

Plate 7. *A) Well-rounded, amygdaloidal basalt boulder in red pebble conglomerate stratigraphically below calc-alkaline HB basalt at sample site 13AM334 (UTMs: 307781m W; 5377284m N; NAD 27, Zone 22); B) Subrounded, outsized clast of amygdaloidal basalt in red pebbly sandstone, 1 m above the agglomerate at sample site 13AM199 (UTMs: 308047m W; 5377750m N; NAD 27, Zone 22).*

(the age of tuff within red cobble conglomerate at Southward Head, 1 m below a calc-alkaline HB flow) and older than *ca.* 592 Ma (the age of the tuff interbedded with PCvb2 and PCvb1 rocks).

Finally, the relative age of PCvb1 and PCvb2 rocks is clarified. The best evidence of relative age comes from a PCvb1 mafic dyke that cuts a PCvb2 flow (Mills and Sandeman, *this volume*). In a recent investigation into the petrochemistry of mafic dykes on the Bonavista Peninsula, Mills and Sandeman (2017) describe two petrochemical dyke sets that are similar to PCvb2 (Type 2 dykes) and PCvb1 (Type 3 dykes). They conclude that Type 2 dykes are older than Type 3 dykes, based, in part, on the spatial restriction of the former to CPG rocks and the latter to younger MG rocks. Similarity of the petrochemical data between PCvb2 and Type 2 dykes, and PCvb1 and Type 3 dykes, is consistent with PCvb2 magmatism preceding PCvb1. Mills and Sandeman (2017) further suggest that Type 3 dykes must be younger than the siltstone that Type 3 dykes locally crosscut in the Trinity area (Figure 1). That siltstone overlies the *ca.* 580 Ma glacial tillite unit (Trinity facies; Normore, 2011; Pu *et al.*, 2016). Although it is premature to suggest that PCvb1 is also younger than 580 Ma, it is clear that Bull Arm Formation magmatism in the Sweet Bay–Bonavista area prevailed from at least *ca.* 600 Ma (HB unit) to post-580 Ma (Type 3 dykes) and marks a progression from arc-like to extensional magmatism. Relative to PCvb2 rocks, those of PCvb1 have smaller negative Nb anomalies, slightly higher Th/Yb, Nb/Yb ratios and slightly lower TiO_2/Yb ratios, consistent with their derivation from a shallower, more enriched asthenospheric (or lithospheric) mantle source, consistent with progressive extension likely lasting for at least 20 m. y.

CONCLUSIONS

Redbeds of the Kate Harbour formation include channelized gravels and wavy-bedded sandstones locally preserving coarse wave-ripples, consistent with a shallow-marine to alluvial depositional environment, and shoaling-up of the CPG basin near its margin. These rocks are broadly penecontemporaneous with the conglomeratic Cannings Cove Formation of the lowermost MG, and indicate that some redbeds in the western Avalon Terrane in Newfoundland belong to a sequence that is considerably older (*ca.* 600 Ma) than the terminal Neoproterozoic Crown Hill Formation.

The stratigraphic succession exposed along the west side of Cutler Head consists of a north-younging progression from pebbly sandstone and conglomerate overlain by basalt, through a coarse siliciclastic sequence, to andesitic flows at the northernmost tip of Cutler Head. Lithogeochemistry data demonstrates that the lower basaltic flows are calc-alkaline and formed in a mature, continental volcanic arc. In contrast, the andesitic flows at the northern tip of Cutler Head are transitional, tholeiitic to weakly calc-alkaline rocks that are petrochemically similar to PCvb2 (but with lower TiO_2 content), likely derived from a shallow mantle source in an extensional setting. The intervening coarse siliciclastic succession marks a major tectonomagmatic shift that occurred within rocks of the Bull Arm Formation. The andesites, as the earliest product of extensional magmatism, herald this shift at post-600 Ma (the age of tuff within red cobble conglomerate at Southward Head, 1 m below a calc-alkaline HB flow) and pre-592 Ma (the age of the tuff interbedded with PCvb2 and PCvb1 rocks).

The siliciclastic succession above the HB flows and below the andesites is predominantly conglomeratic, consistent with deposition related to extensional faulting. The rapid horizontal and vertical facies changes, sedimentological features such as outsized clasts, and the predominance of diverse conglomerates, including a matrix-supported, boulder conglomerate, are also consistent with (although not diagnostic of) a periglacial setting.

Deposition of PCvb2 rocks preceded PCvb1 deposition. The PCvb2 volcanism likely occurred prior to 592 Ma, the age of a tuff that overlies a PCvb2 flow at Summerville (Wilson, 2015). The PCvb1 magmatism is inferred to be post-580 Ma (the age of Trinity facies rocks), as dykes that are petrochemically similar to PCvb1 flows crosscut siltstone that stratigraphically overlies the Trinity facies (Mills and Sandeman, 2017). In the Sweet Bay area, BAF magmatism persisted, at least, from *ca.* 600 Ma to post-580 Ma, and exhibits a clear shift from earlier (*ca.* 600 Ma) continental arc magmatism to later (pre-592 Ma) extensional (or transtensional) magmatism.

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