Lithos 120 (2010) 407–420

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Origin of the volcanic complexes of La Désirade, Lesser Antilles: Implications for tectonic reconstruction of the Late Jurassic to Cretaceous Pacific-proto Caribbean margin

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ARTICLE INFO

Article history:
Received 2 June 2010
Accepted 24 August 2010
Available online 17 September 2010

Keywords:
La Désirade
Caribbean
Geochemistry
Tectonics
Subduction

ABSTRACT

La Désirade Island is located on the hanging wall of the present-day Lesser Antilles subduction zone and consists of a suite of Mesozoic igneous rocks capped by Neogene limestone. The basement suite contains Kimmeridgian to Tithonian (~153–145 Ma) mafic lava flows and pillow basalts overlain by felsic flows and breccias and intruded by a Mid-Berriasian (~144 Ma) trondhjemite pluton and intermediate to felsic dykes. The mafic rocks form a ~300 m thick sequence which trace element geochemistry reveals to contain, in stratigraphic order: (1) tholeiites with a very weak subduction signature; (2) calc-alkaline and tholeiitic arc rocks containing pelagic and terrigenous sediment slab-related components and (3) arc tholeiites with a minor subduction signature. The mantle wedge source was depleted and did not contain a significant plume-related component. The overlying felsic rocks show similar trace element patterns and incompatible trace element ratios to the mafic units. Factors such as pelagic sedimentary deposition and re-working, low eruption rates and the presence of MORB-like and felsic rocks are best explained by an origin at a back-arc spreading ridge. This back-arc was most likely in the proto-Caribbean (Colombian Marginal) seaway and was related to east-dipping Andean/Cordilleran subduction. Other sites in the Greater Antilles and Central America older than the ~135 Ma westward acceleration of North America appear to corroborate a latest Jurassic–Early Cretaceous east-dipping arc system. The preservation of La Désirade in the fore-arc of the present Antilles arc is consistent with Mid-to-Late Cretaceous inception of west-dipping subduction along the former back-arc axis which had previously given rise to La Désirade.

1. Introduction

The Caribbean plate (Fig. 1) is widely considered to have originated in the Pacific region and subsequently tectonically emplaced between North and South America (e.g. Kerr et al., 2003; Pindell and Kennan, 2009). Plate reconstructions show that the Americas separated during the break-up of Pangaea to form oceanic crust by ~160 Ma in the Gulf of Mexico, proto-Caribbean and Colombian Marginal seaways (Pindell and Kennan, 2009). Divergence between the Americas focussed on the proto-Caribbean seaway until the late Campanian (Pindell et al., 1988; Müller et al., 1999; Pindell and Kennan, 2009). From the Early Triassic onwards, oceanic crust of the Farallon (proto-Pacific) plate subducted beneath North and South America and island arc sequences were accreted to the American continental margins (the Andean/Cordilleran arc) (e.g. Oldow et al., 1989).

Subduction at the proto-Caribbean–Pacific boundary during much of the Cretaceous also generated the "Great Arc" of the Caribbean (sensu Burke et al., 1978; Burke, 1988), including the extinct Greater Antilles arc. However it is unclear whether the earliest stages of the Greater Antilles arc were related to east-dipping or to southwest-dipping subduction. At ~94–89 Ma, to the southwest of the Greater Antilles, the mantle plume-derived Caribbean–Colombian Oceanic Plateau (CCOP) formed on the Farallon Plate (Sinton et al., 1998; Kerr et al., 2003). The CCOP crust is up to 20 km thick, much thicker than "normal" oceanic crust (Edgar et al., 1971; Mauffrey and Leroy, 1997). East-dipping subduction initiated at the western margin of the CCOP during the Campanian which isolated the Caribbean Plate and formed the Costa Rica–Panama arc (e.g. Pindell and Dewey, 1982). By this time, subduction on the Greater Antilles system had become southwest-directed, allowing the Americas to move westwards past the Caribbean Plate (e.g. Mattson, 1979). The Caribbean Plate partially collided with North and South America during the Campanian and moved east along transpressional boundaries into its present location (e.g. Pindell and Dewey, 1982; Kennan and Pindell, 2009; Hastie et al., 2010).

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0024-4937/$ – see front matter
doi:10.1016/j.lithos.2010.08.026

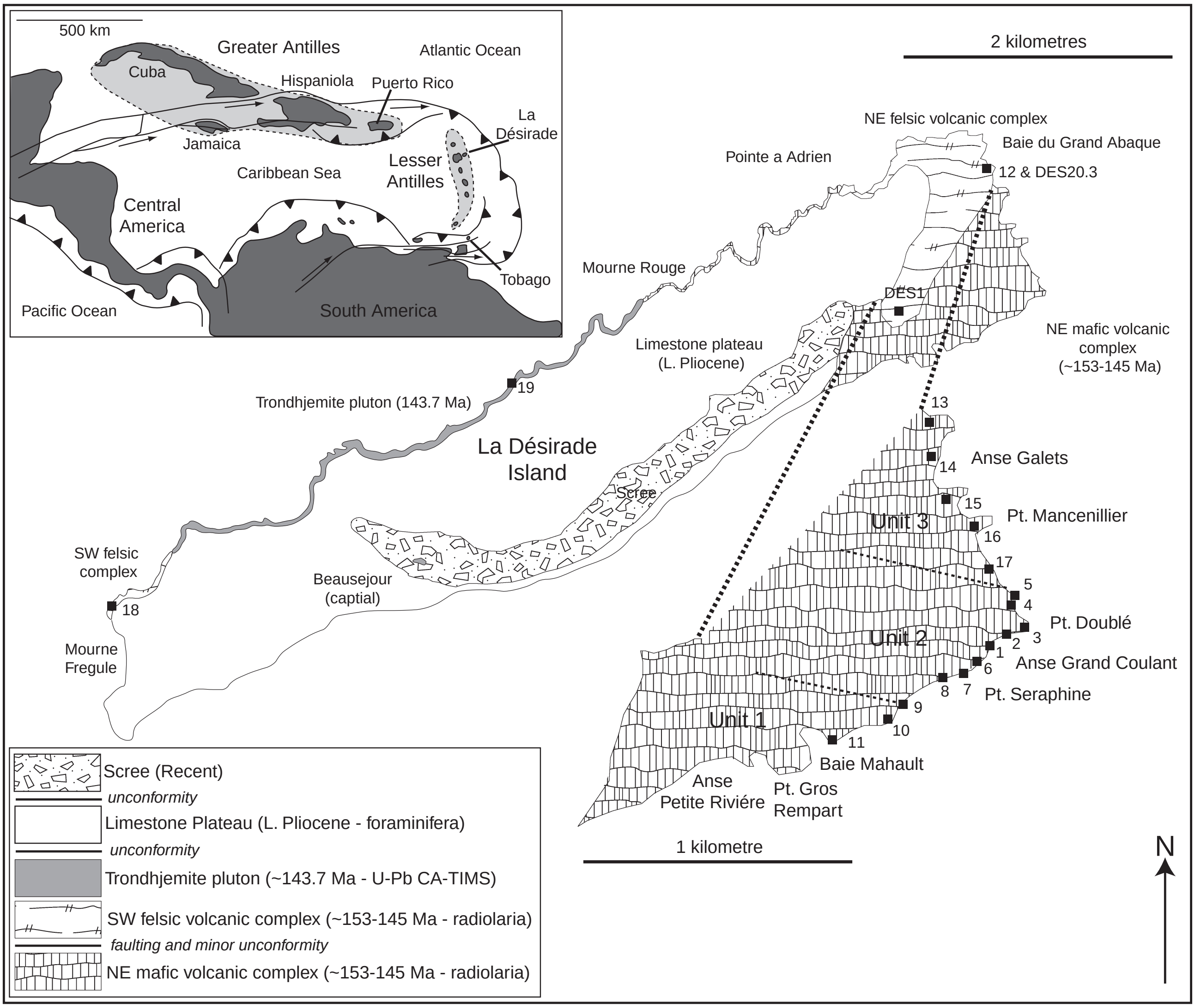

Fig. 1. Simplified geological and location map of La Désirade with insets showing the Caribbean Plate and a stratigraphic column for the island. Intermediate-felsic dykes are scattered throughout the trondhjemite and NE volcanic complexes. Numbers indicate sample locations. For geochronological references, see text.

The cause and timing of the polarity reversal are arguably the most contentious aspects of Caribbean geology (e.g. Hastie et al., 2009; Hastie and Kerr, 2010; Pindell and Kennan, 2009). Atlantic spreading rates increased during the Early Cretaceous (~135–125 Ma) so North America travelled westwards over the mantle faster than South America (Pindell et al., 1988). Some suggest that the effect of this acceleration was to turn the proto-Caribbean–Pacific boundary into a sinistral transform zone which would 'flip' to become a southwest-dipping subduction zone (Greater Antilles arc) during the Aptian–Albian (e.g. Pindell et al., 2006; Pindell and Kennan, 2009). A second model is that the thickened crust of the CCOP collided with the Great Arc of the Caribbean (80–90 Ma), which at that time was east-dipping and still part of the Andean/Cordilleran system. The plateau was too hot, thick and buoyant to subduct, thus, blocking the trench and initiating polarity reversal (e.g. Duncan and Hargraves, 1984; Burke, 1988; White et al., 1999; Kerr et al., 2003; Hastie and Kerr, 2010).

There are also subduction-related rocks in the Caribbean region today which pre-date the westward acceleration of North America and whose origin is the result of Andean/Cordilleran subduction. The preservation of these rocks is due in part to the nature of the 'flip' or subduction polarity reversal in the Greater Antilles region. However, although these rocks are likely to be highly significant in understanding the origin and evolution of the Caribbean Plate, little is known of their distribution and tectonomagmatic setting. In this paper we investigate the Late Jurassic to Early Cretaceous (Mattinson et al., 2008) igneous rocks of the island of La Désirade in the Lesser Antilles (Fig. 1). Previous studies disagree on La Désirade's tectonomagmatic setting, with suggestions ranging from mid-ocean ridge (e.g. Mattinson et al., 1980, 2008) to island arc (e.g. Bouysse et al., 1983; Baumgartner et al., 2008; Cordey and Cornée, 2009). In this paper we use trace element geochemistry to determine the tectonic setting of the rocks, and to identify mantle and crustal inputs into their magmas. Using this new data and published data from Late Jurassic to Early Cretaceous subduction-related fragments from around the Caribbean region, we propose a tectonic reconstruction for the Late Jurassic period and a framework for the preservation of La Désirade following the onset of southwest-dipping subduction in the Greater Antilles.

2. Geological outline of La Désirade

La Désirade (22 km^2) lies 10 km east of Grande Terre, Guadeloupe, on the hanging wall of the active Lesser Antilles subduction zone (Fig. 1). The island is capped by Neogene limestone (Baumgartner-Mora et al., 2004) and has been uplifted on a fault scarp revealing the only suite of Mesozoic volcanic and plutonic rocks in the Lesser Antilles. Trondhjemites and basalts similar to those found on La Désirade have also been dredged from the Falmouth Spur between La Désirade and Antigua and from the Désirade sea trough (Johnston et al., 1971; Fink, 1972; Bouysse, 1984). The presence of Late Jurassic radiolarian assemblages of Pacific origin which pre-date much of the proto-Caribbean seaway demonstrate that La Désirade has travelled eastwards relative to the Americas at the leading edge of the Caribbean Plate (Montgomery et al., 1992, 1994) (Fig. 1).

Approximately 10 km^2 of Mesozoic igneous rocks are exposed on the island, chiefly around the coasts and particularly in the northeast from Baie Mahault to Baie du Grand Abaque (Fig. 1). Recent geochronology and fieldwork (Mattinson et al., 2008) reveal a subaqueous eruptive and intrusive sequence. The first event was eruption of mafic pillow lavas and massive flows, inter-bedded with chert and subordinate limestone. In this paper these are referred to as the *NE mafic volcanic complex*, and are the main focus of our investigation. Magmatism then evolved to felsic compositions (Mattinson et al., 2008) forming the *NE felsic volcanic complex* near Grand Abaque, the central *trondhjemite pluton* and the *SW felsic complex* which consists of dykes and flows around Morne Frégule. Finally, a suite of *intermediate-felsic dykes* which cuts both the pluton and the northeastern complexes was emplaced.

Radiolarians in inter-lava flow chert at Pointe Doublé (NE mafic complex) and Pointe Frégule (SW felsic complex) are from bio-chronostratigraphic zone 4, upper subzone 4β [mid-Upper Tithonian (~150–145 Ma)] (Montgomery et al., 1992; Mattinson et al., 2008). Work by Cordey and Cornée (2009) on the northeast mafic complex has revealed radiolarians dating to the Late Kimmeridgian (~153–150 Ma), indicating a maximum eruption time of ~8 Ma for the northeast mafic complex (timescale of Ogg et al., 2008). Zircons separated from the trondhjemite pluton have been dated by U–Pb chemical abrasion–thermal ionisation mass spectrometry to 143.74 ± 0.33 Ma (Mattinson et al., 2008), i.e. mid-Berriasian of the Lower Cretaceous. The oldest radiolarian age and the U–Pb age indicate igneous activity on La Désirade lasted up to 10 Ma.

The occurrence of pillow basalts and what was interpreted as pelagic chert, lead Mattinson et al. (1980, 2008) to conclude that the mafic rocks of La Désirade were the upper part of an ophiolitic sequence probably formed at a mid-ocean ridge. Bouysse et al. (1983) favoured a subduction-related setting based, in part, on the lack of lower components of an ophiolite such as sheeted dykes, gabbros and ultramafic rocks. There has been a recent re-investigation of the chert of the northeast mafic volcanic complex by Montgomery and Kerr (2009) and Cordey and Cornée (2009) indicating that radiolarites are sparse and that the chert has high levels of MgO and Fe_2O_3, inferring rapid formation in a hydrothermal regime. However there were periods of quiescence during which time pelagic chert and limestone deposition occurred. The subordinate limestones found between the pillows are low in Fe_2O_3 and high in SiO_2 and contain radiolarians and planktonic foraminifera indicating a pelagic origin suggestive of a spreading centre (Montgomery and Kerr, 2009). Because pillow basalts and pelagic sediments are components of both subaqueous arcs and spreading centres and many ophiolites are not analogues for mid-ocean ridges (e.g. Moores and Vine, 1971), but integral parts of supra-subduction zone settings (Pearce et al., 1984), the outcrop geology of the island is not equivocal in resolving a subduction-related or mid-ocean origin. Perhaps the only indicator comes from the predominance of felsic volcanic rocks on La Désirade which is more common to island arcs than mid ocean ridges. Therefore, trace element geochemistry is required to resolve the tectonic setting of these rocks.

3. Rock types and petrography

3.1. NE mafic volcanic complex

The NE mafic volcanic complex outcrops from Baie Mahault to Anse Galets where it is overlain by the northeast felsic volcanic complex. The dominant rock type is a vesicular black to grey-green, often reddened, basalt–basaltic andesite lava, which typically forms pillows up to 1 m across (Fig. 2). Voluminous red cherts (jasper) and minor limestone pinch-ups occur between the pillows (Montgomery and Kerr, 2009), which exhibit right-way-up 'teardrop' structures and glassy rinds. Individual packages of pillow lavas define a crude layering which dips at 10° or more to the north exposing ~300 m of volcanic rocks in stratigraphic order. Additionally, volumetrically rare massive mafic lava flows and 1–2 m thick banded hyaloclastites of <1–3 mm grain size are also found. Some minor faulting occurs with displacements of only a few centimetres to several metres, which may be related to emplacement of the intermediate dyke suite; however, the entire mafic complex is continuous with no recognisable unconformities. The contact with the overlying northeast felsic volcanic complex is faulted (Fig. 2), but chert and basalt clasts are found within the felsic breccias of the overlying unit indicating eruption through the pre-existing mafic complex and an unconformity between the two complexes of unknown length.

In the lower part of the mafic complex, (Loc. 10–11; Fig. 1) the lavas can be divided into two petrographic facies. The first type is fine-grained with 0.5 to 1 mm clinopyroxene phenocrysts set in a groundmass consisting of randomly aligned acicular plagioclase, squat clinopyroxene and Fe–Ti oxides. There are brown/green clays, oxides/haematite patches and in some cases, abundant calcite replacing the original textures. The second type of lava has a grain size of up to 2 mm with plagioclase phenocrysts up to 4 mm. Interstitial plagioclase is more tabular, with clinopyroxene and Fe–Ti oxides that

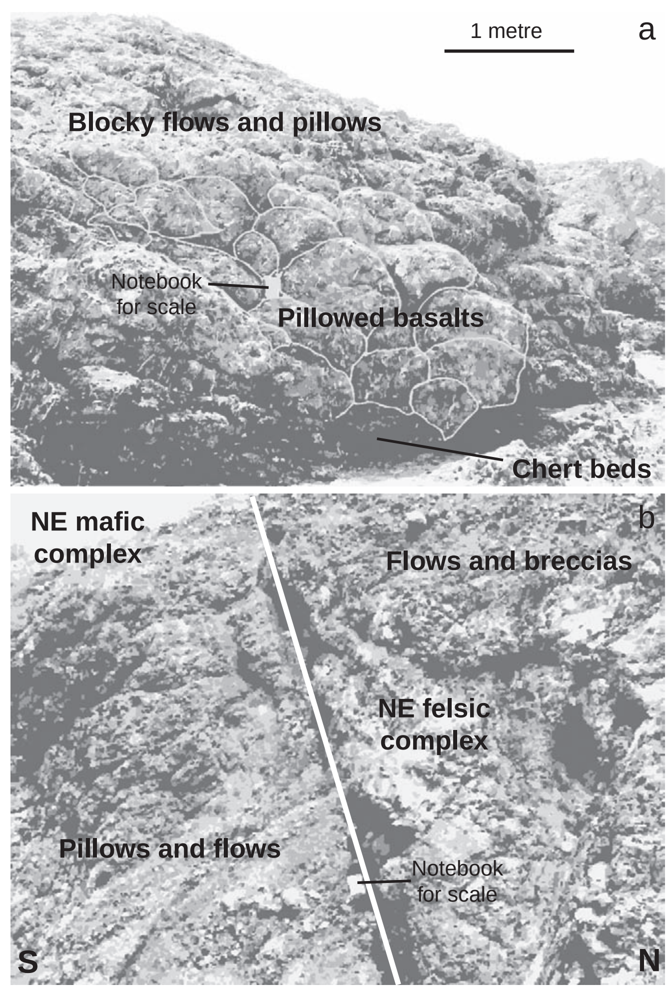

Fig. 2. (a) Pillowed mafic lavas inter-bedded with thin cherts. (b) Faulted contact between the northeast mafic volcanic complex and the northeast felsic volcanic complex.

have needle-like patterns. Replacement minerals in this second type are brown/green clays, oxides/haematite, chlorite, prehnite and pumpellyite.

Overlying these rocks, some of the pillows at Locality 8 (Fig. 1) are quite distinct, consisting of 1 mm grains of hopper-shaped or acicular to elongate splays of clinopyroxene and lesser acicular plagioclase which might indicate rapid quenching of the lava. Replacement minerals are quartz, prehnite, pumpellyite and oxides. Vesicles are infilled by quartz and Fe–Ti oxides. The remaining samples from Localities 8 and 9 (Fig. 1) are largely aphyric, ranging from 0.25 mm to 1 mm grain sizes and consisting of acicular plagioclase, squat clinopyroxene, and Fe–Ti oxides, sometimes comb-like or acicular. Replacement minerals include calcite patches and veins, prehnite and oxides including haematite.

The youngest lavas in the complex (Localities 1–7 and 14–17; Fig. 1) vary in grain size from <0.25 mm to 0.5 mm. Acicular plagioclase dominates the groundmass with elongate to squat clinopyroxene present. Some samples are clinopyroxene-phyric, often with glomeroporphyritic blebs reaching 1 mm whilst others appear glassy with abundant calcite replacement. Other replacement minerals include chlorite, prehnite, pumpellyite, green/brown clays and oxides. The replacement minerals found across the complex are diagnostic of a low-grade prehnite–pumpellyite facies metamorphic assemblage.

3.2. Felsic volcanics and the trondhjemite pluton

The NE felsic volcanic complex outcrops around Grand Abaque and contains orange-weathered massive rhyolitic flows, volcanic breccia and scoria. Breccias are darker in colour than the flows and are vesicular with abundant geodes containing quartz and epidote. Other breccias look similar to basalts and cherts of the NE mafic volcanic complex. The rhyolitic flows and breccias consist mostly of plagioclase and quartz with minor haematite crystals and veins. Some chlorite, clays and epidote are present replacement minerals.

The SW felsic complex occurs at the coast near Mourne Frégule and is regarded as temporally equivalent to the NE felsic complex (Bouysse et al., 1983; Mattinson et al., 2008), containing similar rhyolitic flows. These flows contain plagioclase and quartz phenocrysts up to 1 mm across, with a fine groundmass dominated by plagioclase with minor quartz and oxides. Clays, haematite and epidote are replacement minerals.

A trondhjemite pluton is exposed for 4 km along the north coast of the island. There are a variety of igneous facies, with the majority comprising plagioclase-rich trondhjemite with minor amounts of diorite and albite granite, which are cut by abundant intermediate dykes. The trondhjemite is characterised by 2–3 mm sized grains of tabular plagioclase (~60%), hornblende, quartz, Fe–Ti oxides, titanite and zircon. Alkali feldspar and biotite are absent. The most common replacement minerals are chlorite and epidote.

Although not yet dated by U–Pb methods, the felsic complexes appear of similar age to the pluton (Mattinson et al., 2008). Mattinson et al. (2008) proposed that the pluton intruded the lavas of its own volcanic carapace. These lavas were of the same composition and age as those which formed the NE and SW felsic complexes.

3.3. Intermediate-felsic dykes

Clinopyroxene dolerite, microdiorite, granodiorite and granophyre dykes cut the trondhjemite and NE mafic and felsic complexes (Mattinson et al., 1980). Mattinson et al. (2008) contend that the less evolved dykes are the last magmatism on the island whilst the most felsic dykes are related to the earlier felsic magmatism. The more mafic dykes are yellow-green tinged, 2–3 m thick, trend roughly NE–SW within the NE mafic volcanic complex and show chilled margins with the surrounding pillow basalts. Minor faults within the NE mafic complex occur at angles parallel or sub-parallel to the dykes suggesting a structural control upon dyke emplacement. These dykes have a grain size of around 0.25 mm and contain clinopyroxene phenocrysts (~10%) in a groundmass of elongate plagioclase and minor clinopyroxene and quartz with alteration to chlorite and pumpellyite. Epidote, albite and prehnite have also been reported (Mattinson et al., 1980). Dykes cutting the trondhjemite pluton are dark green, up to 1 m across and have a grain size of 0.25 to 0.5 mm. They are dominated by a groundmass of elongate plagioclase, clinopyroxene and Fe–Ti oxides with rare clinopyroxene phenocrysts. Replacement of the clinopyroxenes by clays and chlorite is very common.

4. Geochemistry

4.1. Analytical methods

Forty-three samples were collected from across the complexes with emphasis on the northeast mafic volcanic complex due to good exposure and the suitability of mafic rocks for petrogenetic study. Fresh material was difficult to obtain because of the vesicular nature and hydrothermal/metamorphic alteration of some of the rocks. The freshest samples were obtained from the centre of pillows or from coeval dyke-lets between the pillows. Each sample was trimmed by rotary saw to remove weathered surfaces, calcite veining and vesicular patches and ground in a steel jaw crusher before powdering in an agate ball mill. Analysis was undertaken at Cardiff University, UK. Loss-on-ignition values were calculated after heating 2 g of each sample at 900 °C for 2 hours. Samples were dissolved using the fluxy-fusion method outlined in McDonald and Viljoen (2006). Major element and Sc abundances were determined by using a JY Horiba Ultima 2 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Trace elements were analysed by a Thermo X7 Series Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Silicate rock standards JB-1A, NIM-G and BIR-1 were run through repeated sample batches. Relative standard deviations show precision of 1–5% for most major and trace elements for JB-1A. 2σ values encompass certified values for the vast majority of elements. Representative analyses from the different complexes are shown in Table 1. Full analytical results including repeat runs of standard basalt JB-1A can be found in the Supplementary Information.

4.2. Element mobility

High loss-on-ignition values (Table 1) are likely to be due to subsolidus alteration processes. Mobilisation of many major and trace elements such as Si, Mg, Na, K, Ba and Sr is therefore to be expected, as has been noted for other Cretaceous Caribbean igneous rocks (e.g. Hastie et al., 2007). Elements considered to be relatively immobile under low-grade metamorphism (up to greenschist grade) and hydrothermal alteration processes are the rare Earth elements (REE), high field strength elements (HFSE) along with Co, Cr, Ni, Sc, V, Y and P (e.g. Pearce, 1983; Seewald and Seyfried, 1990). Nb (a HFSE) is considered immobile, hence elements for samples within a given magmatic suite that are also immobile should show clear trends related to intra-magmatic differentiation processes when plotted against Nb (c.f. Cann, 1970).

The NE mafic volcanic complex can be split into three units based on their geochemistry (Section 5.1). Unit 1 consists of the lowermost clinopyroxene and plagioclase-phyric lavas (Localities 10 and 11) whereas Unit 2 covers Localities 1 to 9 and Unit 3 is found at Localities 14 to 17 (Fig. 1). Representative major and trace elements in the three units are plotted against Nb in Fig. 3 to demonstrate elemental mobility. None of the recognised units display coherent intra-magmatic differentiation trends for the major elements (except Al_2O_3 and TiO_2) or large ion lithophile elements (LILE). Conversely,

Table 1
Representative data for the La Désirade mafic volcanic units and felsic complexes.

Number	IND/10.2	IND/11.2	IND/4.1	IND/5.1	IND/15.2	IND/16.1	DES20.3	IND/18.2	IND/19.9	IND/19.11	IND/19.2	5.14D3
Class	BAS	BA	BAS	BA	BA	BA	DAC	DAC	TROND	TROND	DAC	AND
Type	TH/MOR	TH/MOR	CA/IA	TH/IA	TH/BAB	CA/BAB	TH/IA	TH/IA	TH/IA	TH/IA	TH/IA	TH/IA
Unit	1	1	2	2	3	3	NE FEL	SW FEL	TROND	TROND	DYKE	DYKE
SiO_2	52.28	52.41	56.66	55.68	51.05	51.27	77.27	71.86	74.72	74.58	57.57	54.13
TiO_2	0.73	0.81	0.71	0.71	1.02	1.21	0.46	0.55	0.30	0.28	1.14	1.00
Al_2O_3	15.65	16.57	14.76	14.63	15.17	14.15	10.44	13.25	12.70	12.80	14.58	16.08
Fe_2O_3(T)	7.96	9.33	5.98	6.27	9.35	10.18	2.18	3.89	3.55	3.32	12.21	10.47
MnO	0.11	0.07	0.09	0.09	0.10	0.08	0.03	0.06	0.10	0.09	0.37	0.16
MgO	5.54	3.19	4.05	3.44	3.78	2.22	0.34	2.42	0.68	0.62	3.18	4.08
CaO	6.69	8.30	5.75	7.96	10.17	6.34	0.28	0.20	1.94	1.95	2.79	4.88
Na_2O	5.07	5.69	7.29	7.08	5.10	6.09	6.19	6.23	5.37	5.26	5.17	8.30
K_2O	0.25	0.12	0.21	0.09	0.06	0.06	0.15	0.07	0.12	0.16	0.35	0.07
P_2O_5	0.06	0.10	0.09	0.11	0.16	0.13	0.17	0.15	0.06	0.07	0.16	0.40
LOI	5.96	3.41	4.50	4.64	3.98	7.40	1.92	1.50	1.24	1.24	2.64	0.78
Total	100.31	100.00	100.07	100.69	99.94	99.13	99.43	100.18	100.79	100.36	100.17	100.35
Sc	29.4	31.3	23.0	22.7	31.2	29.7	9.1	15.7	11.3	11.2	30.0	34.3
V	232.5	301.9	226.2	251.6	331.3	498.8	30.1	29.6	20.4	12.7	219.1	329.1
Cr	496.1	278.8	212.6	189.9	129.4	5.5	16.5	34.6	14.4	30.9	11.1	3.7
Co	42.8	33.5	35.0	23.8	32.4	31.0	3.1	3.8	2.5	1.8	12.9	24.9
Ni	110.5	69.2	82.2	77.4	67.3	3.7	2.8	3.2	140.2	5.3	10.1	145.4
Ga	18.4	21.3	17.2	18.7	23.9	28.5	10.4	15.7	18.5	14.5	18.9	20.5
Rb	1.5	2.4	4.6	1.2	1.4	0.5	2.1	1.0	1.5	1.5	3.3	1.5
Sr	89.3	115.1	72.4	55.3	126.9	31.8	34.6	79.5	99.3	118.8	72.7	39.8
Y	26.8	14.7	18.3	15.5	19.6	29.3	48.0	28.9	26.8	23.2	28.8	27.7
Zr	91.1	48.9	67.3	78.9	67.8	105.7	141.4	123.1	146.8	113.1	111.0	98.8
Nb	1.46	1.18	1.87	1.37	1.06	1.49	1.47	2.18	1.41	1.12	2.71	1.83
Ba	19.9	2894.5	50.6	46.6	43.1	31.4	23.0	18.5	66.9	50.5	91.9	21.2
Hf	2.41	1.08	1.87	1.99	1.50	2.65	3.36	3.18	3.48	2.88	2.51	2.53
Ta	0.10	0.08	0.12	0.09	0.11	0.18	0.12	0.13	0.08	0.07	0.16	0.15
Th	1.35	0.08	0.55	0.28	0.10	0.74	0.52	0.37	0.44	0.44	0.36	0.44
La	2.89	1.96	3.26	3.31	2.10	3.15	7.09	3.72	5.18	4.12	4.84	4.46
Ce	8.35	5.44	7.97	8.50	6.46	8.87	15.33	11.29	12.68	10.37	13.39	11.81
Pr	1.66	0.99	1.51	1.44	1.12	1.60	3.46	1.98	1.93	1.63	2.21	2.01
Nd	8.19	4.80	7.29	6.48	5.44	8.07	17.43	9.21	8.34	7.02	10.11	9.97
Sm	3.00	1.72	2.42	2.18	1.95	2.96	5.43	3.19	2.63	2.35	3.30	3.19
Eu	0.98	1.44	0.86	0.74	0.87	1.12	1.43	0.91	0.74	0.67	1.01	1.11
Gd	4.33	2.16	3.86	2.67	2.62	3.81	6.28	4.37	3.49	3.04	4.14	3.70
Tb	0.67	0.36	0.52	0.41	0.46	0.67	1.04	0.69	0.57	0.52	0.66	0.63
Dy	4.56	2.46	3.26	2.70	3.04	4.64	6.95	4.72	3.89	3.59	4.38	4.19
Ho	0.93	0.48	0.63	0.51	0.61	0.93	1.35	0.95	0.79	0.72	0.86	0.84
Er	2.72	1.42	1.86	1.54	1.78	2.71	4.13	2.95	2.39	2.27	2.55	2.56
Tm	0.44	0.21	0.29	0.24	0.28	0.44	0.67	0.48	0.40	0.36	0.41	0.42
Yb	3.06	1.44	2.04	1.71	1.90	2.83	4.36	3.31	2.77	2.44	2.74	2.79
Lu	0.45	0.23	0.29	0.27	0.29	0.45	0.69	0.53	0.42	0.40	0.42	0.44

BAS = basalt, BA = basaltic andesite, AND = andesite, DAC = dacite, TH = tholeiitic, CA = calc-alkaline, MORB = MORB-like, IA = island arc-like, BAB = back-arc basin-like, LOI = loss on ignition. The complete data set can be found in the Supplementary Information.

immobile trace elements (e.g. Zr, Th and Yb) display coherent intra-magmatic differentiation trends against Nb within each unit. On this basis, Al_2O_3, TiO_2, the REE, HFSE and Co, Cr, Ni, Sc, V and Y have not been significantly mobilised and may be used in petrogenetic interpretation. Interestingly, on the Zr vs. Nb diagram, two sub-groups can be seen which both display divergent trends against Nb, with 8 samples from Units 1 and 2 following a lower Zr/Nb trend.

Major element classification diagrams such as SiO_2 vs. K_2O (Peccarillo and Taylor, 1976) cannot be used on La Désirade due to sub-solidus alteration processes so the Th vs. Co diagram of Hastie et al. (2007) for island arc volcanic rocks is used (Fig. 4). The diagram is an immobile element proxy for SiO_2 and K_2O and is able to classify lavas on the basis of rock suite and type. Fig. 4 shows that the majority of La Désirade lavas range from tholeiitic basalts to rhyolites.

4.3. Geochemical results from the northeast mafic complex

4.3.1. Unit 1

The lavas contain ~45–56 wt.% SiO_2, 0.6–1.75 wt.% TiO_2, 13–18 wt.% Al_2O_3 and 3–6 wt.% MgO and can be classified as tholeiitic basalts (Fig. 4). Vanadium ranges from 230 to 310 ppm, Cr from 280 to 450 ppm and Ni from 40 to 140 ppm. Chondrite-normalised REE patterns (8–30 times chondrite) are flat to slightly light (L)REE depleted with some positive Eu anomalies (Fig. 5). The N-MORB-normalised multi-element plots show a wide spread of values but many samples are slightly depleted with respect to N-MORB (Fig. 5). They have small negative Nb–Ta anomalies, relatively flat to slightly negative Zr–Hf profiles and a slight depletion in Ti. Some samples are slightly enriched in Th/La whilst others are depleted. All samples show a small negative Ce anomaly (Fig. 5).

4.3.2. Unit 2

These rocks have 43–58 wt.% SiO_2, 0.4–0.8 wt.% TiO_2, 13–16 wt.% Al_2O_3 and 3.4–6.6 wt.% MgO and are mostly tholeiitic and calc-alkaline basaltic andesites (Fig. 4). Compared to Unit 1, Unit 2 lavas are more siliceous and have lower TiO_2 concentrations. They contain high abundances of V, Cr and Ni—190–340, 190–990 and 80–210 ppm respectively. The chondrite-normalised REE patterns for Unit 2 vary from flat to slightly LREE enriched and are generally more depleted in the middle (M)REE and heavy (H)REE than the rocks of Unit 1 (Fig. 5). Overall the HREE are 5–15 times chondrite with some small positive Eu anomalies. The N-MORB-normalised multi-element plot shows

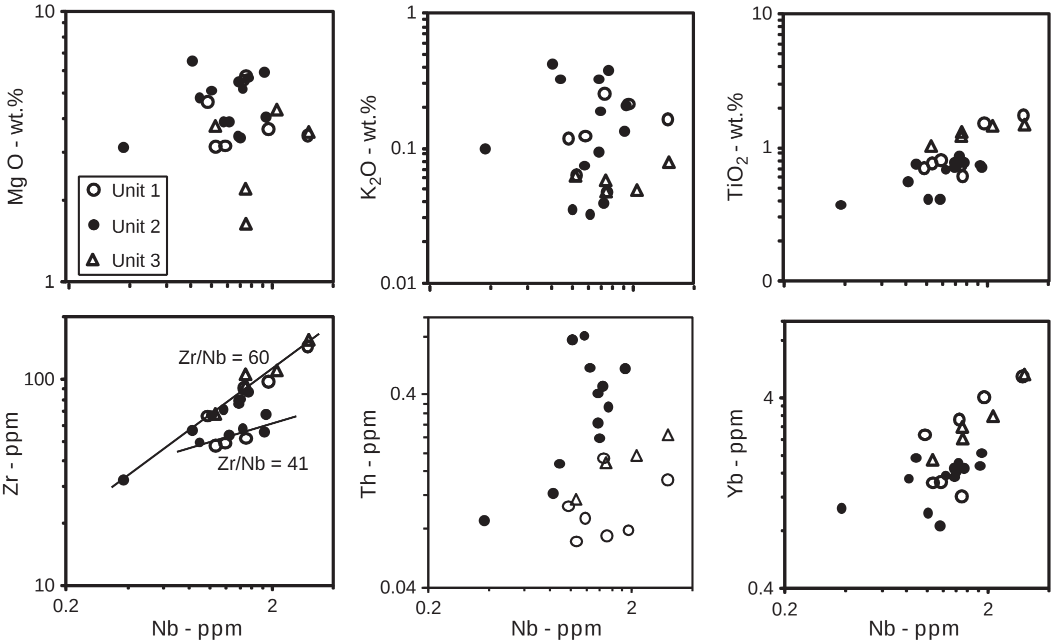

Fig. 3. Differentiation plots to assess element mobility within the NE mafic volcanic unit.

that Unit 2 lavas are quite depleted in the MREE and HREE relative to N-MORB. Unit 2 lavas also have negative Nb–Ta anomalies (Fig. 5) along with both positive and negative Zr–Hf anomalies. Ti is also depleted relative to the MREE. Th is strongly enriched over the LREE in all samples compared to the depletion in Unit 1 and all samples possess negative Ce anomalies (Fig. 5).

4.3.3. Unit 3

The lavas are mostly tholeiitic basaltic andesites (Fig. 4). SiO_2 varies from 47 to 61 wt.% and MgO from 1.7 to 3.8 wt% whilst TiO_2 is consistently above 1 wt.%, much higher than in Unit 2. These rocks contain similar levels of V (130–500 ppm) to the other Units, but much less Cr (10–130 ppm) and Ni (5–65 ppm). The chondrite-normalised REE patterns of Unit 3 are flat to slightly LREE-depleted which is similar to the rocks of Unit 1 (Fig. 5), however on the N-MORB-normalised plot (Fig. 5), Nb–Ta depletions are present, unlike Unit 1. Zr–Hf is only very slightly enriched or depleted relative to the REE, Ti is depleted relative to the REE and there are some marked Ce depletions relative to La and Pr, more like Unit 2 (Fig. 5).

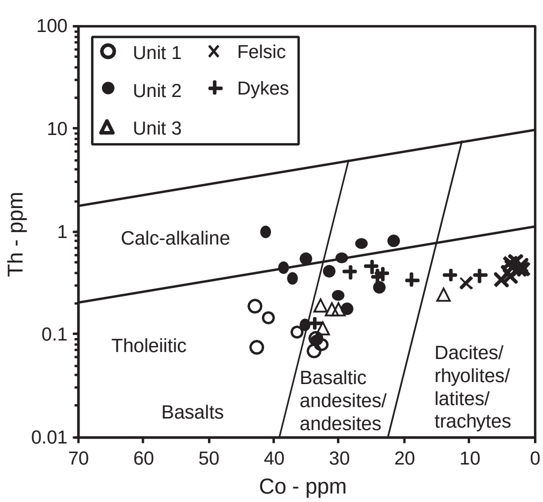

Fig. 4. Th–Co plot (Hastie et al., 2007) showing the tholeiitic to calc-alkaline affinity of the NE mafic volcanic complex and the tholeiitic affinity of the felsic complexes of La Désirade. Felsic = NE and SW felsic volcanic complexes and trondhjemite pluton, Dykes = intermediate-felsic dykes.

4.4. Felsic volcanic and plutonic rocks

SiO_2 ranges from 62 to 79 wt.%, Al_2O_3 from 10 to 15 wt.%, MgO from 0.3 to 3.6 wt.% and TiO_2 from 0.3 to 0.9 wt.%. Ni, Cr and V are considerably lower than in the NE mafic complex. The felsic rocks have nearly identical chondrite-normalised REE patterns to each other (Fig. 5), which fall completely within the range of the NE mafic complex. These patterns are flat to very slightly LREE- and HREE-enriched with negative Eu anomalies. The N-MORB-normalised plot (Fig. 5) shows that the felsic complexes all have pronounced positive Th and Zr–Hf and negative Nb–Ta, Ce and Ti anomalies, characteristics which are similar to Unit 2 of the NE mafic complex.

4.5. Intermediate-felsic dykes

The dykes range from basaltic andesites to rhyolites (Fig. 4) and have a spread of SiO_2 contents from 50 to 58 wt.%. Al_2O_3 ranges from 13 to 16 wt.%, MgO from 3.2 to 7.5 wt.% and TiO_2 from 0.5 to 1.3 wt.%. Contents of V (30–340 ppm), Cr (5–145 ppm) and Ni (5–145 ppm) fall between those of the mafic and felsic complexes. These dykes overlap almost completely with both the felsic and mafic rocks on the chondrite-normalised plot (Fig. 5), with the exception that the dykes do not have negative Eu anomalies but many of the felsic rocks do. On the N-MORB normalised plot (Fig. 5), the dykes are again similar to the felsic rocks but do not have positive Zr–Hf anomalies or such pronounced negative Ti anomalies.

4.6. Radiogenic isotopes

Mattinson et al. (1980) reported Pb and Sr radiogenic isotope ratios from the trondhjemite pluton (Fig. 1) and Gauchat (2004) analysed Pb, Nd and Sr isotopic ratios from all magmatic complexes on the island. Given the level of alteration present, it is unlikely that the Sr and Pb isotopic values can be used to assess petrogenetic processes or mantle sources (e.g. Thompson et al., 2003; Hastie, 2009). $^{144}Nd/^{143}Nd$ ratios are more resistant to sub-solidus alteration processes and so are likely to represent the primary composition of

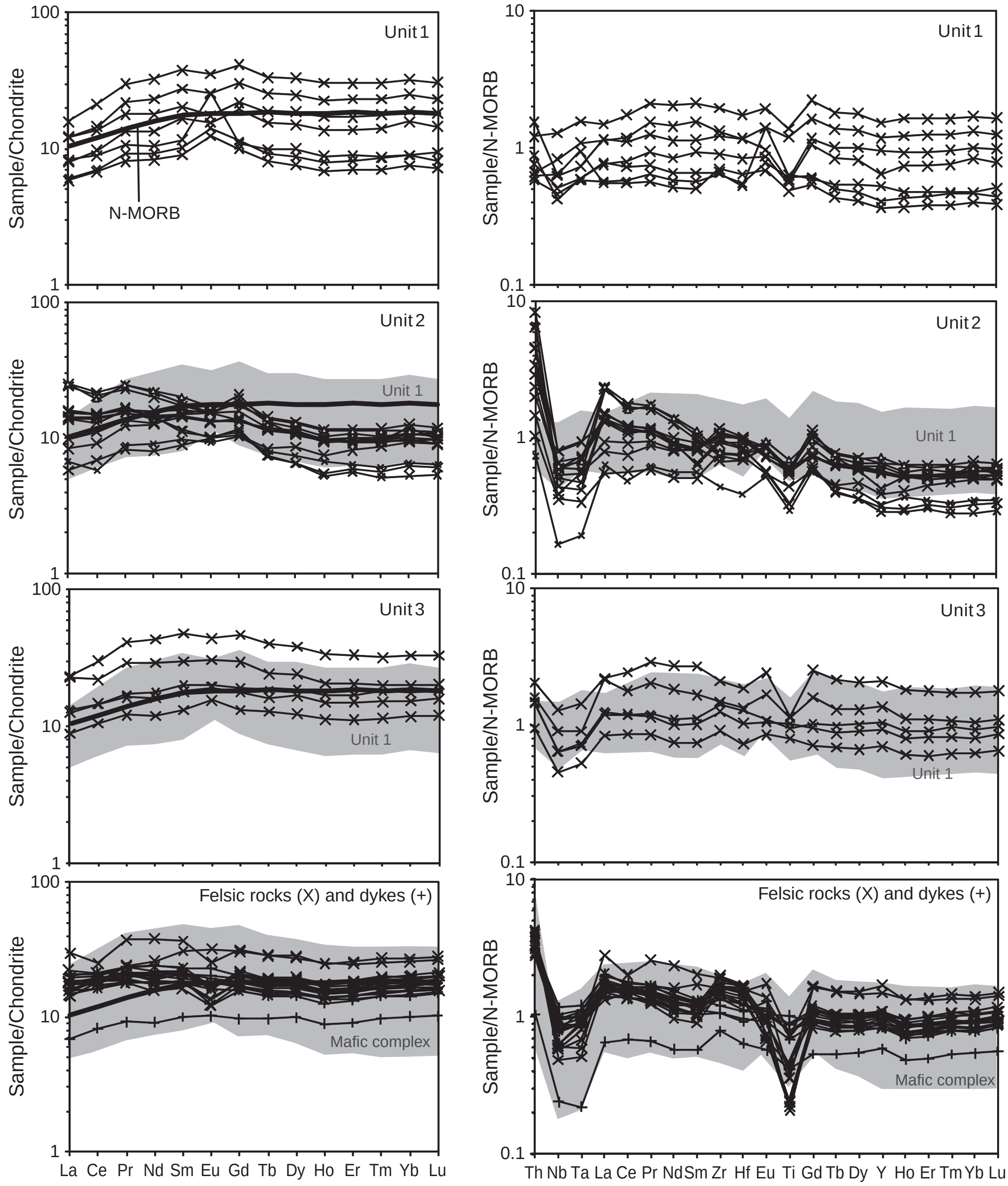

Fig. 5. REE patterns and multi-element plots for (1) each volcanic unit of the mafic complex and (2) the rocks of the NE and SW felsic volcanic complexes, trondhjemite pluton and the intermediate to felsic dykes. Normalising values for chondrite are from McDonough and Sun (1995) and for N-MORB from Sun and McDonough (1989).

the lavas (e.g. White and Patchett, 1984). The $^{144}Nd/^{143}Nd$ ratios are depleted relative to bulk earth and span a narrow range from 0.512786 to 0.512914 but insufficient data are available for each sample to calculate initial $^{144}Nd/^{143}Nd$ ratios or compare isotopic values with trace element ratios. However, these ratios overlap between the different complexes on the island, suggesting that the mantle source region for all the igneous complexes was relatively homogeneous whilst the depleted values indicate that old continental crustal material was not involved in the petrogenesis of these rocks.

5. Discussion

5.1. Subduction-related origin of the La Désirade complexes

The new geochemical data demonstrates that many of the volcanic and plutonic rocks contain variable enrichments in Th relative to the HFSEs and negative Ce, Nb–Ta and Ti anomalies on N-MORB-normalised multi-element plots (Fig. 5). These features are characteristic of supra-subduction zone settings and not mid-ocean spreading centres (e.g. Pearce and Peate, 1995; Pearce and Stern, 2006).

Nevertheless, negative Nb–Ta anomalies could be formed by: (1) crustal contamination as the La Désirade magmas ascended and/or (2) slab-related fluids which enrich a mantle wedge in LILEs and LREEs and not Nb and Ta, the latter remaining in rutile in the subducting oceanic slab (e.g., Saunders et al., 1980; Pearce and Peate, 1995; Elliot, 2003). Fieldwork and Nd isotope data suggest that the basement below La Désirade is not composed of continental crust (Gauchat, 2004). Also, zircons separated for U–Pb dating show no evidence of inheritance from older continental basement (Mattinson et al., 2008). As a consequence, the geochemical character of the La Désirade lavas (e.g. negative Nb–Ta anomalies) is related to subduction zone processes and not continental contamination.

The Th/Yb vs. Ta/Yb diagram of Pearce (1983) (Fig. 6) shows that Units 1 and 3, which do not have strong Nb–Ta anomalies (Fig. 5), plot

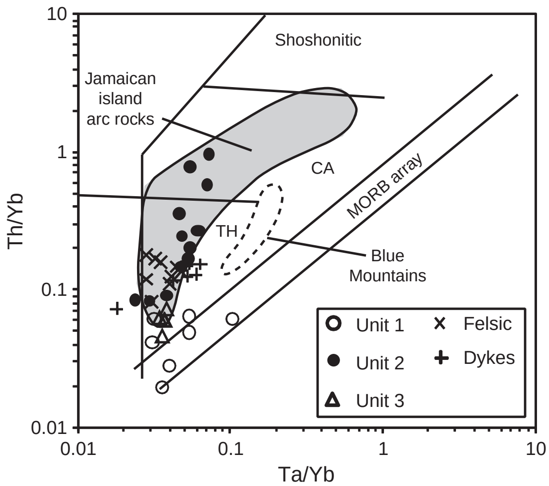

Fig. 6. Th/Yb vs. Ta/Yb plot (Pearce, 1983) showing the subduction zone affinity of the La Désirade Mesozoic complexes. TH = tholeiitic, CA = calc-alkaline. Jamaican island arc data are from Hastie (2009, in press), Jamaican Blue Mountains back-arc rocks from (Hastie et al., in press) plot at higher Ta/Yb than the Désirade rocks due to a plume component in the mantle source, but demonstrate their intermediate character between MORB and island arc rocks.

in or close to the MORB array similar to some MORB-like back arc basin lavas (e.g. Pearce and Peate, 1995; Pearce and Stern, 2006). Unit 2 lavas, which have marked negative Nb–Ta and Ti anomalies, have much higher Th/Yb ratios (0.08 to 0.95) than Units 1 and 3. The Unit 2 lavas also plot above the MORB array on Fig. 6, similar to other Caribbean arc lavas, such as those found on Jamaica (Hastie et al., 2009, 2010).

The felsic volcanic and plutonic rocks and intermediate-felsic dykes also plot within the Jamaican island arc field on Fig. 6, albeit at lower Th/Yb ratios. This diagram therefore shows that many of the rocks on the island have compositions compatible with a supra-subduction zone origin, but there are also N-MORB-like compositions present in Unit 1 of the NE mafic complex.

5.2. Nature of the mantle wedge

The presence of mafic rocks with high concentrations of V, Cr and Ni is consistent with derivation from a mantle source (e.g. Perfit et al., 1980). Flat HREE patterns for the mafic samples on N-MORB-normalised plots also suggest that the source was shallow and garnet-free. Low MgO contents (mostly <6 wt.%) indicate that the mafic rocks have undergone substantial fractional crystallisation. Therefore, to study the composition of the mantle source region, immobile trace element ratios are used which are not modified by moderate fractionation processes in mafic rocks. These trace elements also have to be absent from fluids derived from the downgoing slab. Zirconium, Nb and Yb are not mobilised from the subducting slab in aqueous fluids and are thus described as 'conservative.' elements. However, when the slab and/or its sedimentary veneer undergo partial melting these elements contribute to the slab-flux, and are termed 'non-conservative' elements (Pearce and Peate, 1995).

Adakites are formed when siliceous slab-related melts, (with LREE, La/Yb and Sr/Y enrichment), erupt without interaction with the mantle wedge (e.g. Defant and Drummond, 1990). Conversely, when assimilation occurs, high-Mg andesites or low-silica adakites are formed (e.g. Yogodzinski et al., 1995; Martin et al., 2005). Plutonic trondhjemite–tonalite–granodiorite suites (TTGs) are common components of Archean and Paleoproterozoic terranes and are compositionally similar to adakites (Smithies, 2000; Condie, 2005). However none of these rock types have been identified on La Désirade and furthermore the La Désirade trondhjemite has a markedly different composition to TTGs or adakites. Therefore, there is not an obvious slab melt component in the La Désirade igneous rocks.

As a result of Nb, Zr and Yb being variably mobilised in a slab-melt, slab-melt lavas lie above the mantle array on a Zr/Yb vs. Nb/Yb plot (Fig. 7a) (Pearce and Peate, 1995). The accumulation of zircon may also occur in felsic rocks so that when they are plotted on Fig. 7a, they too plot above the MORB array. Many of the La Désirade mafic rocks plot within the MORB array on Fig. 7a, demonstrating the conservative behaviour of the HFSE and HREE. Because the fields on ratio–ratio plots are constructed on the basis of percentile contours, some scatter is inevitable on the Zr/Yb vs. Nb/Yb diagram; however, the mafic rocks from Unit 2 that have positive Zr–Hf anomalies on N-MORB normalised plots (Fig. 5) plot above the MORB array. These rocks also plot on the high Zr/Nb trend on the variation diagram (Fig. 3). These anomalies may indicate non-conservative behaviour of the HFSE which implies that the highest values of Zr on trace element ratio–ratio plots should be viewed with caution and the only lowest values considered representative of the mantle composition. The intermediate-felsic dykes plot within the MORB array indicating conservative behaviour of the HFSE and HREE, so these may be used alongside the majority of the mafic rocks to study the mantle source. Some felsic volcanic and plutonic rocks do plot above the MORB array on the Zr/Yb vs. Nb/Yb plot, consistent with their marked positive Zr–Hf anomalies on the N-MORB normalised diagram (Fig. 5).

Mafic plume lavas from Iceland and elsewhere (e.g. Thompson et al., 2003), consistently fall between the tramlines on the Nb/Y vs.

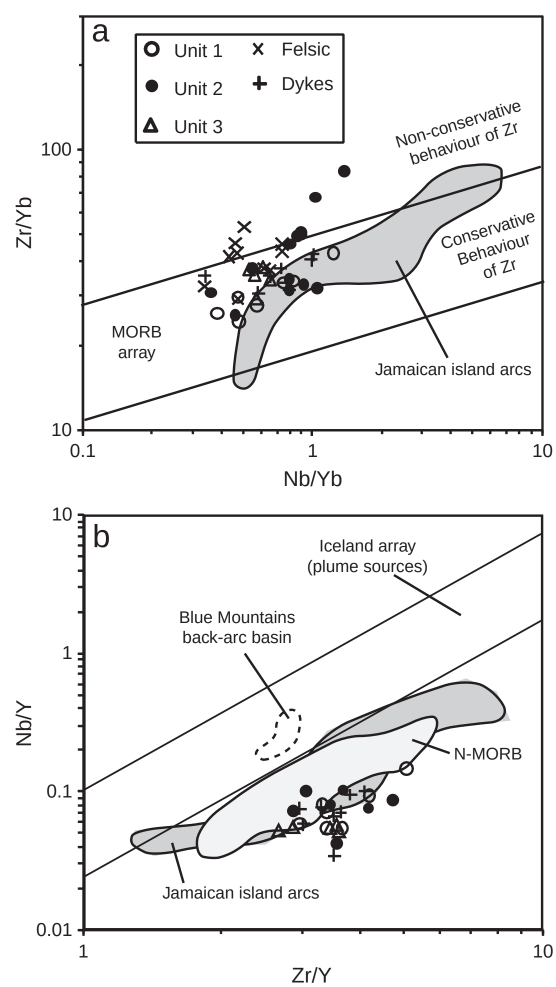

Fig. 7. (a) Zr/Yb vs. Nb/Yb diagram (Pearce and Peate, 1995) which tests for conservative behaviour of Zr during subduction processes. (b) Nb/Y vs. Zr/Y plot comparing plume and N-MORB sources. Sources: N-MORB—Fitton et al. (1997); Jamaican island arc rocks—Hastie et al. (2009, in press).

Zr/Y plot of Fitton et al. (1997) compared to rocks derived from N-MORB-like sources which lie below the lower tramline (Fig. 7b). This distinction can be applied in subduction settings (e.g. the Lau Basin) where Nb, Zr and Y have behaved conservatively (Hastie et al., 2009, 2010). As can be seen on Fig. 7b, the conservative values for the La Désirade rocks plot beneath the tramlines close to the N-MORB field, similar to Jamaican arc rocks derived from N-MORB-like sources (Hastie et al., 2010) and unlike arc-like rocks derived from plume-like sources such as the Blue Mountains Inlier, Jamaica (Hastie et al., 2010).

Zr/Nb ratios are also used to indicate the type of mantle involved in the petrogenesis of the La Désirade rocks. Many subduction-related rocks have enriched Zr/Nb ratios of ~40–120, related to an N-MORB-like source region (e.g. Wendt et al., 1997; Carpentier et al., 2009). Values <40 are much less common (Carpentier et al., 2009), but have been linked to derivation from more enriched plume-like mantle sources (e.g. Wendt et al., 1997; Hastie et al., 2010).

As most back-arc and arc magmas are generated by >10% partial melting (e.g. Pearce and Parkinson, 1993; Pearce and Stern, 2006) Zr/Nb ratios in mafic arc lavas should reflect the composition of the source and will not be affected by low degrees of partial melting. Hence, island arc suites with Zr/Nb significantly lower than the value of ~40 may indicate a mantle–plume related source region. Ignoring the samples with positive Zr–Hf anomalies, the La Désirade mafic rocks have Zr/Nb ratios of 30 to 85 (mean = 52). The low Zr/Nb trend on Fig. 3 has a Zr/Nb ratio ~41, whereas the high trend has a Zr/Nb ~60. Both the trends on the differentiation plot (Fig. 3) and the absolute Zr/Nb ratios of the mafic lavas are therefore consistent with a largely non-plume-related, depleted mantle wedge source.

5.3. Nature of the subducted component

The LILE, LREE and Th in a subducting basaltic slab and its sedimentary veneer behave non-conservatively and mobilise into the slab-flux to contaminate the overlying mantle wedge (e.g. McCulloch and Gamble, 1991; Pearce and Parkinson, 1993; Pearce and Peate, 1995; Elliot, 2003; Plank, 2005). Some LILE such as Ba and Sr have been mobilised during sub-solidus hydrothermal and metamorphic alteration, leaving the immobile LREE and Th as the most suitable elements to use for assessment of the subduction component in the La Desirade samples.

In modern arcs the Th/La ratio of arc basalts mirrors the Th/La ratio of the forearc sediment (Plank, 2005) with Th and La significantly enriched in sediments derived from terrigenous sources (Th/La >0.3) relative to N-MORB (Plank, 2005). Many arcs trend from low absolute Th/La ratios (<0.1) to high Th/La (>0.1), indicating input, in part, from fluid released by subducting terrigenous sediment (Plank, 2005). Furthermore, negative Ce anomalies on N-MORB-normalised plots are related to incorporation of fluids from oxidised subducted pelagic sediment in the mantle wedge (Hole et al., 1984; McCulloch and Gamble, 1991). The Ce anomaly is expressed as a ratio of the N-MORB-normalised observed Ce concentration (Ce_{NMN}) to the expected Ce concentration (Ce^*_{NMN}), thus: $Ce/Ce^* = Ce_{NMN}/((La_{NMN} - Pr_{NMN})/2) + Pr_{MNM}$. A Ce/Ce* ratio consistently <1 confirms that the slab-flux is, at least in part, derived from an oxidised pelagic sedimentary source.

The mafic rocks of Unit 1 and 3 have Ce/Ce* ratios from 1 to 0.85 and Th/La <0.07 (Fig. 8) suggesting a limited oxidised pelagic sediment fluid input with no evidence of fluid related to subducted terrigenous sediment in the mantle wedge. Unit 2, as has already been shown, (Figs. 5 and 6) has the most marked arc signature of the three units and has a trend from Ce/Ce* ~1–0.75 at relatively high Th/La (0.07–0.22). These data point to a significant slab fluid flux related to both subducted terrigenous and pelagic sediments into the source of Unit 2 compared to Units 1 and 3. Units 1 and 3 'trend back' to Th/La ratios similar to those found in DMM, the calculated source for mid-ocean ridge basalts (Workman and Hart, 2005). The felsic volcanic and plutonic rocks and dykes have also been plotted on Figure 8 as Ce/Ce* ratios are unlikely to have been affected significantly by crystal fractionation. The felsic volcanic and plutonic rocks define a trend from Ce/Ce* ~1–0.75 at moderately high Th/La (0.07–0.1) which is a similar trend to some of the rocks of Unit 2, indicating a significant involvement of fluid related to subducted pelagic sediment. The dykes plot relatively close to Ce/Ce* = 1 with Th/La ~0.1 indicating the presence of some subducted terrigenous sediment.

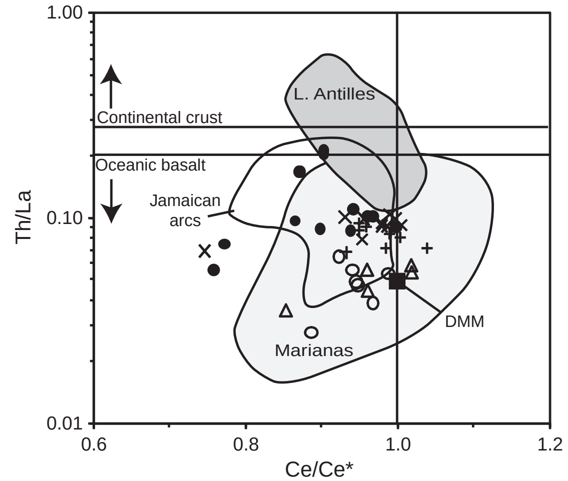

Fig. 8. Th/La vs. Ce/Ce* diagram (after Hastie et al., 2009, in press). Continental crust plots above Th/La = 0.29 and oceanic crust plots below Th/La = 0.2. Arc lavas involving slab-flux from pelagic oxidised sediments plot to the left of Ce/Ce* = 1 and arc lavas involving slab-flux from terrigenous sediments plot towards high values of Th/La similar to the continental crust. Examples of arc rocks involving slab-flux from dominantly pelagic oxidised (Marianas) and terrigenous (Lesser Antilles) sediments are shown. Cretaceous Jamaican island arc rocks show both pelagic and terrigenous sediment-related slab fluxes. The majority of La Désirade arc and back-arc rocks show fluid flux related to pelagic sediment, with Unit 2 of the NE mafic volcanic complex showing terrigenous sedimentary input. Symbols as for previous figures.

5.4. Tectonic setting

The geochemical results indicate the presence of an intra-oceanic subduction zone, however, the subduction-related input into the mantle wedge varied considerably. For example, the weak supra-subduction zone signature of Units 1 and 3 is best explained by a back-arc supra-subduction origin as opposed to an arc axis or fore-arc setting (Pearce and Stern, 2006). A back-arc setting incorporates aspects of both the argued-for ridge settings (pillow lavas, slow eruption rate, and pelagic sedimentation) (Mattinson et al., 2008; Montgomery and Kerr, 2009) and subduction-related chemistry. Furthermore, because (1) the faulted contact between the northeast mafic and felsic complexes is a minor feature since fragments of the mafic complex can be found within the felsic complex and (2) the felsic rocks also share a subduction-related chemistry broadly similar to Units 2 and 3, the entire Mesozoic suite was erupted in a back-arc setting in a period of ~10 Ma (Late Kimmeridgian to Mid Berriasian).

The argument for a single tectonic setting for all the complexes can be explored geochemically because the evolution of the mantle source and subducted sediment-related fluid fluxes of the complexes can be identified in stratigraphic order (Fig. 9). Although the felsic complexes and intermediate-felsic dykes are more evolved than the mafic complex (Fig. 9a), Fig. 9b shows, using La/Yb_{NMN} ratios, that the samples in all the complexes on the island are mostly tholeiitic in character. Where Nb has behaved conservatively and represents the contribution from the mantle alone, Nb/Yb_{NMN} (~0.6–1) (Fig. 9c) varies with no obvious trends towards increasing depletion or enrichment in the incompatible element composition of the mantle source through time. Th/La values (Fig. 9d) show that

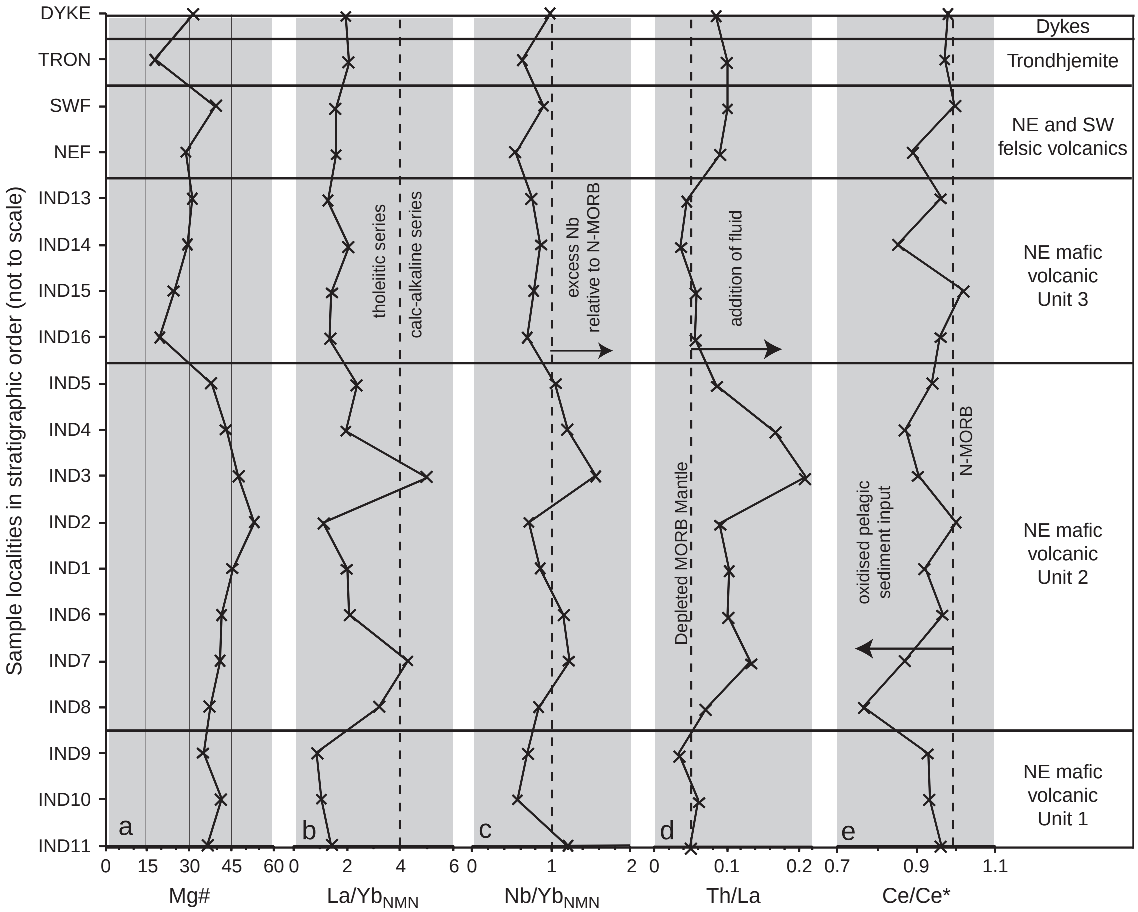

Fig. 9. Chemostratigraphic column for La Désirade. (a) Magnesium number. (b) La/Yb_{NMN} ratios showing a pattern of LREE enrichment in mafic Unit 2, also the broadly tholeiitic character of magmatism on La Désirade. (c) Nb/Yb_{NMN} ratios with the lowest ratio of ~0.6, similar to N-MORB. (d–e) Th/La and Ce/Ce* ratios showing the contribution of fluids related to subducted terrigenous sediment (high Th/La) and subducted oxidised pelagic sediment (causes Ce/Ce* <1 in arc lavas). See text for details.

mafic Unit 2, the felsic rocks, and dykes, all contain varying degrees of input from slab-fluids related to terrigenous sediments. Ce/Ce* ratios (Fig. 9e) show that the pelagic sediment-related flux mostly mirrors that from terrigenous sediments in mafic Units 1 and 2, but that this association does not hold true for mafic Unit 3, the felsic rocks or the dykes. Therefore at various times throughout the eruptive and intrusive sequence, different types of sediment had been subducted and contributed to the mantle source, but again there is no identifiable stratigraphic pattern. The fact that the mantle source composition and sedimentary components show few trends is, in part, due to the relatively rapid formation (~10 Ma) of the suite of complexes in a stable tectonic setting.

5.5. Palaeo-latitudinal position of La Désirade

The Mid-Late Jurassic separation of the Americas left a complex region of intra-arc spreading, transverse motions and continued east-dipping subduction at the proto-Caribbean/Pacific boundary (e.g. Fig. 7 of Pindell and Kennan, 2009). The western proto-Caribbean has been dubbed the Colombian Marginal Seaway by Pindell and Kennan (2009) (Fig. 10) and was in the back-arc with respect to the Andean–Cordilleran subduction zone. This Colombian Marginal Seaway is a logical position in which La Désirade could have initially formed. Terrigenous input to the subduction system could be derived from the mature Andean/Cordilleran arc and the source of magmatism would be the depleted back-arc mantle. La Désirade therefore formed in the proto-Caribbean realm, but would become an integral part of the Caribbean Plate during the inception of southwest-dipping Greater Antilles subduction.

A basin between Guerrero and Chortis and continental North America did not open until the Early Cretaceous (Pindell and Kennan, 2009) and was closed by ~120 Ma along the Motagua–Polóchic suture by west-dipping subduction (Harlow et al., 2004; Geldmacher et al., 2008) perhaps linked to the Caribbean Great Arc to the south (Tardy et al., 1994; Dickinson and Lawton, 2001; Umhoefer, 2003). Because of this rapid Cretaceous basin opening and closure, La Désirade could not form in such a position. The intra-oceanic east-dipping Andean/Cordilleran subduction zone in Central America (see Fig. 9 of Geldmacher et al., 2008) may have had its own back-arc between the arc and Guerrero and Chortis. This back-arc would be several degrees of latitude to the north of the Colombian Marginal Seaway but is a more northerly location of origin for La Désirade suitable?

Of the models which use the mantle reference frame, Duncan and Hargraves (1984) focus proto-Caribbean spreading on the palaeo-equator whilst Pindell and Kennan (2009) show the western edge of the Colombian Marginal Seaway centred on 10° N in the Late Jurassic. However, both Montgomery et al. (1994) and Mattinson et al. (2008) argue that Upper Jurassic radiolarian assemblages found on La Désirade, Puerto Rico, Hispaniola and Cuba all belong to the Northern or Southern Tethyan province of Pessagno et al. (1993). This implies an origin between 22 and 30° N or S of the equator. Jurassic radiolarian-bearing strata from the Blake Bahama Basin (Baumgartner, 1984) are assigned to the Central Tethyan Province (Pessagno et al., 1993) and should have been deposited at lower latitudes than the Caribbean occurrences.

The latitudinal findings contradict a near-equator origin for La Désirade and suggest that the radiolarian assemblages on La Désirade, Puerto Rico, Hispaniola and Cuba (Montgomery et al., 1994;

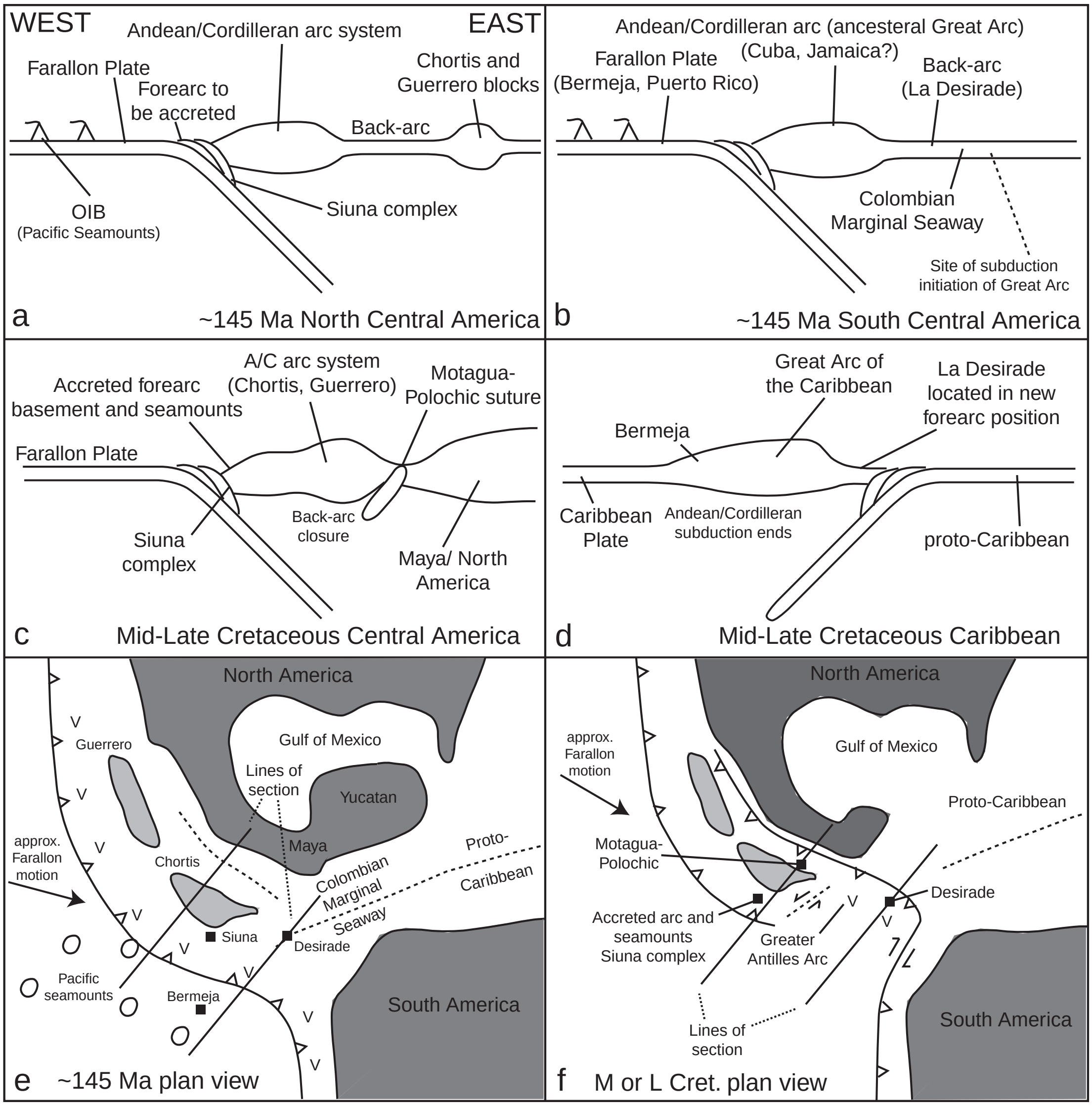

Fig. 10. Schematic tectonic model of the Caribbean and Central America (not to scale) with cross-section and plan views in Late Jurassic (145 Ma) and post-subduction polarity reversal Cretaceous times. Model adapted from Geldmacher et al. (2008) with plate motions taken from Pindell and Kennan (2009).

Mattinson et al., 2008) were derived from anything between ~1000 and ~3000 km north of the Colombian Marginal Seaway. An origin for these rocks south of the equator is unlikely because of southeast-directed subduction of Farallon crust in the Late Jurassic (Glazner, 1991; Pindell and Kennan, 2009). These outcrops would therefore have to migrate south-eastward with respect to North America to be later incorporated in the Caribbean Plate. Many studies of oblique convergence in modern and ancient arc systems and recent sandbox experiments show that the strike–slip component is largely taken up in the fore-arc and the arc, not the back-arc (e.g. Beck, 1983; ten Brink et al., 2009). Applied to the Andean/Cordilleran system it would be difficult to migrate La Désirade south-eastwards significantly with respect to North America. Therefore, we suggest that the original palaeo-latitudinal findings should be re-considered, a view shared by Pindell and Kennan (2009), as they place La Désirade close to the equator in the Colombian Marginal Seaway.

5.6. Pre-Aptian subduction-related rocks preserved in the Caribbean and Central America

Although there are many pre-Aptian rocks are found at various locations around the Caribbean and in Central America, we focus here on the fragments that formed during Andean/Cordilleran subduction. Baumgartner et al. (2008) have argued that such fragments exist in western Central America and on Cuba, Jamaica and Puerto Rico. This section uses their possible locations within the Andean/Cordilleran system to propose a regional plate tectonic reconstruction for the Late Jurassic.

5.6.1. Central America

Rocks found in melanges in Mexico, Nicaragua and Costa Rica belong to what has been called the Mesquito Composite Oceanic Terrane, the components of which were accreted to Central America as part of the Andean/Cordilleran arc system and lie north of the CCOP (Baumgartner et al., 2008). Tectonised gabbros and volcanic rocks, some with island arc chemistry and others of within-plate origin, have been dredged from the fore-arc basement of Guatemala and Mexico. These ~100 to 180 Ma rocks record a long history of east-dipping Farallon Plate subduction (Geldmacher et al., 2008). At Santa Elena in Costa Rica, three mafic volcanic island arc-related units have been identified with radiolarians ranging from 109 to 124 Ma (Hauff et al., 2000; Hoernle et al., 2004). Beneath Santa Elena is the Santa Rosa accretionary complex which has a more within-plate character (Hauff et al., 2000), but radiolarian ages from 93 to 190 Ma, contemporary to

La Désirade (Baumgartner and Denyer, 2006). The Santa Elena and Santa Rosa complexes are possible equivalents to the Guatemalan forearc (Geldmacher et al., 2008). The Siuna complex in Nicaragua is a mélange of serpentinites, gabbros and metamorphosed sedimentary and mafic igneous rocks including Middle to Upper Jurassic radiolarian cherts (Baumgartner et al., 2008). A phengite ^{40}Ar–^{39}Ar cooling age of 139.2 ± 0.4 Ma from the high-pressure parts of the Siuna mélange indicates active subduction and exhumation shortly after the formation of La Désirade (Flores et al., 2007).

5.6.2. Cuba

Cuba is built partly of allochthonous suites of Mesozoic subduction–accretion complexes thrust together during collision with the Bahama Platform (Stanek et al., 2009). At the base of the Las Villas Syncline in west-central Cuba (Stanek et al., 2009) the Mabujina unit (Somin and Millán, 1981) consists of amphibolites and gneissic granitoids of island arc origin (Kerr et al., 1999; Blein et al., 2003) with the gneiss dated to 133 Ma (U–Pb zircon) (Rojas-Agramonte et al., 2006). It is therefore possible that some subduction-related units on Cuba are contemporary in origin to La Désirade however the chronology is far from certain.

5.6.3. Jamaica

The Lower and Upper Devils Racecourse Formations (sic) of the Benbow inlier (Burke et al., 1969) consist of a lower bimodal island arc tholeiite sequence and an upper suite of calc-alkaline basalt–basaltic andesite island arc rocks (Hastie et al., 2009). The formations are separated by a sedimentary succession containing Hauterivian fossil assemblages at its base (Skelton and Masse, 1998). The >136 Ma Lower Devils Racecourse Formation arguably contains the oldest arc-axis lavas in the Caribbean. Although Hastie et al. (2009) and Pindell and Kennan (2009) argue the undated Lower and Aptian Upper Formations were erupted in one single tectonic setting, this is far from certain given: (1) 2600 m of sedimentary rocks, (2) faulting between the two Formations (Burke et al., 1969) and (3) the need for detailed mapping of the Benbow Inlier (Hastie et al., 2009). The Lower Devils Racecourse Formation may represent an east-dipping Andean/Cordilleran arc setting.

5.6.4. Puerto Rico

Much of Puerto Rico is made up of middle to Late Cretaceous island arc assemblages (Jolly et al., 2001); however, to the southwest of the Cretaceous rocks lies the Bermeja complex (Mattson, 1960) which consists of a tectonic melange of oceanic serpentinite, amphibolite, basalt and chert (Schellekens, 1998). The cherts have yielded a ~90 Ma history from the Early Jurassic to the Middle Cretaceous including Kimmeridgian–Tithonian radiolarian- and Pantannelid-bearing tuffaceous cherts which overlap in age with La Désirade (Montgomery et al., 1992, 1994; Schellekens, 1998). The tuffaceous nature of the chert may indicate deposition close to an island arc source, whilst the gabbros and greenstones apparently have a supra-subduction zone origin (Montgomery et al., 1994; Schellekens, 1998). Accretion of the Bermeja complex occurred during the Early Cretaceous before the deposition of Cenomanian sedimentary rocks (Schellekens, 1998). It is unlikely that the Bermeja complex was formed close to a west-dipping subduction zone because of its age range and south-westerly position relative to the younger Greater Antilles arc assemblages. Hence, Bermeja may also represent part of the Andean/Cordilleran system.

5.6.5. Plate tectonic reconstruction of Middle America during the Late Jurassic

In Figs. 10a, b and e we present a model which proposes that the arc rocks discussed previously were related to the east-dipping Andean/Cordilleran subduction system and were part of the Mesquito Terrane of Baumgartner et al. (2008). Complexes such as Bermeja formed near the Andean/Cordilleran fore-arc and were obducted onto the Greater Antilles arc. Some subduction-related rocks such as those found in Jamaica may have been part of the original arc axis. La Désirade formed as part of the back-arc region. Further north, Late Jurassic to Early Cretaceous east-dipping subduction resulted in the formation of the depleted island arc rocks of the Guatemalan fore-arc (Geldmacher et al., 2008) and the subduction of the Siuna high-pressure rocks (Flores et al., 2007; Baumgartner et al., 2008). Within-plate rocks also dredged from the Guatemalan fore-arc were erupted on the Pacific Plate and later accreted to the subduction mélange (Geldmacher et al., 2008). We argue that there was not necessarily a Cretaceous polarity reversal event analogous to the Caribbean along the western margin of Central America, so eastwards subduction and accretion of the fore-arc and seamounts continued through the Cretaceous (Fig. 10c).

5.7. Tectonic framework for preservation of La Désirade in a southwest-dipping arc system

In most interpretations of Caribbean geology, a reversal of Greater Antilles arc subduction polarity from northeast-dipping to southwest-dipping is required to facilitate relative eastwards motion of the Caribbean Plate in-between the Americas, as first proposed by Mattson (1979) and two possible timings of reversal were outlined in the introduction—120 Ma and 80–90 Ma. This paper will not discuss the relative merits of either model, as we have no new data pertaining to the timing of the polarity reversal however we highlight the point that the preservation of La Désirade is a key aspect of the polarity reversal event.

An analogue for the preservation of La Désirade is to be found in the back-arc region of the Scotia Sea during its Late Cretaceous to Paleogene evolution where a back-arc formed in relation to a Pacific arc which ran from South America to the Antarctic Peninsula. South America accelerated westwards relative to Antarctica in the mid-Cretaceous causing back-arc compression and eventually the subduction of the Atlantic plate beneath the former back-arc (Dalziel, 1985; Barker and Lonsdale, 1991; Barker et al., 1991; Barker, 2001). Subduction initiated along the former back-arc ridge (Barker, 2001, Fig. 5), meaning half of the original oceanic back-arc was preserved and lies today in the South Sandwich fore-arc. We have generated a similar model in Fig. 10c, d and f which could apply to the Mid Cretaceous (~125 Ma) in the case of Aptian–Albian subduction polarity reversal or to the Late Cretaceous (~85 Ma) in the case of a later reversal.

Aptian subduction initiation, probably in response to the westward acceleration of North America, occurred along a zone running from along the western margin of the basin between Guerrero/Chortis and the North American mainland. The Guerrero/Chortis basin then closed along the Motagua/Polóchic suture (Harlow et al., 2004; Geldmacher et al., 2008; Pindell and Kennan, 2009). In the Caribbean region, southwest-dipping subduction initiation (or polarity reversal) occurred to the east of La Désirade. The pre-existing Andean/Cordilleran arc was the approximate axis upon which the new Greater Antilles arc built up. To the southwest of the arc axis, the old Andean/Cordilleran forearc (e.g. Bermeja) was preserved. To the east of the arc axis, the new subduction zone began destruction of the proto-Caribbean seaway but the rate of slab roll-back must have equalled or exceeded the rate of westward motion of the Americas over the mantle through the Cretaceous to the present in order to prevent subduction erosion and the destruction of the crust containing La Désirade. The abundant high-pressure metamorphic belts present in the Greater Antilles may be the manifestation of a different regime further to the north.

6. Conclusions

La Désirade hosts the only Mesozoic rocks exposed in the Lesser Antilles. The entire suite was erupted in around ~10 Ma in the latest

Jurassic to Early Cretaceous. Detailed investigation of the trace element content of the rocks of the northeast mafic volcanic complex reveals that they originated in a back-arc supra-subduction setting by partial melting within a depleted mantle wedge. The mantle wedge was fluxed by fluids derived partly from variable quantities of subducted pelagic and terrigenous sediments along with a possible slab or subducted crust-related melt component which slightly altered the MORB-like immobile trace element ratios.

The back-arc lay to the east of the Andean/Cordilleran east-dipping subduction zone in the Colombian Marginal Seaway prior to the inception of a southwest-dipping Greater Antilles arc. Other Late Jurassic to Early Cretaceous Caribbean and Central American subduction-related rocks appear to corroborate the presence of an east-dipping Andean/Cordilleran arc. We suggest that in the Caribbean region, initiation of southwest-dipping subduction occurred to the east of La Désirade whereas in Central America a continual record of east-dipping subduction is present.

Supplementary data to this article can be found online at doi:10.1016/j.lithos.2010.08.026.

Acknowledgements

I.N. acknowledges NERC PhD studentship NE/F00219X/1. J.A.G. acknowledges the Irving Fund and the Norman Kemp travel scholarship of the University of St. Andrews. Laura Cotton assisted in the field. The Oualiri Beach Hotel, Beauséjour provided accommodation and transport. Karine Gauchat supplied the radiogenic isotope data, Iain McDonald ran the elemental analyses at Cardiff University and James Pindell has discussed many aspects of the origins and evolution of the Caribbean region with us. Helpful reviews by Javier Escuder-Viruete and Grenville Draper improved the manuscript.

References

Barker, P.F., 2001. Scotia Sea regional tectonic evolution: implications for mantle flow and palaeocirculation. Earth Science Reviews 55, 1–39.

Barker, P.F., Lonsdale, M.J., 1991. A multichannel seismic profile across the Weddell Sea margin of the Antarctic Peninsula: regional tectonic implications. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W. (Eds.), Geological Evolution of Antarctica. Cambridge University Press, Cambridge, pp. 237–241.

Barker, P.F., Dalziel, I.W.D., Storey, B.C., 1991. Tectonic development of the Scotia Arc region. In: Tingey, R.J. (Ed.), Geology of Antarctica. Oxford University Press, Oxford, pp. 215–248.

Baumgartner, P.O., 1984. A Middle Jurassic–Early Cretaceous low latitude radiolarian zonation based on unitary association and age of Tethyan radiolarites. Eclogae Geologicase Helvetiae 77, 729–837.

Baumgartner, P.O., Denyer, P., 2006. Evidence for middle Cretaceous accretion at Santa Elena Peninsula (Santa Rosa Accretionary Complex), Costa Rica. Geologica Acta 4, 179–191.

Baumgartner, P.O., Flores, K., Bandini, A.N., Girault, F., Cruz, D., 2008. Upper Triassic to Cretaceous Radiolaria from Nicaragua and northern Costa Rica—the Mesquito Composite Oceanic Terrane. Ofioliti 33, 1–19.

Baumgartner-Mora, C., Gauchat, K., Baumgartner, P.O., 2004. Larger Foraminifera (Nummulitinae, Archaiasinids) in the Neogene shallow water limestone of the Désirade island, Guadeloupe (French Antilles). Abstracts of the Second Swiss Geoscience Meeting, Lausanne, 19th–20th November, 2004.

Beck Jr., M.E., 1983. On the mechanism of tectonic transport in zones of oblique subduction. Tectonophysics 93, 1–11.

Blein, O., Guillot, S., Lapierre, H., Mercier de Lépinay, B., Lardeaux, J.-M., Millan Trujillo, G., Campos, M., Garcia, A., 2003. Geochemistry of the Mabujina complex, central Cuba: implications on the Cuban Cretaceous arc rocks. Journal of Geology 111, 89–110.

Bouysse, P., 1984. The Lesser Antilles island arc: structure and geodynamic evolution. Initial Reports of the Deep Sea Drilling Project 78A, 83–103.

Bouysse, P., Schmidt-Effing, R., Westercamp, D., 1983. La Desirade Island (Lesser Antilles) revisited: Lower Cretaceous radiolarian cherts and arguments against an ophiolitic origin for the basal complex. Geology 11, 244–247.

Burke, K., 1988. Tectonic evolution of the Caribbean. Annual Reviews of Earth and Planetary Science 16, 201–230.

Burke, K., Coates, A.G., Robinson, E., 1969. Geology of the Benbow Inlier and surrounding areas, Jamaica. In: Saunders, J.B. (Ed.), Transactions of the Fourth Caribbean Geological Conference, pp. 229–307.

Burke, K., Fox, P.J., Sengor, A.M.C., 1978. Buoyant ocean floor and the evolution of the Caribbean. Journal of Geophysical Research 83 (B8), 3949–3954.

Cann, J.R., 1970. Rb, Sr, Zr and Nb in some ocean floor basaltic rocks. Earth and Planetary Science Letters 10, 7–11.

Carpentier, M., Chauvel, C., Maury, R.C., Matielli, N., 2009. The "zircon effect" as recorded by the chemical and Hf isotopic compositions of Lesser Antilles forearc sediments. Earth and Planetary Science Letters 287, 86–99.

Condie, K.C., 2005. TTGs and adakites: are they both slab melts? Lithos 80, 33–44.

Cordey, F., Cornée, J.J., 2009. New radiolarian assemblages from La Désirade Island basement complex (Guadeloupe, Lesser Antilles arc) and Caribbean tectonic implications. Bulletin of the Geological Society of France 180, 399–409.

Dalziel, I.W.D., 1985. Collision and cordilleran orogenesis: an Andean perspective. In: Coward, M.P., Ries, A.C. (Eds.), Collision Tectonics: Geological Society of London Special Publication, vol. 19, pp. 389–404.

Defant, M.J., Drummond, M.S., 1990. Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature 347, 662–665.

Dickinson, W.R., Lawton, T.F., 2001. Carboniferous to Cretaceous assembly and fragmentation of Mexico. Bulletin of the Geological Society of America 113, 1142–1160.

Duncan, R.A., Hargraves, R.B., 1984. Plate tectonic evolution of the Caribbean region in the mantle reference frame. In: Bonini, W.E., Hargraves, R.B., Shagam, R. (Eds.), The Caribbean–South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir, vol. 162, pp. 81–93.

Edgar, N.T., Ewing, J.I., Hennion, J., 1971. Seismic refraction and reflection in the Caribbean Sea. American Association of Petroleum Geologists Bulletin 162, 81–93.

Elliot, T., 2003. Tracers of the slab—inside the subduction factory. Geophysical Monograph 138, 23–45.

Fink Jr., L.K., 1972. Bathymetric and geologic studies of the Guadeloupe region, Lesser Antilles island arc. Journal of Marine Geology 12, 267–288.

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 Letters 153, 197–208.

Flores, K., Baumgartner, P.O., Skora, S., Baumgartner, L., Müntener, O., Cosca, M., Cruz, D., 2007. The Siuna Serpentinite Mélange: An Early Cretaceous Subduction/Accretion of a Jurassic Arc. Eos Transactions of the American Geophysical Union 88, Fall Meet. Supplement Abstract T-11D-03.

Gauchat, K., 2004. Geochemistry of Désirade Island rocks (Guadeloupe, French Antilles). MS Thesis, University of Lausanne (unpublished).

Geldmacher, J., Hoernle, K., van den Bogaard, P., Hauff, F., Klügel, A., 2008. Age and geochemistry of the Central American forearc basement (DSDP Leg 67 and 84): insights into Mesozoic arc volcanism and seamount accretion on the fringe of the Caribbean LIP. Journal of Petrology 49, 1781–1815.

Glazner, A.F., 1991. Plutonism, oblique subduction, and continental growth: an example from the Mesozoic of California. Geology 19, 784–786.

Harlow, G.E., Hemming, S.R., Avé Lallement, H.G., Sisson, V.B., Sorensen, S.S., 2004. Two high-pressure low-temperature serpentinite-matrix mélange belts, Motagua fault zone, Guatemala: a record of Aptian and Maastrichtian collisions. Geology 32, 17–20.

Hastie, A.R., 2009. Is the Cretaceous primitive island arc series in the circum-Caribbean region geochemically analogous to the modern island arc tholeiite series? In: James, K.H., Lorente, M.A., Pindell, J.L. (Eds.), The Origin and Evolution of the Caribbean Plate: Geological Society of London Special Publication, vol. 328, pp. 399–409.

Hastie, A.R., Kerr, A.C., 2010. Mantle plume or slab window?: Physical and geochemical constraints on the origin of the Caribbean oceanic plateau. Earth Science Reviews 98, 283–293.

Hastie, A.R., Kerr, A.C., Pearce, J.A., Mitchell, S.F., 2007. Classification of altered island arc rocks using immobile trace elements: development of the Th–Co discrimination diagram. Journal of Petrology 48, 2341–2357.

Hastie, A.R., Kerr, A.C., Mitchell, S.F., Millar, I.L., 2009. Geochemistry and tectonomagmatic significance of Lower Cretaceous island arc lavas from the Devils Racecourse Formation, eastern Jamaica. In: James, K.H., Lorente, M.A., Pindell, J.L. (Eds.), The Origin and Evolution of the Caribbean Plate: Geological Society of London Special Publication, vol. 328, pp. 339–360.

Hastie, A.R., Kerr, A.C., McDonald, I., Mitchell, S.F., Pearce, J.A., Wolstencroft, M., Millar, I.L., 2010. Do Cenozoic analogues support a plate tectonic origin for Earth's earliest continental crust? Geology 38 (6), 495–498.

Hastie, A.R., Ramsook, R., Mitchell, S.F., Kerr, A.C., Millar, I.L., Mark, D.F., 2010. Age and geochemistry of compositionally distinct back-arc basin lavas, implications for the tectonomagmatic evolution of the Caribbean plate. The Journal of Geology 118, 655–676.

Hauff, F., Hoernle, K.A., Van den Bogaard, P., Alvarado, G.E., Garbe-Schönberg, D., 2000. Age and geochemistry of basaltic complexes in western Costa Rica: contributions to the geotectonic evolution of Central America. Geochemistry, Geophysics, Geosystems. 1. doi:10.1029/1999GC000020.

Hoernle, K.A., Hauff, F., van den Bogaard, P., 2004. A 70 m.y. history (139–69 Ma) for the Caribbean large igneous province. Geology 32, 697–700.

Hole, M.J., Saunders, A.D., Marriner, G.F., Tarney, J., 1984. Subduction of pelagic sediments: implications for the origin of Ce-anomalous basalts from the Mariana Islands. Journal of the Geological Society of London 141, 453–472.

Johnston, T.H., Schilling, G.J., Oji, Y., Fink Jr., L.K., 1971. Dredged greenstones from the Lesser Antilles island arc. Eos (Transactions of the American Geophysical Union) 52, 246.

Jolly, W.T., Lidiak, E.G., Dickin, A.P., Wu, T.-W., 2001. Secular geochemistry of central Puerto Rican island arc lavas: constraints on Mesozoic tectonism in the eastern Greater Antilles. Journal of Petrology 42, 2197–2214.

Kennan, L., Pindell, J.L., 2009. Dextral shear, terrane accretion and basin formation in the Northern Andes: best explained by interaction with a Pacific-derived Caribbean Plate? In: James, K.H., Lorente, M.A., Pindell, J.L. (Eds.), The Origin and Evolution of the Caribbean Plate: Geological Society of London Special Publication, vol. 328, pp. 487–531.

Kerr, A.C., Iturralde-Vinent, M.A., Saunders, A.D., Babbs, T.L., Tarney, J., 1999. A new plate tectonic model of the Caribbean: implications from a geochemical reconnaissance of Cuban Mesozoic volcanic rocks. Bulletin of the Geological Society of America 111, 1581–1599.
Kerr, A.C., White, R.V., Thompson, P.M.E., Tarney, J., Saunders, A.D., 2003. No oceanic plateau—no Caribbean Plate? The seminal role of an oceanic plateau in Caribbean plate evolution. In: Bartolini, C., Buffler, R.T., Blickwede, J.F. (Eds.), The circum-Gulf of Mexico and the Caribbean; hydrocarbon habitats, basin formation and plate tectonics: American Association of Petroleum Geologists Memoir, vol. 79, pp. 126–168.
Martin, H., Smithies, R.H., Rapp, R.P., Moyen, J.-F., Champion, D.C., 2005. An overview of adakite, tonalite–trondhjemite–granodiorite (TTG) and sanukitoid; relationships and some implications for crustal evolution. Lithos 79, 1–24.
Mattinson, J.M., Fink, L.K., Hopson, C.A., 1980. Geochronologic and isotopic study of the La Desirade basement complex: Jurassic oceanic crust in the Lesser Antilles. Contributions to Mineralogy and Petrology 71, 237–245.
Mattinson, J.M., Pessagno Jr., E.A., Montgomery, H., Hopson, C.A., 2008. Late Jurassic age of oceanic basement at La Désirade Island, Lesser Antilles arc. In: Wright, J.E., Shervais, J.W. (Eds.), Ophiolites, Arcs and Batholiths: A Tribute to Cliff Hopson: Geological Society of America Special Paper, vol. 438, pp. 175–190.
Mattson, P.H., 1960. Geology of the Mayagüez area, Puerto Rico. Bulletin of the Geological Society of America 71, 319–362.
Mattson, P.H., 1979. Subduction, buoyant braking, flipping, and strike–slip faulting in the northern Caribbean. The Journal of Geology 87, 293–304.
Mauffrey, A., Leroy, S., 1997. Seismic stratigraphy and structure of the Caribbean igneous province. Tectonophysics 283, 61–104.
McCulloch, M.T., Gamble, J.A., 1991. Geochemical and geodynamical constraints on subduction zone magmatism. Earth and Planetary Science Letters 102, 358–374.
McDonald, I., Viljoen, K.S., 2006. Platinum-group element geochemistry of mantle eclogites: a reconnaissance study of xenoliths from the Orapa kimberlite, Botswana. Transactions of the Institutions of Mining and Metallurgy, Section B 115, 81–91.
McDonough, W.D., Sun, S.-S., 1995. The composition of the Earth. Chemical Geology 120, 223–254.
Montgomery, H., Kerr, A.C., 2009. Rethinking the origins of the red chert at La Désirade, French West Indies. In: James, K.H., Lorente, M.A., Pindell, J.L. (Eds.), The Origin and Evolution of the Caribbean Plate: Geological Society of London Special Publication, vol. 328, pp. 457–467.
Montgomery, H., Pessagno Jr., E.A., Munoz, I., 1992. Jurassic (Tithonian) radiolaria from La Désirade (Lesser Antilles): preliminary paleontological and tectonic implications. Tectonics 11, 1426–1432.
Montgomery, H., Pessagno Jr., E.A., Pindell, J.L., 1994. A 195 Ma terrane in a 165 Ma ocean: Pacific origin of the Caribbean Plate. GSA Today 4, 1–6.
Moores, E.M., Vine, F.J., 1971. The Troodos massif, Cyprus and other ophiolites as oceanic crust: evaluation and implications. Philosophical Transactions of the Royal Society of London 268A, 443–466.
Müller, R.D., Royer, J.-Y., Cande, S.C., Roest, W.R., Maschenkov, S., 1999. New constraints on the Late Cretaceous/Tertiary plate tectonic evolution of the Caribbean. In: Mann, P. (Ed.), Caribbean Basins. : Sedimentary Basins of the World, vol. 4. Elsevier Science, pp. 33–59.
Ogg, J.G., Ogg, G., Gradstein, F.M., 2008. The concise Geologic Time Scale. Cambridge University Press, Cambridge.
Oldow, J.S., Bally, A.W., Avé Lallemant, H.G., Leeman, W.P., 1989. Phanerozoic evolution of the North American Cordillera, United States and Canada. In: Bally, A.W., Palmer, A.R. (Eds.), Geology of North America—an overview. : Geology of North America, vol. A. Geological Society of America, Boulder, Colorado, pp. 139–232.
Pearce, J.A., 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins. In: Hawkesworth, C.J., Norry, M.J. (Eds.), Continental Basalts and Mantle Xenoliths. Shiva, Nantwich, pp. 230–249.
Pearce, J.A., Parkinson, I.J., 1993. Trace element models for mantle melting: applications to volcanic arc petrogenesis. In: Prichard, H.M., Alabaster, T., Harris, N.B.W., Neary, C.R. (Eds.), Magmatic processes and Plate Tectonics: Geological Society of London Special Publication, vol. 76, pp. 373–403.
Pearce, J.A., Peate, D.W., 1995. Tectonic implications of the composition of volcanic arc magmas. Annual Reviews in Earth and Planetary Sciences 23, 251–285.
Pearce, J.A., Stern, R.J., 2006. Origin of back-arc basin magmas: trace element and isotopic perspectives. In: Christie, D.M., Fisher, C.R., Lee, S.-M., Givens, S. (Eds.), Back-arc spreading systems: geological, biological, chemical and physical interactions: AGU Geophysical Monograph Series, vol. 116, pp. 63–86.
Pearce, J.A., Lippard, S.J., Roberts, S., 1984. Characteristics and tectonic significant of supra-subduction zone ophiolites. In: Kokelaar, B.P., Howells, M.F. (Eds.), Marginal basin geology: volcanic and associated sedimentary and tectonic processes in modern and ancient marginal basins: Geological Society of London Special Publication, vol. 16, pp. 77–94.
Peccarillo, A., Taylor, S.R., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. Contributions to Mineralogy and Petrology 58, 63–81.
Perfit, M.R., Gust, D.A., Bence, A.E., Arculus, R.J., Taylor, S.R., 1980. Chemical characteristics of island-arc basalts: implications for mantle sources. Chemical Geology 30, 227–256.
Pessagno Jr., E.A., Blome, C.D., Hull, D., Six Jr., W.M., 1993. Middle and Upper Jurassic Radiolaria from the western Klamath terrane, Smith River subterrane, northwestern California: their biostratigraphic, chronostratigraphic, geochronologic, and paleolatitudinal significance. Micropalaeontology 39, 93–166.
Pindell, J.L., Dewey, J.F., 1982. Permo-Triassic reconstruction of Western Pangea and the evolution of the Gulf of Mexico/Caribbean region. Tectonics 1, 179–211.
Pindell, J.L., Kennan, L., 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. In: James, K.H., Lorente, M.A., Pindell, J.L. (Eds.), The Origin and evolution of the Caribbean Plate: Geological Society of London Special Publication, vol. 328, pp. 1–55.
Pindell, J.L., Cande, S.C., Pitman, W.C., Rowley, D.B., Dewey, J.F., La Brecque, J.L., Haxby, W.F., 1988. A plate kinematic framework for models of Caribbean evolution. Tectonophysics 151, 121–138.
Pindell, J.L., Kennan, L., Stanek, K.P., Maresch, W.V., Draper, G., 2006. Foundations of Gulf of Mexico and Caribbean evolution: eight controversies resolved. Geologica Acta 4, 303–341.
Plank, T., 2005. Constraints from thorium/lanthanum on sediment recycling at subduction zones and the evolution of the continents. Journal of Petrology 46, 921–944.
Rojas-Agramonte, Y., Kröner, A., García-Casco, A., Iturralde-Vinent, M.A., Wingate, M.T.D., Liu, D.Y., 2006. Geodynamic implications of zircon ages from Cuba. Geophysical Research Abstracts 8, 04943. SRef-ID: 1607-7962/gra/EGU06-A-04943.
Saunders, A.D., Tarney, J., Weaver, S.D., 1980. Transverse geochemical variations across the Antarctic Peninsula: implications for the genesis of calc-alkaline magmas. Earth and Planetary Science Letters 46, 344–360.
Schellekens, J.H., 1998. Geochemical evolution and tectonic history of Puerto Rico. In: Lidiak, E.G., Larue, D.K. (Eds.), Tectonics and geochemistry of the northeastern Caribbean: Geological Society of America Special Paper, vol. 322, pp. 35–66.
Seewald, J.S., Seyfried, W.E., 1990. The effect of temperature on metal mobility in subseafloor hydrothermal systems: constraints from basalt alteration experiments. Earth and Planetary Science Letters 101, 388–403.
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.
Skelton, P.W., Masse, J.P., 1998. Revision of the lower Cretaceous rudist genera *Pachytraga* Paquier and *Retha* Cox (Bivalvia: Hippuritacea) and the origins of the Caprinidae. Geobios 22, 331–370.
Smithies, R.H., 2000. The Archaean tonalite–trondhjemite–granodiorite (TTG) series is not an analogue of Cenozoic adakite. Earth and Planetary Science Letters 182, 115–125.
Somin, M.L., Millán, G., 1981. Geologija metamorficheskich kompleksoc Kuby. Isdat. Nauka, Moscow. 219pp.
Stanek, K.P., Maresch, W.V., Pindell, J.L., 2009. The geotectonic story of the northwestern branch of the Caribbean Arc: implications from structural and geochronological data of Cuba. In: James, K.H., Lorente, M.A., Pindell, J.L. (Eds.), The Origin and Evolution of the Caribbean Plate: Geological Society of London Special Publication, vol. 328, pp. 361–398.
Sun, S.-S., McDonough, W.D., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins: Geological Society of London Special Publication, vol. 42, pp. 313–345.
Tardy, M., Lapierre, H., Freydier, C., Coulon, C., Gill, J.-B., Mercier de Lepinay, B., Beck, C., Mertinez, J., Talavera, O., Ortiz, E., Stein, G., Bourdier, J.-L., Yta, M., 1994. The Guerrero suspect terrane (western Mexico) and coeval arc terranes (the Greater Antilles and the Western Cordillera of Colombia): a late Mesozoic intraoceanic arc accreted to cratonal America during the Cretaceous. Tectonophysics 320, 49–73.
ten Brink, U.S., Marshak, S., Granja Bruña, J.-S., 2009. Bivergent thrust wedges surrounding oceanic island arcs: insights from observations and sandbox models of the northeastern Caribbean plate. Bulletin of the Geological Society of America 121, 1522–1536.
Thompson, P.M.E., Kempton, P.D., White, R.V., Kerr, A.C., Tarney, J., Saunders, A.D., Fitton, J.G., McBirney, A., 2003. Hf–Nd isotope constraints on the origin of the Cretaceous Caribbean plateau and its relationship to the Galapagos plume. Earth and Planetary Science Letters 217, 59–75.
Umhoefer, P.J., 2003. A model for the North American Cordillera in the Early Cretaceous: tectonic escape related to arc collision of the Guerrero terrane and a change in North America plate motion. In: Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.L., Martín-Barajas, A. (Eds.), Tectonic evolution of northwestern Mexico and the southwestern USA: Geological Society of America Special Paper, vol. 374, pp. 117–134.
Wendt, J.I., Regelous, M., Collerson, K.D., Ewart, A., 1997. Evidence for a contribution from two mantle plumes to island-arc lavas from northern Tonga. Geology 25, 611–614.
White, W.M., Patchett, J., 1984. Hf–Nd–Sr isotopes and incompatible element abundances in island arcs: implications for magma origins and crust–mantle evolution. Earth and Planetary Science Letters 67, 167–185.
White, R.V., Tarney, J., Kerr, A.C., Saunders, A.D., Kempton, P.D., Pringle, M.S., Klaver, G.T., 1999. Modification of an oceanic plateau, Aruba, Dutch Caribbean: implications for the generation of continental crust. Lithos 46, 43–68.
Workman, R.K., Hart, S.R., 2005. Major and trace element composition of the depleted MORB mantle (DMM). Earth and Planetary Science Letters 231, 53–72.
Yogodzinski, G.M., Kay, R.W., Volynets, O.N., Koloskov, A.N., Kay, S.M., 1995. Magnesian andesite in the western Aleutian Komandorsky region: implications for slab melting and processes in the mantle wedge. Bulletin of the Geological Society of America 107, 505–519.