Results in Geochemistry 6 (2022) 100015

Contents lists available at ScienceDirect

Results in Geochemistry

journal homepage: www.journals.elsevier.com/results-in-geochemistry

Chronology and geochemistry of the Caribbean Large Igneous Province in Jamaica

Simon F. Mitchell [a], Andrew C. Kerr [b,*], Alan R. Hastie [c]

[a] Department of Geography and Geology, The University of the West Indies, Mona, Kingston 7, Jamaica
[b] School of Earth and Environmental Sciences, Cardiff University, Park Place, Cardiff, Wales CF10 3AT, UK
[c] School of GeoSciences, University of Edinburgh, King's Buildings, The Grant Institute, Edinburgh EH9 3FE, UK

ARTICLE INFO

Keywords:
Jamaica
Oceanic plateau
Caribbean

ABSTRACT

Jamaica has a complex geological history with rocks belonging to the Cretaceous Caribbean Large Igneous Province (CLIP) in the east and Cretaceous oceanic island arc rocks in the centre and west. We present a new geochemical dataset for the CLIP and correlate this dataset and previous datasets using radiolarians and planktic foraminifers to the geological timescale. The palaeontological dating indicates that two phases of plateau activity – 'main' phase in the late Turonian-mid Coniacian (c. 92-87 Ma) and an 'extended' phase in the Coniacian to mid Campanian (c. 88-75 Ma). These phases are also seen in the Beata Ridge and on the Lower Nicaragua Rise. The geochemistry indicates that both phases are typical large igneous province plateau basalts. The 'main' phase has slightly more depleted light rare earth elements than the extended phase, indicating mantle source heterogeneity, and a $(Sm/Yb)_n > 1$ indicates a deeper average depth of melting for the 'main' phase. The association of the basalts with sediments containing specific microfossil assemblages clearly demonstrates the existence of these two magmatic phases in Jamaica.

Introduction

The Caribbean Large Igneous Province (CLIP) underlies much of the Caribbean Plate and is exposed in some Caribbean islands including Hispaniola and Jamaica (Sinton et al., 1998; Hastie et al., 2008; Mitchell, 2020) (Fig. 1). The main eruption phase occurred during the late Turonian to early Coniacian (91-89 Ma), but in the northern Caribbean (Hispanola, Jamaica, the Beata Ridge and the Lower Nicaragua Rise) eruptions of lava and emplacement of sills continued into the late Campanian (75-72 Ma) (Dürkefälden et al., 2019a, b). In Jamaica, these CLIP rocks are inter-bedded with cherts, siliceous mudstones, pelagic limestones, sandstones and shales. Radiolarians and planktic foraminifers provide a biostratigraphy (Montgomery and Pessagno, 1999; Mitchell, 2020). One dataset has previously been published for the CLIP rocks of Jamaica (Hastie et al., 2008). The map location of the samples in Hastie et al. (2008) is correct (their Fig. 4); however, these samples are located in the Sulphur River and not the Island River (as stated in Hastie et al., 2008). In this contribution we reproduce the locations of the Hastie et al. (2008) dataset and locate a new geochemical dataset of CLIP rocks in Jamaica (Fig. 2) and place them in their correct stratigraphical context. We also briefly comment on the significance of the new dataset.

Geology

Caribbean Large Igneous Province rocks are exposed in the southern flanks of the Blue Mountains to the north of the community of Bath (Fig. 2). Two formations are present, the Bath Formation and the overlying Cross Pass Formation (The Paleocene Moore Town Formation is also present but is not discussed in this paper). The Bath Formation consists of alternations of predominantly igneous and thin intervals of sedimentary rocks. The igneous rocks are largely composed of basalts, although a few tuffs have been recorded (Hastie et al., 2008). In the lower part of the succession (seen in Devils River and Indian Cony River) pillow basalts are inter-bedded with occasional cherts and a thin unit of red mudstone. The basalts grade upwards into hyaloclastites which are overlain by a thin pelagic limestone and a sequence of shales and sandstones (Fig. 2). The red mudstone yields late Turonian-mid Coniacian (c. 92-87 Ma) radiolarians (Montgomery and Pessagno, 1999) and the pelagic limestone yields Coniacian (90-86 Ma) planktic foraminifers (Mitchell, 2020). The new dataset (location 3 in Fig. 2) represents analyses of pillow basalts (indicating they are contemporaneous with the

* Corresponding author.
E-mail address: kerra@cf.ac.uk (A.C. Kerr).

https://doi.org/10.1016/j.ringeo.2022.100015
Received 19 April 2022; Received in revised form 15 June 2022; Accepted 28 June 2022
Available online 1 July 2022

Fig. 1. Regional map of the eastern Caribbean and northern South America showing the locations of places mentioned in the text and accreted fragments of the CLIP. Adapted from Kerr (2014).

sediments) from a transect along Devils River and therefore represents the main phase of CLIP activity.

The dataset published by Hastie et al. (2008) came from transects along two rivers (locations 1 and 2 in Fig. 2). Interlayered sedimentary rocks consist of cherts and limestones with fossils (radiolarians and planktic foraminifers) that indicate stratigraphic positions from the mid Coniacian-upper Coniacian (probably upper Coniacian) to mid Campanian (88-75 Ma) i.e., younger than those at location 3. The field relationships of the basalts are not so clear and they may represent pillow basalts or sills. These younger basalts represent an extended phase of CLIP volcanism in the northern Caribbean (e.g., the Beata Ridge and Lower Nicaragua Rise: Dürkefälden et al., 2019a, b).

The Bath Formation is overlain by the Cross Pass Formation. This consists of deep-water shales and sandstones without igneous rocks. There is no biostratigraphic data for this unit and it is tentatively attributed to the late Campanian-early Maastrichtian (Mitchell, 2020).

Methodology and techniques

Following crushing and powdering in an agate Tema mill, 0.1 ± 0.0005 g of sample was fused with 0.4 ± 0.0005 g Li-metaborate flux and dissolved in a ~5% HNO_3 solution with a 1 ppm Rh spike. Major element abundances were determined by using a JY Horiba Ultima 2

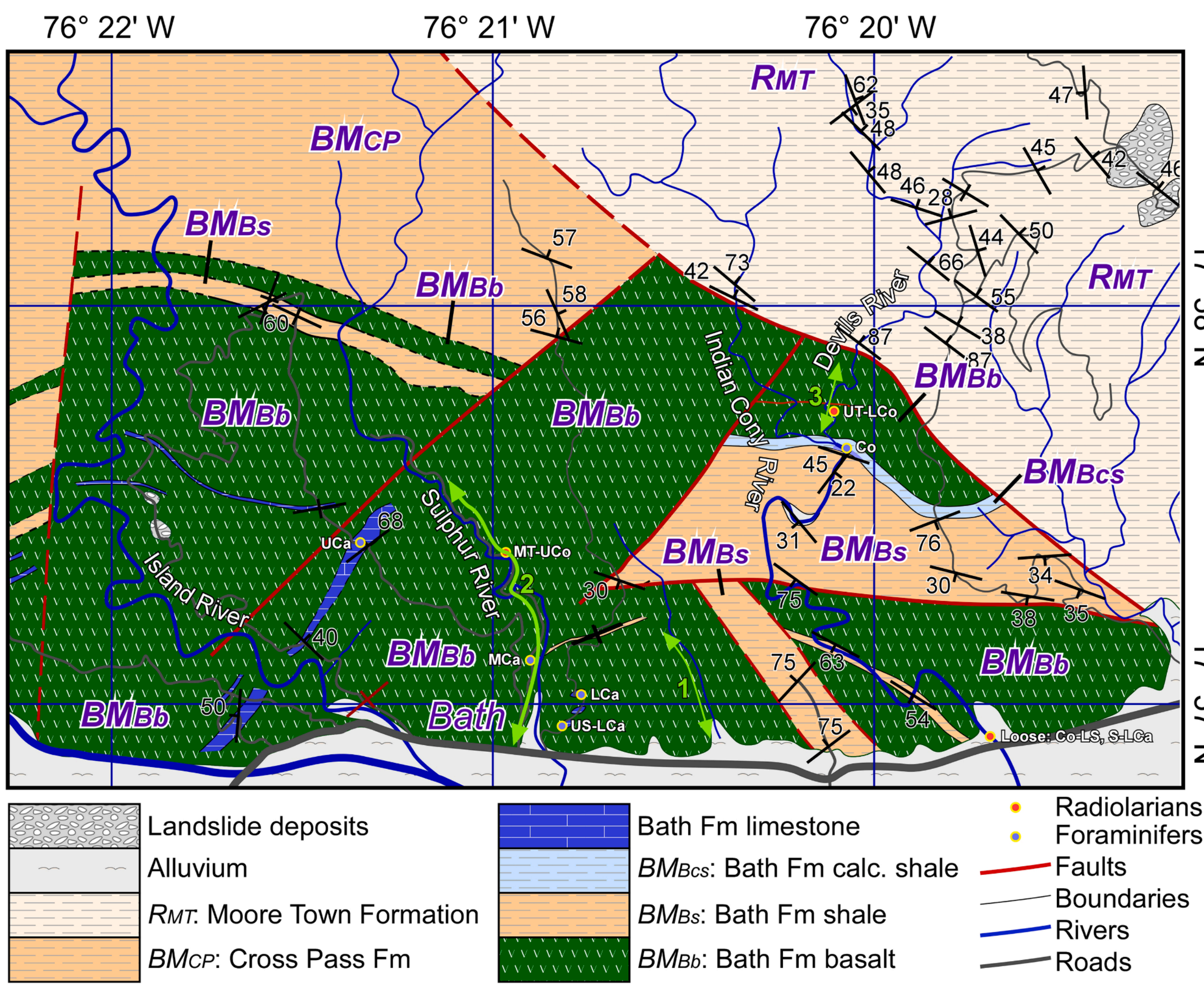

Fig. 2. Geology of the area north of Bath (SE Jamaica) showing the Bath Formation consisting of basalts (*BMBb*) and inter-layered sedimentary rocks (*BMBcs, BMBcs* and limestone) overlain by the Cross Pass Formation. Fossiliferous horizons are shown (Co, Coniacian; S, Santonian; Ca, Campanian; L, lower; M, middle; U, upper). Transects 1 (AHBD27-30) and 2 (AHBD09-26) represent the samples analysed by Hastie et al. (2008). Transect 3 represents the samples presented here. Transects are marked by green lines with arrows.

inductively coupled plasma optical emission spectrometer (ICP-OES) and trace elements were analysed by a Thermo X7 series inductively coupled plasma mass spectrometer (ICPMS) at Cardiff University, United Kingdom (Table 1). A full description of the analytical procedures and equipment at Cardiff University can be found in McDonald and Viljoen (2006). Replicate analyses of international reference materials JB-1a, BIR-1, W2, JA-2, MRG-1 and JG-3 ensured the accuracy and precision of the analyses. Most elements did not deviate more than 5% from standard values and have relative standard deviations below 5%. Replicate analyses of Jb-1a analysed during the present study are given in Appendix 1.

Results

Despite the fact that the new samples from the Bath basalts (location 3 on Fig. 2) are a few million years older than those reported by Hastie et al. (2008) they have a similar range of major element compositions (Table 1). MgO ranges between 5.9 and 8.6 wt.% and TiO_2 between 1.2 and 1.5 wt.% (Fig. 3a). MgO and TiO_2 ranges reported by Hastie et al. (2008) are 6–9 wt.% and 1.1–1.6 wt.% respectively. In terms of incompatible trace elements, the Bath basalts from the present study lie almost entirely within the compositional range of the basalts in Hastie at al. (2008), with broadly flat (with the exception of a negative Th anomaly) primitive mantle normalised multi-element patterns (Fig. 4). In more detail however, there are subtle differences, with the basalts in the present study having both more depleted light rare-earth elements (LREE) [$(La/Nd)_n$ average 0.88 as opposed to 1.0 for the basalts in Hastie et al. (2008)] and more depleted heavy rare-earth elements (HREE) [$(Sm/Yb)_n$ average 1.2 and 1.1 for the basalts in Hastie et al. (2008)] (Fig. 3b). Like the basalts reported by Hastie et al. (2008) the

Table 1
New major and trace element data from the Bath basalts, Jamaica.

	DR6	DR7	DR8	DR9	DR10	DR11	DR12
SiO_2 (wt.%)	50.50	47.72	49.21	48.23	54.14	50.07	49.64
TiO_2	1.27	1.26	1.44	1.45	1.20	1.34	1.48
Al_2O_3	14.07	14.34	13.35	13.85	11.62	12.64	13.58
Fe_2O_3 (total)	12.74	13.43	14.33	13.77	11.47	12.79	12.72
MnO	0.25	0.21	0.25	0.30	0.33	0.35	0.30
MgO	5.85	8.03	5.53	7.44	7.75	8.40	8.57
CaO	10.13	11.08	11.93	11.51	10.10	8.61	10.86
Na_2O	4.02	3.16	2.36	2.22	1.34	3.83	2.72
K_2O	0.11	0.02	0.21	0.23	0.63	0.43	0.39
P_2O_5	0.09	0.08	0.11	0.10	0.08	0.09	0.10
Total*	99.02	99.32	98.71	99.09	98.65	98.55	100.37
LOI	4.22	5.4	7.57	0.82	7.27	6.14	1.16
Sc (ppm)	49.1	47.4	47.7	51.6	40.4	45.1	54.2
V	327	323	341	358	281	321	380
Cr	163	156	195	93	162	133	126
Co	48	49	48	52	41	44	55
Ni	128	126	407	91	113	107	116
Ga	14.6	17.0	15.3	20.6	11.6	14.2	19.7
Rb	1.1	0.1	1.6	0.7	9.3	2.5	3.3
Sr	177	130	1062	101	1557	382	262
Y	24.3	24.5	27.5	28.4	22.1	24.3	27.1
Zr	69.7	70.2	80.1	85.5	62.8	71.4	90.3
Nb	4.13	4.07	4.43	4.50	3.49	3.89	4.99
Ba	72	121	176	26	3907	146	708
La	3.34	3.44	3.82	4.12	3.93	3.77	3.73
Ce	9.25	9.37	10.55	11.04	8.65	9.42	10.57
Pr	1.50	1.51	1.68	1.76	1.48	1.55	1.77
Nd	7.77	7.78	8.68	8.95	7.38	7.86	9.09
Sm	2.61	2.59	2.81	3.03	2.40	2.53	3.00
Eu	1.00	1.01	1.07	1.16	1.06	0.97	1.25
Gd	3.10	3.11	3.48	3.71	2.89	3.17	3.69
Tb	0.56	0.57	0.64	0.68	0.53	0.58	0.68
Dy	3.73	3.79	4.22	4.46	3.43	3.75	4.44
Ho	0.76	0.77	0.85	0.91	0.69	0.75	0.88
Er	2.31	2.34	2.63	2.73	2.14	2.30	2.66
Tm	0.38	0.38	0.42	0.44	0.33	0.36	0.43
Yb	2.29	2.34	2.64	2.74	2.09	2.28	2.71
Lu	0.37	0.38	0.42	0.45	0.33	0.36	0.42
Hf	1.77	1.77	2.03	2.10	1.59	1.75	2.23
Ta	0.25	0.25	0.27	0.28	0.22	0.24	0.30
Th	0.27	0.26	0.26	0.33	0.25	0.25	0.30
U	0.09	0.08	0.10	0.12	0.13	0.11	0.20

All Fe reported as Fe2O3.
* Analyses reported on an anhydrous basis.

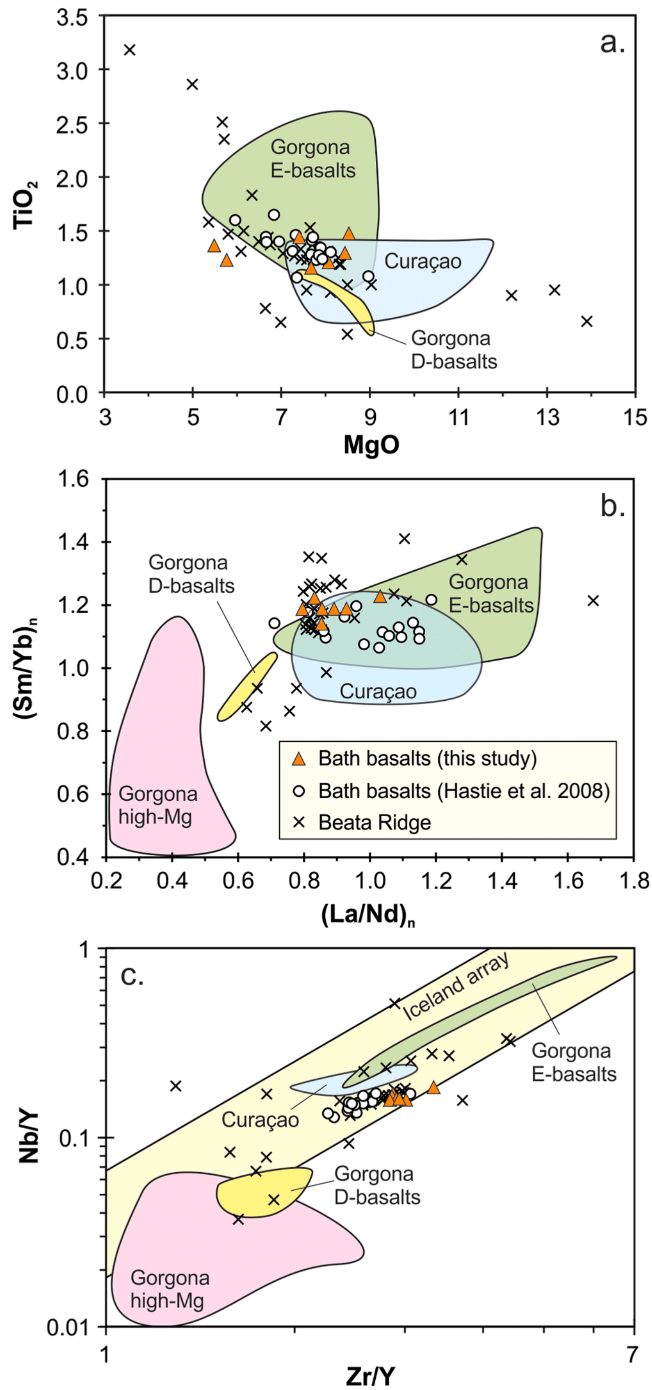

Fig. 3. Representative geochemical diagrams showing the composition of Bath basalts from the present study compared with those reported by Hastie et al. (2008) along with other data and compositional fields from the CLIP: a) MgO vs. TiO_2; b) (La/Nd)n vs. (Sm/Yb)n (normalised to chondrite from Sun & McDonough, 1989) and c) Zr/Y vs. Nb/Y – after Fitton et al. (1997). Other data sources: Kerr et al. (1996), Révillon et al. (1999), Hastie et al. (2016), Beata Ridge Dürkefälden et al. (2019b); Gorgona – data compilation from Kerr (2005).

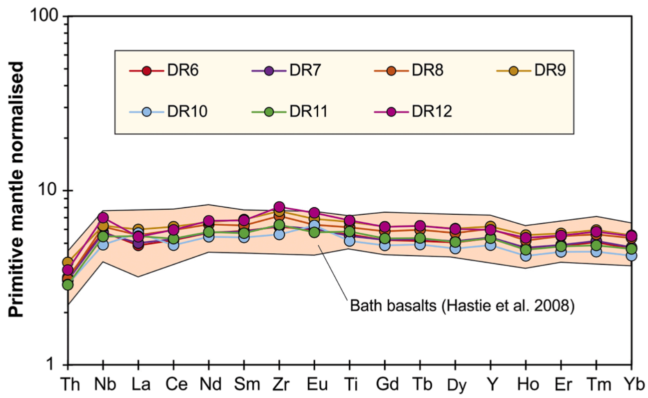

Fig. 4. Primitive mantle normalised (Sun & McDonough, 1989) trace element diagram showing data for the Bath basalts along with a field for the data reported by Hastie et al. (2008).

basalts in this study plot within the Icelandic compositional field on a Zr/Y vs. Nb/Y diagram, but the basalts in the present study have distinctly higher Zr/Y ratios (Fig 3c). The Bath basalts are also compositionally similar to basalts from Curacao, enriched(e)-basalts from Gorgona (Fig. 1) and to the majority of basalts from the Beata Ridge (Figs. 3 and 4).

Discussion

The ages based on microfossils from the Bath basalts in Jamaica agree well with those reported elsewhere (based on radiometric dating) on the northern Caribbean Plate; they are represented by the main phase of CLIP activity in the late Turonian to early Coniacian (92-87 Ma) and an extended CLIP phase from Coniacian to mid Campanian (86-75 Ma). Sample set 2 of Hastie et al. (2008) contains two tuffs with probable Santonian?-Campanian age suggesting proximity to an island arc (Hastie et al., 2008). This is consistent with the CLIP being subducted beneath Jamaica to produce the Mount Hibernia Schist in the mid to late Campanian (West et al., 2014; Mitchell, 2020).

The compositional similarities and ages of basalts reported in this study, not only to CLIP basalts previously reported from Jamaica (Hastie et al., 2008), but also to CLIP basalts from Curacao, Gorgona and the Beata Ridge, indicates that they also belong to the CLIP. Like other oceanic plateaux such as the Ontong Java Plateau, the bulk of the basalts in the CLIP are homogeneous with relatively flat chondrite normalised rare earth element patterns, however the CLIP does display a greater degree of source heterogeneity (see review in Kerr, 2014). The subtle differences in trace element signatures between the basalts in this study and the slightly younger basalts reported from the Bath area by Hastie et al. (2008) also point towards source heterogeneity. With both slight LREE and HREE depletion, the basalts in this study and a subset of the samples reported by Hastie et al. (2008) were clearly derived from a more LREE-depleted [(La/Nd) <1] source with a deeper average depth of melting [$(Sm/Yb)_n > 1$ and higher Zr/Y], than the majority of the Bath basalts (Hastie et al. 2008).

Conclusions

The new biostratigraphic and geochemical data presented here demonstrate that in south-eastern Jamaica the CLIP is represented by a 'main' CLIP phase in the late Turonian to early Coniacian and an 'extended' CLIP phase ranging from the Coniacian to mid Campanian. The basalts have typical oceanic plateau signatures, although the 'main' CLIP phase has slightly more depleted LREE and HREE than the 'extended' CLIP phase, indicating source rock heterogeneity, and were generated from a deeper average depth of melting.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Roshuan Brown for help in collecting samples in the field. Comments from David Peate and an anonymous reviewer helped improve the manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ringeo.2022.100015.

References

Dürkefälden, A., Hoernle, K., Hauff, F., Werner, R., & Garbe-Schönberg, D. (2019a). Second-stage Caribbean Large Igneous Province volcanism: The depleted Icing on the enriched cake. *Chemical Geology, 509*, 45–63.

Dürkefälden, A., Hoernle, K., Hauff, F., Wartho, J.-A., van der Bogaard, P., & Werner, R. (2019b). Age and geochemistry of the Beata Ridge: Primary formation during the main phase (~89 Ma) of the Caribbean Large Igneous Province. *Lithos, 328-329*, 69–87.

Fitton, J. G., Saunders, A. D., Norry, M. J., Hardarson, B. S., & Taylor, R. N. (1997). Thermal and chemical structure of the Iceland plume. *Earth and Planetary Science Letetrs, 153*, 197–208.

Hastie, A. R., Kerr, A. C., Mitchell, S. F., & Miller, I. (2008). The geochemistry of Cretaceous oceanic plateau lavas in eastern Jamaica: Implications for the evolution of the Caribbean plate. *Lithos, 101*, 323–343.

Hastie, A. R., Fitton, J. G., Kerr, A. C., McDonald, I., Schwindrofska, A., & Hoernle, K. (2016). The composition of mantle plumes and the deep Earth. *Earth and Planetary Science Letters, 444*, 13–25.

Kerr, A. C. (2005). La Isla de Gorgona, Colombia: A petrological enigma? *Lithos, 84*, 77–101.

Kerr, A.C. 2014. Oceanic plateaus. In: Holland, H.C. & Turekian K. (series eds.). Treatise on Geochemistry 2nd Edition, Volume 4, Rudnick, R. (ed.) The Crust. Chapter 18, pp. 631-667. Elsevier.

Kerr, A. C., Tarney, J., Marriner, G. F., Klaver, G. Th., Saunders, A. D., & Thirlwall, M. F. (1996). The geochemistry and petrogenesis of the late-Cretaceous picrites and basalts of Curaçao, Netherlands Antilles: A remnant of an oceanic plateau. *Contributions to Mineralogy and Petrology, 124*, 29–43.

McDonald, I., & Viljoen, K. S. (2006). Platinum-group element geochemistry of mantle eclogites: A reconnaissance study of xenoliths from the Orapa kimberlite, Botswana. *Applied Earth Science (Trans. Inst. Min. Metall. B), 115*, 81–93.

Mitchell, S. F. (2020). Cretaceous geology and tectonic assembly of Jamaica. In I. Davison, J. N. F. Hull, & J. Pindell (Eds.), *SP504 The basins, orogens and evolution of the southern Gulf of Mexico and northern Caribbean* (pp. 507–547). Geological Society of London. https://doi.org/10.1144/SP504-2019-210.

Montgomery, H. and Pessagno Jr, E.A. 1999. Cretaceous microfaunas of the Blue Mountains, Jamaica, and of the northern and central Basement Complexes of Hispaniola. In: Mann, P., ed., Caribbean basins, sedimentary basins of the world, 4, 237-246, Elsevier Sciences B. V., Amsterdam.

Révillon, S, Arndt, N. T., Hallot, E., Kerr, A. C., & Tarney, J. (1999). Petrogenesis of picrites from the Caribbean plateau and the North Atlantic magmatic province. *Lithos, 41*, 41–61.

Sinton, C. W., Duncan, R. A., Storey, M., Lewis, J., & Estrada, J. J. (1998). An oceanic flood basalt province within the Caribbean plate. *Earth and Planetary Science Letters, 155*, 221–235.

Sun, S. S, & McDonough, W. F. (1989). Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *Geological Society Special Publications, 42*, 313–345.

West, D P, Jr., Abbott, R. N, Jr., Bandy, B. R, & Kunk, M. J (2014). Protolith provenance and thermotectonic history of metamorphic rocks in eastern Jamaica: Evolution of a transform plate boundary. *GSA Bulletin, 126*, 600–614.