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Source: *The Journal of Geology*, Vol. 120, No. 4 (July 2012), pp. 367-384
Published by: The University of Chicago Press
Stable URL: http://www.jstor.org/stable/10.1086/665798

Age and Petrogenesis of the Lower Cretaceous North Coast Schist of Tobago, a Fragment of the Proto–Greater Antilles Inter-American Arc System

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ABSTRACT

The North Coast Schist of Tobago is part of the leading edge of the Caribbean Plate, which has been in oblique collision with northern South America for much of the Cenozoic. The North Coast Schist is dominated by two volcanic "formations" metamorphosed under greenschist-facies conditions during later deformation. The Parlatuvier Formation mostly consists of mafic to intermediate tuffs and tuff breccias with a U-Pb zircon ID-TIMS age of 128.66 ± 0.23 Ma. Trace element data and radiogenic isotopes reveal that the Parlatuvier Formation is derived from a heterogeneous subduction-modified, locally incompatible trace element–enriched, mantle source with some rocks containing the highest $^{176}Hf/^{177}Hf$ ratios found in the offshore Caribbean. The Mount Dillon Formation comprises silicified tuffs and tuff breccias that are derived from a more isotopically enriched mantle source with a significant slab fluid-related component. A thin belt of amphibolite-facies dynamothermally metamorphosed metavolcanic rocks lies in contact with a younger island arc pluton. Some of these amphibolites have an isotopically similar source to the Parlatuvier Formation but lack a clear subduction-related component. The age, geochemical heterogeneity, and proximal nature of eruption confirm that the North Coast Schist lay within an east-dipping proto–Greater Antilles arc. We propose that the arc system at the time of North Coast Schist magmatism was actively rifting, possibly during development of a back-arc basin. This arc system shut down during the Cretaceous, making way for southwest-dipping Greater Antilles subduction and relative eastward motion of the Caribbean Plate.

Online enhancements: appendix, table PDFs.

Introduction

The Caribbean Plate (fig. 1) is a fragment of Farallon oceanic crust isolated from the eastern Pacific and emplaced between North and South America beginning in latest Cretaceous time (Pindell and Dewey 1982; Duncan and Hargraves 1984). Rifting of the Americas during the Late Jurassic generated oceanic crust in the Gulf of Mexico and proto-Caribbean seaway by ~160 Ma, with spreading continuing in the proto-Caribbean until the Campanian (~75 Ma; Müller et al. 1999; Stern et al. 2011). Farallon oceanic crust subducted beneath North and South America from the Triassic (e.g., Oldow et al. 1989), generating an inter-American arc system at the proto-Caribbean/Farallon boundary. Although the duration and polarity of post-Jurassic subduction processes in the inter-American region are controversial (see below), subduction of either Farallon or proto-Caribbean crust built up the Cretaceous "Great Arc" system (Burke 1988). The Great Arc was dominated by the Greater Antilles island arc (on Jamaica, Cuba, Hispaniola, Puerto Rico, and the Virgin Islands), which mostly dates from ~130–60 Ma, along with the Aves Ridge and

Manuscript received November 17, 2011; accepted March 5, 2012.

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[The Journal of Geology, 2012, volume 120, p. 367–384] © 2012 by The University of Chicago.
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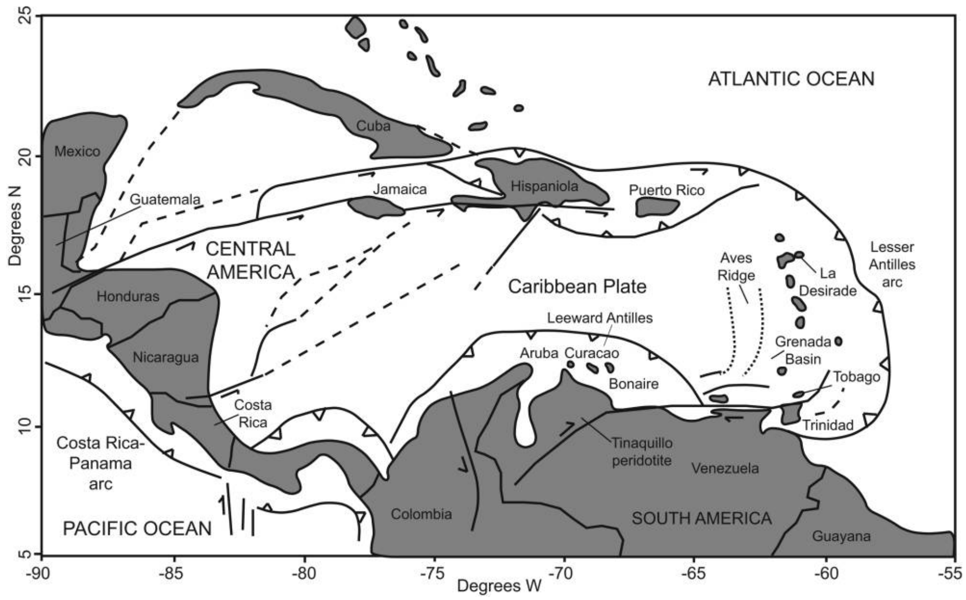

Figure 1. Map of the Caribbean region.

Leeward Antilles arcs (Kerr et al. 2003; Pindell et al. 2005; Neill et al. 2011; Wright and Wyld 2011). At ~94–89 Ma, to the southwest of the Great Arc, the mantle plume–derived Caribbean Oceanic Plateau (COP) formed on the Farallon Plate (Duncan and Hargraves 1984; Sinton et al. 1998; Kerr et al. 2003). The COP crust varies from 8 to 20 km thick (Edgar et al. 1971; Mauffrey and Leroy 1997). East-dipping subduction on the Costa Rica–Panama arc initiated to the west of the COP during the Campanian, isolating the COP and its marginal island arc sequences to form the Caribbean Plate (e.g., Pindell and Dewey 1982; Duncan and Hargraves 1984). The Caribbean Plate partially collided with the Americas at ~75 Ma and has since moved east relative to the Americas along northern and southern transpressional boundaries into its current location (e.g., Pindell and Dewey 1982; Kennan and Pindell 2009).

To transport the Caribbean Plate from the Pacific realm to its present location requires termination of east-dipping Farallon subduction (proto-Greater Antilles arc) and initiation of a new southwest-dipping proto-Caribbean subduction zone (Greater Antilles arc; Mattson 1979). The timing and cause of the onset of southwest-dipping subduction remain controversial (see Hastie and Kerr 2010; Pindell et al. 2011). In some models it is argued that relative plate motions of North and South America during the Early Cretaceous halted Farallon subduction, leaving a sinistral transform zone that would founder, initiating a new northeast-facing proto-Caribbean trench at ~135–125 Ma (e.g., Pindell et al. 2005, 2006, 2011; Pindell and Kennan 2009). Others have argued that the thickened crust of the COP collided with the proto–Greater Antilles system at 90–75 Ma, when the subduction zone was still east-dipping, thus blocking the trench and initiating polarity reversal (e.g., Duncan and Hargraves 1984; Burke 1988; White et al. 1999; Kerr et al. 2003, 2009; Hastie and Kerr 2010).

To refine these models, a detailed understanding of the age and petrogenesis of magmatic units that make up the Caribbean Plate is required. Many previous studies focused on major and minor elements, Sr and Pb isotopes and K-Ar dating, which are all susceptible to modification by subsolidus alteration processes. More recent studies have focused on immobile elements such as the rare earth elements (REEs), high field-strength elements (HFSEs), and Nd and Hf radiogenic isotopes (e.g., Thompson et al. 2003, 2004; Hastie et al. 2007, 2009; Neill et al. 2011), along with U-Pb zircon and baddeleyite geochronology (e.g., Kesler et al. 2005; Mattinson et al. 2008; Wright and Wyld 2011). Nevertheless, many locations containing igneous rocks around the Caribbean have yet to be assessed in detail using these more alteration-resistant methods, and so their significance for the tectonic evolution of the region remains to be fully evaluated.

One such location is Tobago Island in the southeast Caribbean (figs. 1, 2). Tobago is considered to

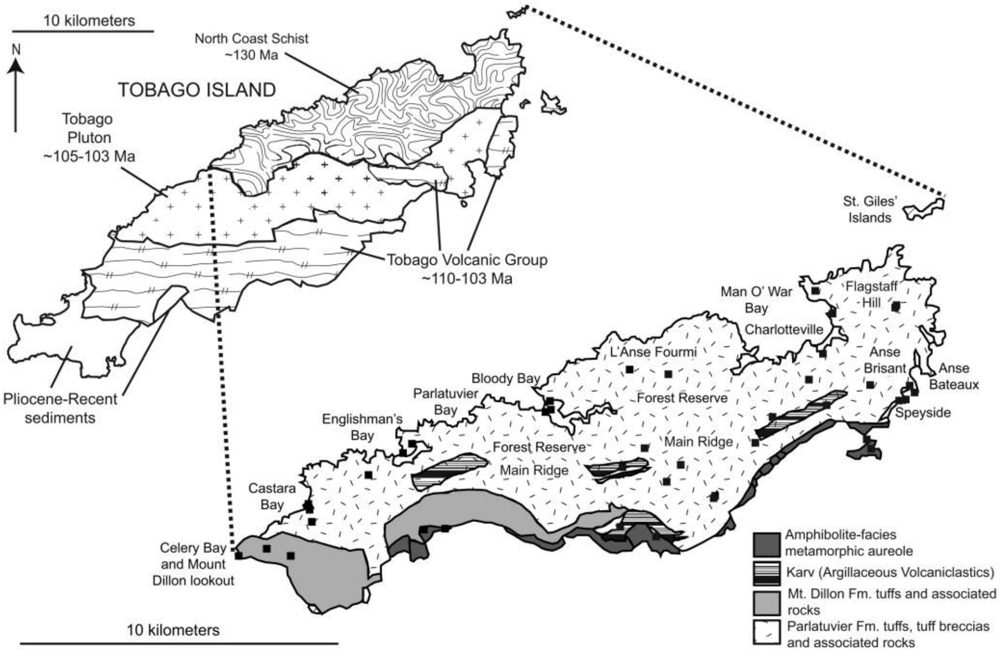

Figure 2. Simplified geologic map of the North Coast Schist, with an inset geologic map of Tobago Island, adapted from Snoke et al. (2001*a*). Squares are sample localities.

represent a composite Mesozoic fragment of the Greater Antilles system, which has been obliquely colliding with the northern margin of South America for the last 45 Ma (Frost and Snoke 1989; Burmester et al. 1996; Snoke et al. 2001*b*). The largely metaigneous North Coast Schist predates the Volcano-Plutonic Suite, the latter comprising the mafic-intermediate Tobago Volcanic Group, the ultramafic-intermediate Tobago Plutonic Suite, and a mafic dyke swarm (fig. 2). The younger Volcano Plutonic Suite is mostly of Albian age (from ~110 to 103 Ma) based on faunal and Ar-Ar hornblende dating (Sharp and Snoke 1988; Snoke et al. 1990; Snoke and Noble 2001). The Lower Cretaceous North Coast Schist is significant as it may predate much of the volcanism and high pressure–low temperature (HPLT) metamorphism in the Greater Antilles (Pindell et al. 2005). It has been proposed that the North Coast Schist was deformed before or during the subduction polarity reversal event (Snoke et al. 1990, 2001*b*; Pindell et al. 2005). Therefore, it is important to explore the petrogenesis of the North Coast Schist and its relationship to Caribbean tectonics. In this study, we report U-Pb dates from one formation and present major and trace element data and Nd-Hf isotope ratios from all the metavolcanic rock types of the North Coast Schist. The data are used to reevaluate the petrogenesis of the North Coast Schist and discuss the setting in which its protoliths were erupted.

Geology of the North Coast Schist

The North Coast Schist (fig. 2) is a belt of metamorphosed rocks (~150 km^2) in north Tobago, bordered by the nonmetamorphosed Tobago Plutonic Suite (Cunningham-Craig 1907; Maxwell 1948). Detailed fieldwork in the 1980s led to a map and special paper by Snoke et al. (2001*a*, 2001*b*), recognizing four units in the North Coast Schist: (1, 2) the greenschist-facies metavolcanic Parlatuvier and Mount Dillon Formations, (3) the greenschist-facies largely metasedimentary Karv Formation, and (4) amphibolite-facies metavolcanic rocks representing the thermal aureole of the plutonic suite. Polyphase folding, faulting, and shearing accompanied the greenschist-facies metamorphism (Snoke et al. 2001*b*), so a stratigraphic order for the North Coast Schist has not been established. In spite of this, the term "formation" has historically been used for the petrologically distinct, mappable metavolcanic successions, and this practice continues here. Distant from the aureole, the formations display the same metamorphic and deformational characteristics, described as occurring in an environment of dextral wrench shear (Snoke et al.

2001*b*). The Mount Dillon and Parlatuvier Formations are fault bounded where the contact is exposed (Snoke et al. 2001*a*). Faulting during pluton subsidence (e.g., Glazner and Miller 1997) has further disrupted the boundary between the Tobago Plutonic Suite and the North Coast Schist (Snoke et al. 2001*b*).

Parlatuvier Formation. The Parlatuvier Formation makes up the majority of the North Coast Schist. Dense rainforest reduces exposure to bays, road cuttings, and streams. The formation is composed of metamorphosed volcanic rocks and rare intrusive outcrops. Most rock types are basic to intermediate fine-grained tuffs and coarser tuff breccias with some volcanic clasts that are up to 50 cm across and largely homogeneous in color and mineralogy. The tuffs and tuff breccias contain fragments of primary plagioclase, hornblende, and clinopyroxene. Typical greenschist-facies assemblages of chlorite and actinolite give the rocks a gray-green color.

Two other sampled rock types occur most commonly toward Speyside (fig. 2). One is a basic-intermediate tuff or tuff breccia with abundant relict plagioclase phenocrysts, reaching 1–2 cm in length, whereas the other has conspicuous fragmental relict hornblende crystals up to 5 cm in length in a tuff matrix. Lavas and sparse basic intrusive rocks are also reported, both containing similar primary and metamorphic mineral assemblages to the voluminous tuffs and tuff breccias (Snoke et al. 2001*b*), but were not found during this study.

Mount Dillon Formation. The Mount Dillon Formation is found in two 1–2-km-wide bands thickening toward the southwest (fig. 2). There are exposures on the shore of Celery Bay, but there is little good exposure inland except around the Mount Dillon lookout (fig. 2). The rocks are mostly felsic fine-grained metatuffs and chert-like beds. The tuff is dark gray when fresh, weathering to a buff color.

In thin section most samples are composed of fine-grained quartz and oxides with chlorite, micas, and pyrite as ubiquitous alteration phases. Many samples contain quartz veins often parallel to the metamorphic fabric, and these are occasionally crosscut by calcite veins. Some samples are more mafic and resemble those of the Parlatuvier Formation. Rarer samples include crystal tuffs with relict quartz and plagioclase phenocrysts up to several millimeters across.

Karv Formation. The Karv Formation is located deep within the forest reserve in the hillside above Englishman's Bay (fig. 2). The formation comprises ~300-m-wide, 1–3-km-long bands of weathered meta-argillites and graphitic schist with some minor mafic tuff-like rocks with mineralogical assemblages similar to the Parlatuvier Formation. No samples have been analyzed for this study.

Amphibolite-Facies Metamorphic Aureole. Amphibolites occur in discontinuous bands at the contact between the plutonic suite and the North Coast Schist, varying from a total thickness of 800 m to slivers <100 m across (fig. 2). In river sections it is possible to walk "down-grade" into the greenschist-facies Parlatuvier Formation (Snoke et al. 2001*a*, 2001*b*), but many contacts are fault-bounded. Snoke et al. (2001*b*) argue for (*a*) greenschist-facies metamorphism of the North Coast Schist protoliths, (*b*) intense shearing and thermal metamorphism associated with the dynamic emplacement of the Tobago Plutonic Suite, and (*c*) reactivation of faults in a brittle regime during thermal subsidence of the pluton. Metamorphic grades range from upper greenschist facies close to the North Coast Schist, to upper amphibolite facies within 20 m of the Tobago Plutonic Suite contact. Felsic leucosomes may indicate incipient wall-rock melting (Snoke et al. 2001*b*).

The sampled rocks are metabasic, ranging from strongly to weakly deformed and from dense, gray equigranular samples to inequigranular rocks with a fine groundmass and large, flattened plagioclase crystals up to 1 cm long. In thin section, many samples contain hornblende, andesine, and diopside (Snoke et al. 2001*b*). Prehnite-pumpellyite grade retrogression is common close to faulted con-

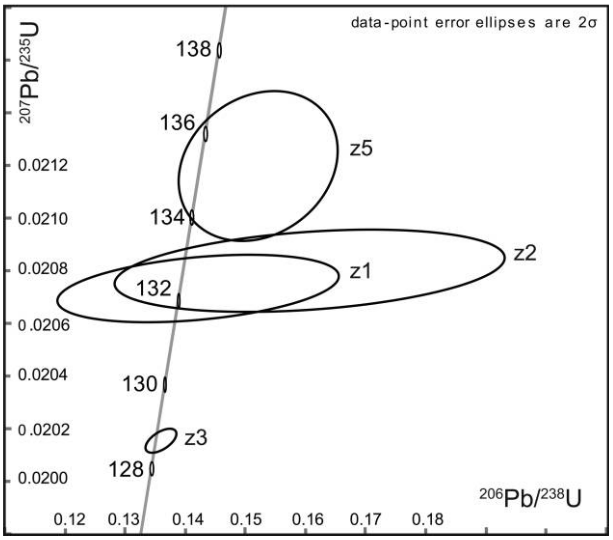

Figure 3. U-Pb isotopic ratio diagram for sample 3A-24, Parlatuvier Formation, North Coast Schist.

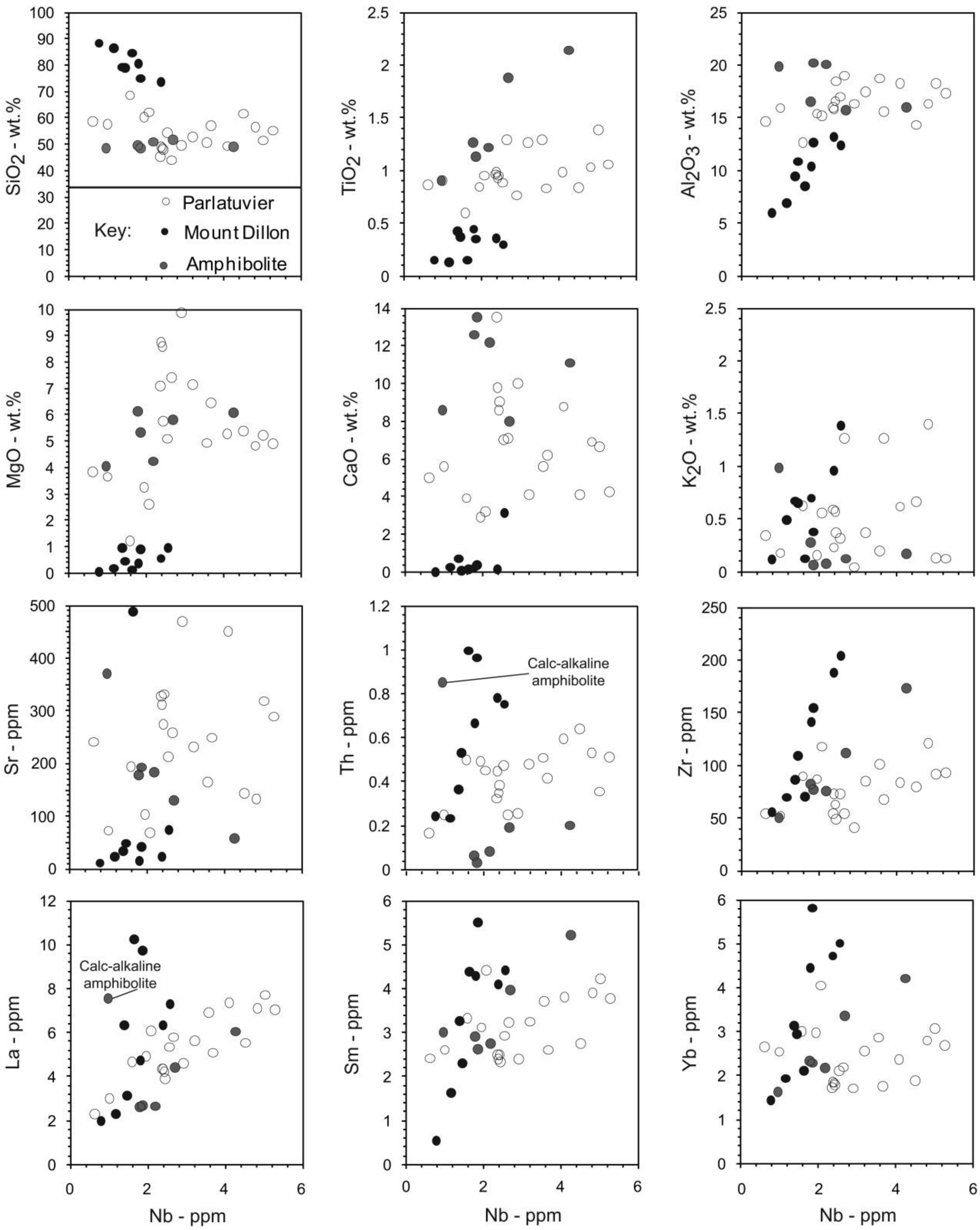

Figure 4. Variation diagrams for several major and trace elements plotted against Nb (Cann 1970). White circles = Parlatuvier; black circles = Mount Dillon; dark gray circles = amphibolites.

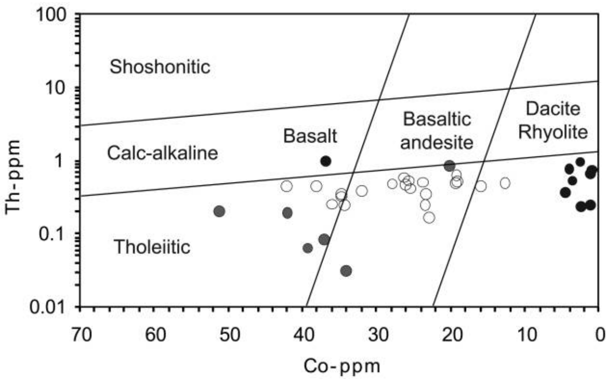

Figure 5. Th-Co plot (Hastie et al. 2007). Symbols as per figure 4.

tacts and most sampled rocks contain retrogressive chlorite.

Geochronological Results

The methodology for the geochronology and major, trace element, and isotope geochemistry is presented in the appendix, available in the online edition or from the *Journal of Geology* office. Four single grains from basaltic andesite sample 3A-24 of the Parlatuvier Formation have $^{206}Pb/^{238}U$ model ages ranging from 135.03 ± 1.46 to 128.66 ± 0.23 Ma (table A1, available as a PDF in the online edition or from the *Journal of Geology* office; fig. 3). The youngest zircon (z3) is the most radiogenic and therefore precise due to the limited uncertainty contribution from the common Pb correction. The U-Pb data are concordant, and as such we consider the $^{206}Pb/^{238}U$ date of 128.66 ± 0.23 Ma as a robust maximum age constraint for sample 3A-24. A hornblende Ar-Ar isochron from a Parlatuvier Formation sample near Speyside gave an age of 115.9 ± 3.2 Ma (Sharp and Snoke 1988), but a plateau could not be defined. This younger age may reflect (*a*) the emplacement of the mafic Tobago Plutonic Suite <500 m from the sample site, which might partially reset the Ar-Ar system, and (*b*) dynamic greenschist-facies metamorphism of the North Coast Schist that might also affect the ability of the hornblende crystal lattice to retain primary magmatic K and Ar concentrations. The eruption ages of the other formations of the North Coast Schist are unknown. However, the new U-Pb zircon constraint, coupled with the age of the younger Volcano Plutonic Suite, indicates deformation occurred between ~129–110 Ma.

Major and Trace Element Geochemistry

Elemental Mobility and Magmatic Units Present. Parlatuvier samples and amphibolite-facies rocks have loss-on-ignition (LOI) values of 1–6 wt% (tables A2, A3, available as PDFs in the online edition or from the *Journal of Geology* office) that indicate moderate subsolidus alteration. The Mount Dillon Formation has LOI values of <1 wt% showing that, although these samples may be silicified, they do not contain significant proportions of clay or calcite. In many Caribbean studies, subsolidus alteration has affected the whole-rock compositions of igneous samples (e.g., Hastie et al. 2007). Most major elements and large ion lithophile elements (LILE) such as K, Na, and Ba are mobilized, whereas the transition metals (Sc, Co, Ni, and Cr), Th, the REE, and HFSE elements such as Y, Ti, Nb, Ta, Zr, and Hf are generally relatively immobile (e.g., Pearce 1996; Thompson et al. 2003; Hastie et al. 2007). Elements or oxides can be plotted against the immobile, largely incompatible trace element Nb (Cann 1970). In a cogenetic suite, a linear (incompatible element) or curved (compatible element) trend with limited scatter should be shown between a given element and Nb. Where an element has been mobilized, significant data scatter should be present that cannot be explained by processes such as partial melting, fractional crystallization, or magma mixing. All analyzed rocks show significant scatter for SiO_2, MgO, CaO, Na_2O, K_2O, Sr, and Ba against Nb (selected elements shown on fig. 4), confirming that these have been mobilized. The REEs, Th, and Zr have different gradients of positive slope with limited scatter against Nb for the different formations, indicating low element mobility and incompatible behavior. Thorium, HFSEs and the REEs will mainly be used to discuss the petrogenesis of the North Coast Schist. The immobile element Th versus Co plot of Hastie et al. (2007) is used to classify these metavolcanic rocks (fig. 5).

There are distinct liquid lines of descent for the Mount Dillon and Parlatuvier Formations, and the amphibolites (fig. 4). The Yb and Zr versus Nb plots show no clear trend for the Parlatuvier Formation. Given coherent liquid lines of descent shown for the light REE and middle REE (LREE and MREE, respectively) such as La and Sm, the lack of trends for Zr and Yb against Nb may be related to variations in source chemistry, partial melting conditions, and perhaps amphibole crystallization rather than element mobilization. These observations suggest that the Mount Dillon and Parlatuvier Formations and most amphibolites are separate suites each displaying geochemical variation related, at least in part, to magmatic differentiation. There is one calc-alkaline amphibolite that has different major and trace element characteristics to the others and lies apart from the rest of the amphibolites on the element versus Nb plots (see "Geochemistry of the Amphibolites" below). The same grade of metamorphism is unlikely to result in two completely different geochemical signatures in the same starting material, so it is likely that the amphibolite-facies metamorphism is overprinting two geochemically distinct protoliths.

Geochemistry of the Parlatuvier Formation. On the Th-Co diagram, the Parlatuvier Formation samples have tholeiitic compositions and range from basalts to basaltic andesites (fig. 5) and major and trace element concentrations are variable. The Parlatuvier Formation has a chondrite-normalized (CN) REE pattern lying at approximately 10–30 times chondrite with no Eu anomalies (fig. 6). Several samples are slightly depleted in the LREE ($La_{CN}/Sm_{CN} < 1$), but most have slightly LREE-enriched patterns ($La_{CN}/Sm_{CN} > 1$) and flat HREE profiles. The N-MORB (mid-ocean ridge basalt) normalized plot (fig. 7) also shows slight LREE enrichment over the MREE for most samples from the Parlatuvier Formation. All the samples have slight negative but variable Nb-Ta, Zr-Hf, and Ti anomalies (fig. 7).

Geochemistry of the Mount Dillon Formation. The siliceous metatuff samples from the Mount Dillon Formation plot almost exclusively as tholeiitic rhyolites on the Th-Co diagram (fig. 5). The samples contain very low concentrations of Al_2O_3 (6–13 wt%), TiO_2 (<0.45 wt%), MgO (<1 wt%), and CaO (<3 wt%), with 3–7 wt% total alkalis. Trace element concentrations are also low (tables A2, A3). On figure 6 the REE concentrations of the majority of Mount Dillon samples range from 10–40 times those of chondrite, with slightly U-shaped REE patterns caused by depletion in the MREE relative to the LREE and HREE (heavy REE). There are significant negative Eu anomalies in many samples. One sample has a strongly U-shaped REE profile with concentrations of the MREE from Nd-Ho <4 times chondrite. Such U-shaped profiles may be associated with fractionation of MREE-compatible minerals such as apatite (Watson and Green 1981) or amphibole. The N-MORB-normalized plot (fig. 7) shows that the formation contains a wide range of incompatible trace element concentrations coupled with significant negative Nb-Ta, Ce, and Ti anomalies. The samples vary from having negative to positive Zr-Hf anomalies relative to the MREE, on the one hand suggesting that zircon crystallization may have played a role in the evolution of the magmas.

Geochemistry of the Amphibolites. The amphibolites are mostly tholeiitic basalts, with the exception of the calc-alkaline basaltic andesite (fig. 5).

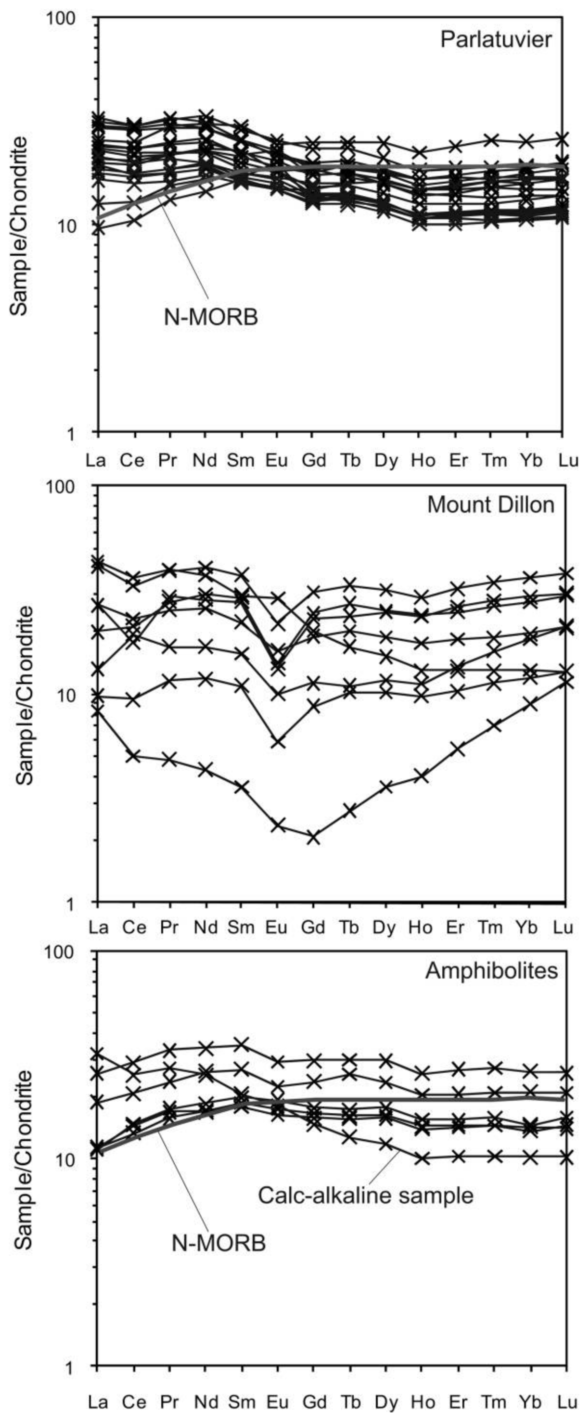

Figure 6. Chondrite-normalized rare earth element plots for the North Coast Schist (normalizing values from Sun and McDonough 1989).

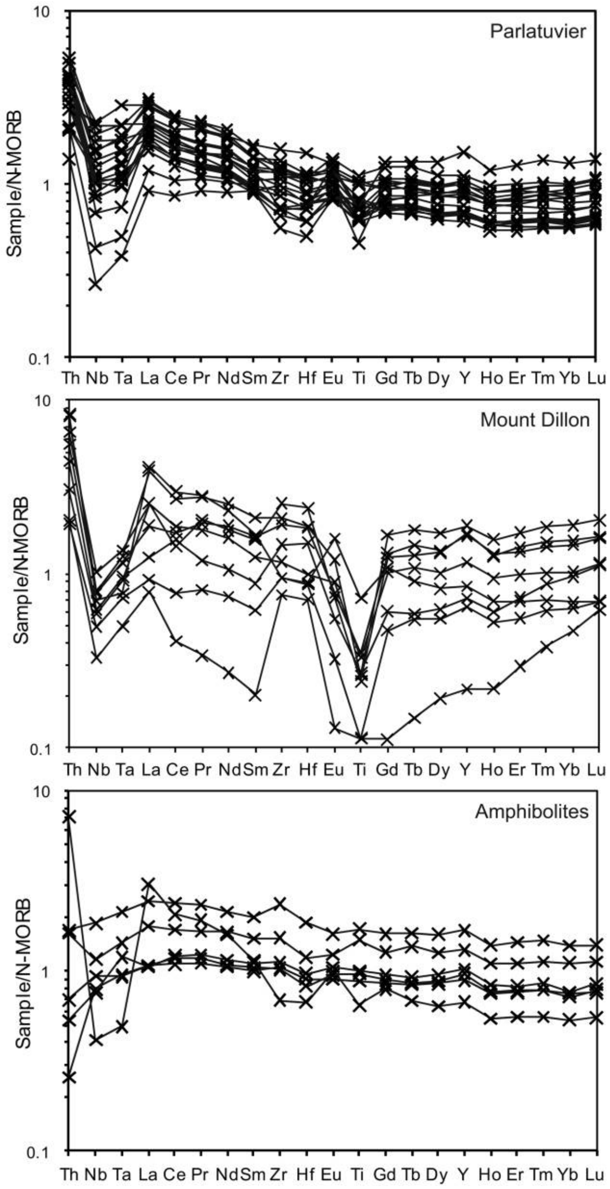

Figure 7. N-MORB-normalized multielement diagrams for the North Coast Schist (normalizing values from McDonough and Sun 1995).

The metabasalts contain consistent concentrations of major and trace elements: SiO_2 = 48–52 wt%, TiO_2 = 0.9–2.1 wt%, Al_2O_3 = 16–20 wt%, MgO = 4–6 wt%, CaO = 9–13 wt%, and total alkalis = 2–5 wt%. The metabasaltic samples have flat to slightly LREE-depleted patterns (fig. 6), while the calc-alkaline basaltic andesite has a sloping REE pattern with significant LREE enrichment relative to the HREE. The N-MORB-normalized plot (fig. 7) shows that most samples have very slight depletion in Th, Nb-Ta, and La compared to other elements. The calc-alkaline basaltic andesitic amphibolite has a large N-MORB-normalized negative Nb-Ta anomaly, enrichment in Th/La and LREE/HREE, and slight negative Zr-Hf and Ti and positive Eu anomalies (fig. 7). This sample is therefore similar only to a high LREE/HREE sample from the Mount Dillon Formation (figs. 4, 7). The geochemical data strongly supports the interpretation that the rocks of the metamorphic aureole include at least two different protoliths.

Radiogenic Isotope Results and Comparison with Other Caribbean Rocks

The Mount Dillon Formation contains significantly less radiogenic Hf than the Parlatuvier Formation whereas the two analyzed amphibolites are tholeiitic basalts that have slightly more depleted Nd but similar Hf isotope ratios compared to the Parlatuvier Formation (table A4, available as a PDF in the online edition or from the *Journal of Geology* office, fig. 8). Nd isotope ratios are very similar to the depleted results obtained by Frost and Snoke (1989). Nd and Hf isotope data are available from just two Caribbean island arc units of a similar age to the North Coast Schist: the ~96 Ma Washikemba Formation, Bonaire (Thompson et al. 2003, 2004), and the 136–125 Ma Devils Racecourse Formation, Jamaica (Hastie et al. 2009), both of which are mafic-felsic sequences derived from depleted MORB mantle. More analyses are available from the isotopically heterogeneous plume-related Caribbean Oceanic Plateau (e.g., Thompson et al. 2003; and references therein). Two amphibolite samples and one sample from the Parlatuvier Formation fall toward the depleted end of the Caribbean Oceanic Plateau field on figure 8. However, the remaining two samples from the Parlatuvier Formation have particularly depleted Hf isotope signatures that are decoupled from the mantle reference line splitting Indian and Pacific mantle domains (Pearce et al. 2007). These two samples have the highest $^{176}Hf/^{177}Hf$ ratios of any crustal rocks hitherto analyzed from the intra-Caribbean region. Such decoupling is seen in proto-Caribbean lithospheric mantle (the Tinaquillo lherzolite) preserved onshore in Venezuela (Choi et al. 2007), although this is allied with extremely depleted ratios with εHf_i of up to +50 (Choi et al. 2007). Samples from the Mount Dillon Formation are overall less depleted compared to the other North Coast Schist rocks and lie in separate fields owing to their different $^{143}Nd/^{144}Nd$ ratios. The sample with the lowest $^{143}Nd/^{144}Nd$ falls in a similar field to the Washikemba Formation, Bonaire (Thompson et al. 2004), whereas the most depleted sample falls close to the

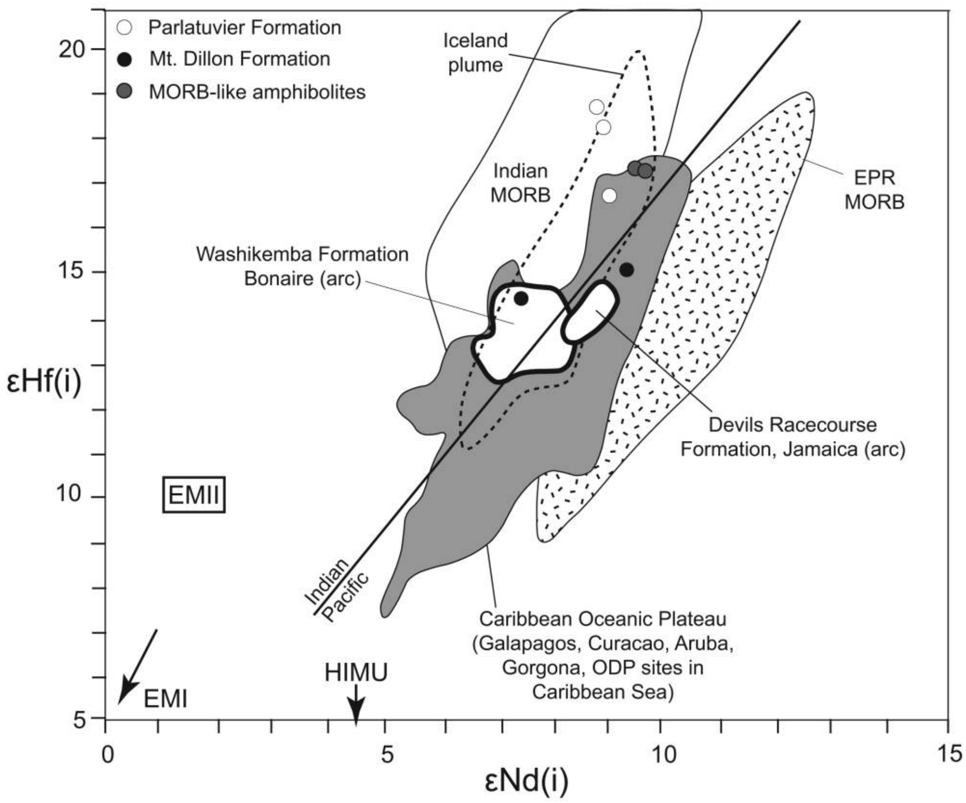

Figure 8. Nd-Hf radiogenic isotope plot for the North Coast Schist. Devils Racecourse: Hastie et al. (2009); Iceland Plume: Kempton et al. (2000); Indian mid-ocean ridge basalt (MORB): Kempton et al. (2002); Indian-Pacific divide: Pearce et al. (2007); Caribbean Plateau and East Pacific Rise MORB: Thompson et al. (2003); Washikemba: Thompson et al. (2004); EMI, EMII, HIMU, mantle reservoirs: Salters and White (1998).

depleted end of the Caribbean Oceanic Plateau field and is also isotopically similar to the Devils Racecourse Formation, Jamaica (Hastie et al. 2009).

Discussion

Petrogenesis of the Parlatuvier Formation. The low MgO contents (<10 wt%) indicate that the Parlatuvier samples have undergone a significant degree of fractional crystallization before eruption. In order to understand the tectonic setting of these rocks and their petrogenesis, this study will focus on immobile incompatible trace element ratios that are largely unaffected by fractional crystallization processes in mafic rocks.

The enrichment of the LILE and LREE and relative depletion in the HFSE (fig. 7) is taken to represent the product of partial melting of a subduction-modified mantle source (Saunders et al. 1980; Thirlwall et al. 1994; Pearce and Peate 1995; Tatsumi and Kogiso 1997; Elliot 2003). Nevertheless, most of the Parlatuvier samples have only a slight enrichment in Th/Yb with respect to the MORB array on figure 9*a* and are therefore dissimilar to tholeiitic-calc-alkaline island arc rocks characterized by high Th/Yb versus Ta/Yb ratios (Pearce 1983; Pearce and Peate 1995). Some back-arc basin rocks are characterized by Th/Yb ratios that lie between the MORB array and the associated arc samples from the arc-axis because the back-arc mantle source receives a relatively lower flux of LILE and LREE (Pearce and Stern 2006; Hastie et al. 2010; Neill et al. 2010). Although Th/Yb enrichment can be caused by the assimilation of continental crust into the ascending magma, radiogenic isotope signatures rule out the assimilation of ancient crust (fig. 8).

Mantle Source Characteristics of the Parlatuvier Formation. The Parlatuvier rocks range from low to high Ta/Yb ratios (fig. 9*a*). The higher Ta/Yb ratios are similar to those of mafic to intermediate arc and back-arc rocks from the Aves Ridge and Jamaica (Hastie et al. 2010; Neill et al. 2010), these other examples being related to melting of a plume-influenced mantle wedge formed by subduction beneath the Caribbean Oceanic Plateau (Hastie et al.

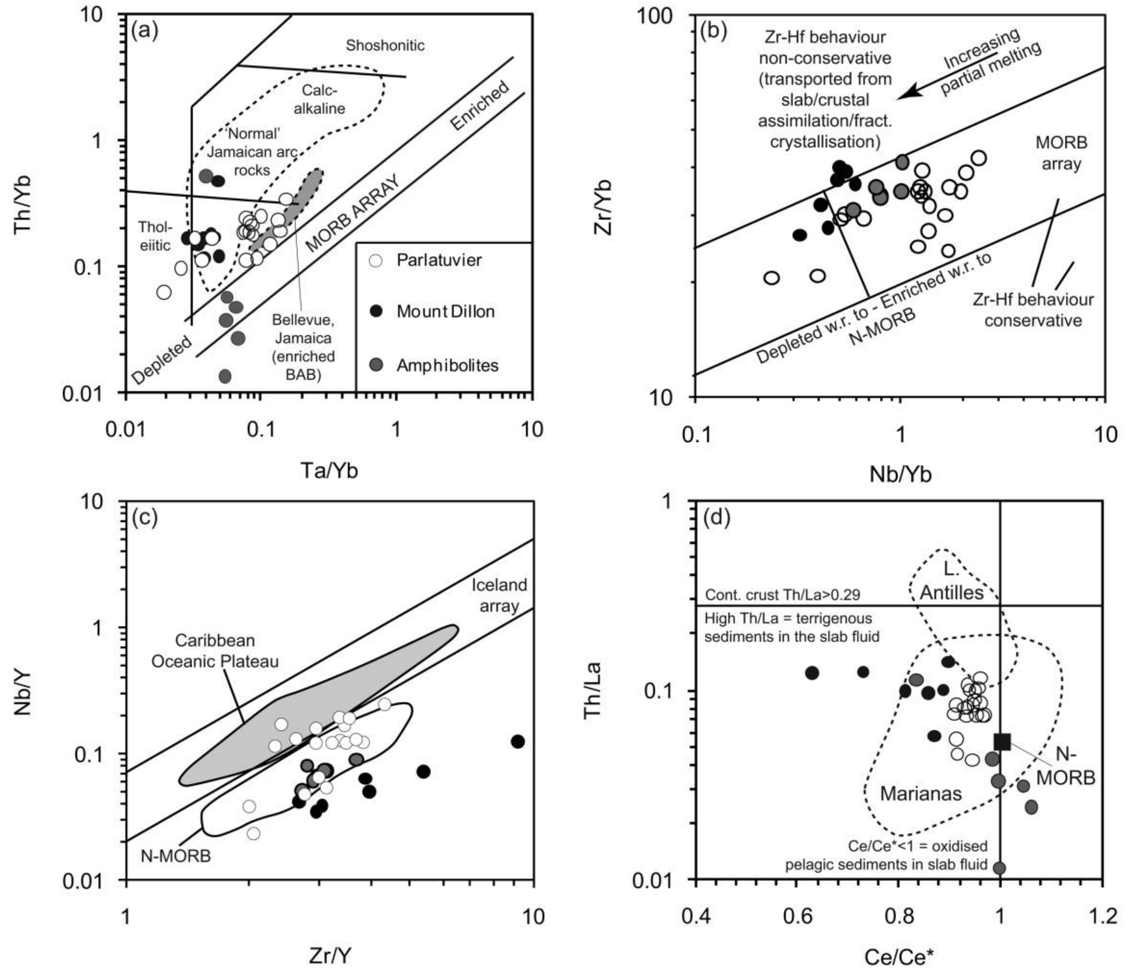

Figure 9. *a*, Th/Yb versus Ta/Yb (Pearce 1983). Jamaican arc lavas: Hastie et al. (2010). *b*, Zr/Yb versus Nb/Yb (Pearce and Peate 1995). *c*, Nb/Y versus Zr/Y. N-MORB (mid-ocean ridge basalt) and Iceland array: Fitton et al. (1997); Caribbean plateau rocks: Hastie et al. (2010). *d*, Th/La versus Ce/Ce* plot (Hastie et al. 2009). Basalts of the Marianas arc (low Th/La, low Ce/Ce*) are plotted as an example of an arc system that, apart from arc detritus, receives only pelagic sediment into the trench. Basalts of the southern Lesser Antilles arc (high Th/La, moderate Ce/Ce*) are dominated by subduction of terrigenous sediments derived from the Orinoco river system. Fields are taken from Neill et al. (2010).

2010; Neill et al. 2011). In contrast, high Ta/Yb ratios may simply be due to melting of a HFSE-enriched source, whereas lower Ta/Yb ratios are due to melting of a more depleted source.

In order to further investigate the mantle source of the Parlatuvier Formation, it is first necessary to verify if Zr and Hf have been mobilized from a subducting oceanic slab. Zr and Hf are the HFSE most likely to be mobilized during dewatering and/or partial melting of the oceanic slab and its sedimentary veneer (Woodhead et al. 2001). As noted by Pearce and Peate (1995), if subduction-related rocks have received little or no excess Zr or Hf from a slab-derived fluid or melt, they should plot within the MORB array on a Zr/Yb versus Nb/Yb diagram (fig. 9*b*). The rocks of the Parlatuvier Formation plot within the MORB tramlines on figure 9*b*, so it is therefore concluded that the Zr-Hf signatures in the Parlatuvier Formation are largely a product of the mantle source composition.

This conclusion means that the Nb/Y versus Zr/Y diagram (Fitton et al. 1997) can be utilized to further assess the range of depleted and enriched compositions implied by the Th/Yb versus Ta/Yb diagram. The Nb/Y versus Zr/Y plot was originally designed to separate Icelandic basalts from plume-related and N-MORB-like mantle sources, the former being characterized by systematically higher Nb/Y ratios, compared to N-MORB, and lying between a set of tramlines, the so-called Iceland array.

On figure 9*c*, fields for N-MORB and the Caribbean Oceanic Plateau are plotted along with data from the North Coast Schist. The Parlatuvier data plot in two groups, with most rocks straddling the lower tramline between N-MORB and mantle plume-type compositions, whereas nine samples plot below the lower tramline and have N-MORB-like characteristics. Therefore, the Parlatuvier Formation is geochemically heterogeneous and is the product of melting of both HFSE-depleted and HFSE-enriched subduction-modified mantle sources. There is no relationship between isotopic decoupling and Nb/Y versus Zr/Y systematics, that is, high $^{176}Hf/^{177}Hf$ samples are above and below the lower tramline on figure 9*c*. Variable degrees of partial melting move melt compositions subparallel to the Iceland tramlines, so the vertical spread displayed by the Parlatuvier Formation is ascribed to HFSE-enrichment and depletion of the mantle source (Fitton et al. 1997).

Subduction-Related Component in the Parlatuvier Formation. Th/La ratios in island arc lavas that are higher than typical oceanic basalts (<0.19; Plank 2005) are likely to indicate the involvement of fluid derived from continental- or arc-derived terrigenous sediments in the mantle source (Plank 2005). Furthermore, negative Ce anomalies on normalized plots indicate the subduction of oxidized pelagic sediments (Hole et al. 1984; Plank and Langmuir 1988; Ben Othman et al. 1989; McCulloch and Gamble 1991; Elliott 2003). This anomaly can be expressed as a Ce/Ce* ratio, where $Ce/Ce^* = Ce_{NMN}/[(La\text{-}Pr)_{NMN}/2] + Pr_{NMN}$; thus, $Ce/Ce^* < 1$ may indicate an input from fluids derived from subducted oxidized pelagic sediments. The Parlatuvier Formation has very low Th/La ratios (0.04–0.11), which suggests that little terrigenous sediment was subducted and released fluids into the mantle wedge. Ce/Ce* ratios are 0.92–1.0, suggesting that oxidized sediments have played little role in the petrogenesis of these rocks. Figure 9*d* confirms the conclusions derived from figure 9*a* and shows a minimal input of subducted sediment to the source of the Parlatuvier Formation.

Isotopic Considerations and the Tectonic Setting of the Parlatuvier Formation. Cretaceous arc rocks with high initial $^{176}Hf/^{177}Hf$ ratios ($\varepsilon Hf_i > 15$) are unknown within the present-day Caribbean Plate, although samples from only a handful of localities have been analyzed for Hf isotopes. We deal first with the possibility of a subduction-related influence on the isotopic systematics of these rocks. Although in many cases Hf is retained within the down-going oceanic slab and sediments, the introduction of just a small proportion of Hf-bearing fluid, such as a sedimentary partial melt from the slab or bulk contamination from subducted sedimentary material, can significantly lower the Hf isotope ratio of the resultant arc magma (Woodhead et al. 2001; Carpentier et al. 2009). Carpentier et al. (2009) generated mixing curves for the bulk contamination by Atlantic sediment, both zircon-poor and zircon-rich, of the mantle source of Lesser Antilles arc volcanoes. Just 1% sediment contamination could lower the Hf isotope ratio of the depleted mantle by >3 ε units and Nd values by >5 units. Given the extremely depleted isotopic composition of the Parlatuvier Formation, it seems unlikely that significant contamination of the mantle source by fluids and/or melts carrying unradiogenic Hf isotope ratios derived from subducted sediments took place.

The decoupled Parlatuvier Formation samples also lie outside of the range of most ocean island basalts (OIB) and are far more depleted than typical OIB mantle end-members such as EMI and EMII (Salters and White 1998) but are similar to Indian Ocean MORB (Pearce et al. 2007) and the depleted parts of the Iceland plume (fig. 8; Kempton et al. 2000). An isotopically depleted and slightly subduction-modified asthenospheric source for the Parlatuvier Formation is possible, although the North Coast Schist significantly predates plume-related activity in the Caribbean region and is isotopically more depleted than known oceanic plateau outcrops (fig. 8; Kerr et al. 2003; Thompson et al. 2003). Other studied subduction-related locations of a similar age from the Caribbean region such as the ~153–143 Ma volcano-plutonic complexes of La Désirade Island, Guadeloupe (Neill et al. 2010), and the ~136–125 Ma Devils Racecourse Formation, Jamaica (Hastie et al. 2009), represent partial melting of depleted MORB-type mantle wedge sources (fig. 8). HFSE-enriched or plume-type mantle therefore did not influence the mantle wedge composition of the inter-American arc on a large scale during the Upper Jurassic-Lower Cretaceous.

One possibility is that the Parlatuvier Formation contains a South American subcontinental lithospheric mantle (SCLM) component. The North Coast Schist probably formed to the south of the Caribbean region, possibly during rifting of a Colombian-Ecuadorian back-arc to the inter-American arc system (Pindell and Kennan 2009; Villagómez et al. 2011). Fragments of South American SCLM may have been a component of the arc mantle and may have contributed to the unusual geochemical characteristics of the Parlatuvier Formation. Studies of melting of SCLM rifted into oceanic settings suggest that HIMU, EMI, and EMII mantle components are present (e.g., O'Reilly et al. 2009; Coltorti et al. 2010; Kamenov et al. 2011). Nevertheless, global studies of continental peridotite have shown that Hf isotope ratios in SCLM are in fact highly variable and may be significantly decoupled from the mantle array as a partial result of long-term isolation from the convecting mantle (Schmidberger et al. 2002; Ionov et al. 2005).

As has been previously mentioned, the only exposed fragment of proto-Caribbean lithospheric mantle that has analyzed Hf isotope ratios is the Tinaquillo lherzolite of Venezuela. The most isotopically depleted Tinaquillo samples are interpreted to be SCLM depleted in melt during proto-Caribbean rifting (Choi et al. 2007). It is unlikely that the Parlatuvier Formation was derived from the melting of a source identical to Tinaquillo, because of the exceptionally high $^{176}Hf/^{177}Hf$ isotope ratios in the lherzolite, but a similar type of source remains a possibility. The subduction-related characteristics of the Parlatuvier Formation could be derived from fluids related to subduction of Farallon oceanic crust at ~129 Ma.

Petrogenesis of the Mount Dillon Formation. On an N-MORB-normalized plot (fig. 7), a number of Mount Dillon samples lie sub parallel to one another, and differences in their REE and HFSE concentrations may be linked by silicification processes or fractional crystallization of REE-incompatible phases. Negative Eu anomalies (fig. 6) in most Mount Dillon samples indicate that they have undergone plagioclase fractionation. However, most samples have large positive Zr-Hf anomalies, and several have U-shaped REE profiles that might be caused by fractionation of apatite and/or amphibole, which have low $D_{REE/HFSE}$ (Watson and Green 1981; Klein et al. 1997). Nb-Ta and Ti anomalies may also be enhanced by fractionation of magnetite and ilmenite. Although these rocks are felsic and contain very low concentrations of MgO, Ni, and Cr, we can rule out an association with high-silica adakites (Martin et al. 2005) that are common in subduction-related settings and usually form by partial melting of the subducting oceanic crust. Adakites have high La/Yb ratios and HREE depletion due to residual garnet in their source (Defant et al. 1992; Martin et al. 2005), which is not the case for the Mount Dillon Formation. It is a logical conclusion that the Mount Dillon Formation is mantle-derived, especially given its depleted isotopic ratios, and has simply experienced a high degree of fractional crystallization and silicification pre- and posteruption, respectively.

The Mount Dillon samples have quite low Ce/Ce* ratios, ranging from 0.6–0.9 (fig. 9*d*), which, assuming these ratios have not been affected by fractional crystallization, may indicate the involvement of fluid derived from subducted oxidized pelagic sediment in the mantle source. Isotopically, the Mount Dillon samples are much less depleted than the Parlatuvier samples and are similar to the compositions of Lower Cretaceous arc rocks from Jamaica and Bonaire that were formed by melting of a slab fluid-hydrated depleted mantle (fig. 8; Thompson et al. 2004; Hastie et al. 2009). In conclusion the Mount Dillon Formation protoliths probably formed by the partial melting of a slab-derived, fluid-influenced mantle wedge isotopically distinct from the source of the Parlatuvier Formation, followed by significant amounts of fractional crystallization and silicification.

Petrogenesis of the Amphibolites. The majority of mafic, tholeiitic amphibolites have $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ ratios similar to the Parlatuvier Formation, relatively flat normalized REE patterns and high concentrations of Ni (<138 ppm) and Cr (<322 ppm), pointing clearly toward an origin by partial melting of mantle peridotite. These rocks plot within and below the MORB array on figure 9*a* and show no relative enrichment in Th. As discussed above, it is possible that the high grade of metamorphism may have affected the LILE, HFSE, and REE profiles of these rocks. Nevertheless, on figure 9*a* these rocks do not appear to have any subduction-related enrichment of the LREE or Th over the HFSE. The lack of a subduction-related component is confirmed by very low Th/La ratios (<0.03) and Ce/Ce* ratios close to 1 (fig. 9*d*). The amphibolites have low Ta/Yb ratios (fig. 9*a*) and lie below the Iceland array on figure 9*c*. A depleted mantle source therefore appears appropriate for the amphibolites. The calc-alkaline amphibolite sample has a high Th/Yb ratio (fig. 9*a*) most consistent with partial melting of a subduction-modified mantle source. On figure 9*c*, the calc-alkaline amphibolite plots beneath the lower Iceland tramline, indicating a depleted mantle source. The sample has low Ce/Ce* compared to the Parlatuvier Formation but a similar Th/La ratio (fig. 9*d*), so it appears to be a typical island arc rock derived from the partial melting of a depleted mantle source, fluxed by a substantial pelagic sediment-related component.

Tectonic Setting of the North Coast Schist. The North Coast Schist is dominated by the metamorphosed equivalents of crystal-bearing tuff breccias and tuffs, along with rarer volcanogenic sediments. The amphibolite-facies rocks also appear to be composed of metamorphosed tuffs (Snoke et al. 2001*b*). These associations led Snoke et al. (2001*b*) to con-

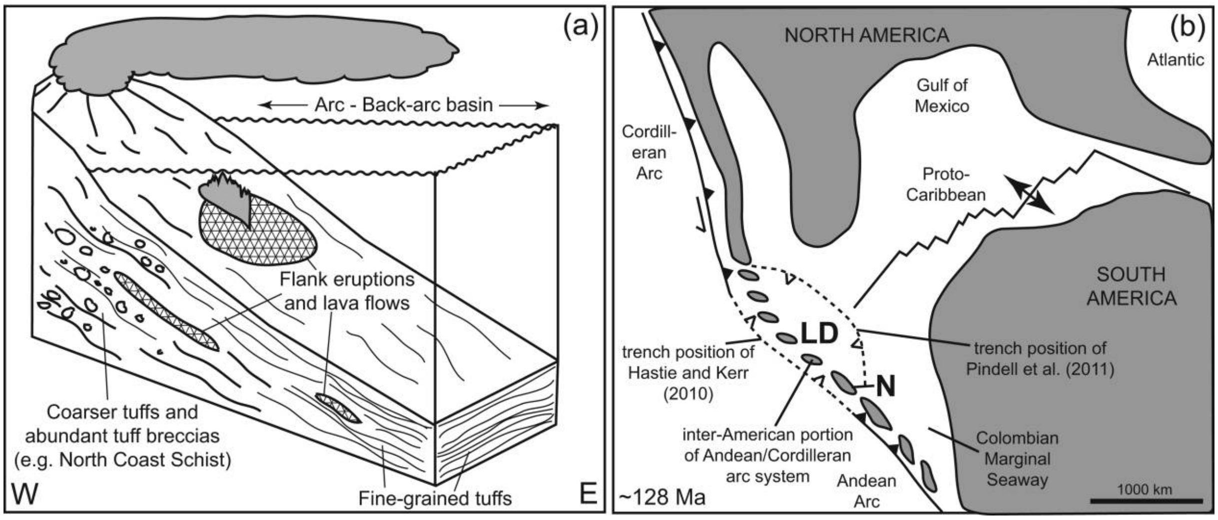

Figure 10. *a*, Schematic block diagram of facies associations modified from the Grand Cañon Formation of Baja California (Busby-Spera 1988), representing a possible analogue for the North Coast Schist. *b*, Potential tectonic setting, accounting for the two models of Caribbean tectonic evolution discussed in the text. LD = La Désirade volcano-plutonic complexes; N = North Coast Schist protoliths (modified from Pindell and Kennan 2009; Villagómez et al. 2011).

clude that the North Coast Schist protoliths were deposited within the clastic fringe of an island arc system (Sigurdsson et al. 1980; Carey and Sigurdsson 1984). Contrary to the model of Sigurdsson et al. (1980), however, Snoke et al. (2001*b*) propose that the North Coast Schist protoliths lay on the fore-arc, not back-arc, side of the island arc. However, the variety of mantle sources and presence of rocks with only mildly subduction-related geochemical signatures requires a more thorough evaluation of the geodynamic setting.

No pillow lavas have been found and volcanic activity was mostly explosive and therefore probably related to eruption within shallow water in a relatively mature supra-subduction system. The presence of coarsely fragmental tuff breccias (clasts up to 50 cm across) suggests that deposition was proximal to the eruption site. The overall thickness of the present-day North Coast Schist (at least ~2 km) may be misleading, as tight to isoclinal folding suggests repetition of individual facies. Nevertheless, the North Coast Schist comprises a substantial thickness of primary volcanic material to the near-total exclusion of nonvolcanic sediments (Snoke et al. 2001*a*). The North Coast Schist facies are compared the Gran Cañon Formation of Cedros Island, Baja California (Busby-Spera 1988; Critelli et al. 2002). This formation contains pyroclastic material erupted on the nether flank of an island arc system during the building and rifting of the arc (Critelli et al. 2002). The proximal facies (mafic and felsic tuffs and tuff breccias, interspersed with occasional lava flows interpreted as flank-fissure eruptions), appear similar to the North Coast Schist (Busby-Spera 1988). A representation of this setting is in figure 10*a*.

We therefore propose that the rocks of the Parlatuvier and Mount Dillon Formations are derived from isotopically distinct sources within the mantle wedge of an island arc, fluxed to variable degrees by fluids derived from the down-going oceanic crust. They were erupted within the arc axis or to the rear of a mature arc in relatively shallow water. Another piece of evidence potentially supporting a mature arc system is the presence of significant amounts of felsic volcanic material (the Mount Dillon Formation). This constraint suggests that the North Coast Schist was not part of a "new" southwest-dipping Greater Antilles arc system that some models propose to have initiated at ~135–125 Ma (Pindell and Kennan 2009; Pindell et al. 2011). Melting of relatively fluid-free mantle, perhaps during rifting or back-arc basin growth, probably generated the MORB-like signatures of the amphibolites. The isotopic similarity of the amphibolites to the most isotopically enriched member of the Parlatuvier Formation suggests that the two suites of rocks have a similar mantle wedge component.

Figure 10*b* shows a potential location in which the protoliths of the North Coast Schist were initially erupted (after Villagómez et al. 2011). By the end Jurassic, northern South America was a continental passive margin facing the widening proto-Caribbean seaway to the north (Pindell and Kennan 2009). Northwest of the continent, the Farallon plate subducted beneath the proto-Caribbean seaway, generating the proto-Greater Antilles arc; with back-arc basin rocks forming on the proto-Caribbean side of the arc, such as the volcano-plutonic complexes of La Désirade (Neill et al. 2010; Corsini et al. 2011). The back-arc basin is proposed to have extended south to Colombia and Ecuador as the Colombian Marginal Seaway between South America and the inter-American arc (Pindell and Kennan 2009; Villagómez et al. 2011). Models suggest the Colombian Marginal Seaway opened between approximately 135–125 Ma, and was closed during the middle Cretaceous (Maresch et al. 2009; Pindell and Kennan 2009). We propose that the northernmost Colombian Marginal seaway flanking the proto-Greater Antilles arc was the most realistic deposition site for the North Coast Schist protoliths. Unlike the depleted proto-Caribbean mantle further north, the mantle wedge may have been partly composed of isolated "blobs" of South American SCLM. Periodic fluid flux from the down-going Farallon slab to the west generated the subduction-related geochemical signatures in the Parlatuvier and Mount Dillon Formations. Periods of low fluid flux or arc extension (opening of the Colombian Marginal Seaway?) may have resulted in the formation of the MORB-like amphibolite protoliths.

Remaining Problems. Given the subsolidus alteration experienced by most Caribbean rocks, immobile element geochemical studies of other exposures, and Nd-Hf isotope analysis, needs to be undertaken to improve the picture of the tectonic configuration of the Caribbean region during the Early Cretaceous. We have focused mostly on the petrogenesis of the North Coast Schist, but it remains to be understood why the formations were later buried, deformed, and metamorphosed. In models of ~125 Ma initiation of southwest-dipping proto-Caribbean subduction (e.g., Maresch et al. 2009; Pindell et al. 2011), it is possible that the North Coast Schist protoliths were deformed between ~129 and ~110 Ma as they were translated from the rear-arc portion of the east-dipping inter-American arc system into the fore-arc of the new southwest-dipping subduction zone during a polarity reversal event (see fig. 17 of Maresch et al. 2009). The mélange-like character of the North Coast Schist, coupled with the presence of pumpellyite in the metamorphic assemblage (Snoke et al. 2001*b*; indicating somewhat higher pressures than in a typical "Barrovian" medium pressure-temperature metamorphic scenario), is suggestive of deformation within a fore-arc setting. From 110 Ma, mantle wedge melting beneath the Greater Antilles arc would generate the Volcano Plutonic Suite (Snoke et al. 2001*b*). Tobago is along-strike from metamorphosed oceanic and continental margin rocks on Margarita Island (Venezuela), which underwent HPLT metamorphism at ~115–100 Ma, perhaps during subduction beneath the new southwest-dipping Greater Antilles arc as the North Coast Schist was being deformed on the upper plate (Maresch et al. 2009). The structural and deformational history of the North Coast Schist (e.g., Snoke et al. 2001*b*) must be properly reconciled with these and other Caribbean tectonic models (e.g., COP collision model of Duncan and Hargraves 1984; Kerr et al. 2003). The age of the other North Coast Schist formations and chronological data from shear bands and mylonites in the North Coast Schist, might be useful in this regard. Greenschist-facies metavolcanic rocks similar to the Parlatuvier Formation have been described from the Bocas 1 well, some 100 km west of Tobago, so the rocks exposed on Tobago may represent a significant portion of southern Caribbean crust (Speed and Smith-Horowitz 1998). The age, petrogenesis and tectonic history of these locations remain to be explored in detail.

Conclusions

1. The North Coast Schist of Tobago contains deformed metaigneous and metasedimentary rocks accepted to be a fragment of the Mesozoic Pacific-derived Caribbean Great Arc.

2. The Parlatuvier Formation (128.66 ± 0.23 Ma) comprises greenschist-facies mafic-intermediate tuffs, tuff breccias, and rare lavas formed by partial melting of a heterogeneous subduction-modified, isotopically depleted source. Two samples from the Parlatuvier Formation have the highest recorded $^{176}Hf/^{177}Hf$ isotope ratios in any rocks hitherto studied from the allochthonous Caribbean Plate.

3. The Mount Dillon Formation contains greenschist-facies silicic/silicified tuffs and tuff breccias that are derived from an isotopically depleted subarc mantle source. Rare mafic volcanic rocks have been overprinted by later amphibolite-facies dynamothermal metamorphism but are derived from a depleted mantle source that may not have been subduction modified.

4. The association of rock types and geochemical signatures is due to the formation of the North Coast Schist protoliths close to the northernmost

part of the Colombian Marginal seaway (a back-arc basin) within the east-dipping Great Arc system. The limited subduction component and the variable HFSE ratios in the North Coast Schist relates to the nature of fluid flux derived from the east-dipping Farallon oceanic slab, and to preexisting mantle heterogeneities. Metamorphism of the North Coast Schist occurred at ~129–110 Ma during an episode of wrench shearing, before the development of the voluminous Tobago Volcano-Plutonic Suite during Mid-Cretaceous subduction and the growth of the Greater Antilles arc system.

ACKNOWLEDGMENTS

I. Neill acknowledges Natural Environment Research Council (NERC) studentship (NE/F00219X/1). A NERC grant (IP/1064/1108) supported radiogenic isotope analysis. A. W. Snoke and K. R. Chamberlain kindly provided samples. K. Persad, R. Maraj, and I. Gomes aided with fieldwork. I. McDonald and L. Woolley analyzed the major and trace elements, and N. Boulton and Dan Condon assisted with radiogenic isotope analysis and U-Pb dating. We thank A. W. Snoke and G. Draper for their helpful reviews.

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