7. THE LESSER ANTILLES ISLAND ARC: STRUCTURE AND GEODYNAMIC EVOLUTION[1]

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ABSTRACT

Extensive onshore fieldwork combined with marine geology cruises carried out in the Lesser Antilles Ridge (Barbados area excepted) provide new insights to the physiography and structure of this island arc and permit a speculative reconstitution of the evolution of the area since the Late Jurassic.

The present configuration of the Lesser Antilles island arc is due to the westward underthrusting of the Atlantic oceanic crust under the Caribbean Plate. The rate of convergence of this active margin is slow: 2.2 cm/yr.

Most significant is the sharp contrast between the northern and southern Lesser Antilles. In the northern half, the basement of the ridge is thought to be Mesozoic and connected to the Greater Antilles island arc. In the southern half (south of Guadeloupe archipelago), the island arc existed only since the Eocene. From Grenada to Martinique the subduction pattern was not modified from Eocene until Present. From Guadeloupe to the northern end of the Lesser Antilles, two volcanic ridges were successively superimposed on the older island arc basement: an outer (eastern) arc, volcanically active from Eocene to possibly early Miocene, and an inner (western) arc, volcanically active from late Miocene to Present. In between, from Martinique to Guadeloupe, the situation was transitional. The westward jump of the volcanic line that occurred in the northern part of the Lesser Antilles during the Miocene may have been consecutive to the interaction of an Atlantic fracture zone ridge (Barracuda) with the subduction process.

The relation between Aves Swell and Lesser Antilles Ridge is discussed and the Grenada Basin is interpreted as a trapped back-arc basin.

INTRODUCTION

The Lesser Antilles arc to the north and the South Sandwich archipelago (Scotia Arc) to the south are the only two active island arcs of the Atlantic Ocean, other similar features being mainly concentrated on the western side of the Pacific Ocean.

Geological studies of the islands started long ago, but the submarine areas of the Ridge, in a strict sense (i.e., excluding the neighboring basins or sedimentary accumulations like Barbados Ridge), had been, until recently, little surveyed. The ARCANTE project, conducted by the Bureau de Recherches Géologiques et Minières (French Geological Survey), is devoted to the onshore and offshore geological and structural study of the Lesser Antilles arc, with a special emphasis on the French West Indies areas. Our field surveys and marine geology cruises have provided some new insights in to the geology of some islands (particularly Martinique, Guadeloupe, les Saintes, Marie-Galante, la Désirade, St. Bartholomew, St. Martin, Redonda) and to the physiographic and structural pattern of most of the Lesser Antilles submarine ridge. In this paper, I will try to summarize results and ideas developed by our ARCANTE research group (particularly, Andreieff et al., 1976; Westercamp and Mervoyer, 1976; Andreieff et al., 1979; Bouysse, 1979; Westercamp, 1979, Bouysse, Andreieff, and Westercamp, in press; Bouysse, Schmidt-Effing, and Westercamp, 1983; Bouysse and Guennoc, 1983; and Westercamp and Andreieff, in press).

Because the Lesser Antilles volcanic arc is the main physiographic feature of the eastern Caribbean convergent margin, this chapter is intended as a background for Volume 78A. Although the chapter was elaborated in the framework of personal concepts dealing with the structural evolution of the region, I hope that it will be of some use in understanding the geological environment of the Leg 78A drill sites.

GENERAL SETTING

The Lesser Antilles island arc (Fig. 1), comprising a score of major islands, is about 850 km long, with a radius of curvature of about 450 km. It stretches from the South American continental margin to the Anegada Passage, which marks the boundary with the Greater Antilles. It underlines the eastern boundary of the Caribbean Plate (Malfait and Dinkelman, 1972; Jordan, 1975; Tomblin, 1975; Bowin, 1976; Ladd, 1976; Dorel, 1978; Burke et al., 1978) underthrust, in a subduction zone, by the oceanic crust of the western Atlantic Ocean.

The Lesser Antilles Ridge has been described as a double arc, coalescent in its southern part and diverging at the latitude of Dominica (Martin-Kaye, 1969, Fink, 1972). The *outer arc* (to the east) was thought to be volcanically active from the Eocene to early Miocene, and the *inner arc* or recent arc (to the west) active from the late Miocene to Present. The northeastern branch, where only older volcanic rocks crop out on some of the islands, is called the *Limestone Caribbees* (Marie-Galante, Grande-Terre of Guadeloupe, la Désirade, Antigua, Barbuda, St. Bartholomew, St. Martin, Tintamarre, Anguilla, Dog, and Sombrero). The rest of the archipelago, which bears the active or recent volcanoes, is called the *Volcanic Caribbees* (Fig. 2) (Grenada, Grenadines, St. Vincent, St. Lucia, Martinique, Dominica, les Saintes,

[1] Biju-Duval, B., Moore, J. C., et al., *Init. Repts. DSDP*, 78A: Washington (U.S. Govt. Printing Office).
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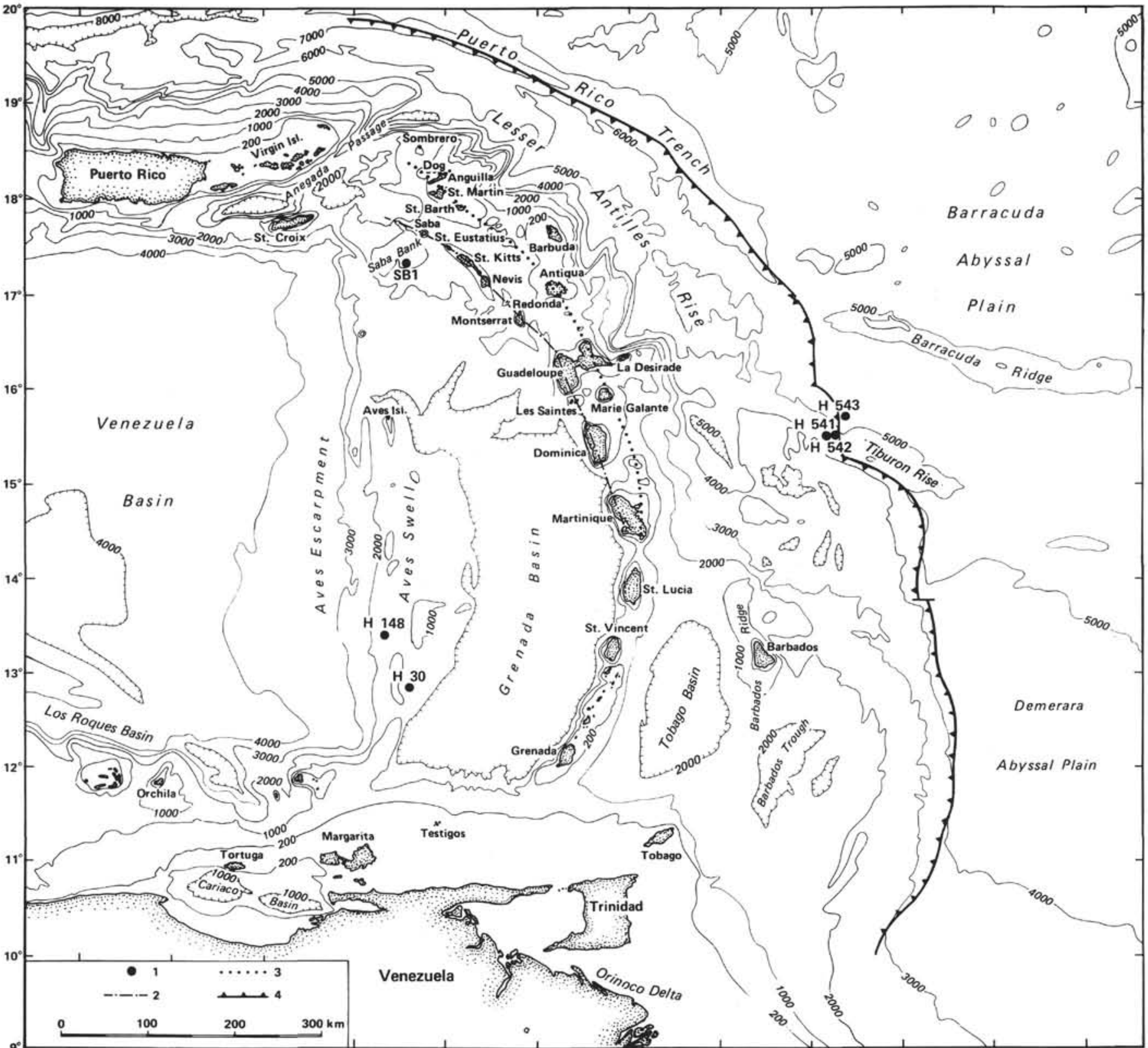

Figure 1. Eastern Caribbean. (Bathymetry [isobaths: 200 m and every 1000 m], simplified from Case and Holcombe [1980], is slightly modified. For toponymy and detailed bathymetry between St. Lucia and Anguila, refer to Fig. 3. Key: 1 = drill sites [SB1 = Saba Bank exploratory well; H = DSDP holes]; 2 = inner arc; 3 = outer arc; 4 = deformation front [after Case and Holcombe, 1980].)

Basse-Terre of Guadeloupe, Montserrat, Redonda, Nevis, St. Kitts, St. Eustatius, and Saba).

To the west, from Guadeloupe southward, the Lesser Antilles arc ridge has steep slopes delineating the western arcuate border of the Grenada Basin, whose maximum depth is 2800 m. This Basin is filled with about 7 km of sediments (Uchupi, 1975). Farther to the west, the Grenada Basin is bounded by the Aves Swell, which is thought to have been an active island arc from Late Cretaceous to Paleocene (Nagle, 1972; Fox and Heezen, 1975; Clark et al., 1978). The western side of Aves Swell is connected to the Venezuelan Basin by the Aves Escarpment, a 600-km-long rectilinear feature joining the Venezuelan continental margin to the Greater Antilles.

On the eastern side of the Lesser Antilles are two main morphostructures. One is the southeast termination of the Puerto Rico Trench, more than 6000 m deep, which is linked to the arc ridge by the Lesser Antilles Rise. The Trench progressively merges southward into the Barbados accretionary prism (Mascle et al., 1977), which has a maximum thickness of about 20 km (Westbrook, 1975). The prism culminates at Barbados Island and is made of sediments mainly derived from the South American rivers (the Orinoco, and later, the Amazon).

An intriguing problem was raised when Fink (1968) reported a K-Ar age of 142 Ma (Upper Jurassic) for a trondhjemite outcropping in the center of la Désirade, and occurrences of pillow basalts associated with cherts

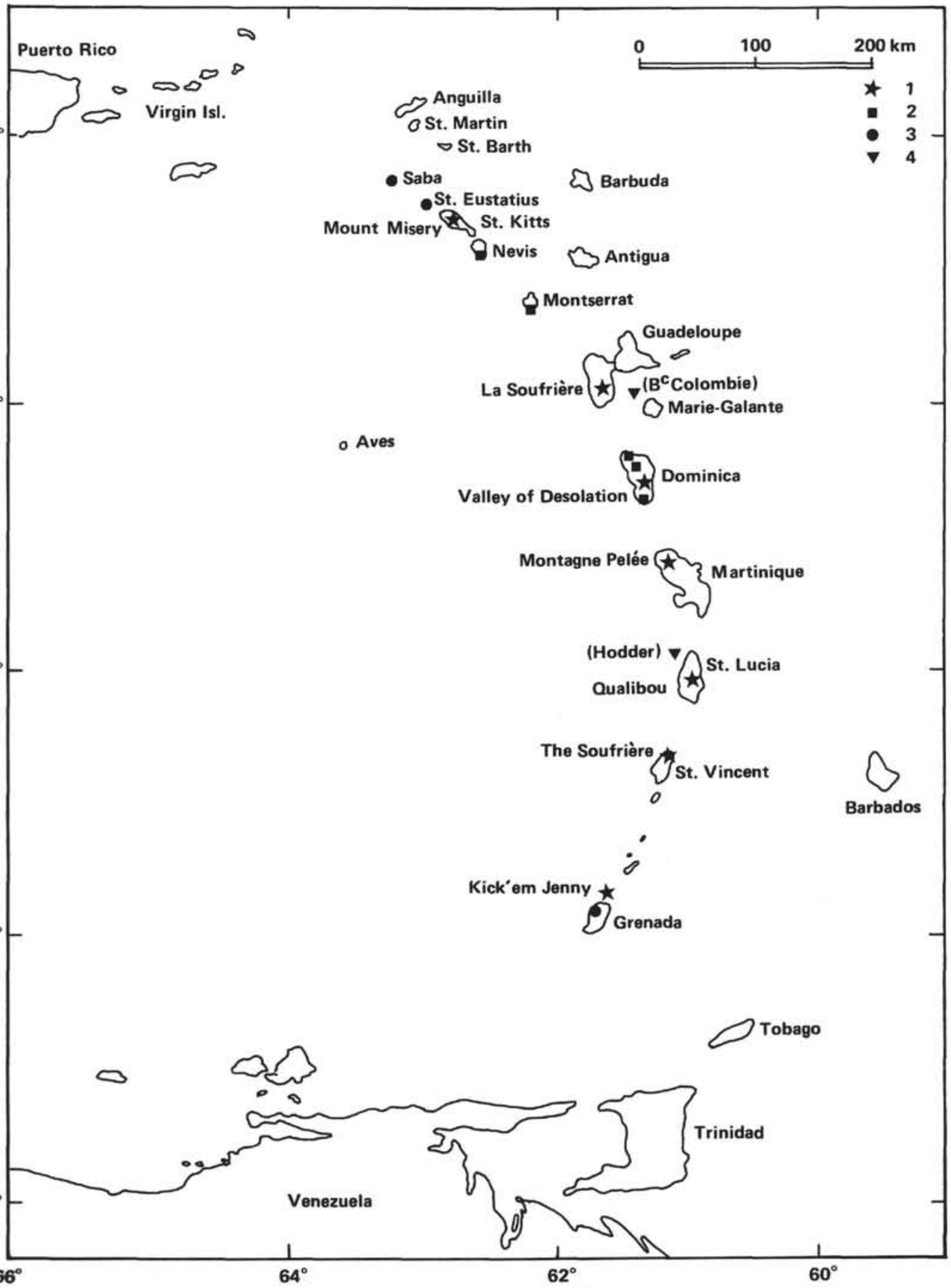

Figure 2. Location of the active volcanoes of the Lesser Antilles, modified after Robson and Tomblin (1966). (Key: 1 = volcanoes with recorded eruptions; 2 = volcanoes exhibiting solfataric or fumarolic activity, with no recorded eruptions; 3 = volcanoes with well-preserved morphology that probably have erupted within the past few thousand years; 4 = previously postulated active submarine volcanoes, in reality nonexistent. B^c Colombie = Colombie Bank.)

to the northeast of the same island. This age, disputed by some authors (Dinkelman and Brown, 1977; Briden et al., 1979), and the so-called "ophiolitic complex" led to various tentative interpretations concerning the evolution of the East Caribbean area. The most favored hypothesis conceives of la Désirade as a slice of oceanic crust (either of Atlantic or Caribbean origin) that was uplifted or scraped off, and piled up, during the Cenozoic, against the Lesser Antilles Ridge (Mattinson et al., 1973 and 1980; Fox and Heezen, 1975; Dinkelman and Brown, 1977). The alternative hypothesis is that la Désirade might have been part of the Greater Antilles island arc encompassing, possibly, the whole Lesser Antilles area to the South American border (Fink, 1968 and 1972; Fink et al., 1971).

The present configuration of the Lesser Antilles arc is mirrored by the recent volcanoes of the inner arc. They are distributed along a narrow alignment, actually not as a perfect arcuate pattern, but showing three more or less rectilinear and equivalent sections (Fig. 11D), according to an insular segmentation (see Stoiber and Carr, 1973; Ranneft, 1976; Marsh, 1979). The central segment, bearing the three largest islands of the archipelago (Martinique, Dominica, and Basse-Terre of Guadeloupe), is very straight. This tripartite subdivision is probably related to a major segmentation of the Wadati–Beninoff zone in three slabs (Tomblin, 1975; Dorel, 1978), sinking no deeper than 190 km (earthquake depth limit). From new seismic data supplied by Dorel (1978, 1981), it seems that the Atlantic crust, underthrust below the Caribbean crust, is presently part of the South America Plate. This Plate is probably decoupled, at present, from the North America Plate by a slight right-lateral movement (0.2 cm/yr.) along a transform fault connected to the east–west segment of the Puerto Rico Trench. The continuity of north–south trending magnetic anomalies crossing Barracuda Ridge (Peter and Westbrook, 1976) precludes the possibility of placing the boundary between North America and South America plates along this fracture zone, as previously stated (see for example, Bowin, 1976).

The Lesser Antilles is a slow-moving active margin with a convergence rate of about 2.2 cm/yr. (Dorel, 1978 and 1981; Tovish and Schubert, 1978). This value is low when compared to other convergent margins and, therefore, the volcanic and seismic effects of the subduction are relatively subdued.

In Table 1, the recent volcanic activity of the Lesser Antilles is compared to two other island arcs and to one continental arc (cordillera) of approximately the same length (5 to 6° of latitude) but with different rates of subduction. The rather low seismicity of the Lesser Antilles has been discussed by Dorel et al. (1971) and Dorel (1978 and 1981); the earthquake magnitudes greater than 6 are uncommon. Under the present volcanic axis, the depth of the subducted slab is about 100 km to the north and the south, and about 120 km for the central segment.

Historic recorded eruptive or fumarolic activity (since the seventeenth century) occurred (Fig. 2) at Kick'em Jenny

Table 1. Eruptive activity of four convergent margins between 1900 and 1980 (from Simkin et al., 1981).

Convergent margins	Erupting volcanoes	Number of eruptions	Rate of convergence (cm/yr.)
Lesser Antilles	4	16	2
Marianas	10	31	2 to 6
New Hebrides (Vanuatu)	7	58	10
Middle America (Guatemala to Costa Rica)	19	145	9 to 13

Note: The four convergent margins, of approximately the same length, are compared with the convergence velocity (rounded values from Molnar and Atwater, 1978; Tovish and Schubert, 1978). Out of the 16 eruptions of the Lesser Antilles, 9 have been recorded from the very young submarine volcano, Kick'em Jenny (between 1938 and 1977).

(a submarine volcano, north of Grenada), Soufrière of St. Vincent, Qualibou caldera in St. Lucie, Montagne Pelée in Martinique, Valley of Desolation in Dominica, la Soufrière of Guadeloupe, and Mount Misery in St. Kitts (Robson and Tomblin, 1966). Although relatively less frequent, some eruptions have had very dramatic consequences, such as the 1902 eruption of Montagne Pelée, killing the 28,000 inhabitants of St. Pierre. The most recent eruptions occurred in 1976 at la Soufrière of Guadeloupe, in 1977 at the Kick'em Jenny (Sigurdsson and Sparks, 1979), as well as in 1979 for the Soufrière of St. Vincent.

STRUCTURE AND SUBMARINE MORPHOLOGY OF THE ISLAND ARC

The disposition and extension of the insular shelves and submarine banks are, to some extent, a good mirror of the structure of the island arc (Figs. 1 and 3). These marine terraces are built up by Pliocene–Quaternary shallow-water limestones in which algal debris forms the dominant component.

Southern Segment (Fig. 1)

In the southern part of the arc, the slopes looking toward the Grenada Basin are rather steep, contrasting with the gentler ones of the Atlantic side, which are connected with the Barbados accretionary prism. From Grenada to St. Lucia, the arc is narrow with only one volcanic ridge. The width of the insular shelves (islands included) is less than 28 km. Around St. Lucia and St. Vincent, the shelves delineate a rather limited "crown." By contrast, only one elongated (170-km-long) terrace encompasses Grenada and the Grenadines archipelago. Globally considered, the islands and islets are made of volcanic formations whose dated effusives span from 21 Ma (early Miocene) to Present (Briden et al., 1979) and of sediments and pyroclastic tuffs ranging from possibly early or middle Eocene (but surely late Eocene) to early Miocene (Martin-Kaye, 1969).

In Martinique, the eruptive centers migrated progressively from a prebasal Miocene igneous substratum in the east, to Quaternary volcanics in the west (Andreieff et al., 1976; Gérard et al., 1981). The oldest K-Ar date is 27 Ma[3] (late Oligocene); the 36-Ma age supplied by Nagle et al. (1976) was not confirmed (J. C. Baubron, personal communication, 1981). The Martinique shelf is relatively well developed to the northeast, and north of the island the outer and inner arcs diverge.

Outer Arc

Contrary to the interpretation of Fink (1972), there is no offset of the outer arc axis off Dominica. In fact, a curvilinear alignment, more or less continuous, of submarine banks (guyotlike features, with an igneous core) and islands where middle Eocene to Oligocene volcanic

[3] The dating of the stratigraphic boundaries (Neogene excluded) adopted in this paper is quoted from the latest revised scales (Odin and Curry, 1981; Odin and Kennedy, 1982; Odin, 1982).

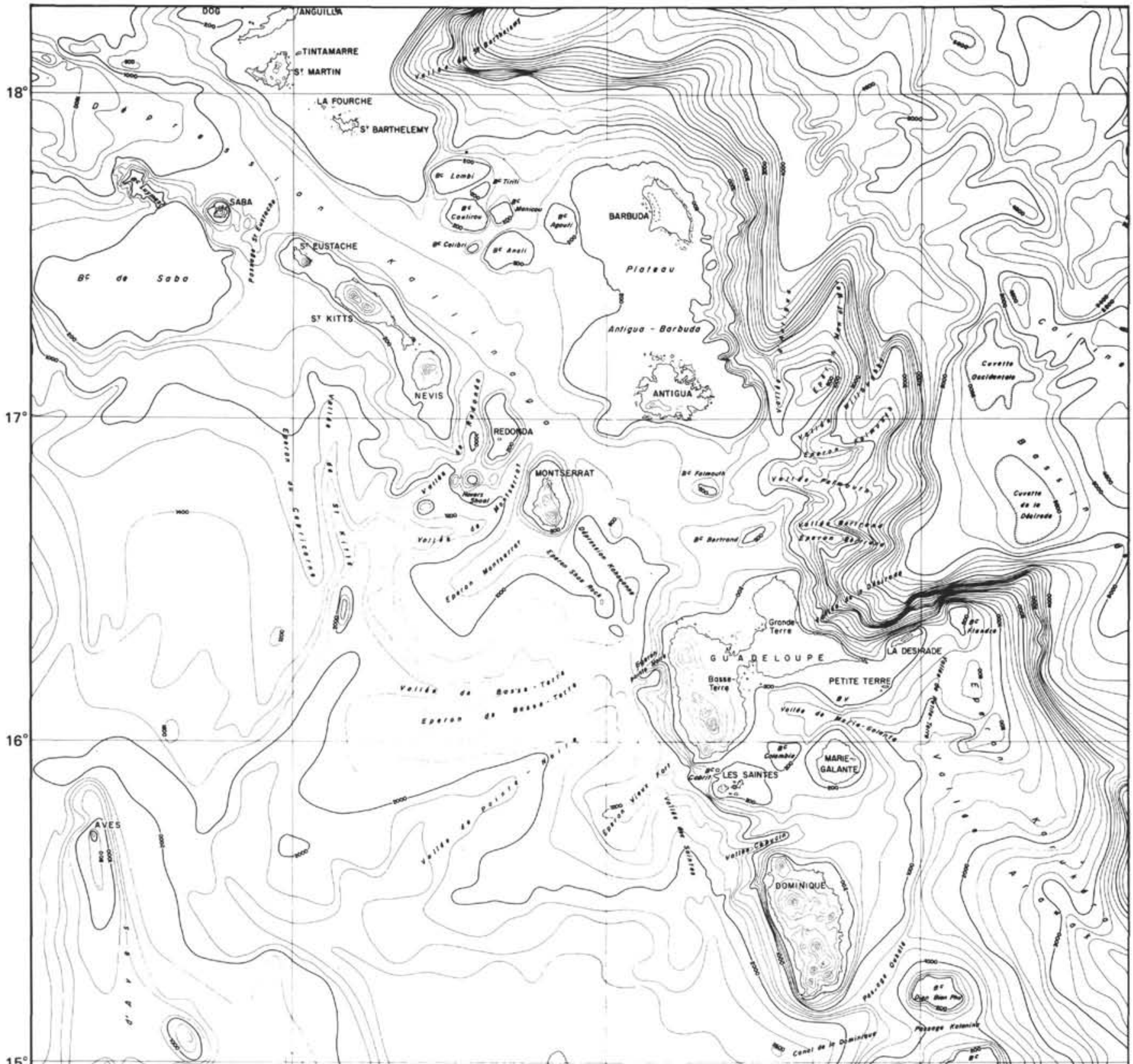

Figure 3. Bathymetric sketch between St. Lucia and Anguilla (ARCANTE 1 cruise) (modified from Bouysse, 1979). (Contour interval is 200 m [offshore and onshore]. For bathymetric data used and new physiographic names, see Bouysse [1979]. B.V. = Banc des Vaisseaux. Translation: B^c = bank; bassin = basin; colline = hill; cuvette = small basin; dorsale = ridge; éperon = spur; fosse = trench; vallée = valley.)

effusives or intrusives generally crop out (Bouysse, 1979) can be followed. The row of the outer arc is made up of the following succession (Fig. 3):

Amérique and Dien Bien Phu banks (Fig. 4)

Marie-Galante, blanketed with Pliocene-Quaternary reefal limestones (in October, 1981, extremely restricted basal outcrops of upper Miocene and lower Pliocene volcanic tuffs and foraminifer limestones were discovered here—(Andreieff et al., in press)

Grande-Terre of Guadeloupe, the basement of which is completely concealed by Pliocene-Quaternary limestones (Andreieff and Cottez, 1976)

Bertrand and Falmouth banks

Antigua, consisting of upper Eocene to lower Oligocene lava flows and volcaniclastic deposits overlain by the Antigua Formation limestones (Martin-Kaye, 1969; Frost and Weiss, 1979) of the basal upper Oligocene (*Globigerina ampliapertura* Zone; P. Andreieff, personal communication, 1982); hence some K-Ar radiometric ages, supplied by Nagle et al. (1976)—20.0 and 24.0 Ma—and by Briden et al. (1979)—23.2 Ma—seem to be too young

the seven Animal banks: Agouti, Anoli, Colibri, Coulirou, Manicou, Titiri, and Lambi (Bouysse, 1979)

St. Bartholomew (= St. Barth), where the eruptive episode (with limestone intercalations) was restricted to a short period of 2 to 3 Ma in the middle Eocene (Andreieff, 1982; Westercamp and Andreieff, in press); these formations are

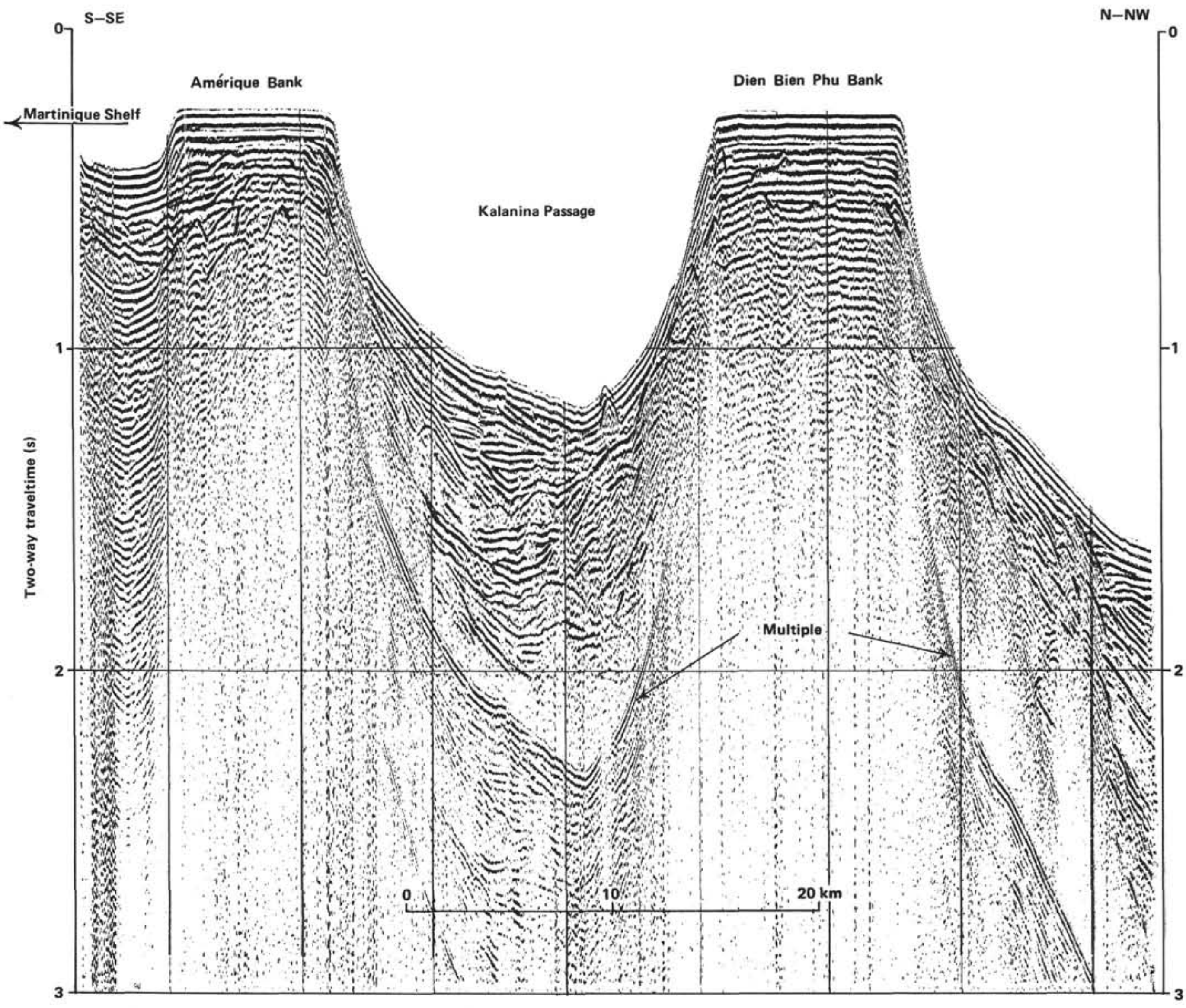

Figure 4. Water-gun seismic profile (ARCANTE 1 cruise) across the Amérique and Dien Bien Phu banks (N-NE of Martinique, Fig. 3). (Despite the interference with the multiple reflections, it is possible to infer a guyotlike structure for these platforms, with a Pliocene–Quaternary limestone cap. Some first reflection horizons have been underlined.)

intruded by Oligocene plutonic rocks (24–32 Ma—Nagle et al., 1976; Briden et al., 1979)

St. Martin, having middle and upper Eocene volcaniclastics and sediments, upper Eocene to lower Oligocene intrusives (28.4–37.2 Ma), and upper Miocene limestones and marls (Nagle et al., 1976; Briden et al., 1979; Andreieff et al., 1981; Andreieff, 1982)

Anguilla, mainly made of a table of upper lower to basal middle Miocene deposits (Andreieff, 1982) overlying a poorly exposed volcanic basement

Dog, an islet geologically similar to Anguilla, and which is the northernmost emerged area displaying outer arc volcanic remains (Martin-Kaye, 1969)

Of the remaining Limestone Caribbees, two islands should not be ascribed to the outer arc, contrary to the assumption of former authors (Martin-Kaye, 1969; Fink, 1972; Butterlin, 1977). La Désirade and Barbuda are situated outside (to the east) of the row just described. La Désirade is made of a lower Pliocene tablelike calcareous plateau underlain by an igneous complex. As a result of recent detailed fieldwork (Westercamp, 1980; Bouysse, Schmidt-Effing, and Westercamp, 1983), we conclude that this basement was entirely originated by island-arc magmatic processes. The "central acid massif," where the trondhjemite crops out, is Upper Jurassic (Mattinson et al., 1973 and 1980). For the "northeast volcanic complex," including the so-called "ophiolitic" pillowed basalts and associated cherts (Fig. 5), the chemistry of the primary clinopyroxenes from the lavas is clearly consonant with an island-arc magmatism (Le Guen de Kerneizon et al., 1979). The radiolarian cherts indicate the Early Cretaceous (Hauterivian–Barremian; Bouysse, Schmidt-Effing, and Westercamp, 1983). The low-lying island of Barbuda is exclusively composed of Quaternary limestones (Martin-Kaye, 1969; A. Mascle, personal communication, 1982). Its igneous basement is unknown, but Eocene and Oligocene volcanics might also be missing, as at la Désirade. For Sombrero, closer to the outer arc, the situation is not clear. This islet is made of Pliocene–Quaternary reefal limestones (P. Andreieff, personal communication, 1982).

An outstanding feature, to the north of Guadeloupe, is the wide extension of the two insular shelves of Antigua-Barbuda (4000 km^2) and of Anguilla–St. Barth (4500 km^2).

Inner Arc

In the volcanically active inner arc north of Martinique, only Pliocene–Quaternary volcanic formations

Figure 5. La Désirade Island (Guadeloupe archipelago), Pointe Mansenilier, northeastern coast. (Radiolarian cherts, near those at the base of the cliff [arrows], are Lower Cretaceous; they are overlain by pillowed basalts. This section belongs to the "northeast volcanic complex" of the island igneous basement.)

crop out, except at St. Kitts where Baker (1969, 1981) claims a 7.5 ±2Ma date and at les Saintes where a maximum age of 6.2 Ma was supplied by Javet and Alsac (1974)—both late Miocene dates. For other islands, scarce K-Ar determinations (Westercamp and Mervoyer, 1976; Briden et al., 1979) give values of 3.5 and 4.4 Ma for the oldest ages in Basse-Terre of Gaudeloupe and in Montserrat, respectively, and only two dates in Dominica (1.1 and 1.8 Ma).

The shallow terraces of the inner arc have a more reduced size than those of the outer arc. But where volcanic activity is long extinct, as at les Saintes (2.8 Ma ago—Javet and Alsac, 1974) and Redonda (1.5 Ma ago—Baubron et al., 1979), the submerged platforms have a significant extension with respect to the emerged areas. The small (less than 2km^2) but high (300 m) rocky islet of Redonda (Fig. 6) is a basaltic monogenetic volcano of the basal Pleistocene. It has pierced through the sedimentary terrace capping an older volcanic substratum. Its highly basic character is a rather uncommon feature in the Lesser Antilles and is probably related to a major transverse fault (Baubron et al., 1979). Nearby and to the southwest of Redonda, the Havers shoal is a guyot where lower Pliocene tuffitic limestones and an upper Pleistocene quartz-dacite crop out (Andreieff et al., 1979).

The inner arc terminates at the Luymes Bank, to the north of Saba Island (Bouysse et al., 1981). It is a small and elongated shoal made of a volcanic ridge capped with Pliocene–Quaternary sedimentary strata (Fig. 7). Dredge hauls on its western flank recovered porphyritic andesites 3.6 Ma old (middle Pliocene). This age and the morphology of the Bank suggest that volcanic activity may have ended before the Pleistocene, so that the Island of Saba is presently the northernmost active center of the inner arc, although no historic eruptions have been recorded there.

Evidence for the existence of an older basement beneath the upper Neogene inner-arc buildup are middle Eocene neritic limestone boulders found in volcanic ejecta in the south part of Nevis (Hutton, 1968).

Intra-Arc Depression

In the northern half of the archipelago, between the outer and inner arcs, an intra-arc trough, named Kalinago depression (Bouysse, 1979), stretches from the north of Guadeloupe to the Anegada Passage (Fig. 1). The trough is narrow (20–50 km wide), about 250 km long, and ranges in depth from about 600 to 2000 m at its north end. Two transverse swells, located between Redonda and Antigua, and between St. Eustatius and the southern tip of Anguilla–St. Barth shelf, subdivide this depression into three parts (Fig. 10). The maximum sedimentary infilling is not known (more than 2 km?), but the post-middle Miocene sediments are less than 1 km thick except, locally, to the north of Guadeloupe and at the northern end of the trough (Bouysse and Guennoc, 1983).

The structure of this depression was probably initiated, at least with its gross characteristics, by the jump

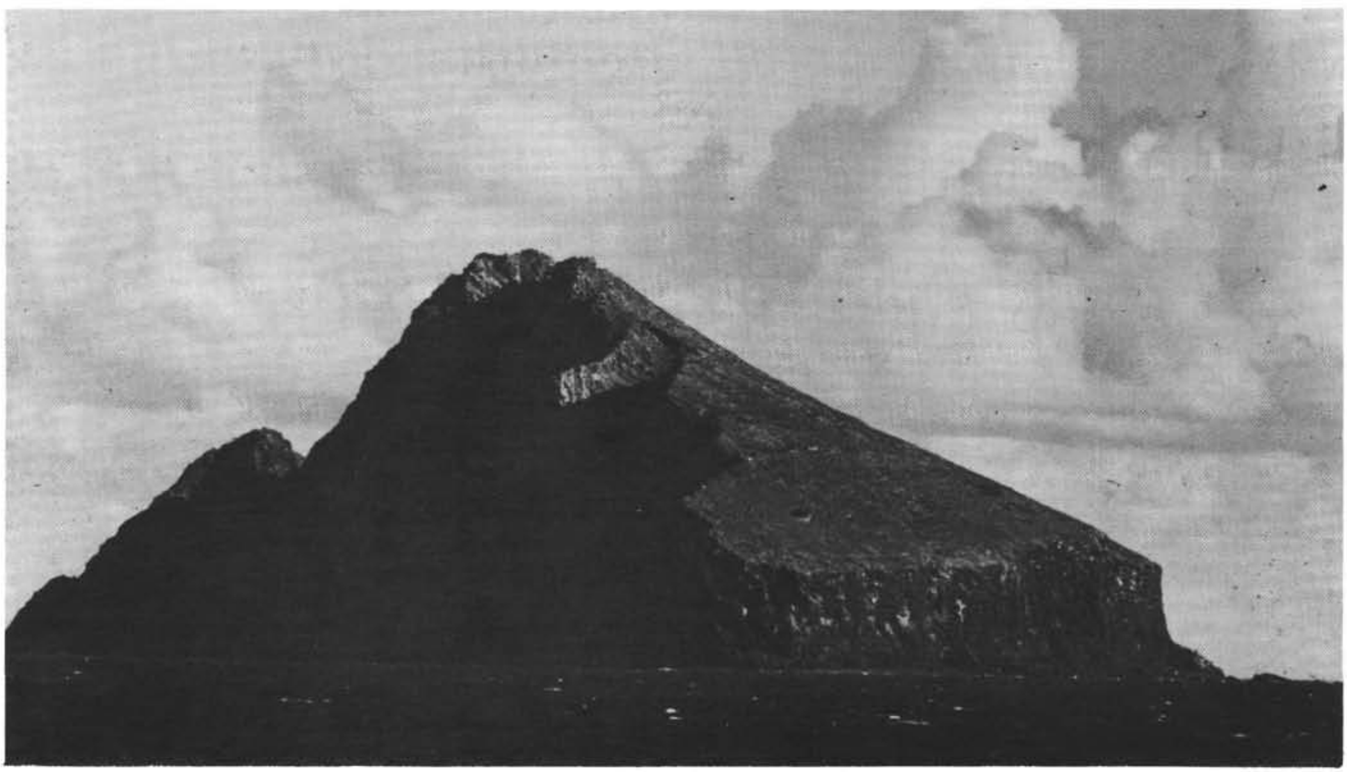

Figure 6. Redonda islet (inner arc, recent volcanoes) with west-northwest facing cliffs. (This half conical, 300-m-high, monogenetic volcano has been extinct since about 1.5 Ma.)

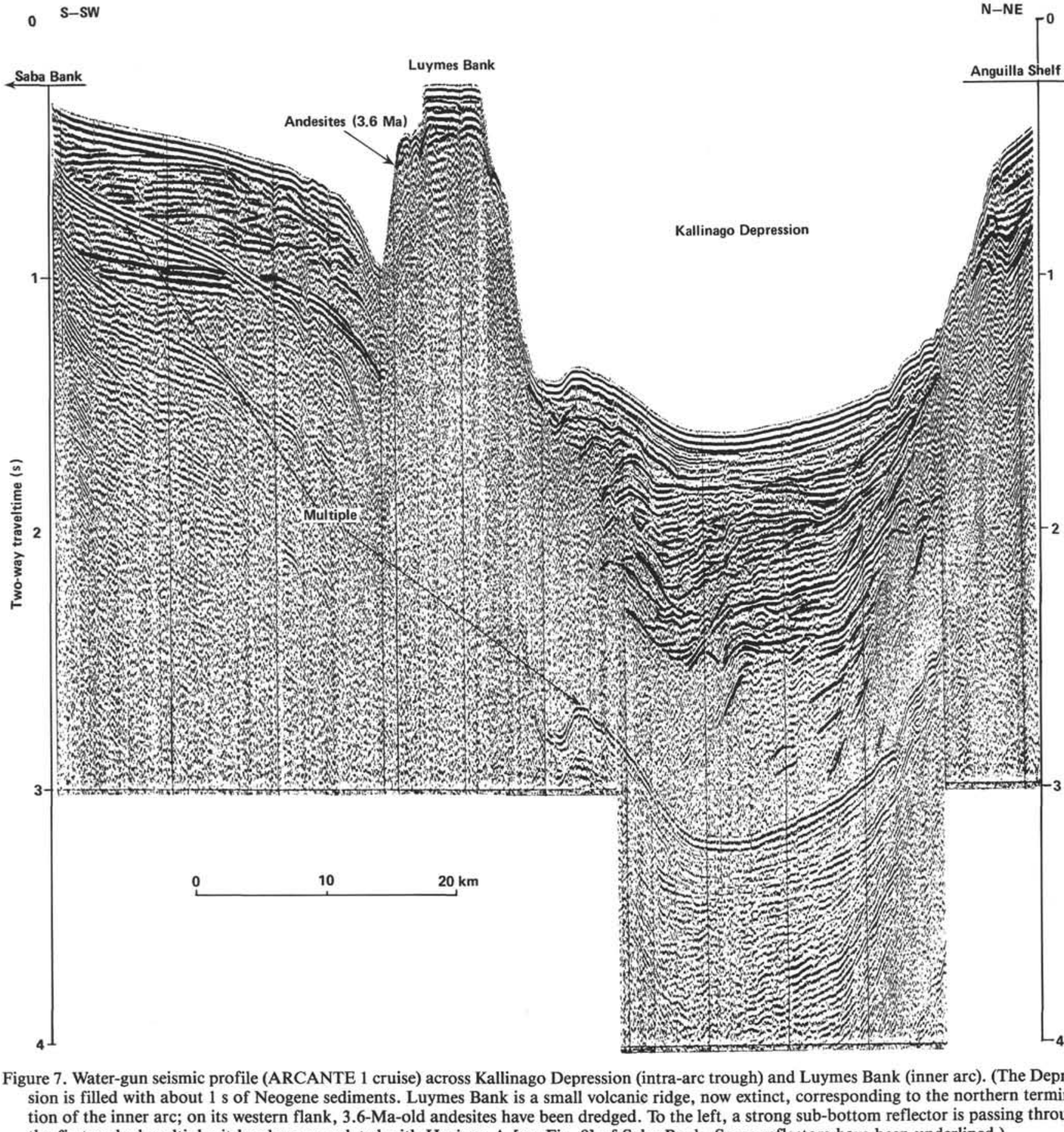

Figure 7. Water-gun seismic profile (ARCANTE 1 cruise) across Kallinago Depression (intra-arc trough) and Luymes Bank (inner arc). (The Depression is filled with about 1 s of Neogene sediments. Luymes Bank is a small volcanic ridge, now extinct, corresponding to the northern termination of the inner arc; on its western flank, 3.6-Ma-old andesites have been dredged. To the left, a strong sub-bottom reflector is passing through the first seabed multiple; it has been correlated with Horizon A [see Fig. 9] of Saba Bank. Some reflectors have been underlined.)

of the volcanic line from the outer to the inner arc. This event occurred in the Miocene and triggered the buildup of a western volcanic ridge. Fink (1972) suggested that the morphological gap between these two arcs could have been induced by extensional rifting related to a back-arc spreading, as demonstrated by Karig (1971) for the western Pacific area. This interpretation seems very unlikely, because the volcanic line jumped westward, away from the trench, and not toward the trench, as required by the splitting process inferred from areas where back-arc spreading is well documented.

Northeastern Flanks

Between Guadeloupe and Sombrero, the eastern flanks of the Lesser Antilles Ridge have steep slopes (Figs. 1 and 3). They are made of a succession of spurs and V-shaped, flat-bottomed, reentrant valleys: Désirade, Antigua, St. Barth, and Anguilla sea troughs. The Désirade escarpment (Fig. 8), stretching along some 70 km in an east-northeast direction, north and parallel to la Désirade Island, is one of the most impressive physiographic features of the world: locally it drops 4700 m, over a horizontal distance of 9 km (more than 27° declivity).

The Karukera Spur, striking parallel to the arc ridge axis, is perpendicular to the Désirade escarpment. It constitutes the easternmost part of the Lesser Antilles Ridge. It culminates at the Flandre Bank (northeast of la Désirade), whose Pliocene-Quaternary cover is underlain by "greenstones" resembling and probably structurally linked to la Désirade igneous basement. The axis of the spur deepens stepwise to the south. I feel that the Karukera Spur is the southernmost extension of a pre-Eocene basement that has not been obliterated here, as it was at

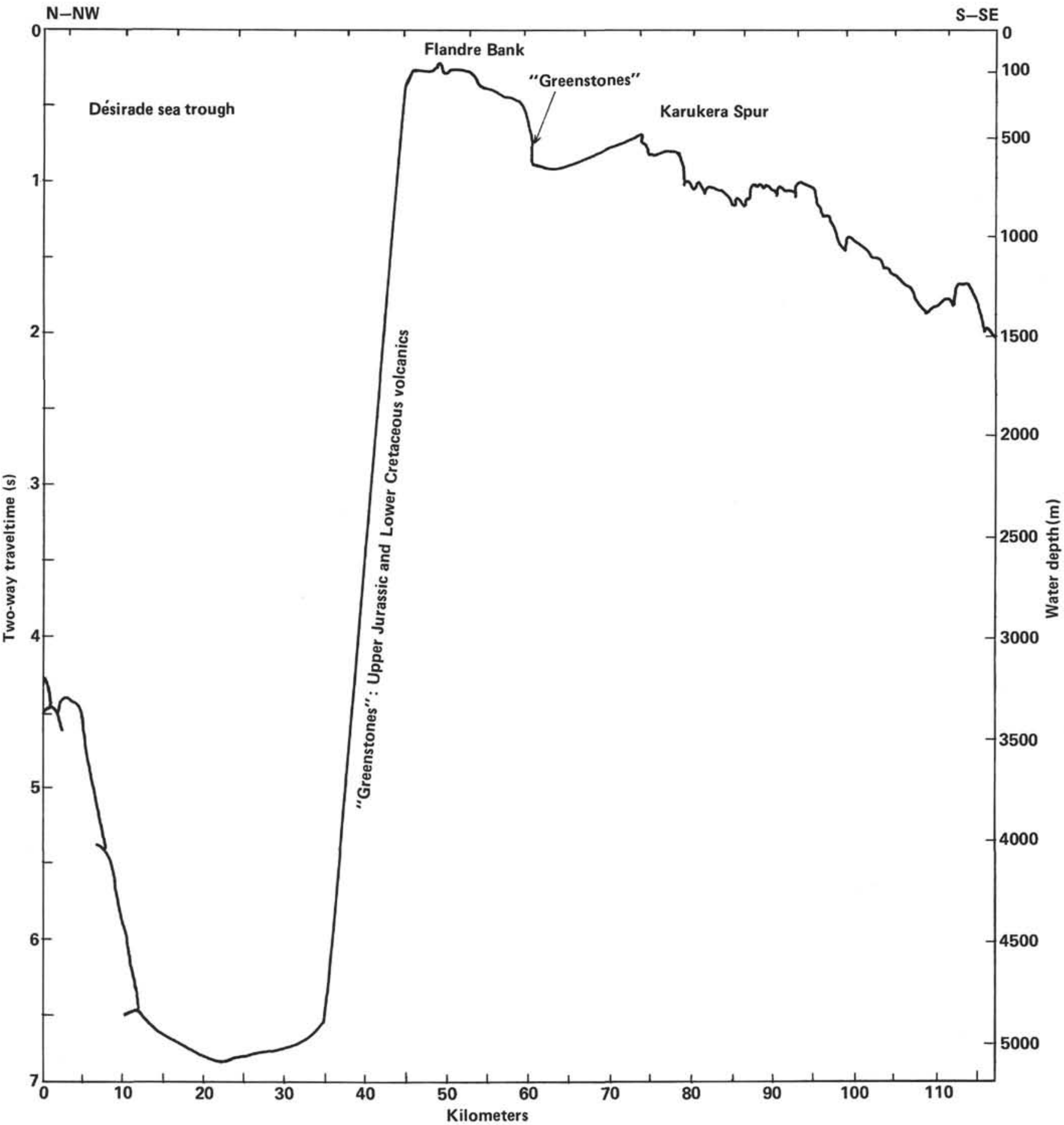

Figure 8. The Désirade escarpment, one of the steepest submarine slopes of the world. (Note the regular drop of almost 5 km. "Greenstones" from the la Désirade Island Mesozoic igneous basement crop out all along the escarpment. Flandre Bank is the easternmost shoal of the Guadeloupe area. The morphology of Karukera Spur is rugged.)

la Désirade, by the subsequent phases of the Cenozoic island arc magmatism.

On the slopes of these northeastern flanks, the post-middle Miocene deposits are poorly represented; hence, older formations are exposed (Fig. 10): Upper Jurassic and Lower Cretaceous epimetamorphosed igneous rocks along the Désirade escarpment (Fig. 8) (Andreieff et al., 1979; Bouysse, Schmidt-Effing, and Westercamp, 1983); Upper Cretaceous fossiliferous volcanic tuffs eastward of Antigua and Barbuda and to the north and northeast of Anguilla (Fox and Heezen, 1975); Paleocene–Eocene neritic deposits to the north of Anguilla (Fox and Heezen, 1975); and lower Eocene and middle and upper Oligocene limestones east of Grande-Terre and southeast of Barbuda (Andreieff et al., 1979). On the Falmouth Spur (Fig. 3), extending between the Désirade and Antigua seatroughs, we have dredged a quartz–diorite that shows some similarities to the trondhjemite of la Désirade Island. Unfortunately, no significant radiogenic age could be obtained.

Northwestern Flanks

Contrasting with the northeast (Atlantic) slopes, the northwest (Caribbean) flanks are draped by a rather thick overburden of post-middle Miocene sediments (Fig. 9) (Bouysse and Guennoc, 1983). No formations older than Pliocene have been dredged to the west of the inner arc (see Andreieff et al., 1979). Recently, some Quaternary, but now extinct, submarine volcanic peaks have been discovered and/or sampled off Martinique, Basse-Terre of Guadeloupe (Anonymous, 1981; Bouysse, unpublished data: ARCANTE 1980 and 1981 cruises), and off Redonda platform (Havers Shoal, see earlier discussion).

The Saba Bank, a wide (2100 km^2) and shallow platform (depth range: 20–40 km), is located west of the northern termination of the inner arc. An exploratory well (Fig. 1), drilled in 1977 by Marathon Oil Co., supplied data of upmost importance concerning the geology of the area[4] (Fig. 9). After having drilled a 2858-m-thick Cenozoic sedimentary cover, the well penetrated an additional 119 m into porphyritic andesite, whose radiometric (K-Ar) age is 64.5 ± 3.7 Ma, near the boundary between Paleogene and Upper Cretaceous. Marathon Oil reports that "the strongly porphyritic character could mean that the rock [andesite] was a near-surface intrusion . . . and/or part of a volcanic feeder system." The base of the igneous formation was not reached, but multichannel seismic surveys strongly suggest the presence of an extensive sedimentary section (probably Upper Cretaceous) beneath the volcanic unit. This sedimentary section could extend to a depth of some 4100 m below sea level. Hence, the volcanic formation did not originate as oceanic crust but was related to a regional magmatic pulse, as evidenced by nearby St. Croix Island (U.S. Virgin Islands, see Fig. 1) situated in the Anegada Passage and where the emplacement of plutonic intrusions occurred between 64 and 74 Ma (Speed et al., 1979). Therefore, the Saba Bank appears to contain rocks of an older island arc cycle, predating the incipience (in the Eocene) of the outer volcanic arc of the Lesser Antilles. The sedimentary blanket resting unconformably on the volcanic substratum contains carbonate and clastic sequences, with some pyroclastic intercalations of upper Eocene or Oligocene to lower Miocene. The nearest micropaleontological control, made some 100 m above the top of the andesite, indicates lower middle Eocene (Nemec, in press).

[4] Unpublished information transmitted in 1979 by Mr. Clark Gomes Casseres, Saba Bank Resources N. V., Curaçao. (See: Andreieff et al., 1979; Bouysse, 1979; Bouysse, Andreieff, and Westercamp, in press; Bouysse and Guennoc, 1983; Nemec, in press.)

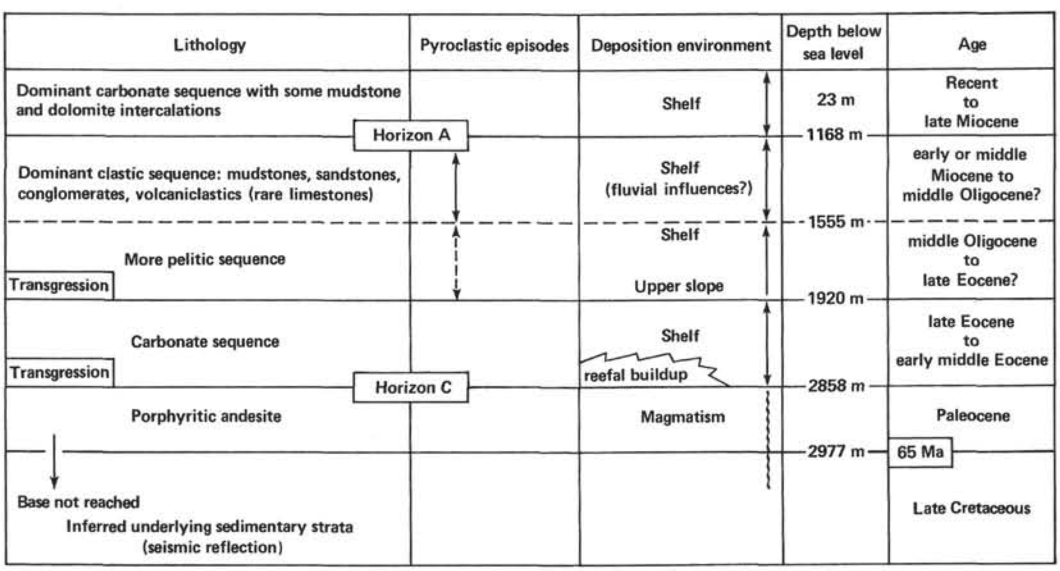

Figure 9. Summary of exploratory Well SB1 drilled on Saba Bank by Marathon Oil Co. in 1977. (Location: 17°17′22″N and 63°25′34″W; water depth: 23 m. Information kindly transmitted in 1979 by Mr. C. Gomes Casseres [Saba Bank Resources N.V., Curaçao].

Active Submarine Volcanism

In the *Catalogue of the Active Volcanoes of the World. Part XX: West Indies* (Robson and Tomblin, 1966), three active submarine volcanoes are noted: from south to north, the "Kick'em Jenny" (No. 16-16) north of Grenada, "Hodder's Volcano" (No. 16-13) west of St. Lucia, and a "submarine volcano near Marie-Galante" (No. 16-7).

In reality the Kick'em Jenny is the only submarine volcanic edifice in activity in the Lesser Antilles. It is a volcanic cone, built-up on the western slope of the South Grenadines Bank, and made of amphibole-bearing basalts (Sigurdsson and Sheperd, 1974). The first recorded eruption occurred in 1939 and, up to now (late 1982), 8 other presumed outbursts (1943 to 1977) have taken place; only 2 of them have been observed directly on the surface, in 1939 and 1974. The former crater, still extant in 1972, disappeared after the last 1977 outburst. The volcano is growing regularly and its top is now 160 m below sealevel (Sigurdsson and Sparks, 1979; Bouysse, unpublished data; ARCANTE 3 cruise, 1981).

Thanks to a Seabeam (multibeam echo-sounder computerized system) survey, carried out in December 1980 (ARCANTE 2 cruise), it can be asserted that the Hodder volcano does not exist. Its reported existence was based on two discolored seawater patches observed on 9 May 1902 by Major Hodder west of Castries, St. Lucia (Anderson and Flett, 1903). At the site of this event, no volcanic structure is to be observed. In my opinion, this phenomenon was due to recurrent faulting triggered by the dramatic volcano-seismic crisis of May 1902, which provoked the concomitant eruptions of Montagne Pelée in Martinique and of the Soufrière of St. Vincent (Bouysse, 1982; Bouysse and Sigurdsson, 1982).

The water column surging observed by Blainville in 1843 between Basse-Terre of Guadeloupe and Marie-Galante was in reality a submarine geyser spouting from the Colombie Bank (Bouysse, 1980). This seamount is not a volcano but a small submarine bank covered with a continuous sedimentary cover, at least 100 m thick. The water outburst is related to a series of violent earthquakes, which was one of the most destructive in the history of the Lesser Antilles (magnitude >8; Dorel, 1981).

General Organization of the Lesser Antilles and the Problem of the Aves Swell

By considering the general features and the morphological pattern of the Lesser Antilles (Fig. 10), I was led to conclude (Bouysse, 1979) that there is a sharp contrast between the northern and southern parts of the archipelago. One of the most striking observations is that the 1000-m isobath encircles two areas separated by a depression that runs between Martinique and Dominica. Each part corresponds to about half (425 km) of the total curvilinear length of the Lesser Antilles ridge. The northern area is three times larger than the southern one: 50,300 km^2 versus 16,600 km^2. This discrepancy reflects, to my mind, a major difference of origin between the northern and southern Lesser Antilles. The major axis of discontinuity runs, sublatitudinally, from the north of Aves Swell to the north of Grenada Basin, the south of Guadeloupe archipelago, and between the southern end of Puerto Rico Trench and the northern border of Barbados accretionary prism. This observation has been documented in a previous paper (Bouysse, 1979) independently of the assumption of Meyerhoff and Meyerhoff (1972), which it corroborates, postulating an inactive "Dominica fault."

In the nothern part of the Lesser Antilles, the wide space occupied by the island arc ridge coincides with the occurrence of a Mesozoic substratum reported, up to now, at Saba Bank, la Désirade, and along the north and northeast flanks of the Lesser Antilles. In the southern part, the volcanic basement is rather narrow, with the oldest island arc formations not older than lower or middle Eocene. For that reason, I think that the substratum of the northern Lesser Antilles belongs to an *ancient arc* related to the Greater Antilles, which were an active island arc during the Mesozoic (see, for example, Donnelly, 1975), whereas the southern part, from Dominica or Martinique, is younger and was initiated, as an island arc, only in the Eocene.

As stated by Case (1975), a pronounced high of the gravity field (see also Weeks et al., 1971; Bowin, 1976) extends from the Lesser Antilles through Los Testigos to Margarita, both islands being located on the Venezuelan continental shelf. The anomalies (Bouguer and isostatic anomalies) overlie metamorphosed Mesozoic rocks and ultramafics at Margarita. Nevertheless, I do not feel that this main geophysical feature necessarily implies the continuity of a Mesozoic basement from the Greater Antilles to the Venezuelan borderland, through the entire length of the Lesser Antilles. This positive geophysical axis might be ascribed to other causative processes: why not to a later (Eocene?) orogenic pulse? In any case, Nagle (1971) noted that it is very uncertain what happens to the Lesser Antilles structural trend south of Grenada. From isostatic anomaly data, it is evident that the Lesser Antilles are not in isostatic equilibrium, and considerable excess mass is present beneath the islands (Case, 1975).

Aves Swell (or Ridge) and Grenada Basin have raised debate regarding their relations with the Lesser Antilles island arc and, more generally, with the subduction process acting at the eastern boundary of the Caribbean Plate.

The morphological pattern of Aves Swell seems to indicate that its northern termination passes not far from Aves Islet (Fig. 1), and not at the junction of the Greater and the Lesser Antilles, as stated by Fox and Heezen (1975). The Aves Swell has long been an enigma to Caribbean geologists (Donnelly, 1975), but there is now a broad agreement considering this Ridge as an ancient island arc structure (Bunce et al., 1970; Weeks et al., 1971; Nagle, 1972; Keary, 1974 and 1976; Donnelly, 1975; Fox and Heezen, 1975; Keary et al., 1975; Westbrook, 1975; Biju-Duval et al., 1978; Clark et al., 1978). The Aves Swell, breaking the sea surface only at tiny Aves Island (made of Quaternary reefal limestones and sands), is aseismic (Weeks et al., 1971). It is formed by

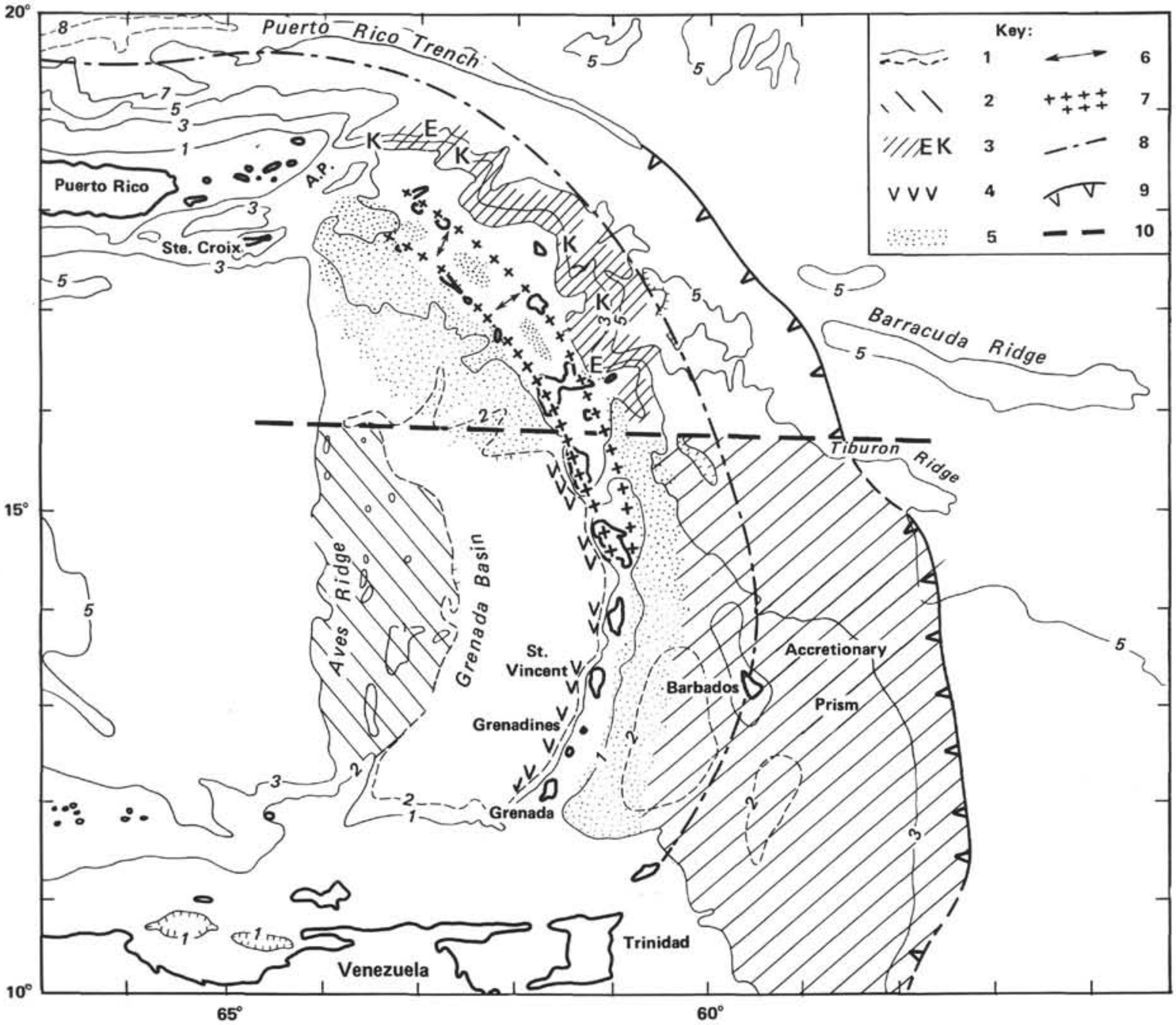

Figure 10. Schematic morphostructural setting showing the contrast between the northern and southern parts of the Lesser Antilles Ridge and neighboring areas. (Key: 1 = isobaths in kilometers; 2 = insular shelves and submarine banks; 3 = steep NE flanks with outcrop of Eocene (E) and Upper Cretaceous (K) formations; 4 = steep western slopes of the southern Lesser Antilles Ridge; 5 = thick recent sedimentation on the Ridge flanks; 6 = Kallinago transverse swells; 7 = inner and outer arcs axis; 8 = axis of negative gravity anomaly (after Bowin, 1976); 9 = overriding deformation front; and 10 = line separating northern and southern provinces.)

two flanking ridges of volcanic origin, enclosing a central, sediment filled, trough (Keary, 1976). Like the Lesser Antilles, the Aves Swell displays a short-wavelength, high-amplitude magnetic anomaly pattern typical of features created by magmatic processes (Keary et al., 1975; Clark et al., 1978). Dredging carried out on the slopes of protruding seamounts brought up sedimentary and volcanic rocks, and locally to the south (not far from the Venezuelan margin), granodiorites and diabases (Fox et al., 1971; Nagle, 1972; Fox and Heezen, 1975). Three samples of the granodioritic intrusions, somewhat weathered, provided K-Ar ages of respectively 78 and 89 Ma (lower Senonian), 65 and 67 Ma (upper limit of Senonian), and 57 and 58 Ma (upper Paleocene). The ages obtained for the diabase are 57 and 60 Ma. Fox and co-workers (1971, 1975) noted that the granitic rocks may represent the northern edge of the South American platform, but they suggested that the Aves Swell is underlain by granitic crust derived from oceanic material. Petrological studies (Walker et al., 1972) indicated that the granitic rocks are primitive and most likely from upper mantle. It is now established (Lameyre and Bowden, 1982) that granitoid series do not necessarily imply that they are related to continental crust processes; the granodiorites are the plutonic expression of island arc or active margin calc-alkaline suites. Furthermore, same types of rocks, but of the Oligocene, occur in the Lesser Antilles at St. Martin and St. Bartholomew (Christman, 1953; Nagle et al., 1976; Westercamp and Andreieff, in press). The other igneous rocks (effusive volcanics) have not been dated, but it seems that they are capped by post-Paleocene sedimentary formations (Nagle, 1972; Fox and Heezen, 1975). The Eocene to lower Miocene neritic limestones were followed by mid-Miocene to Holocene pelagic sedimentation. DSDP Hole 30 (Fig. 1) bottomed in middle Miocene, after 430 m of penetration in pelagic ooze (Shipboard Scientific Party, 1970); DSDP Hole 148 penetrated only

272 m of sediments represented by Pliocene–Quaternary pelagic ooze resting unconformably on volcanic sands containing lower Miocene, Paleocene, and Upper Cretaceous microfauna (Shipboard Scientific Party, 1973).

The K-Ar ages, if they are fully reliable, reflect magmatic activity from Late Cretaceous to Paleocene. The shallow-water environment, subsequent to the cessation of the volcanic activity, induced the formation of carbonate platforms built over the volcanic pedestals, such as later took place in the northeast part of the Lesser Antilles. The persistence, and probably the increase of the subsidence, led to a lowering of some 1000 m and to a complete submersion of the ridge (Aves Islet excepted). As for the Lesser Antilles arc, seismic refraction data show that the crust thickens notably beneath the Aves Swell (Tomblin, 1975). The crust is nearly in isostatic balance (slightly negative), judged from the values of isostatic anomalies (Keary, 1974; Case, 1975). Heat-flow measurements made along a section joining the Venezuelan Basin to the east of the Lesser Antilles agree with an island arc formation for the Aves Swell, with high values attributed to radiogenic sources concentrated during subduction in the past (Clark et al., 1978).

From the present data, it is difficult to determine the polarity of the former Wadati-Benioff zone beneath the Aves Swell. Donnelly (1975) seems to favor a subduction zone dipping from the west, although it is commonly assumed that the polarity was the same as that of the present Lesser Antilles (see, for example, Tomblin, 1975). I would be inclined to agree with a subducting slab plunging from the east of Aves Swell, mainly because of the arcuate nature of the eastern flank of the ridge.

It has been suggested that the Aves Swell may have represented a remnant arc (third arc) such as Karig (1971, 1972, 1974) has proposed for some of the West Pacific island arcs, and that, consequently, the Grenada Basin might have been created by an active marginal basin spreading. An alternate possibility is that the Grenada Basin was a trapped basin when the locus of the underthrusting of the Atlantic crust stepped back—probably in early Eocene—from the Aves Swell to its present position underneath the southern Lesser Antilles.

The first hypothesis was mentioned or supported by Donnelly (1975), Westbrook (1975), Shurbet (1976), Boynton et al. (1979), Uyeda and Kanamori (1979), and Uyeda (1982). The second hypothesis was favored by Freeland and Dietz (1971) and Keary (1976). For other authors, the present state of knowledge is inconclusive as to make a choice between the two possibilities (Nagle, 1972; Keary, 1974; Tomblin, 1975). If we use the terminology of Uyeda and Kanamori (1979), our alternative is between an inactivated and a trapped back-arc basin. If Aves Swell really split off from the Lesser Antilles Ridge, the onset of the westward relative drift should have occurred in late Paleocene or early Eocene. Consequently, the crust of Grenada Basin should not be older than Eocene. On the other hand, the back-arc spreading should have ceased a long time ago, because Grenada Basin is filled, as established earlier in this chapter, by several kilometers of sediments. Furthermore, there are no remnant higher heat-flow values inside this Basin (Clark et al., 1978) marking the trace of an older mid-basin accretionary volcanic ridge. Besides, numerous multichannel seismic profiles, run for oil exploration, did not reveal any concealed remnant topographic high of the basement underneath the sedimentary cover of the Grenada Basin (A. Mascle, personal communication, 1982). The Grenada Basin is also characterized by lack of organized magnetic anomalies (see for example, Keary et al., 1975). Although not generalized and less distinct than "normal" accreted oceanic crust, magnetic anomalies have been identified in a number of presently or formerly active marginal basins (Molnar and Atwater, 1978; Jurdy, 1979). But the most important point is the absence of a common origin for the igneous basement of the Aves Swell (pre-Eocene) and its supposed counterpart (as required by Karig's model), the southern half of the Lesser Antilles (post-Paleocene).

For all these reasons, I assume that the Grenada Basin is a trapped back-arc basin and, hence, that the Aves Swell is the predecessor of the southern Lesser Antilles.

GEODYNAMIC EVOLUTION

The data just presented allow us to propose a very schematic and speculative evolutionary scenario for the eastern border of the Caribbean Plate (Bouysse, 1979; Bouysse, Andreieff, and Westercamp, in press). The question of subduction polarity in the Greater Antilles during the Mesozoic and early Cenozoic remains elusive and is doubtless complex (see Donnelly, 1975). Nevertheless, in order to address it, and despite the fact that knowledge of the geodynamic evolution of the Greater Antilles is so incomplete, I have taken into account the suggestions of Mattson (Mattson, 1979; Mattson and Pessagno, 1979).

Stage 1 (Fig. 11A). Near the end of the Jurassic, the northern Antilles were connected to the Greater Antilles active island arc, with a subduction zone possible plunging toward the north. This stage may have lasted from Oxfordian (?) to Early Cretaceous (ca. 150 to ca. 110 Ma).

Stage 2 (Fig. 11B). This stage lasted from Aptian to the beginning of Eocene (ca. 110 to ca. 50 Ma). The subduction polarity flipped, dipping to the south in the Greater Antilles. However, in the western Greater Antilles, the subduction ended earlier (about 85 Ma, Santonian). Beyond the Guadeloupe archipelago, the Wadati-Benioff zone extended, possibly offset by a transform fault, to the south where it generated the Aves Ridge island arc. During this time, the buildup of the northern Lesser Antilles basement was completed, whereas to the south of Guadeloupe, oceanic crust was present east of the Aves Swell.

Stage 3 (Fig. 11C). From Eocene (early? or middle?) to late Oligocene (or possibly early Miocene), the former pattern no longer existed. Subduction ceased in the Greater Antilles and under Aves Swell. In the eastern Greater Antilles, the eastward retreat of the volcanic activity possibly overlapped the end of stage 2 and the beginning of stage 3. This is documented by the latest island arc eruptive activity, which occurred during early and middle Eocene in easternmost Cuba, east Jamaica,

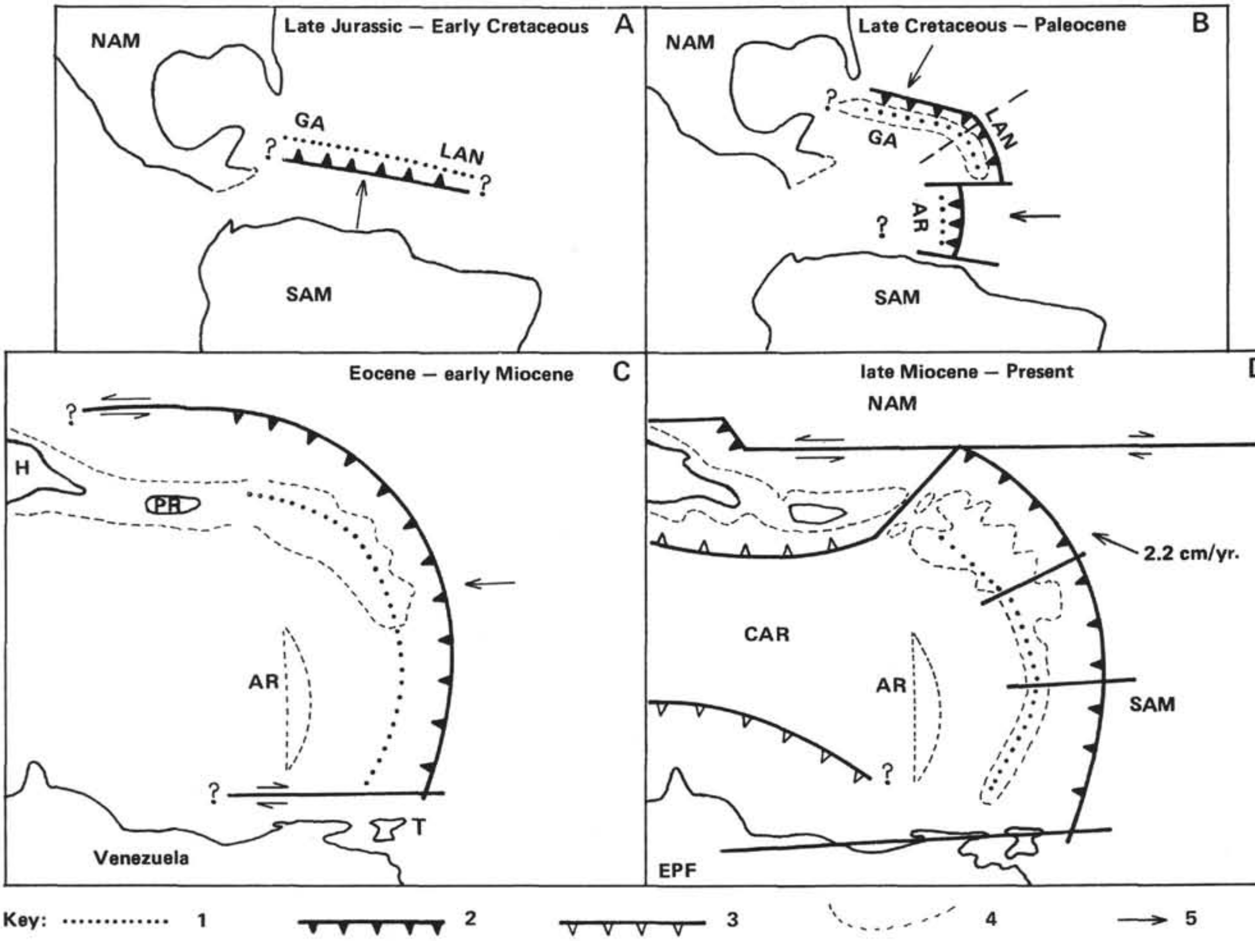

Figure 11. A–D. Evolutionary scenario proposed for the Lesser Antilles island arc from Mesozoic to Present discussed in the text. (Key: 1 = active volcanic line [note the Present tripartite segmentation of this line in Fig. 11D]; 2 = subduction zone; 3 = incipient subduction zone in Fig. 11D [Los Muertos Trench to the north; foot of Curaçao Ridge to the south; after Mascle et al., 1977]; 4 = island arc basement built up during the former stage(s); 5 = general orientation of the subduction vector. GA = Greater Antilles; LAN = northern Lesser Antilles; AR = Aves Ridge; CAR, NAM, and SAM = Caribbean, North America and South America plates (after Dorel, 1978); H = Hispaniola; P.R. = Puerto Rico; T = Trinidad; EPF = El Pilar fault.

Hispaniola, and Puerto Rico (Mattson and Pessagno, 1971; Cox et al, 1977). The ultimate stage of plutonic activity was recorded in Puerto Rico between 38 and 46 Ma (middle to late Eocene) and at the eastern tip of the Greater Antilles—in the Virgin Island where the Virgin Gorda batholith yielded an age of about 35 Ma (Cox et al., 1977), that is, the Eocene/Oligocene boundary. For the first time, subduction occurred along the entire length of the present Lesser Antilles. The eastward jump of the southern subduction zone generated the Grenada Basin by trapping the oceanic crust between Aves Ridge and the southern Lesser Antilles. During this third stage, the narrow Lesser Antilles outer arc was active and was superimposed, in the northern half, on the Mesozoic island arc basement.

This major rearrangement in the Caribbean, from the onset of the Eocene, might be linked with planetary plate reorganizations triggered by the Tethyan collisions occurring around 40 to 55 Ma (Rona and Richardson, 1978).

Stage 4 (Fig. 11D). From Grenada to St. Lucia, the former subduction process persisted unmodified from the Miocene until Present, which explains the narrowness of the related insular ridge. In the central part of the Lesser Antilles, the volcanic axis shifted progressively across a zone of moderate width, from the outer arc emplacement to its present position, producing *an intermediate arc*. This arc is particularly obvious in Martinique (Andreieff et al., 1976; Westercamp, 1977 and 1979; Gérard et al., 1981) and may have also occurred in the Guadeloupe archipelago, as suggested by the morphological setting. But it is still a matter of speculation because of the lack of sufficient deep drill holes through the sedimentary cover that masks the volcanic substratum of Grande-Terre of Guadeloupe.

In the northern third of the Lesser Antilles (see Fig. 12), the volcanic line jumped from the outer arc to the inner arc after a time gap of some 10 to 20 Ma (cessation of activity during the upper Oligocene or early Miocene; renewal during the late Miocene). This jump could have been initiated by the arrival, in the subduction zone, of the western extremity of the Barracuda Ridge. This segment is thought to be presently located under the Lesser Antilles, in the area of Antigua (Marlow

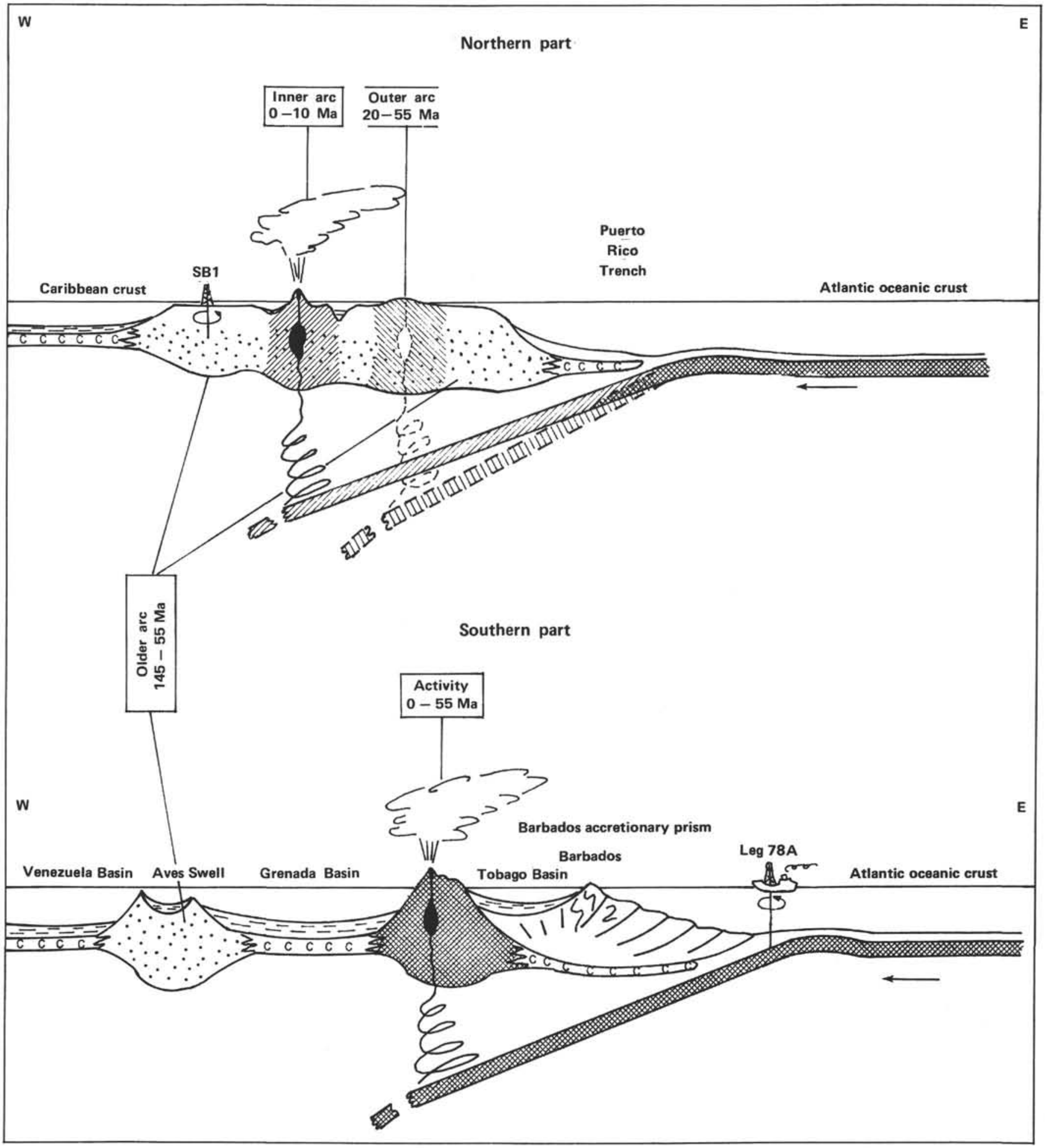

Figure 12. Interpretative schematic sections across the northern and southern Lesser Antilles Ridge. (In the northern part, the subduction process is assumed to have been interrupted between 20 and 10 Ma, possibly due to the arrival of the western tip of Barracuda Ridge in the subduction trench; consequently the volcanic activity jumped from the outer to the inner arc. Both arcs were superimposed on an older island arc basement related to the Greater Antilles and to Aves Swell. In the southern part, the subduction geometry remained unchanged from Eocene. SB1 = Saba Bank exploratory well. Caribbean crust is represented by C).

et al., 1974; Peter and Westbrook, 1976; McCann and Sykes, 1981). The Barracuda Ridge is an aseismic but not buoyant (Bowin, in press) oceanic ridge, associated with Atlantic fracture zones. Consequently, I suggest that this interaction was accommodated by a modification of the geometry of the subduction and, possibly, by a momentary interruption of the progression of the plunging slab. In any case, because of the density of the Ridge, the subduction resumed with a slightly modified angle of dip. When the tip of the slab again reached critical depth (about 100 km), volcanism was reactivated and initiated the present inner arc. Between Guadeloupe and Martinique, the effect on the progression of the subducting slab was attenuated and only a progressive shift of the volcanic line is observed, decreasing gradually to the south. South of Martinique, the subduction was not affected.

ABOUT THE MAGMATIC ACTIVITY OF THE LESSER ANTILLES ISLAND ARC

In this chapter, I shall not dwell on magmatic evolution and characterization of the Lesser Antilles. The interested reader is requested to refer to the general publications of Tomblin (1975), Gunn and Roobol (1976), Brown et al. (1977), Donnelly and Rogers (1978, 1980), Westercamp (1979), and Smith et al. (1980). I shall only briefly mention some general statements. According to mineralogical assemblages, petrochemistry, geochemistry, relative chronology and tectonic setting, five rock series are distinguished (Westercamp, 1979): (1) tholeiitic series (first stage, mainly submarine); (2) primary calc-alkaline series; (3) secondary calc-alkaline series; (4) olivine-rich subalkaline basalt series (occurring along transverse faults, probably bounding lithospheric blocks); and (5) alkaline series (exclusively located at the southern end of the archipelago—Grenadines and Grenada). It seems that the temporal succession of the first three series characterizes the complete evolution of an island arc section limited in time and space. For example, this succession occurred during the very short magmatic cycle (2 or 3 Ma, in the middle Eocene) of St. Barth, as demonstrated by Westercamp and Andreieff (in press). As stressed by Smith et al. (1980), piecing together a model of the magmatic variation and plate mechanism for the Lesser Antilles is still a highly speculative exercise, because for most islands the chemistry and ages of the different volcanic centers are not known.

If one considers the Lesser Antilles arc as a whole, one can see that it was volcanically active, without major interruptions, from Late Jurassic to Present. For this purpose I have plotted on Figure 13 all the evidence of magmatic activity known to us until now: morphological evidence (for recent volcanoes), K-Ar dates, fossiliferous intercalations in volcanic formations, pyroclastic tuffs (Christman, 1953, 1972; Westermann and Kiel, 1961; Robson and Tomblin, 1966; Baker, 1969, 1981; Martin-Kaye, 1969; Robinson and Jung, 1972; Mattinson et al., 1973, 1980; Javet and Alsac, 1974; Sigurdsson and Shepherd, 1974; Andreieff et al., 1976; Arculus, 1976; Nagle et al., 1976; Westercamp and Mervoyer, 1976; Andreieff et al., 1979; Baubron et al., 1979; Briden et al., 1979; Frost and Weiss, 1979; Andreieff et al., 1981; Jackson, 1980; Andreieff et al., in press; Bouysse, Schmidt-Effing, and Westercamp, 1983; Westercamp and Andreieff, in press; Bureau de Recherches Géologiques et Minières (BRGM) unpublished data). The tuffs, of course, do not necessarily indicate that the relevant eruption has taken place *in situ* but elsewhere in the neighborhood of their occurrence. This provisional inventory provides limited information because it only documents the existence of the studied outcrops of the Lesser Antilles Ridge (Saba Bank excepted). Nevertheless it might provide a guide to the investigation of volcanic ashes interspersed in cores from sites drilled during Leg 78A or perhaps to be drilled in the sedimentary basins of the eastern Caribbean.

In a recent paper, Sigurdsson et al. (1980) studied the problem of late Quarternary volcanogenic sedimentation in the Lesser Antilles arc and came to very interesting conclusions. For the last 10,000 yr., over 80% of the total volcanic bulk produced in the Lesser Antilles arc has been deposited as volcanogenic sediments in the adjacent marine basins. There is a high asymmetry in the distribution of volcanogenic sediments around the arc. Over 70% of the total volcanogenic sedimentation from the arc is supplied to the Grenada Basin in the form of sediment gravity flows. Conversely, ash-fall layers prevail in the Atlantic. This east-west opposition is due to the contrasting effects of prevailing high altitude wind direction (westerlies, above km altitude) and different submarine arc slope physiography (steep western slopes versus gentler and irregular eastern slopes) and ocean currents (westward prevailing current transportation).

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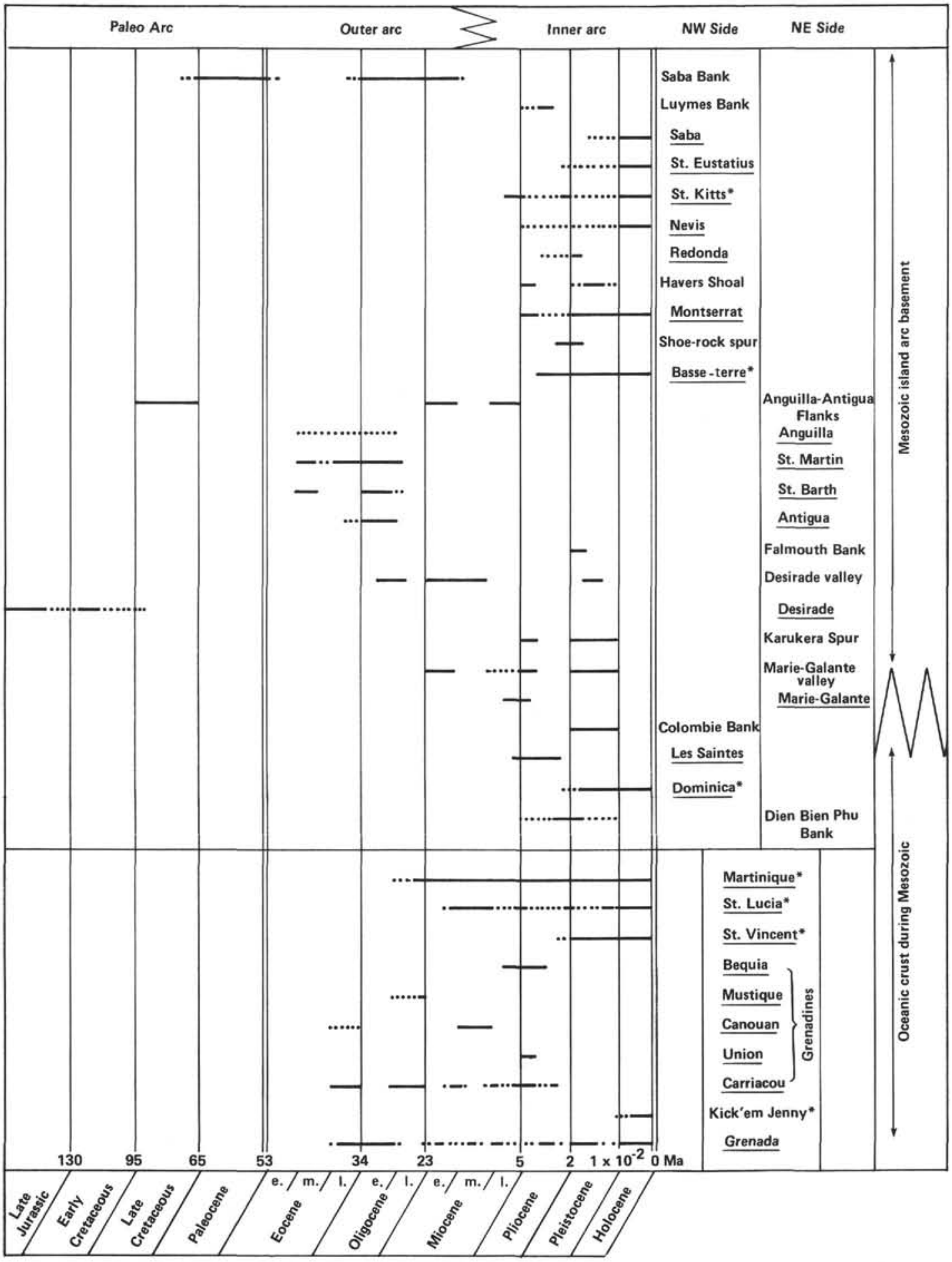

Figure 13. Direct evidence (effusive or intrusive rocks) or indirect evidence (tuffs) of volcanic activity in the Lesser Antilles area, between Late Jurassic and Present, from stratigraphic or radiometric-age data. (Dotted line = assumed activity; asterisk = historic recorded eruptions; submarine features are not italicized. For data sources, refer to the text. Geographic features are listed from north at the top of the figure to south at the bottom, except that the outer (NE side) and inner (NW side) portions of the arc to the north are listed separately.