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4. THE LESSER ANTILLES ISLAND ARC[1]

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ABSTRACT

The Lesser Antilles island arc is composed of two Cenozoic volcanic arcs, the older (early Eocene to mid-Oligocene) and the Recent (early Miocene to Present) arcs, superimposed on a Meszoic proto-arc belonging to a larger geodynamic feature, the Mesozoic Caribbean arc (M.C.A.), initiated in the Early Cretaceous. The Lesser Antilles arc experienced two major volcanic interruptions of 8-to-10 m.y. duration each. The first interruption accompanied the Paleocene opening of the Grenada Basin, with oceanic crust forming in the southern part of the basin. The splitting of the central part of the M.C.A. (eastern Caribbean) isolated a remnant arc, the Aves Swell, from an active arc, the Lesser Antilles. The second volcanic interruption occurred in late Oligocene, as a consequence of a first-order tectonic event: the collision of a buoyant Atlantic aseismic ridge. Thereafter, the subduction geometry of the renewed volcanic line (Recent arc) was modified in the northern half by a westward jump from the outer arc to the inner arc. In the Neogene, the subduction of non-buoyant ridges had second-order, but nevertheless significant, effects on the tectonics and volcanism of the arc.

The development pattern of the construction of the arc ridge by volcanic processes is described. Emphasis is placed on the role of subducted sediments in the generation of orogenic magmas and, conversely, on the role of subducted ridges in the local interruption of arc volcanism. The morphology of the underthrust oceanic crust controls the magmatic activity of the island arc, and particularly the development, in space and time, of "arc compartments."

INTRODUCTION

This paper summarizes the main results of a research program of the Bureau de Recherches Géologiques et Minières devoted to the geological study (*sensu lato*) of the Lesser Antilles island arc. This program, labeled ARCANTE, was completed in 1987, after more than a decade of field work, onshore and offshore, involving regular mapping, biostratigraphy, petrology, volcanology, marine geology, geochronology, and so on. Several laboratories have been associated in this scientific endeavor, in particular the Université de Bretagne Occidentale (Brest), the Institut Français du Pétrole, and the Centre National pour l'Exploitation des Océans/Institut Français de Recherche pour l'Exploitation de la Mer (CNEXO/IFREMER).

In the DSDP volume for Leg 78A, one of us (Bouysse, 1984) published a provisional synthesis of the ARCANTE results available at that time. Since then, further work has led us to modify some of our previous conclusions (e.g., the origin of the Grenada Basin) and to improve our knowledge of the evolution of the Lesser Antilles, one of the best-studied island arcs on Earth. A recent synthesis of the geology and structure has been prepared by Maury et al. (in press). We refer the reader to these two publications for exhaustive references.

GENERAL SETTING

The active island arc of the Lesser Antilles (Fig.1) marks the eastern boundary of the Caribbean Plate, which is underthrust, in a westward-dipping subduction zone, by the oceanic crust of the western central Atlantic Ocean. It is part of a wider island arc system (the eastern Caribbean) including, to the west, a back-arc basin (Grenada Basin) and a remnant arc (Aves Swell). Farther to the west, the Venezuela Basin is one of the main oceanic basins (with abnormally thick crust; cf. e.g., Saunders, Edgar, et al., 1973) of the Caribbean Plate.

Lesser Antilles

The many islands of the Lesser Antilles arc (cf. Bouysse, 1979; Bouysse and Guennoc, 1983b; Bouysse et al., 1985a, for further details) define a 850-km-long curve from Grenada to Sombrero, linking the Venezuelan continental borderland, to the south, with the eastern tip of the extinct Greater Antilles island arc (Puerto Rico–Virgin Islands platform) in the north. The Greater and Lesser Antilles are separated by the Anegada Passage, a probable Neogene graben complex. The larger islands, with an area greater than 750 km^2, are located in the center of the archipelago: Martinique (1100 km^2), Dominica (790 km^2), Basse Terre of Guadeloupe (950 km^2).

In the southern half of the archipelago, there is only one, rather narrow, submarine ridge from Grenada to Martinique. The northern half is morphologically more complex. Beyond the Dominica Passage, which is the deepest sill cutting through the arc and slightly deeper than 1200 m, the physiographic pattern is as follows:

1. To the east lies a series of shallow banks and insular platforms, some of them quite large (more than 4000 km^2);
2. To the west lies a narrow volcanic ridge bearing Recent or active volcanic constructions;
3. In between, from Guadeloupe northward, the narrow (about 50 km) and elongated (ca. 250 km) Kallinago Depression (from −600 to −2000 m) extends into St. Croix Basin, an extensional basin belonging to the Anegada Passage (cf. Jany et al., 1987);
4. To the west of and close to the northern end of the Recent volcanic ridge lies a wide (2100 km^2) and very shallow submarine platform, the Saba Bank.

The morphology of the slopes of the Lesser Antilles Ridge displays an asymmetric pattern. Slopes of the northeast quadrant, from La Désirade to the Anegada Passage, are tectonized and steep. They directly link shallow platforms to the great depths (> 5000 m) at the southeast end of the Puerto Rico Trench. La Désirade escarpment is one of the steepest submarine slopes of the world (a continuous drop of 4700 m with

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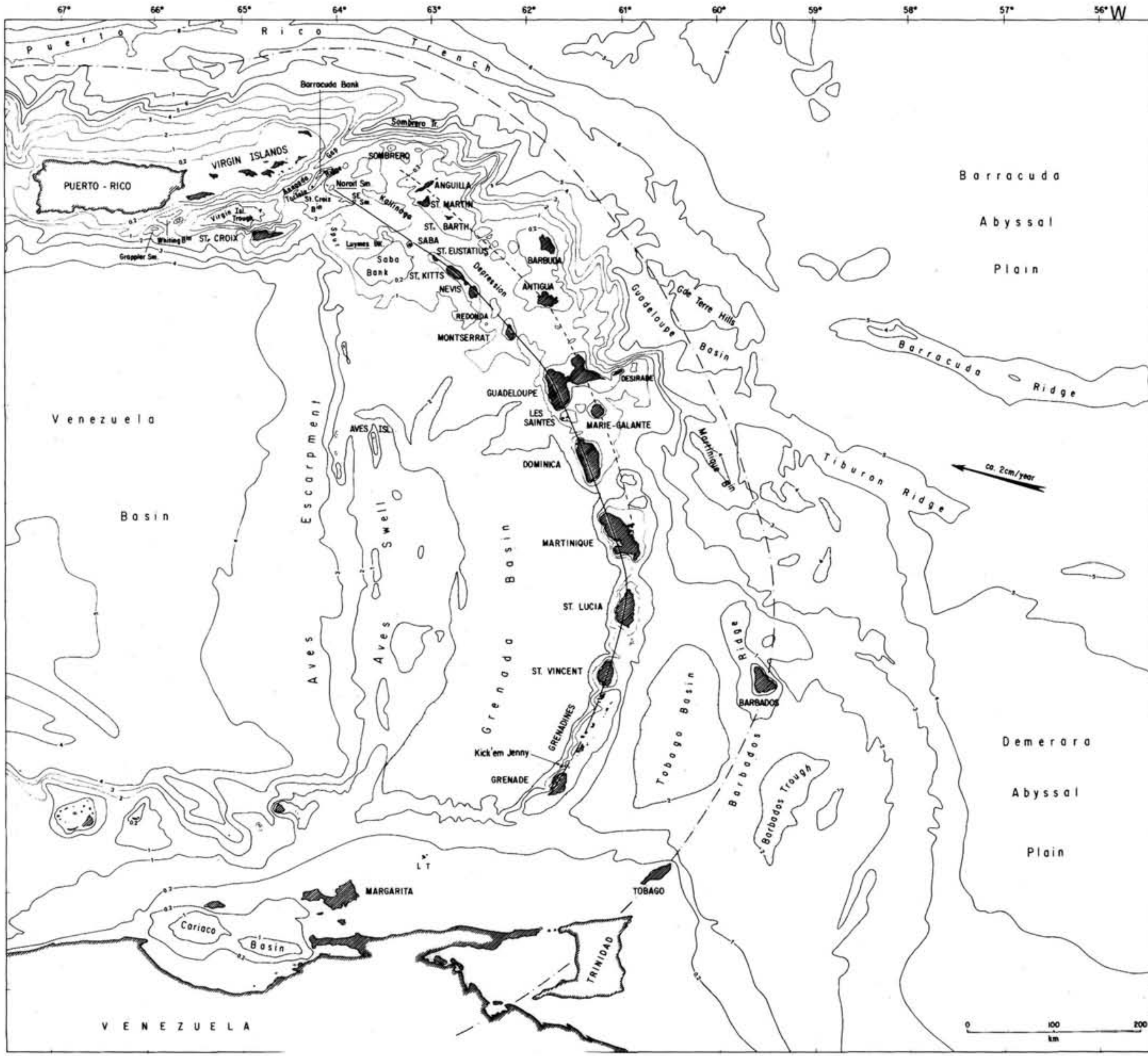

Figure 1. General setting of the Lesser Antilles in the eastern Caribbean. Bathymetry interval is 200 m and every km. Dashed line: contact between Caribbean Plate and "Atlantic" Plate (oceanic crust). Dotted line: Outer (= older) arc, in activity from early Eocene to mid Oligocene. Fine continous line: Recent (= inner, from Martinique northward) arc, in activity from early Miocene to Present. South of Martinique, older and Recent arcs are intermixed. L.T. = Los Testigos.

more than 27°slope; cf. Bouysse et al., 1983a). Recent deposits are poorly represented; the older formations of the arc structure are exposed. The slopes of the northwest side have a gentler dip and are draped by a rather thick overburden of Neogene sediments. South of Guadeloupe the situation is reversed: rather gentle slopes facing the Barbados accretionary prism can be opposed to the steep flanks connecting the Grenada Basin.

Owing to their nature, age, and disposition, the islands of the Lesser Antilles archipelago can be assigned to arc components of diverse types.

1. The *Limestone Caribbees* correspond to islands with no volcanic activity during the late Oligocene and the Neogene; they are partially or totally overlain by carbonate deposits. Located to the north of Martinique, they are all surrounded by the shallow platforms of the northeast: Marie Galante, Grande Terre (of Guadeloupe), La Désirade, Antigua, Barbuda, St. Bartholomew, St. Martin (and the nearby Tintamarre islet), Anguilla, Dog, and Sombrero. Marie Galante, Grande Terre, Barbuda, Tintamarre, and Sombrero don't expose a volcanic basement. The latter is lower Oligocene (Antigua), Eocene-Oligocene (St. Bartholomew, St. Martin, Anguilla, Dog), or even Mesozoic (Uppermost Jurassic and lower Cretaceous at La Désirade).

2. The *Volcanic Caribbees* correspond to the islands having Neogene volcanic constructions, regardless of earlier history. In contrast to the Limestone Caribbees, they have high relief (maximum elevation: 1467 m at La Soufrière of Guadeloupe). Strictly speaking, some small islands of the Grenadines group, in the southern Lesser Antilles, did not experience post-Oligocene volcanism (Battowia, Baliceaux, Mustique, Savan, Tobago Cays; cf. Westercamp et al., 1985), and could be classified as Limestone Caribbees; nevertheless, they lack Neogene deposits and are included here with the Volcanic Caribbees.

3. The *Older arc* was active from the beginning of early Eocene (evidence in St. Martin, cf. Andreieff et al., 1988; and in DSDP Hole 543 of Leg 78A) to mid-Oligocene (30–28 Ma). This former volcanic line, for which the overall width might not have exceeded a few tens of kilometers, extends along Grenada, the Grenadines, (St. Vincent seems to be relatively young and to be slightly offset, westward of this axis), St. Lucia, Martinique, Amerique and Dien Bien Phu banks, Marie Galante, Grande Terre of Guadeloupe, Bertrand and Falmouth banks, Antigua, Animals banks, St. Bartholomew, St. Martin, Anguilla, and Dog.

4. The *Recent arc* has been active since the early Burdigalian (22–19 Ma; cf. Andreieff et al., 1987) and includes Grenada, the Grenadines (with the above mentioned exceptions), St. Vincent, St. Lucia, Martinique, Dominica, Les Saintes, Basse Terre (of Guadeloupe), Montserrat, Redonda, Nevis, St. Kitts, St. Eustatius, and Saba. Beyond Saba, a 110-km-long submarine segment (including Luymes bank and Noroit seamount; cf. Bouysse *et al.*, 1985b) represents the northern termination of the Recent arc, but has been extinct since the late Pliocene.

5. The *outer arc* and *inner arc* correspond, respectively, to the eastern (older arc) and western (Recent arc) volcanic rows, north of Martinique, whereas to the south the two arcs are intermixed and not merely juxtaposed as previously thought (Fig. 2). Therefore, south of Martinique, the concept of an outer vs. inner arc is not relevant.

6. The *Proto-arc* or *Mesozoic arc* constitutes the substratum of the Lesser Antilles arc and may have been part of a wider *Mesozoic Caribbean arc* including the Greater Antilles to the north, the Aves Swell, and the Aruba-Blanquilla Chain (including the Villa de Cura nappe of the Caribbean Mountain System), to the south (cf. Bouysse, 1988). In the Lesser Antilles, the Mesozoic basement has been recognized beneath the Saba Bank, on the northern and northeastern slopes of the submarine arc, and at La Désirade island, where 120- to 130-Ma-old arc volcanics crop out (cf. Bouysse et al., 1983 and 1985a). The crust of the Lesser Antilles arc has an average thickness of about 30 km (Boynton et al., 1977; Westbrook, in Maury et al., in press). Referring to geophysical data, Westbrook concludes that the narrowness of the bathymetric ridge south of Guadeloupe is due to the loading of the eastern rim of the arc-crust by the sedimentary pile of the Barbados accretionary prism. To the south of Grenada, the arc structure bends toward the south-southwest and extends as far as Los Frailes islet and Margarita, where Cretaceous volcanics crop out (cf. also Case et al., 1984). Between Grenada and Margarita, the arc massif is concealed beneath the sediments of the Venezuelan margin. About halfway between those two islands, it is exposed at Los Testigos islets, where calc-alkaline metavolcanics have yielded a K/Ar age of ca. 45 Ma (Santamaria and Schubert, 1974). This questionable dating has been recently validated by oil exploration studies (new radiometric datings controlled by biostratigraphic determinations; J. F. Stephan, pers. commun., 1988). Consequently, the southern tip of the older arc of the Lesser Antilles may have extended, in the middle Eocene, about 150 km beyond Grenada.

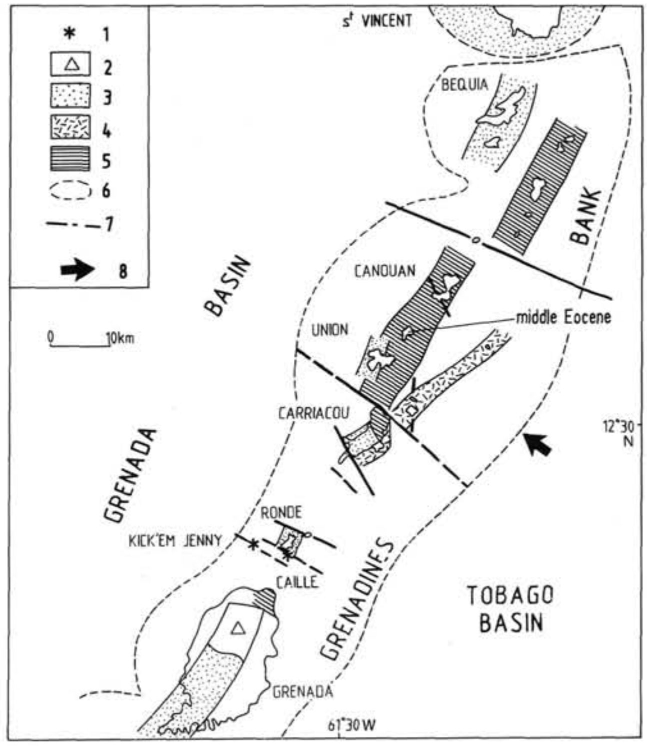

Figure 2. Evolution of the volcanic front (V.F.) of the southern termination of the Lesser Antilles, since the Oligocene (after Westercamp et al., 1985, slightly modified), showing the imbrication of the older and Recent arcs. 1: Recent volcano; 2: Calc-alkaline Pleistocene V.F. (Mt. St. Catherine); 3: Early Pliocene calc-alkaline V.F. 4: Middle Miocene andesitic V.F. 5: Oligocene calc-alkaline V.F. 6: Grenadine platform (−200-m isobath); 7: transverse fault; 8: Central compartment, slightly uplifted, with the oldest (middle Eocene) outcrops.

In the northern half of the Lesser Antilles, the older volcanic arc pierces, in a more or less central position, the Mesozoic basement, while the Recent volcanic arc lies over the western flank of this substratum, probably accentuating its general westward tilting (see below). This volcano-isostatic subsidence continues today, and has been recognized in Grande Terre and Basse Terre of Guadeloupe where the Riss-Würm interglacial terrace (160,000–85,000 yr B.P.) is progressively tilted toward the west

(Battistini et al., 1986). Another effect of the Recent arc was to individualize the Kallinago depression on its eastern side.

Biostratigraphic and chronostratigraphic synthesis of the Cenozoic sedimentary deposits of the Lesser Antilles (Fig. 3) has been recently proposed by Andreieff (Andreieff et al., 1987, unpublished). Other recent revisions of the geology of the Lesser Antilles concern the Grenadines (Westercamp et al., 1985), Martinique (Andreieff et al., 1988a), and St. Martin (Andreieff et al., 1988b).

Grenada Basin and Aves Swell

The Grenada Basin, about 150 km wide, separates the Lesser Antilles arc from the Aves Swell. It extends for 600 km from the Venezuelan margin to the Saba Bank. Its southern two-thirds are occupied by a very flat seabottom (average depth of 2990 m). The water depth decreases to the north where the physiographic pattern shows a series of valleys and spurs, most of them being rooted in the northwestern flank of the Lesser Antilles Ridge. The southern half of the basin is underlain by a blanket of sediments that increases southward in thickness, up to 9 km (cf. e.g., Pinet et al., 1985). This region is characterized by a thick oceanic crust (14 km; Boynton et al., 1979), quite different from the 6-km-thick normal Atlantic crust. To the north, the crust is thicker still (cf. Speed, Westbrook, et al., 1984), wedging out in the eastern part of the Saba Bank (Nemec, 1980). This northern region may correspond to stretched island arc crust. According to the depth of the oceanic crust and to heat-flow data, the age of the opening of the Grenada Basin is around 60 Ma (Bouysse, 1988).

The Aves Swell (cf. Bouysse et al., 1985, for a recent synthesis) is completely submerged except at the tiny Aves islet. The ridge is mainly deeper than 1000 m. From its rather smooth morphology, due to the blanketing effect of Cenozoic sediments, 15 or so banks and small ridges rise up. They represent remnants of sunken volcanic islands capped by middle Eocene shallow water limestones and younger deposits. This crescent-shaped ridge is more than 500 km long, with a maximum width of about 150 km. Its eastern border matches the curvature of the Lesser Antilles arc. Its crustal structure and thickness is very similar to that of the Lesser Antilles (Boynton *yt al.*, 1979). North of Saba Bank, the Aves Swell merges with the northern tip of the latter arc. To the south, it may link, through a right-angle bend, with the Aruba-Blanquilla Chain. Rock dredgings from the Aves Ridge have provided arc volcanics with radiometric and biostratigraphic ages ranging from Turonian to Paleocene. The crustal thickness of the Aves Swell strongly suggests a mature arc structure, and its initiation as an island arc should be far older than the Turonian.

If one concurs with the hypothesis that arc volcanism and back-arc oceanic crust accretion are mutually exclusive (e.g., Scott and Kroenke, 1981; cf. discussion in Bouysse, 1988), the timing of the different phases of arc volcanism in the Lesser Antilles and Aves Swell is consistent with the opening of the Grenada Basin during the Paleocene and supports the above age estimate from geophysical data. This extensional phase lasted about 8 million yr.

Adjacent Atlantic and Subduction Zone

The surface contact between the Caribbean Plate and the Atlantic crust is marked by a strong negative gravity anomaly axis that lies about 170 km from the present volcanic line of the Lesser Antilles. To the north, the axis coincides with the Puerto Rico Trench reaching more than 6000 m. Southward, the trench becomes progressively filled by the large detrital input from the South American rivers (Orinoco and Amazon), and finally gives way to the Barbados Ridge complex, the most famous and best-studied example of sedimentary accretionary prism in the world. The width and thickness of this prism increase southward until the ridge emerges at Barbados island. Here, the deformation front is more than 300 km away from the trace of the subduction zone.

Judging from magnetic anomalies and from the basalt cored at DSDP reference hole 543 (Biju-Duval, Moore et al., 1984), the age of the Atlantic crust subducted beneath the Lesser Antilles is Late Cretaceous (Fig. 4), but southeast of Barbados island it appears to be older, Jurassic, or Early Cretaceous (Westbrook et al., 1984). The boundary between the North America and South America Plates is ill defined and is probably diffuse along most of the front of the Lesser Antilles arc (cf. Bouysse and Westercamp, 1988). However, Roest and Collette (1986) suggest that the present boundary is located along the Barracuda–Fifteen Twenty fracture zone.

Although Sykes et al. (1982) have postulated that the convergence rate and vector between the Caribbbean and "Atlantic" Plates are respectively of ca. 4 cm/yr and 245° (WSW), most authors agree with values of ca. 2 cm/yr and 285° (WNW), (cf. e.g., Minster and Jordan, 1978; Rosencrantz and Sclater, 1986; Pindell et al., in press). The Lesser Antilles active margin is unusual in that it is characterized by old oceanic crust (>100 Ma) subducted at a very low subduction rate.

Recent studies of the seismicity of the Lesser Antilles provide an improved picture of the configuration of the Benioff zone beneath the Lesser Antilles island arc (Wadge and Shepherd, 1984). North of Martinique, the Benioff zone strikes north-northwestward with a dip of 50°–60°W and reaches a greater depth (maximum = 210 km). To the south, it strikes north-northeastward with a dip of 45°–50°W, but reaches only a depth of 170 km and is less seismically active. The resulting kink in the slab forms an angle of 130°. South of Grenada, the Benioff zone gradually becomes near vertical. Beneath the Recent volcanic line the depth to the subducted slab is not constant: it varies between 140 and 160 km from Saba to Basse Terre of Guadeloupe, is about 180 km at Dominica and Martinique, and lies at 100 to 140 km from St. Vincent to Grenada.

Recent and historically active volcanoes form a regularly curved line (Fig. 5). The most active centers are located in St. Vincent (Soufrière), Martinique (Mount Pelée), Dominica (southern part), and Basse Terre (Soufrière). Since the European settlement (1635) in Guadeloupe, all six eruptions of the latter volcano have had a phreatic origin. In Dominica, a an unusually voluminous (for the Lesser Antilles) ignimbritic eruption—the Roseau ignimbrite—occurred at about 30,000 yr B.P., with a production of some 60 km^3 of tephra (Carey and Sigurdsson, 1980). The dramatic 1902 eruption of Mount Pelée killed all the 28,000 inhabitants of St. Pierre (save one), and is one of the most catastrophic eruptions in the history of mankind. The present stage of activity of the Soufrière of St. Vincent shows an increase in explosivity (Sigurdsson, 1981). The only active submarine volcano of the Lesser Antilles is the Kick'em Jenny, in the southern Grenadines (Sigurdsson and Shepherd, 1974; Bouysse et al., 1988). It is a small and very young edifice, with its summit at 160 m water depth. Since 1939, nine eruptions have been recorded. Large submarine volcanoes have been recognized on the western flanks of Martinique (Schoelcher) and Basse Terre of Guadeloupe (Vieux Fort and Directeur); they were active during the Pliocene (Bouysse et al., 1985c).

The average spacing of the nine active or quiescent volcanoes (Kick'em Jenny; Soufrière of St. Vincent; Qualibou; Mount Pelée; Morne Patates; Wotten Waven; Soufrière of Guadeloupe; Soufrière of Montserrat; Mount Misery; see Fig. 5) is about 80 km. The least volcanic gap is 10 km, between Morne Patates and Wotten Waven; the greatest, about 120 km, is between Kick'em Jenny and Soufrière of St. Vincent. A tentative estimation of the volume of volcanic products erupted during the past

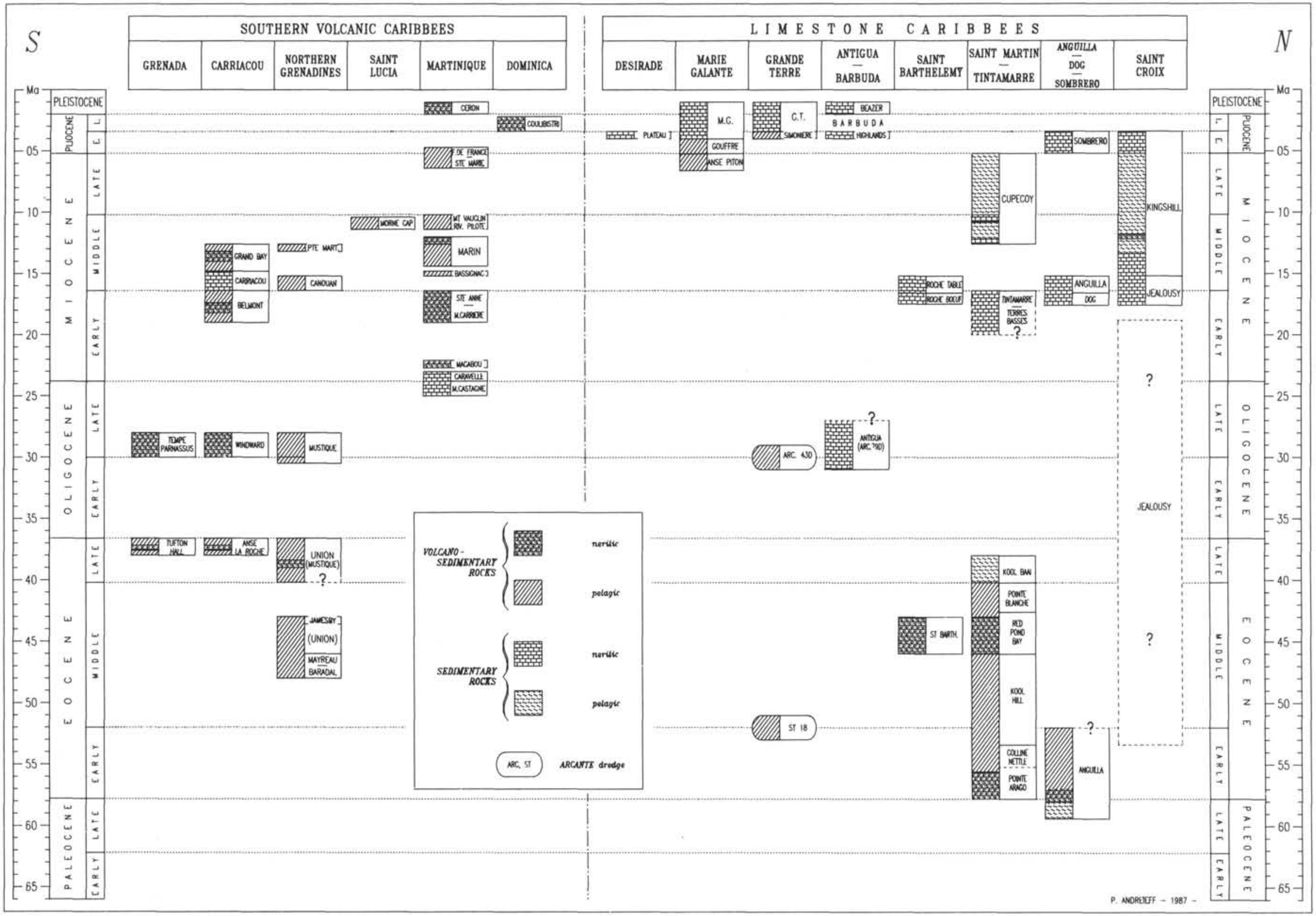

Figure 3. Chronostratigraphy and geochronology of the Cenozoic sedimentary formations of the Lesser Antilles (after Andreieff, in Andreieff et al., 1987).

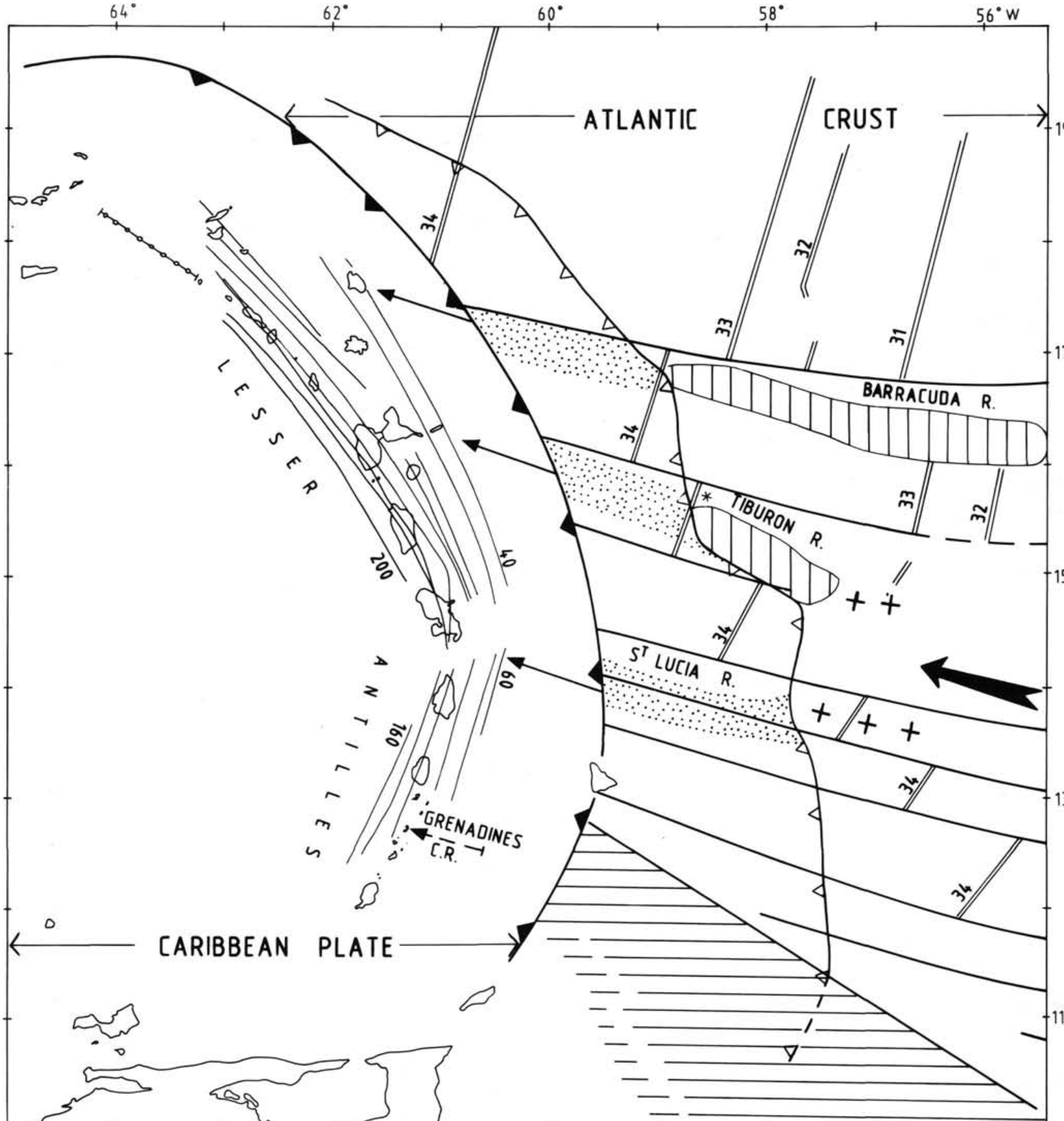

Figure 4. Structure and subduction of the Atlantic oceanic crust in the eastern Caribbean (after Bouysse and Westercamp, 1988). The structure (from Westbrook, 1982 and in Speed, Westbrook, et al., 1984, is modified and simplified). Line with black triangles: subduction trace; line with open triangles: Barbados Complex deformation front. Double line and sub-perpendiular simple line: Late Cretaceous magnetic anomaly with corresponding number, and fracture zone; horizontally hatched area: assumed Late Jurassic and Early Cretaceous crust. Aseismic ridge: buried beneath Atlantic sediments, crosses; morphologically expressed, vertical hatching; concealed beneath Barbados prism, stippled; ridge extension in the subduction zone, fine arrow; Grenadine C.R, hypothetical crypto-ridge of the Grenadines. The subduction (from Wadge and Shepherd, 1984, is simplified). Isobaths of the subduction zone, every 20 km. Thick arrow: convergence azimuth adopted in this paper; line with fine circles: extinct northern termination of the Recent arc (Bouysse et al., 1985b); asterisk (near Tiburon Ridge): reference Hole 543 of DSPD Leg 78A.

100,000 yr shows higher productivity in the central part of the Lesser Antilles arc (Wadge, 1984). The global production for the same period is of ca. 300 km, with a rate of 4 $km^3 \cdot Ma^{-1} \cdot km^{-1}$ along the arc. This last figure is nearly eight times lower than that for the Central America arc.

To the east of the Barbados deformation front, the morphology of the Atlantic oceanic crust is not uniform (Fig. 4), but is dominated by west-northwest trending ridges and troughs associated with fracture zones (Westbrook, 1982; Westbrook et al., 1984). To the north, the Barracuda and Tiburon Ridges rise

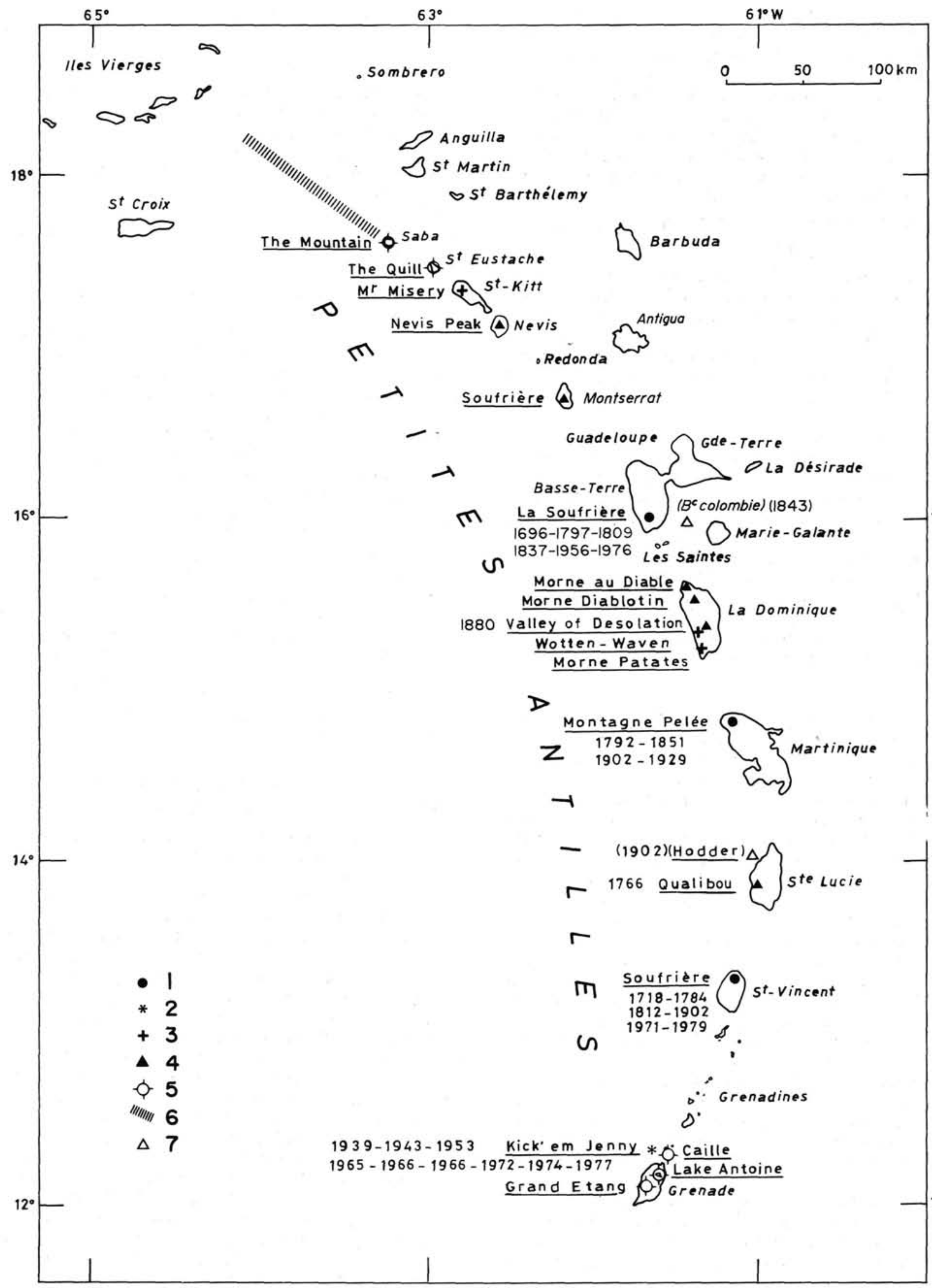

Figure 5. The active and Recent volcanoes of the Lesser Antilles. 1: Active volcano with eruption date(s). 2: Same, except submarine volcano. 3: Volcano with no historic eruption but whose onset is taken as certain. 4: Volcano with very reduced or extinct magmatic activity, but which is still able to produce phreatic explosions. 5: Recent but extinct volcano. 6: Submarine northern termination of the Holocene arc, extinct since about 3 Ma. 7: Submarine spot where an "eruption" was erroneously reported.

more than 2 km above the basement. A third ridge, located to the south, the St. Lucia Ridge, is a buried feature. These ridges, oriented transversally to the detrital influx from the south, exert a damming effect. Thus the abyssal sediments above the Atlantic crust decrease in thickness from more than 7 km south of 11°N to some 200 m north of Barracuda Ridge. These ridges extend beneath the Barbados Ridge complex, where they control locally its morphology (west-northwest trending steps). They are not gravimetrically compensated; i.e., they are non-buoyant features (Bowin, 1980; Stein et al., 1982).

INTERACTION OF SUBDUCTED ASEISMIC RIDGES

The subduction of ridges of oceanic Atlantic crust and their interaction with the evolving of the Lesser Antilles island arc was addressed in more detail in a previous paper (Bouysse and Westercamp, 1988).

From their theoretical modeling of aseismic ridges, subduction, and vertical motion of the overriding plate, Moretti and Ngokwey (1985) conclude that:

1. Only uncompensated (buoyant) ridges are able to cause major uplift of the overriding plate (up to more than 2000 m). An event of this type may have been responsible for the dramatic rise of the northeast flank of the Lesser Antilles Ridge (more than 2000 m uplift in the La Désirade area (Bouysse et al., 1983a) and the subsequent major volcanic interruption and jump, in late Oligocene (see below);
2. Compensated (non-buoyant) ridges (like Barracuda, Tiburon, and St. Lucia Ridges) induce only very moderate uplifts, up to about 200 m. As an example, the uplift of about 100 m of the Pliocene-Pleistocene deposits constituting Barbuda island, on the fore-arc, might be due to the subduction of the Barracuda Ridge.

Subducted ridges exert other effects of first and second order. In the first case, buoyant ridges cannot be absorbed by the subduction. They are underplated beneath the frontal part of the arc and might block the progression of the subducted slab. Consequently the volcanic activity of the island arc might be halted for several million years. An event of this type is thought to have induced the general extinction of arc volcanism at the end of the Paleogene and to be the cause of the jump of the volcanic front from the outer arc to the inner arc (see below).

In the second case, non-buoyant ridges have been more subdued, but nevertheless there have been significant effects on both tectonics, volcanism, and seismicity.

In relation to tectonics, the formation of large transverse faults such as the Montserrat-Marie Galante fracture that cuts the central part of the Lesser Antilles arc in the Guadeloupe area (cf. Fig. 12 in Bouysse et al., 1988) may be attributed to subduction of non-buoyant ridges. This faulting may favor hydrothermal activity and the emplacement of geothermal fields (e.g., Bouillante field in Basse Terre of Guadeloupe).

In relation to volcanism, the occurrence of a local volcanic gap may result when a subducted non-buoyant ridge slips beneath the volcanic front of the arc. To explain this phenomenon, it has been suggested that arc magmatism is triggered by the dehydration and/or fusion of subducted sediments overlying the plunging slab (Westercamp, 1988, and see below). Oceanic ridges are covered by a reduced amount of sediments that are preferentially off-scraped and piled up in the accretionary prism. In the Lesser Antilles, volcanic gaps induced by ridge subduction are thought to occur in several places:

1. Along the 110-km-long northern termination of the Inner arc, a volcanic gap may be due to subduction of the non-buoyant Barracuda Ridge. This segment might also include Saba Island farther to the south, if one assumes that the latter is now extinct.
2. Between Soufrière of Guadeloupe and the Soufrière Hills of Montserrat lies a 90-km volcanic gap possibly due to subduction of the non-buoyant Tiburon Ridge. The influence of Tiburon Ridge might extend 65 km more to the north, toward St. Kitts. The intervening islands of Montserrat, Redonda, and Nevis are of moderate size but have a reduced, or lack of recent magmatic activity.
3. Between Soufrière of St. Lucia and Mount Pelée is a volcanic gap of 110 km, possibly attributable to the subduction of the non-buoyant St. Lucia ridge.

There is no morphological or geophysical evidence of a subducting Atlantic ridge along the more than 120-km-long dormant section between Soufrière of St. Vincent and the Kick'em Jenny and Mount St. Catherine (Grenada area). Nevertheless, geological arguments led Bouysse and Westercamp (1988) to suggest the interaction of a ridge in its final stage of subduction, the "Grenadine crypto-ridge."

When the frontal tip of a subducted ridge passes beneath the volcanic line, it triggers sudden transverse shifts of the eruptive centers, followed by a centrifugal (longitudinal) migration of the volcanoes on either side of the arc segment above the ridge. The latter phenomenon is well demonstrated by the timing of the volcanic activity in Martinique and St. Lucia.

Ridge subduction may also affect shallow seismicity, inside or in contact with the overlying plate. As pointed out by Stein et al. (1982), a non-buoyant feature like Barracuda ridge can flex the overriding plate solely because of its elevation (asperity effect) or interact mechanically when the tip of the ridge is in contact with the upper plate. The seismicity level of the Lesser Antilles, while low for a convergent margin, is higher in the region north of St. Lucia that is characterized by the subduction of the three recognized Atlantic ridges, and is substantially more active than the region south of St. Lucia.

SUMMARY OF THE HISTORY OF THE LESSER ANTILLES

The following pages briefly review material documented and discussed in two recent papers (Bouysse, 1988; Bouysse and Westercamp, 1988).

The Lesser Antilles arc was part of a much larger geodynamic feature, the *Mesozoic Caribbean arc* (M.C.A.) including the Aruba-Blanquilla Chain (i.e., the Venezuelan and Dutch southern Lesser Antilles), Aves Swell, and the Greater Antilles (cf. also e.g., Burke, 1988). This single island arc system was probably initiated in the eastern Pacific, about 130–120 Ma ago. The latter age is substantiated by the oldest volcanics of proven arc origin: the "Primitive Island Arc" basalts of the eastern part of La Désirade island with intercalated radiolarian cherts of Barremian-Hauterivian age (Bouysse et al., 1983b). Paleomagnetic measurements suggest that the M.C.A. originally had an overall north to south trend (cf. Bouysse, 1988). By the end of Late Cretaceous, the M.C.A. approached the entrance of the seaway between North and South America with a northeastward movement (cf. Fig. 5, in Bouysse, 1988). The southern branch of the arc collided progressively with the South American continent. This drastic change in the conditions of the subduction probably triggered the splitting of the eastern Caribbean proto-arc (the central segment of the M.C.A.), leading to the detachment of the substratum of the Lesser Antilles from the Aves Swell (from that time on, a remnant arc). The Grenada back-arc basin opened, forming in its southern half, closest to the cratonic mass, new oceanic crust. The northern branch of the

M.C.A. collided with the Florida-Bahamas platform so that Cuba was incorporated into the North America Plate. Subsequently to this major tectonic phase, the Caribbean Plate was reorganized during the Eocene, being forced to move in an eastward direction. It generated east to west strike-slip motions along the northern and southern boundaries of the plate and the local opening of Cayman Trough.

Due to the choking of the northern and southern subduction zones accompanying the arc collisions, the arc volcanic activity was progressively restricted to the central part of the M.C.A. In the Greater Antilles, the last plutonic intrusions are dated at 46 to 38 Ma in Puerto Rico, and at 36 Ma (i.e., the earliest Oligocene) in the Virgin Islands (Cox et al., 1977). As noted previously, the easternmost part of the southern branch of the M.C.A. was still active, at Los Testigos, during the middle Eocene. The opening of the Grenada Basin during the Paleocene lasted some 8 m.y. and was coeval with the cessation of volcanism in the eastern Caribbean proto-arc. By the very beginning of the Eocene, the volcanic activity resumed and settled on the Lesser Antilles Ridge, forming the older arc and leading to the "modern" history of the Lesser Antilles. The volcanism of the older arc was active until the mid-Oligocene. Its extinction seems to be slightly earlier in the northern Lesser Antilles (ca. 31 Ma in Antigua) than in the southern part of the archipelago (between 30 and 28 Ma in the Grenadines; cf. Andreieff et al, 1987). The volcanic standstill lasted about 10 m.y. Resumption of volcanism is recorded slightly earlier in Martinique (ca. 22 Ma) than in the Grenadines (ca. 19 Ma). This new volcanic line formed the Recent arc, more or less coincident with the older arc in the southern Lesser Antilles, but from Martinique northward the Recent (inner) arc was progressively offset to the west with respect to the older (outer) arc. A major tectonic event must be the cause for this long and generalized volcanic gap and for the 50-km shift of the locus of the volcanism in the north. We have suggested that this event might be due to the arrival, in front of the northern part of the subduction zone, of a buoyant aseismic ridge probably of the same type and age as those of the South-Newfoundland Ridge and Bermuda bulge (cf. fig. 6 in Bouysse and Westercamp, 1988). Due to its buoyancy, the ridge could not be absorbed by the subduction and became underplated beneath the frontal rim of the island arc crust (Fig. 6c). Consequently, this part of the arc was tilted to the west, and its eastern edge was dramatically uplifted (more than 2 km at La Désirade). The subduction stopped all along the arc. The horizontal stress exerted by the "Atlantic" Plate caused the rupture of the subducted slab, progressively absorbed by the asthenosphere. A new slab was forming and, after some 10 m.y., its tip reached the depth necessary to produce a new volcanic front. In the northern part of the arc, the underplated ridge induced a flattening of the subducting slab, explaining the "jump" of the volcanic axis. To the south, the slab subducted at the same angle as before, there being no mechanical deviation between the moving plates. The slight delay in the timing of the southern volcanic events might correspond to the reaction delay to the northern collision.

The early Burdigalian renewal of the arc volcanism can be recognized only in the southern part of the Lesser Antilles, where the volcanic line was superimposed upon the former arc, generating shallow submarine and/or subaerial eruptive centers. By contrast, to the north, the volcanic line was emplaced on the lowered western rim of the arc or in the nearby basin. Consequently, several million years elapsed before the top of the volcanic constructions could emerge to form new islands, individualizing the Kallinago depression. To the east, large shallow carbonate platforms were formed during the Neogene, capping more or less completely the "dead" outer arc.

From early Miocene onward, the Lesser Antilles arc acquired its present general characteristics. Non-buoyant ridges are subducted, but their interaction with the arc is only of second order and was previously briefly reviewed.

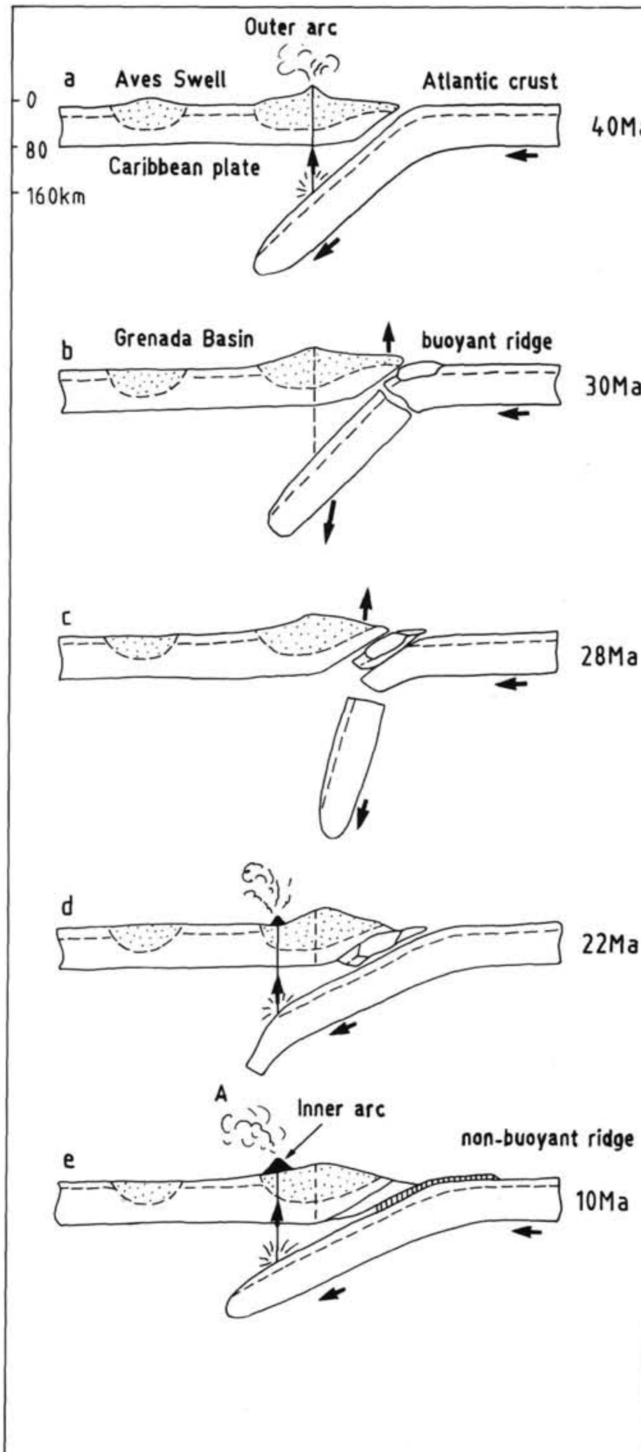

Figure 6. Series depicting the collision of a buoyant ridge with the northern part of the Lesser Antilles Ridge (after Bouysse and Westercamp, 1988). Stippled areas: arc crust.

The morphological contrast between the northern and the southern eastern Caribbean can be explained as a combination of different effects:

1. Grenada Basin: southern "oceanization" vs. northern rifting;

2. Near Atlantic: Barbados accretionary prism overloading in the south vs. reduced sedimentary cover in the north;

3. Arc ridge: no collision in the south vs. collision and uplift in the north.

Oil exploration surveys have shown that a deformation occurs at the southern end of Grenada Basin, with reverse faulting toward the Venezuela continental margin (Pinet et al., 1985). Geological studies carried out in Grenada (Speed, 1985) and in the Grenadines (Westercamp et al., 1985) suggest that this front extends to the northeast, crossing obliquely the Grenadines platform. This compressive tectonics affected the Paleogene and Miocene deposits but not the Pliocene-Quaternary reefal platform, and probably accomodated a general phase of convergence between the North and South American Plates thought to have occurred between 38 and 9 Ma (Ladd, 1976).

VOLCANIC PROCESSES AND MAGMA GENESIS

Historic volcanism illustrates the diversity of volcanic processes and types of erupted magmas in the Lesser Antilles. These include submarine eruptions of Mg-rich and hornblende-bearing basalts of the Kick'em Jenny, "nuées ardentes" related to andesitic dome constuction at Mount Pelée, and phreatic eruptions at Soufrière of Guadeloupe and at the Valley of Desolation in Dominica.

Volcanic formations belonging to the proto-arc (Mesozoic Caribbean arc, La Désirade) and to the older arc (Grenadines and outer arc) have been uplifted and eroded at different levels, depending on the importance of local tectonic events. Consequently, they document the early stages of formation of the Lesser Antilles, taken as an example of intra-oceanic island arc. Because most of these volcanics are hydrothermally altered, their primary characteristics are generally obliterated. Therefore, valuable petrological and geochemical data concerning the magmatism of the older arc are scarce or lacking. Volcanic formations of the Recent arc have not been significantly eroded and document the later, shallow submarine and subaerial stages of the volcanism.

The discussion that follows, dealing with volcanic processes, is based on geological data from the two Cenozoic arcs of the Lesser Antilles. The problem of arc compartmentation (an arc compartment is a small unit of volcanic arc with a characteristic spatial and temporal evolution of its magmatic series) and magma genesis is treated only with the abundant data from the Recent arc. Before turning to these topics, volcanic rock series are briefly presented.

Lava Types and Volcanic Rock Series

Volcanic rocks of the Lesser Antilles display a wide range of compositions, SiO_2 being typically bracketed between 48 and 66%. They are generally highly porphyritic with abundant plagioclase and varying percentages of olivine, clinopyroxene, orthopyroxene, hornblende, opaque minerals, quartz, and biotite. Acid andesites ($57 \le SiO_2 < 63\%$) predominate over basic andesites ($53 \le SiO_2 < 57\%$), both being, by far, the most widely represented. Basalts ($48 \le SiO_2 < 53\%$) and dacites ($63 \le SiO_2 < 68\%$) are relatively uncommon, whereas picritic basalts ($SiO_2 < 48\%$) and rhyolites ($SiO_2 \ge 68\%$) are extremely rare. The prevalence of andesites, low TiO_2 content ($< 1.2\%$), Ni, Cr, and K_2O ($< 2\%$), and high content of CaO and Al_2O_3 demonstrate the general low-K calc-alkaline character of the Lesser Antilles volcanic rocks.

Volcanic rock associations are rather complex and have led, in the past, to a great number of classifications. A study of the distribution of basic end members (using averaged analyses) of individual volcanic centers, in relation to six eruptive periods (0–1 Ma; 1–3 Ma; 3–6 Ma; 6–9 Ma; 9–12 Ma; 12–22 Ma) enabled Maury and Westercamp (1985) to distinguish two major lava groups:

1. A Mg-rich basalt (Mg 0 > 8%; Ni > 100 ppm) and related basaltic andesite group: these lavas exhibit an alkaline character in Grenada and the Grenadines, and a subalkaline one in the central part of the archipelago; and

2. An Al-rich basalt and related rocks group, exhibiting the common characteristics of orogenic magmas: this second group, largely predominant over the first one, can be subdivided into four types of volcanic rock series (Maury and Westercamp, 1985; Baker, 1984; Escalant, 1988):

A. Arc tholeiites showing all the mineralogical and geochemical patterns recognized by Jakes and White (1972): flat REE distribution pattern; $K_2O^{50} \le 0.5\%$; Sr, Pb, and Nd isotopic ratios similar to MORB values;

B. Low-K calc-alkaline series: $K_2O^{50} \sim 0.5\%$; slightly higher content of other incompatible elements and of Sr and Pb isotopic ratios;

C. Medium-K calc-alkaline series: $0.5 < K_2O^{50} < 0.9\%$;

D. High-K (relatively) calc-alkaline series: $K_2O^{50} > 0.9\%$; relatively high content of other incompatible elements; La/Yb ratio > 2; $^{87}Sr/^{86}Sr > 0.7050$.

Table 1 shows the mean analyses of the basaltic end members of these volcanic groups.

Volcanic Processes

In La Désirade, dramatically uplifted and eroded as seen above, the eastern part of the island exhibits the most ancient (lower Cretaceous) calc-alkaline volcanics of the Lesser Antilles. This formation is composed of pillow-lava flows with intercalated radiolarian cherts. The absence of limestones hints at deep depositional conditions, i.e., beneath the carbonate compensation depth (CCD). Hence, this association represents probably the very first stages of construction of the arc ridge above the oceanic floor.

As soon as the ridge crest rose above the CCD, pelagic calcareous deposits replaced the radiolarites. Eocene formations in Mayreau island (Grenadines) exemplify this intermediate stage of construction. Volcanic activity remained essentially effusive. Hyaloclastites generated by hydro-explosions can contribute to the construction of the pile, in water depths less than 2000 m, corresponding to the critical pressure of H_2O.

As the top of the ridge approached sea level, hydromagmatic explosions prevailed over effusive activity, and hyaloclastites became the prominent factor of the ridge building. Reefal limestones replaced pelagic limestones. Most of the Grenadines, the Vauclin-Pitault chain in Martinique, and volcanics and associated sedimentary deposits of St. Martin, St. Bartholomew, and Antigua are good examples of the pre-emersion stage of the island arc.

Just as the active centers of the volcanic ridge emerged, a drastic change in the eruptive processes occurred: effusive activity took over from hydromagmatic explosions, and large basaltic and andesitic shield volcanoes were built with piles of massive lava-flows. Morne Jacob, in Martinique, the Axial Chain of Basse-Terre, the early stage of formation of Mount Gimie in St. Lucia, and Morne Diablotin in Dominica, illustrate this post-emersion stage of the arc ridge. It is worthy of note that emersion didn't occur simultaneously along the arc.

As the area above sea-level reached several hundreds of km^2, pyroclastic formations started contributing to the development of the island. Eruptive vents concentrated progressively and composite strato-volcanoes replaced shield volcanoes. Mount Pelée in Martinique, Soufrière of St. Vincent, and Qualibou caldera in St. Lucia, are typical examples of the mature stage of the arc ridge.

Table 1. Selected mean analyses of basaltic rocks of the Lesser Antilles (from Maury and Westercamp, 1985; and Escalant, 1988. n = number of analyses, σ = dispersion.

	Al - RICH BASALTS								Mg - RICH BASALTS			
Types	Arc-tholeiite		low-K		medium-K		high-K		subalkaline		"alkaline"	
Examples	Martinique (St Anne ser.)		Mt Misery		Montserrat		Mt St catherine		Ilet à Ramiers		Mt St Catherine	
	%	σ(n=9)		σ(n=5)		σ(n=7)		σ(n=4)		σ(n=2)		σ(n=6)
SiO_2	50.18	0.54	50.16	1.93	51.10	1.62	51.45	1.75	47.63	0.60	47.20	2.23
TiO_2	0.63	0.14	0.97	0.09	1.02	0.28	0.89	0.12	0.75	0.06	0.89	0.10
Al_2O_3	18.66	0.68	19.84	0.74	18.96	1.22	17.70	0.60	15.44	0.20	15.42	1.51
Fe_2O_3*	9.09	0.71	9.57	0.53	9.54	0.49	8.75	1.02	9.45	0.00	9.60	0.63
MnO	0.16	0.05	0.16	0.01	0.17	0.01	0.15	0.01	0.17	0.01	0.17	0.07
MgO	5.93	0.87	4.93	1.28	4.90	0.91	5.70	1.45	13.22	0.04	11.79	1.67
CaO	11.09	0.72	11.20	1.19	10.17	1.11	10.31	1.77	10.91	0.03	11.47	0.11
Na_2O	2.30	0.28	3.12	0.65	2.92	0.50	3.22	0.65	1.96	0.08	2.28	0.45
K_2O	0.51	0.06	0.44	0.09	0.70	0.22	1.20	0.25	0.28	0.02	0.59	0.18
P_2O_5	0.10	0.01	0.07	0.01	0.08	0.04	0.21	0.15	0.10	0.02	0.17	0.13
	p.p.m.											
Rb	6	2	8	0	8	4	24	15	2	0	15	7
Sr	371	42	261	17	344	82	881	265	180	4	571	181
Ba	113	11	110	20	70	7	445	71	58	10	343	142
Cr	39	2	56	54	50	24	52	18	863	17	730	245
Ni	19	1	16	15	13	10	40	16	237	5	288	48

This pattern of development of the Lesser Antilles island arc is sketched in Figure 7. Note that, with the development of the arc, the volcanic front migrates westward. This is a common, but not universal, feature of the eruptive activity in the Lesser Antilles.

Time and Space Relationship of Magmatic Series: Arc-compartment

The distribution in space and time of recognized volcanic rock series in the Recent arc is quite complex (Fig. 8). It is at variance with classical generalized models assuming either chronological evolution transverse to the arc, from tholeiites to high-K calc-alkaline series (Jakes and White, 1969), or a permanent along-arc gradation from tholeiites, at one end, to high-K calc-alkaline series, at the other (e.g., Brown et al., 1977, for the Lesser Antilles).

One of the best ways to study the magmatic evolution of the Lesser Antilles is to turn particular attention to the reconstitution of intra-island sequences in relation to individual volcanic centers, rather than to deal with an island as a whole, and to use well-constrained chronological (biostratigraphic and radiometric) data. In this way, the eruptive behaviour of the Lesser Antilles seems to be characterized by elemental (modular) areas of a few tens of km in length and width, with a rather continuous volcanic activity for several millions years. Such areas have been referred to as *arc compartments* (Westercamp, 1988). The concept of an arc compartment emphasizes the magmatic composition and evolution. It is not directly related to the segmentation of the Benioff Zone into several slabs dipping at different angles, but rather to the distribution of sedimentary basins at the surface of the slab. Therefore the concept is somewhat different from the concept of an *arc segment* introduced earlier by Stoiber and Carr (1973). Arc segmentation refers to (sub-) contemporaneous events and to larger arc blocks, from about one hundred to several hundred kilometers in length; the geometry of the subducting slab controlling the segmentation of the volcanic line and, among other things, the composition, trend, and abundance of arc volcanism.

Three major types of arc compartments (types A, B, and C) are recognized, as follows:

Type A

This type is illustrated by the Miocene formations of Martinique and St. Lucia, and by the central part of Martinique during the Pliocene. Concomitantly with decreasing age: (1) the volcanic front migrates from east to west; (2) the volume of lavas decreases; (3) the volcanic activity shifts from submarine to subaerial environment; (4) there is a progressive change from arc tholeiites and low-K calc-alkaline series, mainly basic, to medium-K and high-K calc-alkaline series, mainly acid. Fractional crystallization within intra-crustal magma chambers is thought to play a major role in the evolution of each of these series.

Type B

This type is exemplified by St. Kitts island and the Pleistocene volcanics of Basse Terre, in the north, and by the segments Bequia-St. Vincent and Canouan-northern Grenada, in the south (Fig. 8). Concomitantly with decreasing age: (1) the volcanic activity migrates along the arc axis; (2) the volume and the magmatic characters of the lavas remain.

Type C

This type is characterized by the Pliocene-Pleistocene volcanic formations of southwest Martinique, Montserrat, Nevis, and Saba islands. In this case, the volcanics are represented by highly porphyritic rocks showing complex mineral assemblages and belonging to medium-K calc-alkaline series. No progressive change is observed, unlike in type A, from low-K to "high-K" volcanic associations. Common banded lavas, occurrence of cog-

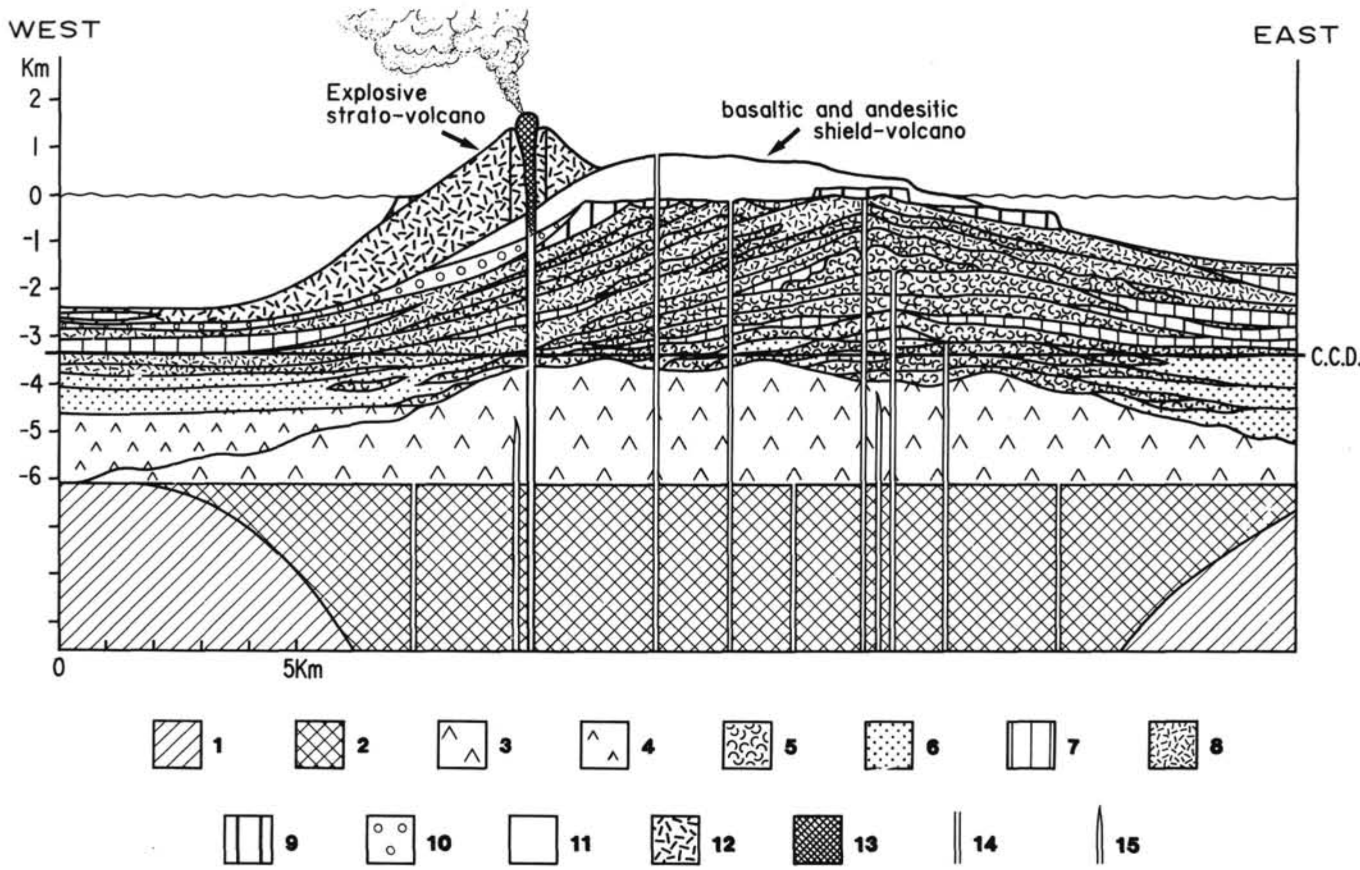

Figure 7. Schematic structure of the Lesser Antilles Ridge, showing the different types of geological units. 1: Primitive oceanic crust; 2: oceanic crust modified ("continentalized") by successive arc magma injections; 3: Volcanic and sedimentary formations of the Mesozoic arc; 4: First volcano-sedimentary formations of the back-arc basin; 5: Submarine lava flow (generally, pillow-lavas); 6: Radiolarian cherts; 7: Pelagic limestones; 8: Hyaloclastites; 9: Shallow platform limestones; 10: Reworked facies; 11: Massive subaerial lava flows; 12: Pyroclastic brecciae; 13: Dome; 14: Volcanic conduit; 15: Dyke; CCD: Carbonate compensation depth.

nate basic xenoliths, and coexistence of unequilibrated mineral assemblages (e.g., quartz and Mg-olivine) emphasize the prominent role of magma mixing in the eruptive processes.

Arc compartments of intermediate character (between types A, B, and C) exist and point to the complexity of magma evolution in the Recent arc of the Lesser Antilles, which is a classic example of an intraoceanic arc.

Magma Generation

Published geochemical and isotopic studies of the Lesser Antilles lavas have emphasized the role of subducted sediments (e.g., White and Dupré, 1986), dehydration of the meta-basaltic upper part of the subducting slab (Hawkesworth and Powell, 1980), interbedded sediments within the arc crust (Davidson, 1986), and arc-crust thickness (Escalant, 1988). Whether the contamination by sediments occurs via a fluid phase or a partial melt remains unclear. Also unclear is the contribution of M0RB-type end members: i.e., the subducted oceanic crust and/or the portion of mantle just overlying the plunging slab.

The distribution in space and time of volcanic activity in the Lesser Antilles (Fig. 8) sheds an insight into and provides constraints on this strongly debated problem. Westercamp (1988) pointed out the apparent contradiction between the continuity of the convergence motion of the Atlantic crust vs. the Caribbean Plate during the last 20 Ma, and the discontinuous buildup of the Lesser Antilles volcanic ridge during the same time.

He demonstrated the necessity of a discontinuous process superimposed on the steady-state convergence process. He proposed that the sediments of varying thickness overlying the subducted oceanic crust play this role. The worldwide signature of subducted sediments in arc magma genesis (Hole et al., 1984) substantiates this hypothesis.

Referring to this still speculative model (Fig. 9), some comments can be made: (1) The along-arc distribution and duration of the volcanic activity of arc-compartments are linked, respectively, to the width and to the length of subducted sedimentary basins or depressions individualized at the surface of the subducted oceanic crust. (2) The spatial extension and duration of volcanic gaps depend, respectively, on the width and length of subducted ridges. (3) Mg-rich basalts and primitive arc-tholeiites (e.g., Redonda islet, between Montserrat and Nevis) move upward through transverse faulting (Fig. 8) triggered by the interaction of the subducted ridges with the overriding plate (frontal pushing and asperity effects). In this model, the contribution of subducted sediments proceeds from partial melting rather than from derived fluids for two main reasons. First, experimental petrology shows that dehydration of metamorphic mineral assemblages, thought to constitute the upper layer of the subducted slab, occurs below a pressure of 30 Kb (i.e., above 80 km depth; cf. e.g., Wyllie, 1973). Second, the depth of the Benioff Zone beneath the volcanic line of the Lesser Antilles ranges between 100 and 180 km (see above). Thus, the arc magmas derive from the dehydrated zone of the slab, and probably result from partial melts.

Detailed geochemical and mineralogical studies carried out on the lavas of Martinique (Escalant, 1988) and St. Lucia (P.

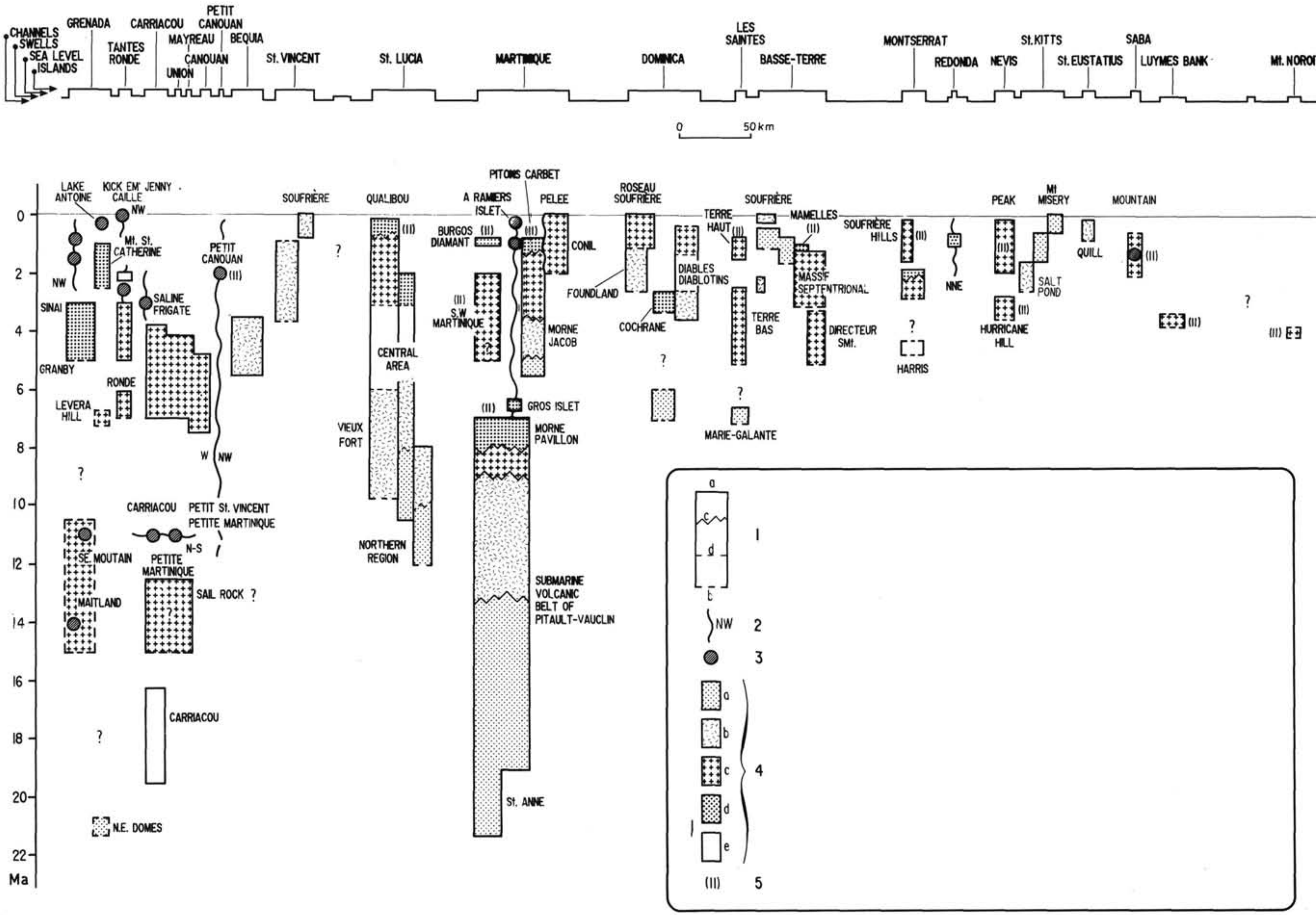

Figure 8. Correlation chart for the Recent arc of the Lesser Antilles according to geological mapping and biostratigraphic studies combined with K/Ar data (after Westercamp, 1988; for sources of data, refer to that publication). The entire arc is schematically represented from Grenada to Noroit seamount (see Fig. 1). 1: volcanic edifices or arc-compartments: a, well-established limit of volcanic activity; b, volcanic activity continues, presumably below; c, progressive geochemical change from one type of series to another; d, inferred time for serial character change of the magmatism. 2: Major transverse fault. 3: Mg-rich basalts and related rocks. 4: "Normal" orogenic series: a, arc-tholeiites; b, low-K series; c, relatively medium-K series; d, relatively high-K series; e, undetermined geochemical character; 5: highly porphyritic calc-alkaline rocks indicating magma mixing.

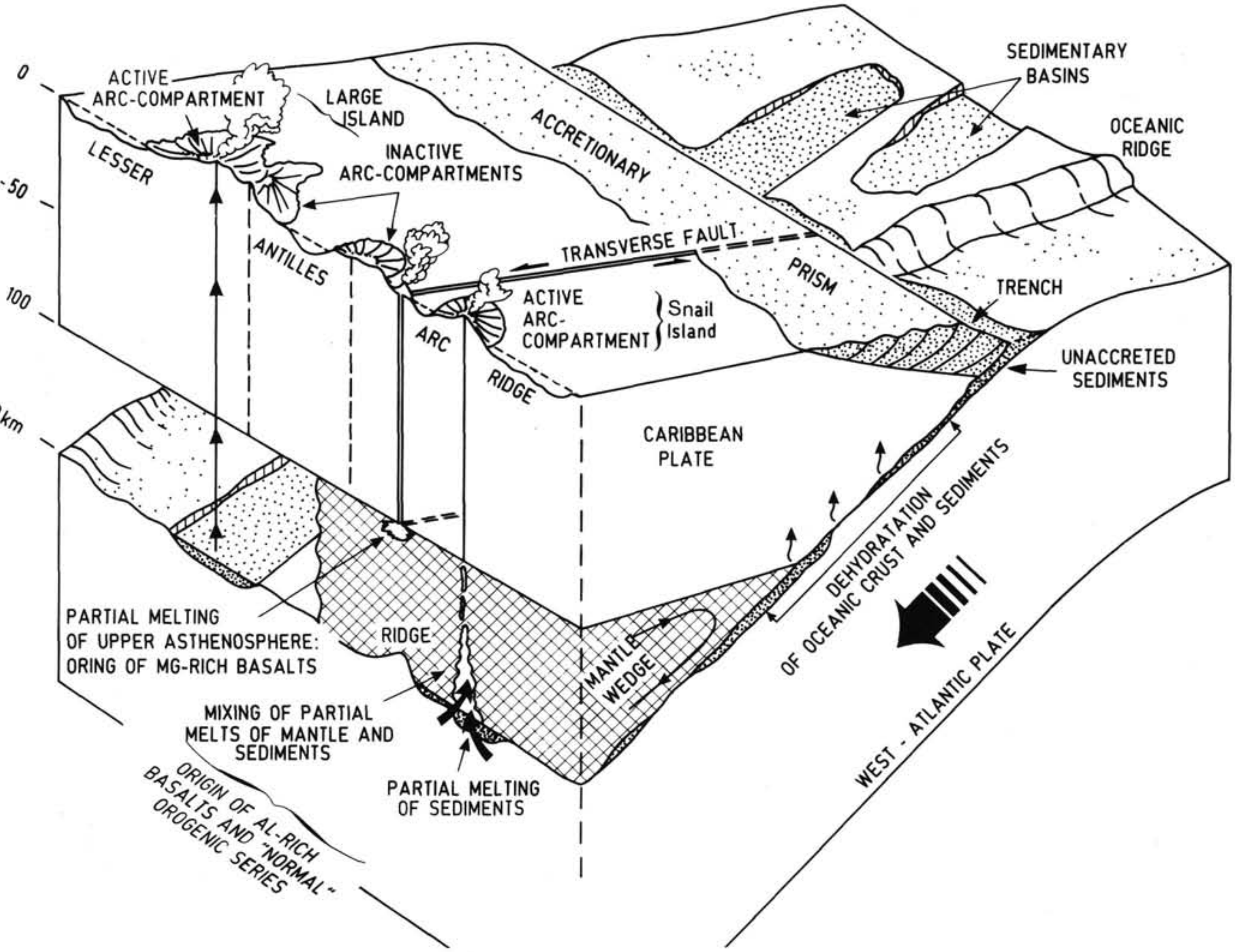

Figure 9. Generalized model for magma generation in the Lesser Antilles arc-trench system (modified after Westercamp, 1988.

Vidal and coworkers, in progress) suggest a more complicated situation (Westercamp and Maury, in preparation). Fluid release is thought to be initiated in the asthenospheric wedge above the 100 km depth. Thereafter, the enriched mantle is carried downward by convection and undergoes partial melting when it reaches the vertical of the volcanic line (cf. Tatsumi et al., 1986). Tholeiitic and low-K calc-alkaline magmas are produced. As the arc compartment develops, medium-K calc-alkaline magmas replace the earlier ones.

CONCLUSION

The Lesser Antilles island arc was initiated, probably as a component of the wider Mesozoic Caribbean arc, in the Early Cretaceous; therefore, it can be considered as the oldest active intraoceanic island arc in the world. In its main characteristics, the Lesser Antilles arc is somewhat atypical: old subducted oceanic crust, a very slow convergence rate, rather low volcanic production rate, low seismicity level, and a single back-arc spreading phase. The arc is the site of two major volcanic gaps, each of about the same duration, 8 to 10 m.y. The early one, in the Paleocene, was triggered by the opening of Grenada Basin. A later interruption (Fig. 10), by the end of the Paleogene, resulted from the collision of a buoyant Atlantic aseismic ridge.

As regards the recording of the volcanic history of the Lesser Antilles in the form of ash layers deposited in the fore-arc region, it should be kept in mind that a significant number of volcanoes have erupted in a submarine environment, so that there was no production of subaerial ashes to be dispersed by the wind circulation system (for the latter, cf. Sigurdsson et al., 1980). As an example, in the older arc the volcanoes of St. Martin and St. Bartholomew are entirely emplaced below sea level.

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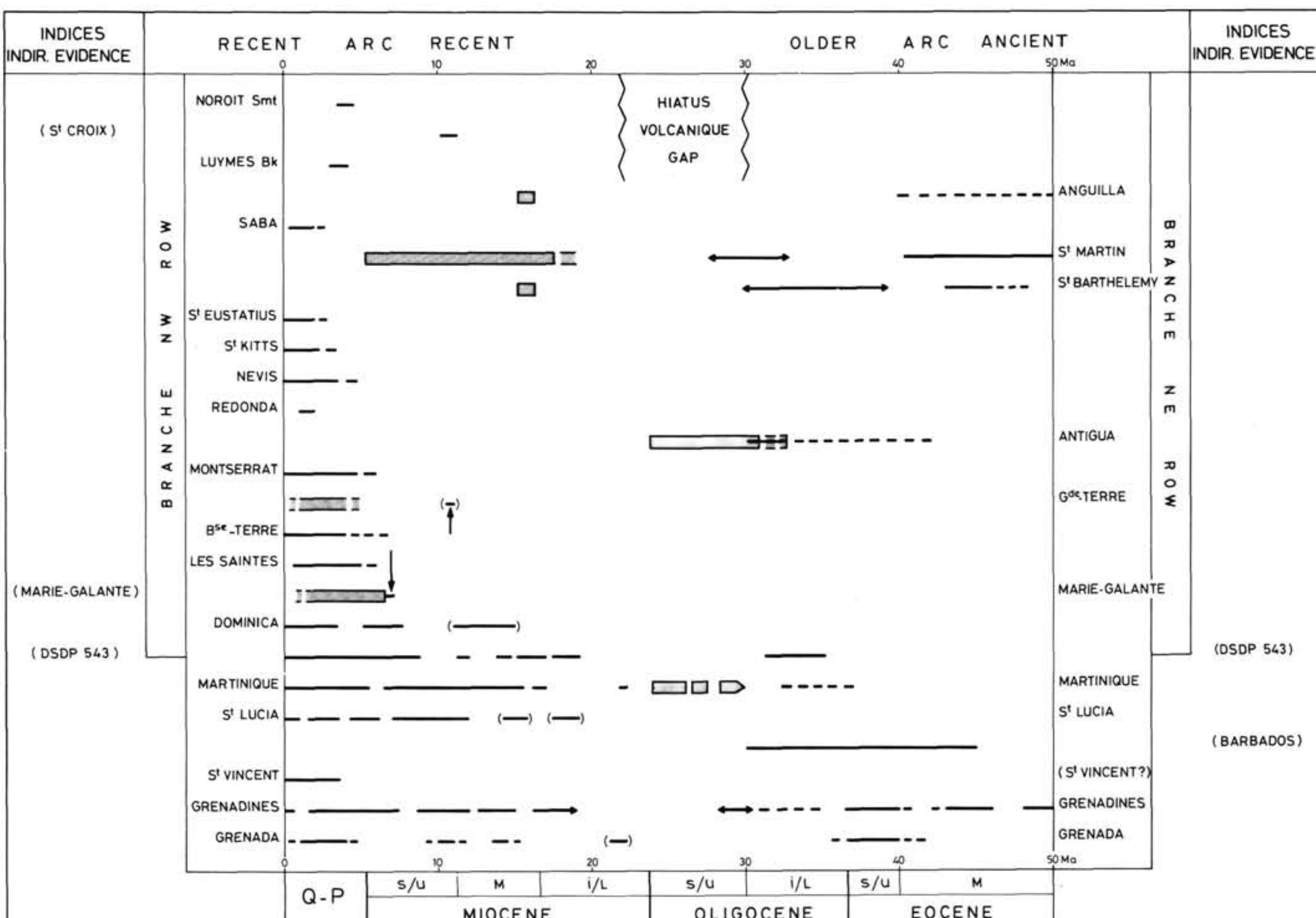

Figure 10. Timing, since 50 Ma, of volcanic phases corresponding to dated outcrops of the Lesser Antilles arc or to indirect evidence (from Bouysse and Westercamp, 1988). Segments with arrows refer to the stratigraphic range of the determination. Thick segments refer to sedimentary deposits (mainly limestones) showing no trace of local volcanic activity. Segments between brackets refer to dubious or very isolated datings.