The Geological Society of America
Special Paper 513
2015

Evolution of the Caribbean plate and origin of the Gulf of Mexico in light of plate motions accommodated by strike-slip faulting

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ABSTRACT

Restoration of plate consumption recorded by Caribbean arc volcanism reveals probable plate movements that led to the emplacement of the proto–Caribbean plate into the present Caribbean region and provided the space necessary to accommodate the rotation of the Yucatán Peninsula concurrent with the opening of the Gulf of Mexico between ca. 170 Ma and 150 Ma. Fault movement of the Yucatán, caused by edge-driven processes, resulted in counterclockwise rotation, as shown by paleomagnetic studies. Restoration of Yucatán rotation necessitates the presence of a paleogeography different from the current distribution of the Greater and Lesser Antilles.

During emplacement of the Caribbean plate region, four magmatic belts with distinct ages and different geochemical characteristics are recorded by exposures on islands of the Antilles. The belts distinguish the following segments of Cretaceous and Tertiary magmatic arcs: (1) an Early Cretaceous geochemically primitive island-arc tholeiite suite (PIA/IAT) typically containing distinctive dacite and rhyodacite that formed between Hauterivian and early Albian time (ca. 135–110 Ma); (2) after a hiatus at ca. 105 Ma of ~10 m.y., a voluminous, more-extensive calc-alkaline magmatic suite, consisting mainly of basaltic andesite, andesite, and locally important dacite, developed beginning in the Cenomanian and continuing into the Campanian (ca. 95–70 Ma); (3) a second (calc-alkaline) suite, spatially restricted relative to the older belts, that consists of volcanic and intrusive rocks, which formed between the early Paleocene and the middle Eocene (ca. 60–45 Ma); and (4) a currently active calc-alkaline suite in the Lesser Antilles typically composed of a basalt-andesite-dacite series that began to develop in the Eocene (ca. 45 Ma).

Plate convergence took place along northeastward- or eastward-trending axes during the formation of the Caribbean, which is outlined by the Antillean islands and Central and South America. Movements were facilitated by strike-slip faults, commonly trench-trench transforms, as subducting crust was consumed. Restoration of apparent displacements of at least several hundreds of thousands of kilometers along the inferred lateral faults of the Eocene and younger Cayman set separating Puerto Rico, Hispaniola, and the Oriente Province of southeastern Cuba brings together Eocene volcanic rocks revealing a magmatic domain along the paleo–south-southwestern

Lidiak, E.G., and Anderson, T.H., Evolution of the Caribbean plate and origin of the Gulf of Mexico in light of plate motions accommodated by strike-slip faulting, *in* Anderson, T.H., Didenko, A.N., Johnson, C.L., Khanchuk, A.I., and MacDonald, J.H., Jr., eds., Late Jurassic Margin of Laurasia—A Record of Faulting Accommodating Plate Rotation: Geological Society of America Special Paper 513, p. 1–88, doi:10.1130/2015.2513(01). For permission to copy, contact editing@geosociety.org.

margin of the Greater Antilles. The transforms along the southern margin of the Caribbean plate are mainly obscured by contractional deformation related to the northward motion of South America as it was thrust over the faulted plate margin. Restoration of the Caribbean plate also translates the Nicaragua Rise westward, thereby revealing a pathway along which Pacific oceanic lithosphere, mainly composed of a large, Late Cretaceous igneous province (Caribbean large igneous province), manifest as an oceanic plateau (Caribbean-Colombian oceanic plateau), converged toward and subducted beneath the southern flank of the Cretaceous Greater Antilles magmatic belt between 65 and 45 Ma. The Eocene arc rocks overlie or abut previously recognized Early and Late Cretaceous subduction-related units. Eocene consumption of Pacific lithosphere ceased with the arrival, collision, and accretion of buoyant lithosphere composed of Caribbean large igneous province. The Greater Antilles formed during Late Cretaceous subduction of Jurassic ocean crust beneath an Early Cretaceous arc formed at the eastern margin of the proto–Pacific plate. Formation of a volcanic edifice above Early Cretaceous arc rocks was followed by plate collision and coupling of the Greater Antilles belt against the Bahama Platform. The most straightforward path of the Greater Antilles into the Caribbean is along northeast-striking transforms, one of which coincided with the eastern margin of the Yucatán Peninsula. The transform appears to link the Motagua suture to the Pinar del Rio Province of western Cuba. To the southeast, the arc was transected by a second transform, perhaps coinciding with the present trace of the Romeral fault in northwestern South America and extending northeast to the eastern terminus of the Virgin Islands. During Late Cretaceous convergence, a segment of the extinct Early Cretaceous arc, developed at the Pacific margin, was carried northeastward.

INTRODUCTION

This paper builds upon basic geologic information from many sources, especially from Puerto Rico, Virgin Islands, Hispaniola, Cuba, and Jamaica (Fig. 1), each of which is sufficiently areally extensive to record regional stratigraphic, structural, and geochemical relationships (Donnelly et al., 1990; Lewis and Draper, 1990; Mann et al., 1991; Dolan and Mann, 1998; Lidiak and Larue, 1998; Iturralde-Vinent and MacPhee, 1999; Iturralde-Vinent and Lidiak, 2006; Mann, 2007; Garcia-Casco et al., 2011). These works recognized important geologic units including Cretaceous volcanic belts, coarse Maastrichtian conglomerate, ultramafic complexes, distinctive metamorphic rocks, Paleogene arc rocks, late Eocene–Oligocene sedimentary units, and unconformities and hiatuses that commonly coincided with the cessation of arc magmatism, collisions, and following uplift. Mann et al. (1991) identified a number of events that are important to understanding the evolution of the Caribbean, including: Early Cretaceous island-arc growth, late pre-Aptian uplift and erosion, post-Albian island-arc growth, Campanian deformation and metamorphism, post-Campanian to middle Eocene island-arc growth, Eocene island-arc collision, and late Eocene and younger strike-slip faulting and regional contraction. This information about rock units and geologic processes influences our conclusions about Caribbean history and paleogeography.

Iturralde-Vinent and Lidiak (2006) noted that many of the details of the origin of the Caribbean plate (Fig. 1) and its fringing arc system have been characterized. However, controversy persists in regard to the number and origin of magmatic arcs, the timing and polarity of the subducting plate or plates, the proposed origin of the Caribbean plate itself, and finally the pre-Cretaceous rifting and breakup of Pangea that resulted in the separation of North and South America and the development of proto-Caribbean oceanic crust, which preceded the formation of the great arc (Duncan and Hargraves, 1984; Burke, 1988; Ross and Scotese, 1988; Donnelly et al., 1990; Pindell and Barrett, 1990; Lebron and Perfit, 1994; Jolly et al., 1998b; Kerr et al., 2003; Pindell et al., 2006; Pindell and Kennan, 2009; van der Lelij et al., 2010; Neill et al., 2011; Wright and Wyld, 2011; Seton et al., 2012).

Perhaps the most complete paleogeographic model of Caribbean evolution was offered by Iturralde-Vinent and MacPhee (1999). Their model (Fig. 2) provides a template that may be constrained by geochronologic and geochemical studies published after 2000, which are referenced herein. The successful model also should address plate-tectonic considerations stemming from issues such as those raised by Pindell et al. (2006). These include:

(1) the degree of freedom in the Gulf of Mexico–Caribbean kinematic framework that is allowed by Atlantic opening parameters,
(2) the counterclockwise rotation of the Yucatán block during the opening of the Gulf of Mexico,
(3) the Pacific origin of the Caribbean oceanic crust,
(4) the Aptian age and plate-boundary geometry of the onset of west-dipping subduction of proto-Caribbean crust beneath Caribbean lithospheres,

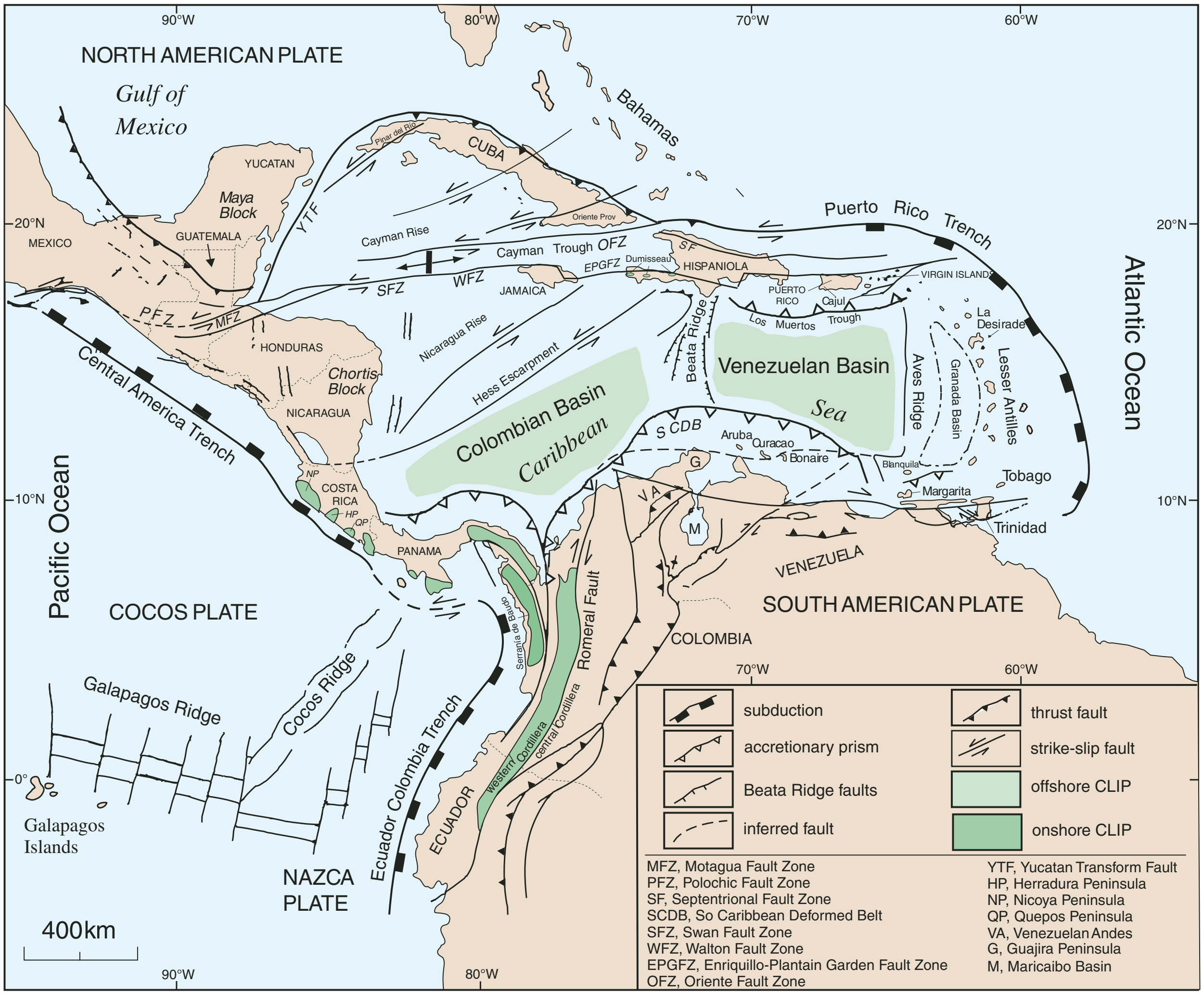


Figure 1. General tectonic and reference map of the Caribbean region showing selected geographic and tectono-stratigraphic elements and major faults. Base map was adapted and modified from Giunta et al. (2006), with additions. CLIP—Caribbean large igneous province.

(5) the origin and causal mechanism of the Caribbean large igneous province, and
(6) the number and origin of magmatic arcs in the northern Caribbean.

Recently, Boschman et al. (2014) published a paper detailing a kinematically quantified tectonic evolutionary model of the Caribbean region since ca. 200 Ma. Their approach differs from our paper presented here in that we emphasize the regional stratigraphic, structural, and geochemical relationships of the main geologic units.

PURPOSE

The purpose of this paper is to develop a viable and geologically rigorous plate-tectonic model that reveals the Jurassic and later evolution of the Gulf of Mexico and the adjacent Caribbean region beginning with Middle to Late Jurassic rifting and development of proto-Caribbean oceanic crust that accompanied the breakup of Pangea (Pindell and Kennan, 2009, and references therein). The model differs from previous work in that the role of plate-bounding strike-slip faults is emphasized, especially those Jurassic sinistral faults that accommodated the opening of the Caribbean and Gulf of Mexico via linkage between the western margin of North America and the Atlantic Ocean. In order to recognize the Jurassic paleogeography, we have attempted to look beyond the Tertiary and Cretaceous events.

APPROACH

Our approach involves an overarching four-step process: (1) Recognize the distribution and history of subduction-related rocks and plateau-forming basalt and other mafic and ultramafic units encompassed within the Caribbean region; (2) interpret the plate-tectonic processes that led to the present Caribbean

geology; (3) offer restorations that reveal the paleogeography at the beginning of the Cretaceous; and (4) propose a model to close the Gulf of Mexico.

Cretaceous and Paleocene volcanic, volcanogenic, and plutonic rocks characterize the geology of the Greater Antilles. Some workers have suggested the presence of a magmatic arc, the "Great Arc of the Caribbean" (Burke, 1988), that formed along the western margin of the proto-Caribbean and includes the present-day Greater Antilles, Lesser Antilles, Aves Ridge, and Netherlands Antilles.

Among the rocks of the "Great Arc," we recognize some major geochemically distinct volcanic rock associations. The rock associations include three that are subduction-related suites and a fourth that formed a plateau in a plume-like environment (Fig. 3). The Cretaceous subduction-related suites are subalkaline rocks and are characterized by depleted concentrations of high field strength elements (HFSEs; Nb, Ta, Zr, Hf, and Ti) and different concentrations of light rare earth elements (LREEs). The two Cretaceous groups are subdivided into a geochemically primitive island-arc or island-arc tholeiite group (PIA/IAT) containing low concentrations of both LREEs and thorium (Th; 0.245–1.35 ppm) and a geochemically more-evolved calc-alkaline group consisting of greater concentrations of LREEs and Th. Figure 3 shows that these rocks display distinctive patterns on typical incompatible-element or spider-type diagrams.

The calc-alkaline group can be further subdivided into a medium-Th calc-alkaline and a high-Th calc-alkaline to shoshonite group, with Th used as a proxy for K_2O and Co used as a proxy for SiO_2 on other standard classification-type diagrams, such as total alkali–silica (TAS; [SiO_2 vs. $Na_2O + K_2O$]) diagrams (Hastie et al., 2007; Pearce et al., 2014). Mobile elements are not used herein in classifying these Caribbean rocks because most are susceptible to low-temperature alteration (Jolly et al., 1998b; Lidiak and Jolly, 1998; Jolly et al., 2001; Hastie et al., 2007). The third main volcanic rock association is the plateau basalt of Caribbean large igneous province. These rocks are not depleted in HFSEs and typically display a characteristic within-plate smooth incompatible-element pattern (Fig. 3).

As discussed previously, Figure 3 shows those volcanic associations that we regard as being widespread in the Caribbean and important to our discussion of the tectonic development of the region. Additionally, we refer the reader to other important rock associations or rock units in the Caribbean that include but are not limited to the following: the Quaternary volcanic centers of central Hispaniola (Wertz, 1985; Vespucci, 1987; Kamenov et al., 2011); Mabujina amphibolite complex of Cuba (Rojas-Agramonte et al., 2011); oceanic tholeiite in the northern ophiolite belt of Cuba (Kerr et al., 1999); igneous rock of the Mataguá, Camujiro, Colombia, and La Mulata units of Cuba (Kerr et al.,

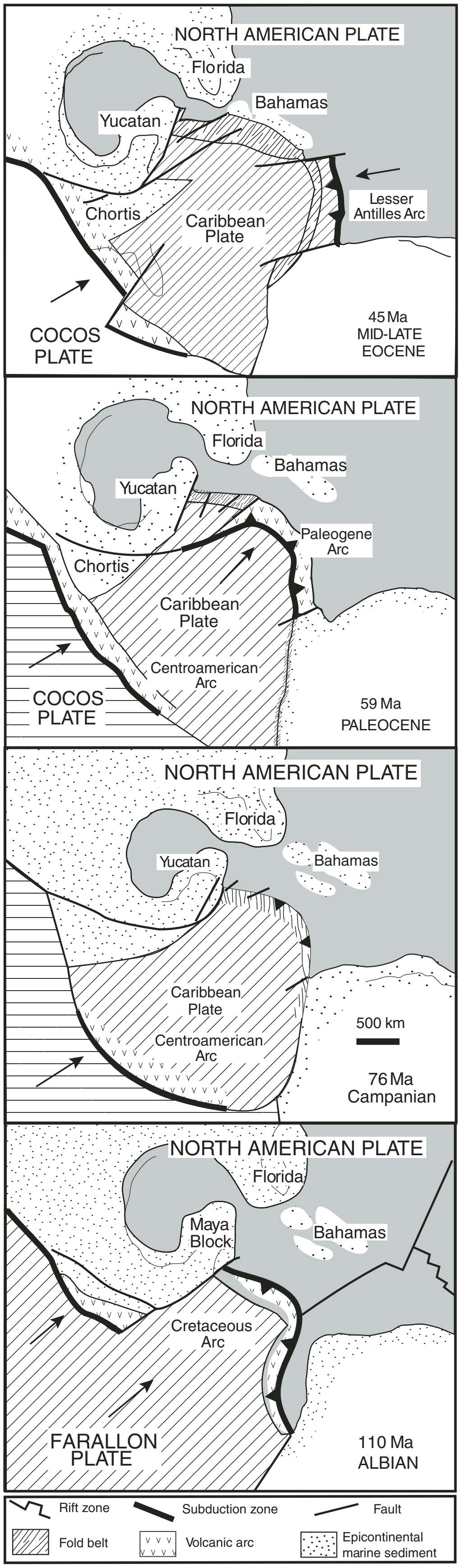


Figure 2. Plate-tectonic model of the Caribbean region from Albian through Eocene, adapted from Iturralde-Vinent and MacPhee (1999).

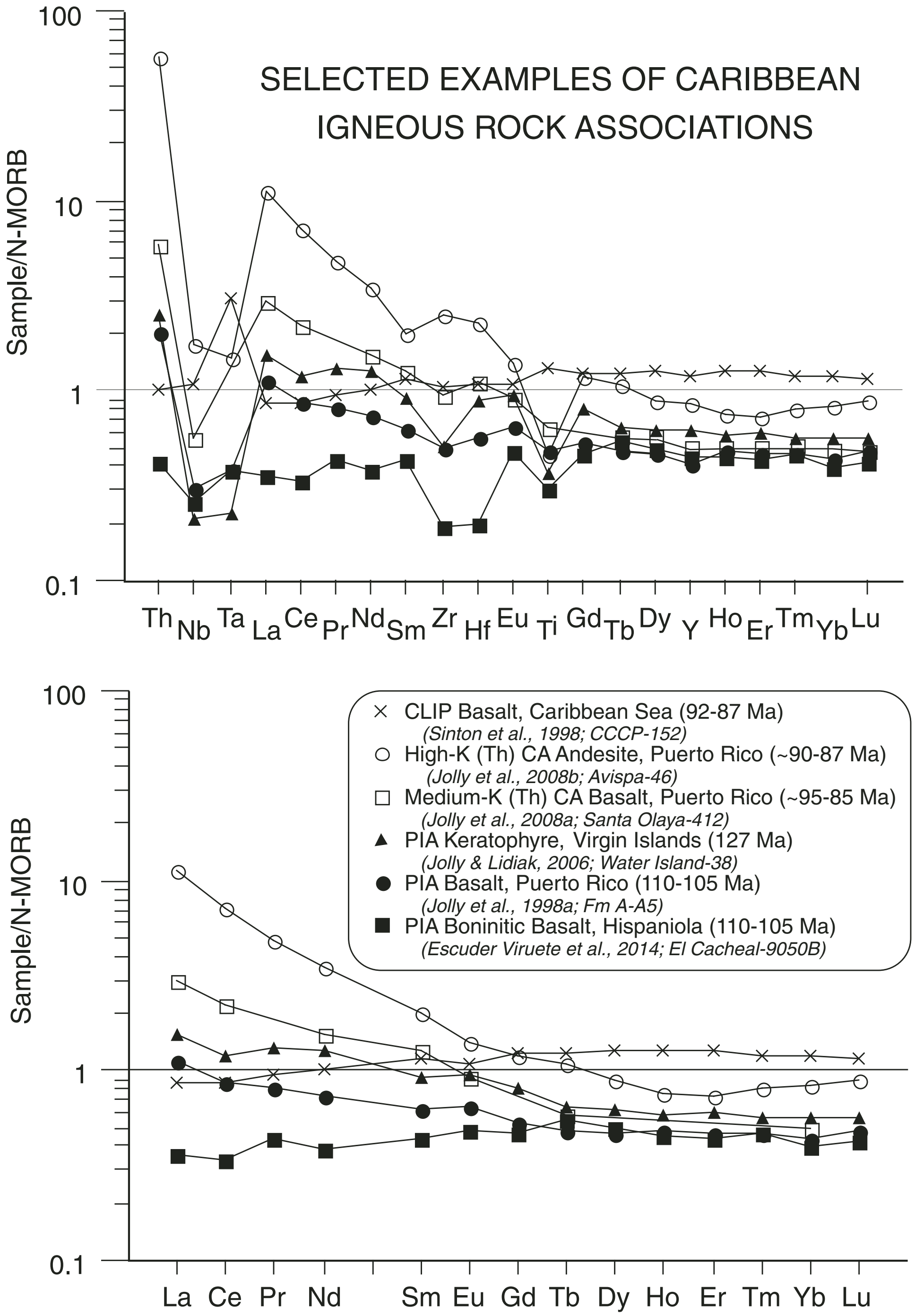


Figure 3. Geochemical plots of selected examples of Caribbean main igneous rock associations in the Caribbean region. Data sources: Sinton et al. (1998); Jolly and Lidiak (2006); Jolly et al. (1998a, 2008a, 2008b); Escuder Viruete et al. (2014). N-MORB—normal mid-ocean-ridge basalt. Normalizing factors are from Sun and McDonough (1989). See text for discussion. CLIP—Caribbean large igneous province; CA—calc-alkaline; PIA—primitive island arc.

1999); the Morel volcanics of Cuba (Proenza et al., 2006); the Porvenir and Provincial Formations of Cuba (Blein et al., 2003); and the high-Mg Río Loco andesite of Puerto Rico (Jolly et al., 2007; Lidiak et al., 2011).

As part of the first step, our approach has been to review previous geological work while incorporating recently published geochronologic and geochemical information that bears upon the number of subduction-related magmatic episodes and helps to identify small plates and their boundaries that accommodated convergence of the proto–Pacific Ocean toward the margin of the North America plate. For each plate-movement episode, we have attempted to identify correlative igneous and sedimentary rock suites and a cogenetic trench. We have tried to identify indications of cessation of subduction, such as magmatic lulls, development of regional unconformities, and related other features such as cooling ages from metamorphosed units recording pronounced

uplift. We recognize four subduction episodes that, along with prominent strike-slip faulting, played an essential role in the development of the Gulf of Mexico and Caribbean Sea: (1) late Eocene to Holocene, (2) Paleocene and early Eocene (ca. 65–45 Ma), (3) Late Cretaceous (ca. 95–70 Ma), and (4) Early Cretaceous (ca. 135–110 Ma). Some faults, active during each episode, coincided with boundaries of small (microplates) and commonly intersected and/or linked trenches.

We also summarize information about the Late Cretaceous Caribbean large igneous province, which underlies the Caribbean-Colombian oceanic plateau and constitutes much of the Caribbean seafloor, as well as mafic domains exposed in adjacent continental margins. We assume that the termination of arc segments and the linear margins of Caribbean microplates are related to trench-trench transforms or strike-slip faults.

In the second step, we assess the proposed geologic processes from the view of their viability with respect to plate-tectonic processes and also strive to correlate the formation of magmatic arcs with consumption of subductable lithosphere that may help to constrain the postulated subduction polarity. We recognize two pulses of movement associated with the insertion of the Caribbean-Colombian oceanic plateau from the Pacific into the present Caribbean region.

In the third step, we utilize large strike-slip faults that contributed to the breakup of Pangea and opening of the Gulf of Mexico (Anderson and Schmidt, 1983; Klitgord and Schouten, 1986; Schouten and Klitgord, 1994). Kinematically viable restorations are proposed for each pulse of eastward plate movement. We attempt to restore displacements along principal faults based upon inferred correlations between offset geologic units.

Major plate processes of the model, most of which have been previously recognized but not integrated, include the following: (1) Late Jurassic formation of the Gulf of Mexico by means of movements along sinistral faults and concurrent rotation of the Yucatán Peninsula; (2) convergence at the west margin of the paleo–Caribbean plate accommodated by consumption of proto-Pacific lithosphere at an eastward-dipping subduction zone, beginning ca. 135 Ma, and culminating in the Early Cretaceous soon after 110 Ma; (3) initiation of westward-dipping subduction at the western margin of the paleo-Caribbean, which led to northeastward migration of the Late Cretaceous arc (and underlying Early Cretaceous arc) accompanied by consumption of Late Jurassic oceanic crust between the Cretaceous arc(s) and the North American Maya block and Bahama Platform and collision and obduction of the arc onto the platforms; (4) collision of the arc(s) against the North American Bahama Platform, terminating subduction; (5) Late Cretaceous collision followed by resumption of westward-dipping subduction of Pacific oceanic lithosphere that took place during the Paleocene and early Eocene until arrival and collision of buoyant Caribbean large igneous province lithosphere against the southwest side or back of the dormant Late Cretaceous arc; (6) continued eastward-dipping convergence toward the Atlantic, as recorded by northeasterly striking sinistral faults that segmented Cuba; and (7) continued convergence, becoming more easterly and leading to further development of sinistral movements accommodated partly within the Cayman Trough, which led to separation of Hispaniola from southeastern Cuba, and Puerto Rico from Hispaniola concurrent with development of the Lesser Antilles arc.

MULTIPLE MAGMATIC ARCS IN THE CARIBBEAN

The number and origin of magmatic arcs in the Caribbean have been subjects of ongoing debate for decades (for example, Mattson, 1979; Burke, 1988; Pindell and Barrett, 1990; James, 2006; Pindell et al., 2006; Pindell and Kennan, 2009; Garcia-Casco et al., 2011; Wright and Wyld, 2011). A principal issue has to do with the development of Caribbean volcanic rocks. Are they parts of: (1) a single arc that evolved at the leading edge of the Caribbean plate from Early Cretaceous to the present, or (2) multiple, independent, volcanic arcs that record changes in subduction polarity before and during insertion of the Cretaceous volcanic rocks that crop out on the islands of the Antilles. Evidence that may be used to assess the concepts includes: (1) geochemistry of each arc's igneous suite (Donnelly et al., 1990; Iturralde-Vinent and Lidiak, 2001; Iturralde-Vinent, 2003); (2) the crystallization ages of the extrusive and intrusive units that comprise the geochemically comparable suites (Rojas-Agramonte et al., 2011); (3) major unconformities accompanied by magmatic quiescence that separate subduction-related episodes (Lebron and Perfit, 1993); and (4) the role of regional tectonics in plate development (Pindell et al., 2006). With these general points in mind, we present some pertinent stratigraphic characteristics of exposures of igneous rocks in the Antilles followed by a discussion of possible subduction polarities.

Our assessment of published geochemical, geochronologic, and stratigraphic studies leads us to the same conclusion reached by Simon et al. (1999). As shown in Figure 4, they concluded that remnants of three extinct, subduction-related magmatic belts may be recognized: (1) an Early Cretaceous geochemically primitive island-arc tholeiite (PIA/IAT), typically containing distinctive dacite and rhyodacite, that formed between Hauterivian and early Albian time (ca. 135–110 Ma); (2) after a hiatus, a voluminous, more extensive calc-alkaline magmatic suite, consisting largely of basaltic andesite and andesite with locally important dacite, that developed beginning in the Cenomanian and continued into the Campanian (ca. 95–72 Ma); and, ~10 m.y. later, (3) a second (calc-alkaline) suite, areally restricted relative to the older belts, which consists of volcanic and intrusive rocks that formed from early Paleocene to middle Eocene time (ca. 60–45 Ma). Crucial elements in the resolution of the magmatic episodes are interpreted U-Pb ages from zircons, most of which, as referenced herein, have been published in the past 15 yr. As noted here, pauses in subduction-related magmatism generally correspond with regional unconformities marked by erosional surfaces and/or the development of carbonate units and other nonvolcanic strata.

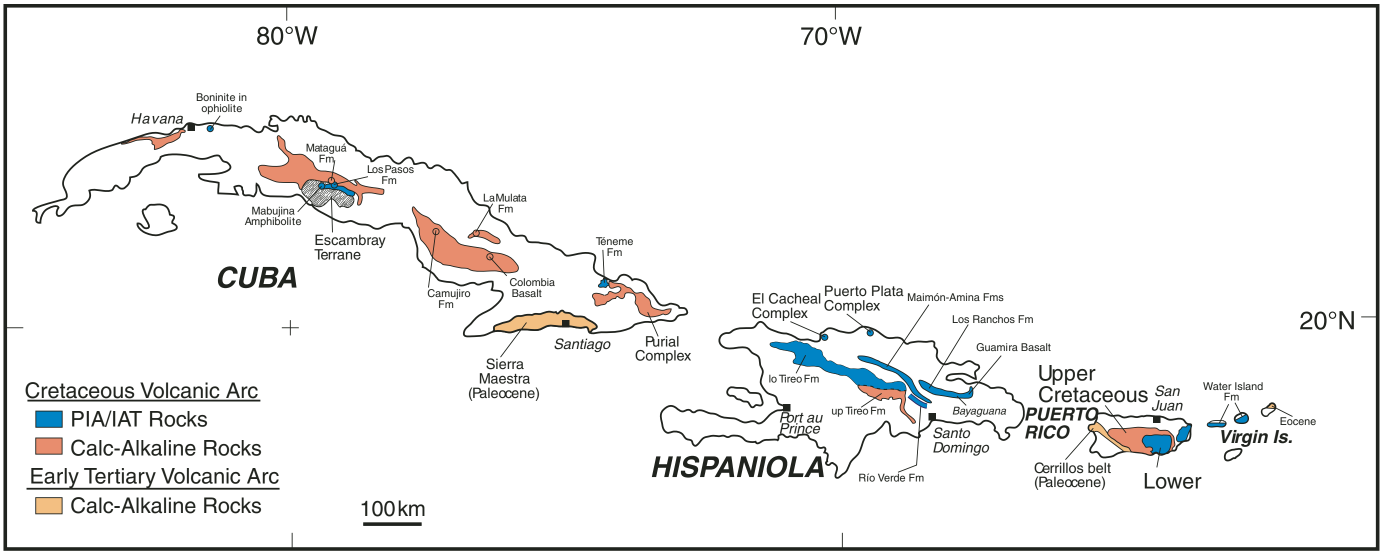


Figure 4. Generalized map showing primitive island arc/island-arc tholeiite (PIA/IAT) and calc-alkaline (CA) fringing arc system rocks of the Greater Antilles, adapted from Lebron and Perfit (1993), Simon et al. (1999), and Rojas-Agramonte et al. (2011), with additions.

Early Cretaceous Island-Arc Tholeiite Volcanic Phase (Ca. 135–110 Ma)

Donnelly and coworkers (Donnelly et al., 1971; Donnelly and Rogers, 1978; Donnelly and Rogers, 1980; Donnelly et al., 1990) first recognized the presence of geochemically primitive island-arc (PIA/IAT) strata in a bimodal sequence of spilitized basalt and keratophyre (dacite to rhyodacite) comprising the Water Island Formation, U.S. Virgin Islands (Figs. 5, 6, and 7A). PIA-type lavas typically have low large ion lithophile element (LILE), LREE, and HFSE abundances, low Th, U, and radiogenic Pb, and near-horizontal or slightly depleted normalized LREE spectra. Trace-element distribution is broadly equivalent to conventional modern island-arc tholeiite (IAT) series (Jakes and Gill, 1970). Subsequent research demonstrated that PIA/IAT volcanics are also present in the Louisenhoj Formation (Figs. 7B, 8A, and 9A) of the Virgin Islands (Jolly et al., 2006), the pre–Robles Rio Majada (Figs. 7C, 8B, and 9B) and Daguao, Figuera, and lower Fajardo (Figs. 7D, 8C, 8D, 9C, and 9D) units of eastern Puerto Rico (Jolly et al., 1998a, 2001, 2002), Los Ranchos, lower Tireo, Rio Verde, Los Caños, El Cacheal, and Tortue-Amina-Maimón-Amina Formations (Figs. 7F–7H, 8H–8J, and 9H–9J) of Hispaniola (Donnelly et al., 1990; Lewis et al., 2000, 2002; Escuder Viruete et al., 2006, 2010, 2014), the Los Pasos, Téneme, Quibijan, and Sagua La Chica Formations of Cuba (Figs. 7I, 8G, and 9G; Iturralde-Vinent, 1996d; Kerr et al., 1999; Blein et al., 2003; Díaz de Villalvilla et al., 2003; Proenza et al., 2006; Torró et al., 2015a, 2015b), and Mabujina and related gneisses in central and eastern Cuba (Iturralde-Vinent, 1996c, 1996b; Diaz de Villalvilla, 1997; Rojas-Agramonte et al., 2011), and lower Devils Race Course Formation (Figs. 7J, 8F, and 9F) in Jamaica (Hastie et al., 2009). Included herein are PIA/IAT rock suites displaying slightly elevated Th contents that, on the basis of this element, are essentially transitional to calc-alkaline compositions, such as the Pitahaya, Río Abajo, and Torrecilla units of eastern Puerto Rico, Los Cãnos of Hispaniola, and the upper Devils Race Course Formation of Jamaica (Figs. 7E, 7H, and 7J). Except for the Téneme, all of these PIA/IAT volcanic rocks typically comprise the initial Early Cretaceous units in the Caribbean region.

Virgin Islands

The oldest rocks in the Virgin Islands are known as the Water Island Formation, a 2–4-km-thick bimodal unit that consists mainly of PIA/IAT keratophyric (dacitic) lava flows and related volcaniclastic rocks (80%), basaltic lava and breccia (20%), and minor radiolarian chert (Fig. 6; Donnelly, 1966; Rankin, 2002; Jolly and Lidiak, 2006). Zircon from a Water Island Formation keratophyre flow on St. John yielded a U-Pb date of 127 Ma (John Lewis, 2014, personal commun.), establishing a Barremian age for the formation, which is closely similar to other PIA/IAT units on Hispaniola and Cuba. Radiolaria from near the top of the formation are of probable late Aptian to earliest Albian age, suggesting that the entire formation may be Early Cretaceous in age. Conformably overlying the Water Island is the 0.5–1.5-km-thick, PIA/IAT-type basaltic Louisenhoj Formation, which consists of volcanic breccia, conglomerate, volcanic wacke, shale, chert, andesite, basalt, tuff, and rare limestone. The ~100-m-thick Outer Brass Limestone, in turn, overlies the Louisenhoj conformably. The limestone is dated by planktonic foraminifera as late Turonian to late Santonian (Pessagno, 1976; Rankin, 2002).

Puerto Rico

In southeastern Puerto Rico (Figs. 10 and 11A), the lowest volcanic suite (Río Majada and Daguao-Figuera Formations)

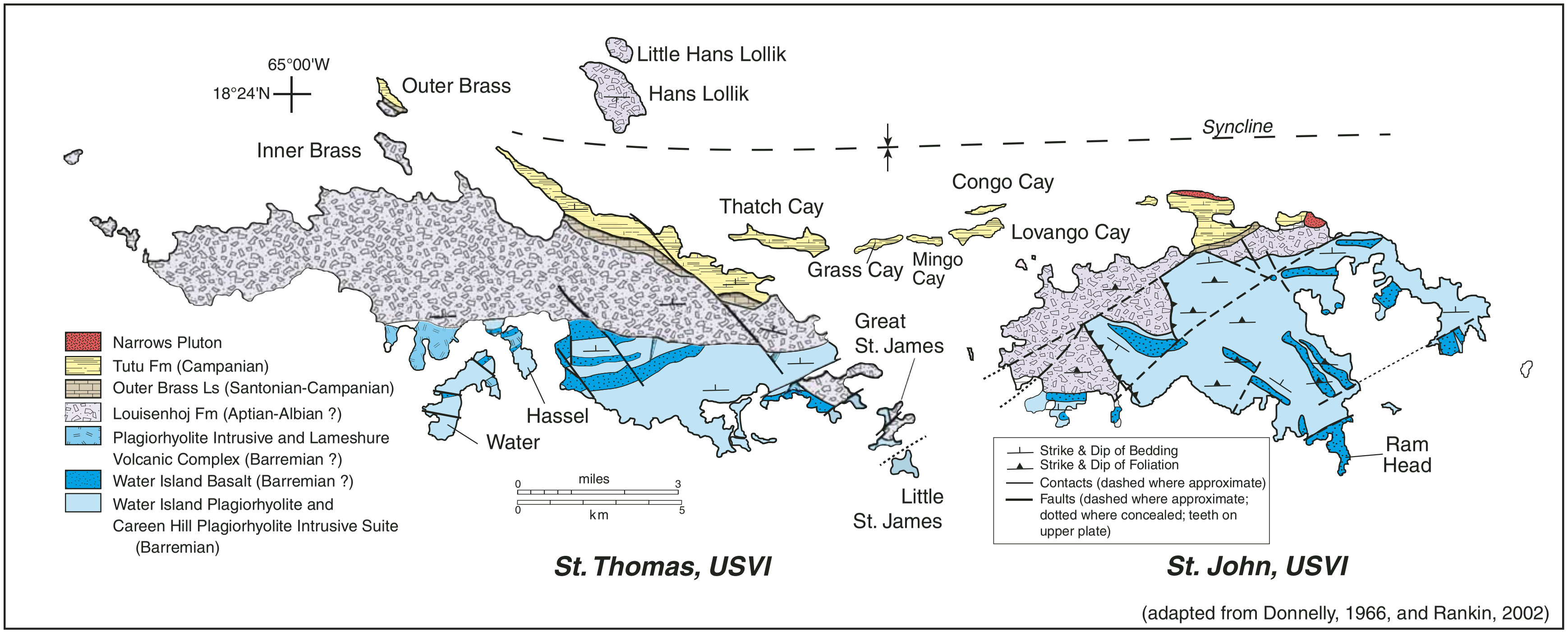


Figure 5. Geologic map of the U.S. Virgin Islands, adapted from Donnelly (1966) and Rankin (2002).

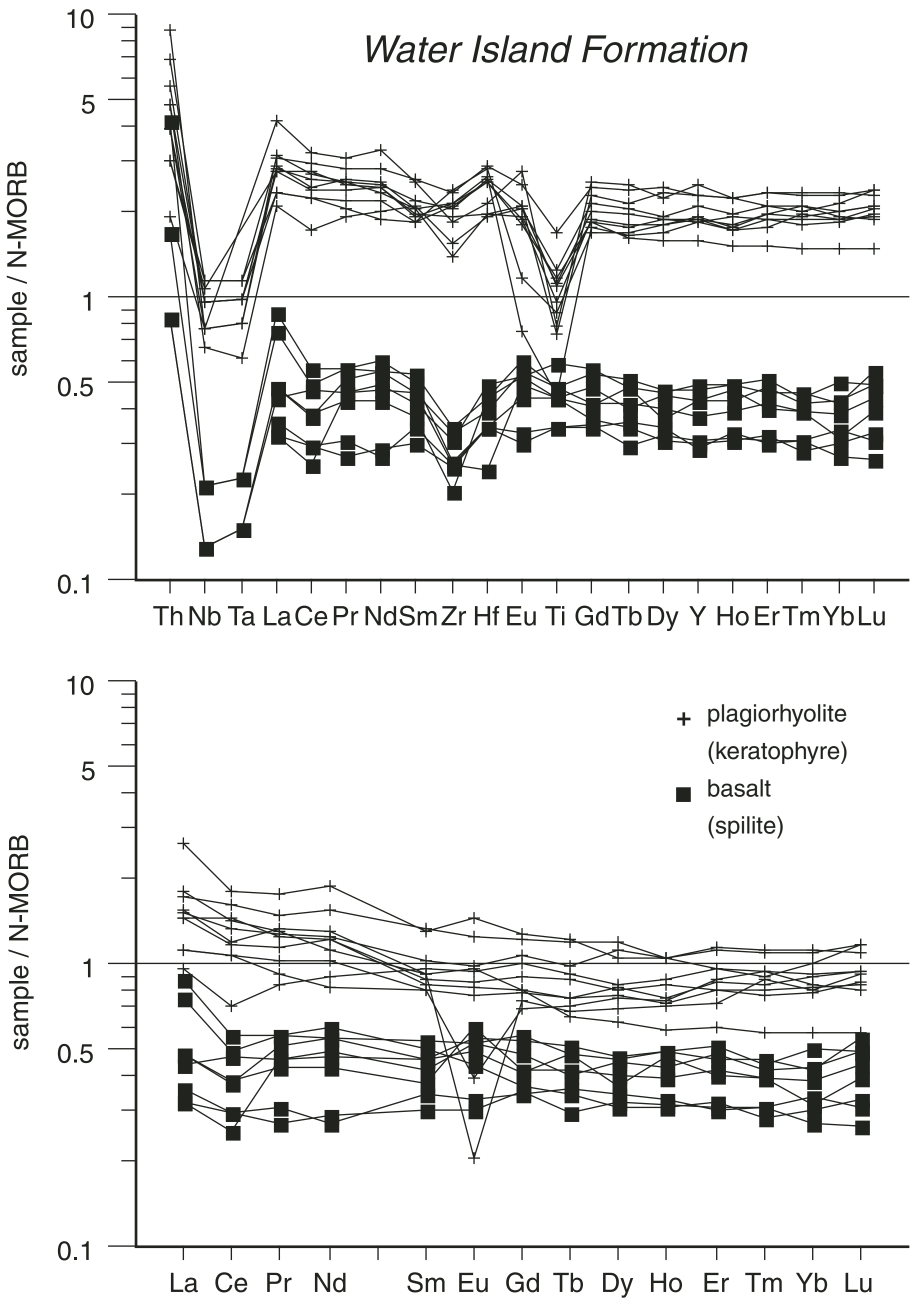
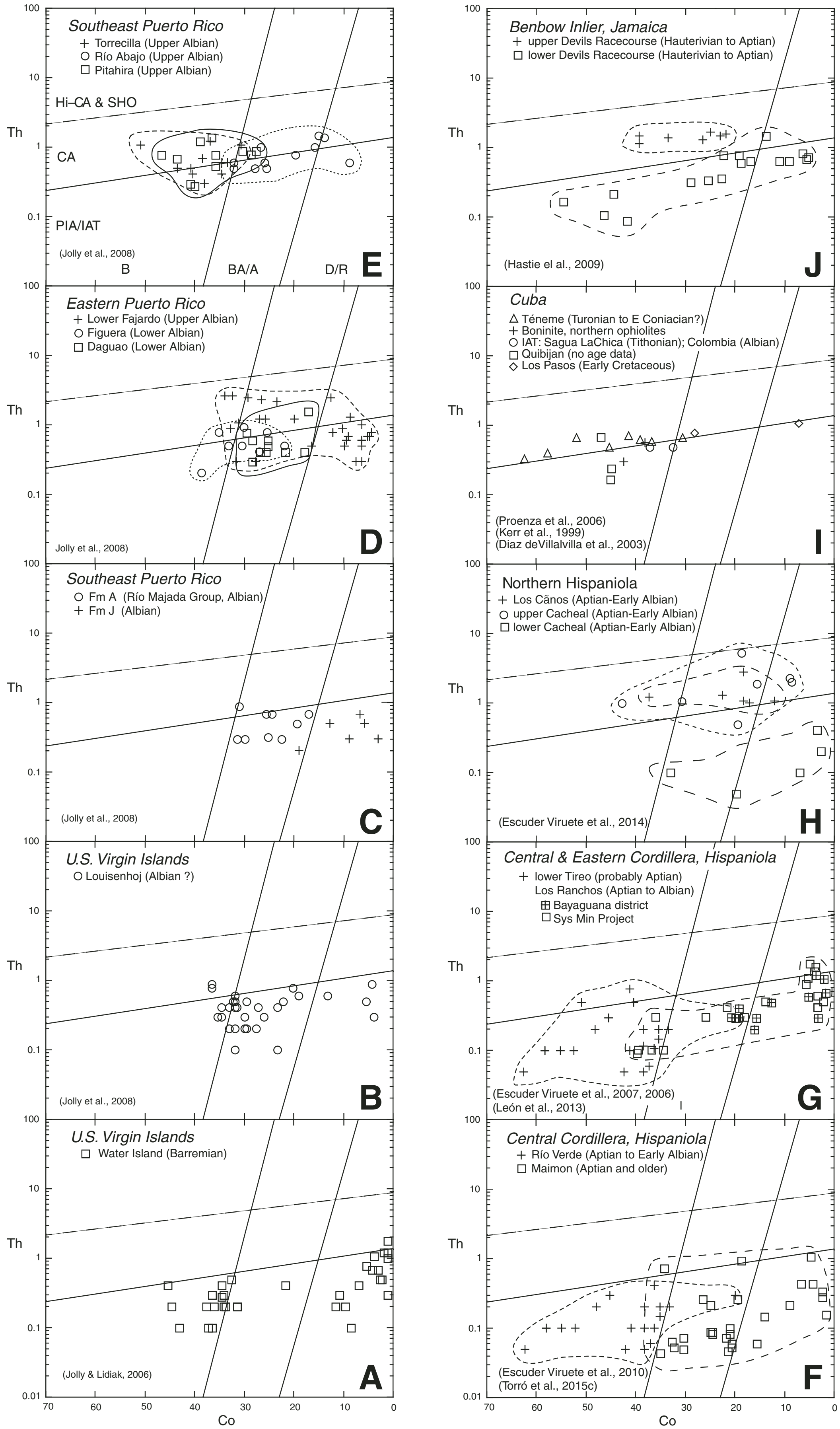


Figure 6. Geochemical plots of normalized incompatible trace-element (ITE) and rare earth element (REE) patterns of primitive island arc/island-arc tholeiite (PIA/IAT) in the PIA/IAT Water Island Formation, U.S. Virgin Islands. Characteristics of these and other PIA/IAT rocks are low Th concentrations, near-horizontal or slightly depleted light (L) REE spectra, and depleted Nb, Ta, and other high field strength elements (HFSEs) such as Zr, Hf, and Ti. Note also the higher elemental concentration in the plagiorhyolite (keratophyre) than in the basalt (spilite). Data are from Jolly and Lidiak (2006). Normalizing factors are from Sun and McDonough (1989). N-MORB—normal mid-ocean-ridge basalt.

consists of more than 6 km of volcanic rocks composed in large part of augite-plagioclase phyric lava flows and lava breccia that probably formed between ca. 120 and 105 Ma (Berryhill and Glover, 1960; Briggs, 1973; M'Gonigle, 1977; Jolly et al., 1998a; Schellekens, 1998a). In places, the volcanic units are intruded by the San Lorenzo Batholith, the early phases of which have PIA affinities (Smith et al., 1998). In the Cayey area of southeastern Puerto Rico, Berryhill and Glover (1960) subdivided the pile of volcanic rock into formations on the basis of several local unconformities (Fig. 11B, Formation A, B, and C: Río Majada Group). A carbonate reef mapped as Aguas Buenas Limestone, interpreted to underlie 2.5 km of additional voluminous augite-plagioclase–rich extrusives (Torrecilla Breccia), contains Albian fauna and rests unconformably on the lower volcanic pile (Río Majada Group; Fig. 11B). A nearby second carbonate reef, which contains correlative Albian fossils (Douglass, 1961; Sohl and Kollmann, 1985), is designated as Río Maton Limestone and forms the base of the Robles Formation (Fig. 11B). Although similar to Aguas Buenas, Briggs (1969) and Kazor and Rogers (1990) argued that the limestone horizons are separate, despite complex structural relations that obscure the stratigraphic relationships. Unfortunately, because of confusion in the


Southeast Puerto Rico
+ Torrecilla (Upper Albian)
○ Río Abajo (Upper Albian)
□ Pitahira (Upper Albian)
Hi–CA & SHO
CA
PIA/IAT
(Jolly et al., 2008)
B
BA/A
D/R
E
Eastern Puerto Rico
+ Lower Fajardo (Upper Albian)
○ Figuera (Lower Albian)
□ Daguao (Lower Albian)
Jolly et al., 2008)
D
Southeast Puerto Rico
○ Fm A (Río Majada Group, Albian)
+ Fm J (Albian)
(Jolly et al., 2008)
C
U.S. Virgin Islands
○ Louisenhoj (Albian ?)
(Jolly et al., 2008)
B
U.S. Virgin Islands
□ Water Island (Barremian)
(Jolly & Lidiak, 2006)
A
Th
Co
Benbow Inlier, Jamaica
+ upper Devils Racecourse (Hauterivian to Aptian)
□ lower Devils Racecourse (Hauterivian to Aptian)
(Hastie el al., 2009)
J
Cuba
△ Téneme (Turonian to E Coniacian?)
+ Boninite, northern ophiolites
○ IAT: Sagua LaChica (Tithonian); Colombia (Albian)
□ Quibijan (no age data)
◇ Los Pasos (Early Cretaceous)
(Proenza et al., 2006)
(Kerr et al., 1999)
(Diaz deVillalvilla et al., 2003)
I
Northern Hispaniola
+ Los Cãnos (Aptian-Early Albian)
○ upper Cacheal (Aptian-Early Albian)
□ lower Cacheal (Aptian-Early Albian)
(Escuder Viruete et al., 2014)
H
Central & Eastern Cordillera, Hispaniola
+ lower Tireo (probably Aptian)
Los Ranchos (Aptian to Albian)
⊞ Bayaguana district
□ Sys Min Project
(Escuder Viruete et al., 2007, 2006)
(León et al., 2013)
G
Central Cordillera, Hispaniola
+ Río Verde (Aptian to Early Albian)
□ Maimon (Aptian and older)
(Escuder Viruete et al., 2010)
(Torró et al., 2015c)
F

identification and mapping of the Río Maton and Aguas Buenas Limestones, this issue has never been resolved, and the question of correlation remains open (Krushensky and Schellekens, 2001). In any case, by ca. 100 Ma, unconformable conglomerate, turbiditic sandstone and siltstone, and submarine basaltic lava began to accumulate in a major basin developed upon the earlier flows and breccia overlain locally by Albian reefal carbonate.

Volcanic rocks of PIA/IAT affinity are not exposed in western Puerto Rico. The oldest exposed rocks are part of the Bermeja complex (Mattson, 1960; Mattson and Pessagno, 1979; Schellekens, 1998a, 1998b; Marchesi et al., 2011; Lao-Davila, 2014; Lao-Davila and Anderson, 2009; Lao-Davila et al., 2012). This complex consists of allochthonous serpentinized peridotites that were emplaced onto a sequence of Jurassic to mid-Cretaceous (Santonian) pelagic chert (Marquita Chert). The peridotite contains abundant rafts and blocks of normal mid-ocean-ridge basalt (N-MORB)–type amphibolites (Las Palmas Amphibolite) and tholeiite and associated trondhjemite fractionates (Lower Cajul MORB), also of N-MORB affinity (Jolly et al., 2007; Lidiak et al., 2011). These rocks are overlain subsequently by a younger sequence of Caribbean large igneous province–like plateau basaltic and andesitic lava flows (Upper Cajul Formation) that crop out in two distinct geographic areas; one outcrop has enriched (E) MORB geochemical characteristics, and the other has oceanic-island basalt (OIB) geochemical characteristics. Overlying these rocks are Late Cretaceous to Eocene (85–45 Ma) calc-alkaline island-arc strata.

Hispaniola

Los Ranchos Formation extends for 140 km in the Cordillera Oriental and is separated by a major fault from the Maimón and Amina Formations of the Cordillera Central (Fig. 12A; Kesler et al., 1991a, 1991b; Lewis et al., 2000). To the north, Los Ranchos is covered by Los Haitises Limestone of Pliocene–Pleistocene age. Along its southern border, it is overlain by the Hatillo and Los Canos Limestones of Albian age. Both Bourdon (1985) and Lebron and Perfit (1994) reported that Los Ranchos units in the western part of the belt differ from those in the eastern part. We thus restrict our discussion on the geochemistry to those units in the eastern part, even though similar gold mineralization in both areas supports the view that both units should be correlated (Kesler et al., 2005).

Los Ranchos Formation in the eastern area sampled by the European Sysmin Project consists of a >3-km-thick sequence of bimodal volcanic and volcaniclastic rocks intruded by tonalitic batholiths and dikes. Three stratigraphic units are recognized (Escuder Viruete et al., 2006), a lower unit of boninitic basaltic and andesitic flows, a middle unit of altered dacite to rhyolite flows, and an upper basaltic unit.

Los Ranchos Formation formed between ca. 118 and 111 Ma, as shown by U-Pb zircon interpreted ages (Kesler et al., 2005; Escuder Viruete et al., 2006). Re-Os dating of molybdenite from Puerto Viejo records comparable ages of 112.1–111.5 Ma (Nelson et al., 2015). In the Bayaguana Los Ranchos area (Fig. 12A), quartz diorite plutons include the Cotui stock, which yields an interpreted U-Pb age from zircon of ca. 112 Ma. The Cotui stock extends southward into the Zambrana Valley, which is thought to be underlain largely by coeval intrusive rock but yields a somewhat older U-Pb interpreted age of 115.5 ± 0.3 Ma (Escuder Viruete et al., 2006).

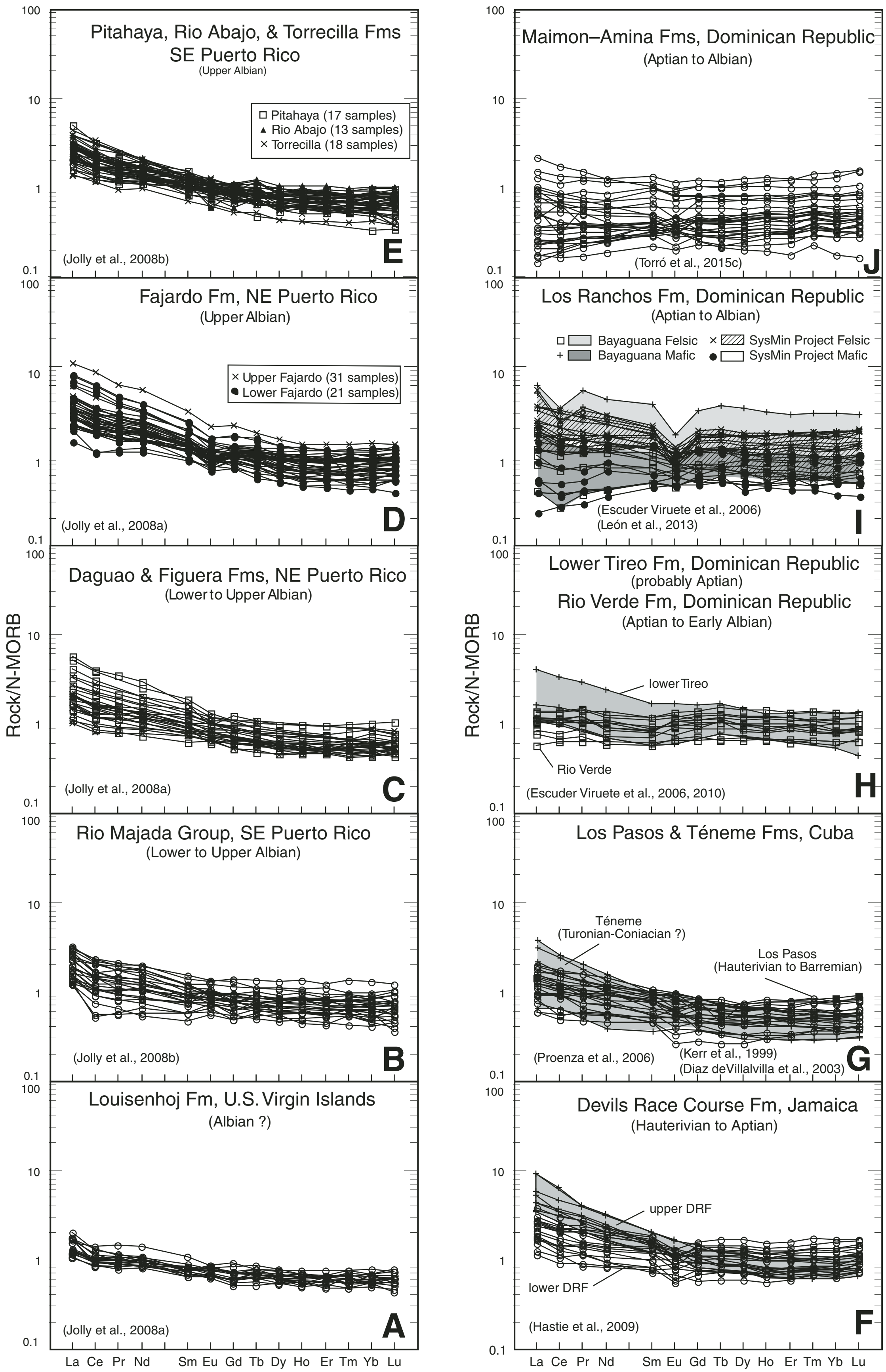
Los Ranchos belt is separated from the northwest-trending Maimón-Amina belt by the Maimón thrust, which forms the eastern boundary of the Maimón Formation (Bowin, 1966). The Maimón Formation crops out in the Cordillera Central and extends for a distance of ~73 km along a NE-trending belt (Fig. 12A). The formation is in fault contact with the Loma Caribe Peridotite and the Peralvillo Sur Formation to the southwest and with Los Ranchos Formation to the northeast (Lewis et al., 2002). The Maimón Formation consists of low-grade metamorphosed and variably deformed pre-Albian bimodal volcanic and volcaniclastic rocks in which basaltic protoliths predominate over intermediate and felsic compositions (Torró et al., 2015b, 2015c).

Geochemically, the basaltic rocks of the Maimón Formation range from low-Ti tholeiite with boninitic affinity to typical oceanic-island-arc tholeiite (PIA/IAT; Lewis et al., 2000; Escuder Viruete et al., 2007c; Nelson et al., 2011; Torró et al., 2015b, 2015c). Felsic rocks are composed of quartz-feldspar tuff and porphyry that exhibit similar depleted trace-element signatures, indicating a common source (Nelson et al., 2011). The presence of depleted basalts with boninitic affinities in oceanic-island-arc tholeiites is also a characteristic feature of the Izu-Bonin-Mariana forearc in the eastern Pacific (Bloomer et al., 1995; Reagan et al., 2010; Ishizuka et al., 2014). This observation led Lewis et al. (2000) to suggest that the Maimón Formation and associated volcanogenic massive sulfide deposits formed in a nascent primitive island arc, probably in a forearc basin. A modern analog has been proposed for the Izu-Bonin-Mariana forearc by Ishizuka et al. (2014), in which ocean crust was generated in the initial stages of subduction and the earliest stage of island-arc formation.

The age of the Maimón Formation is uncertain, as the formation is fault bounded, and attempts to date the unit by isotopic methods have not been successful. However, Pb isotope ratios ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$) are extremely low (Horan, 1995), suggesting that it is one of the oldest units in the Greater Antilles (Lewis et al., 2000; Escuder Viruete et al., 2006; Nelson et al., 2011).

A major shear zone, called La Meseta, separates Maimón and related formations to the north and northeast from strata

Figure 7. Plots of Th vs. Co abundances in primitive island arc/island-arc tholeiite (PIA/IAT) volcanic arc rocks of the Greater Antilles, which show similar geochemical characteristics. Data for Los Ranchos Formation: Bayaguana district—León et al. (2013); European Sys Min Project modified from Escuder Viruete et al. (2006) with additions from León et al. (2013). Th-Co discrimination boundaries: Hastie et al. (2007); Pearce et al. (2014). Abbreviations: B—basalt; BA/A—basaltic andesite and andesite; D/R—dacite and rhyolite; CA—calc-alkaline; SHO—shoshonitic. Data sources are listed in the figure.


Pitahaya, Rio Abajo, & Torrecilla Fms
SE Puerto Rico
(Upper Albian)
Pitahaya (17 samples)
Rio Abajo (13 samples)
Torrecilla (18 samples)
(Jolly et al., 2008b)
E
Fajardo Fm, NE Puerto Rico
(Upper Albian)
Upper Fajardo (31 samples)
Lower Fajardo (21 samples)
(Jolly et al., 2008a)
D
Daguao & Figuera Fms, NE Puerto Rico
(Lower to Upper Albian)
(Jolly et al., 2008a)
C
Rio Majada Group, SE Puerto Rico
(Lower to Upper Albian)
(Jolly et al., 2008b)
B
Louisenhoj Fm, U.S. Virgin Islands
(Albian ?)
(Jolly et al., 2008a)
A
Maimon–Amina Fms, Dominican Republic
(Aptian to Albian)
(Torró et al., 2015c)
J
Los Ranchos Fm, Dominican Republic
(Aptian to Albian)
Bayaguana Felsic
Bayaguana Mafic
SysMin Project Felsic
SysMin Project Mafic
(Escuder Viruete et al., 2006)
(León et al., 2013)
I
Lower Tireo Fm, Dominican Republic
(probably Aptian)
Rio Verde Fm, Dominican Republic
(Aptian to Early Albian)
lower Tireo
Rio Verde
(Escuder Viruete et al., 2006, 2010)
H
Los Pasos & Téneme Fms, Cuba
Téneme
(Turonian-Coniacian ?)
Los Pasos
(Hauterivian to Barremian)
(Proenza et al., 2006)
(Kerr et al., 1999)
(Diaz deVillalvilla et al., 2003)
G
Devils Race Course Fm, Jamaica
(Hauterivian to Aptian)
upper DRF
lower DRF
(Hastie et al., 2009)
F
Rock/N-MORB
100
10
1
0.1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

comprising the Tireo Group, which extends as a continuous belt from the Haitian border into the Cordillera Central (Fig. 12A). The Tireo Group consists of two main volcanogenic units. The lower sequence is distinguished by basaltic flows among andesitic vitric-lithic tuff, volcanic breccia, clastic sedimentary rocks, and limestone that constitute an island-arc tholeiitic suite; the upper unit consists of high-Mg andesite, dacite to rhyolite flows, tuff and breccia, Nb-enriched basalt, and intrusive dikes and domes of rhyolite (Lewis et al., 1991; Escuder Viruete et al., 2007a).

The Tireo Group records an important change in composition from a lower island-arc suite rich in tholeiite to an upper unit characterized by low-K calc-alkaline basalt and andesite. The lower tholeiitic basalt-andesite suite has geochemical characteristics that strongly resemble Los Ranchos Formation geochemistry (Escuder Viruete et al., 2007a). Additional indications of correlation are sedimentary interbeds with fossil ages as old as late Aptian and limestone formations (Constanza and El Convento) that cap the tholeiitic rocks and contain Turonian fossils, which limit the formation of lower Tireo Group units to >95 Ma. The stratigraphic relations are compatible with fossil and geochronologic (U-Pb, $^{40}Ar/^{39}Ar$) data on the Tireo Group indicating that magmatism occurred in the lower sequence before ca. 100 Ma.

The late Aptian–early Albian (120–110 Ma) Rio Verde complex (Escuder Viruete et al., 2010) crops out along strike and mainly southeast of the Loma Caribe serpentinized peridotite in central Hispaniola. It consists of variably deformed mafic igneous and meta-igneous rocks with a volcanic arc signature and subordinate sedimentary rocks. Felsic volcanic rocks are absent. The Rio Verde is in part coeval with the nearby Los Ranchos, Amina, and Maimón Formations. The $^{40}Ar/^{39}Ar$ plateau dates of 118–110 Ma on Rio Verde amphibolite correspond to similar dates from the felsic volcanics of Los Ranchos Formation units (Kesler et al., 2005; Escuder Viruete et al., 2007a; Nelson et al., 2011). Compared to the Los Ranchos, Amina, and Maimón Formations, the Rio Verde displays only a weak subduction-related chemical signature, implying that it may have evolved in a rifted arc or backarc basin setting (Escuder Viruete et al., 2010).

Cuba

Cuba consists of a wide variety of Jurassic, Cretaceous, and Early Tertiary orogenic rocks (Fig. 13), and it is one of the most complex regions in the entire Caribbean (Lewis and Draper, 1990; Iturralde-Vinent, 1994, 1996c). The island consists essentially of two separate structural provinces, a complex fold belt of Mesozoic and Early Tertiary continental and oceanic units and a younger, only slightly deformed late Eocene to Holocene sedimentary sequence that unconformably overlies the fold belt (Iturralde-Vinent, 1994).

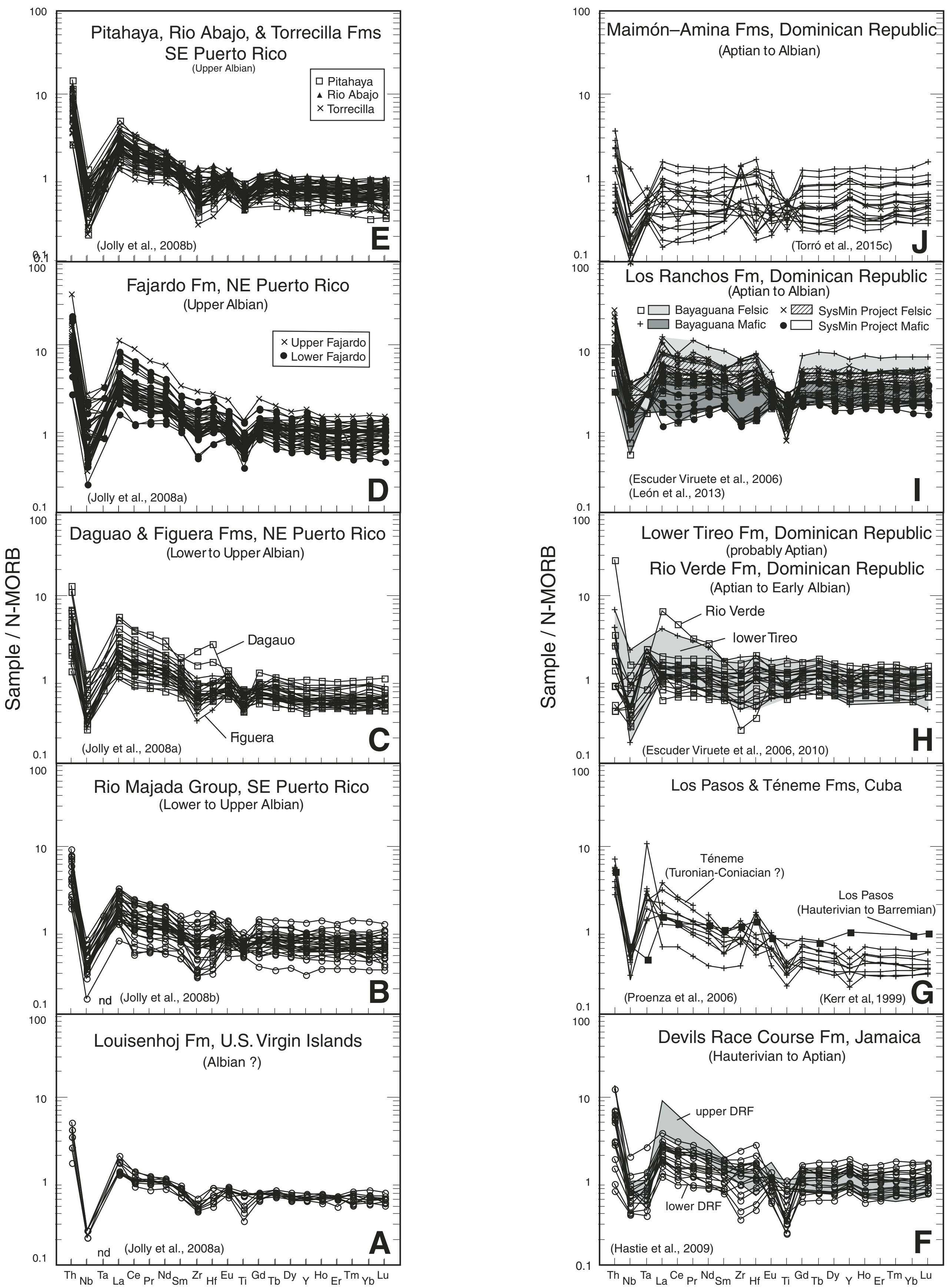
Early Cretaceous volcanism is recorded mainly by volcanic rocks of Los Pasos Formation of central Cuba (Fig. 14A; Diaz de Villalvilla et al., 1994, 2003; Diaz de Villalvilla, 1997; Iturralde-Vinent, 1996b, 1998; Blein et al., 2003). Los Pasos Formation geochemistry is very similar to the Maimón Formation of the Cordillera Central of Hispaniola in that both units are bimodal, both have primitive Pb isotopic signatures and similar IAT/PIA trace-element compositions, and both contain volcanic massive sulfide deposits.

The age of the Los Pasos Formation and probably the nearby, similar, Porvenir is considered Hauterivian?–Barremian on the basis of the biostratigraphic age of the Mataguá Formation that overlies it (Garcia-Delgado et al., 1998). Interpreted ages from U-Pb isotope ratios in magmatic zircons from an unfoliated granodiorite intruding the Los Pasos Formation yield a concordant intrusive age of 125 Ma (Rojas-Agramonte et al., 2011). The crosscutting pluton and resemblance to geochemically similar, bimodal rocks from Early Cretaceous volcanic units on other islands of the Greater Antilles constrain its age. Nearby orthogneisses yield interpreted ages from zircon between ca. 133 and 112 Ma (Rojas-Agramonte et al., 2011), including a trondhjemitic orthogneiss from the Jicaya River that represents the oldest phase of granitoid magmatism in this area and the entire Caribbean (Antillean) region (Fig. 14A).

The Early Cretaceous Los Pasos Formation is the oldest unit in the Greater Antilles of Cuba (Diaz de Villalvilla et al., 1994, 2003; Kerr et al., 1999; Blein et al., 2003; Rojas-Agramonte et al., 2011). The Los Pasos Formation forms the southern limb of a synformal structure (Iturralde-Vinent, 1998). To the south, it is in contact with the 89–83 Ma Manicaragua Batholith (Rojas-Agramonte et al., 2011). To the north, the formation is covered by arc-related sequences of the Aptian–Albian Mataguá Formation. Rocks of the Los Pasos Formation are mainly of volcanic origin, consisting of felsic dacite-rhyolite composition with lesser volumes of interlayered basalt, basaltic tuff, and andesite.

The northern ophiolite belt of east-central Cuba (Fig. 14B) consists of a mélange containing blocks of eclogite, garnet-amphibolite, amphibolite, blueschist, greenschist, quartzite, metapelite, antigorite, and various types of intrusive rocks that occur as blocks or intrusive gabbro and diabase of the ophiolitic sequence. Within the mélange, small- to medium-size linear bodies, crudely concordant with the internal structure, and dikes crop out. These rocks consist of diorite, quartz diorite, tonalite, and granodiorite. Interpreted zircon ages of the igneous rocks that fall within the interval between 86 and 72 Ma demonstrate the presence of Late Cretaceous magmatic rocks intrusive into the older, accretionary prism (Rojas-Agramonte et al., 2010). An eclogite block yields Ar-Ar ages (amphibole and phengite) ranging from 123 to 103 Ma and an Rb-Sr isochron age (phengite–omphacite–whole rock) of 118 Ma (Schneider, 2000; see also Garcia-Casco et al., 2002). These authors suggested that the eclogite formed

Figure 8. Plots of normalized rare earth elements (REE) compositions from Early Cretaceous PIA/IAT volcanic arc rocks, Greater Antilles. Data for Los Ranchos Formation: Bayaguana district—León et al. (2013); European Sys Min Project modified from Escuder Viruete et al. (2006) with additions from León et al. (2013). Normalizing factors are from Sun and McDonough (1989). Data sources are listed in the figure. DRF—Devils Race Course Formation.


Sample / N-MORB
Pitahaya, Rio Abajo, & Torrecilla Fms
SE Puerto Rico
(Upper Albian)
Pitahaya
Rio Abajo
Torrecilla
(Jolly et al., 2008b)
E
Fajardo Fm, NE Puerto Rico
(Upper Albian)
Upper Fajardo
Lower Fajardo
(Jolly et al., 2008a)
D
Daguao & Figuera Fms, NE Puerto Rico
(Lower to Upper Albian)
Dagauo
Figuera
(Jolly et al., 2008a)
C
Rio Majada Group, SE Puerto Rico
(Lower to Upper Albian)
nd
(Jolly et al., 2008b)
B
Louisenhoj Fm, U.S. Virgin Islands
(Albian ?)
nd
(Jolly et al., 2008a)
A
Maimón–Amina Fms, Dominican Republic
(Aptian to Albian)
(Torró et al., 2015c)
J
Los Ranchos Fm, Dominican Republic
(Aptian to Albian)
Bayaguana Felsic
Bayaguana Mafic
SysMin Project Felsic
SysMin Project Mafic
(Escuder Viruete et al., 2006)
(León et al., 2013)
I
Lower Tireo Fm, Dominican Republic
(probably Aptian)
Rio Verde Fm, Dominican Republic
(Aptian to Early Albian)
Rio Verde
lower Tireo
(Escuder Viruete et al., 2006, 2010)
H
Los Pasos & Téneme Fms, Cuba
Téneme
(Turonian-Coniacian ?)
Los Pasos
(Hauterivian to Barremian)
(Proenza et al., 2006)
(Kerr et al, 1999)
G
Devils Race Course Fm, Jamaica
(Hauterivian to Aptian)
upper DRF
lower DRF
(Hastie et al., 2009)
F
100
10
1
0.1
Th Nb Ta La Ce Pr Nd Sm Zr Hf Eu Ti Gd Tb Dy Y Ho Er Tm Yb Lu

during Early Cretaceous subduction and was later incorporated into a mélange, which was exhumed rapidly during Aptian–Albian times.

PIA/IAT arc rocks are also present as clasts in the pre-Camujiro sedimentary sequence of the Camaguey area of east-central Cuba (Figs. 5 and 15). The clasts unconformably overlie the pre-Camujiro section beneath basal units of Albian age.

Jamaica

In Jamaica, the Devils Race Course Formation is a Hauterivian to Aptian (136–122 Ma) unit, based upon ages from fossils (Figs. 1 and 16; Hastie et al., 2009, and references on paleontology therein). The lower part of the formation is composed of basaltic andesite, dacite, and rhyolite, with negative Nb and Ti anomalies on N-MORB diagrams (Hastie et al., 2009), suggestive of an island-arc tholeiite (PIA/IAT) composition.

Bonaire

In the ABC islands (Aruba, Bonaire, Curaçao) of the Netherlands Antilles (Fig. 1), van der Lelij et al. (2010) and Wright and Wyld (2011), who studied the volcanic and plutonic sections, produced geochronologic information that provides new insight into the evolution of the magmatic units. They demonstrated that each of these islands records a different episode of Caribbean geologic history. Bonaire consists of island arc–related Early to Late Cretaceous volcanic and volcaniclastic strata cut by shallow arc-related plutons (Wright and Wyld, 2011). Thick, mafic volcanic units of Aruba (Aruba Lava Formation) and Curaçao (Curaçao Lava Formation) are interpreted to represent exposures of the Caribbean-Colombian oceanic plateau (Beets et al., 1984; Kerr et al., 1996a; White et al., 1999). These rocks, which are discussed later herein, are intruded by 89–86 Ma arc-related plutons and dikes (van der Lelij et al., 2010; Wright and Wyld, 2011), reflecting Late Cretaceous magmatism.

The main volcanogenic unit on Bonaire is the Washikemba Group, which is chemically related to the PIA/IAT series (Beets et al., 1984). Recent work, however, recognized the presence of two units separated by a NW-trending fault: (1) bimodal intermediate to felsic volcanogenic and hypabyssal rocks of the Washikemba Group, and (2) apparently underlying argillite, conglomerate, and chert comprising the Matijs Group (Wright and Wyld, 2011). Both units are intruded by shallow plutons. Both groups display relatively flat REE patterns, and negative Nb, Ta, and Ti anomalies if plotted against chondrite or primitive mantle (Beets et al., 1984; Thompson et al., 2004; Wright and Wyld, 2011), indicative of a primitive arc setting.

Fossils from pelagic sediments in the lower Washikemba Group have been interpreted as middle to late Albian (Beets et al., 1977). Two zircon samples from the Washikemba rocks yielded U-Pb ages of 98.2 Ma for a tuff and 94.6 Ma for a rhyodacite block (Wright and Wyld, 2011). Collectively, the Washikemba Group thus may have accumulated over a period from the mid- or late Albian to Cenomanian time. The underlying argillite within the Matijs Group is intruded by diabase stocks, one of which yielded a U-Pb age of 111.6 Ma, based upon preliminary in situ secondary ion mass spectrometry (SIMS) dating of seven individual microbaddeleyite grains (Humphrey, 2010). The argillite unit is therefore Albian or older based upon microbaddeleyite geochronology.

Tobago

Mesozoic island-arc rocks on the island of Tobago (Fig. 1) may be divided into several west-trending lithologic belts, which include the North Coast Schist, a mainly meta-igneous sequence of mafic and ultramafic rocks, and a younger mafic intermediate Tobago Volcanic Group (Maxwell, 1948; Snoke et al., 2001a, 2001b; Neill et al., 2012). The North Coast Schist consists of two mappable units: the Parlatuvier Formation, composed of mafic to intermediate tuff and breccia, and the Mount Dillon Formation, composed of silicified tuff and tuff breccia. Zircon from basaltic andesite in the Parlatuvier Formation yielded a U-Pb isotope dilution–thermal ionization mass spectrometry (ID-TIMS) date of 128.66 Ma (Barremian) for the unit (Neill et al., 2012). An ammonite-radiolarian assemblage in the upper part of the Tobago Volcanic Group indicated an Albian age (ca. 105 Ma; Snoke et al., 1990; Snoke and Noble, 2001).

Trace elements indicate that both the Parlatuvier and Mount Dillon Formations consist almost entirely of PIA/IAT compositions (Neill et al., 2012). For example, on Th-Co discrimination diagrams (Hastie et al., 2007), both the Parlatuvier basalt to basaltic andesite and the Mount Dillon rhyolite plot in the tholeiite field. Furthermore, both display essentially flat REE patterns on chondrite-normalized diagrams and negative, although variable, Nb, Ta, and Ti spikes on N-MORB–normalized diagrams.

Lesser Antilles

The small island of La Désirade lies ~10 km east of Guadeloupe and contains the only exposed Jurassic volcanic and plutonic rocks in the Lesser Antilles (Fig. 1). Trondhjemite and mafic volcanic rocks similar to those found on La Désirade have also been dredged from a nearby steep submarine escarpment (Johnson et al., 1971; Fink, 1972; Bouysse et al., 1983).

The geologic units exposed on La Désirade consist of a suite of Mesozoic igneous rocks capped by Neogene limestone (Mattinson et al., 2008; Neill et al., 2010). The lower part of the suite contains mafic lava flows and pillow basalt interbedded with chert and limestone (NE mafic volcanic complex) overlain by felsic flows and breccia (NE felsic volcanic complex) intruded by

Figure 9. Plots of normalized incompatible trace-element compositions (ITE) from early Cretaceous primitive island arc/island-arc tholeiite (PIA/IAT) volcanic arc rocks, Greater Antilles. Data for Los Ranchos Formation: Bayaguana district—León et al. (2013); European Sys Min Project modified from Escuder Viruete et al. (2006) with additions from León et al. (2013). Normalizing factors are from Sun and McDonough (1989). Data sources are listed in the figure.

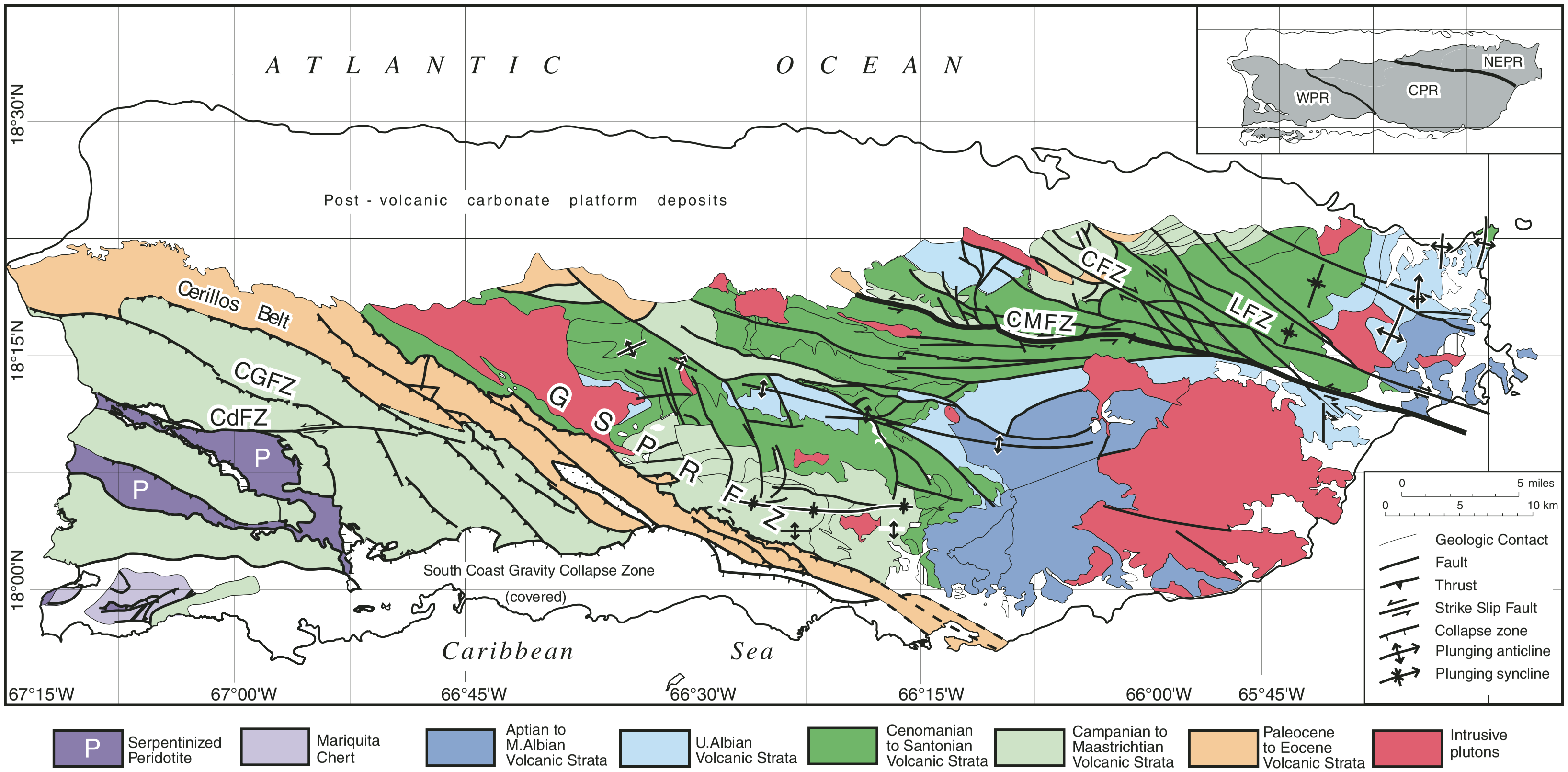


Figure 10. Generalized geologic map of Puerto Rico. Fault abbreviations: CMFZ—Cerro-Mula fault zone; CFZ—Carraizo fault zone; CGFZ—Cerro Goden fault zone; CdFZ—Cordilleran fault zone; GSPRFZ—Greater Southern Puerto Rican fault zone; LFZ—Leprocomio fault zone. Figure is adapted from Jolly et al. (1998b). WPR—western Puerto Rico; CPR—central Puerto Rico; NEPR—northeast Puerto Rico.

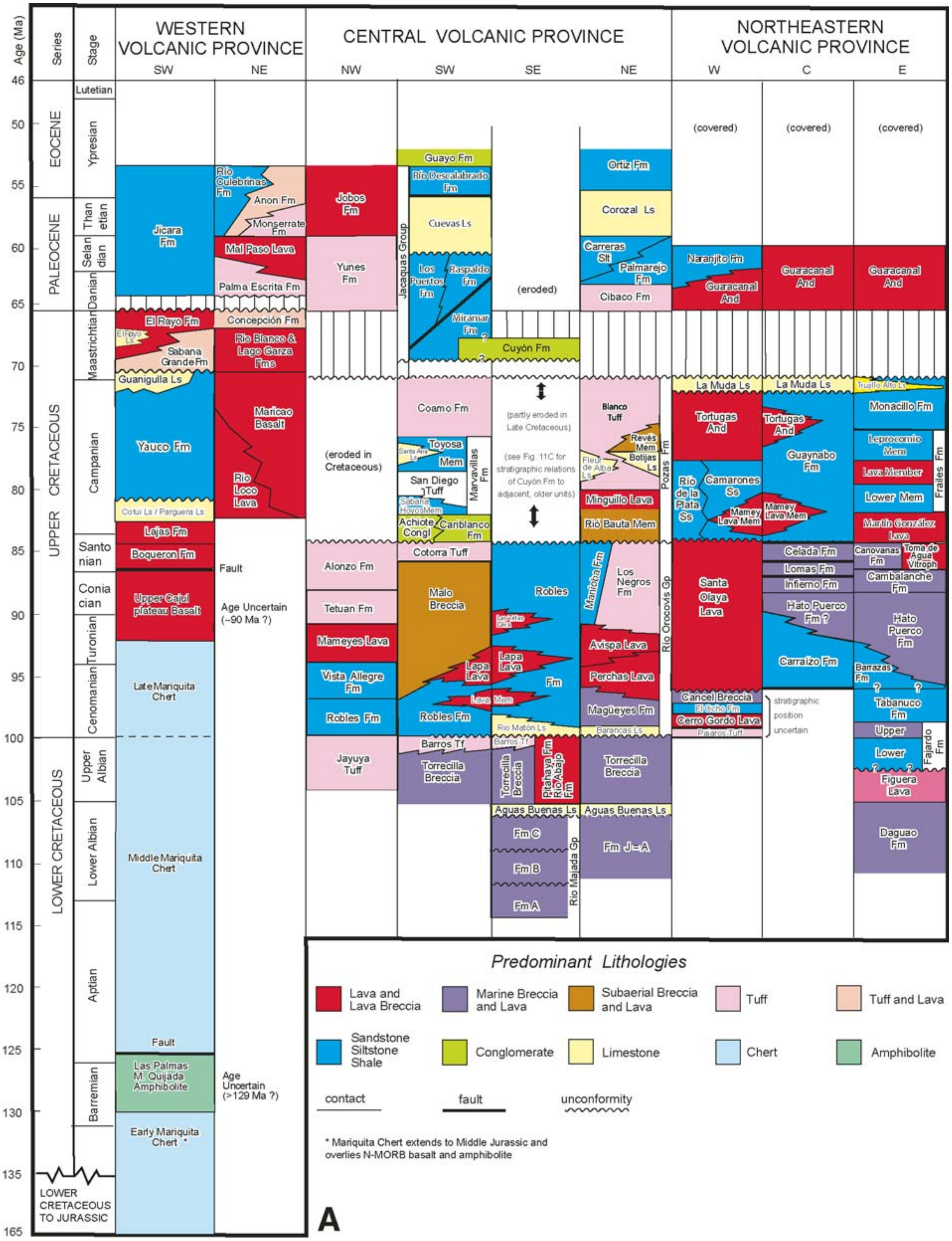


Figure 11 (*Continued on following page*). (A) Puerto Rico stratigraphic column, adapted from Jolly et al. (1998b). Age of the Guanigulla Limestone is from Santos (1999). Ls—Limestone; Slt—Siltstone; Fm—Formation; And—Andesite; Vitroph—Vitrophyre. N-MORB—normal mid-ocean-ridge basalt. (B) Interpretation of unconformities in Cayey Quadrangle, Puerto Rico, adapted from Berryhill and Glover (1960). (C) Interpretation of unconformities in south-central Puerto Rico, adapted from Glover (1971). Cg—Conglomerate.

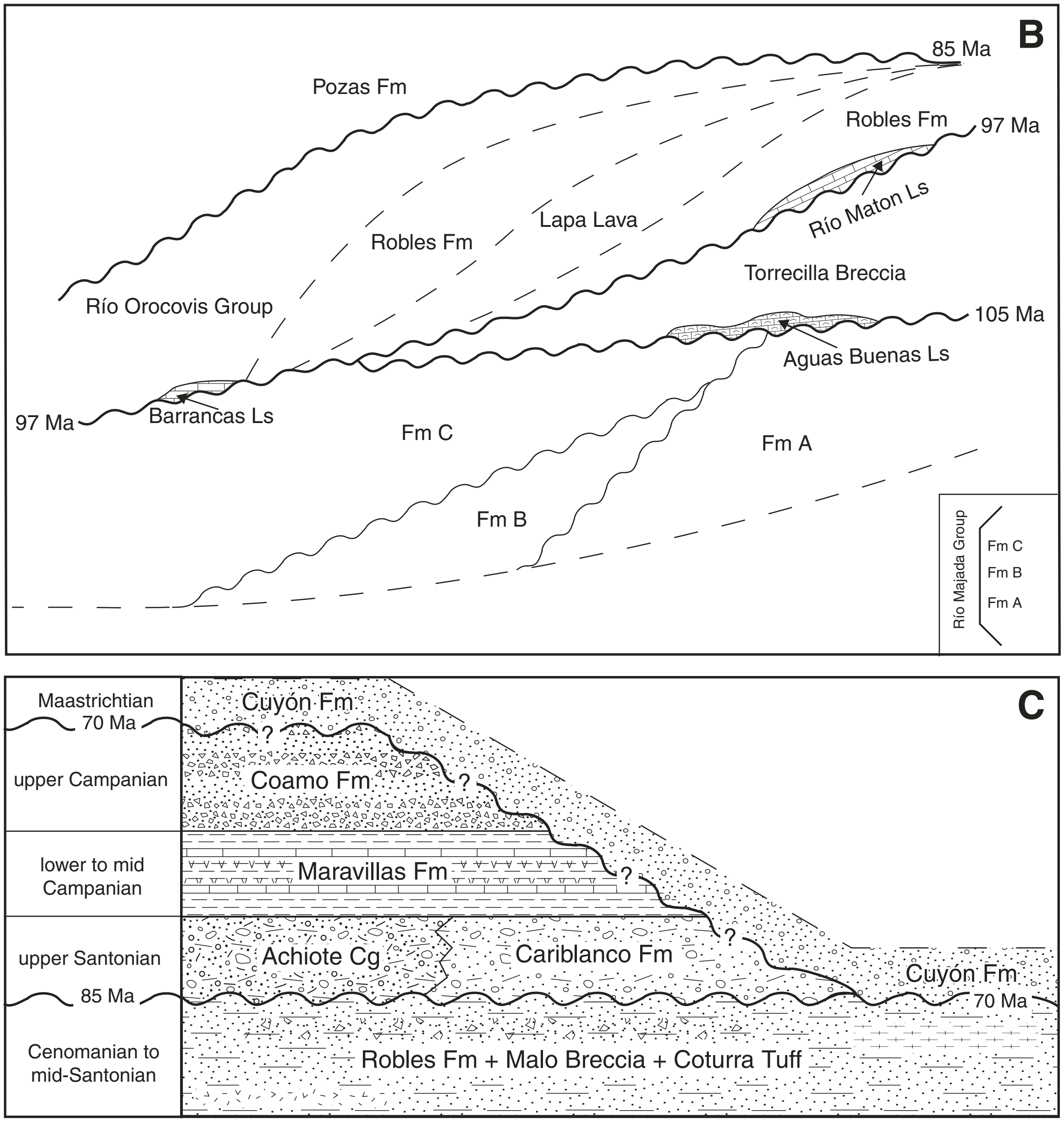


Figure 11 (*Continued*).

a trondhjemite pluton and intermediate to felsic dikes (SW felsic complex; Neill et al., 2010). The mafic complex consists of 300 m of the following units (from bottom up): (1) arc tholeiite (PIA/IAT) with a weak subduction component; (2) calc-alkaline and PIA/IAT rocks containing a slab-related component; and (3) PIA/IAT rocks with a minor subduction component (Neill et al., 2010). Chondrite and N-MORB elemental plots of units within the mafic complex, the felsic complex, trondhjemite pluton, and the dikes show mainly flat REE and incompatible-element patterns with only minor Nb, Ta, and Ti negative anomalies, indicative of a predominant PIA/IAT setting (Neill et al., 2010). The overlying felsic volcanics are similar to the mafic rocks in displaying similar REE and other incompatible-element patterns, but they apparently have not yet been dated by U-Pb methods.

Chert units interbedded with lava flows from both the NE mafic complex and the SW felsic complexes contain Kimmeridgian to Tithonian (ca. 153–145 Ma) radiolaria (Bouysse et al., 1983; Montgomery et al., 1992; Mattinson et al., 2008). These radiolaria, which represent the oldest biostratigraphic assemblage found in the Lesser Antilles, including similar radiolarian-bearing chert in Puerto Rico and the Dominican Republic, are of apparent Pacific origin (Montgomery et al., 1994a, 1994b;

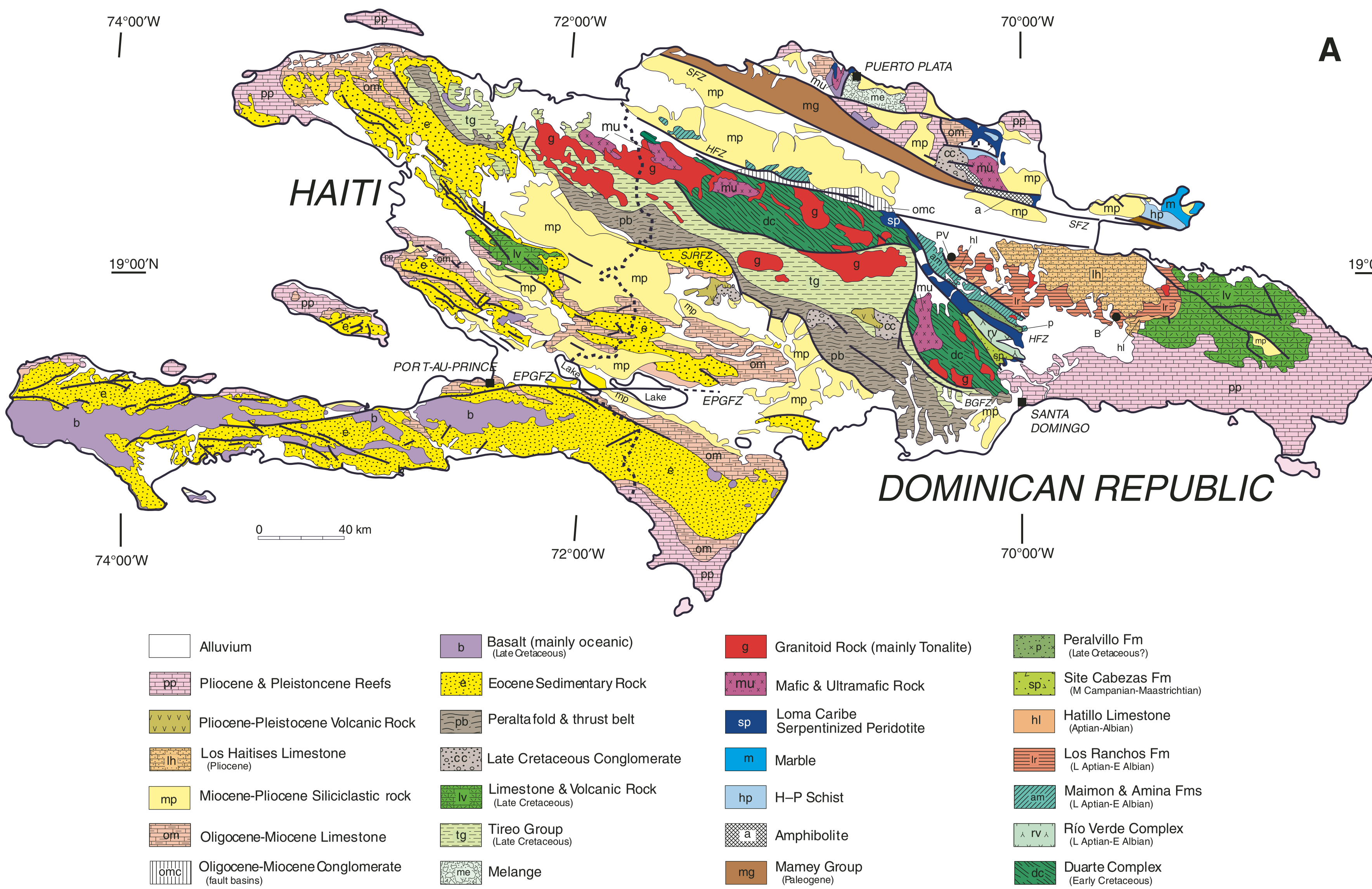


Figure 12 (*Continued on following page*). (A) Geologic map of Hispaniola, adapted and modified from Lewis and Draper (1990), Draper and Lewis (1991), and Escuder Viruete et al. (2007b), with additions from John Lewis (written commun., July 2015). Fault zone abbreviations: SFZ—Septentrional fault zone; HFZ—Hispaniola fault zone; BGFZ—Bonao–La Guácara fault zone; HVFZ—Hato Viejo fault zone; LMFZ—La Mesata fault zone; RBFZ—Río Baiguaque fault zone; SJRFZ—San Juan Restauración fault zone; EPGFZ—Enriquillo–Plantain Garden fault zone. Map districts: B—Bayaguana; PV—Pueblo Viejo. (B) Geologic map of the Cordillera Central, Hispaniola, adapted from Escuder Viruete et al. (2010).

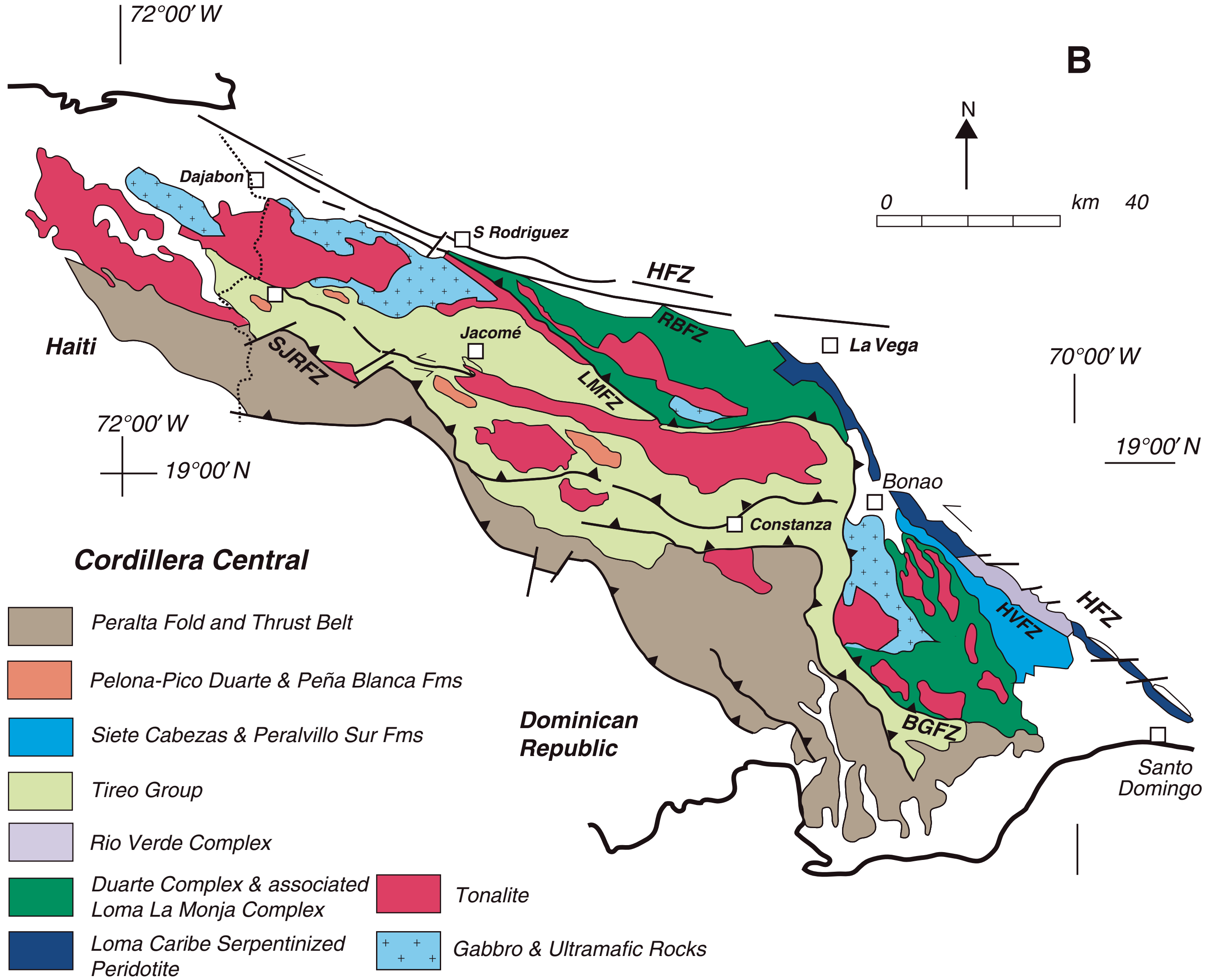


Figure 12 (*Continued*).

Montgomery and Kerr, 2009). This Jurassic age is in close agreement to a U-Pb date of 143.74 Ma on zircons separated from the trondhjemite pluton utilizing chemical abrasion–thermal ionization mass spectrometry (Mattinson et al., 2008).

In summary, the presence of PIA/IAT volcanics (including local boninitic rocks) and other primitive island-arc rocks suggests that the Water Island and Louisenhoj Formations of the Virgin Islands, the Rio Majada and Daguao-Figuera sequences of Puerto Rico, Los Ranchos, Amina, Maimón, Los Cános, El Cachear, and probably the lower Tireo Group formations in Hispaniola, and the lower Devils Race Course Formation in Jamaica formed in an Early Cretaceous nascent island arc. In addition, in Cuba, correlative rocks are present in the Early Cretaceous Los Pasos Formation, and possibly the pre-Camujiro sequence. Equivalent rocks are inferred to be present, based upon stratigraphic and chronologic relations among units, juxtaposed along faults, on the island of Bonaire. Volcanic rocks having PIA/IAT affinity also crop out on the island of Tobago (Barremian) and on La Désirade (Kimmeridgian) in the Lesser Antilles.

Late Cretaceous Magmatism (Ca. 95–70 Ma)

Puerto Rico

The change from Early Cretaceous PIA/IAT volcanism to mainly calc-alkaline volcanism during the Late Cretaceous is recorded in the rocks from the various islands of the Greater Antilles. The transition is best documented in Puerto Rico, where detailed USGS quadrangle mapping and abundant geochemical data are available (Jolly et al., 1998a, 1998b, 2001, 2002; Schellekens, 1998a; Lidiak et al., 2008). The oldest deposits, Aptian to

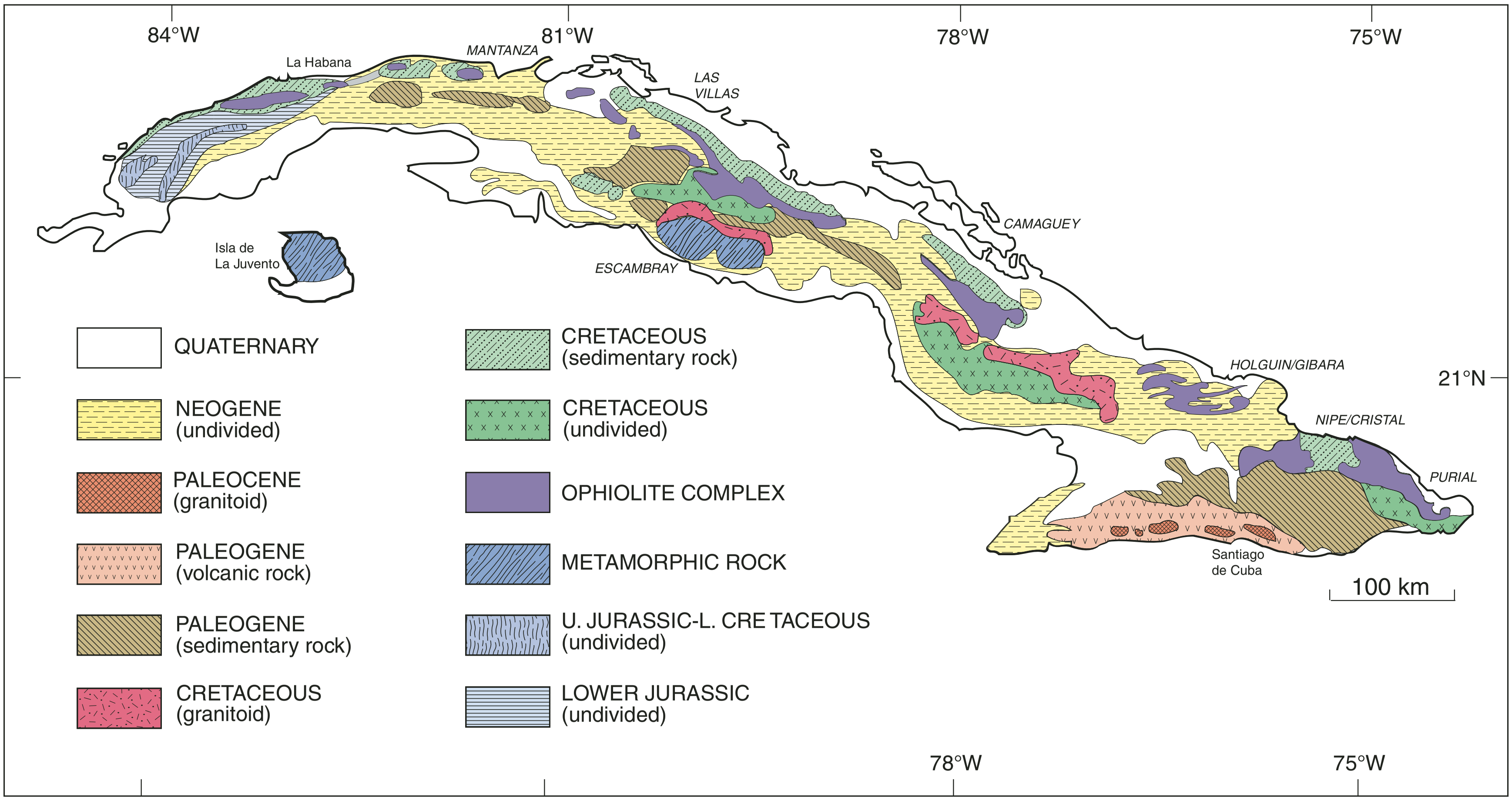
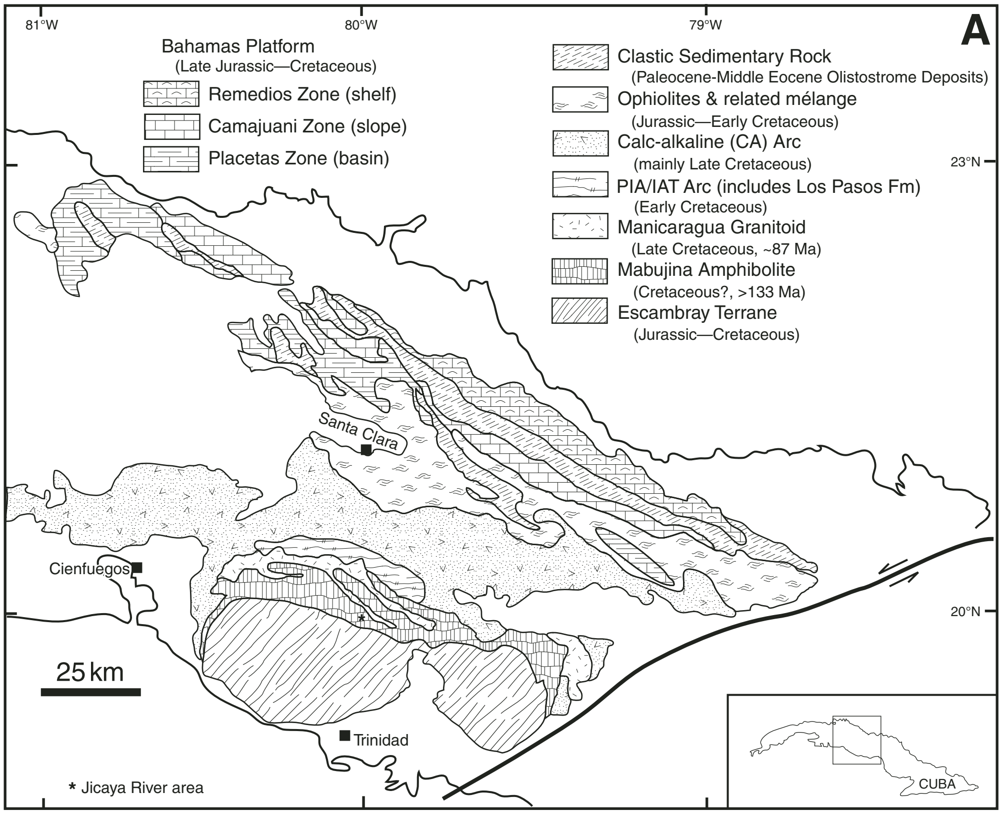


Figure 13. Geologic map of Cuba, adapted from Lewis and Draper (1990), who compiled the map from the following publications: Butterlin (1977); Case and Holcombe (1980); Ministerio de la Industria Básica, Cuba (1985).



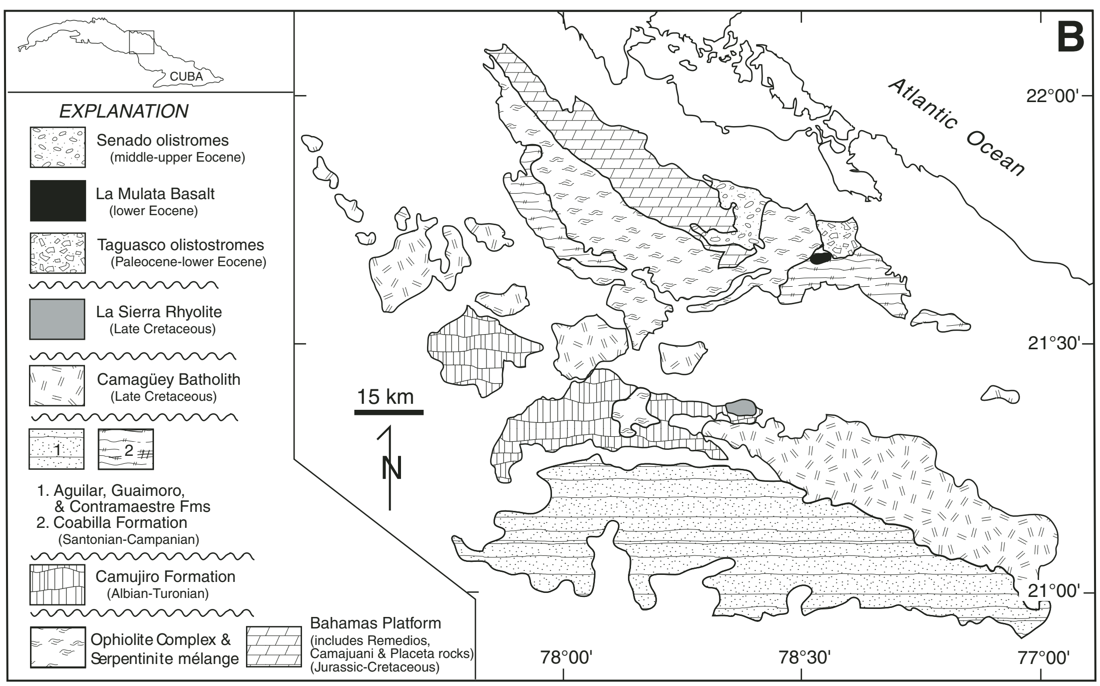


Figure 14. (A) Geologic map of central Cuba, adapted from Iturralde-Vinent (1996c), Garcia-Delgado (1998), and Rojas-Agramonte (2011). PIA/IAT—primitive island arc/island-arc tholeiite. (B) Geologic map of the Camagüey District, east-central Cuba, adapted from Hall et al. (2004) and Kesler et al. (2004).

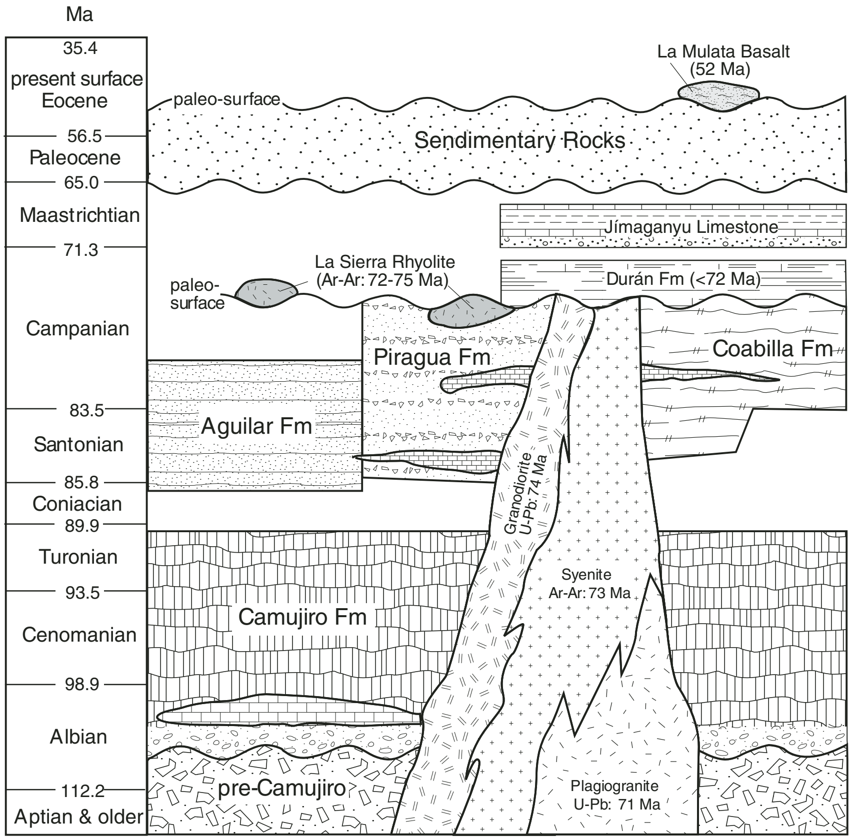


Figure 15. Schematic section showing apparent stratigraphic relationships of volcanic and sedimentary rock units in the Camagüey area, east-central Cuba, adapted and modified from Iturralde-Vinent (1996e) and Kesler et al. (2004).

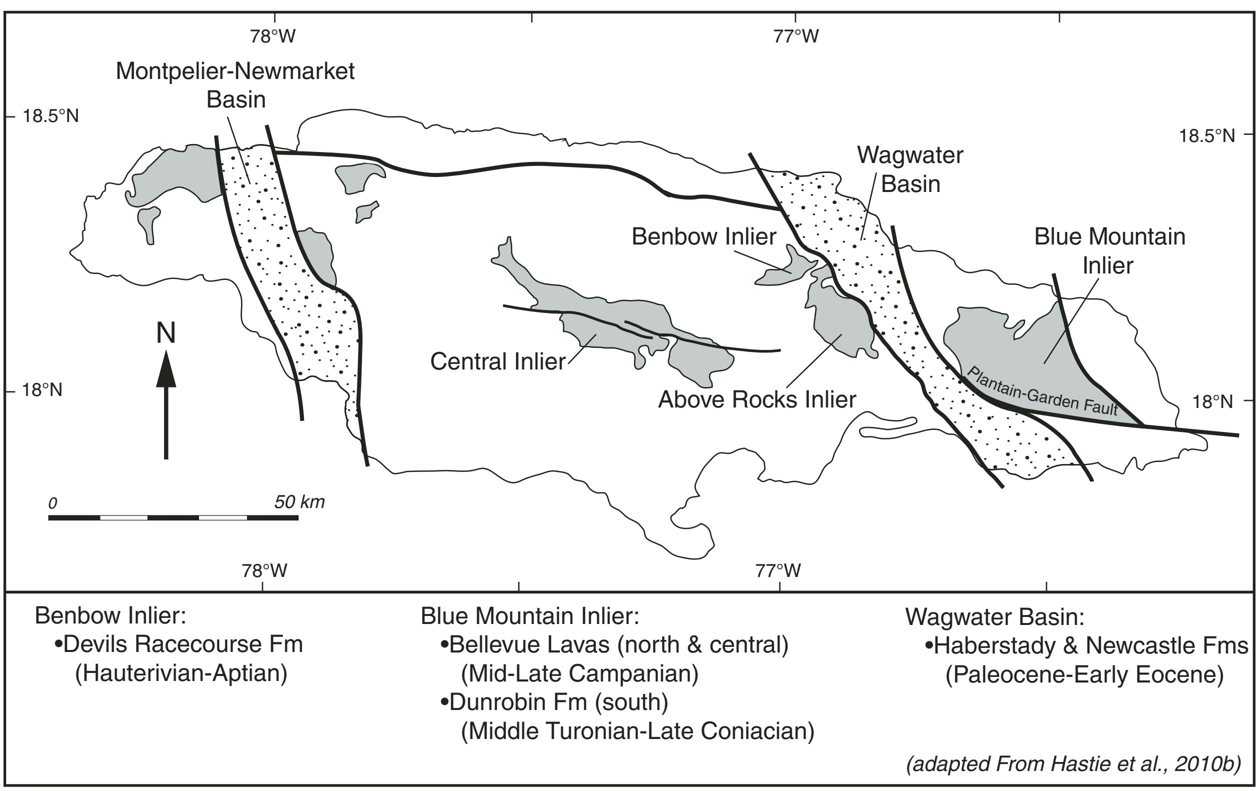


Figure 16. Generalized geologic map of Jamaica, adapted from Hastie et al. (2010b).

early Albian age, ca. 120–105 Ma, consist predominantly of PIA/IAT basalt and related volcanic rocks of the Río Majada Group of central Puerto Rico and the Daguao-Figuera sequence of northeast eastern Puerto Rico (Figs. 7C, 7D, 8B, 8C, 9B, and 9C).

The transition to mainly calc-alkaline volcanic rocks takes place in the late Albian Torrecilla-Pitahaya units of central Puerto Rico (Fig. 7E) and the lower Fajardo Formation of northeast eastern Puerto Rico (Figs. 7D). Overlying units of Cenomanian to Campanian age (Lapa Lava of Robles Formation, Avispa and Perchas Formations of Rio Orocovis Group, upper Fajardo Formation, Tortugas Andesite, and correlative strata of west-central Puerto Rico, i.e., Malo Breccia, Vista Alegre Formation, Mameyes Formation, Tétuan Formation) consist mainly of medium- to high-Th calc-alkaline basalt, basaltic andesite, andesite, and felsic derivatives (Figs. 17A, 17D, 17E–17F), which display elevated REE and other incompatible-element compositions (Figs. 18A, 18D, 18F–18H, 19A, 19D, 19F–19H). In northeast eastern Puerto Rico, during this 90–70 Ma time interval, the older units (Hato Puerco Tuff, Celada, Infierno, and Lomas Formations, Santa Olaya Lava) (Figs. 17A–C) contain both calc-alkaline and PIA/IAT compositions, whereas younger units such as the Tortugas Andesite (Fig. 17D) are entirely of calc-alkaline composition. The transition in Aptian–Albian time from geochemically primitive PIA/IAT compositions to the more-evolved calc-alkaline series was probably the result of variations in subduction-related components rather than a major reversal in the polarity of subduction, as evidenced by the absence of an extensive unconformity in the Puerto Rico–Virgin Islands region at this time interval and the fact that the transition occurs at slightly different times in different parts of the region.

As noted in the preceding paragraph, several of the Cenomanian to Campanian formations in central Puerto Rico (Lapa, Avispa, Perchas, Mameyes, Tétuan) have Th concentrations that lie along or near the calc-alkaline to high-calc-alkaline and shoshonitic boundary (Figs. 17E and 17F). The question arises as to whether any of these rocks are shoshonites (sensu stricto). Jolly (1971) previously referred to basalt and andesite of the Lapa Formation as shoshonite on the basis of high SiO_2. Although all of these Cenomanian to Campanian units have K_2O compositions high enough (4.7–7.9 wt%) to qualify as being shoshonitic, none of these Puerto Rican rocks has Th contents that approach continental-margin shoshonite. For example, shoshonite of the Aeolian arc (Ellam et al., 1988), the Aegean region (Pe-Piper and Piper, 1989; Pe-Piper et al., 2009), the Roman magmatic province (Conticelli et al., 2009), Somma-Vesuvius volcano (Di Renzo et al., 2007), and Stromboli volcano (Vezzoli et al., 2014) all have Th content predominantly greater than 10 ppm Th, with some approaching 50 ppm Th. In partial contrast, oceanic shoshonite from the Marianas (Sun and Stern, 2001) has Th contents of 2.2–14.9 ppm and partly overlaps the Puerto Rico rocks at lower Th compositions. These Puerto Rico rocks can thus more likely be classified as high-calc-alkaline rocks rather than shoshonite, but perhaps the issue should remain open until a more definitive evaluation can be made.

In western Puerto Rico (Fig. 20), island-arc volcanism commenced in Santonian time (ca. 85 Ma) and continued into the Eocene, with a marked hiatus near the end of the Cretaceous (Fig. 11A). As noted previously, these rocks lie with apparent unconformity on the older ultramafic complex. The Boqueron and Lajas Formations, the older units within this western arc sequence, display elevated incompatible-element concentrations together with shallow negative Nb anomalies, slightly positive Zr-Hf anomalies, and high Nb/Zr ratios, all of which are indicative of enriched source compositions (Jolly et al., 2007; Lidiak et al., 2011). Geochemical data from these lavas cluster near the boundary between the tholeiite and calc-alkaline fields of Miyashiro (1974) and have been characterized as being high-Mg andesite, hornblende basalt and andesite, and high-Fe augite basalt (Jolly et al., 2007). Th concentrations indicate that all of these rocks have distinct calc-alkaline compositions (Fig. 21). Furthermore, they display elevated LREE (5–10 times N-MORB) and essentially flat heavy (H) REE patterns on normalized plots (Fig. 22) and depleted concentrations of Nb, Ta, and Ti and to a lesser extent Zr and Hf on standard incompatible-element diagrams (Fig. 23), typical of subduction-related sequences (Jolly et al., 2007; Lidiak et al., 2011). Most Late Cretaceous rocks have only slightly less primitive initial Nd isotope compositions than PIA/IAT, although they are enriched in LREEs compared to the Early Cretaceous rocks (Frost et al., 1998; Jolly et al., 2008a).

Virgin Islands

The Virgin Islands are similar to Puerto Rico in displaying a transition from PIA/IAT to calc-alkaline volcanism (Figs. 7B and 17H). As noted above, the Water Island Formation of PIA/IAT affinity is conformably overlain by the Louisenhoj Formation, which is overlain, in turn, by the Outer Brass Limestone and the succeeding conformable Tutu Formation (Rankin, 2002; Jolly et al., 2006). The Tutu Formation consists of volcanic wacke, shale, conglomerate, siltstone, and minor limestone, basalt, and andesite, or their metamorphic equivalents. The Tutu occupies the core of the east-trending Narrows syncline, with the north-dipping Water Island–Louisenhoj–Outer Brass strata on the south flank. Donnelly (1959) and Helsley (1960) originally mapped the south-dipping strata on Hans Lollik Island (Fig. 5) as being of Eocene age, overturned, and part of a large homocline that continues into the British Virgin Islands. However, Rankin (2002) found that the strata on Hans Lollik Island are upright, and their position along the north side of the Narrows syncline implies that they are not of Eocene age but are instead probably part of the Cretaceous Louisenhoj Formation.

The Tutu Formation is of apparent late Santonian to Campanian (ca. 85–72 Ma) age (Rankin, 2002). It has distinct calc-alkaline geochemistry (Jolly et al., 2006) with slightly elevated LREE patterns (2–10 times N-MORB) and flat HREE patterns, elevated Th concentrations, and prominent negative Nb spikes on typical incompatible-element diagrams.

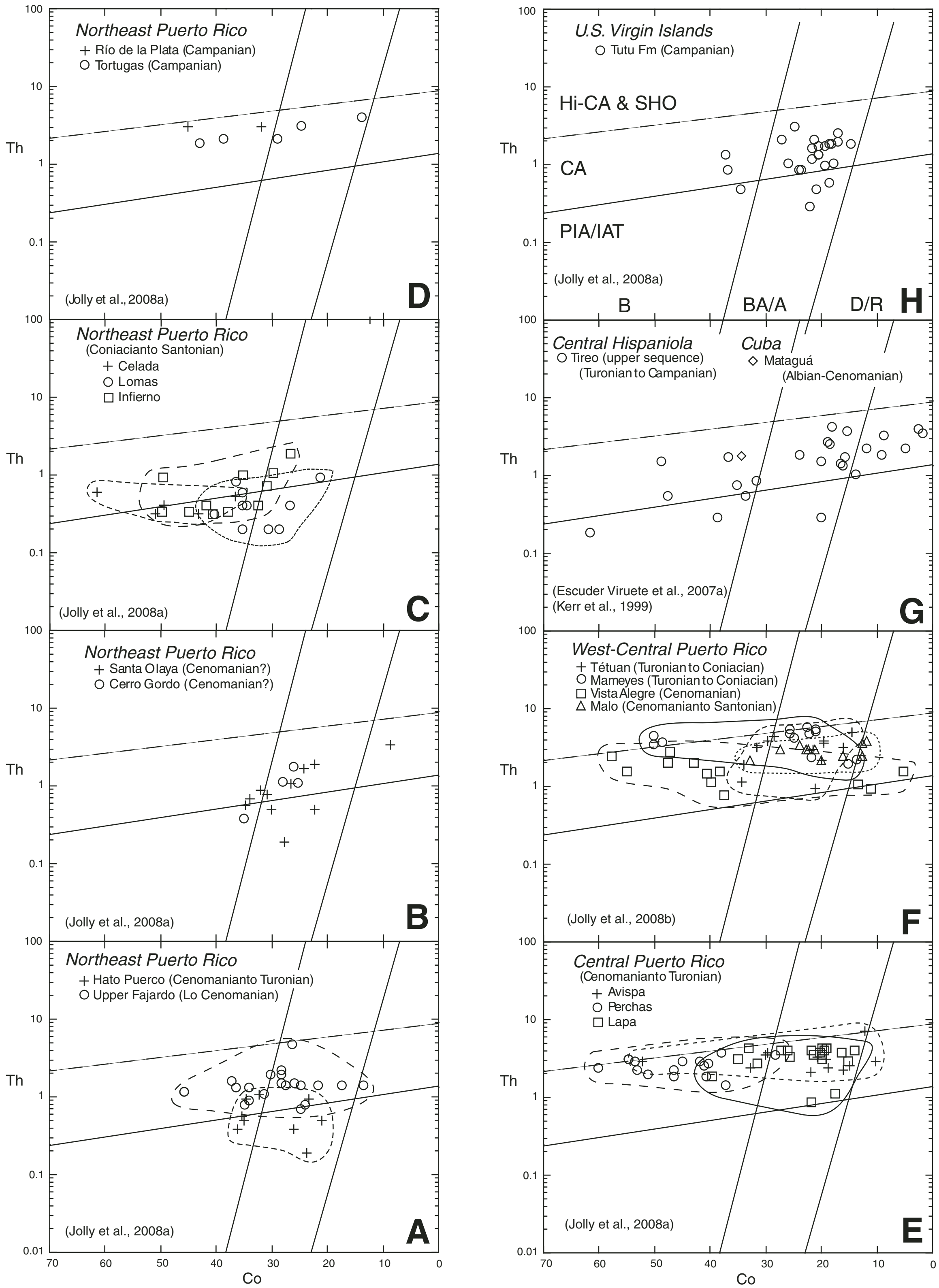
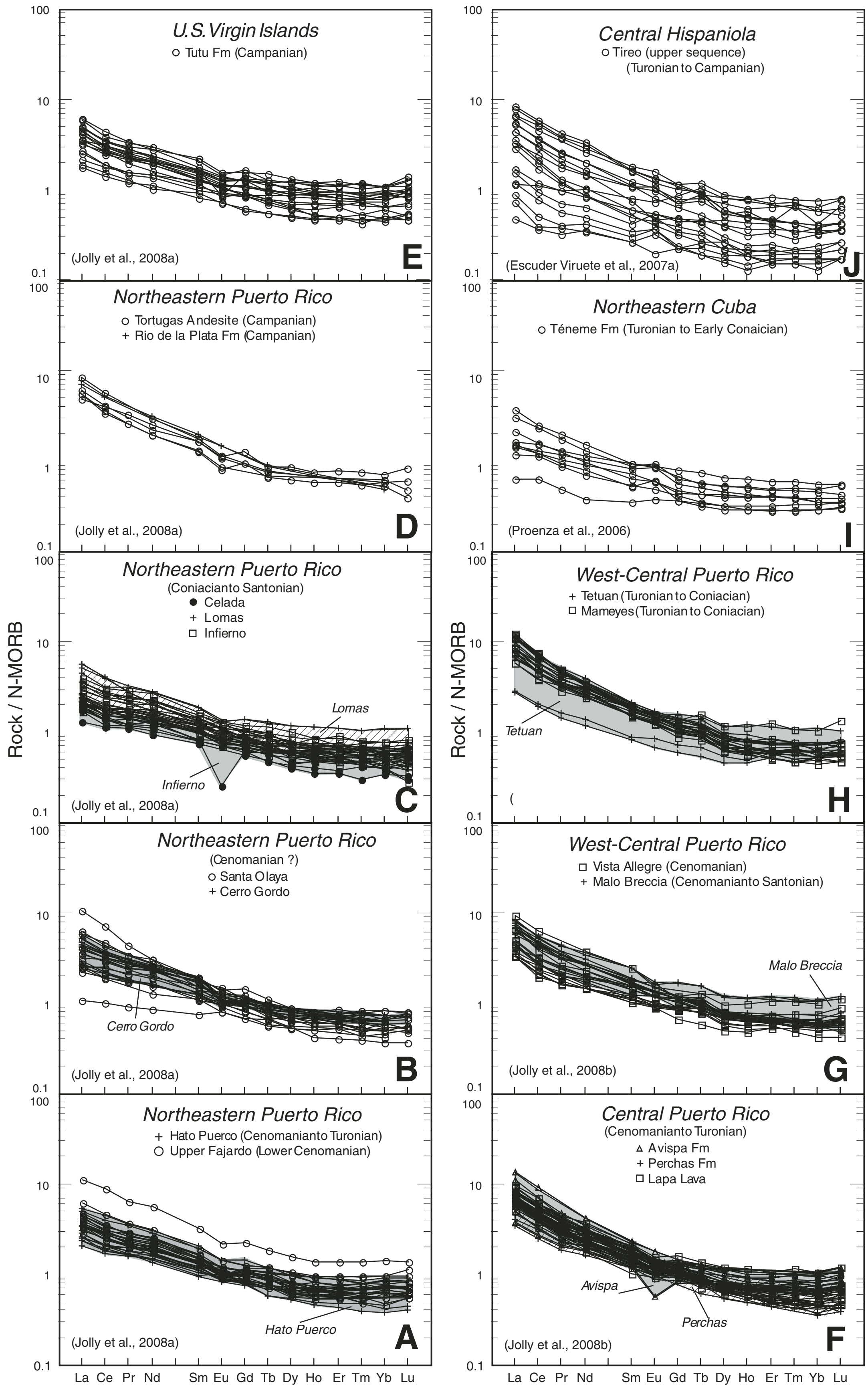


Figure 17. Plots of Th vs. Co abundances of Late Cretaceous calc-alkaline (CA) volcanic-arc rocks, Greater Antilles. Th-Co discrimination boundaries are from Hastie et al. (2007) and Pearce et al. (2014). Abbreviations: B—basalt; BA/A—basaltic andesite and andesite; D/R—dacite and rhyolite; CA—calc-alkaline; SHO—shoshonitic; PIA/IAT—primitive island arc/island-arc tholeiite. Data sources are listed in the figure.


U.S. Virgin Islands
Tutu Fm (Campanian)
(Jolly et al., 2008a)
E
Central Hispaniola
Tireo (upper sequence) (Turonian to Campanian)
(Escuder Viruete et al., 2007a)
J
Northeastern Puerto Rico
Tortugas Andesite (Campanian)
Rio de la Plata Fm (Campanian)
(Jolly et al., 2008a)
D
Northeastern Cuba
Téneme Fm (Turonian to Early Conaician)
(Proenza et al., 2006)
I
Northeastern Puerto Rico
(Coniacianto Santonian)
Celada
Lomas
Infierno
(Jolly et al., 2008a)
C
West-Central Puerto Rico
Tetuan (Turonian to Coniacian)
Mameyes (Turonian to Coniacian)
Tetuan
H
Northeastern Puerto Rico
(Cenomanian ?)
Santa Olaya
Cerro Gordo
(Jolly et al., 2008a)
B
West-Central Puerto Rico
Vista Allegre (Cenomanian)
Malo Breccia (Cenomanianto Santonian)
Malo Breccia
(Jolly et al., 2008b)
G
Northeastern Puerto Rico
Hato Puerco (Cenomanianto Turonian)
Upper Fajardo (Lower Cenomanian)
Hato Puerco
(Jolly et al., 2008a)
A
Central Puerto Rico
(Cenomaniantо Turonian)
Avispa Fm
Perchas Fm
Lapa Lava
Avispa
Perchas
(Jolly et al., 2008b)
F
Rock / N-MORB
100
10
1
0.1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

Hispaniola

In Hispaniola, clearly recorded Albian uplift and erosion were followed by a magmatic lull that lasted from soon after 110 Ma (Kesler et al., 2005) until eruption of the upper Tireo Group began, perhaps as early as 95 Ma (Lewis and Jimenez, 1991). Tireo strata are overlain with apparent conformity by the Campanian–Maastrichtian sediments of the Trois Rivieres–Peralta belt (Lewis and Jimenez, 1991). The upper Tireo volcanic section (Fig. 17G) in the Dominican Republic is composed of Nb-enriched basalt, high-Mg andesite, adakite, and dacite to rhyolite flows, tuffs and breccia, domes and dikes (Lewis and Jimenez, 1991; Sandoval et al., 2015; Escuder Viruete et al., 2007b, 2008; and references therein). The oldest interpreted U-Pb dates from zircon in porphyritic rhyolite in the upper Tireo units are ca. 91 Ma (Escuder Viruete et al., 2007a). These rocks and equivalent formations in eastern Hispaniola (Lebron and Perfit, 1994), Puerto Rico (Jolly et al., 1998a), and the Virgin Islands (Jolly et al., 2006) record an important change in composition from that of a PIA/IAT suite characterized by tholeiite basalt to medium-Th calc-alkaline basalt, andesite, and dacite (Figs. 17–19).

Cuba

In Cuba, unconformities marked by conglomerate suggest that erosion of Early Cretaceous volcanic units began within the Albian (ca. 105 Ma) and, at least locally, lasted until the Coniacian–Santonian interval (ca. 90–84 Ma), when volcanism was renewed (Iturralde-Vinent, 1996b, 1996a, 1996d). Three of the Cretaceous formations, consisting of volcanic and sedimentary rocks, are recognized in northeastern Cuba, including Quibiján, Santo Domingo, and Téneme (Knipper and Cabrera, 1974; Quintas, 1988a, 1988b, 1989; Gyarmati and Leye O'Connor, 1990; Torres and Fonseca, 1990; Quintas et al., 1994; Iturralde-Vinent, 1996c, 1996b, 1996e; Gyarmati et al., 1997; Kerr et al., 1999; Iturralde-Vinent et al., 2006). The Quibiján Formation consists of more than 500 m of mainly porphyritic and amygdaloidal basalt, which is locally pillowed, and tuffaceous rocks within the Quibiján River basin (Quintas, 1988a, 1988b, 1989). The Santo Domingo Formation is composed of sills of porphyritic andesite that locally intrude tuff and tuffaceous rocks intercalated with scarce limestone beds that form a section more than 2000 m thick (Iturralde-Vinent, 1976). The Téneme Formation consists of basalt, andesite, and less common dacite with minor intercalations of well-bedded foliated limestone and shaly limestone. It displays transitional geochemistry from PIA/IAT to calc-alkaline compositions (Figs. 7I, 8G, and 9G). In the type area, the Téneme Formation contains a Turonian or early Coniacian planktonic foraminifera assemblage. Volcanic units within the formation are intruded by ca. 90 Ma quartz diorite (Proenza et al., 2006). Exposures also include nonmetamorphosed or slightly metamorphosed Late Cretaceous marine pyroclastic and sedimentary rocks, including andesite-basaltic agglomerate and tuff of the Turquino Formation (Iturralde-Vinent, 2003).

Sedimentary rocks, e.g., Téneme, Morel, Quibiján, Santo Domingo, and Purial Formations, intercalated in volcanic and metavolcanic sections of eastern Cuba yield Cretaceous through Danian microfossils (Iturralde-Vinent et al., 2006). Fossil ages indicate that the sedimentary rocks accumulated between ca. 90 and 70 Ma, within the interval defined by isotopic ages from magmatic units (Rojas-Agramonte et al., 2010, 2011, and references therein).

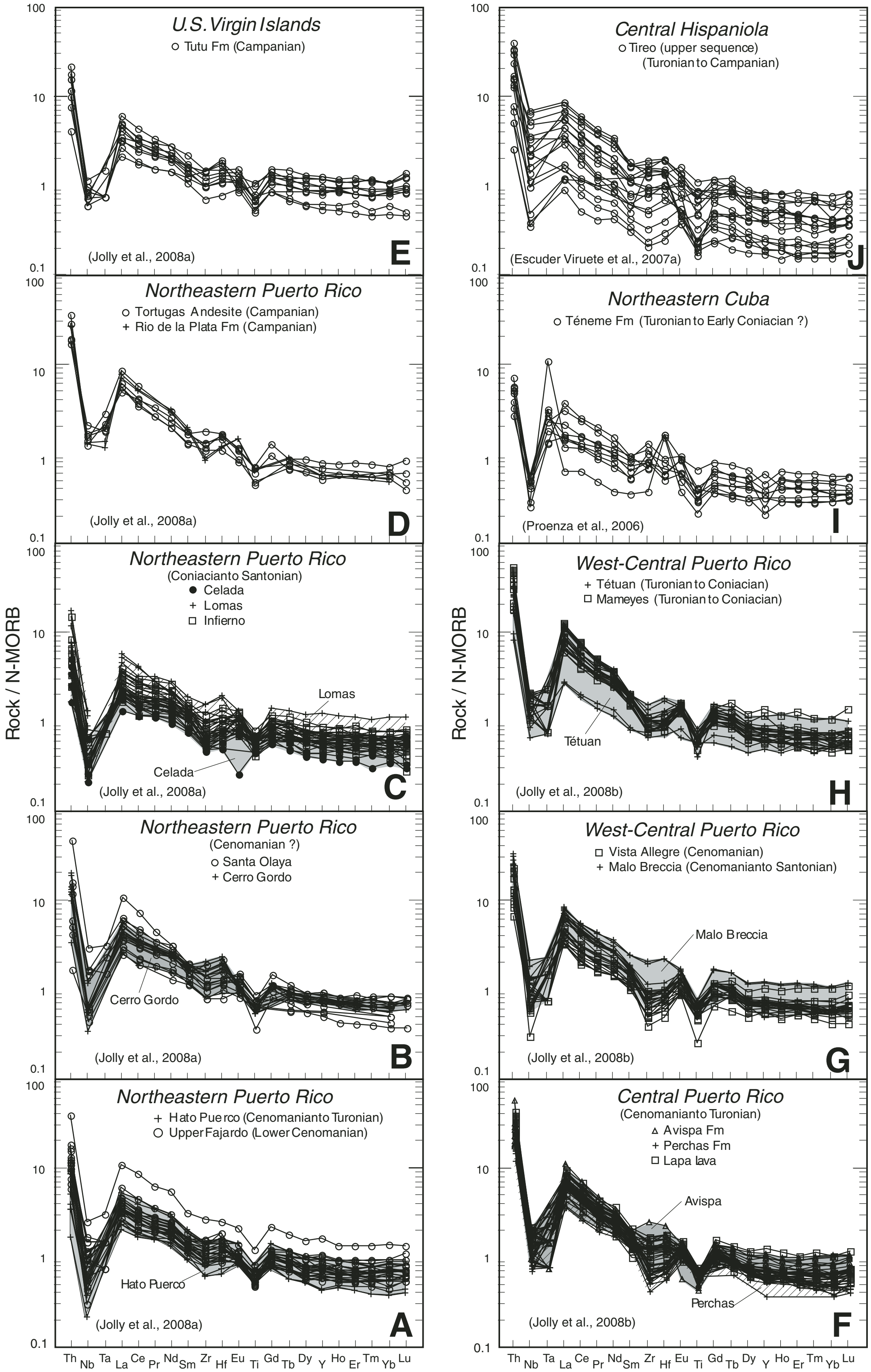
The protolith of the Purial metamorphic complex likely includes Maastrichtian–early Danian rocks, as well as units of Campanian and older age. This fact suggests that the metamorphism that affected the Purial rocks took place probably in the late Maastrichtian and was coeval with the detachment, exhumation, and emplacement of mafic-ultramafic thrust-sheet bodies. This event, recorded in eastern Cuba–western Hispaniola and Guatemala, might have been related to the insertion of thick oceanic ridges into the subduction zone (Garcia-Casco et al., 2006).

In central Cuba, widespread late calc-alkaline and less common island-arc tholeiite volcanism is indicated by interpreted zircon ages as old as ca. 94 Ma from orthogneiss intrusive into the Mabujina amphibolite complex (Fig. 14A; Rojas-Agramonte et al., 2011). The Mabujina amphibolite complex is thought to represent the deepest exposed section of the Early Cretaceous volcanic arc and its oceanic basement in Cuba. Late Cretaceous dates from single zircons in trondhjemitic orthogneiss and amphibolite from the complex yield interpreted ages of 93.8 ± 0.5 Ma and 92 ± 0.7 Ma, whereas amphibolite samples from the eastern part of the complex yield similar ages of ca. 93 Ma and zircon inheritance at 315, 471, 903, and 1059 Ma. Samples from the Manicaragua Batholith, which intrudes both the Mabujina amphibolite complex and the Cretaceous volcanic arc, yield interpreted ages that fall within the interval between ca. 90 and 83 Ma.

Jamaica

In the Blue Mountain Inlier (Fig. 16), the mid- to late Campanian (ca. 75 Ma) Bellevue lavas form two distinct groups—a basaltic and basaltic andesite subgroup and an andesitic to dacitic subgroup (Hastie et al., 2010b). The Bellevue lavas, considered to be arc-related, show moderate enrichment in LREE and slightly negative Ce anomalies on chondrite-normalized diagrams; furthermore, on N-MORB–normalized diagrams, Th displays only moderate enrichment, and Nb and Ta are only slightly depleted. On a Th-Co discrimination diagram, the lavas plot in the island-arc tholeiite field or along the island-arc tholeiite–calc-alkaline boundary (Hastie et al., 2010b). According to Hastie et al. (2009), the transition from island-arc tholeiite (PIA/IAT) to calc-alkaline rocks took place in the mid-Barremian (ca. 127 Ma), as shown by the change from island-arc tholeiite in the lower part of the

Figure 18. Plots of normalized rare earth element (REE) compositions from Late Cretaceous calc-alkaline (CA) volcanic-arc rocks, Greater Antilles. Normalizing factors are from Sun and McDonough (1989). Data sources are listed in the figure. N-MORB—normal mid-ocean-ridge basalt.



Rock / N-MORB
Th Nb Ta La Ce Pr Nd Sm Zr Hf Eu Ti Gd Tb Dy Y Ho Er Tm Yb Lu
U.S. Virgin Islands
Tutu Fm (Campanian)
(Jolly et al., 2008a)
E
Central Hispaniola
Tireo (upper sequence) (Turonian to Campanian)
(Escuder Viruete et al., 2007a)
J
Northeastern Puerto Rico
Tortugas Andesite (Campanian)
Rio de la Plata Fm (Campanian)
(Jolly et al., 2008a)
D
Northeastern Cuba
Téneme Fm (Turonian to Early Coniacian ?)
(Proenza et al., 2006)
I
Northeastern Puerto Rico
(Coniacian to Santonian)
Celada
Lomas
Infierno
(Jolly et al., 2008a)
C
West-Central Puerto Rico
Tétuan (Turonian to Coniacian)
Mameyes (Turonian to Coniacian)
Tétuan
(Jolly et al., 2008b)
H
Northeastern Puerto Rico
(Cenomanian ?)
Santa Olaya
Cerro Gordo
(Jolly et al., 2008a)
B
West-Central Puerto Rico
Vista Allegre (Cenomanian)
Malo Breccia (Cenomanian to Santonian)
Malo Breccia
(Jolly et al., 2008b)
G
Northeastern Puerto Rico
Hato Puerco (Cenomanian to Turonian)
Upper Fajardo (Lower Cenomanian)
Hato Puerco
(Jolly et al., 2008a)
A
Central Puerto Rico
(Cenomanian to Turonian)
Avispa Fm
Perchas Fm
Lapa lava
Avispa
Perchas
(Jolly et al., 2008b)
F

Devils Race Course Formation (Benbow Inlier) to calc-alkaline composition in the upper part.

Aruba and Curacao

On Aruba, the presence of Late Cretaceous arc-related rocks is indicated by the 89.1–88.6 Ma Aruba Batholith that is intrusive into the Aruba Lava Formation (of Caribbean large igneous province affinity; discussed in the following). The batholith has typical subduction-related geochemistry, including negative Nb anomalies, tonalite-trondhjemite-granodiorite (TTG) characteristics, and elevated Sr/Y adakitic ratios (White et al., 1999; van der Lelij et al., 2010; Wright and Wyld, 2011).

On Curaçao, dioritic dikes intrude the Cretaceous Curaçao Lava Formation and overlying Knip Group. The younger set of leucodiorite dikes intrudes the Knip Group. The older set of quartz diorite dikes intrudes the Caribbean large igneous province–like Curaçao Lava Formation and yields a U-Pb zircon date of 86.2 Ma, essentially coeval with the Aruba Batholith (Wright and Wyld, 2011). Chemically, the quartz diorite dikes are very similar to the Aruba Batholith with nearly identical primitive mantle–normalized incompatible-element compositions, negative Nb and Ta spikes, slight LREE enrichment, and high Sr/Y ratios (Wright and Wyld, 2011). Thus, Curacao, like Aruba, records the presence of the Caribbean large igneous province during arc-related magmatism at ca. 89–86 Ma.

Aves Ridge

The largely submerged Aves Ridge (Fig. 1) lies immediately west of the Lesser Antilles. The ridge is a north-trending arcuate structure that extends for ~500 km from Aves Island to Margarita Island. Most researchers suggest that the ridge originated as a Late Cretaceous to Paleocene island arc (Bougault et al., 1984; Pindell and Kennan, 2009).

Various types of igneous rocks have been collected from dredge hauls along the ridge, including basalt, andesite, and granite (e.g., Fox et al., 1971). The La Blanquilla Island mafic rocks have LREE-enriched chondrite-normalized REE patterns, moderately enriched Th, and prominent Nb, Ta, and Ti depletions, which suggested to Neill et al. (2011) an origin in a west-dipping subduction zone of mainly calc-alkaline affinity. U-Pb analyses were also carried out on individual zircons from fresh granitoids, using ion microprobe methods. These results yielded a concordant date of 75.9 Ma (Neill et al., 2011). U-Pb analyses on zircons from two granitic plutons immediately southwest of the Aves Ridge indicated a crystallization age of 75.5 Ma for granodiorite and 58.7 Ma for tonalite (Wright and Wyld, 2011).

Figure 19. Plots of normalized incompatible trace-element (ITE) compositions from Late Cretaceous calc-alkaline (CA) volcanic-arc rocks, Greater Antilles. Data sources are listed in the figure. Normalizing factors are from Sun and McDonough (1989). N-MORB—normal mid-ocean-ridge basalt.

Nicaragua and Cayman Rises

The Nicaragua and Cayman Rises (Fig. 1) are major submarine structures of poorly known origin in the western Caribbean region. Knowledge of the regions derives mainly from geophysical surveys, stratigraphic studies of drill-hole samples, and geochemical-geochronologic studies of dredge hauls and drill-core samples.

Along the Nicaragua Rise, clastic sedimentary and carbonate rocks, extrusive units, and igneous intrusions have been penetrated by numerous wells in the region. Among the plutons, according to Lewis et al. (2011), there are three granitoids of calc-alkaline chemical affinity. These rocks lie in the high-K field and are similar to the Above Rocks pluton of Jamaica (see Lidiak and Jolly, 1996) and Terre Nueve (Haiti) intrusions. All three of these intrusions unconformably underlie middle Eocene sedimentary rocks and are considered to be of Late Cretaceous–Paleocene age (Lewis et al., 2011). Low trace-element and Pb, Nd, and Sr isotopic compositions (Lewis et al., 2011) show no evidence of a continental component, suggesting that the eastern and northern areas of the Nicaraguan Rise area are not underlain by continental crust of the Chortis block.

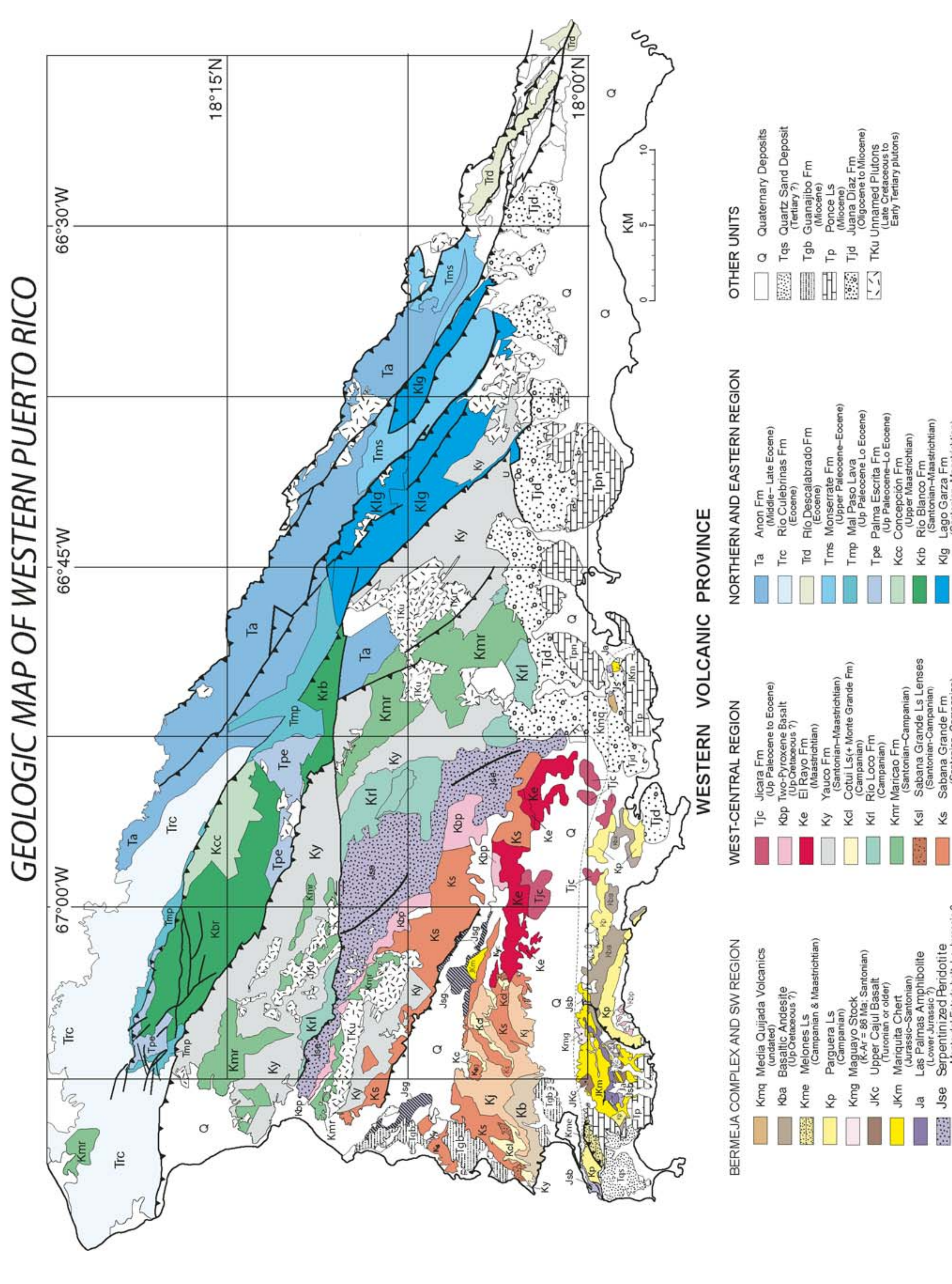
In marked contrast are the calc-alkaline granitoid and volcanic rocks immediately to the north and northwest from the western part of the Cayman Ridge. West Cayman granitoid magmatism (66–62 Ma) is slightly older than Sierra Maestra magmatism (60–47 Ma) of eastern Cuba but overlaps in age with the Above Rocks pluton (Jamaica), Terre Neuve (Haiti), and plutons of offshore Nicaragua. Moderately enriched Pb, Nd, and Sr isotopic ratios of these Late Cretaceous–Paleocene granitoids indicate they were intruded into continental crust (Lewis et al., 2009). These preliminary results suggest that the continent-ocean boundary passes through the Nicaraguan Rise, although the location and transition from continental to oceanic crust are not known.

Paleocene–Eocene Arc (Ca. 60–45 Ma)

Cuba

An unconformity within the Campanian of Cuba separates the deformed Late Cretaceous arc basement from overlying Paleocene to early Eocene island volcanic strata (Fig. 24). The southern axial portion of this Early Tertiary arc consists of calc-alkaline extrusive and pyroclastic rocks (El Cobre Group) intruded by plutons of granodiorite and granite (Iturralde-Vinent, 1996a). The extrusive units of this arc are of Danian and early Eocene ages, whereas the plutonic rocks are slightly younger, middle to late Eocene. The northern part of the arc consists of pyroclastic and sedimentary rocks of probable backarc provenance. Volcanic activity diminished and terminated by about early middle Eocene time.

More than 4000 m of Paleogene tholeiitic, low K_2O, volcanic rocks (Cazanas et al., 1998) underlie the main part of the Sierra Maestra Mountains in southeastern Cuba. The principal formation, El Cobre Group, consists of three undivided volcanic units: a lower sequence characterized by lavas and pyroclastic


GEOLOGIC MAP OF WESTERN PUERTO RICO
67°00'W
66°45'W
66°30'W
18°15'N
18°00'N
KM
0 5 10
WESTERN VOLCANIC PROVINCE
BERMEJA COMPLEX AND SW REGION
Kmq Media Quijada Volcanics (undated)
Kba Basaltic Andesite (Up Cretaceous ?)
Kme Melones Ls (Campanian & Maastrichtian)
Kp Parguera Ls (Campanian)
Kmg Maguayo Stock (K-Ar = 86 Ma; Santonian)
JKc Upper Cajul Basalt (Turonian or older)
JKm Mariquita Chert (Jurassic–Santonian)
Ja Las Palmas Amphibolite (Lower Jurassic ?)
Jse Serpentinized Peridotite Monte del Estado belt–Lo Jurassic ?
Jsg Serpentinized Peridotite Rio Guanajibo belt–Lo Jurassic ?
Jsb Serpentinized Peridotite Sierra Bermeja belt–Lo Jurassic ?
WEST-CENTRAL REGION
Tjc Jicara Fm (Up Paleocene to Eocene)
Kbp Two-Pyroxene Basalt (Up Cretaceous ?)
Ke El Rayo Fm (Maastrichtian)
Ky Yauco Fm (Santonian–Maastrichtian)
Kcl Cotui Ls (+ Monte Grande Fm) (Campanian)
Krl Rio Loco Fm (Campanian)
Kmr Maricao Fm (Santonian–Campanian)
Ksl Sabana Grande Ls Lenses (Santonian-Campanian)
Ks Sabana Grande Fm (Santonian–Campanian)
Kj Lajas Fm (Lower Campanian)
Kb Boqueron Fm (Santonian)
NORTHERN AND EASTERN REGION
Ta Anon Fm (Middle– Late Eocene)
Trc Rio Culebrinas Fm (Eocene)
Trd Rio Descalabrado Fm (Eocene)
Tms Monserrate Fm (Upper Paleocene–Eocene)
Tmp Mal Paso Lava (Up Paleocene Lo Eocene)
Tpe Palma Escrita Fm (Up Paleocene–Lo Eocene)
Kcc Concepción Fm (Upper Maastrichtian)
Krb Rio Blanco Fm (Santonian–Maastrichtian)
Klg Lago Garza Fm (Santonian–Maastrichtian)
OTHER UNITS
Q Quaternary Deposits
Tqs Quartz Sand Deposit (Tertiary ?)
Tgb Guanajibo Fm (Miocene)
Tp Ponce Ls (Miocene)
Tjd Juana Diaz Fm (Oligocene to Miocene)
TKu Unnamed Plutons (Late Cretaceous to Early Tertiary plutons)

and volcaniclastic rocks of diverse compositions, from basalt to rhyolite; a middle unit characterized mainly by andesite, andesite-basalt to dacite and rhyodacite that record explosive volcanism; and an upper unit with a preponderance of basaltic and basaltic-andesite pyroclastic and volcaniclastic rocks and lavas (Mendez-Calderon, 1997). Sedimentary and pyroclastic rocks of the Pilón Formation are considered to be equivalent to El Cobre. Overlying both units is the Caney Formation, characterized by pyroclastic and sedimentary rocks, agglomerates, and lava flows (Iturralde-Vinent, 1996a; Garcia-Delgado et al., 1998).

The volcanic units are intruded by low- to medium-K, calc-alkaline granite yielding U-Pb sensitive high-resolution ion microprobe (SHRIMP) single zircon emplacement ages between 60.5 Ma and 48.3 Ma (Rojas-Agramonte et al., 2006). The plutonic rocks record the youngest episode of subduction-related magmatism in Cuba, Hispaniola, or Puerto Rico.

Figure 25 is a north-south cross section representing the main elements of the Paleocene–Eocene arc of eastern Cuba from the Cayman Trench northward. As shown on the diagram, the arc developed on the preexisting Cretaceous and older rocks of Cuba. The deformations and thrust faults within the foreland basin are partially isochronous with the activity of the volcanic arc at the Cayman Ridge–Sierra Maestra belt (Iturralde-Vinent, 2003).

Virgin Islands

Strata of Maastrichtian to Early Tertiary age are not exposed in the Virgin Islands, implying the presence of a major unconformity, a prominent fault complex, or both. The absence of latest Cretaceous–Early Tertiary strata records a major break in stratigraphic conformity in the Greater Antilles, particularly in Puerto Rico, Hispaniola, and Cuba, and implies that an important structural or stratigraphic discordance also occurs in the Virgin Islands.

Previously unpublished field work by Lidiak on Tortola and Jost Van Dyke island in the British Virgin Islands indicates that revision of the structure and stratigraphy is warranted. Helsley (1960) previously mapped volcanogenic rocks on Tortola, Jost Van Dyke, and Hans Lollik (U.S. Virgin Islands) as the Eocene Tortola Formation, consisting of three members: Hans Lollik (eastern volcanic center), Sage Mountain (western volcanic center), and Shark Bay. He mapped the structure as a large homocline with the units on Hans Lollik and southern Tortola Islands being overturned to the south and with the units on Jost Van Dyke and northern Tortola being near vertical or being upright and dipping north.

Figure 26 shows the revised general geology and structure of the western British Virgin Islands. The geologic map of the U.S.

Figure 20. Geologic map of western Puerto Rico, adapted from U.S. Geological Survey 7.5′ quadrangle maps. See Jolly et al. (1998b, their figure 3) for references to individual U.S. Geological Survey quadrangle maps. Ls—Limestone.

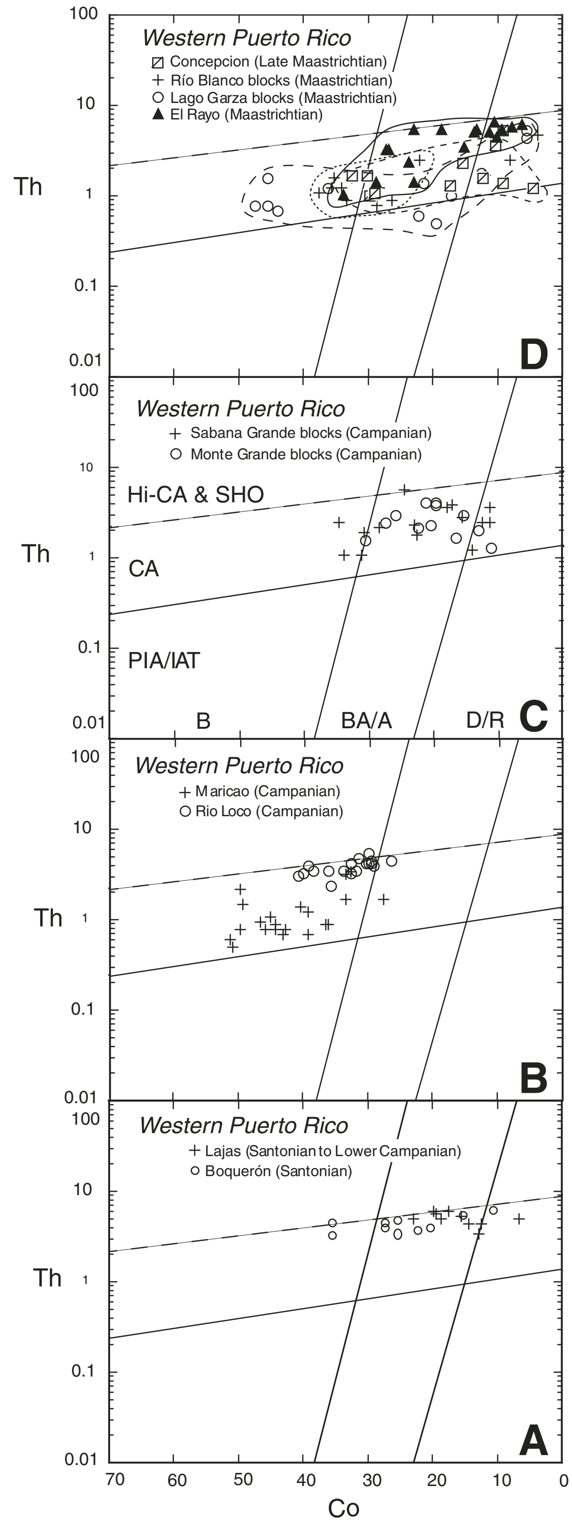
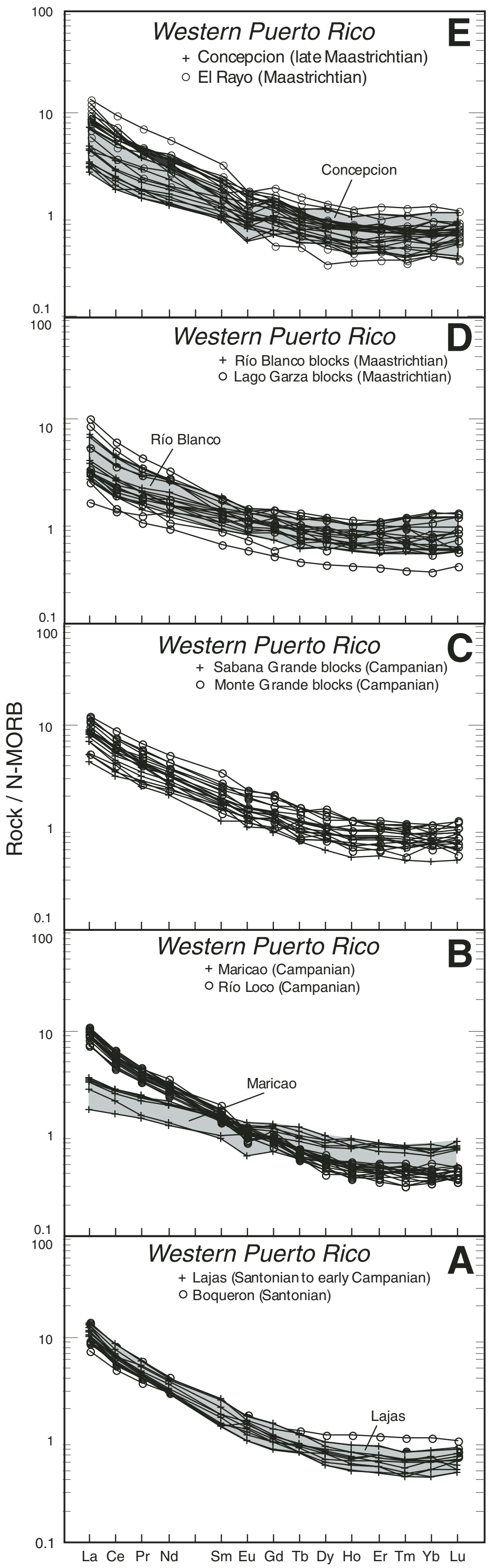


Figure 21. Plots of Th vs. Co abundances from Late Cretaceous calc-alkaline (CA) volcanic arc rocks, western Puerto Rico. Th-Co discrimination boundaries: Hastie et al. (2007). Abbreviations: B—basalt; BA/A—basaltic andesite and andesite; D/R, dacite and rhyolite; SHO—shoshonitic; PIA/IAT—primitive island arc/island-arc tholeiite. Data sources: Jolly et al. (2007) and Lidiak et al. (2011).



Virgin Islands (Rankin, 2002) is included for regional coverage. The main features are two east-trending folds. A southern syncline, the Narrows syncline, strikes eastward between St. Thomas and Hans Lollik Islands and extends through the Narrows region of Sir Francis Drake Channel. The northern fold, the Tortola anticline, essentially parallels the syncline and passes south of Jost Van Dyke and across central Tortola. The presence of these folds, along with new observations of the structure and stratigraphy on Hans Lollik, Tortola, and Jost Van Dyke Islands, provides the basis for the reinterpretation.

On Hans Lollik island, Rankin (2002) recognized that the rocks cropping out on the island are not overturned and of Eocene age but, on the basis of graded and channeled beds, are upright, dip to the south, and are part of the Cretaceous Louisenhoj Formation. Furthermore, the bedding orientations indicate that the rocks on Han Lollik Island occupy part of the northern limb of the Narrows syncline. Consistent with these structures are graded beds and bedding/cleavage intersections on SW Tortola, which indicate that the Tutu Formation and the unnamed unit immediately to the north are upright with a major syncline located to the south. Similar bedding/cleavage relationships also apply on Jost Van Dyke.

Helsley (1960) also reported the presence of Eocene fossils, as identified by W. Bronnimann, W. Storrs Cole, and J.W. Wells, from two localities, one from central Jost Van Dyke and the other from Shark Bay of NW Tortola. Neither location was specified. The limestone fragments from the Jost Van Dyke locale were from a volcanic breccia and probably were not deposited in situ. The second site, a limestone lens on NW Tortola, was located along a Pleistocene (?) bench on the west side of Shark Bay (Fig. 26; 18°27′14″N, 64°38′30″W).

As the term Hans Lollik Member is no longer applicable (Rankin, 2002), several new stratigraphic names are necessary for clarity. As already noted, Rankin (2002) recognized the presence of the Louisenhoj Formation on Hans Lollik island. We suggest that a similar-aged unit occurs on central Tortola immediately north of, and stratigraphically underneath, the Tutu Formation (Fig. 26). This proposed unnamed unit is lithologically and geochemically very similar to the Louisenhoj Formation, but not identical, as might be expected from units possibly having separate volcanic centers. Revision of the presently recognized Eocene units on Jost Van Dyke and central and northern Tortola is also necessary. The term White Bay Formation is tentatively used for the breccia, conglomerate, tuff, and sandstone on southern Jost Van Dyke and central Tortola; Shark Bay Formation is recognized for the breccia, greenish tuff, and limestone on northern Jost Van Dyke and northern Tortola.

Figure 22. Plots of normalized rare earth elements (REE) in Late Cretaceous calc-alkaline (CA) volcanic arc rocks, western Puerto Rico. N-MORB—normal mid-ocean-ridge basalt. Data sources: Jolly et al. (2007) and Lidiak et al. (2011). Normalizing factors are from Sun and McDonough (1989).

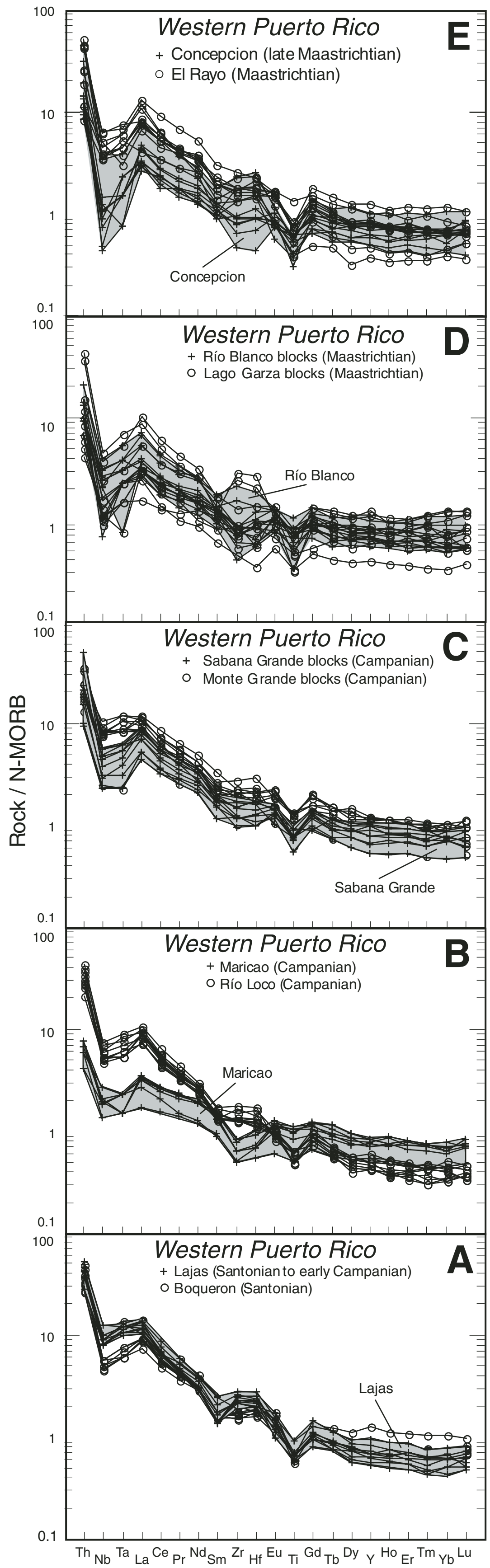


Figure 23. Plots of normalized incompatible trace-element (ITE) abundances in Late Cretaceous calc-alkaline (CA) volcanic arc rocks, western Puerto Rico. Data sources: Jolly et al. (2007) and Lidiak et al. (2011). Normalizing factors are from Sun and McDonough (1989). N-MORB—normal mid-ocean-ridge basalt.

The youngest volcanogenic unit in the Virgin Islands is the Necker Formation, consisting predominantly of fine-grained, quartz-bearing felsic tuff along with minor breccia and tuffaceous sandstone. The Necker is probably cogenetic with the Virgin Islands Batholith, as evidenced by contact metamorphic effects in the lower part of the unit and the presence of fragments of batholith-derived granophyre and diorite in the upper part (Helsley, 1960). The plutonic rocks of the composite calc-alkaline Virgin Islands Batholith range in composition from gabbro to adamellite to granite pegmatite (Helsley, 1960; Longshore, 1965; Donnelly and Rogers, 1980; Lidiak and Jolly, 1996). Late Eocene K-Ar (Cox et al., 1977; Vila et al., 1986) and $^{40}Ar/^{39}Ar$ (Rankin, 2002) ages of 39–35 Ma are consistent with an Eocene age for the Necker Formation (Helsley, 1960).

Puerto Rico

In Puerto Rico, Tertiary volcanic rocks comprise major map units in the northeastern, central, and western volcanic provinces (Fig. 10). In the central part of the island, the exposed Paleocene and Eocene units include intermediate hornblende-bearing lava breccia (Jobos Formation) and underlying tuff (Yunes Formation). In the San Juan area of northeastern Puerto Rico, the distinctive hornblende-bearing agglomeratic Guaracanal Andesite contains foraminifera from thin discontinuous algal limestone near its base that indicates a Paleocene age (Pease, 1968a). The $^{40}Ar/^{39}Ar$ dates of 63 Ma (Story et al., 2013) on hornblende are consistent with this age assignment. The Guaracanal Andesite rests unconformably on the Maastrichtian La Muda Limestone and its stratigraphic equivalents (Pease, 1968b; Jolly et al., 1998b). An older unconformity separates the Campanian Tortugas Andesite from the overlying La Muda Limestone (Fig. 11A). The lavas, and other Early Tertiary volcanic strata, are preserved in fault blocks along the northern margin of the province (Lidiak, 1965; Pease, 1968b; Glover, 1971). Extensive strata at this stratigraphic level are buried beneath younger platform sediments of Oligocene or later age (Frost et al., 1998; Larue et al., 1998; Montgomery, 1998). Tertiary deposits to the south form the predominantly tuffaceous Upper Paleocene to Eocene Jacaguas Group (Glover and Mattson, 1967; Mattson, 1967, 1968a, 1968b; Glover and Mattson, 1973), the basal unit of which is the Miramar Conglomerate.

Faults separate the strongly disrupted Jacaguas Group from Eocene deposits of the Cerrillos belt (Fig. 10) to the northwest (Glover, 1971; Dolan et al., 1991). Cerrillos rocks comprise a narrow, northwest-trending belt, 5–10 km wide, of moderately

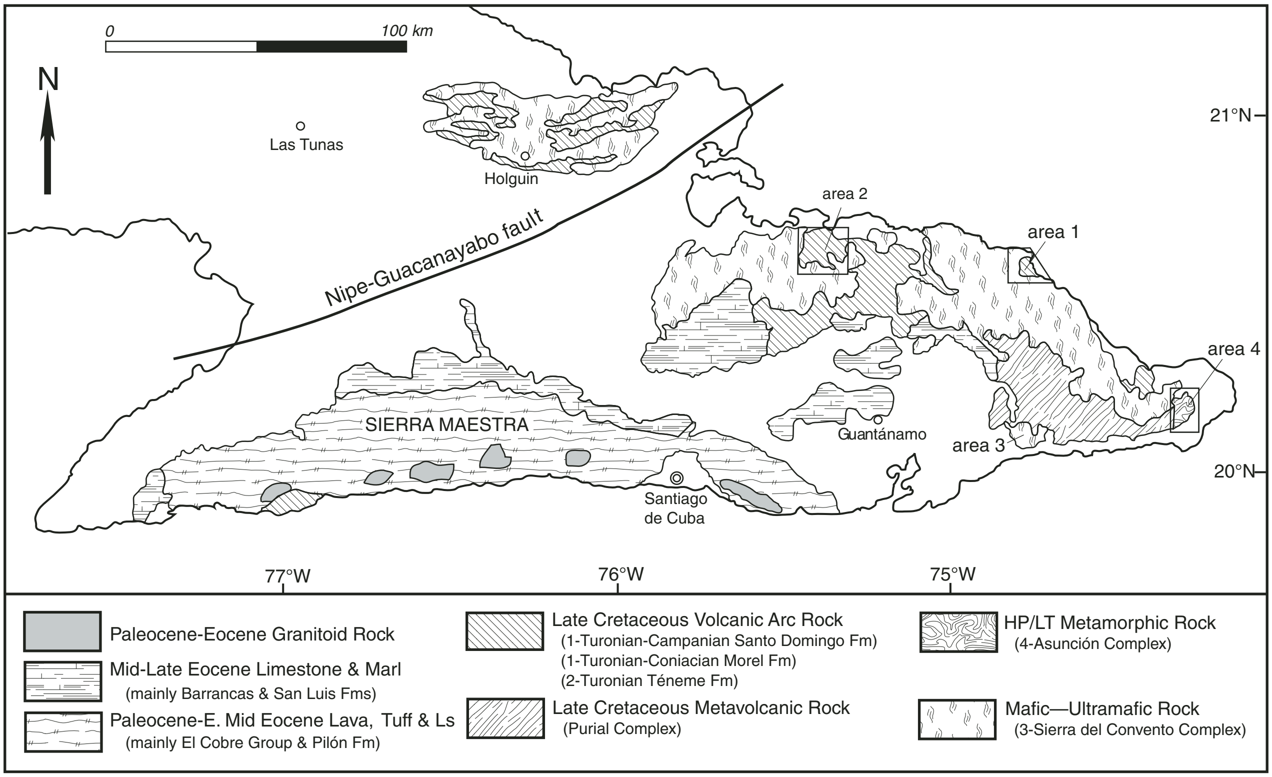


Figure 24. Geologic map of eastern Cuba, adapted from Iturralde-Vinent et al. (2006) and Rojas-Agramonte et al. (2006). Ls—Limestone; Fm—Formation; HP/LT—high-pressure/low-temperature.

to steeply dipping sedimentary and volcanic rocks that extends for 110 km across western Puerto Rico. This Eocene or Cerrillos belt (Figs. 10 and 20) includes three major formations: (1) the Río Culebrinas Formation in the northwest, composed of mostly sedimentary rocks, (2) mixed volcaniclastic and epiclastic rocks of the equivalent Monserrate and Río Descalabrado Formations, and Jicara Formation to the west (Dolan et al., 1991), and (3) the Anón Formation in the central segment, composed of volcanic and volcaniclastic strata.

The thick (>2800 m), middle Eocene Río Culebrinas Formation is mostly sandstone and conglomerate with less common grayish-green altered ash beds, especially in the lower part of the formation. Sedimentary structures indicate that many of these beds are turbidites. Slumps and folds in some units are compatible

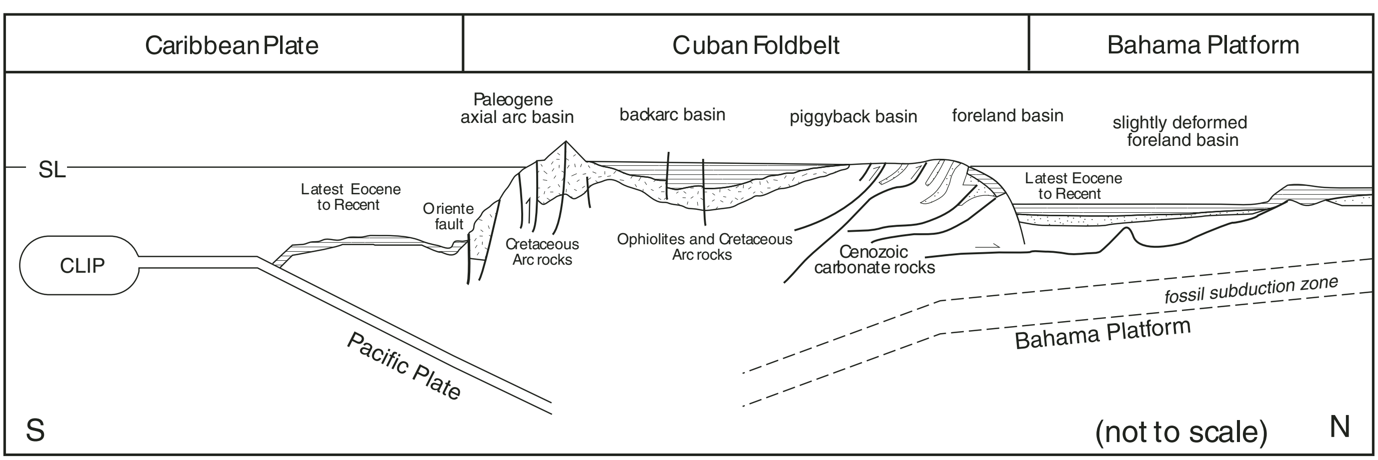


Figure 25. Schematic cross section of Paleocene–Eocene arc, eastern Cuba, adapted and modified from Iturralde-Vinent (2003). CLIP—Caribbean large igneous province.

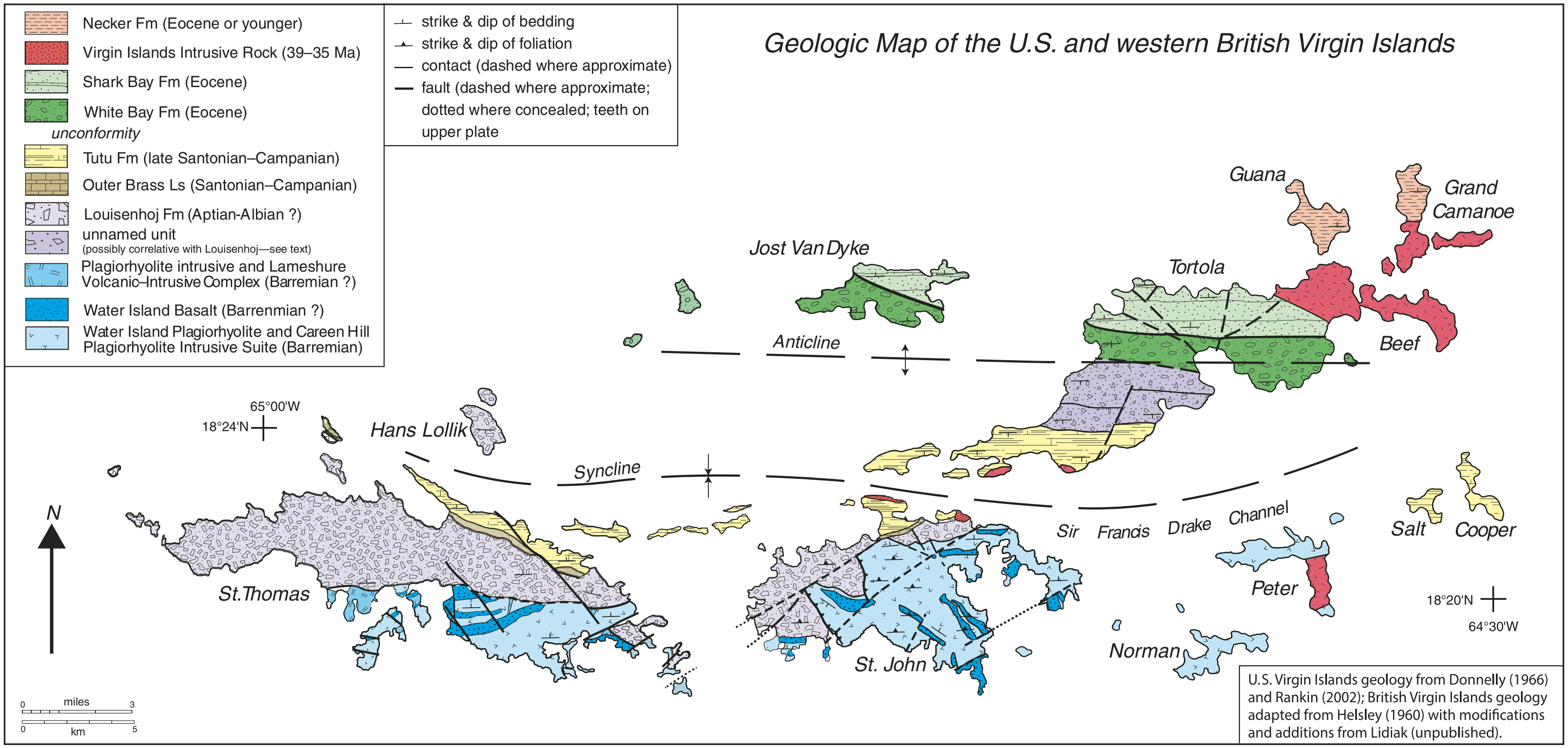


Figure 26. Geologic map of the U.S. and western British Virgin Islands. U.S. Virgin Islands geology is from Donnelly (1966) and Rankin (2002); British Virgin Islands geology adapted from Helsley (1960) with modifications and additions from Lidiak (included in this figure). Ls—Limestone; Fm—Formation.

with downslope movements. The Río Culebrinas rocks conformably overlie lower middle Eocene Mal Paso basalt (McIntyre, 1971) and, along strike to the southeast, grade laterally into the volcanic Anón Formation, which is composed of dacitic lava and shallow intrusive rocks, pyroclastic rocks, and related sandstone and mudstone (Mattson, 1968a, 1968b; Dolan et al., 1991).

The comparable Monserrate and Río Descalabrado Formations are mainly andesitic tuff, lapilli tuff, thin vitric-crystal tuff, sandstone, mudstone, and conglomerate, which is best developed near the base (Mattson, 1967; Glover, 1971). Fossils from these units indicate a middle Eocene age (Pessagno, 1961; Dolan et al., 1991). A megabreccia, consisting of a chaotic mixture of rock types derived from the Robles through the Río Descalabrado Formations, occurs between allochthonous plates in the Río Descalabrado quadrangle (Glover, 1971).

A prominent unit in the Eocene belt is the Anón Formation (Mattson, 1967, 1968a, 1968b), which is composed primarily of alluvial fans, dacitic tuff, and vent-related concentrations of lava, commonly extensively intruded by subvolcanic feeder stocks and dikes (Nelson and Monroe, 1966; Nelson, 1967; Nelson and Tobisch, 1967, 1968; Mattson, 1968a; McIntyre, 1971, 1975; Tobisch and Turner, 1971; Krushensky and Monroe, 1975; Krushensky and Monroe, 1978a, 1978b; Krushensky and Curet, 1984).

The Cerrillos volcanic and sedimentary rocks may record deposition in two intra-arc basins, the Rio Culebrinas to the northwest and the Monserrate–Rio Descalabrado to the southeast. These basins were separated by a central volcanic zone, the Anón and immediately adjacent Mal Paso and Palma Escrita volcanic and volcaniclastic rocks (Dolan et al., 1991). The geochemical composition of all of these western Puerto Rican rocks (Rio Culebrinas, Anón, Monserrate, Mal Paso, and Palma Escrita) reveal distinct calc-alkaline (CA) characteristics, typical of this volcanic belt (Figs. 27C and D). Similar high-Th contents (>1.0 ppm) also apply to the Guaracanal Andesite (Fig. 27A) of east-central Puerto Rico and the Yunes Formation of west-central Puerto Rico (Fig. 27B).

Frost et al. (1998) showed that Eocene and Oligocene rocks of Puerto Rico, the Virgin Islands, and St. Martin have similar Pb isotope characteristics, but less-radiogenic present-day Nd isotope ratios, compared to modern volcanic rocks of the northern part of the Lesser Antilles (Davidson, 1987; Davidson et al., 1993), possibly recording a low terrigenous sediment input in part of the arc.

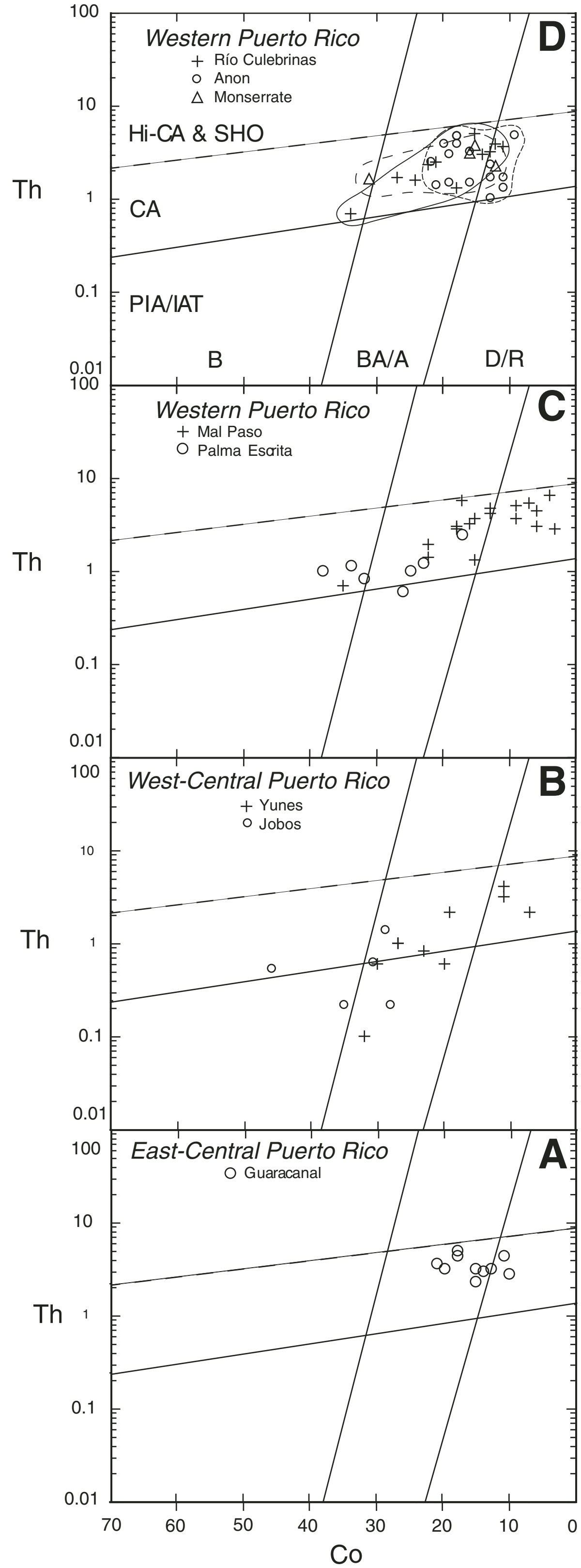


Figure 27. Plots of Th vs. Co abundances in Eocene calc-alkaline (CA) volcanic arc rocks, Puerto Rico. Th-Co discrimination boundaries: Hastie et al. (2007) and Pearce et al. (2014). Abbreviations: B—basalt; BA/A—basaltic andesite and andesite; D/R—dacite and rhyolite; SHO—shoshonitic; PIA/IAT—primitive island arc/island-arc tholeiite. Data source: Lidiak, personal observation, 2014.

Hispaniola

Strata of Eocene and younger age on Hispaniola (Fig. 12A) consist mainly of clastic and carbonate rocks deposited in sedimentary basins that lie unconformably on older basement rocks (Lewis and Draper, 1990; Mann et al., 1991; Draper et al., 1994). According to these authors, basins formed as a result of extensive west-trending, left-lateral, strike-slip faulting. Calc-alkaline volcanic rocks younger than middle Eocene are absent, suggesting that middle to late Eocene collision terminated arc-related volcanism; limited alkaline volcanism (Kamenov et al., 2011) in the Cordillera Central in Pliocene to Pleistocene time is apparently related to strike-slip tectonic activity (Mann et al., 1991; Draper et al., 1994).

Three major Tertiary sedimentary basins (Peralta, El Mamey, and Taverna belts) provide important information about the Eocene–Miocene tectonic evolution of Hispaniola and the northern Caribbean (Dolan et al., 1991). The Peralta belt of the Cordillera Central consists of two basinal sequences, the fault-bounded Lower to Upper Eocene Peralta Group and the Middle Eocene to Lower Miocene Rio Ocoa Group. The basins are currently elongate parallel to the Late Cretaceous Greater Antilles island arc. Although the Peralta is rich in volcanic rock fragments, it does not contain ash beds or other primary volcanic detritus. The sedimentary rocks of the Rio Ocoa also consist of epiclastic arc detritus along with minor shallow-water carbonates. The Peralta rocks record development of an Eocene accretionary prism (Dolan et al., 1991).

The El Mamey belt of northern Hispaniola records deposition in a narrow, elongate basin parallel to the arc rocks exposed in the Cordillera Central to the south. The belt consists of Upper Eocene to Lower Miocene siliciclastic turbidite, marine conglomerate, and minor calcarenite that postdate the main period of Eocene subduction. An angular unconformity separates folded El Mamey belt rocks from Upper Miocene flat-lying marls of the overlying Villa Trina Formation, indicating a period of Miocene folding, uplift, and erosion, possibly related to the development of a restraining bend in the northern part of the northern Caribbean plate boundary zone (Dolan et al., 1991).

The Taverna belt is a small fault-bounded sequence of Oligocene sandstone, mudstone, and conglomerate that crops out in the northern foothills of Cordillera Central. Basinal development occurred during two distinct periods: early Oligocene and late Oligocene to early Miocene. Sedimentation ended during the early Miocene, when Taverna belt rocks were gently folded, eroded, and covered by shallow-marine conglomerates of the Cercado Formation during strike-slip tectonic activity (Dolan et al., 1991).

Jamaica

About 3700 m of folded and faulted Paleocene to early Eocene (ca. 58–50 Ma) sedimentary and volcanic rocks comprise the Wagwater Group of eastern Jamaica (Jackson and Smith, 1978). Within this group, the Halberstadt and Newcastle volcanic formations (Jackson and Smith, 1978) crop out in the northern and central parts of the Wagwater Basin. The Halberstadt volcanics consist of high-Nb basalts, whereas the Newcastle volcanics consist of adakitic rhyodacites (Jackson and Smith, 1978; Hastie et al., 2010a, 2011). Based on the average of two $^{40}Ar/^{39}Ar$ dates of 52.74 Ma from separate splits of groundmass rhyodacite lava, the age of both the Halberstadt and Newcastle volcanics is ca. 53 Ma (Hastie et al., 2010a).

The Newcastle rhyodacite has an adakitic-like major-element composition, low Y and HREE concentrations, and negative Nb and Ta anomalies on N-MORB–normalized multi-element diagrams (Hastie et al., 2010a). Newcastle also has low Sr (<400 ppm), MgO (≤2.0 wt%), Ni (mostly ≤30 ppm), and Cr (mainly ≤40 ppm) compared to modern adakites. In contrast, the high-Nb, plume-related Halberstadt basalts are distinctive and have intraplate alkaline compositions; however, according to Hastie et al. (2010a), they are unlike typical mantle plume oceanic-island basalt lavas in that they were generated in a subduction zone setting. The presence of rocks with a negative Ce anomaly, high Th/Nb ratio, and Sr and Nd isotopic ratios similar to the Newcastle lavas implies that both the Halberstadt and Newcastle magmas are from source regions with comparable composition (Hastie et al., 2011). Hastie et al. (2010a, 2011) suggested further that north-directed underthrusting of Caribbean oceanic plateau crust beneath Jamaica in Early Tertiary time led to the generation of Newcastle and Halberstadt magmas from separate but genetically related source regions.

Ultramafic and Ultramafic-Mafic Assemblages

Ultramafic Rocks

Serpentinized peridotite crops out as isolated and dismembered remnants of former ophiolitic tectonic belts along the northern margin of the Caribbean plate in Cuba, Hispaniola, and Puerto Rico. These serpentinized spinel peridotites, of probable Late Jurassic or Early Cretaceous protolith age, include the Mayarí-Cristal and Moa Baracoa belts of eastern Cuba (Proenza et al., 1999), the Loma Caribe belt in the Cordillera Central of Hispaniola (Lewis et al., 2006a, 2006b), and the Monte del Estado belt of southwest Puerto Rico (Schellekens, 1991; Jolly et al., 1998b; Lao-Davila and Anderson, 2009; Marchesi et al., 2011).

Comparison of Cr- and Al-bearing spinel from the different serpentinized peridotite bodies suggests that they record contrasting petrogenetic histories. For example, Monte del Estado peridotite resembles abyssal peridotites that have not been affected by a subduction component and probably represents a relict of the proto–Caribbean–Atlantic Ocean generated by seafloor spreading in Late Jurassic–Early Cretaceous times (Lewis et al., 2006a). In contrast, Loma Caribe, Mayarí-Cristal, and Moa Baracoa peridotites correspond to depleted abyssal or suprasubduction zone peridotites that represent a heterogeneous suboceanic mantle at a subduction zone environment related to the Greater Antilles arc (Proenza et al., 1999; Lewis et al., 2006a).

Ultramafic-Mafic Assemblages

Ultramafic-mafic assemblages are significant geologic features because they do not represent typical ocean crust ophiolite

but represent instead the roots of the lower levels of an island arc (DeBari and Coleman, 1989). These complexes are regarded as the remains of a magma chamber that crystallized at the base of an intraoceanic island arc. A typical ultramafic-mafic assemblage is a layered sequence wherein basal rocks are dunite and harzburgite overlain by a narrow zone of websterite and clinopyroxenite and, above these rocks, a thick layer of gabbro that may be garnet-bearing at its base (DeBari and Coleman, 1989). This assemblage is common in many island-arc sequences exposed at deeper crustal levels.

Examples of ultramafic-mafic complexes exposed in the Greater Antilles are the ultramafic-mafic intrusives of the Loma de Cabrera Batholith (Lewis et al., 2013), the Puerto Plata ophiolitic complex (Escuder Viruete et al., 2014), and the high-pressure garnet serpentinized peridotites along the Samana Peninsula (Saumur et al., 2010), all of which are in the Dominican Republic.

CARIBBEAN LARGE IGNEOUS PROVINCE ROCKS: DISTRIBUTION, GEOCHEMICAL CHARACTER, AND AGE

In addition to Cretaceous and Early Tertiary magmatic arcs, rocks interpreted as part of large igneous provinces are recognized on the basis of their geochemical character. Kerr et al. (2003) provided a useful summary of the characterizing features of these oceanic plateau rocks and further described exposures of such rocks throughout the Caribbean region and northern Andes (Fig. 1). The most extensive submarine plateau basalt domain is the Caribbean large igneous province that comprises the Caribbean-Colombian oceanic plateau. The basaltic rocks have ages between 91 and 88 Ma and include locally large exposures within the margins of adjacent continental areas (Kerr et al., 2000). In addition to the widespread Caribbean-Colombian oceanic plateau basaltic rocks, other geochemically similar rock suites of Aptian and Campanian–Maastrichtian ages are recognized.

The extent and composition of the Caribbean plateau basalts (Fig. 28) suggested to Kerr et al. (2000, 2003) that they may differ from typical oceanic-island basalt (OIB) sequences in that most oceanic-island basalt provinces are smaller and have more enriched incompatible trace elements than do the Caribbean plateau basalts. However, despite outcrops, deep-sea drilling, and various geophysical surveys, our understanding and knowledge of these Caribbean plateau basalts remain limited.

Aptian Oceanic Plateau Rocks

Hispaniola

Duarte complex. The Duarte complex (Bowin, 1966) is a heterogeneous body of metamorphosed and deformed basaltic to

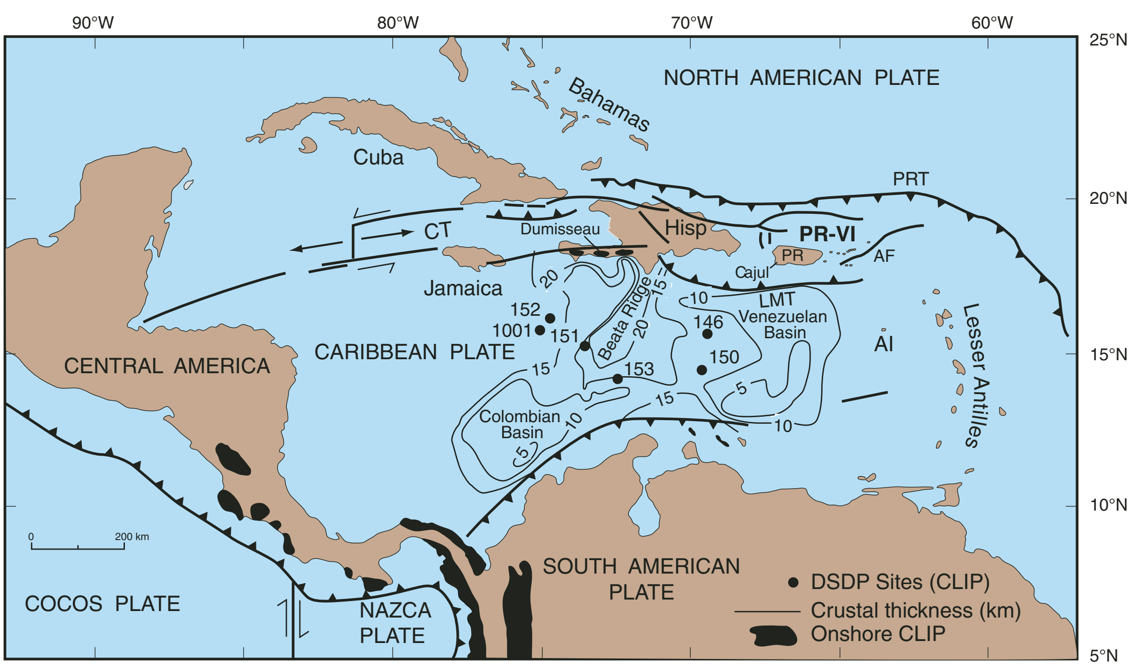


Figure 28. Map of the Caribbean region showing principal structural elements of the tectonic boundary between the North American and Caribbean plates (lines represent fault zones; teeth represent polarity of subduction zones). Closed circles and numbers indicate locations of Deep Sea Drilling Project (DSDP) drilling sites within the Caribbean large igneous province (CLIP). Contours in the Caribbean Basin represent thickness (km) of oceanic crust (seismic velocity <7.4 km/s; adapted from Mauffret and Leroy, 1997). Additional features: AF—Anegada fault; AI—Aves Island; CT—Cayman Trough; LMT—Los Muertos Trench; PR—Puerto Rico; PRT—Puerto Rico Trench; PR-VI—Puerto Rico–Virgin Islands microplate.

ultramafic rocks cropping out as two massifs in the Cordillera Central (Draper and Lewis, 1989, 1991). The massifs are intruded by tonalite stocks and batholiths of Late Cretaceous and Paleogene age (Kesler et al., 1991c; Escuder Viruete et al., 2007b). The section thickness is at least 3 km and could be as much as 9 km. Bowin (1975) and Palmer (1979) suggested the rocks represent a fragment of oceanic crust based on their oceanic-island basalt character and their ankaramite lithology (Lewis et al., 1983). Donnelly et al. (1990) pointed out the similarity to oceanic-island alkali basalts and suggested the rocks were originally a seamount chain, such as those forming the Hawaiian Islands today.

The age of the Duarte complex has been controversial. A Late Jurassic age was determined for the Duarte unit on the basis of the lower unit of the Duarte complex being in apparent direct contact with ~150 m of red radiolarian-bearing ribbon cherts, which are well exposed at El Aguacate in a thin belt near Janico at the eastern end of the western Duarte massif (Montgomery et al., 1994a). Detailed mapping (Lapierre et al., 1999) showed the contact to be faulted, leading to the conclusion that the Duarte complex is, at least in part, considerably younger than the Late Jurassic (Lapierre et al., 1999).

The Ar/Ar laser probe step heating (Lapierre et al., 1999) of hornblende crystals from an amphibolite in the southeast massif yielded cooling ages (Lewis et al., 1999) between 87 and 86 Ma. Other amphibolites from the northwestern massif yielded Ar-Ar hornblende plateau cooling ages of 93.9 ± 1.4 Ma and 95.8 ± 1.9 Ma. Based on the interpretation that the dates record cooling, Escuder Viruete et al. (2007b) also summarized the evidence that supports an Early Cretaceous age for the Duarte complex. Based upon regional, stratigraphic, geochronological, and structural data, they concluded that there is very strong evidence that the basaltic rocks of the Duarte complex were extruded in the Early Cretaceous, probably in the Aptian.

Curacao

The Curacao Lava Formation, which crops out on the island of Curacao, Netherlands Antilles, consists of a 5-km-thick sequence of submarine lava flows of picrite to olivine-phyric tholeiite in the lower part of the formation and olivine-phyric tholeiite to plagioclase-clinopyroxene tholeiite in the upper part (Beets, 1972; Beets et al., 1984). The lavas are commonly pillowed, with minor intercalations of basaltic hyaloclastite and some diabase sills. A single, thin succession of pelagic limestone and siliceous shale, containing Albian ammonites (Wiedmann, 1978), interlayered with hyaloclastites provides an age constraint. A U-Pb microbaddeleyite date of 112.7 ± 7.3 Ma (Humphrey, 2010) from diabase intruding the Upper Curacao Lava Formation is in general agreement with the ammonite age.

The basaltic rocks display distinct plateau-like geochemical characteristics. Trace-element compositions of the lavas are intermediate between N-MORB and E-MORB, have flat REE patterns, and do not contain a depleted Nb spike (Fig. 29E; Kerr et al., 1996a). A special feature of some of the basalts is that they have unusually high $^{87}Sr/^{86}Sr$ of 0.70321–0.70671 (Kerr et al., 1996a). These workers concluded that the presence of picritic (high-Mg) magmas suggests their derivation from an anomalously hot plume-derived mantle.

Late Cretaceous (Turonian) Plateau Rocks (Caribbean-Colombian Oceanic Plateau)

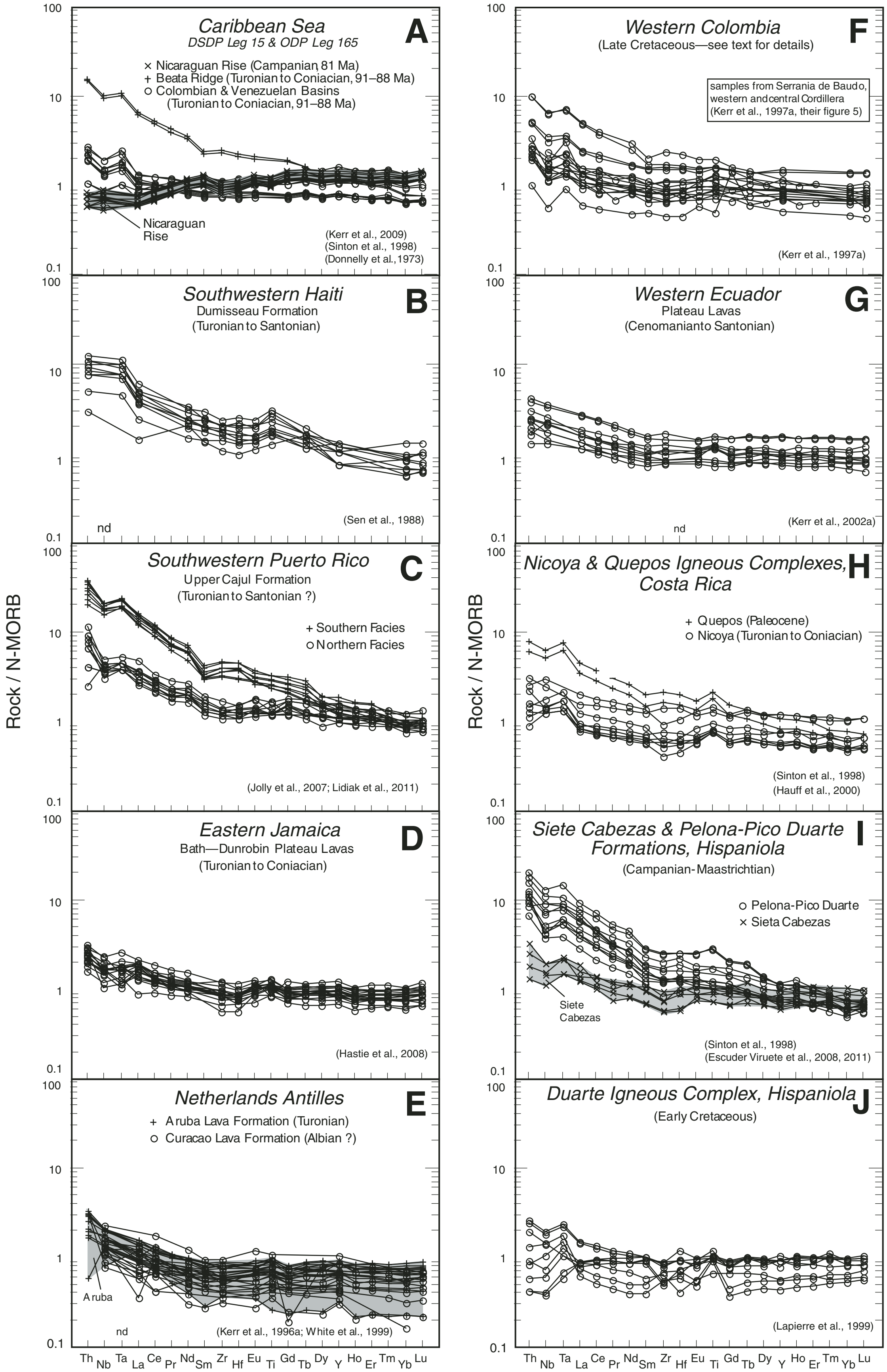
Caribbean Sea

A large, 6×10^5 km^2 plateau province composed of basalt underlies most of the Caribbean Sea (Donnelly et al., 1973; Sinton et al., 1998; Hauff et al., 2000; Revillon et al., 2000). In the area of the Caribbean Sea (Fig. 28), crustal thickness varies from 20 km along the Beata Ridge to less than 10 km south of Puerto Rico (Case et al., 1990; Mauffret and Leroy, 1997). Donnelly (1994) recognized that the submerged, upper surface of the plateau-forming crustal basalt may be correlated with Reflector B″ of the Caribbean Sea and units present in the Venezuela and northern Colombia Basins (Edgar et al., 1971; Bezada et al., 2010). Kerr et al. (1996b, 2000, 2002a) postulated, based upon geochemical data, that the Caribbean-Colombian oceanic plateau formed in response to development of a large volume of rapidly erupted basalt at the beginning of the Late Cretaceous.

According to Kerr et al. (2000, 2003), Caribbean plateau lavas may constitute three geochemical suites, not all of which may be exposed in a typical outcrop (Kerr et al., 1997b, 1998): (1) basalt, picrite (olivine basalt), and komatiite with LREE-depleted chondrite-normalized patterns; (2) basalt with LREE-enriched patterns; and (3) basalt with essentially flat REE patterns. The latter two types (Fig. 29A) commonly form the upper part of the plateau sequence, with the more heterogeneous high-MgO basalts lying near the base of the plateau.

Caribbean large igneous province/Caribbean-Colombian oceanic plateau rocks are not restricted to submarine exposures. Outcrops of ca. 87–90 Ma basalt from Jamaica, Hispaniola, Puerto Rico, Aruba, Costa Rica, Panama, and Colombia (Fig. 1) not only define the margin of the Caribbean large igneous province but also strongly suggest that the plateau locally was accreted (obducted?) onto the southern border of the Greater Antilles and northwestern South America (Kerr et al., 1997b, 1998, 2009). The common presence of basalt with flat REE patterns in continental exposures suggested to Kerr et al. (1997b, 1998) that the upper basaltic layers have been typically obducted, whereas the lower sequence of layered gabbro, pyroxenite, and dunite is either restricted to deeper-level thrust sheets or was subducted into the mantle during the process of accretion and imbrication.

The age of the Caribbean large igneous province/Caribbean-Colombian oceanic plateau is constrained by paleontologic and isotopic data. Samples collected from drilling the submerged plateau rocks during Deep Sea Drilling Project (DSDP) Leg 15 (Donnelly et al., 1973) and Ocean Drilling Program Leg 163 (Donnelly et al., 1990) include massive basalt flows and thick, coarse-grained diabase sills overlain by or intruding foraminiferal limestone of late Turonian (90 Ma) and early Campanian (80 Ma) age (Donnelly et al., 1973; Donnelly, 1994). The $^{40}Ar/^{39}Ar$ ages



Rock / N-MORB
Caribbean Sea
DSDP Leg 15 & ODP Leg 165
A
× Nicaraguan Rise (Campanian, 81 Ma)
+ Beata Ridge (Turonian to Coniacian, 91–88 Ma)
○ Colombian & Venezuelan Basins (Turonian to Coniacian, 91–88 Ma)
Nicaraguan Rise
(Kerr et al., 2009)
(Sinton et al., 1998)
(Donnelly et al., 1973)
Southwestern Haiti
Dumisseau Formation
(Turonian to Santonian)
B
nd
(Sen et al., 1988)
Southwestern Puerto Rico
Upper Cajul Formation
(Turonian to Santonian ?)
C
+ Southern Facies
○ Northern Facies
(Jolly et al., 2007; Lidiak et al., 2011)
Eastern Jamaica
Bath—Dunrobin Plateau Lavas
(Turonian to Coniacian)
D
(Hastie et al., 2008)
Netherlands Antilles
E
+ Aruba Lava Formation (Turonian)
○ Curacao Lava Formation (Albian ?)
Aruba
nd
(Kerr et al., 1996a; White et al., 1999)
Western Colombia
(Late Cretaceous—see text for details)
F
samples from Serrania de Baudo, western and central Cordillera (Kerr et al., 1997a, their figure 5)
(Kerr et al., 1997a)
Western Ecuador
Plateau Lavas
(Cenomanian to Santonian)
G
nd
(Kerr et al., 2002a)
Nicoya & Quepos Igneous Complexes, Costa Rica
H
+ Quepos (Paleocene)
○ Nicoya (Turonian to Coniacian)
(Sinton et al., 1998)
(Hauff et al., 2000)
Siete Cabezas & Pelona-Pico Duarte Formations, Hispaniola
I
(Campanian-Maastrichtian)
○ Pelona-Pico Duarte
× Sieta Cabezas
Siete Cabezas
(Sinton et al., 1998)
(Escuder Viruete et al., 2008, 2011)
Duarte Igneous Complex, Hispaniola
J
(Early Cretaceous)
(Lapierre et al., 1999)
100
10
1
0.1
Th Nb Ta La Ce Pr Nd Sm Zr Hf Eu Ti Gd Tb Dy Y Ho Er Tm Yb Lu

from the basaltic rocks at the margin of the Caribbean basin as well as from drill cores fall between 91 and 88 Ma (Sinton et al., 1998). Basalts, geochemically similar to the principal plateau-forming units (Caribbean large igneous province), from Beata Ridge yield dates younger than 80 Ma, and these were also considered part of the Caribbean large igneous province by Révillon et al. (2000).

The following paragraphs briefly describe exposures of mafic rocks that have geochemical and temporal similarities to the oceanic basalt that comprises the crust of the Caribbean Sea.

Hispaniola

On Hispaniola, outcrops in southwestern Haiti expose the Dumisseau Formation (Figs. 1 and 12A), a complex of igneous and sedimentary rocks consisting of interbedded pillowed and massive basalt, picrite, diabase, pelagic limestone, and volcanogenic turbidites (Maurrasse et al., 1979; Sen et al., 1988; Lewis and Draper, 1990; Sinton et al., 1998). The units, which are presumed to be an uplifted section of Caribbean Sea oceanic crust, are distinct from arc rocks as evidenced by flat to slightly elevated LREE patterns and the absence of Ta-depleted (and Nb-depleted) concentrations on chondrite- or N-MORB–normalized diagrams (Fig. 29B). The lowest lavas are LREE-depleted, similar to N-MORB, whereas overlying, younger lavas are LREE-enriched, similar to E-MORB (Sen et al., 1988). The $^{40}Ar/^{39}Ar$ dates from five samples from both groups fall between 92 and 89 Ma, with an average of 91.7 Ma, and are statistically indistinguishable from one another, indicating eruption of compositionally distinct lavas at about the same time interval (Sinton et al., 1998).

Jamaica

Generally massive, tholeiitic basaltic lavas with rare pillow texture, intercalated with tuff (Hastie et al., 2008), comprise the Dunrobin Formation that is exposed in the Blue Mountains inlier (Fig. 16). The restricted exposures preclude determination of the extent and thickness of the volcanic section. Radiolarians from mudstone and chert within the stratigraphic succession that are of middle Turonian to late Coniacian age (92–86 Ma; Montgomery and Pessagno, 1999) indicate correlation with the Caribbean large igneous province/Caribbean-Colombian oceanic plateau. The basalts display flat, nearly parallel patterns on typical normalized REE and other incompatible-element diagrams (Fig. 29D) and have concentrations of ~4–8 times primitive mantle values (Hastie et al., 2008). The lack of any negative Nb or Ta anomaly indicates that the lavas do not have any arc or backarc affinities. This geochemical signature is consistent with correlation to Caribbean oceanic plateau rocks. Hastie et al. suggested further that the presence of intercalated plateau basalt and island-arc tuff implies that the oceanic plateau was close to a subduction zone.

Puerto Rico

Basaltic and andesitic lava flows mapped as Upper Cajul Formation (ca. 90 Ma?) have been interpreted as Caribbean-Colombian oceanic plateau equivalents (Figs. 29C and 30; Jolly et al., 2007; Lidiak et al., 2011). The Upper Cajul rocks crop out among rafts and blocks of amphibolite (Las Palmas Amphibolite), basalt of N-MORB affinity, mapped as Lower Cajul Formation, and Jurassic to Late Cretaceous (ca. 188–90 Ma) pelagic Mariquita Chert (Montgomery et al., 1994a, 1994b) in serpentinized peridotite that forms the Bermeja Complex in southwestern Puerto Rico. Exposures of the Upper Cajul Formation are known from two different areas. A northern exposure consists of fault blocks in the Mariquita Chert that are characterized by E-MORB geochemistry (Jolly et al., 2007; Lidiak et al., 2011). To the south, the mafic rocks, which are interlayered with Mariquita Chert (Volckmann, 1984), have oceanic-island basalt geochemical characteristics.

The ages of the mafic rocks are poorly constrained. The oldest apparent ages of 129 Ma and 113 Ma (Barremian and Aptian) are K-Ar dates on hornblende from amphibolite at Sierra Bermeja (Mattson, 1964; Cox et al., 1977) that probably reflect later metamorphic events. Younger dates of 88.5 Ma, 88.3 Ma, 87.0 Ma, and 85.1 Ma (Tobisch, 1968; Cox et al., 1977; Schellekens, 1991) from Sierra Bermeja are also minimum ages and may represent subsequent tectonic or igneous activity. The Aptian-Albian and Turonian dates may record subduction-related or other igneous activity known in the Caribbean.

A unique interpretation of these K-Ar dates as they relate to the geology of the Bermeja complex is not possible at present. However, a key to better understanding the sequential development of the complex is the Mariquita Chert. The reported ages of the cherts are mainly Jurassic to Early Cretaceous, but they also record ocean-floor pelagic sedimentation at ca. 90 Ma (Montgomery et al., 1994a, 1994b), prior to emplacement in the serpentinite mélange. An episode of serpentinite emplacement to crustal levels and development of mélange was initiated after ca. 90 Ma. Some exotic blocks of chert, amphibolite, and basalt in the mélange must be ca. 90 Ma or older. A nonunique interpretation of the mafic rocks is that the amphibolite protoliths are mainly of Jurassic to possibly Early Cretaceous (>129 Ma to ca. 113 Ma) age and that the undated basalts of the various Cajul formations are at least 90 Ma and possibly older. We interpret the Bermeja complex assemblage as recording Paleocene (?) mixing of ocean-floor chert, ocean-ridge basalt, and younger plateau rocks in response to accretion and related obduction.

Aruba

The Aruba Lava Formation on the island of Aruba, Netherlands Antilles (Fig. 1), consists of a section of basalt and diabase,

Figure 29. Plots of normalized incompatible trace-element (ITE) compositions in Caribbean large igneous province (CLIP) rocks, Caribbean region. Data sources are listed in the figure (DSDP—Deep Sea Drilling Project; ODP—Ocean Drilling Program). Normalizing factors are from Sun and McDonough (1989). N-MORB—normal mid-ocean-ridge basalt; small nd—not determined.

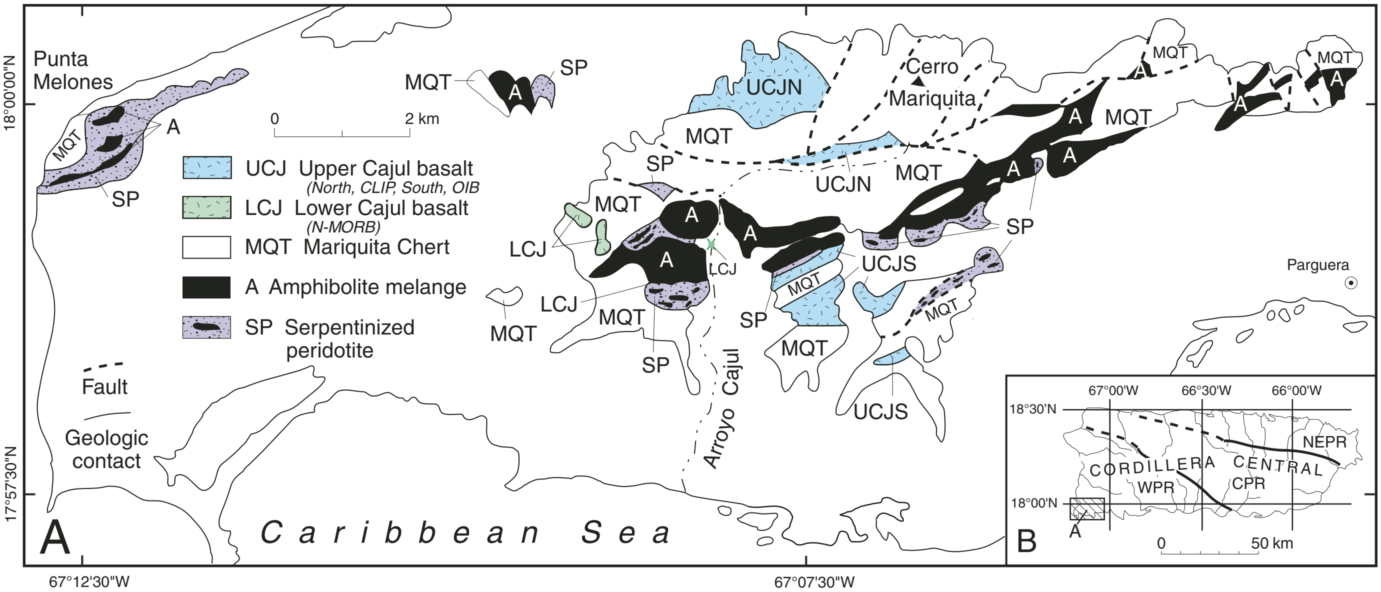


Figure 30. (A) Geologic map of Sierra Bermeja region, southwest Puerto Rico, illustrating exposures of serpentinized spinel peridotite mélange containing numerous blocks of amphibolite (SP), Mariquita Chert (MQT), Las Palmas Amphibolite mélange (A), and Lower Cajul basalt (LCJ), Upper Cajul Basalt, northern section (UCJN), and Upper Cajul Basalt, southern section (UCJS). Figure is adapted and modified from Volckmann (1984). CLIP—Caribbean large igneous province; OIB—oceanic-island basalt; N-MORB—normal mid-ocean-ridge basalt. (B) Inset map shows location of Sierra Bermeja region in southwest Puerto Rico. WPR—western Puerto Rico; CPR—central Puerto Rico; NEPR—northeast Puerto Rico.

pyroclastic and volcaniclastic beds, and phyllite more than 3 km thick (Beets et al., 1984). The section is intruded by a composite tonalite-gabbro batholith (Westermann, 1932; Beets et al., 1984; White et al., 1999; Wright and Wyld, 2011). Multi-element plots of Aruba lavas (Fig. 29E) display flat patterns without a depleted Nb anomaly (White et al., 1999). The chemistry of the Aruba Lava Formation resembles that of the basalts of the older Curacao Lava Formation (discussed in a following section) except for the absence of picrite and the presence of more-evolved ferro-basalt in the upper part of the Aruba lava flows (Beets et al., 1984). The Ar systematics and $^{40}Ar/^{39}Ar$ dates are disturbed and therefore not reliable (White et al., 1999). However, ammonite imprints (Beets et al., 1984) suggest that the fauna is Turonian (ca. 93–89 Ma). This age is consistent with U-Pb zircon data indicating an emplacement age of 89 ± 2 Ma for the Aruba Batholith (Wright and Wyld, 2011). These dates indicate the Aruba lavas formed during the main phase of Caribbean plateau basalt magmatism. The composition and homogeneous character of the Aruba lavas suggest an enriched mantle source, similar to that of the older Early Cretaceous Curacao Lava Formation.

Costa Rica

Radiometric $^{40}Ar/^{39}Ar$ dates on basalt, diabase, and gabbro from the Nicoya Peninsula and adjacent areas are 90–88 Ma and 84–83 Ma (Sinton and Duncan, 1997; Sinton et al., 1998), suggesting correlation with the Caribbean large igneous province/Caribbean-Colombian oceanic plateau. The Nicoya (ca. 90 Ma) and the Herradura (ca. 80 Ma) terranes consist of fault-bounded sequences of sedimentary rocks, tholeiitic pillow basalt and sheet flows, and plutonic rocks that have plateau-like geochemical characteristics (Fig. 29H) and that are similar to basalt from the Galapagos Islands (Fig. 1; Hauff et al., 1997; Sinton and Duncan, 1997; Hauff et al., 2000). Hauff et al. (2000) interpreted the geochemical patterns to indicate similarity to the generation of Caribbean large igneous province/Caribbean-Colombian oceanic plateau rocks along a Galapagos hotspot.

Western Colombia and Western Ecuador

In western Colombia, three NNE-trending belts, namely, the Central Cordillera, the Western Cordillera, and the Serrania de Baudó (Fig. 1), along the Pacific Coast (Millward et al., 1984; Aspden et al., 1987; Kerr et al., 1997a, 2002a) contain exposures of igneous rocks composed of mainly basalt, diabase, and picrite. Rocks from the Western Cordillera and Serrania de Baudó are mainly basalt having tholeiitic affinities with generally flat and parallel N-MORB–normalized patterns (Fig. 29F).

The Western Cordillera of Ecuador consists of allochthonous blocks that accreted onto northwestern South America during the Late Cretaceous to Eocene (Goosens and Rose, 1973; Spikings et al., 2001; Hughes and Pilatasig, 2002; Kerr et al., 2002b; Vallejo et al., 2006, 2009). These blocks consist of oceanic plateau basalt, island-arc tholeiite, and minor calc-alkaline lava (Kerr et al., 2002b). Mafic and ultramafic rocks of oceanic plateau affinity crop out in the Western Cordillera as the Pallatanga Formation

and San Juan unit (Vallejo et al., 2009) and in coastal Ecuador as the Piñon Formation (Kerr et al., 2002b). These rocks have E-MORB and oceanic plateau geochemical characteristics (Fig. 29G), suggesting eruption from a mantle plume (Lebrat et al., 1985; Lapierre et al., 2000; Hughes and Pilatasig, 2002; Kerr et al., 2002b; Mamberti et al., 2003). In contrast, igneous rocks of the Central Cordillera to the east are more compositionally diverse, ranging from moderately enriched (E-MORB) to relatively depleted (Kerr et al., 1997a, 2002b).

Isotopic data from mafic rocks exposed in the belts yield Cretaceous dates. Basaltic rocks along the Pacific Coast of Colombia (Serrania de Baudó) yield $^{40}Ar/^{39}Ar$ dates between 78 Ma and 73 Ma. A single plateau date from the Western Cordillera is apparently older at 91.7 Ma (Kerr et al., 1997a, 2003; Sinton et al., 1998). In addition, basalts from Gorgona Island yield whole-rock $^{40}Ar/^{39}Ar$ dates of 88.3–86.7 Ma. The dates from Serrania de Baudó are consistent with paleontological evidence from intercalated sedimentary rocks. Basalts from the Central Cordillera have Ar-Ar dates of 92–84 Ma, indicating they are part of the Caribbean-Colombian oceanic plateau according to Kerr (Kerr et al., 1997a, 2002b). A U-Pb (SHRIMP) zircon date from the San Juan unit is 87.1 Ma (Vallejo et al., 2006). This age is consistent with a $^{40}Ar/^{39}Ar$ date on hornblende of 88.1 Ma from the coastal Piñon Formation (Luzieux et al., 2006), and it suggests that these rocks crystallized at the same time as the Caribbean-Colombian oceanic plateau (ca. 91–88 Ma). However, Vallejo et al. (2009) also noted that the San Juan unit may be Early Cretaceous based on a Sm/Nd date of ca. 123 Ma (Lapierre et al., 2000). Also, Kerr et al. (2002b) argued on the basis of uncertain stratigraphy that the Piñon Formation may be older than 94 Ma.

Summary, Distribution, and Ages: Ca. 89 Ma Plateau Rocks

Oceanic basement of the Caribbean Sea, composed of anomalously thick, Late Cretaceous, ca. 89 Ma oceanic crust (Mauffret and Leroy, 1997; Sinton et al., 1998; Mauffret et al., 2001), comprises a Caribbean Sea oceanic plateau (e.g., Lapierre et al., 2000; Kerr et al., 2003; Mamberti et al., 2003). A ca. 90 Ma age of Caribbean large igneous province/Caribbean-Colombian oceanic plateau crust is indicated by fossiliferous limestone interbedded with plateau basalt at the DSDP Leg 15 drill site (Donnelly et al., 1973, 1990).

Plateau-like crustal sequences crop out in Panama, Costa Rica, Aruba, Hispaniola, and Puerto Rico (Girard, 1981; Beets et al., 1984; Sen et al., 1988; Frisch et al., 1992; Kerr et al., 1997b, 2003; Sinton and Duncan, 1997; Sinton et al., 1998; Lapierre et al., 2000; Revillon et al., 2000; Jolly et al., 2007; Lidiak et al., 2011). Lithological, geochemical, and chronological similarities among rocks with oceanic plateau affinities are recognized in northwestern South America (McCourt et al., 1984; Millward et al., 1984; Aspden and McCourt, 1986; Aspden et al., 1987; Megard, 1987; Spadea et al., 1989; Nivia, 1996; Kerr et al., 1998, 2003; Spikings et al., 2001; Kerr and Tarney, 2005), especially west of the Romeral fault, on the western side of the Central Cordillera (Vallejo et al., 2009) and Gorgona Island (Restrepo and Toussaint, 1974). The rocks with oceanic plateau affinity of Colombia range between 91.7 ± 2.7 Ma and 70.0 ± 3.5 Ma (Bourgois et al., 1982; Kerr et al., 1997a; Sinton et al., 1998; Walker et al., 1999). Vallejo et al. (2009) postulated that the leading edge of the Caribbean plateau, and an overlying arc, collided with the Ecuadorian sector of South America during the late Campanian–Maastrichtian (ca. 75–65 Ma). They further pointed out that shear sense indicators within a principal bounding fault, the Calacalí-Pujilí-Pallatanga fault (Hughes and Pilatasig, 2002), and paleomagnetically constrained block rotations (Luzieux et al., 2006) record a dextral sense of movement associated with east-northeastward–oriented collision of the Caribbean plateau.

Latest Cretaceous (Campanian–Maastrichtian) Large Igneous Provinces

Central Hispaniola

Peloma–Pico Duarte Formation. The Peloma–Pico Duarte Formation crops out in the area of Pico Duarte and unconformably (?) overlies units of the Tireo Group (Escuder Viruete et al., 2011; Sandoval et al., 2015). The unit consists of massive, homogeneous, basaltic submarine flows that are locally interlayered with mafic tuffs, hyaloclastite, and intruded by synvolcanic dikes and sills of basalt and diabase (Escuder Viruete et al., 2011). Felsic volcanic rocks are absent. Two ^{40}Ar-^{39}Ar dates on the Pelona–Pico Duarte yielded plateau ages of 79.4 Ma and 68.4 Ma, which suggest that these magmas are younger but possibly in part coeval with volcanism at ca. 80–75 Ma (Revillon et al., 2000; Escuder Viruete et al., 2011). The Pelona–Pico Duarte rocks are slightly more enriched but otherwise similar to Siete Cabezas volcanics (Fig. 29J). Trace-element compositions show that both units are very similar to the plateau basalt of the Caribbean large igneous province/Caribbean-Colombian oceanic plateau along the Beata Ridge (Sinton et al., 1998) in having a moderately enriched or E-MORB component, including relatively flat REE concentrations, and lacking negative Nb-Ta anomalies on N-MORB–normalized diagrams. These geochemical characteristics resemble those of the Caribbean large igneous province/Caribbean-Colombian oceanic plateau basalt.

Siete Cabezas Formation. The Peloma–Pico Duarte rocks are slightly more enriched but otherwise similar to Siete Cabezas volcanics (Fig. 29I). The Siete Cabezas Formation crops out along a narrow, 60 km belt adjacent to the northeastern flank of the Duarte complex. The rocks are generally well exposed with little deformation and are generally fresh with little hydrothermal alteration except for some specific areas. The structural stratigraphic relations with other units including the Duarte complex are not clear (Sandoval et al., 2015), but based on the recent mapping by the European SYMIN project, Escuder Viruete et al. (2008) stated that the Siete Cabezas Formation unconformably overlies the Duarte complex in the Villa Altagracia area. The formation consists of fine-grained massive fresh vitric basalt, interpreted as sheet flows, with a varied mix of vitroclastic breccia, tuff, and basalt with pillow texture. True hyaloclastic breccia is present. A 0.6 km belt of volcaniclastic sedi-

mentary rock with radiolarian-bearing tuff and chert interlayered with basalt was sampled by Montgomery and Lewis in 1996. Studies of these samples indicate a Campanian to Maastrichtian age (Sinton et al., 1998; Montgomery and Pessagno, 1999). Sinton et al. (1998) obtained consistent ^{40}Ar-^{39}Ar ages with both whole-rock (69.0 ± 0.7 Ma) and plagioclase (68.5 ± 0.5 Ma) analyses. The Siete Cabezas basalt at 69 Ma is the youngest land fragment of oceanic plateau basalt in the northern Caribbean, together with samples from Costa Rica and DSDP Leg 15 (Sinton et al., 1998, 2000; Hauff et al., 2000), and they meet the geochemical constraints for a plume origin.

The ages and the geochemical characteristics of the lavas led Lewis et al. (2002) to attribute this unit to the Caribbean large igneous province. Siete Cabezas basalt is dominantly tholeiitic (subalkalic), transitional, and alkalic basalt (Donnelly et al., 1990; Lewis and Draper, 1990; Sinton et al., 1998; Lewis et al., 2002; Escuder Viruete et al., 2008) and has REE and other incompatible-element contents that indicate derivation from nonsubducted enriched mantle sources that approximate E-MORB compositions (Fig. 29I; Escuder Viruete et al., 2008). The proposed origin of the Siete Cabezas basalt is that it represents a Caribbean plume component that erupted in a probable extensional setting, with the resulting compositions having nonarc geochemical affinities (Escuder Viruete et al., 2008, 2011).

Puerto Rico

Another unit in Puerto Rico for which geochemical characteristics are comparable to the Caribbean large igneous province is the Maricao Basalt. The Maricao Basalt consists of large blocks and is closely associated with the Yauco Formation. Its stratigraphic position is uncertain; however, its age is probably Campanian or Maastrichtian. Maricao geochemistry is rather distinct (Fig. 23B), having only slightly elevated LREE contents and rather subdued Nb and Ta negative anomalies, which are distinct from other Late Cretaceous calc-alkaline rocks in western Puerto Rico and not dissimilar to the Siete Cabezas and Peloma–Pico Duarte Formations of Hispaniola.

Costa Rica

As noted previously, plateau-like basalts in Costa Rica have been recognized by Hauff et al. (2000), Hoernle et al. (2004), and Sinton et al. (1998) at three locations: Nicoya Peninsula, Herradura (Playa Jacoó), and Quepos Peninsula. In addition to the previously noted $^{40}Ar/^{39}Ar$ dates on basalt, diabase, and gabbro of 90–88 Ma and 84–83 Ma from the Nicoya Peninsula (Sinton and Duncan, 1997; Sinton et al., 1998), a single $^{40}Ar/^{39}Ar$ date of 63 Ma was obtained from a Quepos basalt. Older $^{40}Ar/^{39}Ar$ dates of 139–111 Ma were determined on glasses from pillow basalts of the Nicoya complex (Hoernle et al., 2004).

All three of the complexes (Nicoya complex, Jacoó basalt, Quepos basalt) are remarkably similar in major-element, trace-element, and Sr-Nd isotope geochemistry. They basically display plateau, plume-like moderately enriched (between N-MORB and E-MORB) patterns on incompatible-element diagrams, without negative Nb or Ta spikes (Fig. 29I). These geochemical similarities are comparable to those of the Caribbean Cretaceous oceanic plateau (Caribbean large igneous province/Caribbean-Colombian oceanic plateau; Hauff et al., 1997; Sinton et al., 1998), however their ages are diverse.

Origins of the Caribbean Large Igneous Province/ Caribbean-Colombian Oceanic Plateau

The presence of exposed pelagic chert that contains fauna of Pacific origin (Montgomery et al., 1994a, 1994b) has led to the common acceptance of the idea that the overlying Caribbean plateau has moved eastward from the Pacific into the Caribbean basin (e.g., Pindell et al., 2005). A Pacific origin for Caribbean large igneous province was first suggested by Duncan and Hargraves (1984) and was later demonstrated by the presence of Lower to Upper Jurassic radiolaria of Pacific provenance in red ribbon chert from the Bermeja complex of Puerto Rico, the Duarte complex of Hispaniola, and from La Désirade (Montgomery et al., 1994a). The distributions of Caribbean large igneous province rocks that crop out on the southern margins of some islands of the Greater Antilles are compatible with eastward movement of the Caribbean large igneous province/Caribbean-Colombian oceanic plateau. Hastie and Kerr (2010) concluded from melt models that eruption above a mantle plume such as the Galapagos hotspot was the best source for the ca. 90 Ma plateau basalt.

REGIONAL UNCONFORMITIES—INTERRUPTIONS OF SUBDUCTION AND UPLIFT EVENTS

Islandwide stratigraphic correlations of Cretaceous volcanic rocks, such as the correlation chart for Puerto Rico offered by Jolly et al. (1998b, their figure 11A), provide a useful starting point for the recognition of regional unconformities. Three regional unconformities that are generally marked by sedimentary rocks, including conglomerate low in the sections and overlying carbonate beds, signal interruptions in volcanism that focus attention upon magmatic lulls, which may signal important changes in plate motion. In addition to conglomerate, some unconformities are covered by remarkably coarse deposits containing poorly sorted blocks, the largest of which, called olistostromes, are measured in kilometers. The regional hiatuses, which may be constrained by fossil and isotopic ages, are as follows: (1) Early Cretaceous (Albian): cessation of volcanism ca. 110 Ma, resumption of sedimentation ca. 100 Ma, followed by magmatism at ca. 96 Ma; (2) Late Cretaceous (Campanian): cessation of magmatism by ca. 72 Ma, followed by abrupt uplift and resumption of sedimentation by ca. 71 Ma; and (3) late Eocene: cessation of magmatism by 48 Ma.

Albian

In Puerto Rico, Albian carbonate reefs including the Aguas Buenas Limestone and nearby Rio Maton Limestone, suggest a

time of clear water perhaps contemporaneous with a pause in volcanism (Fig. 11B). However, the reefs have been interpreted to be separate limestone horizons (Briggs, 1969; Kazor and Rogers, 1990), although structural relations shown by quadrangle maps (Berryhill and Glover, 1960; Rogers, 1979) are sufficiently complex that correlation of the reefal units is not precluded.

The Albian carbonate beds in Puerto Rico fall within the time of the well-documented unconformity in Hispaniola (Russell and Kesler, 1991; Lebron and Perfit, 1994) that is recorded by conglomerate and the reefal Hatillo Limestone, which interrupted the volcanic succession sometime between ca. 110 and 100 Ma. Accumulation of ~100 m of Hatillo reefal limestone above a thin (<10 m), disconformable, discontinuous layer of chert-pebble conglomerate records a pause in magmatism. Marine invertebrates recovered from the Hatillo Limestone establish its age as late early Albian (ca. 108 ± Ma; Myczynski and Iturralde-Vinent, 2005) and indicate its correlation with the Cañas Limestone, which also formed in shallow water and contains fossils similar in age to those of Hatillo Limestone (Bowin, 1966). Las Lagunas Formation (Bowin, 1966), which concordantly overlies the Hatillo Limestone and consists of a monotonous succession of epiclastic tuff, mudstone, and rarely limestone, began to accumulate during Cenomanian time (Boisseau, 1987).

Stratigraphic and structural relationships in the central Dominican Republic indicate that locally strong Early Cretaceous deformation coincided with the cessation of the Early Cretaceous island-arc magmatism (Draper et al., 1996; Fig. 12 herein). The age of the deformation is constrained by a penetrative fabric that distinguishes the Ozama and El Altar shear zones. Rocks of the Maimón belt and Los Ranchos Formation record this fabric. The carbonate units are younger than ca. 111 Ma, the U/Pb interpreted crystallization age of the highest Los Ranchos member (Kesler et al., 2005). The unconformably overlying chert-pebble conglomerate (Russell and Kesler, 1991) and fossiliferous Hatillo Limestone (Bowin, 1966) are not penetratively deformed (Draper et al., 1996). Rojas-Agramonte et al. (2010) noted that K-Ar dates for high-pressure blocks in central Cuba (Somin and Millán, 1981; Iturralde-Vinent et al., 1996) cluster around ca. 110 Ma, suggesting that cooling and perhaps uplift took place at that time.

In Cuba, a mid–late Albian unconformity is marked by conglomerate that contains pebbles of plutonic, volcanic, and metamorphic rocks having arc affinities (Iturralde-Vinent, 1996b; Kerr et al., 1999). In any case, by ca. 100 Ma, these authors suggested that unconformable conglomerate, turbiditic sandstone and siltstone, and submarine basaltic lava began to accumulate in a major basin developed upon the earlier flows and breccia overlain locally by Albian reefal carbonate.

In summary, the Hattillo Formation, along with Constanza and El Convento, all of which probably are correlative with the Rio Maton, coincided with the cessation of the initial phase of arc magmatism recorded in the Greater Antilles. The pause lasted for ~15 m.y. or less, until eruption of the upper Tireo Formation, which began perhaps as early as 93 Ma (Lewis et al., 1991; Escuder Viruete et al., 2007a; Rojas-Agramonte et al., 2010). The upper Tireo Group, which is composed of Nb-enriched basalt, high-Mg andesite, and dacite to rhyolite flows, tuff and breccia, and intrusive dikes and domes of rhyolite (Lewis et al., 1991), records an important change in composition from an island-arc suite of PIA/IAT to low-K calc-alkaline basalt and andesite (Escuder Viruete et al., 2007a; Figs. 18 and 19 herein).

Santonian

Jolly et al. (1998b) showed unconformities interrupting stratigraphic sections in the Central Volcanic Province between ca. 85 and 80 Ma. Stratigraphic relations shown by Glover (1971) suggested that coarse debris of the Achiote and Carriblanco Formations marks the unconformity (Fig. 11C).

Late Campanian

Sedimentary strata, commonly calcareous, also mark a regional unconformity of probable late Campanian age (ca. 71 Ma) that interrupts Late Cretaceous magmatism on several Caribbean islands. In Puerto Rico, by the Maastrichtian, the accumulation of limestone (La Muda Limestone) and clastic strata (Monacillo Formation) signaled the cessation of Late Cretaceous magmatism (Tortugas Andesite and lavas of Friales Formation; Jolly et al., 1998b; Fig. 11A herein). The important latest Cretaceous–earliest Tertiary tectonic event and interruption of magmatic arc activity are identified by means of an erosional hiatus embracing the late Maastrichtian through Danian, which relates to uplift and erosion of the Cretaceous arc (Jolly et al., 1998b).

Stratigraphic disconformities recorded by rocks in the Virgin Islands also suggest uplift and erosion during the Late Cretaceous. On St. Croix, U.S. Virgin Islands, outcrops reveal a thick sequence of folded Upper Cretaceous turbidite and related rocks of volcanogenic origin that accumulated in an arc tectonic setting (Whetten, 1966; Speed et al., 1979; Speed and Joyce, 1989, 1991; Larue, 1994). These sedimentary rocks are intruded by two dioritic plutons, dated by $^{40}Ar/^{39}Ar$ at 69–70 Ma (Smith et al., 1998), and by a series of calc-alkaline sills and dikes (Lidiak and Jolly, 1998) also dated by $^{40}Ar/^{39}Ar$ at 78 Ma (Kappelman et al., 2013). These Upper Cretaceous rocks are unconformably overlain by Miocene limestone (Whetten, 1966; Lidz, 1988). A Late Cretaceous hiatus is also present immediately to the north in the British Virgin Islands and adjacent St. Thomas and St. John of the U.S. Virgin Islands, where an apparent unconformity separates Campanian Congo Bay Limestone from the Eocene Necker Formation (Helsley, 1960; Rankin, 2002; Jolly et al., 2006).

In Hispaniola, the nonvolcanic late Campanian–Maastrichtian Trois Riviere Formation covers older Cretaceous volcanic units (Lewis et al., 1991). Lewis et al. further pointed out that the overlying, latest Maastrichtian–Paleocene Don Juán Formation, which consists of coarse-grained and poorly sorted red terrestrial conglomerate, records the uplift and erosion of the Cretaceous Tireo volcanic arc rocks. The conglomerate and

olistostromal rocks containing ophiolite-derived material (Pindell and Draper, 1991) comprise the lower half of the Late Maastrichtian–Paleocene Imbert Formation, which may be compared to the La Picota Formation of eastern Cuba (Fig. 31; Iturralde-Vinent and MacPhee, 1999). These rocks and relationships suggest uplift and support the idea of a tectonic phase, as identified by Bowin (1966) and outlined by Mann et al. (1991, "phase 4" therein) and Draper et al. (1994), affecting the island-arc terrane of Hispaniola.

In north-central Cuba, comparable units include Upper Maastrichtian strata that consist of calcareous clastic rocks resting unconformably upon Turonian calcareous strata of the Bahamas margin (Fig. 14; van Hinsbergen et al., 2009). The hiatus is further constrained by the U-Pb SHRIMP interpreted crystallization ages between ca. 74 and 72 Ma from blocks of I-type granitoids in the northern ophiolite mélange (Rojas-Agramonte et al., 2010). These ages overlap with whole-rock Ar/Ar cooling dates from volcanic and plutonic rocks in the Camaguey area (Hall et al., 2004; Kesler et al., 2004). Ar/Ar ages of 72–75 Ma were obtained for rhyolite-rhyodacite domes of the La Sierra Formation, which Hall and Kaiser believed formed upon a contemporaneous paleosurface (Fig. 15). In summary, magmatism that had ceased by 70 Ma was followed by accumulation of carbonate rocks.

In Jamaica, the volcanic arc section displays an interruption of the volcanic activity along with uplift, thrust tectonics, and a latest Campanian–early Maastrichtian hiatus, followed by deposition of Late Maastrichtian limestone and clastic rocks (Mitchell, 2006); ophiolite obduction took place during the Maastrichtian (Wadge et al., 1982). Furthermore, Maastrichtian to Paleocene coarse-grained sedimentary rocks (Bowden Pen and Moore Town Formations) have been compared to the Sepur Formation of Guatemala (Robinson, 1994).

Mapping and age determinations in the Netherlands Antilles of Aruba, Curacao, and Bonaire led Wright and Wyld (2011) to conclude that each of these islands preserves its own Cretaceous stratigraphic, magmatic, and structural sequence of geologic events. It was not until the latest Cretaceous to Paleogene that the three islands began to merge into a common tectonic history. During this time, there was exhumation of batholithic rocks on Aruba, strata derived in part from South America were deposited on Bonaire and Curaçao, and all three islands were unconformably overlain by Eocene limestone (Wright and Wyld, 2011).

Late Eocene (Ca. 44 Ma)

The short-lived episode of subduction-related magmatism documented between 61 and 48 Ma by Rojas-Agramonte et al. (2004, 2006) probably included La Mulata columnar basalt, which yields dates of ca. 50 Ma (Hall et al., 2004; Fig. 14 herein). Hall et al. (2004) noted that the scattered fresh exposures reveal vertical orientation of columns, suggesting that the La Mulata erupted onto a paleosurface similar to the present surface (Fig. 15). Sedimentary rocks overlie La Mulata and also have been reported from Sierra Maestra to the east (Fig. 24; Lewis and Straczek, 1955; Cobiella Reguera, 1988; Garcia-Delgado and Torres Silva, 1997). Rojas-Agramonte et al. (2004) reported that subvolcanic bodies, which cut the strata, yield U-Pb zircon ages between ca. 50 and 47 Ma. They also pointed out that stratigraphic relations record significant surface uplift and denudation along the axis of the Sierra Maestra and that a hiatus may be recognized at ca. 44 Ma (Rojas-Agramonte et al., 2006, their figure 3).

EMPLACEMENT OF OLISTOSTROMES FOLLOWING INTERRUPTIONS OF ARC MAGMATISM, COOLING, AND DEVELOPMENT OF REGIONAL UNCONFORMITIES

The ages of the three regional unconformities—ca. 105 Ma, 71 Ma, and ca. 48–45 Ma—that coincide with interruptions of arc magmatism generally correlate with cooling ages in metamorphic and igneous rocks. The unconformably overlying units may include carbonate strata and/or clastic units that contain

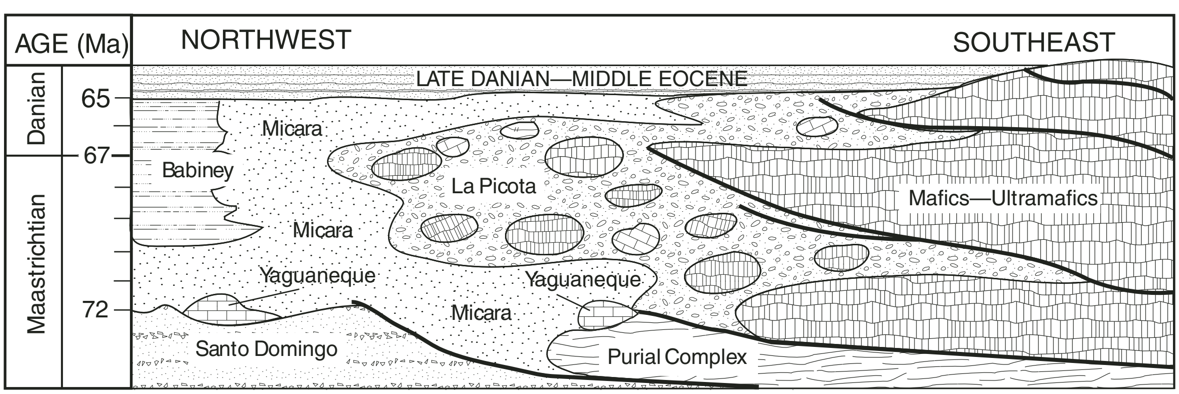


Figure 31. Diagrammatic cross section of the Mícara and La Picota late Maastrichtian–early Danian formations showing olistostromes (La Picota Formation) emplaced with thrust faults and obduction of ultramafic bodies against disconformably overlying units. Figure is adapted from Iturralde-Vinent et al. (2006).

debris and large blocks (olistoliths), which are commonly attributed to gravity-driven, downslope movement of sediment (Fig. 31). Stratigraphic relationships, especially those in Cuba and southwestern Puerto Rico, suggest to us that temporally separate pulses of contraction, uplift, and olistostrome emplacement may be recognized following cessation of Late Cretaceous and Paleocene subduction-related magmatism and occurring contemporaneously with contraction, uplift, and cooling.

Aptian–Albian (Ca. 120–105 Ma)

No olistostromal deposits have been reported from suites of Early Cretaceous volcanic and sedimentary layers. However, strong deformation that took place after ca. 110 Ma, during Aptian emplacement of peridotite onto Early Cretaceous volcanic rocks, is recognized in Hispaniola (Draper et al., 1996). Studies of pargasite and other metamorphic minerals in mélange rocks from Hispaniola and Cuba indicate that cooling of amphibolite masses began at ca. 105 Ma, and that by ca. 100 Ma, the argon retention temperature of amphibole had been reached (Krebs et al., 2008; Lázaro and García-Casco, 2008). The cooling ages are younger than the youngest known crystallization ages of magmatic rocks of the Early Cretaceous magmatic suite in Cuba, ca. 112 Ma (Rojas-Agramonte et al., 2011), and in Hispaniola, ca. 111 Ma (Kesler et al., 2005). Analyses of time, temperature, and pressure data acquired from rocks within the Sierra del Convento mélange in eastern Cuba led Lazaro et al. (2009) to conclude that cooling from peak temperature took place between 115 and 107 Ma. The cooling ages correspond well with the inferred age of the Aptian unconformity.

Late Campanian (Ca. 71 Ma)

Stratigraphic and geochronologic data indicate the Campanian as the time of termination of magmatic activity in the Antillean volcanic arc, and concomitant deformation, uplift, cooling, and erosion of Cretaceous volcanic and ophiolitic rocks. Latest Campanian–Maastrichtian sedimentary rocks generally overlie with angular unconformity the deformed late Campanian and older volcanic-plutonic suites in Cuba (Pushcharovsky, 1988; Pushcharovsky et al., 1989; Iturralde-Vinent, 1994, 1998) and in Puerto Rico (Fig. 11A; Pease, 1968a; Jolly et al., 1998b). In central Cuba, latest Campanian clastic rocks overlying older Cretaceous units were derived from erosion of ophiolite and Cretaceous volcanic-plutonic arc rocks (Bronnimann and Rigassi, 1963; Iturralde-Vinent, 1976, 1977; Albear and Iturralde-Vinent, 1985; Iturralde-Vinent, 1995, 1998; Tada et al., 2003).

Late Cretaceous cooling ages reported from high-pressure blocks in serpentinite mélanges cluster around 70 Ma in Cuba (Garcia-Casco et al., 2008b; Lazaro et al., 2009), the Dominican Republic (Krebs et al., 2008), and Guatemala (Harlow et al., 2004). Cooling was contemporaneous with the sudden arrest of magmatic activity in the Late Cretaceous arc (Iturralde-Vinent, 1994, 1998; Hall et al., 2004; Kesler et al., 2004).

Perhaps the best example of the transition from Late Cretaceous arc magmatism to uplift and cogenetic collision is found in eastern Cuba, where the pre–latest Maastrichtian Yaguaneque Limestone, which irregularly overlies the volcanic-bearing Late Cretaceous section (Iturralde-Vinent et al., 2008), crops out. Cobiella et al. (1984) and Quintas (1987, 1988a, 1988b) suggested that the limestone may have accumulated above contemporaneously developing thrust sheets, as indicated by the incorporation of fragments of the limestone into the mainly early Danian (ca. 64 ± Ma) clastic Mícara and La Picota units (Fig. 31; Iturralde-Vinent, 1976, 1977; Iturralde-Vinent et al., 2006; Cobiella et al., 1984; Pushcharovsky, 1988). Emplacement of ophiolite masses, synchronous with deposition of olistostromes (La Picota Formation), probably recorded uplift and exhumation of ophiolite, volcanic arc rocks, and metamorphic complexes concurrent with thrust faulting and obduction (Fig. 31; Iturralde-Vinent et al., 2006).

The Mícara Formation consists of well-bedded, graded, polymictic sandstone and shale, with local intercalations of conglomerate and breccia and, in some sections, well-bedded serpentinitic sandstone and gravel, generally found near thrust sheets of gabbro and serpentinite. The Mícara and La Picota Formations, which contain early Danian fossils (Iturralde-Vinent et al., 2006), commonly grade upward into late Danian marl, marly limestone, and conglomerate with white, tuffaceous intercalations (Gran Tierra and Sabaneta Formations; Iturralde-Vinent, 1976, 1977) that record resumption of subduction-related, mid-Paleocene to mid-Eocene calc-alkaline magmatism (see Rojas-Agramonte et al., 2004). La Picota includes lenses of massive, chaotic layers of pebbles, blocks, and boulders of gabbroic rocks and serpentinite that interfinger with and may be enclosed by the Mícara Formation (Fig. 31).

In western Cuba, late Danian breccia and conglomerate of La Guira Formation correlate with the Mícara Formation (Fig. 32). La Guira strata generally disconformably overlie commonly deformed Cretaceous units (Bralower and Iturralde-Vinent, 1997) and underlie Paleocene and early Eocene units such as the Ancon and Manacas units. These post-Cretaceous units, along with the correlative Capdevila Formation, comprise conformable, well-bedded sections of radiolarian marl and other pelagic (deep-water) carbonate beds that contrast strongly with the coarse underlying units. Saura et al. (2008, his figure 3) showed the Capdevila Formation as accumulating in "piggyback basins" that rested disconformably upon the older, Paleocene thrust duplex.

Similar stratigraphic relations are present in Hispaniola, where, as noted earlier herein, the lower half of the Imbert Formation includes Maastrichtian–early Danian conglomerate and breccia similar to La Picota Formation. Overlying late Danian–Eocene, white, tuffaceous strata are similar to those in Cuba (Iturralde-Vinent, 1994; Iturralde-Vinent and MacPhee, 1999; Iturralde-Vinent et al., 2006).

In western Puerto Rico (Figs. 20 and 33), comparable tectonostratigraphic units may be recorded by calcareous rocks (Fig. 34) that locally are disrupted and incorporated into thick

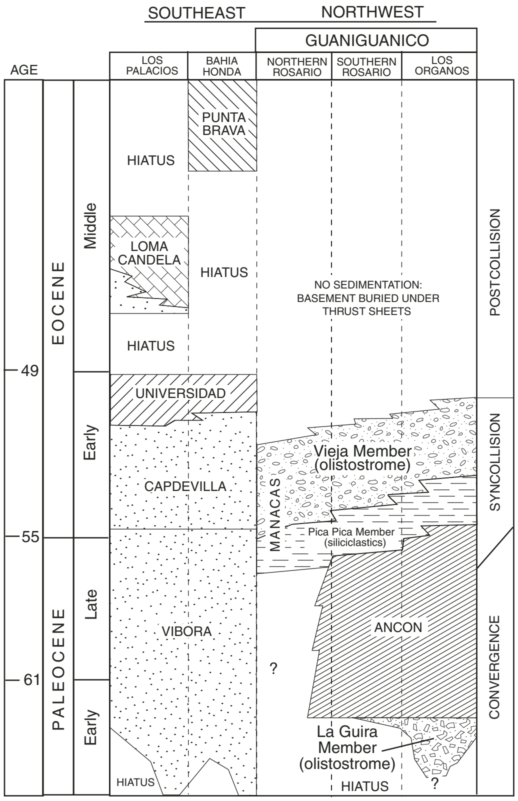


Figure 32. Stratigraphic chart for the uppermost Cretaceous–Eocene units of western Cuba. In this region, late Danian breccia and conglomerate of La Guira olistostromes correlate with Mícara Formation to the east. La Guira strata generally disconformably overlie commonly deformed Cretaceous units (Bralower and Iturralde-Vinent, 1997) and underlie Paleocene and early Eocene units such as Ancon and Manacas. Figure is adapted from Bralower and Iturralde-Vinent (1997).

units, composed mainly of volcanic debris (Fig. 35). In southwest Puerto Rico, similar to Cuba, Campanian carbonate beds characterize formations (Cotui, Melones, Parguera, Peñones) from less than 100 to ~1000 m thick, commonly rich in fossil debris (Figs. 34 and 35). Clastic interbeds, some of which are conglomerate containing clasts of volcanic rock, serpentinite, amphibolite, and chert, may be present. The calcareous units commonly rest upon massive andesite and dacite of the Lajas Formation and are overlain by mainly clastic beds comprising Yauco Formation. The Yauco Formation records penecontemporaneous folds and, as shown by Curet (1986), contains large olistoliths of Campanian carbonate.

Exposures of basalt are common within the Yauco Formation, and the higher part of the unit is a thick debris unit rich in volcanic material. Comparison of coarse debris units shown on quadrangle maps (Krushensky and Monroe, 1978a; Krushensky and Curet, 1984; Curet, 1986) suggests that the Yauco-Maricao debris complex is equivalent to Sabana Grande, Rio Blanco, and Laga Garzas Formations, each of which is rich in volcanic rocks and each of which probably contains large carbonate olistoliths. Our field observations suggest that the Monte del Estado serpentinite mass locally may rest upon Sabana Grande among the debris units. The relationships resemble those shown from Cuba (Fig. 35).

The Latest Cretaceous collisional history of the large islands of the Greater Antilles "arc" also resembles that of the El Peten region of Guatemala. In El Peten, the Sepur Group consists of a lower unit of shale and shaly flysch and minor interbedded polymictic conglomerate and an upper unit composed of the Santa Cruz ophiolite allochthon and sedimentary strata rich in ophiolitic debris (Rosenfield, 1981; Iturralde-Vinent et al., 2006). The ophiolite debris in the Campanian–Paleocene shale-sandstone flysch of the Sepur Group records a major change from a stable platform to a mobile belt.

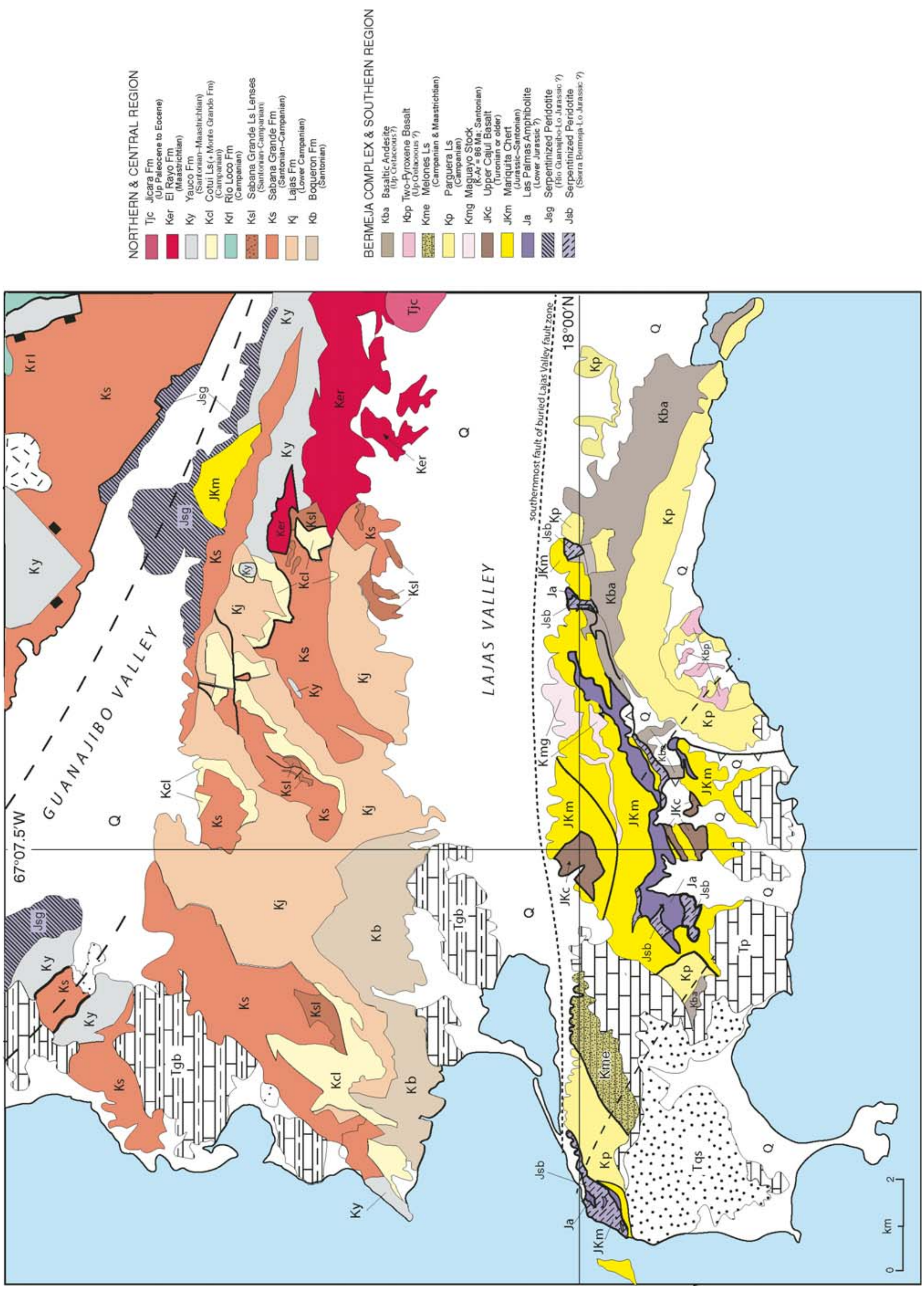
Late Eocene (40–35 Ma)

As noted already herein, the distinctive, olistostrome-bearing Danian Micara and La Picota units grade upward into late Danian, ca. 61 ± Ma marl, marly limestone, and conglomerate with tuffaceous intercalations (Iturralde-Vinent, 1976, 1977). The stratigraphic transition from sedimentary to tuffaceous rocks records the initiation of a Paleocene–middle Eocene (ca. 61–48 Ma) volcanic belt, well preserved in the Oriente Province of eastern Cuba as briefly described earlier herein (Iturralde-Vinent, 1976, 1977; Iturralde-Vinent, 1994, 1998; Rojas-Agramonte et al., 2006).

In western Cuba, the early Eocene Manacas Formation, which locally rests unconformably upon Cretaceous units, contains a second, stratigraphically higher, group of olistostromes (Fig. 32). The olistostromes comprise the ca. 55–50 Ma Vieja Member (Bralower and Iturralde-Vinent, 1997), which developed during the contraction between ca. 60 and 45 Ma (Saura et al., 2008, their figure 10) that followed Paleocene arc magmatism in eastern Cuba.

In north-central Cuba, the Vega Formation, which formed between the late Paleocene (ca. 59 Ma) and early Eocene (ca. 52 Ma), contains olistoliths several kilometers long in a clastic matrix (the Sagua breccia) that rests upon Maastrichtian carbonate rocks (Iturralde-Vinent et al., 2008). However, higher coarse clastic units such as the Rancho Bravo and the olistostromic Maximo Member of the Senado Formation developed between middle to late Eocene time (ca. 40–34 Ma) as shown by fossil ages.

Figure 33. Geologic map of San German and Puerto Real quadrangles of southwest Puerto Rico that show inferred stratigraphic and structural relationships. NW-trending dashed line south of Lajas Valley represents cross section in Figure 36. Figure is adapted from Volckmann (1984), Llerandi-Roman (2004), and Martinez-Colon (2003). Ls—Limestone; Fm—Formation.


NORTHERN & CENTRAL REGION
Tjc Jicara Fm (Up Paleocene to Eocene)
Ker El Rayo Fm (Maastrichtian)
Ky Yauco Fm (Santonian–Maastrichtian)
Kcl Cotui Ls (+ Monte Grande Fm) (Campanian)
Krl Rio Loco Fm (Campanian)
Ksl Sabana Grande Ls Lenses (Santonian-Campanian)
Ks Sabana Grande Fm (Santonian–Campanian)
Kj Lajas Fm (Lower Campanian)
Kb Boqueron Fm (Santonian)
BERMEJA COMPLEX & SOUTHERN REGION
Kba Basaltic Andesite (Up Cretaceous?)
Kbp Two-Pyroxene Basalt (Up Cretaceous?)
Kme Melones Ls (Campanian & Maastrichtian)
Kp Parguera Ls (Campanian)
Kmg Maguayo Stock (K-Ar = 86 Ma; Santonian)
JKc Upper Cajul Basalt (Turonian or older)
JKm Mariquita Chert (Jurassic–Santonian)
Ja Las Palmas Amphibolite (Lower Jurassic?)
Jsg Serpentinized Peridotite (Rio Guanajibo-Lo Jurassic?)
Jsb Serpentinized Peridotite (Sierra Bermeja-Lo Jurassic?)
GUANAJIBO VALLEY
LAJAS VALLEY
southernmost fault of buried Lajas Valley fault zone
67°07.5'W
18°00'N
km
0
2

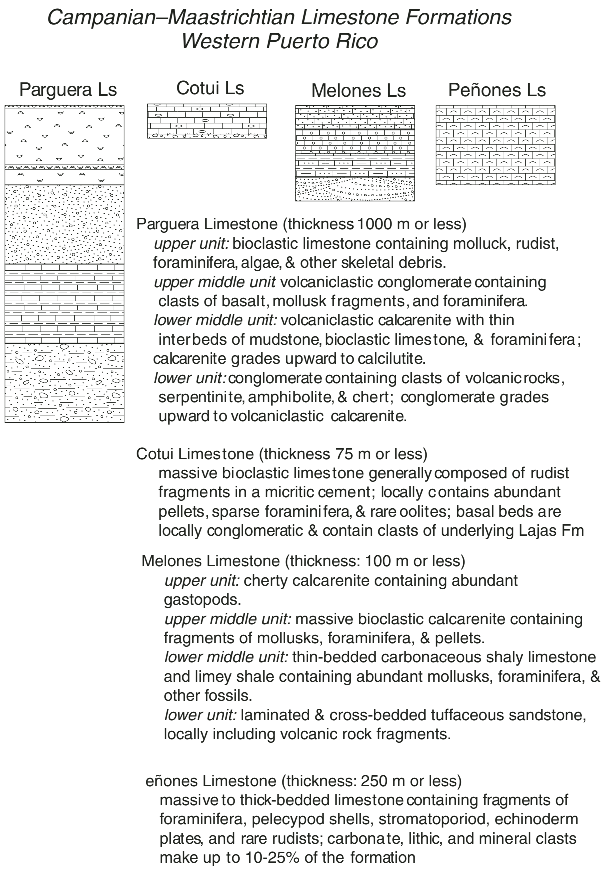


Figure 34. Campanian–Maastrichtian limestone formations, southwestern Puerto Rico, showing lithologic variation and inferred thickness. Figure is adapted from Volckmann (1984).

In southwest Puerto Rico (Fig. 33), bodies of Eocene debris have not been recognized. However, some Eocene formations (e.g., Rio Culebrinas, Monserrate; Fig. 20) contain stratigraphic dislocations and local conglomeratic units suggesting slumping and other gravity-driven penecontemporaneous deformation. In Sierra Bermeja (Figs. 33 and 36), exposures of the Upper Cajul Formation (see earlier herein) are interpreted to indicate emplacement of plateau basalt onto the margin of Puerto Rico after arrival and collision of the Caribbean-Colombian oceanic plateau against the southern margins of the Greater Antilles islands.

ACCRETIONARY PRISMS, MÉLANGES, AND IMPLICATIONS ABOUT THE INITIATION OF EPISODES OF SUBDUCTION, THE POLARITY OF EACH, CONSUMPTION OF LITHOSPHERE, AND RESULTING COLLISION

Uplift, cooling, development of an unconformity, and, locally, emplacement of olistostromes record the termination of each of three past episodes of subduction—Early Cretaceous, Late Cretaceous, and Early Tertiary. In this section, we seek to identify the beginning of each subduction episode based upon information from rocks interpreted as forming in former subduction zones. Further, we infer the polarity of each subduction event and consider the results of consumption of lithosphere with respect to deformation caused by collision.

The presence of boninitic rocks and other primitive island-arc volcanics comprising the Early Cretaceous Los Ranchos, Amina, Maimón, and probably lower Tireo Formations of Hispaniola has been interpreted to indicate formation as part of a nascent island arc, probably in a forearc basin (Lewis et al., 2002; Escuder Viruete et al., 2007c). Krebs et al. (2008) concluded that subduction was under way by 120 Ma and that peak metamorphic conditions were recorded in eclogite blocks by ca. 104 Ma.

In Cuba, correlative rocks are thought to be the Early Cretaceous Los Pasos Formation, which formed during Early Cretaceous subduction beginning before ca. 133 Ma, as shown by the crystallization age of trondhjemitic orthogneiss from the Mabujina amphibolite complex of central Cuba (Fig. 13; Rojas-Agramonte et al., 2011). North of the Mabujina complex, outcrops of mélange contain blocks of eclogite, garnet-amphibolite, amphibolite, blueschist, greenschist, quartzite, metapelite, antigorite, and various types of intrusive rocks that occur as blocks or intrusions of gabbro and diabase. The mélange may record Early Cretaceous subduction, indicated by dates from an eclogite block that yields Ar-Ar ages (amphibole and phengite) ranging from 123 to 103 Ma and an Rb-Sr isochron age (phengite–omphacite–whole rock) of 118 Ma, as suggested by Schneider (2000; see also Garcia-Casco et al., 2002, 2006). These authors suggested that the eclogite formed during Early Cretaceous subduction and was later incorporated into a mélange that was exhumed rapidly during Aptian–Albian time.

In eastern Cuba, the Sierra del Convento mélange contains rocks that yield Early Cretaceous K-Ar and U-Pb zircon ages in the interval between 126 and 103 Ma (Fig. 24; Garcia-Casco et al., 2008b, and references therein). Based upon the analysis of petrological and geochronological data from blocks in the mélange, they concluded that the studied samples began to subduct at ca. 120 Ma. The starting date is comparable to rocks in the Sierra del Convento mélange in eastern Cuba of ca. 120 Ma, which is based upon data collected and analyzed by Lázaro and García-Casco (2008).

The age range during which Early Cretaceous subduction began in Cuba is compatible with U-Pb dates from eclogite protolith of ca. 138 Ma that comprises blocks within serpentinite mélange in northern Hispaniola (Somin and Millán, 1977; Krebs et al., 2008).

Lastly, $^{40}Ar/^{39}Ar$ ratios from phengitic micas in serpentinite-matrix mélange along the Motagua fault in eastern Guatemala yield dates of 125–113 Ma, interpreted as crystallization ages related to subduction (Harlow et al., 2004). Although not directly attached to the Antillean islands, their interpretation of the paleogeography (Fig. 37) suggests alignment and probable correlation to Early Cretaceous rocks of the Greater Antilles.

Interpretations of the polarity of Early Cretaceous subduction are equivocal because no conclusive evidence is known. Mattson

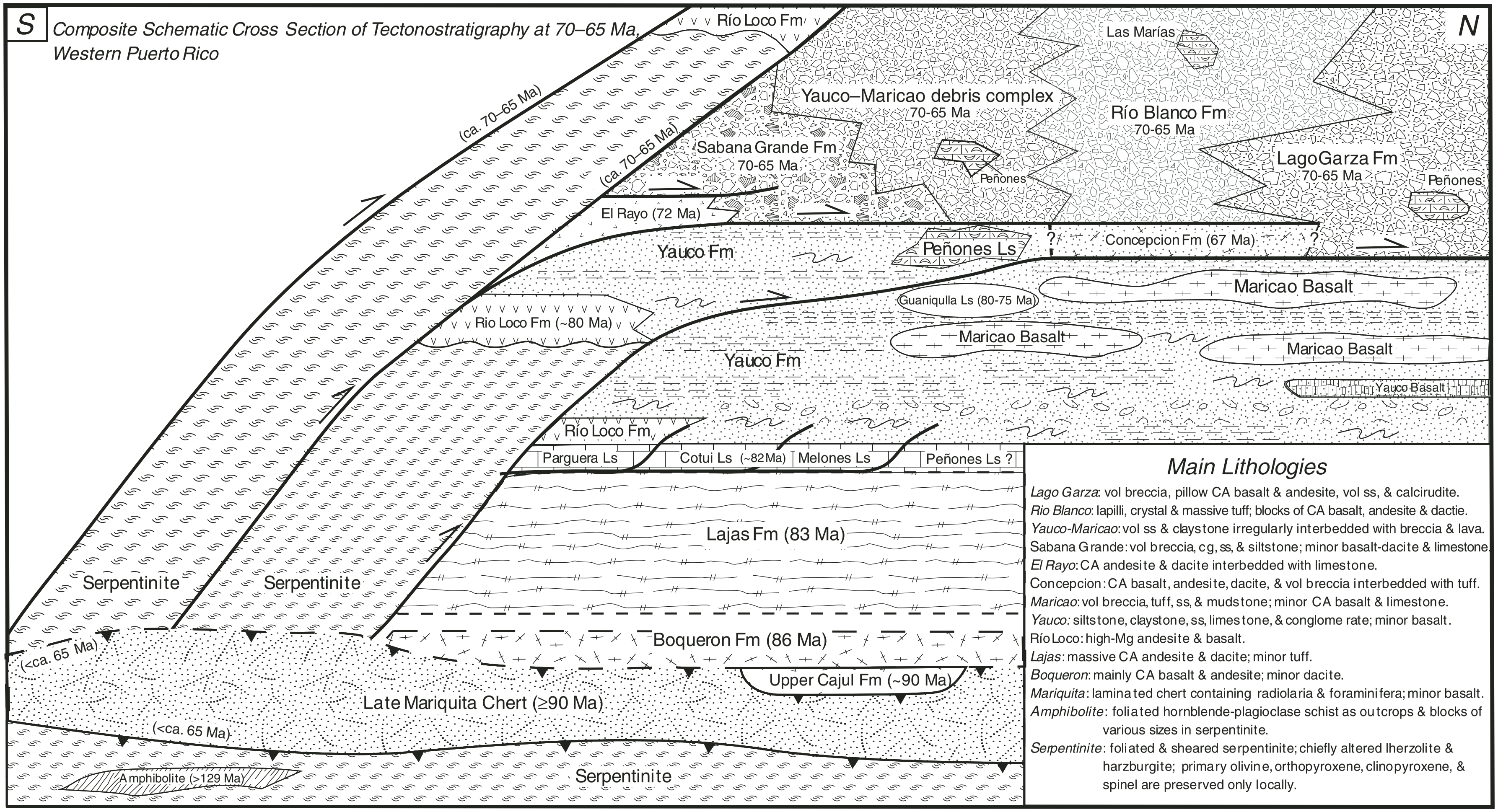


Figure 35. Late Cretaceous composite and schematic structure section, western Puerto Rico, showing speculative stratigraphic and structural relationships among Late Cretaceous layered rocks and older(?) serpentinite. CA—calc-alkaline; ss—sandstone; cg—conglomerate.

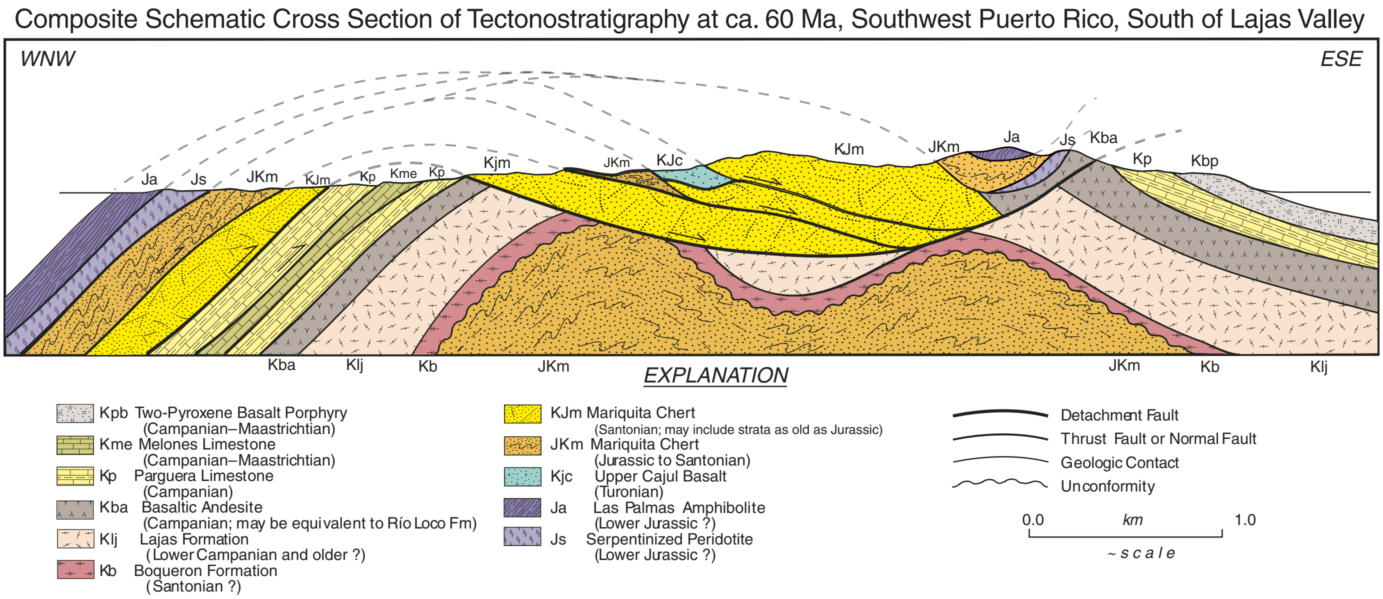


Figure 36. Late Cretaceous composite and schematic structure section, southwest Puerto Rico, south of Lajas fault, showing speculative stratigraphic and structural relationships among Late Cretaceous layered rocks and older(?) serpentinite. See Figure 33 for location of cross section.

(1973, 1979) suggested that the Early Cretaceous rocks, which he thought, without the benefit of the U-Pb crystallization age described here, formed above a slab subducting northeastward, toward the North America plate. We concur with the inferences of Mattson (1979), Draper et al. (1996), and Harlow et al. (2004), who postulated northeast-directed Early Cretaceous subduction based upon consideration of structural relations in Cuba, Hispaniola, and Puerto Rico and paleogeographic relations in Guatemala, respectively, as portrayed in their reconstruction (Fig. 37).

Early Cretaceous northeast-directed subduction beneath Middle America is a straightforward interpretation in light of

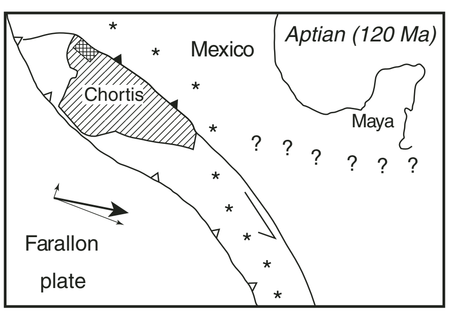


Figure 37. Tectonic and paleogeographic generalized map of the Chortis block and east Pacific region during the Aptian. NE-directed subduction (black teeth) caused the Chortis block (diagonal pattern) to collide with Mexico. New NE-directed subduction zone formed outboard (white teeth). Figure is adapted from Pindell (1994) and Harlow et al. (2004).

subduction that took place during the Early Cretaceous beneath much of the western margin of North America. For example, at this margin, east-northeastward–directed subduction is known to have taken place from at least Baja California northward along the margin beginning ca. 135 Ma (L.T. Silver, 1980, personal commun.; Wetmore et al., 2003).

Burke et al. (1978) concluded that a polarity reversal took place during Early Cretaceous time. Mattson (1979) similarly postulated a change in polarity at ca. 127 Ma (Barremian-Aptian) based upon considerations of ophiolitic, volcanic, and metamorphic rocks in the Greater Antilles and geologic observations summarized in his paper. However, results from recent geochronologic studies that reveal the ranges of subduction-related magmatic episodes (see earlier herein), as well as the times of interruption recorded by magmatic lulls (see following), point to a younger reversal age, likely ca. 110 Ma. The polarity change from northeast- to southwest-directed subduction is supported by Draper et al. (1996), who inferred that structural relations in Hispaniola also suggest the change.

Southwestward-directed subduction in Early Cretaceous time (between 135 Ma and ca. 105 Ma) is not precluded by the data at hand. However, without evidence of a trench-trench transform in western Mexico, which would be needed to accommodate the opposing polarities, northeastward-directed polarity is probable during this time. Whatever the Early Cretaceous plate geometry, it is well established that Albian uplift (105 Ma; and deformation) was followed by a hiatus in magmatism until Late Cretaceous subduction resumed as recorded by: (1) subduction-related plutons as old as ca. 94 Ma in Cuba (Rojas-Agramonte et al., 2011); (2) ca. 90 Ma plutons and formation of the upper Tireo volcanic section (Escuder Virute et al., 2007a, 2008, and

references therein) in Hispaniola; and (3) correlative Albian and younger formations in Puerto Rico (Jolly et al., 1998b), Cuba (Iturralde-Vinent, 1996c, 1996b), Virgin Islands (Rankin, 2002), and Jamaica (Hastie et al., 2009, 2013).

As shown by Iturralde-Vinent et al. (2008, their figure 2) southwest-directed subduction (Fig. 38) would result in consumption of lithosphere between the Bahamas Platform and the magmatic arc forming on the Caribbean (cf. Mattson, 1979, his figure 3). The geometry leads to continent-arc collision as the Bahamian continental lithosphere descended beneath the arc, as summarized in previous sections herein. The collision between the Caribbean and North America plates is recorded by metamorphism and related uplift that took place at ca. 71 Ma concurrent with contractional structures and followed by the development of foredeep basins (e.g., Harlow et al., 2004; Garcia-Casco et al., 2008b; Iturralde-Vinent et al., 2008). Results from paleomagnetic studies on central Cuban Cretaceous arc rocks also show northeastward movement (Renne et al., 1991; Tait et al., 2009) with respect to the North America and South America plates (Housen et al., 2003), culminating with cessation of volcanic activity and collision against the Bahamas Platform by Maastrichtian time.

Our hypothesis that the extinguished Aptian/Albian arc and overlying Cretaceous arc were underthrust by the southwest-dipping Bahamas Platform during Maastrichtian collision conflicts with the ideas of Garcia-Casco et al. (2008a). They suggested that during southwest-directed subduction a composite terrane, called Caribeana, located north of the main Greater Antilles Cretaceous arc and composed of Mesozoic sedimentary rocks, mainly Jurassic, and continental metamorphic rocks of Paleozoic and Grenvillean ages, entered the subduction zone and collided with the Cretaceous volcanic terrane in Late Cretaceous time before the arc reached the Bahamas Platform. According to their hypothesis, following collision and accretion of Caribeana, subduction resumed, and Caribeana along with the Cretaceous arc terrane collided with the Bahamas in the Eocene. As noted in the following, we believe that geologic data fit better with an alternative model.

Although southwest-directed subduction does not conflict with the associated concept of "Caribeana," the Eocene age of collision shown by Garcia-Casco et al. (2008a) is incompatible with the arrest of magmatism and uplift recorded by cooling ages of ca. 70 Ma, development of an unconformity, and emplacement of olistostromes. By Maastrichtian time, collision with the Bahamas Platform had taken place. However, according to Iturralde-Vinent et al. (2006, 2008), collision of the arc against the Bahamas Platform did not take place until the early late Eocene.

Iturralde-Vinent et al. (2006) and Garcia-Casco et al. (2008a) pointed out that the development of the latest Cretaceous–Paleocene olistostrome-bearing deposits coincided with a major tectonic event along the leading edge of the Cretaceous magmatic arc. The exhumation event at ca. 71 Ma is postulated to have followed the subduction of the "Caribeana" continental terrane (Iturralde-Vinent et al., 2006; Garcia-Casco et al., 2008a). However, this scenario would not lead to consumption of oceanic lithosphere between the Cretaceous arc and the Bahamas Platform. Furthermore, the age and distribution of the Paleocene magmatic rocks in eastern Cuba, which best fit with northward-directed subduction (see earlier herein), also argue against the postulated scenario.

Early Tertiary volcanic rocks in the Greater Antilles likely record a return to northeastward-directed subduction as suggested by Mann et al. (1991). They pointed out the possibility that Eocene turbidites and volcanic rocks in Puerto Rico and Hispaniola record part of an accretionary prism and volcanic arc that formed in response to the return to northeast-dipping subduction after a "flip." We concur that subduction of Pacific lithosphere beneath the Cretaceous arc(s), which had previously been accreted to the Bahamas Platform, likely led to the development of the short-lived, 61–48 Ma (Rojas-Agramonte et al., 2011) magmatism, as briefly described earlier herein (Fig. 25).

The consumption of Pacific lithosphere during northeast-directed subduction resulted in movement of the Late Cretaceous plateau rocks eastward until they collided against Hispaniola and Puerto Rico, where their remnants are preserved. Steeply dip-

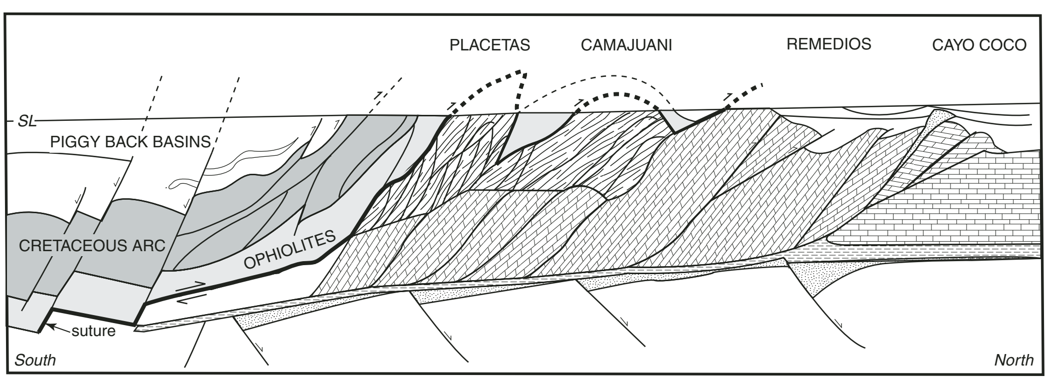


Figure 38. Structural cross section of the Cuban fold-and-thrust belt, adapted from Iturralde-Vinent et al. (2008). The cross section illustrates the deep detachment surface and thrust nappes between the Bahamas Platform and the allochthonous Caribbean plate (serpentinite mélange, ophiolites, and Cretaceous volcanic arc suites).

ping Eocene strata comprising the Cerrillos-Peralta belt in Puerto Rico and Hispaniola (Dolan et al., 1991) probably were tilted during contraction related to the accretion of the thick, Caribbean plateau crust. This proposed Tertiary episode of northeastward-directed subduction followed by collision also is compatible with the second of two pulses of olistostromes emplaced between ca. 71 and 65 Ma and again between ca. 55 and 41 Ma (Iturralde-Vinent et al., 2006, 2008).

RESTORATION OF CARIBBEAN DOMAINS

Tectonostratigraphic analysis and paleomagnetic results lead to the working hypothesis that small plates in the Caribbean region were inserted between North and South America during episodes of subduction (e.g., Iturralde-Vinent and MacPhee, 1999; Mann, 2007; Fig. 2). We recognize three insertions. From youngest to oldest these include: (1) Lesser Antilles plate, from late Eocene to recent, (2) Caribbean-Colombian oceanic plateau or plateau plate, 61–48 Ma, and (3) Greater Antilles PIA/IAT plate, ca. 100–71 Ma.

Each plate insertion was accommodated by two major faults that may be identified or inferred from among those shown by Iturralde-Vinent and MacPhee (1999; Fig. 2 herein). Each pair of faults, active during an episode of convergence, subduction, consumption, and related plate insertion, coincided with the lateral boundaries of a small plate (microplate) and generally linked trenches (Fig. 39).

The pairs of strike-slip faults include the following.

(1) The late Eocene to recent Cayman set and cogenetic faults across the Caribbean basin to the south along the northern margin of South America. The southern faults are largely obscured by younger thrusts. During movement of at least 1000 km, the Lesser Antilles volcanic arc formed as Atlantic Ocean floor was subducted beneath the eastern edge of the Caribbean lithosphere. Continuing convergence and subduction accommodated insertion of the Lesser Antilles plate, composed mainly of the submarine basalt (Caribbean large igneous province) that forms the Caribbean-Colombian oceanic plateau.

(2) Paleocene and early Eocene (ca. 65–45 Ma) faults that coincide with the Hess escarpment on the northwest and, on the southeast, an inferred fault extending from the easternmost Virgin Islands southwestward to a point within the Romeral suture in northwestern South America. During this time, insertion of the lithosphere, including submarine basalt (Caribbean large igneous province) that forms the Caribbean-Colombian oceanic plateau, took place. As the plate moved northeastward, oceanic lithosphere converged toward the southern margin of the Greater Antilles, where the leading Pacific lithosphere was subducted beneath the southern margin of the Greater Antilles from Jamaica and nearby Oriente Province, Cuba, to the Virgin Islands and probably Desirade Island, thereby forming the Paleocene arc.

(3) Late Cretaceous faults accommodated convergence of the PIA/IAT plate toward the Bahama platform between ca. 100 and 70 Ma. The associated faults include a western bounding transform fault that extended along the eastern margin of the Yucatán Peninsula and, to the east, an inferred fault extending southwest from the southern termination of the restored Aves Ridge to a proto–Romeral fault, which transects northwestern South America west of the cohesive Precambrian cratons.

During each episode of convergence and subduction, the bounding faults or "trench-trench transforms" that served as boundaries of small plates (microplates) accommodated lateral movement as the leading edge of oceanic lithosphere was consumed (Fig. 40[1]). We attempted to restore displacements schematically based upon inferred correlations between offset geologic units along pairs of principal faults that are postulated to have bounded each small plate. Movements along the coeval faults are based upon restoration of offset correlative geologic units or rock assemblages during each pulse of northeastward or eastward plate movement.

Post–Mid-Eocene Contraction

Post–mid-Eocene contraction has distorted and obscured most evidence of earlier faults between the Caribbean plates and northern South America. The south Caribbean deformed belt (Bezada et al., 2010; Kroehler et al., 2011) records contraction related to ~200 km of shortening between Hispaniola and Guajira Peninsula (Fig. 1) that has taken place since 38 Ma according to Burke et al. (1978). Their conclusion is based upon the analysis of Ladd (1976). Southward restoration of the deformed belt suggests that the southern limit of the Venezuelan basin and Caribbean-Colombian oceanic plateau was close to the Oca and other principal dextral strike-slip faults along the northern margin of South America.

Currently, the Caribbean–South American plate boundary is distinguished by well logs, seismic profiles, and radiometric and earthquake data that show subduction along a seismic zone that dips 30° to the southeast and terminates 200 km below the Maracaibo Basin (Kellogg and Bonini, 1982). Subduction is associated with contraction that is recorded by folds and thrust faults, including one that placed crystalline basement of the Venezuelan Andes over Tertiary sediments on a fault dipping ~25° extending to the mantle.

Insertion of the Caribbean or Lesser Antilles Plate, Composed of Chortis and Caribbean-Colombian Oceanic Plateau (Late Eocene to Holocene; Figs. 40A, 40B, and 40C)

The Caribbean–Lesser Antilles plate overrides Atlantic Ocean lithosphere as it converges toward the Atlantic Ocean.

[1]Figures 40 and 50 are also available on the CD accompanying this volume and as Data Repository item 2015370 at http://www.geosociety.org/pubs/ft2015.htm or on request from editing@geosociety.org.

Insertion of the plate is achieved by faults that accommodate the movement relative to the North and South America plates. Subduction in response to about 1000 km of plate movement has resulted in consumption of Atlantic crust and led to formation of the active Lesser Antilles arc. Insertion began ca. 50 Ma after collision of the plateau basalt domain (Caribbean-Colombian oceanic plateau plate) against the southern margin of the Late Cretaceous arc rocks underlying the Greater Antilles islands. Following the collision, plate motion in the Caribbean region shifted from a northeast-southwest trend to an easterly trend, as shown by the two large fault zones bounding the Caribbean–Lesser Antilles plate. The northern plate margin is defined by the Cayman set, along which the Greater Antilles have been fragmented. Cogenetic faults along the southern plate margin are now largely obscured by younger thrust faults that record convergence between South America and the Caribbean plate, as described earlier herein.

The northern plate boundary corresponds with faults comprising the Cayman set along the Cayman Trough (Figs. 1 and 39; also known as the Cayman Trench, Bartlett Deep, and Bartlett Trough), a deep basin that contains a small spreading center with pull-apart geometry on the floor of the western Caribbean Sea (Mann, 2007). The trough extends from south of the Sierra Maestra of Cuba toward Guatemala. Within the trough, there is a

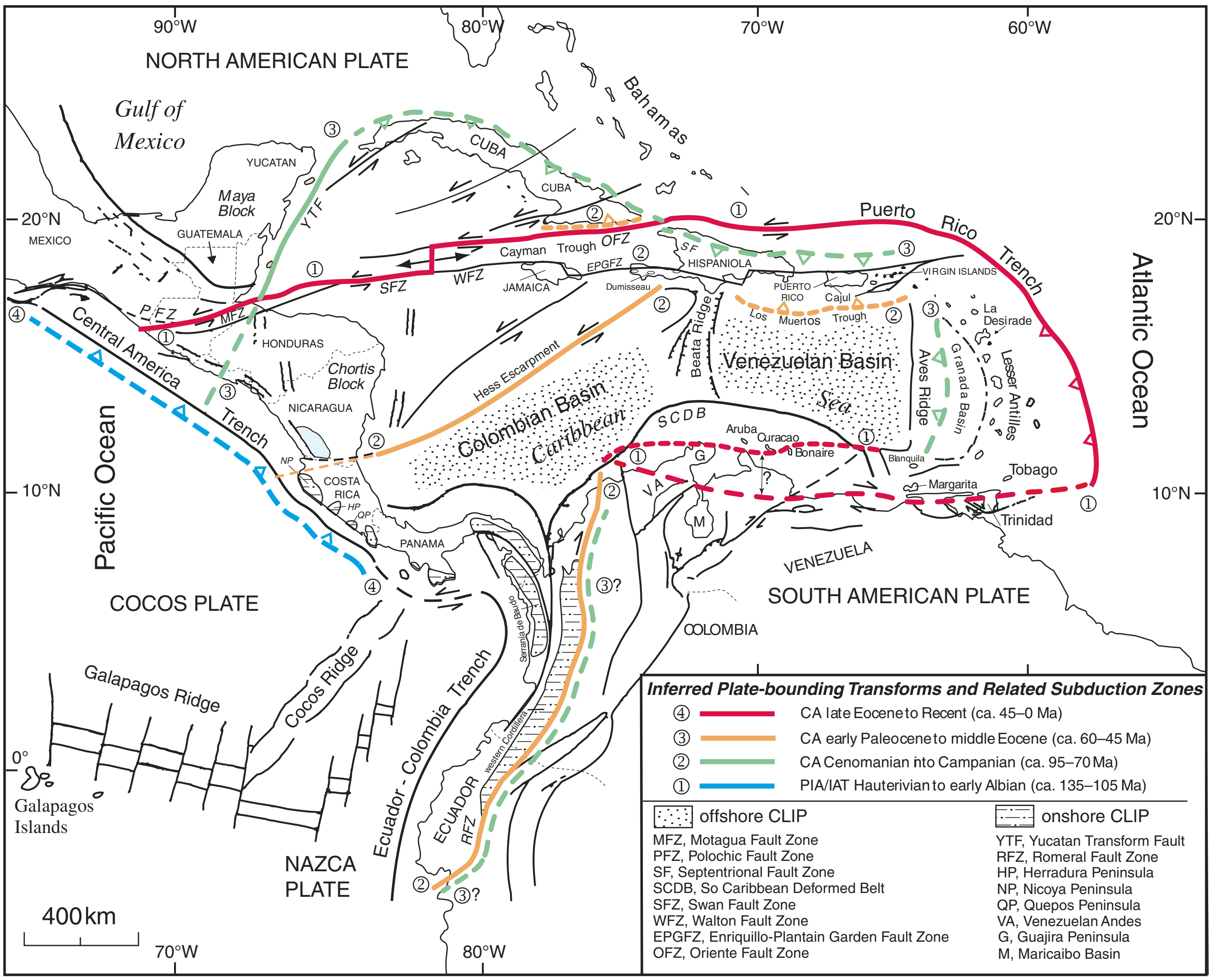


Figure 39. Regional sketch map showing inferred plate-bounding faults and outcrops of remnants of four extinct subduction-related belts that may be recognized in the Caribbean region. They include: (1) an Early Cretaceous island arc, rich in tholeiitic basalt and containing distinctive rhyolite, that formed between Hauterivian and early Albian time (ca. 135–105 Ma); (2) after a hiatus of about 10 m.y. or less, a voluminous, more extensive calc-alkaline (CA) magmatic suite, consisting largely of basaltic andesite and andesite with locally important dacite, which developed beginning in the Cenomanian and continuing into the Campanian (ca. 95–70 Ma); and, ~10 m.y. later or less, (3) a second (calc-alkaline) suite, areally restricted relative to the older belts, that is composed of volcanic and intrusive rocks, which formed from early Paleocene to middle Eocene (ca. 65–45 Ma); and (4) the late Eocene to recent Lesser Antilles island arc (ca. 450 Ma). PIA/IAT—primitive island arc/island-arc tholeiite; CLIP—Caribbean large igneous province.

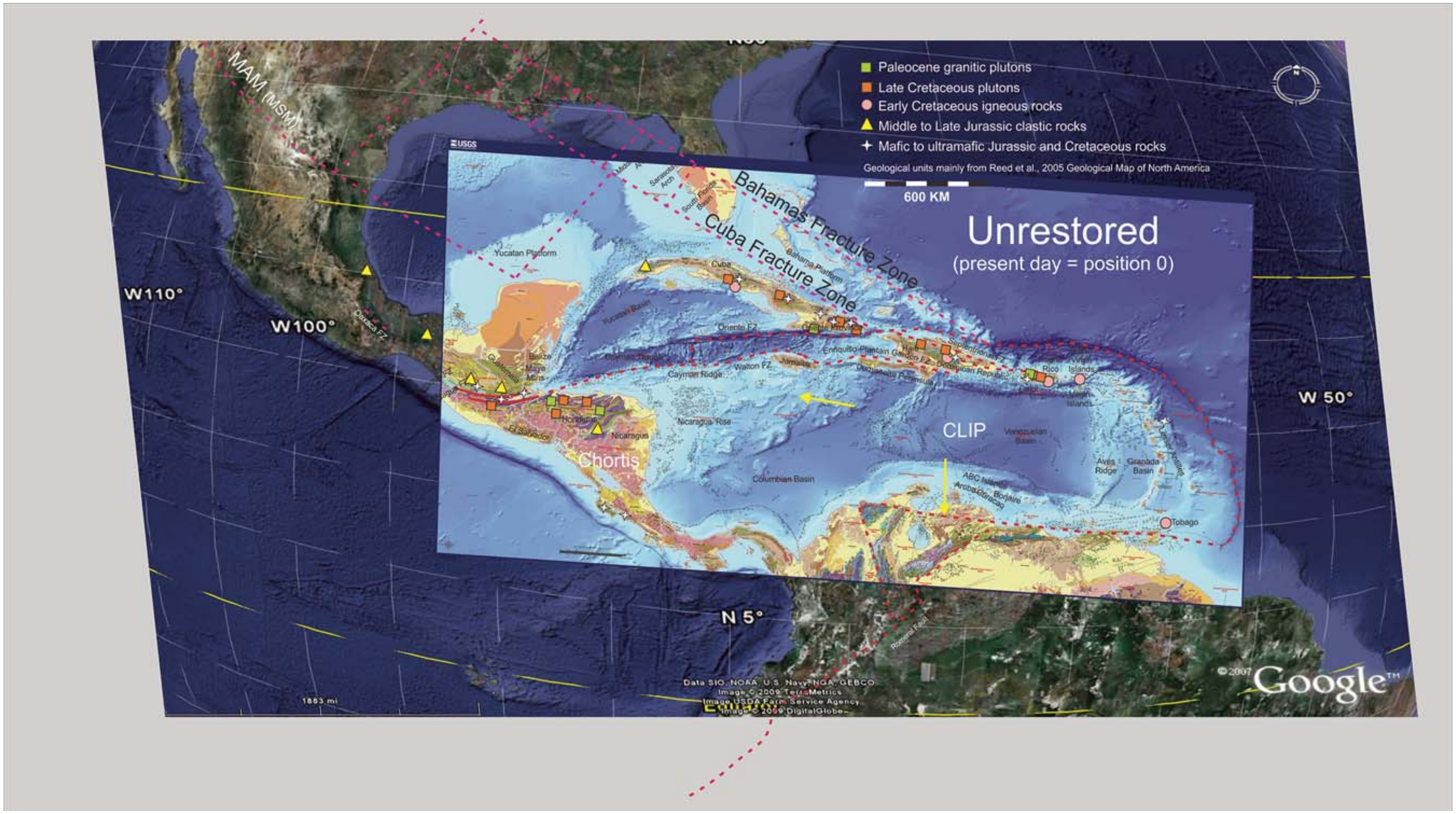


Figure 40 (*Continued on following pages*)[1]. Restoration steps of microplate plate movements in the Caribbean region. Each restoration step is derived from estimates of plate consumption and related plate movement recorded by Caribbean arc volcanism during four distinct episodes: ca. 135–120 Ma; ca. 95–75 Ma; ca. 65–50 Ma; and ca. 50 Ma to present. Each plate movement is accommodated by two major faults that may be identified or inferred from among those shown by Iturralde-Vinent and MacPhee (1999) (Fig. 2 herein). Each pair of faults, active during an episode of convergence, consumption, subduction, and related plate movement, coincides with the lateral boundaries of a small plate or microplate and generally linked trenches The inferred restorations of fault-bounded microplates (cf. Fig. 39 and Mann [2007, his figure 4]) toward the Pacific Basin provide the space necessary to accommodate the rotation of the Yucatán Peninsula concurrent with the opening of the Gulf of Mexico (GOM) between ca. 170 and 150 Ma. Unrestored (present): Features highlighted on the map of the present Caribbean region include the following: (1) geological units from Reed et al. (2005); (2) exposures of: (a) igneous rocks (squares or circles) for which ages have been determined from U-Pb interpreted ages from zircon or fossil control, (b) Middle to Late Jurassic clastic rocks, (c) mafic and ultramafic Jurassic and Cretaceous rocks; (3) selected major faults (red) bounding the Caribbean plate and others transecting northern South America; (4) fracture zones (Bahamas and Cuba, after Klitgord et al., 1984) and inferred faults (e.g., Mojave-Sonora segment [MSM] of Mexico-Alaska megashear [MAM, magenta lines]) postulated to have accommodated the opening of the Gulf of Mexico; and (5) tectono-morphologic features including arches, uplifts, rises, ridges, platforms, basins, and embayments. Yellow arrows show estimates of the amount of Tertiary extension or contraction across inferred plate-boundary transforms.

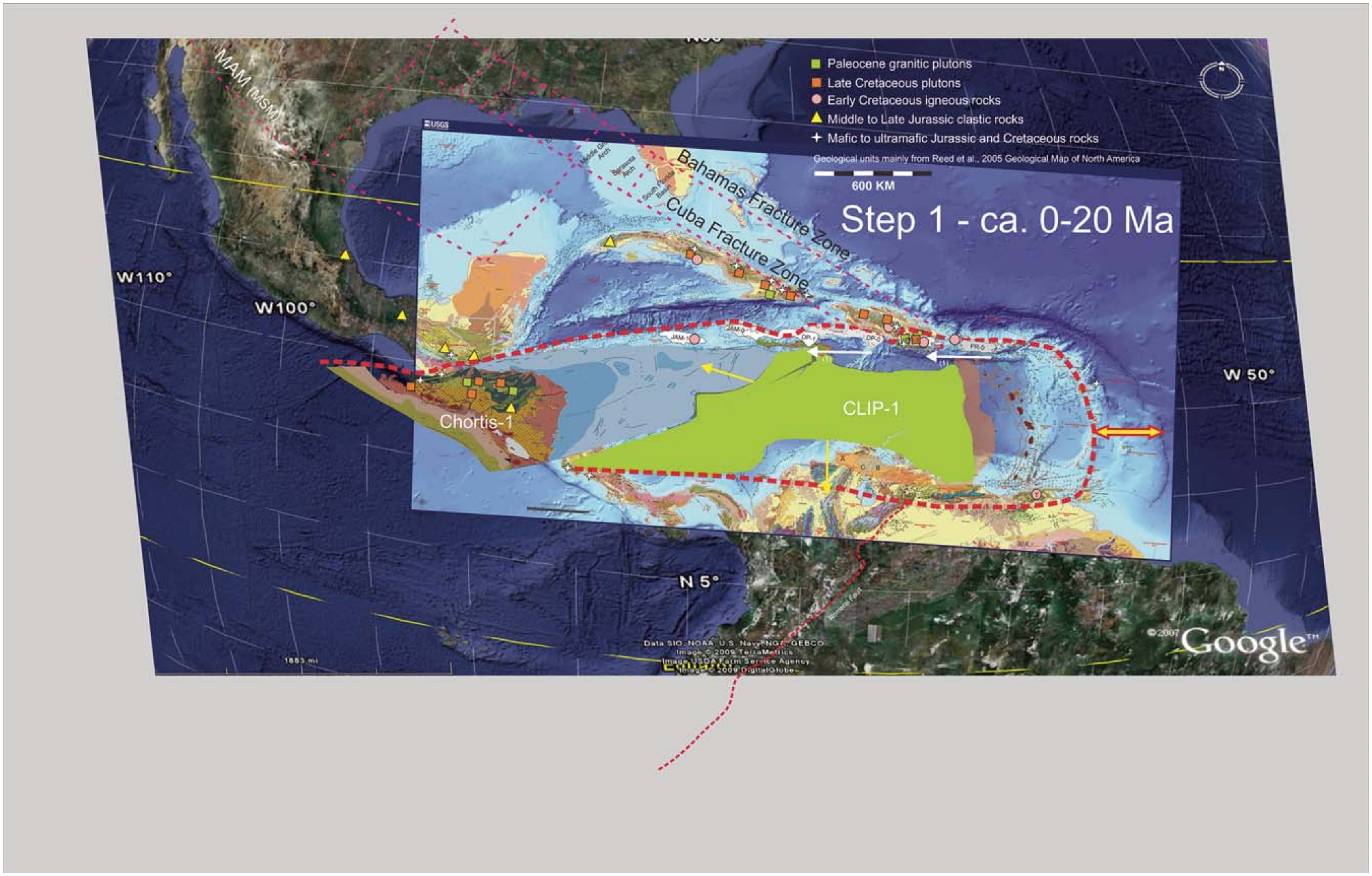


Figure 40 (*Continued*)[1]. Step 1 (ca. 20 Ma): Inferred restoration of Puerto Rico, Dumisseau (Hotte-Salle-Bahoruco) Peninsula, and Jamaica. (1) Red dashed line—inferred plate boundary; (2) white arrows show estimate of movement along the Enriquillo–Plantain Garden–Swan Island fault, along which Puerto Rico, Caribbean large igneous province–like rocks of Dumisseau (Hotte-Salle-Bahoruco Peninsula and Caribbean large igneous province/Caribbean-Colombian oceanic plateau) are inferred to be restored (modified from Iturralde-Vinent and MacPhee, 1999); (3) red arrow with yellow fill—amount of consumption of oceanic lithosphere beneath the Lesser Antilles arc; (4) light yellow—inferred distribution of Late Cretaceous arc rocks, extending south from Greater Antilles (Aves Ridge) and west (ABC islands); (5) bright green—Caribbean large igneous province (CLIP); (6) numbers on shaded, outlined features refer to unrestored (0) and following (1, 2, 3) positions.

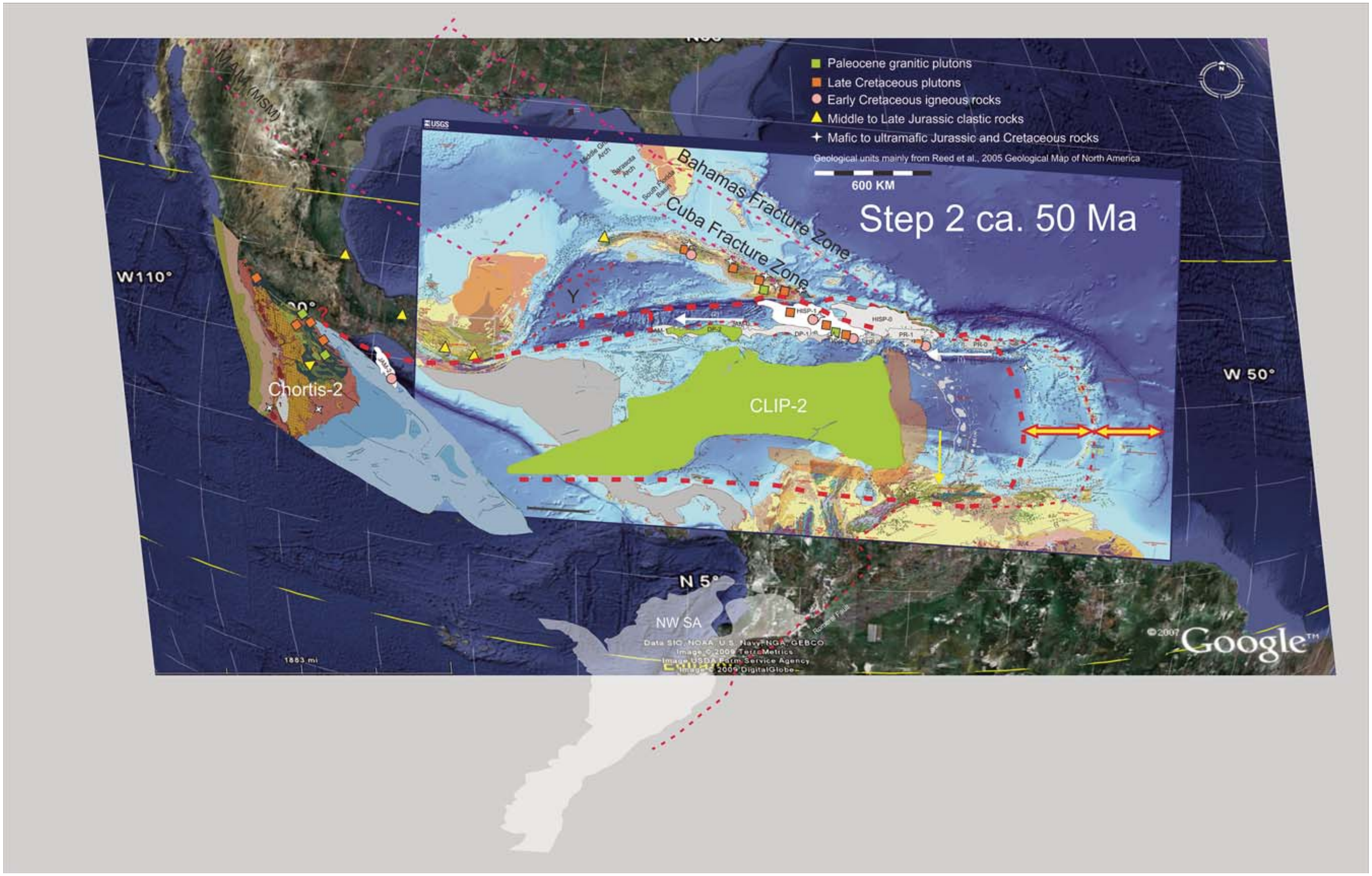


Figure 40 (*Continued*)[1]. Step 2 (ca. 50 Ma): Restoration of much of the Caribbean plate along the Oriente fault (north edge) and faults along the northern margin of South America (south edge), shown by dashed, coarse red lines, of the Hispaniola–Puerto Rico domain to Oriente Province, Cuba, to align segments of Late Cretaceous and Early Cretaceous arc rocks along with additional movement of domains identified in step 1. The restoration, which does not completely close the Cayman Trench, is compatible with the presence of highly extended continental crust at the extremities of the Cayman Trench and opening of the Yucatán Basin at ca. 49 Ma (Mann, 2007, his figures 3 and 4F), which marked the transition from northeasterly directed movement to an easterly direction. (1) Dashed, thin, red lines show inferred position of the Lesser Antilles Trench at ca. 20 Ma; (2) red arrows with yellow fill infer total amount of consumption of oceanic lithosphere beneath the Lesser Antilles arc; (3) Chortis terrane is positioned as suggested by Rogers et al. (2007a); (4) northwestern South America (NW SA, shown by light-gray shading), which lies west of the Romeral and related dextral faults, is restored toward the southwest. Y—Yucatan basin.

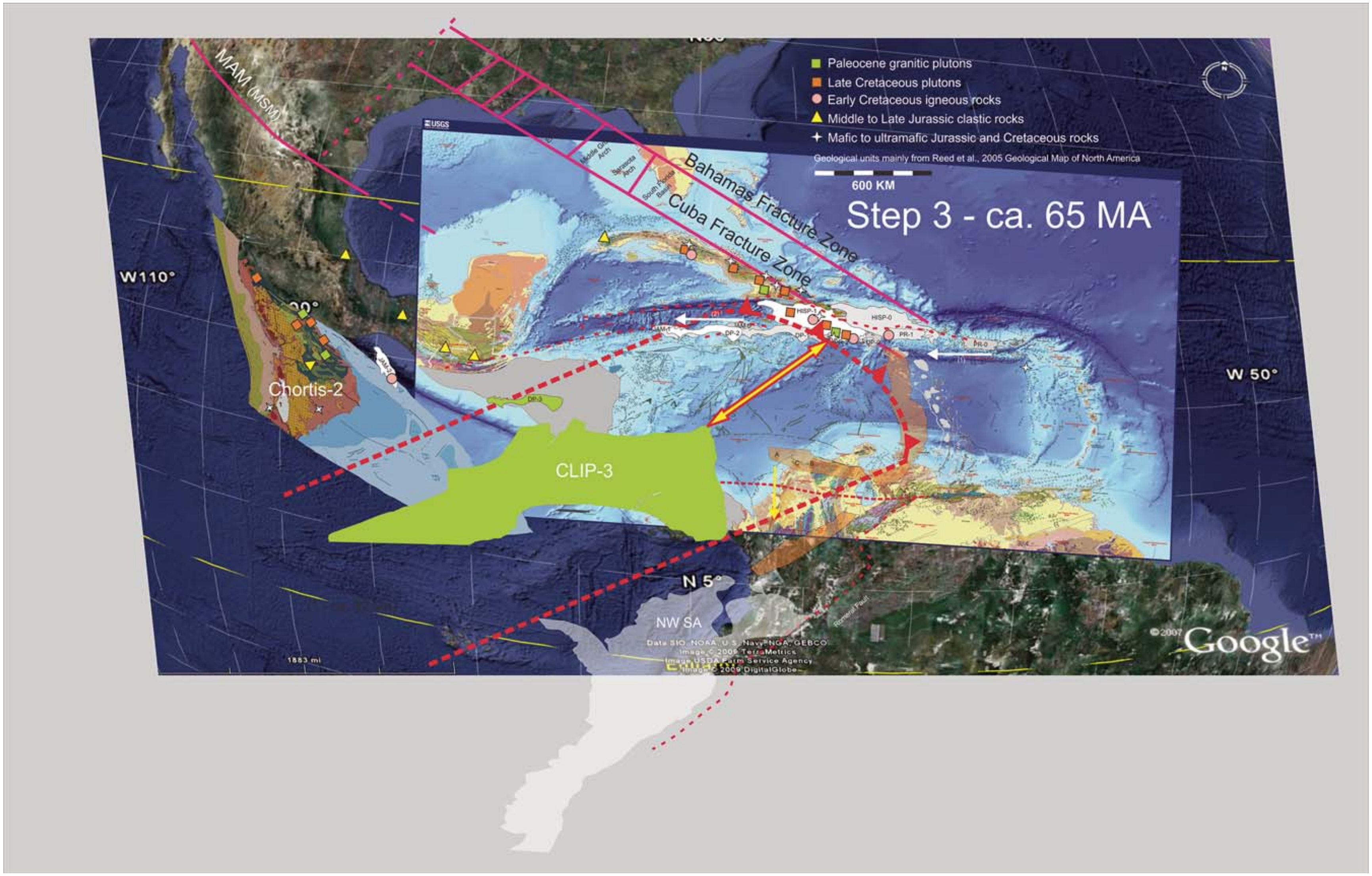


Figure 40 (*Continued*)[1]. Step 3 (ca. 65 Ma): Southwestward restoration of Caribbean large igneous province: (1) Caribbean large igneous province, shown as bright green, is restored southwestward, along inferred transform faults (long dashes), away from an inferred subduction zone (short dashes with solid triangles) described in text, toward the Galapagos Islands' plume, which is postulated as a possible source of Caribbean large igneous province/Caribbean-Colombian oceanic plateau basalt; (2) the ABC islands segment, inferred to have been previously rotated clockwise during shortening within the northern margin of South America, is restored via counterclockwise rotation; (3) red arrow with yellow fill shows the inferred consumption of oceanic lithosphere beneath Greater Antilles between ca. 65 and 50 Ma.

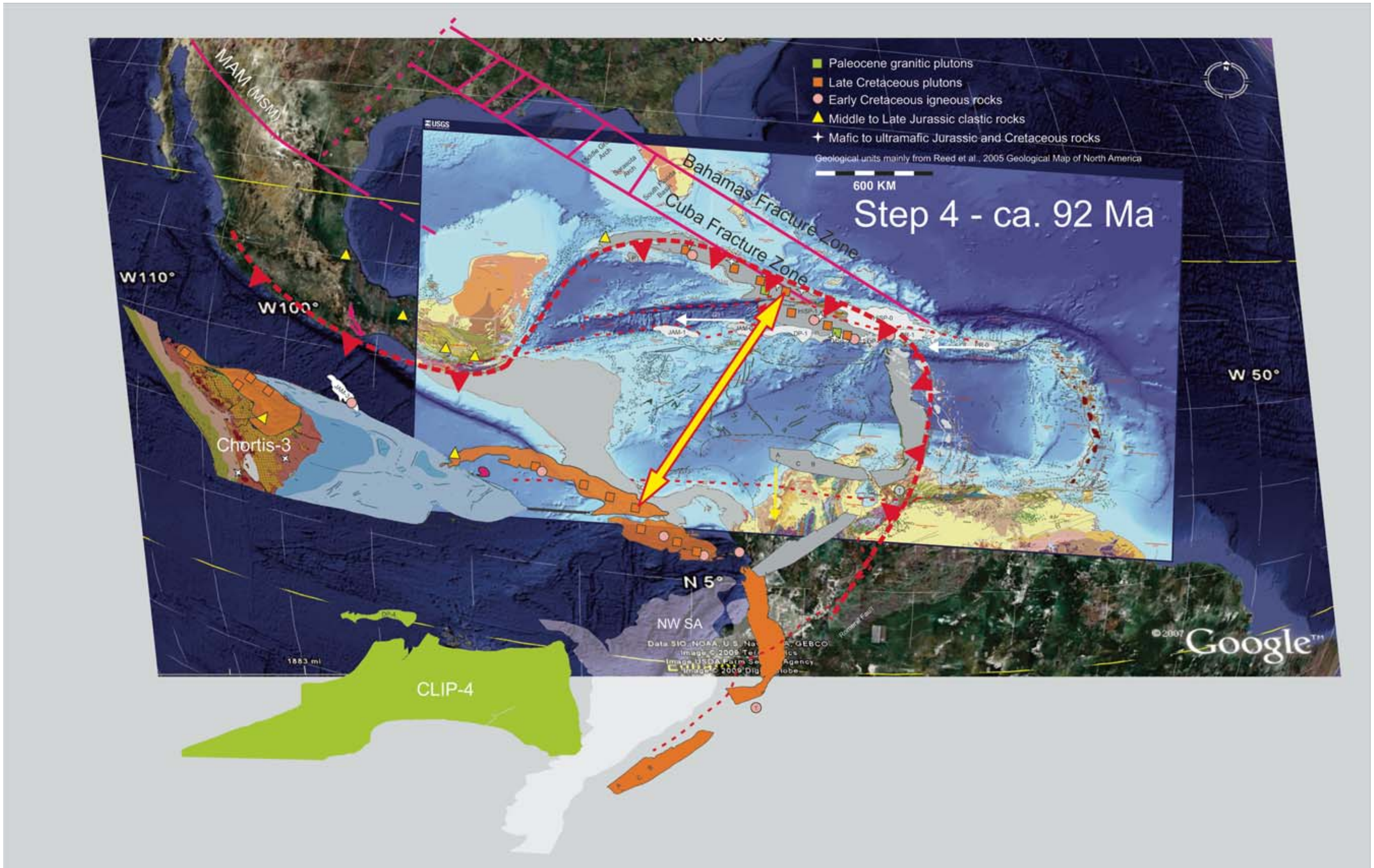


Figure 40 (*Continued*)[1]. Step 4 (ca. 92 Ma): Southwestward restoration of Late Cretaceous arc: (1) Greater Antilles, Aves Ridge, and ABC islands segments are shown with orange fill (orange squares distinguish future Late Cretaceous calc-alkaline plutons); (2) inferred Paleocene faults are shown as red line) and subduction zone is short red dashes with solid triangles; (3) red arrow with yellow fill shows the inferred consumption of oceanic lithosphere beneath Greater Antilles and contemporaneous arc segments; (4) Chortis has been moved away from the margin of Mexico in order to accommodate consumption and resulting development of Late Cretaceous subduction-related magmatic rocks.

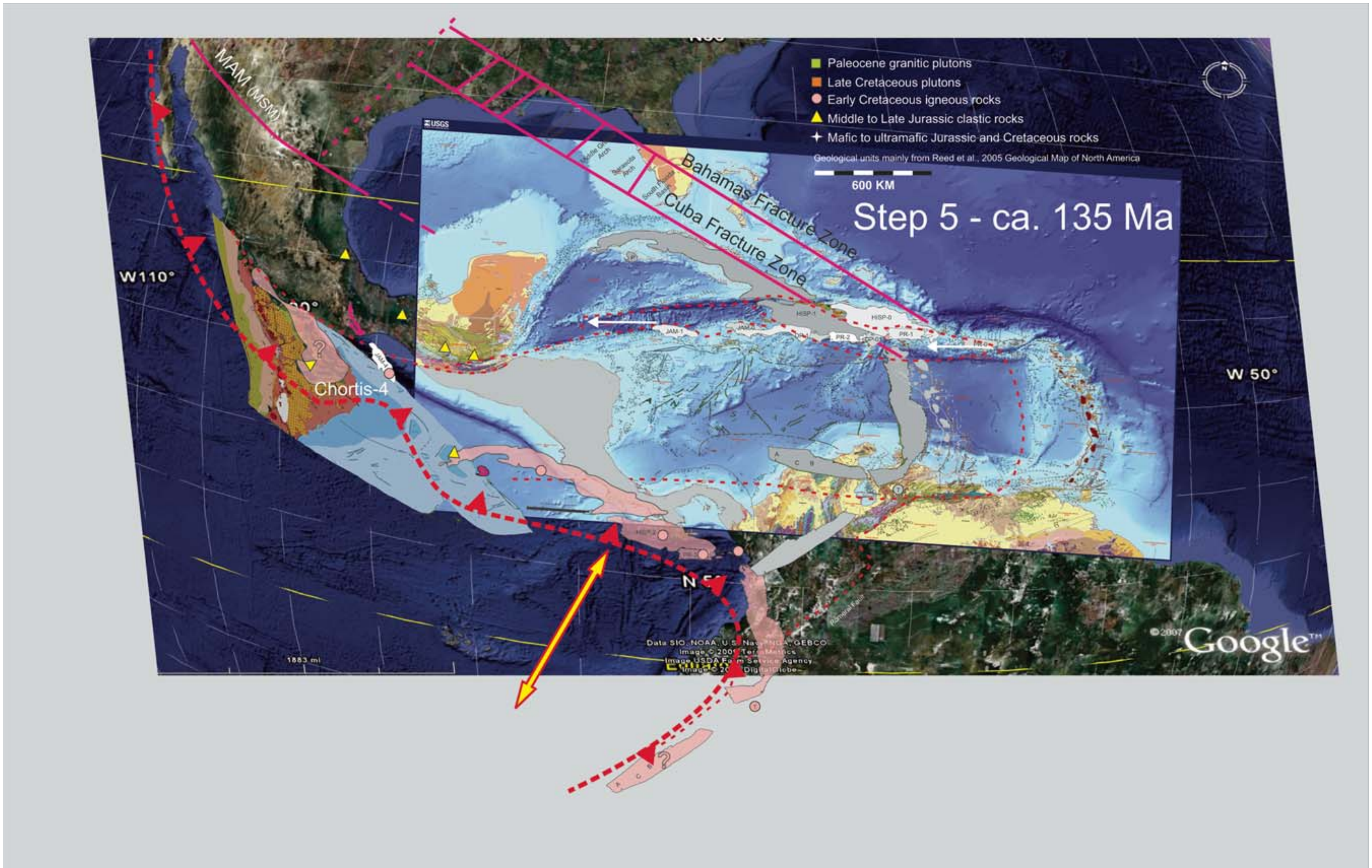


Figure 40 (*Continued*)[1]. Step 5 (ca. 135–110 Ma): Formation of Early Cretaceous primitive island arc/island-arc tholeiite (PIA/IAT) arc: (1) areas highlighted with pink fill are inferred as part of the Early Cretaceous arc; (2) red arrow with yellow fill shows the inferred northeastward-directed subduction of proto–Pacific plate, (3) dashed line with triangles distinguishes inferred Early Cretaceous subduction zone, (4) medium-gray areas show former positions of Caribbean terranes.

slowly spreading north-south ridge at a releasing step that records ~420 km (260 mi) of displacement along the main fault trace, which forms part of the tectonic boundary between the North America plate and the Caribbean plate. The Oriente and Septentrional fault zones bound the trough on the north, whereas the south is bounded by the Swan and Walton faults, the Jamaica restraining bend, and the Enriquillo–Plantain Garden fault zone (e.g., Dolan et al., 1998; Mann, 2007). The bounding strike-fault zones are left lateral. Leroy et al. (1996) pointed out that closure of 1100 km of Eocene and younger oceanic crust in the Cayman Trough would place faulted, older rocks adjacent to the Belize margin of Central America.

Abrupt increases in crustal thickness east and west of the Cayman spreading center that may record the domain of attenuated crust, as shown by ten Brink et al. (2002), are compatible with the estimate of ~1100 km of spreading. Restoration of normal faults in the fault-block province recognized by Leroy et al. (1996) adds an additional 190 km of left-lateral offset along the Cayman Trough. The Cayman faults must have become active after intrusion (ca. 50 Ma) and cooling (ca. 45 Ma) of subduction-related, calc-alkaline plutons exposed in southeastern Cuba (Rojas-Agramonte et al., 2006). Current seismic activity (Mann et al., 1995; Dolan et al., 1998; Calais et al., 2010) and the displacements resulting from our inferred correlations suggest that, currently, the Swan and Walton faults, the Jamaica restraining bend, and the Enriquillo–Plantain Garden fault zone record a through-going fault strand along the south flank of the Cayman Trough that has accommodated a few hundred kilometers of movement.

The southern Eocene boundary of the Lesser Antilles plate has been obscured by deformation as summarized earlier. Active convergence obscures the steep dextral faults that must have accommodated eastward movement of the Caribbean during the late Eocene. Local exposure of active, dextral, strike-slip faults along the margin of northern South America may record the slow eastward movement of the Caribbean plate as indicated by spreading in the Cayman Trough.

The eastward extensions of faults bounding the Cayman Trough separate Cuba and Hispaniola and Puerto Rico (Figs. 1 and 40B). Puerto Rico and the Virgin Islands may be restored against southeastern Hispaniola by ~300 km of motion along the seismically active eastward extension of the Enriquillo–Plantain Garden fault (Fig. 40B; Dolan et al., 1991; Iturralde-Vinent, 2003). We infer that the Enriquillo–Plantain Garden fault extends farther east than shown by Dolan et al. (1998) and bounds the southeastern margin of Hispaniola and the north margin of Puerto Rico. Restoration of ~300 km of movement brings together northwest-trending segments of the correlative Peralta and Cerillos belts of Hispaniola and Puerto Rico, respectively (Dolan et al., 1991; for an alternative model, see also Dolan et al., 1998, their figure 24). Further, the juxtaposition of Hispaniola and Puerto Rico, along with the Virgin Islands, brings together exposures of Paleocene and Eocene rocks that distinguish the domain of calc-alkaline igneous rocks and related sedimentary units restricted to the south-southwestern margin of the eastern Greater Antilles (Iturralde-Vinent and Lidiak, 2006; Rojas-Agramonte et al., 2006). As suggested by Iturralde-Vinent and Gahagan (2002), Hispaniola may be restored to the region south of the Oriente Province, Cuba, by ~400 km of movement along the eastward extension of the Oriente fault (Fig. 40C).

Note that in our reconstruction, we align the Hess escarpment and the Yucatán transform. The restoration adds a few hundred kilometers to the movement along the Cayman faults and approximates the total of ~1000 km that is accepted commonly. In the restoration, the Chortis block is positioned along the margin of southwest Mexico, according to the constraints presented by Rogers et al. (2007b).

Insertion of the Late Cretaceous Caribbean Large Igneous Province/Caribbean-Colombian Oceanic Plateau from the Pacific Northeastward into the Caribbean Region (Fig. 40D)

Restoration of the Lesser Antilles repositions the Late Cretaceous, ca. 92 Ma plateau basalt and related rocks (Caribbean large igneous province/Caribbean-Colombian oceanic plateau), which underlie much of the Caribbean Sea, to the west. The distribution of submarine Caribbean large igneous province/Caribbean-Colombian oceanic plateau basalt and terrestrial exposures of correlative rocks suggests the limits of the Caribbean large igneous province/Caribbean-Colombian oceanic plateau domain (Fig. 39). As outlined already, outcrops of Caribbean large igneous province/Caribbean-Colombian oceanic plateau are known also from Panama, Costa Rica, northwestern South America, Aruba, Hispaniola, Puerto Rico, and Jamaica. In northwestern South America, rocks with lithological, geochemical, and chronological similarities to the Caribbean large igneous province are recognized, especially west of the Romeral fault, where Cediel et al. (2003) identified two large composite terranes (their tectonic realms). The western tectonic realm contains fragments of Mesozoic and Tertiary Pacific oceanic plateaus, aseismic ridges, intraoceanic island arcs, and ophiolites that were accreted at the Romeral fault/suture during and after the Cretaceous (see Sinton et al., 1998, their figure 1; Kerr et al., 2003, their figure 7; Vallejo et al., 2009). The western realm lies outboard of Paleozoic and Precambrian units comprising the Central Cordillera. Although each of these realms has been strongly deformed by young dextral strike-slip faults, the outboard western realm is especially relevant because, according to Vallejo et al. (2009), the Caribbean large igneous province–like rocks moved east-northeastward during collision with the Ecuadorian sector.

The remnants of Caribbean large igneous province rocks exposed in Jamaica, Haiti, and Puerto Rico suggest that the Caribbean large igneous province/Caribbean-Colombian oceanic plateau plate reached this latitude during convergence toward the southern margin of the Greater Antilles (Sinton et al., 1998). As postulated earlier, we suggest that movement of the plate was accommodated by a left-lateral fault, on the northwest, coincident

with the Hess escarpment fault (Figs. 1 and 40D; Iturralde-Vinent and MacPhee, 1999).

The eastward limit of the Caribbean large igneous province/Caribbean-Colombian oceanic plateau plate is constrained by DSDP Leg 15 drill holes, which reached into the uppermost meters of oceanic crust at Sites 146, 150, and 153 in the Venezuelan Basin, and complementary seismic-reflection data (Kroehler et al., 2011), as well as exposures of ca. 90 Ma basalt on Aruba (Kroehler et al., 2011, their figure 2). Although the character of the eastern limit of the Venezuelan Basin is not well defined by the well distribution, it is clear that the southeastern part is not underlain by mafic crust, as shown by seismic lines and well logs that reveal Cretaceous sedimentary strata forming a passive margin above the northern flank of the Guyana Shield of northeastern South America (Di Croce et al., 1999).

The southeast margin of the Caribbean-Colombian oceanic plateau plate is constrained by an inferred fault that extends from the eastern limit of the restored Virgin Islands southwestward as far as northwestern South America, as shown by Iturralde-Vinent and MacPhee (1999) and Figure 39 herein. We chose the termination of the Virgin Islands because we speculate that emplacement of the Caribbean-Colombian oceanic plateau plate and the outcrops of Paleocene volcanic rocks on the Virgin Islands record plate movement and ensuing collision, as discussed in the following. The dextral fault must pass northwest of the Guyana Shield of northeastern South America and continue southwest across the northwestern corner of South America, which is composed of the northern Andean block (e.g., Cediel et al., 2003). The Andean block is mainly orogenic float according to Monod et al. (2010) that has been uplifted during post-Eocene north-directed shortening (Kellogg and Bonini, 1982).

The Paleocene dextral fault that accommodated insertion likely coincided roughly with the trace of the mapped Romeral fault, which delineates the eastern limit of exposures of plateau rocks. Restoration of the complex movements including accretion, displacement along dextral faults, and contraction along the northern margin of South America, as outlined by Burke and coworkers (Burke et al., 1978; Burke, 1988), provides the space that accommodated the insertion of the Caribbean-Colombian oceanic plateau plate.

We postulate that the northeastern limit of the Caribbean-Colombian oceanic plateau plate is delineated by the exposures of plateau rocks in southwestern Hispaniola and southwestern Puerto Rico. The proximity of the Caribbean-Colombian oceanic plateau outcrops to the Los Muertos Trough (Fig. 1) indicates the possibility that the thick plateau crust converged and collided during subduction of oceanic lithosphere beneath an upper plate composed mainly of Cretaceous arc rocks.

Los Muertos Trench, which lies south of the Virgin Islands and Puerto Rico and extends west, south of Dominican Republic, resembles subduction-related ocean-floor topography. The trench corresponds with a shallowly north-dipping zone of thrust faulting marked by focal mechanisms of earthquakes near the top (Byrne et al., 1985) of a thick, ~110 km slab of Caribbean lithosphere (Edgar et al., 1971; Case et al., 1990). The Peralta Group, which may have formed part of an Early Tertiary accretionary prism (Dolan, 1988; Dolan et al., 1991), and the Los Muertos Trench (Dolan et al., 1998) probably represent a Paleogene subduction zone that accommodated convergence and consumption of proto–Pacific oceanic lithosphere until arrival of the Caribbean-Colombian oceanic plateau plate.

We believe that Paleocene igneous rocks exposed in eastern Cuba, Dominican Republic, Puerto Rico, and the Virgin Islands, as described already, record the subduction-related volcanism that took place as oceanic crust from the southwest converged toward the Oriente–Hispaniola–Puerto Rico–Virgin Islands agglomeration. Subduction led to consumption of the proto-Pacific lithosphere east of the Caribbean-Colombian oceanic plateau (Iturralde-Vinent, 1994; Sigurdsson et al., 1997; Pindell et al., 2006; Rojas-Agramonte et al., 2006) as the plate moved northeast (Acton et al., 2000). Therefore, our interpretation is that the end of Eocene magmatic activity records the arrival and collision of Beata Ridge and other thick Caribbean plateau crust against the southeastern margin of the Greater Antilles.

The Trois Riviere–Peralta–Ocoa belt has been interpreted as part of the accretionary prism (Dolan, 1988) that developed in the backarc of the Cretaceous arc (Dolan et al., 1991). However, these rocks lie north of the Los Muertos Trench, where, if subduction took place, an accretionary prism would likely develop.

Insertion of the PIA/IAT Arc Segment during Albian and Late Cretaceous Time (Fig. 40E)

Following the cessation of PIA/IAT Aptian and early Albian magmatism (Fig. 40F) after 110 Ma, as recorded by the development of a regional unconformity at ca. 105 Ma (see previous), a hiatus in magmatism persisted until Late Cretaceous subduction resumed, as recorded by: (1) subduction-related plutons as old as ca. 94 Ma in Cuba (Rojas-Agramonte et al., 2011), (2) ca. 90 Ma plutons (Escuder Viruete et al., 2007a) and formation of the upper Tireo volcanic section (Escuder Viruete et al., 2007a, 2008) in Hispaniola, and (3) correlative Albian and younger formations in Puerto Rico, Cuba, the Virgin Islands, and Jamaica (see references presented earlier herein). As shown by Iturralde-Vinent et al. (2008, their figure 2), southwest-directed subduction would result in consumption of lithosphere between the Bahamas Platform and the formation of a magmatic arc. The volcanic arc formed upon the eroded PIA/IAT basement above the south-southwestward dipping slab that subducted beneath the inactive Aptian arc (Fig. 40F). Results from paleomagnetic studies on central Cuban Cretaceous arc rocks also show northeastward movement (Renne et al., 1991; Tait et al., 2009) with respect to the North America and South America plates (Housen et al., 2003), culminating with cessation of volcanic activity and collision against the Bahamas Platform by the Maastrichtian. At ca. 100–70 Ma, the inactive PIA/IAT arc segment moved north-northeast between the Yucatán transform fault and an inferred, parallel fault east of Aves Ridge.

CARIBBEAN DISCUSSION AND REGIONAL SUMMARY

Discussion

Our interpretation contrasts with those who argue for generation of the Paleocene calc-alkaline igneous rocks in response to south-dipping subduction beneath part of the Greater Antilles zone followed by collision of the Cuban orogen with the Bahamas Platform (North American plate) in the Eocene. The collision coincided with the end of magmatic activity recorded by the oldest zircon fission-track age of 44 ± 4 Ma in the Sierra Maestra of Oriente Province, Cuba (Iturralde-Vinent, 1994, 1998). Previous hypotheses suggest that the Paleocene magmatism records ~1000 km of convergence (Garcia-Casco et al., 2008; Tait et al., 2009), during which the Caribbean plate was brought against the Bahamas Platform (Iturralde-Vinent, 1994; Sigurdsson et al., 1997; Pindell et al., 2006; Rojas-Agramonte et al., 2006).

We consider geological features such as the presence of probable accretionary prism strata (Dolan et al., 1991), accreted Caribbean large igneous province/Caribbean-Colombian oceanic plateau rocks in Sierra Bermeja, and Los Muertos Trough, to be compatible with convergence and north-directed subduction associated with insertion of the plateau plate between 60 and 45 Ma. The Paleocene magmatic event is temporally distinct from the Late Cretaceous event between ca. 96 and 71 Ma that is recorded by well-defined uplift, erosion, cooling, and development of an unconformity between ca. 70 and 60 Ma. The process is well recorded in Cuba, where Late Cretaceous volcanism was interrupted in the latest Campanian (Iturralde-Vinent et al., 2006), but resumed during the Paleocene (Iturralde-Vinent, 1976, 1977, 1994, 1998), as shown by zircon from granitic rocks that yields apparent U-Pb ages between 60 and 46 Ma (Kysar et al., 1998a, 1998b; Rojas-Agramonte et al., 2006; see previous discussion for additional detail and references).

The interruption of magmatism between ca. 70 and 60 Ma has been interpreted as a pause in subduction followed by continued southwestward convergence of the proto-Caribbean (Pindell and Barrett, 1990). However, Jolly et al. (2006) argued that geochemistry of the volcanic rocks of the Greater Antilles varies systematically with time from predominantly PIA/IAT (120–105 Ma), to calc-alkaline basalt (105–97 Ma), and finally to high-K, incompatible-element–enriched basalt and andesite (97–70 Ma). They noted that after a hiatus in magmatism, geochemical trends changed again in the Eocene with eruption of hornblende-bearing calc-alkaline basalts between 60 and 45 Ma. The change may indicate a different source, perhaps related to subduction of Caribbean lithosphere.

Regional Summary

Islands of the Caribbean Antilles generally expose magmatic rocks of Cretaceous and Tertiary ages. The magmatic rocks record four main episodes of convergence and subduction during which arcs formed. The four periods of subduction and arc formation are ca. 135–110 Ma, ca. 100–70 Ma, ca. 65–45 Ma, and ca. 40 to recent. During consumption of oceanic lithosphere, arc segments moved northeast or eastward along trench-trench transforms. We recognize three episodes of plate insertion. From youngest to oldest, these include: (1) Lesser Antilles plate, from late Eocene to recent, (2) Caribbean-Colombian oceanic plateau or plateau plate, 61–48 Ma, and (3) Greater Antilles PIA/IAT plate, ca. 100–71 Ma. Each plate insertion was accommodated by two major faults active during an episode of convergence and subduction. The faults coincided with the lateral boundaries of the small plates (microplates) and generally linked trenches. The pairs of strike-slip faults include the following. (1) The late Eocene to recent Cayman set and cogenetic faults across the Caribbean basin to the south along the northern margin of South America correlate to insertion of the Lesser Antilles plate. The southern faults are largely obscured by younger thrusts. During movement of at least 1000 km, the Lesser Antilles volcanic arc, formed as Atlantic Ocean floor, was subducted beneath the eastern edge of the Caribbean lithosphere. (2) Paleocene and early Eocene (ca. 60–45 Ma) faults coincide with the Hess escarpment on the northwest and, on the southeast, an inferred fault extending from the easternmost Virgin Islands southwestward to a point within the Romeral suture in northwestern South America. As the Caribbean-Colombian oceanic plateau or "plateau plate" converged toward the southern margin of the Greater Antilles, the leading Pacific lithosphere subducted into a trench extending from Cuba to the Virgin Islands. (3) The north-northeast–striking Yucatán transform and its likely southeasterly extension along the Hess escarpment and an inferred, parallel, fault east of Aves Ridge accommodated movement of the PIA/IAT plate between ca. 100 and 70 Ma. The direction of the subducting slab was to the south or southwest (or west).

Magmatic lulls are marked by uplift, erosion, and development of an unconformity that also may be associated with formation of contractional structures and local emplacement of olistostromes. These features suggest that the magmatic lulls coincide with collisions that terminated subduction. The principal collisions took place in the Late Cretaceous and in the Eocene, when, respectively, the Late Cretaceous arc overrode the Bahamas margin of the North America plate and the thick Caribbean large igneous province crust was accreted against the Eocene arc. Westward restoration of the small, fault-bounded plates clears the Caribbean region of thick crust composed of sialic fragments, arc cores, and plateau basalt provinces.

MIDDLE TO LATE JURASSIC EVOLUTION OF THE GULF OF MEXICO

Our paleogeographic model for the Caribbean region during the Late Jurassic results in the removal of post-Jurassic arc rocks, as well as fragments of pre-Jurassic sialic crust that locally underlie the arcs, toward the west or southwest outside the Caribbean basin. The model further implies that during episodes of

Cretaceous convergence, oceanic lithosphere, mainly of Jurassic age, which formed mainly in the Atlantic and Gulf of Mexico basins as described by Klitgord and Schouten (1986) and Schettino and Turco (2009), was consumed. Klitgord and Schouten (1986) recognized problems with Pangea reconstructions based upon fit of continental margins (Bullard et al., 1965) and paleomagnetic data (Van Der Voo et al., 1976; Van Der Voo, 1990) that resulted in overlap of pre-Cretaceous continental rocks. However, analysis of pre-breakup configurations based upon apparent wander paths yields a closure pole very similar to that of Bullard et al. (1965). In light of these results and the simplicity of the Bullard et al. fit, we follow Anderson and Schmidt (1983) in utilizing the configuration of Bullard et al. as a starting point. Schettino and Turco (2009) pointed out that although fragmentation of Pangea took place in phases starting in the Triassic, the onset of mid-Jurassic seafloor spreading did not begin until after 170 Ma, as suggested by Klitgord and Schouten (1986) based upon the age of the oldest drilled oceanic crust (Granstein et al., 1994).

Ideas about the opening of the Gulf of Mexico commonly involve extension between North and South America as well as rotation of the Yucatán block (Pilger, 1978; Humphris, 1979; Buffler et al., 1980; Dickinson and Coney, 1980; Salvador and Green, 1980; Walper, 1980; Hall et al., 1982; Anderson and Schmidt, 1983; Shepherd, 1983; Klitgord et al., 1984; Pindell, 1985; Klitgord and Schouten, 1986; Salvador, 1987). The principal expanse of oceanic gulf crust formed within a pull-apart basin at a releasing step between the Cuba and Mojave-Sonora (now incorporated into Mexico-Alaska megashear) transforms. Next, we offer an updated model of Gulf of Mexico formation based upon sinistral movement along the Mexico-Alaska megashear that led Schouten and Klitgord (1994) to postulate that the Yucatán rotated in response to edge forces that imposed a "rack and pinion" motion. The rotation, which earlier was recognized during paleomagnetic studies by Molina-Garza et al. (1992) and corroborated by Godinez-Urban et al. (2011a), involved ~60° of counterclockwise motion. Rotation is inferred to have been accommodated by faults such as the Oaxaca fault (Alaniz-Alvarez et al., 1996) and a precursor of the Chixoy-Polochic fault in Guatemala (Anderson and Schmidt, 1983). Formation of the Gulf of Mexico probably began concurrently with Jurassic opening of the Atlantic Basin at ca. 170 Ma. By ca. 164 Ma (Bathonian), sufficient movement had taken place so that extensional or transtensional basins had formed, and clastic rocks including parts of Huizachal and Todos Santos were accumulating (Godinez-Urban et al., 2011b; Rubio-Cisneros and Lawton, 2011).

Fault Linkages from the Atlantic Basin to the Northern Gulf of Mexico

Klitgord et al. (1984) recognized the importance of a set of Late Jurassic transforms linking segments of the early Mid-Atlantic Ridge in the southern central Atlantic Basin to ocean floor in the Gulf of Mexico (Fig. 41). They identified several hypothetical, west-northwest–striking fracture zones, including, from southwest to northeast, Campeche, Bahamas, and Cuba. The Bahamas fracture zone extends northwest across southern Florida, where its path is distinguished on the basis of magnetic, gravity, seismic, and deep drill-hole data, along the segmented edge of the southern North America plate during the Jurassic.

Releasing steps that extend southwestward from the Bahamas fracture and link to the Cuba fault separate high-standing blocks (e.g., Sarasota, Middle Ground, and Wiggins arches) from intervening basins (e.g., South Florida, Tampa, Apalachico; Figs. 42 and 43). The pattern of alternating crustal highs and lows may be extended northwestward based upon analysis of the seismic stratigraphy of the Mississippi salt basin, Monroe uplift, north Louisiana salt basin, Sabine uplift, and East Texas basin (Fig. 44; Winker and Buffler, 1988; Dobson and Buffler, 1997). The geometry was shown by Pindell and Kennan (2001, their figure 2), although they de-emphasized the releasing steps along the Bahamas fracture zone in their 2009 update paper.

The Jurassic stratigraphy of the northern and western Gulf of Mexico margins has been extensively studied because of its importance as reservoirs for hydrocarbons. Summary studies (Winker and Buffler, 1988; Goldhammer, 1999; Goldhammer and Johnson, 2003; Horbury et al., 2003) reveal the correlations and depositional environments that characterize the pre-Cretaceous stratigraphy. Hames et al. (2011) contended that a close relationship exists between Late Jurassic stratigraphic units and structures related to the opening of the Gulf of Mexico basin. Figure 44 shows the correspondence of the updip limit of Jurassic units, especially salt, with major craton-bounding faults. The Louann salt, which underlies the correlative Smackover and Zuloaga carbonate formations of Oxfordian age (ca. 164–157 Ma; Granstein et al., 1994; Goldhammer, 1999), accumulated after rifting and seafloor spreading that began no earlier than ca. 170 Ma (Klitgord and Schouten, 1986).

Extension, which began after 170 Ma, continued into the Tithonian, as shown by analysis of seismic data (Fig. 45; Mondelli, 2010) within the East Texas basin, where interpreted normal faults cut the Louann salt and overlying section as high as the top of the Cotton Valley sandstone of probable Tithonian age. Cessation of extension during the Tithonian (152–145 Ma) is compatible with the age of ca. 148 Ma indicated for other faults of the Mexico-Alaska megashear system (e.g., Anderson and Nourse, 2005). Mondelli's restoration indicates that ~22 km of extension was accommodated during accumulation of the Tithonian Cotton Valley sandstone. Extension of the Cotton Valley occurred in addition to the extension during the formation of oceanic crust that formed prior to accumulation of the Louann salt. The salt, which underlies the Norphlet Sandstone and the stratigraphically higher, fossiliferous, Oxfordian Smackover and Zuloaga carbonate strata, must be at least Callovian, i.e., 164 Ma. As shown by Goldhammer and Johnson (2003, their figure 6), it may be as old as Bathonian (168–166 Ma).

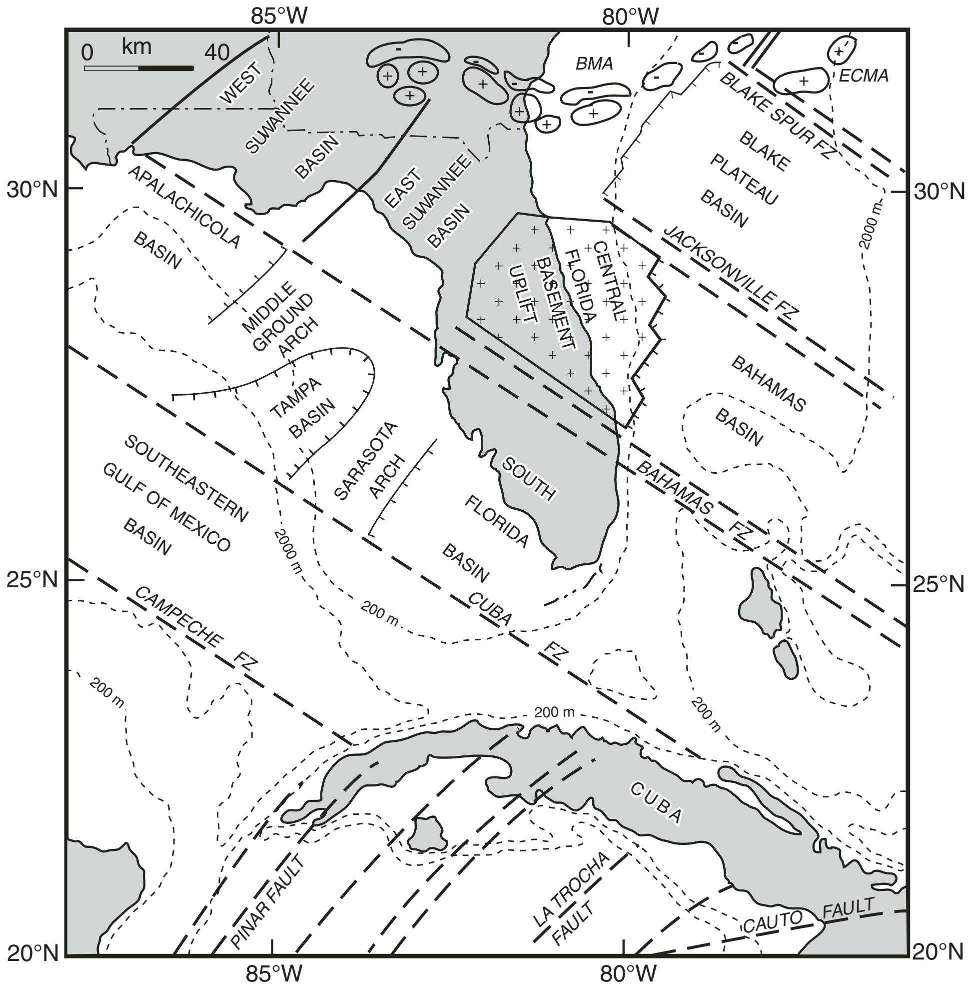


Figure 41. Tectonic map of the Florida-Bahamas-Cuba region (adapted from Klitgord et al., 1984). Main fracture zones (FZ) are indicated. Prominent magnetic anomalies are also shown (ECMA—East Coast magnetic anomaly; BMA—Brunswick magnetic anomaly). Bathymetric contours are in meters. Figure is adapted from Klitgord et al. (1984).

In northeastern Mexico, a pre-Oxfordian age for the evaporite section is indicated by coarse conglomerate and arkose with intervals containing early Oxfordian ammonites (Imlay, 1936) that overlie Minas Viejas gypsum or Paleozoic basement. Along the north flank of the Coahuila block, a section of pre–late Tithonian clastic strata, including debris flows and bouldery conglomerate that crops along the San Marcos fault, may be more than 1000 m thick (Fig. 46; McKee et al., 1990). Near the top of the section, sandstone comprising the Colorado beds records eolian conditions similar to those under which the older Norphlet Formation formed. The clastic units, commonly quite coarse, that are adjacent to high-standing fault blocks of pre-Jurassic rocks at the north and northwest margins of the Gulf of Mexico are compatible with the idea that horsts, formed at releasing steps of sinistral faults, were sources of detritus in the Late Jurassic (McKee et al., 1990; Prather, 1992).

The updip limit of Jurassic strata in northeast Texas (Hames et al., 2011) marks the edge of the area markedly affected by Middle and Late Jurassic extension. The topographic boundary marking the limit of the northwestern Gulf of Mexico domain of extension may have persisted into the Early Cretaceous, when it was marked by development of the Sligo and Cupido reefs (Wilson, 1990, 1999).

Goldhammer and colleagues (Goldhammer et al., 1991; Goldhammer, 1999; Fig. 45) pointed out that the abrupt change in trend of the reef line from northerly to westerly along the south margin of the Coahuila block coincides with the postulated trace of the Mojave-Sonora transform fault (Anderson and Schmidt, 1983). Other faults noted by Goldhammer et al. (1991), such as San Marcos (McKee et al., 1990) and La Babia (Charleston, 1981), which equal the Boquillas-Sabinas lineament (Padilla y Sanchez, 1982, 1986), and the Sabinas fault (Alfonso-Zwanziger, 1978), did not affect the reef trend, probably because they had small movements.

The orientation and age of the Mexico-Alaska megashear (the Mojave-Sonora megashear of Anderson and Schmidt, 1983; Anderson and Nourse, 2005) are kinematically and temporally compatible with plate movements necessary to open the northern part of the Gulf of Mexico as postulated by Anderson and Schmidt (1983, their figure 12).

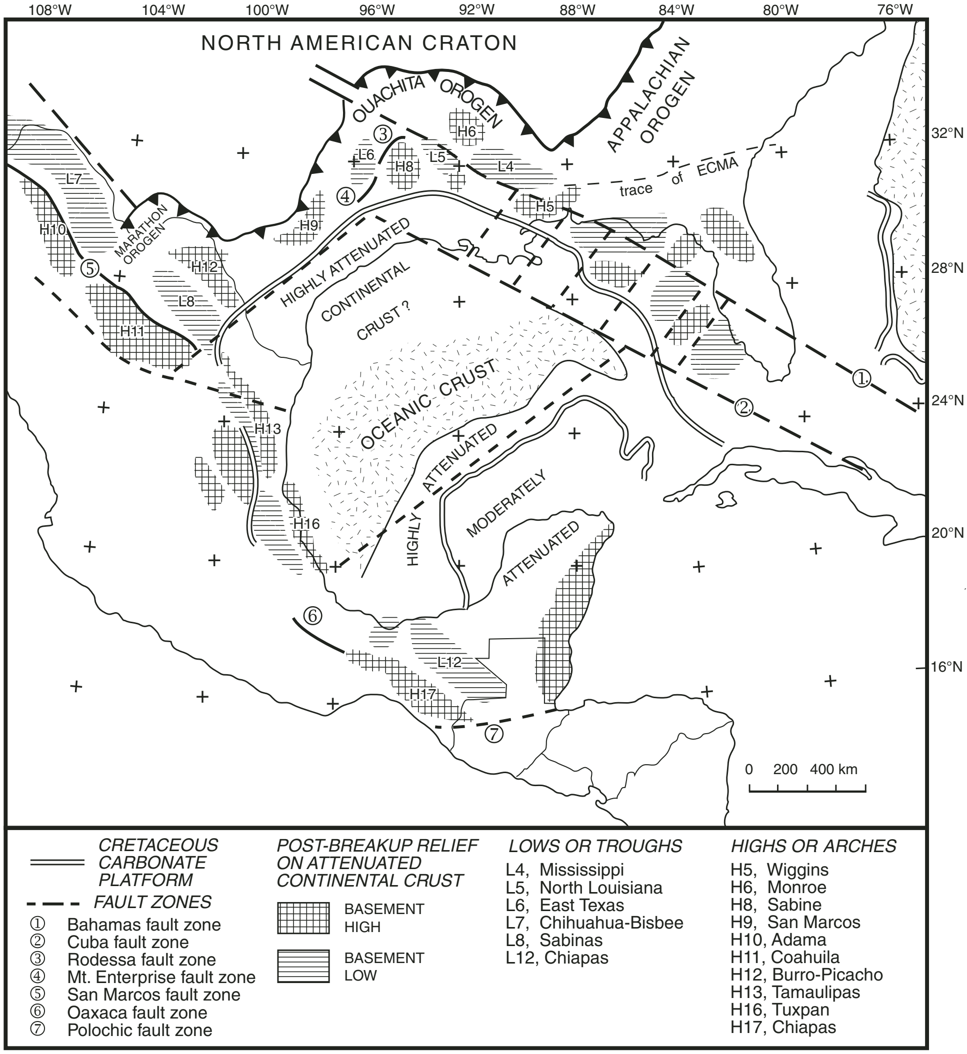


Figure 42. Main tectonic elements of the Mesozoic circum–Gulf Province related to the breakup of Pangea. Figure is adapted from Winker and Buffler (1988). ECMA—East Coast magnetic anomaly.

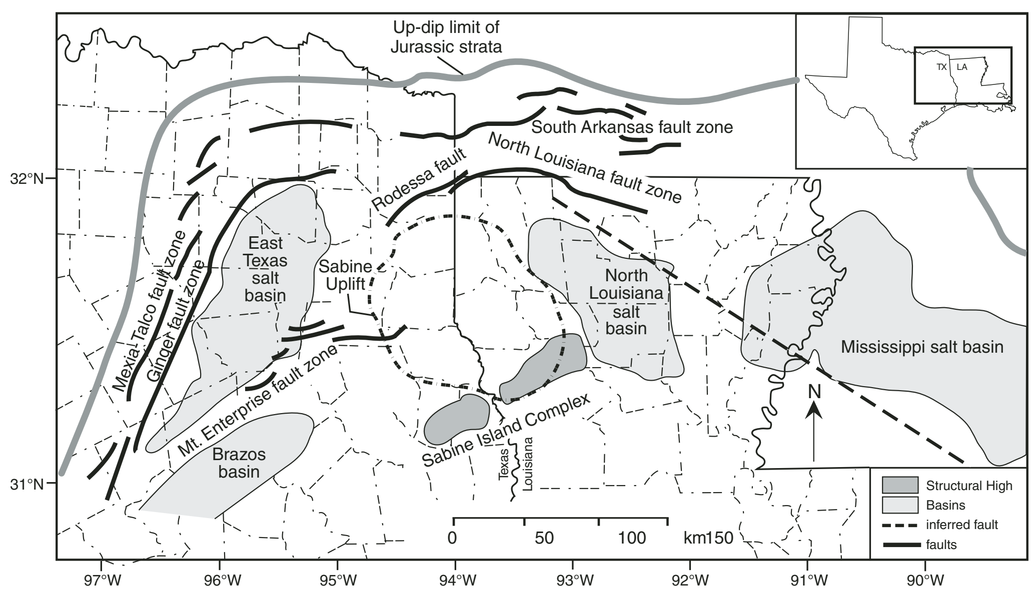


Figure 43. Sketch map of east Texas and west Louisiana showing Late Jurassic structural elements. Some structures formed during opening of the Gulf of Mexico Basin. Areas in medium gray are basins, and areas in dark gray are structural highs. Figure is adapted from Hammes et al. (2011). TX—Texas, LA—Louisiana.

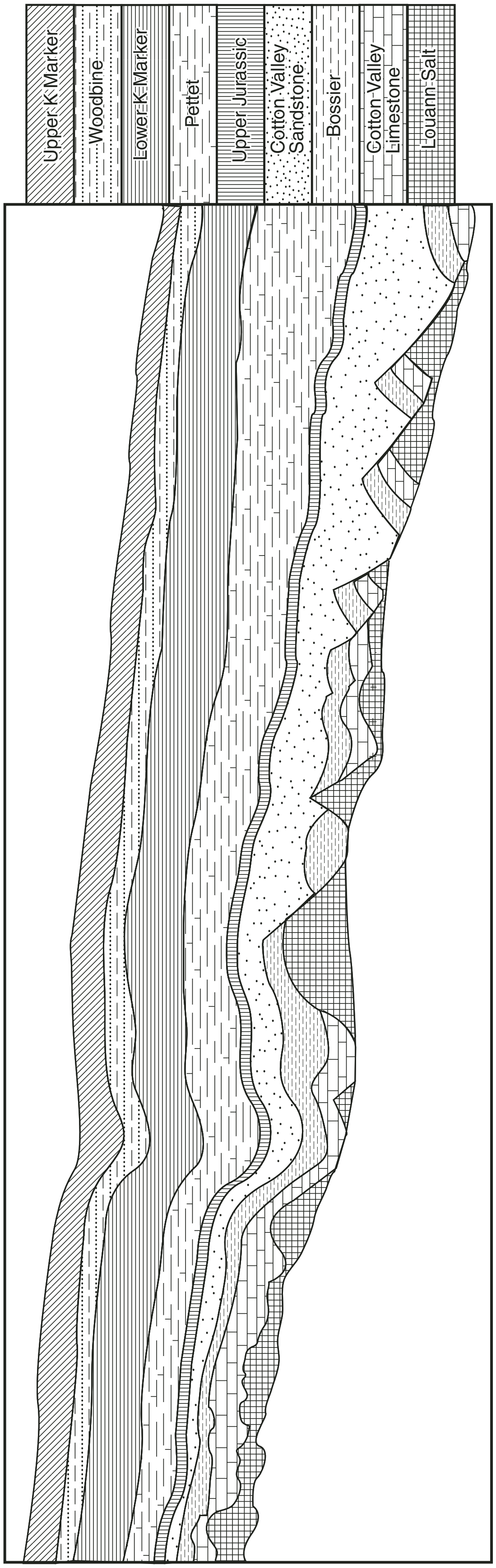


Figure 44. Cross section of East Texas basin showing Upper Jurassic strata and their relation to normal faulting during transtension and timing of salt movement and structural development. Figure is adapted from Mondelli (2010). K—Cretaceous.

Extension within the Southern Margin of the Gulf of Mexico

Similar to the northern part of the Gulf of Mexico, basement uplifts (Horbury et al., 2003, and references therein) and adjacent Middle to Late Jurassic clastic sections that crop out south of the postulated trace of the Mojave-Sonora megashear may record extension. The Middle Jurassic clastic Huizachal Group and Todos Santos Formation that crop out between the Mojave-Sonora and Motagua faults (Fig. 46) suggest an extensional setting contemporaneous with that recorded in the northern Gulf of Mexico. However, paleomagnetic data that record counterclockwise rotation of the Yucatán block (Molina-Garza et al., 1992; Godinez-Urban et al., 2011b) indicate a more complex process involving rotation of the block as schematically shown by Anderson and Schmidt (1983, their figure 12), and further developed by Schouten and Klitgord (1994) (Figs. 47 and 48).

Next, we summarize recent studies of rift-related clastic sections that reveal stratigraphic relationships and accumulation ages (Godinez-Urban et al., 2011a, 2011b; Rubio-Cisneros and Lawton, 2011) and, further, note faults such as Oaxaca (Alaniz-Alvarez et al., 1996; Figs. 46 and 49), the Tamaulipas–Golden Lane–Chiapas transform (Pindell, 1985; Fig. 50[1]), and the Chixoy-Polochic and Motagua faults in Guatemala (Fig. 47) that may have accommodated rotation of the Yucatán block between the large sinistral faults of the Mexico-Alaska megashear set (Anderson and Schmidt, 1983; Schouten and Klitgord, 1994; e.g., Fig. 47).

Ages, Geologic Setting, and Significance of Jurassic Strata in Southeastern Mexico and Guatemala

Red beds beneath Cretaceous carbonate strata crop out south of the Coahuila block, across the inferred trace of the Mexico-Alaska megashear (Mojave-Sonora megashear segment) in eastern Mexico (Fig. 45). The exposures include continental red beds and volcanogenic units assigned to the Huizachal Group, which contains two formations—La Boca Formation and the overlying La Joya Formation (Mixon et al., 1959; Michalzik, 1991). Vertebrate fossils and geochronology (Fastovsky et al., 1995; Fastovsky et al., 2005) indicate that the lower part of the La Boca Formation is mainly Pliensbachian (ca. 183–189 Ma). However, the ages of some igneous rocks and unconformably overlying sedimentary beds are not well constrained.

Recently obtained U-Pb interpreted ages of zircons from igneous rocks and detrital zircons in sedimentary beds reveal that three Jurassic units, separated by unconformities, may be distinguished in Valle de Huizachal (Rubio-Cisneros and Lawton,

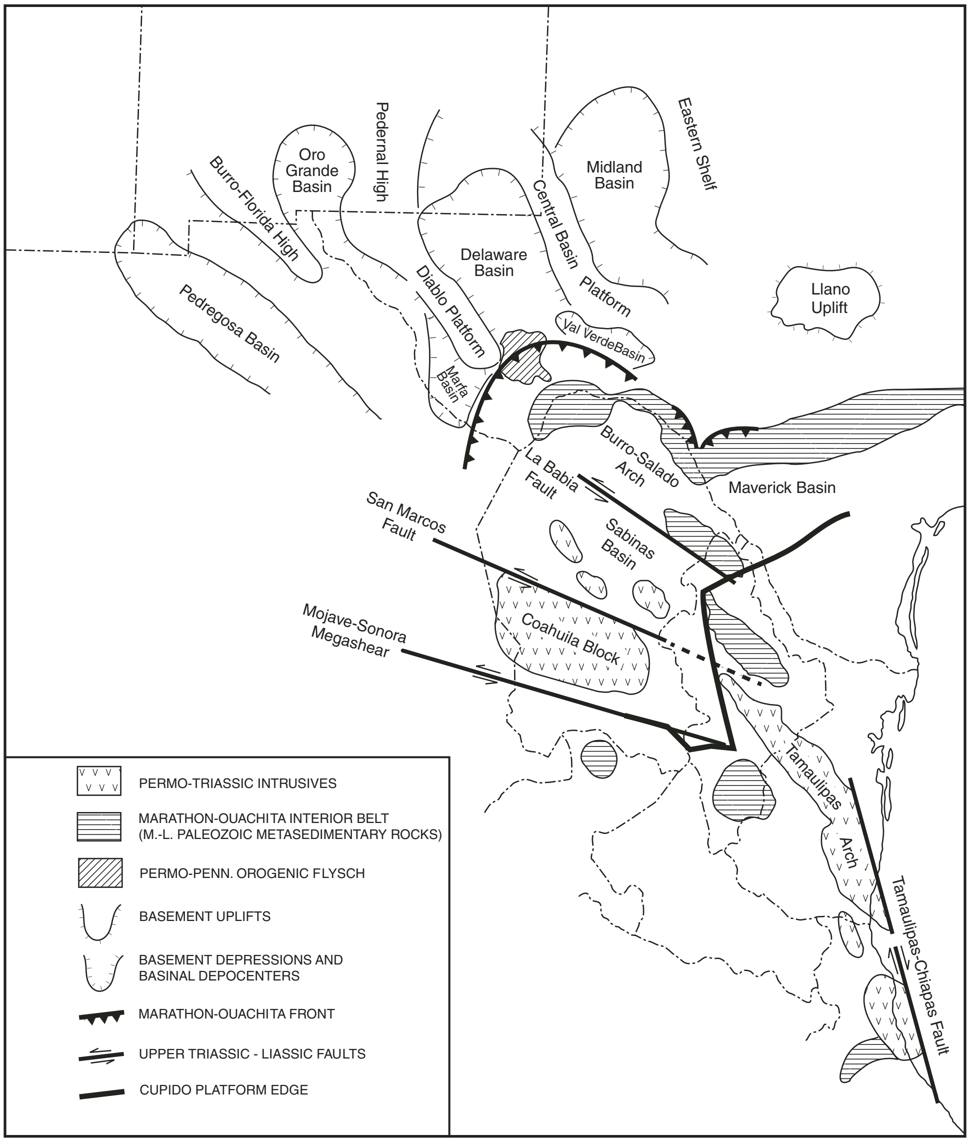


Figure 45. Paleotectonic map of northeastern Mexico, southwestern Texas, and southern New Mexico illustrating major tectonic features. United States and Mexico state outlines are shown for orientation. Figure is adapted from Goldhammer (1999).

2011, and references therein). La Boca Formation consists of two informal members: (1) a lower unit of volcanic and volcaniclastic strata consisting of lapilli tuff, crystal tuff, lava flows, volcaniclastic breccia, ignimbrite, shale, siltstone, sandstone, and conglomerate that is variably altered and metamorphosed, and (2) an upper unit of mainly red siliciclastic strata. The third and highest unit, La Joya, consists of a section of upward-fining red sandstone, shale, and subordinate conglomerate that overlies a basal conglomerate.

The three formations yield interpreted U-Pb zircon crystallization ages and accumulation ages that fall between ca. 190 and 160 Ma. A tuff at the base of the group yielded an interpreted U-Pb age of ca. 189 Ma (Fastovsky et al., 2005), whereas detrital zircons from intercalated clastic beds yielded slightly younger ages between 184 and 183 Ma, with single grains that yielded an age of ca. 179 Ma (Rubio-Cisneros and Lawton, 2011). Discordantly overlying clastic beds yielded Oxfordian ages (164–157 Ma) with a mean age of 163.3 Ma from six zircon grains in one sample. A sample from the base of the overlying La Joya Formation has a concordant grain that yielded a date of 163.6 Ma, which is indistinguishable from the underlying strata. The younger units are rich in Neoproterozoic zircons, suggesting that the older Jurassic volcanic cover was largely eroded prior to deposition.

From the Huizachal Valley in Tamaulipas southward into the state of Hidalgo, Huizachal, or the equivalent Cahuasas Formation, has been mapped adjacent to crystalline basement rocks (for summary and references, see Ochoa-Camarillo et al., 1999; Fig. 50). The unfossiliferous Cahuasas Formation consists of sandstone, conglomerate, and sedimentary breccia and shale of variable thickness (0–1000 m). Its Aalenian (174 Ma) to Bathonian (168 ma) age has been estimated from its position between

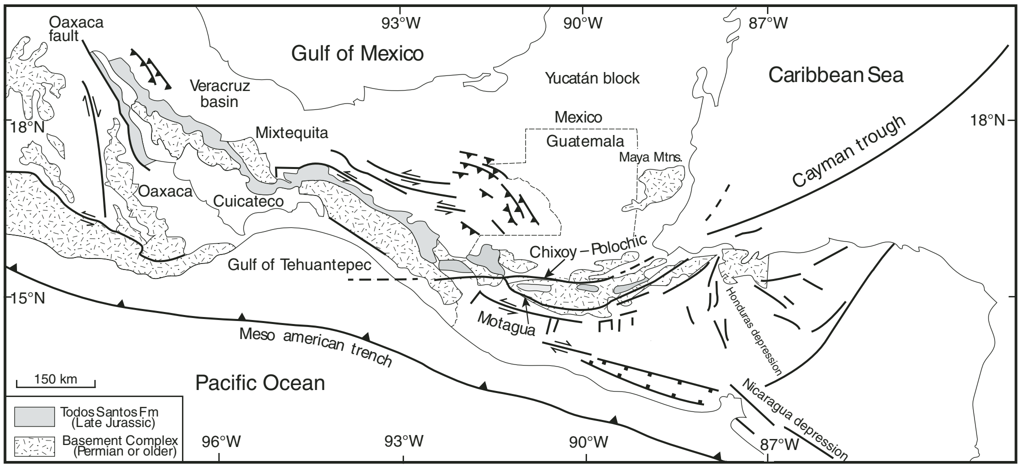


Figure 46. Generalized geologic map of the Todos Santos Formation and basement terranes of southern Mexico and Central America. Figure is adapted from Godínez-Urban et al. (2011b).

overlying fossiliferous strata of Callovian age and underlying Pliensbachian rocks.

South of the Trans-Mexico volcanic belt, red clastic rocks comprise the comparable Todos Santos Formation (Fig. 46). The nonmarine Todos Santos Formation is commonly interpreted as having accumulated in extensional basins during continental rifting in the Gulf of Mexico region (Blair, 1987). The formation

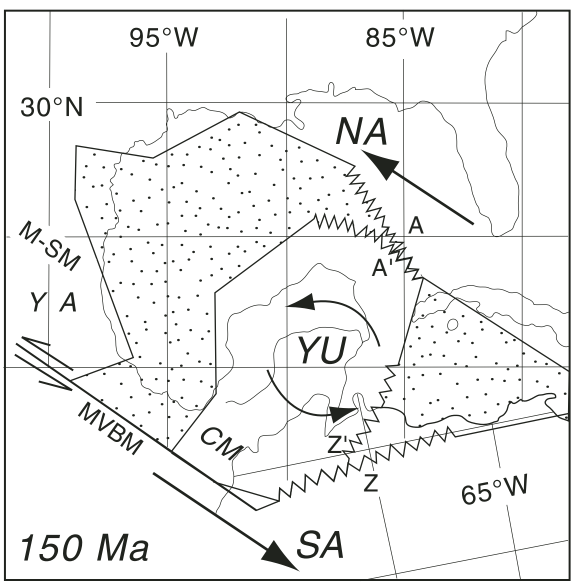


Figure 47. Schematic illustrated mechanism for opening of the Gulf of Mexico according to Schouten and Klitgord (1994). Edge-driven, counterclockwise rotation of a centered Yucatán block (YU) is caused by displacement of North America (NA) from South America (SA). Rifted margins are produced at A-A′ and Z-Z′. M–SM—Mojave-Sonora megashear; MVBM—Mexican volcanic belt megashear. Figure is adapted from Schouten and Klitgord (1994). CM—Chiapas massif; YA—Yaqui block.

crops out along the western margin of the Veracruz basin and continues southeast as a nearly unbroken outcrop belt along the northeastern margin of the Chiapas massif, from whence exposures extend eastward into western Guatemala along the southern flank of the imposing Los Altos Cuchumatanes range (Anderson et al., 1973; Clemons et al., 1974; Godinez-Urban et al., 2011a, 2011b; Fig. 46). Todos Santos units rest unconformably upon rocks of the Chiapas massif and Upper Paleozoic strata in the Chicomuselo uplift (Castro-Mora et al., 1975; López-Ramos, 1981; Fig. 50), suggesting deposition on irregular topography probably formed during extension (Meneses-Rocha, 1985; Blair, 1987). Like the Cahuasas Formation, the Todos Santos Formation is unfossiliferous. However, its position below Kimmeridgian marine beds (Alencaster, 1977) has led to an estimated Late to Middle Jurassic age.

In southeast Mexico, the maroon and red clastic rocks, mapped as Todos Santos Formation, have been subdivided into three units based upon stratigraphic and geochronologic studies (Godinez-Urban et al., 2011b). The highest section, ~600 m thick, is the Jerico Member, characterized by an upper unit of thick-bedded, poorly sorted, coarse-grained, hematitic, pebbly arkose intercalated with several thick horizons (tens of meters) of conglomerate and pebbly sandstone. Pebbles and cobbles of metamorphic rocks, deep-seated plutonic rocks, and abundant quartz are well rounded. The ages and stratigraphic relations established by Godinez-Urban et al. (2011b) leads them to conclude that the Jericó fluvial deposits and associated alluvial-fan deposits accumulated along the Jericó-Concordia fault system in southeastern Mexico (Movarec, 1983; Blair, 1987) during Oxfordian or younger time.

Two units containing volcanic layers underlie the clastic, upper Todos Santos section, El Diamante Member and La Silla Formation. Red mudstone, with sandstone beds 10–90 cm thick, comprises the El Diamante Member, which is more than 200 m thick. Isolated flows of olivine basalt are present high in

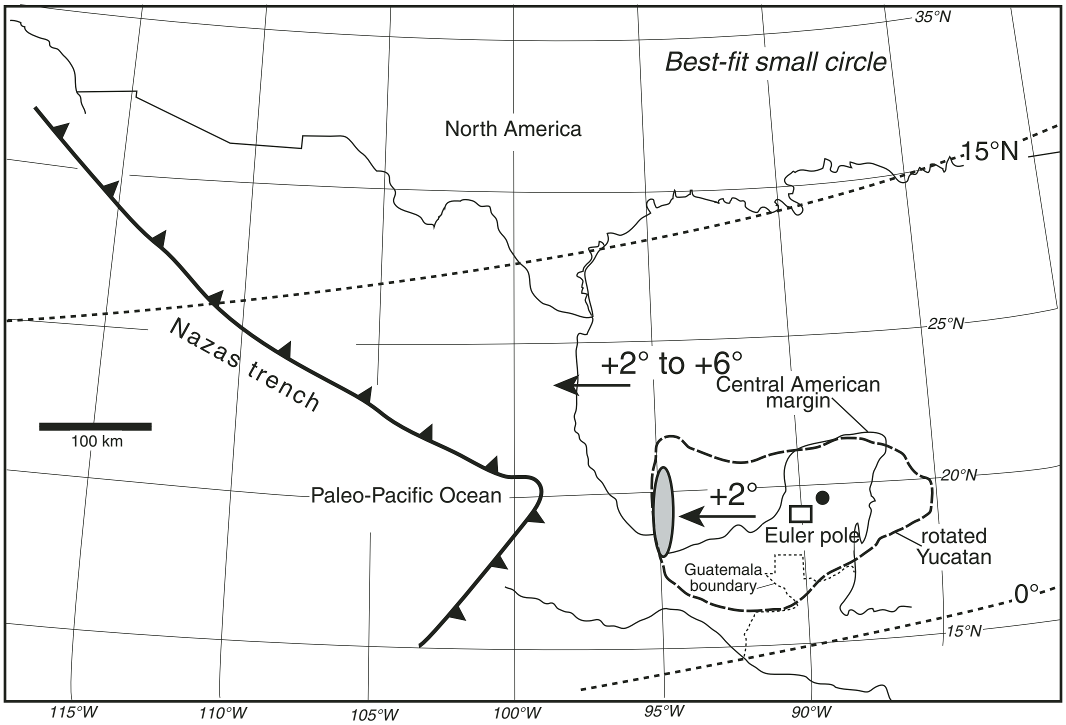


Figure 48. Reconstruction of Middle Jurassic position of the Maya block based on the best-fit pole of paleomagnetic data from the Lower to Middle Jurassic Todo Santos and La Silla Formations of Chiapas, southern Mexico, and the Tehuantepec region, with paleolatitudes observed in Chiapas (arrow marked +2°) and range of paleolatitudes for Huizachal Group in Tamaulipas (arrow marked +2° to +6°). Dotted lines represent paleolatitudes. Euler pole is shown as a square. Figure is adapted from Godínez-Urban et al. (2001a).

this clastic unit. Detrital zircons from El Diamante record ages between ca. 169 and 172 Ma, suggesting that accumulation of the Todos Santos Formation began no earlier than the Bajocian. Locally, El Diamante Member is underlain by intermediate volcanic, hypabyssal, and volcaniclastic rocks and subordinate sandstone, conglomerate, and mudstone (Godinez-Urban et al., 2011b). The volcanic rocks include porphyritic andesite with plagioclase, hornblende, and pyroxene phenocrysts in a gray, red, or purple aphanitic groundmass as well as aphanitic, vesicular to amygdaloidal, basaltic andesite and dacite. Rhyolite is rare. Horizons of tuff and pyroclastic rocks record subaerial deposition.

The units that comprise the La Silla Formation rest upon foliated granitoids. Zircon grains, collected from an andesite layer, most of which yielded concordant dates, provide an estimated age of ca. 191 Ma (Sinemurian).

Exposures of the upper, clastic, Todos Santos strata curve eastward at the international border between Mexico and western Guatemala. The unit is well exposed atop the ~3500-m-high Sierra Los Altos Cuchumatanes, not far from the typical section close to the village of Todos Santos (Figs. 46 and 50). Several hundred meters of conglomerate, arkosic sandstone, and mudstone comprise the Todos Santos Formation "type" section at La Ventosa (Richards, 1963; Anderson, 1969), where two members are recognized: a lower conglomerate member and a conglomerate to mudstone upper member. The upper unit, ~400 m thick, is composed of pebble, granule, and rare cobble conglomerate mixed with siltstone and sandstone, which is commonly arkosic. Clasts are generally quartz or quartzite and may be angular to rounded. Although the base of the unit is probably faulted against Permian limestone, along strike toward the west, a 50–450 m section of limestone-boulder conglomerate suggests the presence of a fault-related buttress unconformity.

The upper part of the Todos Santos Formation may contain, mudstone, siltstone, sandstone, and rare claystone, ~400 m thick, that passes upward into the San Ricardo Formation. The San Ricardo Formation contains two marker beds: a limestone unit, ~25 m thick, called La Ventosa Limestone Member that crops out 50 m above the base, and a pale orange quartz sandstone, ~20 m thick, called the Rosario Sandstone Member that caps the formation. In Chiapas, southern Mexico, Richards measured a second section of about the same thickness and character as the Guatemalan rocks. The base of the Cintalpa measured section (figure 4 *in* Richards, 1963) is nonconformable above granite. The similarity of the measured sections is such that the Todos Santos strata likely record accumulation in a single, continuous basin, whereas El Diamante Member, recognized in Mexico, is only preserved locally. In westernmost Guatemala, close to the border with Mexico, poor exposures of maroon mudstone with

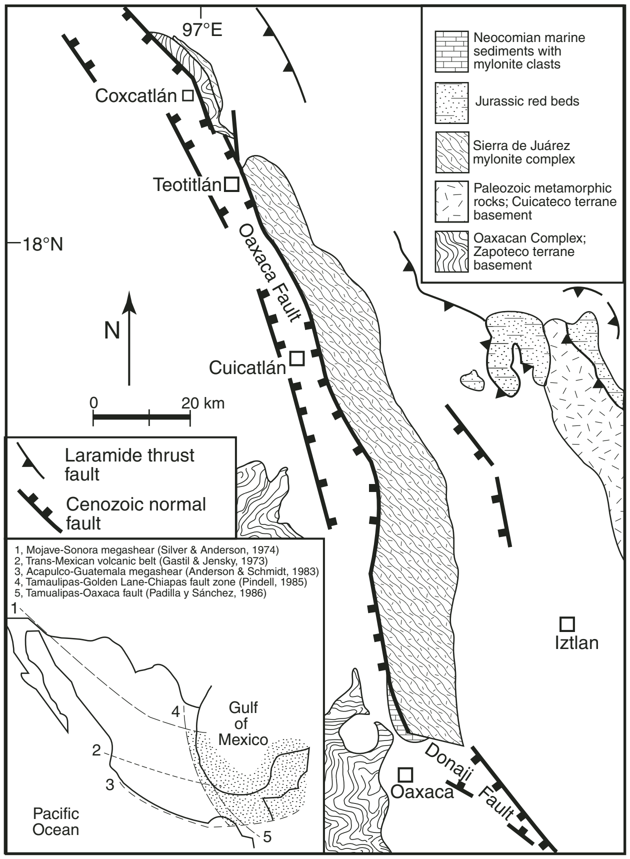


Figure 49. Geologic map of Oaxaca region, Mexico, showing Oaxaca fault. Inset shows major faults in Mexico with probable Jurassic displacements. Figure is adapted from Alaniz-Alvarez et al. (1996).

dark gray volcanic layers along the Chixoy-Polochic fault may be equivalent to El Diamante (this study).

From the Altos Cuchumatanes range, the Todos Santos Formation extends eastward across Guatemala. Walper (1960) reported that an ~700-m-thick section, consisting mainly of shale, sandstone, and conglomerate, cropping out in central Guatemala not far south of the Polochic fault. The lowest beds are sandy mudstone, in fault contact with the Chochal Formation, that grade upward into interbedded sandstone and shale or into fine-grained conglomerate, which contains pebbles of quartz and debris of igneous rocks and schist. A thick sequence of commonly micaceous maroon shale and overlying light brown to gray-green, poorly sorted sandstone follows. The highest beds consist of variegated maroon and green shales, which are conformably overlain by Cretaceous limestone. Where the base of the formation is preserved, an unconformable contact with the Permian Chochal Formation is marked by a basal section consisting of conglomerate ~130 m thick that contains limestone pebbles and cobbles up to 20 cm (8 in.) in diameter in reddish-brown silt. Many cobbles contain Permian fusulinids of upper Leonard age and obviously have been derived by erosion from the underlying limestone. Above the conglomerate, the sequence is made up of ~65 m of pink to purple quartzite overlain by reddish brown, well-indurated, calcareous shale and micaceous sandstone with lenses of conglomerate. In places, the upper part is very calcareous shale with a few chert pebbles. The nonvolcanic, conglomeratic strata of the Todos Santos Formation (sensu stricto), commonly interpreted as an indication of rifting, probably crop out adjacent to normal or strike-slip faults near the western and southern margins of the Yucatán block.

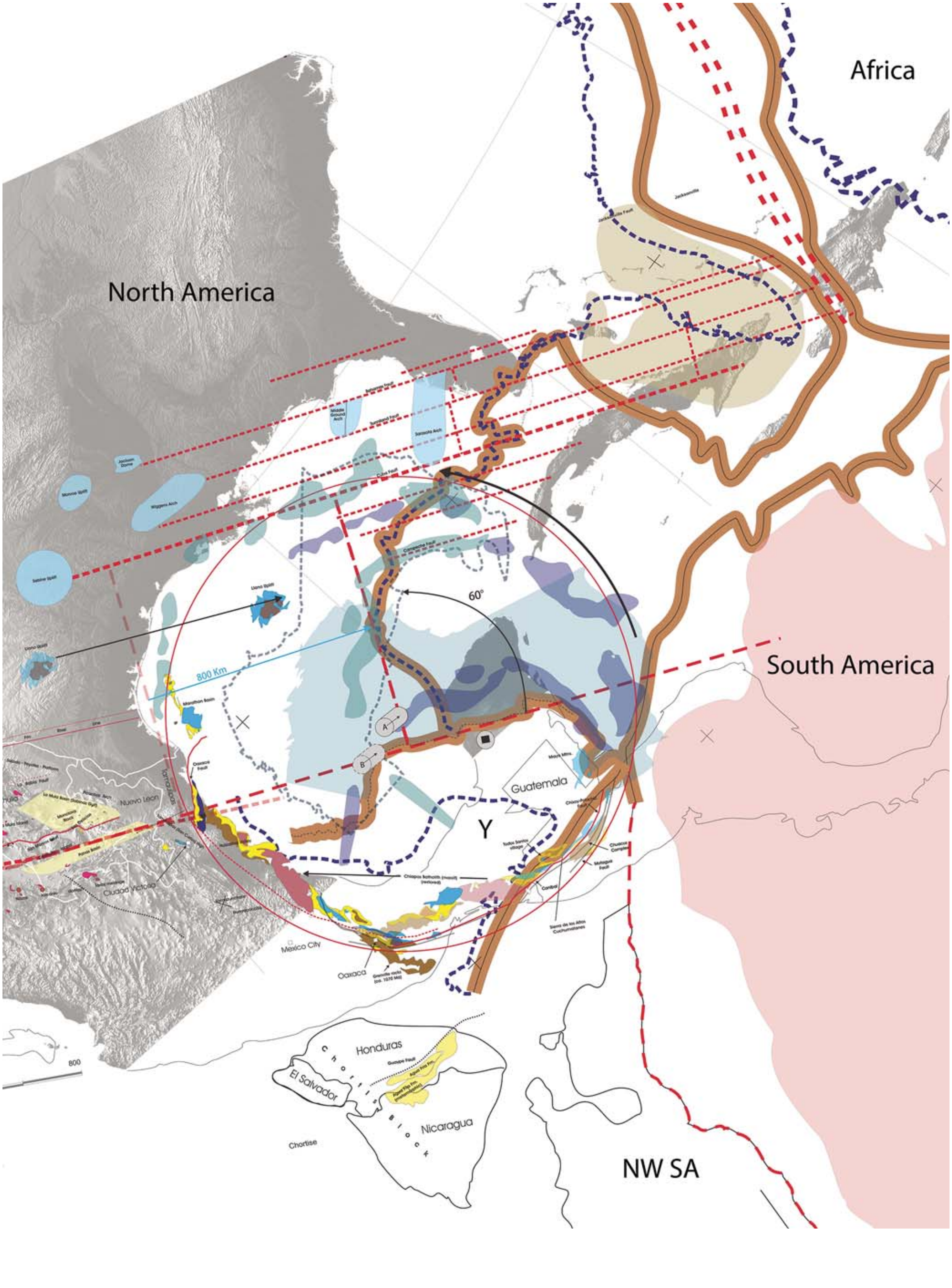
POSSIBLE EQUIVALENTS OF TODOS SANTOS FORMATION ON THE CHORTIS BLOCK

The Todos Santos Formation, which likely accumulated between Bajocian and Tithonian time, resembles the Mid-Jurassic Agua Fria Formation that crops out in Honduras and Nicaragua, mainly south of the Guayape fault in the Chortis block (Fig. 50; Rogers and Mann, 2007). The Todos Santos and Agua Fria Formations are composed of sections, in places more than 1000 m thick, of abundant coastal plain fluvial deposits with less common marine rocks (Rogers et al., 2007c, and references therein).

Rogers and Mann (2007) noted that the Guayape fault coincides with a terrane boundary for more than half of its length, except along its southwest extension, where the boundary diverges northwest and follows a prominent magnetic lineament. North of the Guayape terrane boundary, Grenville to Paleozoic continental metamorphic rocks comprise the basement that in places is characterized by an irregular easterly trending grain. South of the fault boundary, deformed Jurassic metasedimentary rocks comprise a greenschist-grade basement marked by northeast-trending magnetic anomalies.

Cretaceous tectonic features also may be correlative as suggested by Rogers et al. (2007a, 2007c). Within the domain of Jurassic rocks, a second important tectonic feature, the Colon fold belt, is encountered tens of kilometers southeast of the Guayape discontinuity (Rogers et al., 2007b). The Colon belt records shortening associated with the Late Cretaceous collision between the continental block and overlying Jurassic and Cretaceous strata to the north (Rogers et al., 2007b, their figure 5) and the Siuna terrane, a Cretaceous oceanic-island arc (Venable,

Figure 50 (*Continued on following page*)[1]. Postulated paleogeographic pre-opening (ca. 170 Ma) and postopening (ca.150 Ma) configurations (A and B) for the Gulf of Mexico. See Plate 1 of Anderson (this volume) for explanation key to geologic units, structures, patterns, and other features. Rotation of Yucatán block (Y) is caused by forces applied to its edges by sinistral movement of North America, resulting in modest counterclockwise movement about a vertical axis. Axes shown are based upon paleomagnetic results (Godínez-Urban et al., 2011a), of a fit to a pole (21.85640051096578°, –92.515869140625°), empirically determined that accommodates 60° of clockwise rotation of Yucatán in its present position, and a pole at the center of a circle roughly coincident with the Polochic-Motagua fault set of Guatemala and the Oaxaca fault of southern Mexico. NW SA—northwest South America.


Africa
North America
South America
60°
800 Km
Guatemala
Y
Nuevo Leon
Ciudad Victoria
Mexico City
Oaxaca
Honduras
El Salvador
Nicaragua
Chortis Block
NW SA

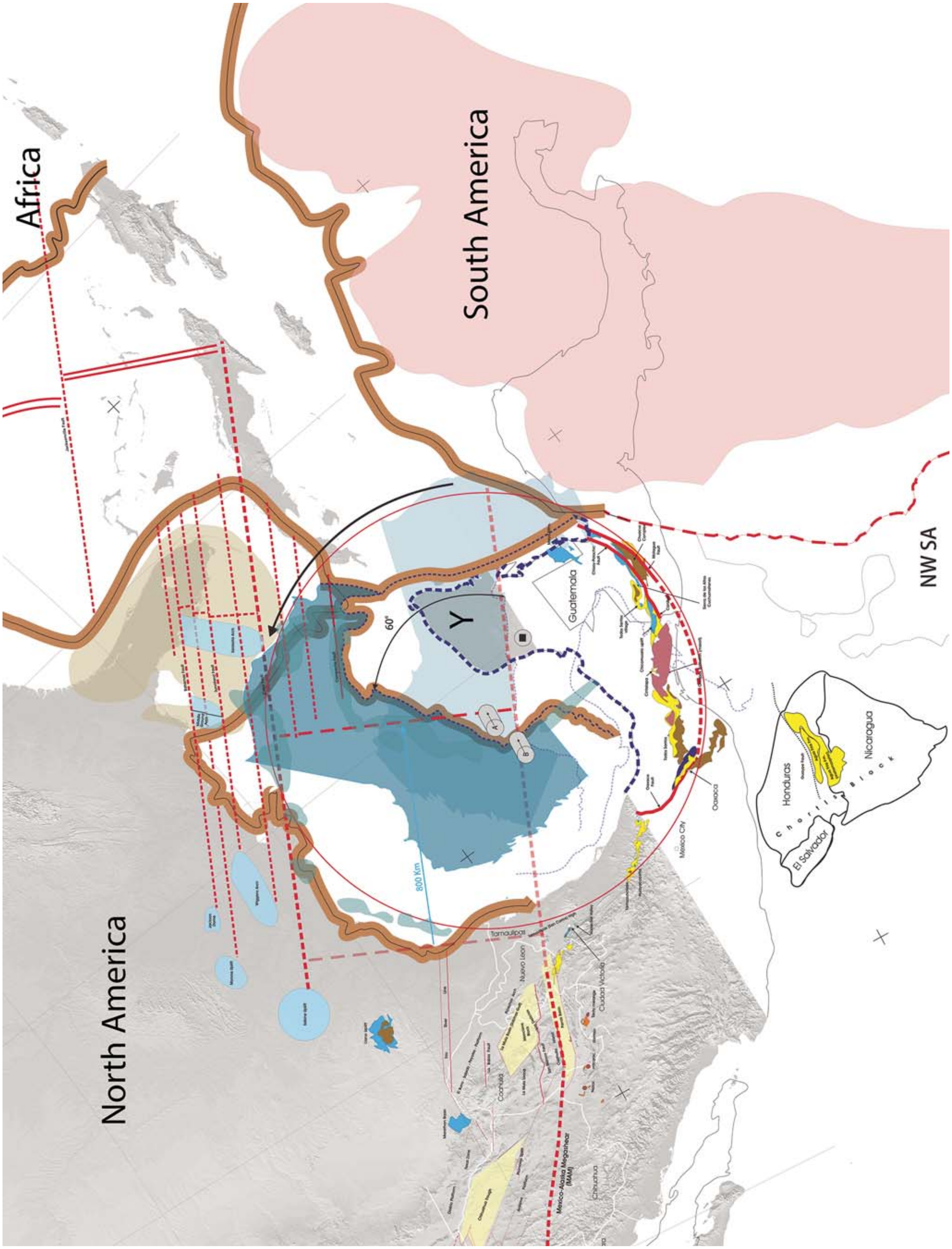


Figure 50 (*Continued*)[1].

1994). Rogers et al. (2007b) considered the Late Cretaceous Colon belt to record the same event as the collision along the Motagua zone in Guatemala, during which the Santa Cruz ultramafic rocks were thrust northward onto strongly metamorphosed rocks of the Chuacus complex (Ortega-Gutierrez et al., 2004, and references therein) and overlying late Paleozoic strata (Anderson et al., 1973, 1985).

The Chortis block is considered by several workers to be allochthonous, having moved eastward by more than 1000 km along sinistral strike-slip faults coincident with the margin of southwestern Mexico and the Motagua fault zone in Guatemala during the Eocene (Rogers and Mann, 2007). Concurrently, the Chortis block rotated 30°–40° in a counterclockwise sense (Gose and Swartz, 1977; cf. with rotation of Yucatán block). A position south of Mexico is supported by Rogers et al. (2007a), who cited similarities in: (1) autochthonous Paleozoic and Precambrian basement domains, (2) geochemical signatures of Cretaceous magmatic belts, and (3) stratigraphy, structures, and tectonic histories of Cretaceous rocks. In the Chortis restoration, Agua Fria rocks of the eastern Chortis terrane are restored hundreds of kilometers west of the similar Todos Santos Formation.

Westward restoration of the Chortis block (Anderson and Schmidt, 1983; Rogers and Mann, 2007), with the Guayape fault and the Late Cretaceous Colon collisional belt embedded within it, places it west of central and northern Guatemala, which lies north of the Motagua suture (Rogers et al., 2007a, their figure 9). The crude alignment of the Guayape discontinuity with the Chixoy-Polochic fault to the east and the Jurassic clastic rocks, adjacent to the faults on the south, is suggestive. The basal beds of the Todos Santos Formation contain boulders of the underlying limestone, indicating proximity to the source area. The Todos Santos Formation extends across much of Guatemala, generally north of the deep valleys along the Chixoy-Polochic zone comprising major strike-slip and thrust faults. It is possible that the two units are correlative and may share a depositional history that includes accumulation within a long, elongate, mid-Jurassic pull-apart basin along a principal Jurassic sinistral fault (cf. Anderson and Schmidt, 1983; Pindell and Barrett, 1990; James, 2006). However, the Jurassic character of the fault zone has been obscured by thrust faulting that uplifted and obducted eclogitic crust, which records Late Cretaceous, late Paleozoic, and perhaps older deep-seated metamorphism (Ortega-Guitierrez et al., 2004). The thrust faulting followed southward-directed subduction, probable consumption of oceanic lithosphere, and resulting Cretaceous collision (e.g., Anderson et al., 1985).

Rotation of the Yucatán Block

The conglomeratic strata of the Todos Santos Formation (sensu stricto), commonly interpreted as an indication of rifting (Godinez-Urban et al., 2011a, and references therein), crop out along the western and southern margins of the Yucatán block. Counterclockwise rotation of the Yucatán block during rifting and opening of the Gulf of Mexico has been proposed in many Gulf of Mexico opening models (White, 1980; Anderson and Schmidt, 1983; Pindell, 1985). As early as 1973, studies by Diller and Vedder (1973) and Uchupi (1973) led each to suggest rotation. The rotation of Yucatán and the surrounding Maya terrane is recorded by paleomagnetic results from the Late Permian Chiapas massif that have been interpreted to reflect large-magnitude counterclockwise rotation of the Maya block with respect to North America (Molina-Garza et al., 1992; Godinez-Urban et al., 2011a; Fig. 48). The rotation indicated by paleomagnetic data for the Chiapas massif, however, is larger (~70°) than suggested in plate reconstructions (35°–60°). Subsequent studies by Molina-Garza on strata from the Todos Santos Formation and underlying volcanic horizons (Molina-Garza et al., 2009; Godinez-Urban et al., 2011a) led to a downward revision of the counterclockwise rotation to between 35° and 40°. Paleomagnetic evidence (Guerrero and Helsley, 1974) shows that rotation, which may have been recorded by Yucatán and the rest of the Maya plate north of the Motagua fault, was completed by the late Oxfordian (ca. 155 Ma).

Jurassic strata that crop out upon the Mixteca terrane, west of the Yucatán block, which comprises much of the Maya plate, also yield paleomagnetic data compatible with rotation (Fang et al., 1989; Ortega-Guerrero and Urrutia-Fucugauchi, 1993, and references therein). Ortega-Guerrero and Urrutia-Fucugauchi suggested that Mixteca moved with North America until ca. 160 Ma, at which time, according to Fang et al., modest rotation may have taken place.

Based upon paleomagnetic data, Schouten and Klitgord (1994) proposed a model in which Yucatán, bounded by major faults, rotated between ca. 170 and ca. 150 Ma (Fig. 47). They postulated that the principal faults that accommodated the rotation were the Bahamas set on the northeast (Klitgord et al., 1984) and the Mojave-Sonora segment of the Mexico-Alaska megashear set on the southwest (Anderson and Schmidt, 1983). As shown by Figure 47 (from Schouten and Klitgord, 1994), rotation of Yucatán probably involved faults along all margins of the microplate, including the postulated Acapulco-Guatemala megashear (Anderson and Schmidt, 1983, their figures 2 and 12) and the Oaxaca fault (Alaniz-Alvarez et al., 1996; Figs. 46 and 49).

Yucatán rotation in this position is compatible with multiple observations. (1) Rotation of Yucatán without additional latitudinal or longitudinal motions (cf. Godinez-Urban et al., 2011a) aligns its long, currently northeasterly facing topographic margin with the Mexico-Alaska megashear, perhaps indicative of a cogenetic origin for the fault and the margin. (2) The southern boundary of the Yucatán block coincides with the Chixoy-Polochic zone, along which clastic Todo Santos red beds commonly crop out. (3) Rotation of the Yucatán block in a southerly position is also compatible with the western boundary of the block that coincides with the Oaxaca fault (Alaniz-Alvarez et al., 1996). The Oaxaca fault forms the western margin of Todos Santos exposures and separates them from continental and marine strata older than ca. 168 Ma that comprise the Cualac Conglomerate and Tecocoyunca Group (Moran-Zenteno et al., 1993).

Structural studies along the fault demonstrate dextral movement between ca. 169 Ma and 163 Ma (Alaniz-Alvarez et al., 1996). Both timing and kinematics of the fault are compatible with rotation of the Yucatán block. The Oaxaca fault may extend northward to a steep north-south–trending basement step that corresponds with geophysical anomalies offshore of eastern Mexico (Buffler and Sawyer, 1985; Ewing, 1991). Pindell (1985) postulated that this structure, the Tamaulipas–Golden Lane–Chiapas transform, accommodated rotation of the Maya block.

The maximum deposition ages interpreted from isotopic results from detrital zircon collected from the Todos Santos red beds studied by Godinez-Urban et al. (2011b) led them to conclude that most of the rotation took place after ca. 171 Ma (or 161 Ma if a single zircon age determination is used as an age estimate). The paleomagnetic study of Guerrero et al. (1990) indicated that rotation apparently was completed by the time of the accumulation of the lower San Ricardo Formation, which contains Late Jurassic fossils. After consideration of available paleontologic data, Godinez-Urban et al. (2011a) suggested that rotation was complete by ca. 151 Ma. These conclusions indicate that the underlying clastic red beds comprising the Todos Santos Formation in Guatemala and the Jericó Member in Mexico accumulated during rotation. They further noted that paleomagnetic data fit best with a Euler pole at 19°N, 265°E, which places the Maya block farther south than most models, although almost coincident with the geometrically constrained model of Anderson and Schmidt (1983) based upon the Bullard et al. (1965) reconstruction.

We postulate that rotation of Yucatán took place between the Mojave-Sonora megashear and Acapulco-Guatemala megashear with a ball-bearing–like mechanism. Counterclockwise rotation was accommodated by dextral shearing along the margins of the Yucatán block. We postulate that the movement was recorded by fabric along the Oaxaca fault (Alaniz-Alvarez et al., 1996) at the southwestern margin of the block. Along the fault, Grenvillian crust of the Oaxacan basement is juxtaposed against mafic rocks that we speculate may be composed of early-formed Gulf of Mexico crust, although derivation from older oceanic basement may not be precluded.

Our restoration (Fig. 50) is based upon an empirical fit using 60° of rotation about a pole at 21°46′41.07″N latitude, 91°13′29.31″W longitude.

GULF OF MEXICO SUMMARY

Oceanic crust of the Gulf of Mexico began to form after 170 Ma, concurrent with the extensional opening of the Atlantic Ocean basin. In the northern Gulf of Mexico, a spreading center formed where a ridge-ridge transform, extending from the Atlantic center along the southern margin of southeastern North America, stepped southwest to the Mojave-Sonora megashear. The resulting pull-apart structure, within which several hundred kilometers of opening has been accommodated, had a floor of oceanic crust.

The southern Gulf of Mexico had a more complicated opening. Movement along the southern flank of the Mojave-Sonora megashear led to drag on the Yucatán block. As the pull-apart formed, the Yucatán block rotated, within the bounding strike-slip faults, counterclockwise. A right-lateral, strike-slip fault, the Oaxaca fault, accommodated movement along the western boundary of the block.

CONCLUSIONS

The evolution of the Caribbean basin involved multiple subduction episodes, from Early Cretaceous until now, accompanied by northeast or eastward movements of small plates between trench-trench transforms. Westward restoration of the small plates reveals an expanse of ocean crust that was forming by 164 Ma by means of movements along sinistral faults. The Gulf of Mexico formed almost simultaneously in response to movements along three major transforms, including, from north to south, Cuba, Mojave-Sonora, and Acapulco. The northern Gulf of Mexico formed as a pull-apart basin at a releasing step between the Cuba and Mexico-Alaska megashear (Mojave-Sonora segment) transforms. Formation of the southern part of the Gulf of Mexico involved ball-bearing–like, counterclockwise rotation of the Yucatán block. By ca. 164 Ma (Bathonian), sufficient extension had taken place so that basins had formed, and clastic rocks were accumulating.

Northeastward-facing subduction, beginning ca. 135 Ma, at the west margin of the paleo– Caribbean plate generated island arc–like volcanism until ca. 110 Ma. By ca. 100 Ma, southwestward-facing subduction began beneath the older arc. Plate consumption led to northeastward migration of the Late Cretaceous and underlying Early Cretaceous primitive island-arc tholeiite (PIA/IAT) arc. Convergence continued along a northeastward trend until the Late Cretaceous arc collided with the Bahamas Bank. Following this Late Cretaceous collision between the composite arc and thick crust close to North America, the polarity of subduction changed from southwest to northeast as a small plate of proto-Pacific lithosphere, bounded by northeasterly striking strike-slip faults, was consumed as it subducted beneath the southern margin of the arcs accreted to North America. Subduction-related magmatism is recorded by volcanic rocks and plutons between ca. 61 and 50 Ma. During convergence, volcanic plateau rocks that formed after ca. 92 Ma moved northeastward until the buoyant, plateau rocks collided with the collage at the southern margin of North America. With the arrival and collision of buoyant lithosphere in the late Eocene, subduction terminated. Initiation of westward-directed subduction of Atlantic Ocean crust was synchronous with development of sinistral faults of the Cayman fault set that resulted in separation of Hispaniola from southeastern Cuba, and Puerto Rico from Hispaniola.

ACKNOWLEDGMENTS

We thank Manuel A. Iturralde-Vinent and John F. Lewis for reviewing the manuscript. Their expertise was important in evaluating and improving the manuscript. We especially

acknowledge the invaluable help of John Lewis in participating in numerous verbal discussions with the senior author on the geology of Greater Antilles, his insightful written comments on the geology of Hispaniola (including his discussion of many aspects on the Los Ranchos, Maimon, and Duarte units), and in making available a good number of hard-to-find copies on Caribbean geology. We also thank Lisard Torró for making available two pre-publication (at the time) manuscripts on the Maimon Formation (Hispaniola) and Pablo León for sending an unpublished data base on the Los Ranchos Formation from the Bayaguana area (Hispaniola). Thanks also go to Lila Diaz de VillalVilla for generously supplying a copy of her paper on the geochemistry of the Los Pasos Formation (Cuba). Finally, the senior author would be remiss without acknowledging the numerous discussions he has had over the years with Wayne T. Jolly and Johannes H. (Hans) Schellekens (both now deceased) on the geology of Puerto Rico.

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Manuscript Accepted by the Society 29 September 2015
Manuscript Published Online 24 November 2015
Printed in the USA

Geological Society of America Special Papers

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Geological Society of America Special Papers 2015;513; 1-88 , originally published onlineNovember 24, 2015
doi:10.1130/2015.2513(01)

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