Abbott, R. N. and Bandy, B. R. 2017. Geochemistry of basalt clasts near the base of the Wagwater Formation, parish of St. Andrew, Jamaica. *Caribbean Journal of Earth Science*, **50**, 19-29. © Geological Society of Jamaica. Available online 2nd December 2017.

Geochemistry of basalt clasts near the base of the Wagwater Formation, parish of St. Andrew, Jamaica

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ABSTRACT. This research addresses the geochemistry of basalt clasts in early Paleocene (c. 65 Ma) conglomerate, near the base of the Wagwater Formation in eastern Jamaica. Incompatible, immobile trace elements imply subalkaline to calc-alkaline island arc basalt, consistent with suprasubduction zone C-MORB (i.e., basaltic magma produced from a subducted MOR, subsequently contaminated during ascent through suprasubduction-zone mantle and crust). Mafic Halberstadt lavas, higher in the Wagwater stratigraphy, have OIB-like, high-Nb (HNB) chemistry, seemingly at variance with a convergent plate-boundary environment. The results imply a change from C-MORB magma to OIB-like, HNB magma. The evolution of the magma is consistent with initial production of MORB magma induced by slab-detachment. Subsequently, partial melting deeper beneath a widening slab-gap and partial melting of metasomatized mantle at shallower depths in the mantle produced the OIB-like, HNB magma. Neither the C-MORB nor the Halberstadt HNB is related to Newcastle adakite in the Wagwater Formation.

Keywords: basalt, C-MORB, trace elements, Paleocene red beds, Jamaica, Caribbean

1. INTRODUCTION

This research is a follow-up to previous studies that addressed (1) zeolite facies burial metamorphism in the lowest exposed strata of the Wagwater Formation (**Abbott et al., 2013a, b**), and (2) anomalously young Paleocene-Eocene $^{40}Ar/^{39}Ar$ ages for the underlying Westphalia Schist (**West et al., 2014**). Along with results from a recent study of the Green Bay Schist (**Abbott et al., 2016**), a much sharper image of the Cenozoic tectonic history of eastern Jamaica has emerged (**Abbott et al., 2016**).

In this study we examine boulder-size clasts of volcanic rock from the lowest exposed sediment in the Wagwater Formation (**Abbott et al., 2013a, b**). While it is well understood that the Wagwater Formation and overlying Richmond Formation occupy a transtensional basin, some details of the tectonic environment remain speculative. We use whole-rock trace element data on the boulders are used to better characterize the tectonic environment. Absolute stratigraphic ages are consistent with the International Commission on Stratigraphy (ICS, **Gradstein et al., 2004**; **Ogg et al., 2016**).

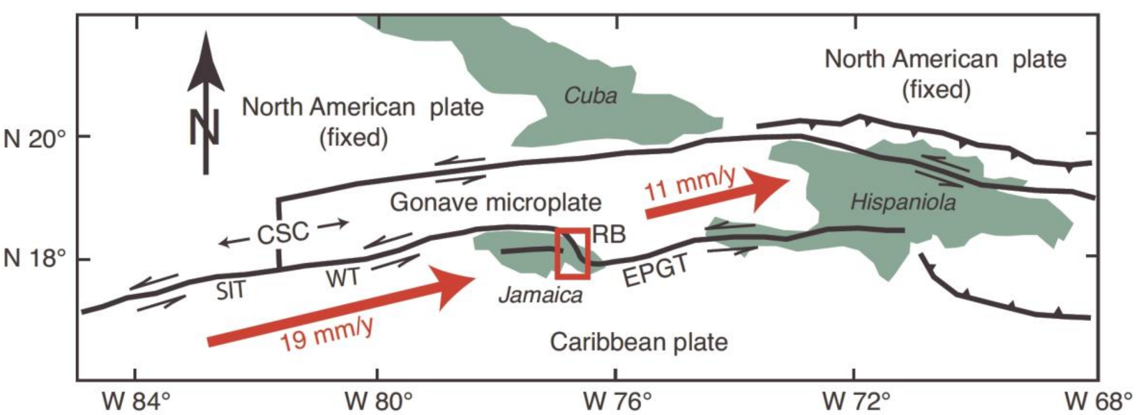

Figure 1. Regional geology. A. Plate tectonic setting of Jamaica. The vectors (DeMets and Wiggins-Grandison, 2007) show the motions of the Caribbean plate and Gonave microplate relative to the North American plate. EPGT = Enriquillo – Plantain Garden transform fault zone, RB = restraining bend, WT = Walton transform fault zone, SIT = Swan Island transform fault zone, CSC = Cayman spreading center. Red box is the study area (Figure 2).

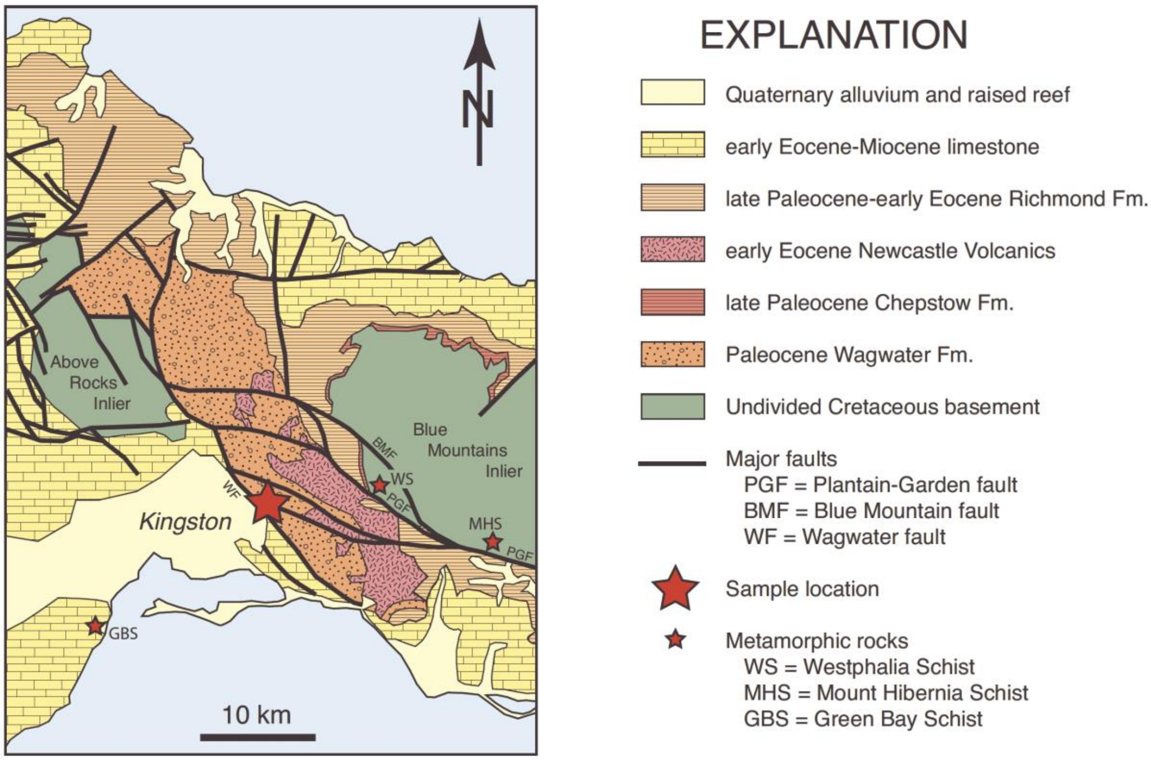

Figure 2. Geologic map of the Wagwater belt and environs, modified from Mann and Burke (1990) with details relating to the distribution of the Richmond Formation from Pickerill et al. (1992).

2. GEOLOGY

The island of Jamaica straddles the boundary between the Caribbean plate and the Gonave microplate (**Figure 1**). West of Jamaica, the boundary is known as the Walton transform fault zone; east of Jamaica, the boundary is known as the Enriquillo-Plantain Garden transform fault zone. The E-W trending left-lateral transform system makes a right-step through eastern Jamaica (**Mann and Burke, 1990**; **Dominguez-Gonzalez, 2015**). This restraining bend (RB in **Figure 1**) accommodates 8 ± 1 mm/y of ENE-WSW directed compression (**DeMets and Wiggins-Grandison, 2007**), responsible for, among other things, lifting the Blue Mountains in eastern Jamaica during the last ~10 My (**Draper, 2008**).

The basement of Jamaica was formed as part of a Cretaceous (or earlier) volcanic island arc, and consists of unmetamorphosed and metamorphosed volcanic, sedimentary and plutonic rocks (e.g., **Robinson, 1994**). These arc-related Cretaceous rocks are now exposed in a number of inliers, where younger strata have been eroded away. The largest of the exposures of Cretaceous rock is the Blue Mountains Inlier in eastern Jamaica (**Figure 2**). The basement is unconformably overlain by Cenozoic strata, the oldest of which is the Paleocene to early Eocene Wagwater Formation. The unconformity indicates that the basement was exposed at the surface by the end of the Cretaceous.

Along the SW margin of the Blue Mountains Inlier, greenschist-blueschist facies Mt. Hibernia schist (**Draper, 1987**; **Abbott et al., 2003**; **Abbott and Bandy, 2008**) and amphibolite facies Westphalia schist (**Draper, 1987**; **Abbott et al., 1996**; **Abbott and Bandy, 2008**) have been uplifted in response to compression at a prominent right-step restraining bend (**Mann et al., 1985**; **Mann and Burke, 2007**) along the Plantain Garden and Blue Mountains faults (**Figure 2**). $^{40}Ar/^{39}Ar$ determinations for Westphalia Schist give an Eocene whole-rock cooling age of 53 Ma and a Middle Paleocene K-feldspar cooling age beginning ~60 Ma (**West et al., 2014**; **Abbott et al., 2011**). These younger ages (50-60 Ma) imply a middle Paleocene-early Eocene thermal event involving temperatures higher than ~250°C (**Abbott et al., 2013a, b**; **West et al., 2014**).

The Cenozoic geology (**Figure 2**) reflects three stages in the evolution of the northern edge of the Caribbean plate (**Figure 3**), summarized here from **Robinson** (**1994**), **Mann and Burke** (**1990**), and **Draper** (**2008**):

(1) Transtensional subsidence: Early Paleocene to middle Eocene red beds and volcanic rocks of the

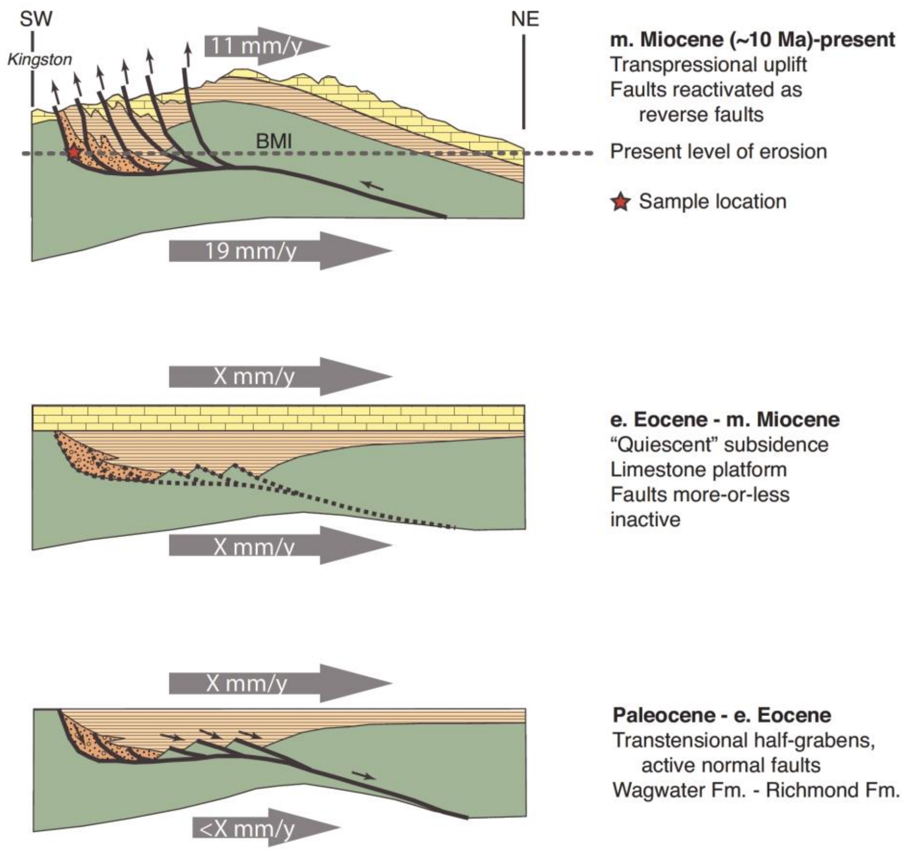

Figure 3. Schematic SW-NE cross sections of the Wagwater Belt, modified from Draper (1998). The sequence, from bottom to top, illustrates the three Cenozoic tectonic stages. In the top cross section (middle Miocene–present, ~10-0 Ma) the gray arrows show the velocities of the Caribbean plate and Gonave plate relative the North American plate (DeMets and Wiggins-Grandison, 2007). In the lower two cross sections (early Eocene–middle Miocene, and Paleocene–early Eocene) the lengths of the gray vectors show qualitative velocities relative the North America plate.

Wagwater and Richmond Formations occupy a NW-trending half-graben, related to transtensional tectonics. The combined thickness is at least 6.8 km thick (**Mann and Burke, 1990**). East-dipping normal faults were active during this time, forming the western margin of the half-graben and affecting the interior of the basin (**Draper, 2008**). Plate tectonic scenarios for this time are consistent in showing or otherwise implicating north- to northwest-directed subduction beneath Jamaica (**Jackson and Smith, 1978**; **Jackson, 1987**; **Mann and Burke, 1990**; **Jackson and Scott, 2002**; **Pindell and Kennan, 2009**; **Pindell et al., 2012**). The tectonic environment may be described as a transtensional boundary above a shallow, flat subduction zone (**Hastie et al., 2015**).

(2) "Quiescence:" Limestone platform: Middle Eocene to Miocene platform limestone overlies the Wagwater and Richmond Formations, and varies in thickness from ~0.9 km (**Draper, 2008**) to ~2.5 km (**Mann and Burke, 1990**). The limestone relates to epeirogenic subsidence, punctuated by minor, but distinct, episodes of uplift (**Mitchell, 2016**).

(3) Transpressional uplift: Late Miocene (~10 Ma, **Draper, 2008**) to Pleistocene carbonate reef deposits are related to ongoing transpressional uplift. Earlier normal faults (stage 1) were reactivated as reverse faults.

The Wagwater Formation is composed of several distinct members (**Mann and Burke** (**1990**). The Ginger River Member is the oldest unit. It consists mostly of poorly sorted, dark red to purple, polymict conglomerate, and accounts for most of the stratigraphy of the formation. Rock samples used in this study come from boulders in the lowest exposed strata in this member. The sample location is indicated in **Figures 2** and **3**. Other members of the formation include the mafic Halberstadt Volcanics, felsic Newcastle Volcanics, gypsum (Brooks Member), Woodford Limestone, Good Hope (formerly Halberstadt) Limestone (**Mitchell et al., 2016**), thin-bedded sandstone and conglomerate (Pencar River Member), and an upper conglomerate (Dry River Member). The conformably overlying Richmond Formation is also divided into a number of members. The Roadside Member makes up most of the formation, and consists of thin bedded sandstone, siltstone and shale, in the form of centimetre to decimetre-scale turbidite layers. Other members include mafic and felsic lavas (Nutfield Volcanics), conglomerate (Albany Member), and organic-rich laminate siltstone and mudstone (Langley Member). East of the Wagwater Belt (*sensu stricto*), the oldest stratum is a thin layer of conglomerate that rests nonconformably on metamorphic rocks of the Blue Mountains Inlier. Here, the basal conglomerate is overlain by Paleocene to early Eocene limestone of the Chepstow Formation (**Figure 2**), which in turn is overlain by undifferentiated turbidites of the Richmond Formation.

3. Methods

3.1. Sampling

Sampling was informed by the mapping of **Mann and Burke** (**1990**) and our previous study (**Abbott et al., 2013a, b**). The lowest exposed strata in the Wagwater Formation (Ginger River Member) are easily accessible on Skyline Drive, near the Kingston community of Papine. Samples JM15-1G and JM15-2 were both collected at 18° 01' 32.2" N, 76° 44' 11.8" W (**Figures 2, 3**). This is one of the same sites sampled for our earlier study (**Abbott et al., 2013a, b**).

3.2. Whole-rock chemical analyses

Two samples (JM15-1G and JM15-2) were selected for whole-rock geochemical analysis. The rock was crushed in a porcelain jaw crusher and powdered in a tungsten carbide shatterbox. A full suite of major- and trace-element analyses (**Table 1**) were done by Acme Analytical Laboratories Ltd. in Vancouver, British Columbia. Analyses were performed on fused rock powders. Major elements were analyzed by Inductively-coupled plasma (ICP)-optical emission spectrometry and trace elements were analyzed by ICP-mass spectrometry. Replicates and an internal standard were analyzed using the same procedures to monitor the analytical reproducibility. Discrepancies among replicate analyses are <5% for the major elements, <5% for trace elements with abundances >10 ppm, and <10% for trace elements with abundances of <10 ppm.

TABLE 1. Whole-rock chemistry, basalt clasts

Sample	JM15-1G	JM15-2
Major elements, wt.%		
SiO_2	59.81	61.97
TiO_2	0.55	0.51
Al_2O_3	14.93	15.98
Fe_2O_3 (t)[1]	6.02	5.42
Cr_2O_3	0.01	0.01
MnO	0.13	0.06
MgO	3.03	0.65
CaO	6.66	5.26
Na_2O	3.26	5.57
K_2O	0.74	0.94
P_2O_5	0.13	0.14
LOI[2]	4.50	3.30
Total	99.77	99.81
Trace elements, ppm		
Sc	18.00	14.00
Ni	30.00	<20
V	180.00	186.00
Co	18.70	6.40
Rb	13.20	16.20
Sr	428.70	579.90
Y	13.20	12.50
Zr	66.30	87.90
Nb	3.80	5.10
Ba	532.00	589.00
La	8.20	7.70
Ce	16.10	17.20
Pr	2.27	2.25
Nd	9.80	9.70
Sm	2.19	1.93
Eu	0.77	0.68
Gd	2.47	2.26
Tb	0.36	0.34
Dy	2.27	2.15
Ho	0.47	0.42
Er	1.39	1.37
Tm	0.20	0.20
Yb	1.33	1.32
Lu	0.22	0.22
Hf	1.90	2.20
Ta	0.20	0.20
Th	0.90	0.80

[1](t)—Total iron is expressed as Fe_2O_3.
[2]LOI—loss on ignition.

4. PETROGRAPHY

The reader is referred to **Abbott et al.** (**2013b**) for a detailed account of the petrography, petrology and geologic history of the basalt clasts. Only relevant information is summarized here. The samples (JM15-1G and JM12-2) come from the interiors of boulders in conglomerate near the base of the Wagwater Formation (Ginger River Member) (**Figure 4A, B**). The rock is essentially a monomict boulder conglomerate with clasts up to 50 cm. The matrix consists of finer grained lithic clasts. The boulder clasts consist of intermediate purple-gray porphyritic volcanic rock. Phenocrysts of euhedral plagioclase, up to 2 mm, are set in a dark purple aphanitic matrix. The rock has sub-mm-scale fractures filled mostly with calcite. In thin section (**Figure 4C**), the well-twinned phenocrysts of plagioclase are partially replaced by µm-scale patches of heulandite (a zeolite). The plagioclase phenocrysts have narrow, µm-scale discontinuous rims of chabazite. Partially to completely pseudomorphed, sub-mm, euhedral phenocrysts of augite are rimmed by amorphous black weathering products, including clay minerals and hematite. Primary augite is partially to completely replaced by celadonite and chlorite (**Figure 4C**). The most abundant minerals include plagioclase (andesine and albite), quartz, celadonite, chlorite and calcite. Other than calcite, the fractures contain euhedral microcrystals laumontite and orthoclase.

Plagioclase and augite in phenocrysts are relict volcanic minerals. Grains of symplectic ilmenite-magnetite may also be primary, but the symplectic intergrowths suggest subsolidus re-equilibration in response to post-eruptive cooling. The order of appearance of the minerals is as follows, inferred from textural relationships (**Abbott et al., 2013a, b**):

(1) Protolith minerals (plagioclase, augite, symplectic Fe-Ti oxide).

(2) Minerals pseudomorphous after augite (mainly celadonite, chlorite, albite), and rutile associated with Fe-Ti oxides.

(3) Minerals in the fractures (laumontite, orthoclase, calcite).

(4) Heulandite, chabazite and albite partially replacing primary plagioclase.

The major-element mineral chemistry is reported in **Abbott et al.** (**2013b**). While the general aspect of the rock gives the impression of andesite, the composition of the relict plagioclase (An_{60}) and augite (Mg#68) are more consistent with basalt.

5. WHOLE-ROCK GEOCHEMISTRY

5.1. Major elements

In the standard total-alkali versus silica (TAS) classification scheme for volcanic rocks (**Figure 5A**) the analyses from **Table 1** for the Wagwater clasts plot as andesite and borderline andesite-trachyandesite. Two average analyses for Halberstadt lava, basalt (n = 3) and spilite (n = 12) (**Jackson, 1977, 1987**; **Jackson and Smith, 1978**), higher in the Wagwater stratigraphy, plot as basalt and borderline basalt–basaltic andesite respectively. Eleven samples of Halberstadt lava, of two types, group-1 and group-2, analyzed by **Hastie et al.** (**2011**), plot broadly from basalt to andesite. Eight representative analyses of Newcastle lavas from **Hastie et al.** (**2010**) plot as borderline rhyolite-dacite. For comparison, the figure also shows analyses of the much older mafic metamorphic rocks in Jamaica: Mount Hibernia Schist and Westphalia Schist (**West et al., 2014**) and Green Bay Schist (**Abbott et al., 2016**). Among the mafic rocks, the TAS classification for the Wagwater clasts is distinct for its high wt.% SiO_2 (**Table 1**). But, this is in part, if not entirely, an artefact of silicification during zeolite facies burial metamorphism (**Abbott et al., 2013a, b**). The unusually low value for MgO (0.65 wt.%) in sample JM15-2 (**Table 1**) can also be attributed metasomatism accompanying metamorphism. **Pearce** (**2014**) offers a cautionary note regarding the use of major elements for classification of magma type (e.g., TAS, total alkali–silica) in metamorphosed or otherwise altered volcanic rocks.

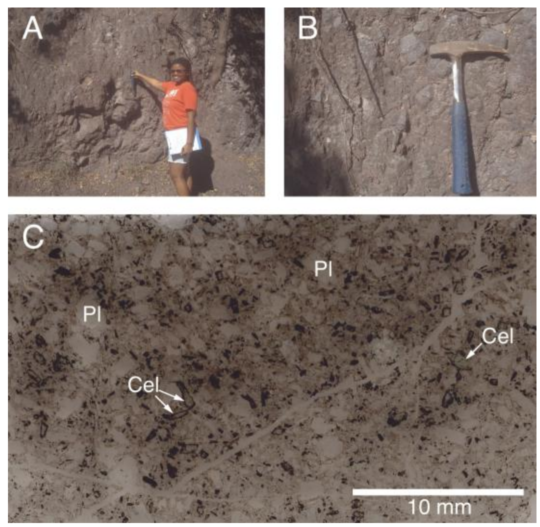

Figure 4. Sample site and petrography. A. Road cut, UWI student Jevanna George for scale. B. Close-up image of conglomerate, dominated by clasts of mafic volcanic rock, locally up to 50 cm in major dimension. C. Digital image of a thin section in plane-polarized light (sample JM12-F, Abbott et al., 2013b). Three celadonite pseudomorphs after augite are indicated. Euhedral phenocrysts of plagioclase are partially to extensively replaced by heulandite and chabazite. Most of the opaque grains are symplectic intergrowths of magnetite and ilmenite. Most of the matrix has been silicified to quartz and albite. Calcite and minute grains of hematite are ubiquitous. The fractures are filled with calcite, laumontite and orthoclase.

5.2. Incompatible, immobile elements

Pearce (**2014**) codifies a clear and concise strategy for interpreting incompatible, immobile-element data. The strategy reflects the conventional wisdom concerning such matters. **Chusi et al.** (**2015**)

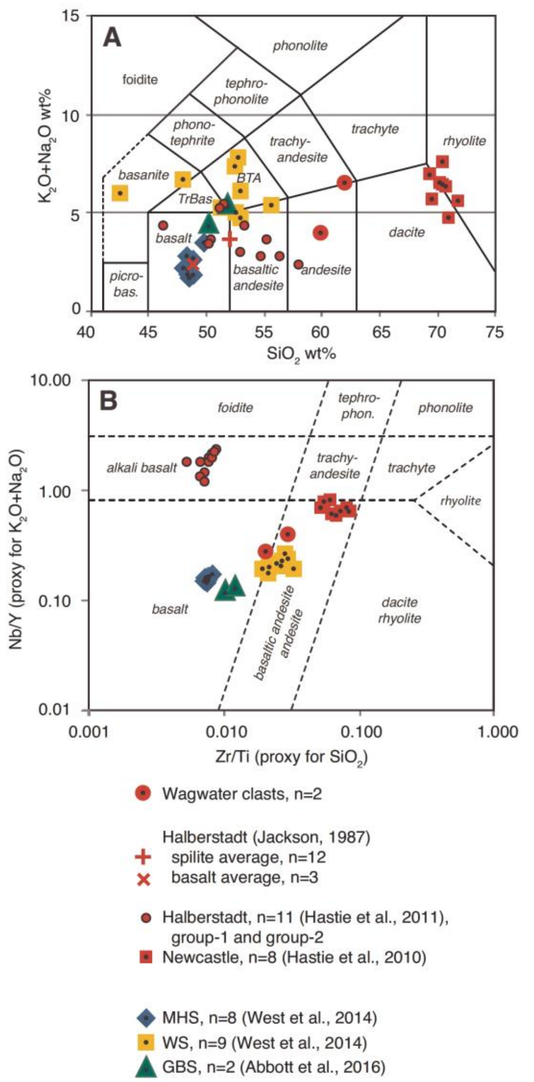

Figure 5. Magma classification. A. Total Alkali–Silica (TAS). BTA = basaltic trachyandesite, TrBas = trachybasalt. B. Nb/Y–Zr/Ti proxy for TAS.

recently tested the strategy, and concluded with a harsh, and well demonstrated, admonition that incompatible, immobile-element data cannot be properly interpreted independently of observed, geological context. With this in mind, for the sake of familiarity, we proceed according to the strategy described by **Pearce** (**2014**).

The point of departure for **Pearce**'s (**2014**) procedure is the incompatible, immobile-element patterns portrayed in **Figure 6**. Analyses are normalized to N-MORB (**Sun and McDonough, 1989**). The elements are ordered according to increasing compatibility. For pairs of elements that behave in a similar fashion (Ta–Nb, Hf–Zr, Ho–Y), the average of the two values of the pair is plotted (**Pearce, 2014**). The pattern for Mt. Hibernia Schist

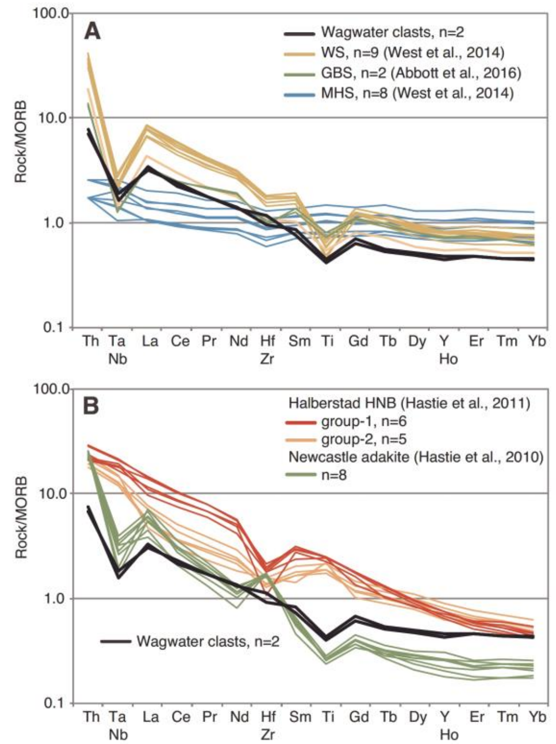

Figure 6. Incompatible, immobile trace elements, normalized to N-MORB (Sun and McDonough, 1989). A. Wagwater clasts compared to older mafic metamorphic rocks in Jamaica. WS = Westphalia Schist, MHS = Mt. Hibernia Schist, GBS = Green Bay Schist. B. Wagwater clasts compared to Halberstadt HNB and Newcastle adakite.

(**Figure 6A**) resembles most closely P-MORB (Plume) (**West et al., 2014**; and see **Hastie et al., 2008**). In terms of trace elements, the pattern for the Wagwater clasts is very similar to those for Green Bay Schist and Westphalia Schist (**Figure 6A**), suggesting a similar C-MORB (contaminated) magma (**Abbott et al., 2016**).

Analyses of eleven samples of Halberstadt lava (group-1 and group-2, **Hastie et al., 2011**) differ from the Wagwater clasts in a number of important ways (**Figure 6B**):

(1) Incompatible, immobile-element ratios for the Halberstadt samples (group-1 and group-2, **Hastie et al., 2011, 2015**) are higher than the ratios for the Wagwater clasts across the whole spectrum of incompatible, immobile elements.

(2) The Wagwater clasts show pronounced negative anomalies for (Ta+Nb)/2 and Ti. In contrast, the Halberstadt samples show slight to distinct positive anomalies for (Ta+Nb)/2 and Ti.

(3) Halberstadt lavas show a distinct negative (Hf+Zr)/2 anomaly.

Except for the negative (Hf+Zr)/2 anomaly, the Halberstadt analyses resemble mostly closely ocean island basalt (OIB, intraplate) (**Hastie et al., 2011**), close to the "Nicoya, Costa Rica" example for an OIB environment (**Pearce, 2014**). The high-Nb character of the Halberstadt samples (29-49 ppm Nb) is unusual and distinct for a subduction environment (**Hastie et al., 2011, 2015**). For this reason, **Hastie et al.** (**2011**) have given these basalts a special designation, HNB (high-Nb basalt), in order to distinguish them from OIB. The Nb-values for the Wagwater clasts (4-5 ppm, **Table 1**) are not unusual. The limited REE data on Halberstadt lava reported previously (**Jackson, 1987**; **Jackson, and Scott, 2002**; **Jackson and Smith, 1978**) are similar to REE values reported by **Hastie et al.** (**2011**). **Jackson** (**1977, 1987**), **Jackson and Smith** (**1978**) and **Jackson and Scott** (**2002**) recognized the intraplate character of the Halberstadt lava. To summarize, the clasts from the lower Wagwater Formation derive from a C-MORB magma, while analyses of Halberstadt lava (**Jackson and Smith, 1978**; **Jackson, 1987**; **Jackson, and Scott, 2002**; **Hastie et al., 2011**) derive from a HNB, OIB-like magma. The difference implies a change from C-MORB to OIB-like HNB during the deposition of the Wagwater Formation.

Analyses of eight samples of Newcastle lava (**Hastie et al., 2010**) differ from the Wagwater clasts in a couple of important ways (**Figure 6B**):

(1) The ratio of Th/Yb is higher in the Newcastle lavas than in the Wagwater clasts, such that ratios for the lower compatibility elements are higher, while the ratios for the higher compatibility elements are lower, in the Newcastle lava than in the Wagwater clasts.

(2) Newcastle lava shows a pronounced positive (Hf+Zr)/2 anomaly.

The incompatible, immobile element pattern (**Figure 6B**) for the Newcastle lavas cannot be interpreted properly in the context of a strategy intended for basaltic rocks (**Pearce, 2014**). Nevertheless, the incompatible, immobile element pattern has the general attributes of arc-related adakite (**Best and Christian, 2001**; **Hastie et al., 2010**).

5.2.1 Proxy for TAS rock classification

For metamorphic and altered igneous rocks, such as those considered here, where primary major element concentrations may have been affected, the Nb/Y–Zr/Ti diagram (**Figure 5B**) is a well-tested proxy for the standard total alkali–silica classification (TAS, **Figure 5A**) (**Pearce, 2014**). We have transposed the axes in Figure 5B from the conventional representation for an easier comparison with the TAS classification (**Figure 5A**).

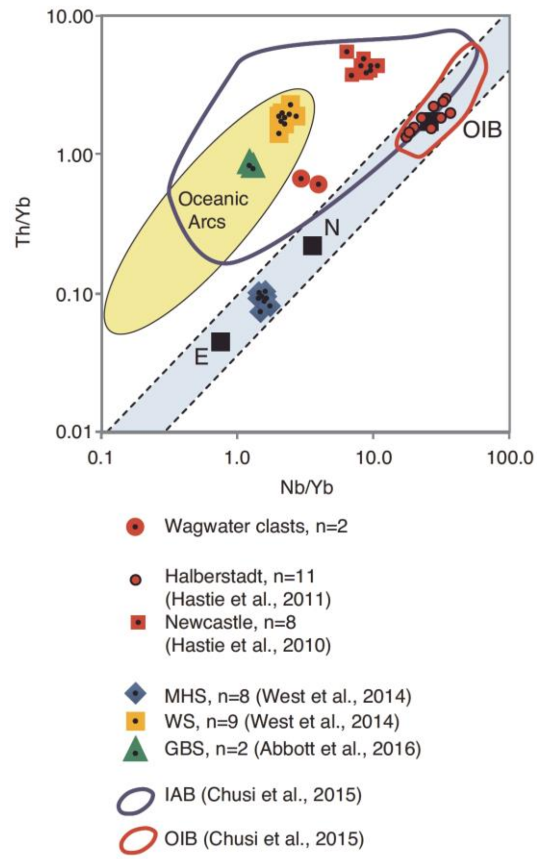

Figure 7. Th/Yb–Nb/Yb diagram, distinguishes between MORB-OIB and non-MORB–OIB magmas. E = E-MORB, enriched in incompatible trace elements, N = N-MORB, normal, OIB = ocean island basalt.

Analyses of Mt. Hibernia Schist and Green Bay Schist plot close together and classify as basalt, even though the tectonic environments are very different, oceanic plateau for the former, island arc for the latter (**Abbott et al., 2016**). Similarly, analyses of Westphalia Schist and Wagwater clasts plot close together and classify as borderline basalt–basaltic andesite, but in this case the ages are very different, Cretaceous or older for the former (>77 Ma, **Lewis et al., 1973**), earliest Paleocene for the latter (c. 65 Ma, **Mann and Burke, 1990**). Both groups of Halberstadt HNB analyzed by **Hastie et al.** (**2011, 2015**) classify as alkali basalt, distinct from the other volcanic rocks in the Wagwater Formation, and distinct from the older metamorphic rocks. Newcastle lava classifies as andesite, close to trachyandesite.

Nb values in Halberstadt lavas reported by **Jackson** (**1987**) for the average spilite (3 ppm) and average basalt (also 3 ppm) are questionably low compared with values (27.56-48.62 ppm) reported by **Hastie et al.** (**2011**) for the same rocks.

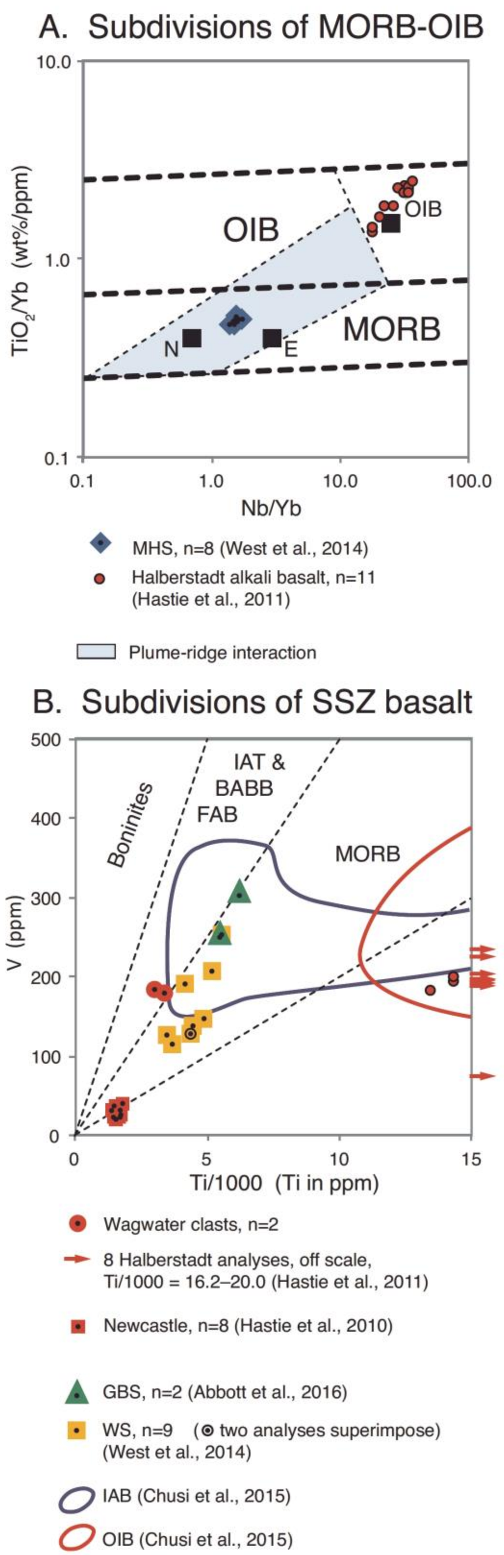

Figure 8. A. Subdivisions of MORB–OIB magmas. N = N-MORB, E = E- MORB, OIB = ocean island basalt. B. Subdivisions of suprasubduction zone magmas (SSZ). IAT = island arc tholeiite, FAB = fore arc basalt, BABB = back arc basin basalt, IAB = island arc basalt.

Otherwise, in the context of **Figure 5B**, values for Y, Zr and Ti reported by **Jackson** (**1987**) and **Jackson and Smith** (**1978**) are consistent with values reported by **Hastie et al.** (**2011**).

5.2.2 Magma type and tectonic setting

The Th/Yb–Nb/Yb diagram (**Figure 7**) distinguishes effectively between MORB–OIB environments and arc-related environments (**Pearce, 2014**, **Chusi et al., 2015**). Analyses for Mt. Hibernia Schist plot in the MORB-OIB array, between N-MORB and E-MORB (**West et al., 2014**), consistent with Pearce's (2014) "Nicoya" example of P-MORB. The Wagwater clasts plot just off the MORB-OIB array, distinct from Green Bay Schist (**Abbott et al., 2016**) and Westphalia Schist (**West et al., 2014**). All of the "off-MORB-OIB" analyses, except the Newcastle analyses, are consistent with the calc-alkaline part of the oceanic arc region (**Pearce, 2014**). Considering only environments that do not involve continental material, according to **Chusi et al.** (**2015**) all of the "off-MORB-OIB" analyses would be classified as subalkaline island arc basalt (IAB). According to **Dilek and Furnes** (**2014**), the Wagwater clasts, Green Bay Schist and Westphalia Schist would be classified as subduction-related, calc-alkaline basalt. Analyses of Halberstadt alkali basalt (HNB, **Hastie et al., 2011, 2015**) plot essentially on the average OIB in the MORB-OIB array, which as noted above is at variance with convergent-plate tectonic environment. **Jackson** (**1977, 1987**), **Jackson and Smith** (**1978**) and **Jackson and Scott** (**2002**) do not provide enough analytical data to apply this classification scheme to their analyses of Halberstadt basalt and spilite. Analyses of Newcastle lavas (**Hastie et al., 2010**) plot off of the MORB-OIB array, but the meaning in this case is not clear because the diagram is not intended for adakite (dacite and rhyolite). The Newcastle adakite analyses are shown only for the purpose of comparison, especially with respect to other volcanic rocks in the Wagwater Formation (C-MORB clasts and Halberstadt HNB).

5.2.3 Subdivisions of tectonic setting

Figure 8 shows subdivisions of the MORB-OIB array and subdivisions of supra-subduction zone (SSZ) basalt (**Pearce, 2014**). The bold, sub-horizontal, dashed lines in **Figure 8A** define two regions, distinguished by the depth of melt production. Analyses of Mt. Hibernia Schist plot in the shallow-melting region, related to a mantle plume, that is, P-MORB (**Abbott et al., 2016**). All of the 11 analyses of Halberstadt HNB (6 of group-1 and 5 of group-2) (**Hastie et al., 2011, 2015**) plot in the deep-melting region, close to average OIB (**Pearce, 2014**). However, details of the trace-element systematics (**Hastie et al., 2011, 2015**) indicate that while group-1 HNB have a deep source, group-2 HNB have a relatively shallower source in metasomatized mantle. Other details indicate that the HNB magma is derived from compositionally variable spinel-garnet peridotite (**Hastie et al., 2011, 2015**). The V–Ti/1000 plot in **Figure 8B** gives information regarding the influence of H_2O, a signature for melting above the subduction zone or contamination of magma ascending through the SSZ. The island arc tholeiite (IAT) and boninite fields indicate melting above a subduction zone, that is, in the mantle wedge. The MORB field indicates melt production beneath the subduction zone, that is, beneath a subducted ocean ridge (**Pearce, 2014**; **Dilek and Furnes, 2014**). Green Bay Schist and Westphalia Schist both plot in the MORB region, variously affected in the SSZ region, i.e., C-MORB. V-Ti/1000 values close to the boundary with the IAT field indicate a greater amount of contamination in the SSZ. The Wagwater clasts plot barely in the rather unspecific field of island arc tholeiite (IAT), back arc basin basalt (BABB) and fore-arc basalt (FAB). However, the trace element ratios (**Figure 6**) favor derivation from MORB magma by contamination in the suprasubduction zone, that is, C-MORB. Of the environments that do not involve continental material, the Wagwater clasts plot in the field designated as "island arc basalt" by **Chusi et al.** (**2015**).

While the V–Ti/1000 plot is not intended for MORB-OIB magmas, the analyses for the Halberstadt alkali basalt (**Hastie et al., 2011**), at least those analyses that plot within the range of the Ti/1000 axis, are shown in order to emphasize the distinction between the Wagwater basalt clasts and the Halberstadt HNB. Lacking analyses for V, the average Ti/1000 values for **Jackson**'s (**1977, 1987**) and **Jackson and Smith** (**1978**) basalt (Ti/1000 = 14.44, n = 3) and spilite (Ti/1000 = 16.24, n = 12) show that these rocks do indeed belong with the Halberstadt lavas. **Jackson** (**1977, 1987**), **Jackson and Smith** (**1978**) and **Jackson and Scott** (**2002**) recognized the intraplate character of Halberstadt basalt and spilite.

Analyses of Newcastle adakites are also plotted in **Figure 6B**, but only for comparison with the Halberstadt HNB and the Wagwater clasts. Otherwise, the V–Ti/1000 plot is not appropriate for such felsic rocks.

6. DISCUSSION AND CONCLUDING REMARKS

Jackson (**1977, 1987**), **Jackson and Smith** (**1978**) and **Jackson and Scott** (**2002**) understood that both subduction-related felsic volcanism (Newcastle dacite and rhyolite) and what passed for intraplate OIB volcanism (Halberstadt basalt) occurred during the deposition of the Wagwater Formation. This study shows that in fact the earliest volcanism was neither of these, but rather subduction-related C-MORB. In a conventional interpretation of incompatible, immobile elements, both C-MORB volcanism and OIB-like volcanism are problematic. C-MORB involves magma produced from a subducted ocean ridge (**Pearce, 2014**), but no earlier, and otherwise susceptible, ocean ridge can be implicated (**Mann and Burke, 1990**; **Pindell and Kennan, 2009**; **Pindell et al., 2012**). OIB involves magma produced in an intraplate environment, but the transtensional Wagwater basin formed above a subduction zone (e.g., **Jackson, 1977, 1987**; **Jackson and Smith, 1978**; **Mann and Burke, 1990**; **Jackson and Scott, 2002**; **Pindell and Kennan, 2009**; **Hastie et al., 2011, 2015**; **Pindell et al., 2012**).

An additional complication is the relationship of the Newcastle adakite lavas (dacite and rhyolite) to the basaltic lavas (C-MORB and Halberstadt HNB). In their most recent interpretation, **Hastie et al.** (**2015**) demonstrate convincingly that Newcastle adakite was the product of partial melting of shallow-subducted, metamorphosed Caribbean Oceanic Plateau (COP). For practical purposes, Newcastle lavas were not affected by mixing, assimilation neither by fractional crystallization (**Hastie et al., 2015**). The magma source and evolution of the Newcastle adakite were not related to the magma source and evolution of Halberstadt HNB (**Hastie et al., 2015**). This certainly makes sense for Newcastle lavas lower in the Wagwater stratigraphy, hence older, than the Halberstadt lavas (**Mann and Burke, 1990**, their fig. 8). We propose that Newcastle volcanism was likewise unrelated to C-MORB volcanism.

We are attracted to a plate-tectonic scenario in which underplating of buoyant Caribbean Oceanic Plateau (COP) caused the cessation of subduction, leading to slab-detachment and foundering of the detached, distal portion of the slab. This is basically the model so well argued by **Hastie et al.** (**2015**, their fig. 14). Cessation of subduction localized the C-MORB and MHB volcanism to a position above the initial slab-detachment and at the same time localized the Newcastle volcanism above the deeper part of the underthrust COP (**Hastie et al., 2015**). We suggest that the C-MORB magmatism was related to the initiation of slab-detachment, which essentially created a divergent situation in the subducting slab. The nascent slab-gap promoted magma production (from immediately beneath) with MORB characteristics. The ascending magma was modified in response to interaction with suprasubduction-zone lithosphere, leading to the observed C-MORB. We envision that during the evolution of the system (generously 65-50 Ma, e.g., **Abbott et al., 2013a, b**), as the slab-gap widened, deeper mantle became involved in melt production, leading to Halberstadt group-1 HNB magma and associated, but shallower, group-2 HNB magma (**Hastie et al., 2011, 2015**). The locus of magma production for the Newcastle adakite could have been very close to, and contemporaneous with, the loci of magma production for both C-MORB and HNB, perhaps much closer than schematically illustrated by **Hastie et al.** (**2015**, their fig. 14).

Accommodation-space for the Wagwater Formation was created by thinning of suprasubduction-zone crust in a transtensional tectonic environment. Extensional tectonics may have been initiated by slab-detachment and subsequent slab-rollback (**Hastie et al., 2015**), or initiated by simple isostatic rebound of the underthrust COP. In either case, pressure would have decreased on the underlying COP and mantle, creating conditions amenable to decompression melting in the source regions for all of the lava types (**Hastie et al., 2015**).

Acknowledgements. *We are beholden to Prof. Trevor A. Jackson (d. 18 January 2016) for introducing us to Caribbean geology, and encouraging us along the way. Thank you, Trevor. We appreciate the comments of the anonymous reviewer.*

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Editorial Responsiblity: Dr S. James-Williamson. Type setting: Prof. S. F. Mitchell

Accepted 31st August 2017