Tectonic Evolution of St. Croix: Implications for Tectonics of the Northeastern Caribbean

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ABSTRACT

Today's Caribbean plate, consisting mainly or wholly of lithospheres of the Colombian and Venezuelan Basin, has migrated with a generally easterly component relative to the North American plate, but the duration and total displacement of such motion are unclear. These may range between 15 and 50 ma and 275 and 1400 km respectively. St. Croix and the eastern Greater Antilles are on a belt of transitional lithospheres that may have been tied mainly to either the North American plate or the Caribbean plate. Alternately, the belt may take up distributed plate boundary motion. Plate tectonics, therefore, provides few constraints on the kinship of St. Croix to nearby terranes.

The geologic evolution of St. Croix, on the other hand, permits or supports several ideas on present and past plate tectonics of the northeastern Caribbean: 1) the eastern Greater Antilles has probably undergone transtension since at least early Miocene time; the horizontal extensional component, NNW-SSE, caused the breakup of the Puerto Rico and Virgin Islands platforms, the Anegada Gap, and the present Puerto Rico Trench; 2) early Paleogene and/or late Cretaceous convergence affected the eastern Greater Antilles, probably due to a downgoing slab at the precursor to the present Puerto Rico Trench; and 3) convergence occurred on the southern wall of the eastern Greater Antilles in the Late Cretaceous, causing the buildup of the accretionary complex that is now the Cretaceous basement of St. Croix. The longitudinal positions of St. Croix with time, however, are still unknown.

INTRODUCTION

St. Croix occupies an important tectonic position in the Caribbean region, near the southern edge of the Greater Antillean ridge and its curve toward the south as the ridge becomes the Lesser Antilles. Moreover, it sits near the boundary between the Greater Antillean transitional lithosphere and the oceanic lithosphere of the Venezuelan Basin (Fig. 1). It is of fundamental interest to know where St. Croix has been geographically since the deposition of its oldest exposed rocks some 90-100 ma ago, as well as the plate boundary phenomena that caused much of St. Croix's geologic evolution. Unfortunately, the plate tectonics of the Caribbean region are so little constrained that it is difficult to assign paleogeographies and paleotectonics to a small terrane, such as the St. Croix platform.

On the other hand, the tectonic evolution of St. Croix provides conditions for models of the plate-tectonic history of the larger northeastern Caribbean. The main postulates coming from St. Croix bear mainly on Cenozoic extension in the northeastern Caribbean, and Paleogene and Cretaceous convergence. This paper addresses first what can be said about present and past plate tectonics of the Caribbean, with emphasis on the northeastern corner. It then applies interpretations of St. Croix's tectonic evolution to plate tectonics of the eastern Greater Antilles from Late Cretaceous to the present.

CARIBBEAN PLATE TECTONICS

The Caribbean region as a domain of related geologic evolution is bounded by the continents of North and South America, and oceanic lithospheres of the Pacific and Atlantic basins (Fig. 1). The region can be divided among three types of lithosphere — that is, crust ± upper mantle lid (Fig. 1) — each with a different tectonic history: 1) the continental cratons which have moved rigidly since the Precambrian; 2) oceanic lithospheres that were all or mostly formed at spreading ridges during Mesozoic and Cenozoic times; and 3) transitional lithosphere which generally has had a tectonic and/or magmatic origin in Mesozoic or Cenozoic times.

The oceanic lithospheres of the Colombian and Venezuelan Basins (Fig. 1) are particularly important because they compose much, if not all, of the modern Caribbean plate and because of the proximity of the Venezuelan Basin to St. Croix. Both basins have anomalously thick crust (about 12 km, Officer *et al.*, 1959; Edgar *et al.*, 1971) which is due to extensive basaltic magmatism of Late Cretaceous age (Edgar *et al.*, 1973). It is not clear whether such magmatism 1) represents emergence of magmatic bodies injected locally into pre-existing, sediment-covered lithosphere within the Caribbean, or 2) is derived from an earlier event in the

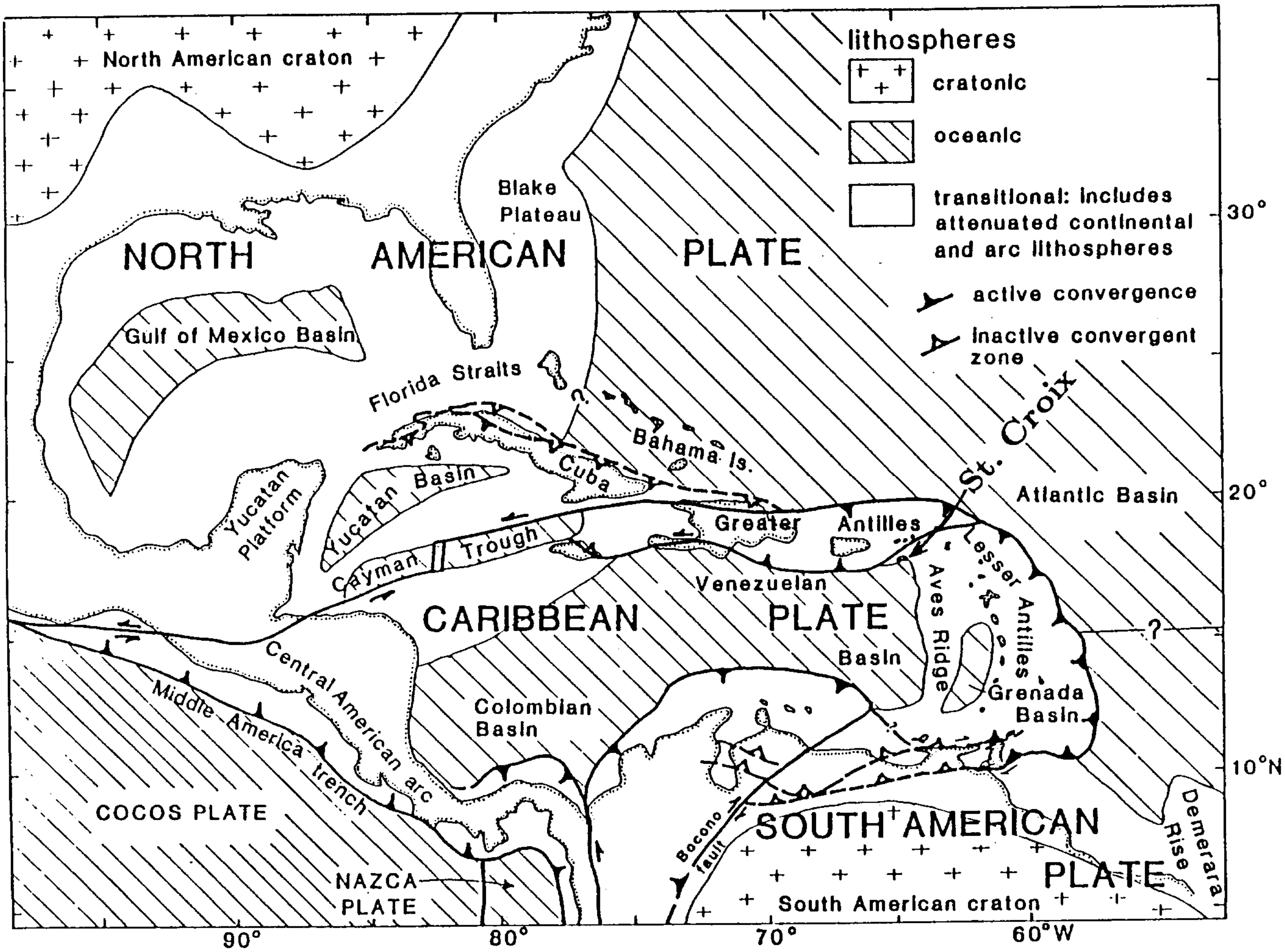

Figure 1. *The Caribbean region: geography and possible array of plates, zones of major, moden displacement (solid lines), and lithospheric types.*

Pacific and has moved into the Caribbean as an exotic terrane. None of the Caribbean oceanic lithospheres has magnetic anomalies that clearly reveal spreading histories or ages.

The transitional lithosphere includes continental fragments, stretched and diked continental crust of mainly passive margin origin, modern and ancient arc crusts, subduction zone complexes, and ophiolites. Many transitional lithospheres are probably composite, such as arc crust built above and cutting across an older oceanic or continental crust. Because St. Croix exposes transitional lithosphere, an objective of geologic and geophysical studies of St. Croix is to assess the history of plate-boundary tectonics and paleogeographic positions of this parcel of lithosphere.

The present Caribbean plate lies within the southern half of the Caribbean region and has motion relative to the North American, Cocos, and Nazca plates, and probably to the South American plate (Fig. 1). Definition of the modern Caribbean plate is difficult because it has no divergent boundary with active spreading except at the Cayman Trough (Fig. 1) and because its seismicity is irregularly distributed and diffuse (Sykes and Ewing, 1965 Molnar and Sykes, 1969; Kafka and Weidner, 1979; Stein *et al.*, 1982; and McCann and Sykes, 1984). The existence of Wadati-Benioff zones and active volcanism of island arc type in parts of Central America and the Lesser Antilles indicate that oceanic slabs of the Cocos and of the North American-South American plates subduct the Caribbean from the west and east, respectively.

At the Cayman Trough (Fig. 1), earthquake focal mechanisms and magnetic anomalies indicate active left-lateral, strike-slip faulting and the opening of a pullapart basin with a spreading ridge between the North American (NA) and Caribbean (Ca) plates. Faults at the Cayman Trough indicate that Ca-NA motion is about N80°E (Molnar and Sykes, 1969; Jordan, 1975; Stein *et al.*, 1988). The Quaternary rate, however, is known only to be between ≤ 15 and 30 mm/yr (Macdonald and Holcombe, 1978; Rosencrantz and Sclater, 1986; Stein *et* al., 1988). Most critical is the uncertainty over the rate and duration of spreading beginning in early or mid-Cenozoic, because it permits a huge range of possible total displacements of today's Caribbean plate - between 275 and 1400 km. If the total displacement of Ca relative to NA has been small, the Venezuelan Basin lithosphere and adjacent transitional lithospheres, including that of St. Croix, may be native to the Caribbean region. If the value is very large, however, the Venezuelan Basin lithosphere is probably exotic to the Caribbean region, and together with parts or all of the Greater Antilles, came out of the Pacific (Malfait and Dinkelman, 1972; Sykes *et* al., 1982; Pindell *et al.,* 1988).

Transitional lithosphere of the Greater Antilles, including that of St. Croix, is probably a composite of fragments or microplates, each of which is moving and/or has moved with respect to one another and to the lithospheres of the North American plate and the Venezuelan Basin (see below). It is a question, therefore, where such pieces originated, whether their histories are related, and whether their Cenozoic displacements are tied mainly to that of North America, the Venezuelan Basin, or neither. The St. Croix platform is one such fragment of the Greater Antilles.

The history of motions between the North American and South American plates is well-recorded in the development of the Atlantic basin (Klitgord and Schouten, 1986; Pindell *et al.,* 1988). This shows that the two cratons pulled steadily apart between the breakup of the Pangean supercontinent in the Jurassic (about 180 ma) and a time in the Late Cretaceous between about 120 and 84 ma (Fig. 2). Thereafter the two American plates have had only small relative motion (Fig. 2), including closure of 200-300 km.

Although the boundaries of the Caribbean region are thus understood, the evolution of lithospheres within the region is not, except to know that they were either formed in or entered the region within the past 175 ma. Options for such origin are: 1) formation by spreading and convergent boundary processes in place; 2) tectonic transport from Pacific and/or Atlantic realms of existing lithospheric fragments; and 3) some combination of these. Some lithosphere, such as the Gulf of Mexico Basin, almost certainly formed in place whereas the existence of rotation in lithospheres in the Caribbean region reflects nonlaminar movements between the diverging continents. Therefore, option 3 is perhaps most probable.

Rocks at the surface of St. Croix are no older than about 98 ma, and St. Croix's first tectonism was between about 70 and 87 ma (Speed *et al.,* 1979; Speed and Joyce, this vol.). Deeper parts of the St. Croix platform, however, could be much older. From what is known of St. Croix, its history may have begun shortly before or after the cessation of NA-SA divergence and during the span of time when the size (NW-SE length) of the region had become more or less constant (Fig. 2). The position of the St. Croix platform as a function of time is, however, completely unconstrained by plate tectonics; it may have evolved locally relative to North America or may have travelled large distances since the Late Cretaceous, coupled to or independent of the Venezuelan Basin lithosphere.

TECTONICS OF THE NORTHEASTERN CARIBBEAN

In the northeastern Caribbean, transitional lithosphere of the Greater Antilles and Lesser Antilles-Ayes Ridge lies between oceanic lithospheres of the North American and Caribbean plates (Figs. 1, 3) and changes trend as a bathymetric edifice by almost 90° at the northeastern corner of the Caribbean Sea (Figs. 1, 3). The existence of transitional lithospheres in both Antillean ridges is indicated by their large crustal thickness and low velocities relative to those of oceanic lithospheres (Fig. 4) and their Late Cretaceous and/or Cenozoic calcalkaline magmatism and deformation (Donnelly, 1966, 1985; Cox *et al.,* 1977; Perfit *et al*., 1980; Mattson, 1984; Donnelly and Rogers, 1980; Bouysse, 1988; Westercamp and Andreieff, 1983).

Plate boundaries - The present Caribbean-North American plate boundary occurs along and/or within the Antillean transitional lithospheres. The position of the plate boundary is reasonably well established in the northern Lesser Antilles (Fig. 3) by a WSW-dipping seismic zone that reaches about 110 km below the chain of active and late Neogene volcanoes (Fig. 3; Stein *et al.,* 1982; McCann and Sykes, 1984; Wadge and Shepherd, 1984). The trace of the boundary shown in Figure 3 is extrapolated to the updip end of the sloping seismic zone. This trace in fact lies below the asiesmic forearc of the Lesser Antilles whose deformation front is well to the east (Fig. 3). The direction and rate of Caribbean-North American plate motion at the Lesser Antillean boundary, however, are imprecisely known. Sykes *et al.,* (1982) used seismicity data of the dipping zone to compute values of N 65° E and 40 mm/yr. In contrast, motion determined with a Ca-Na pole located at the Cayman Trough gives values of ESE and 15 to 20 mm/yr in the northern Lesser Antilles (Jordan, 1975; Stein *et* al., 1988). The difference in the two values may result from 1) the difficulty in interpreting seismicity data for plate-boundary slip (Stein *et al.,* 1988), 2) the possibility that seismicity data give only the downdip component of the motion, and/or 3) the fact that the Caribbean may not be rigid but rather an assembly of microplates such that motion at the Cayman Trough cannot be extrapolated for local relative motions along the entire edge of the North American plate. Therefore, Ca-Na motions in the northern Lesser Antilles are known only to be EW± 25° at rates between roughly 15 and 40 mm/yr.

In the eastern Greater Antilles (Fig. 3), the plate-boundary zone is less well-defined by earthquake distribution and local geologic features, probably because of the existence of heterogeneous deformation throughout the entire ridge (Molnar and Sykes, 1969; Sykes *et al.,* 1982; Mann and Burke, 1984). Interpolating the plate motions between the Cayman Trough and northern Lesser

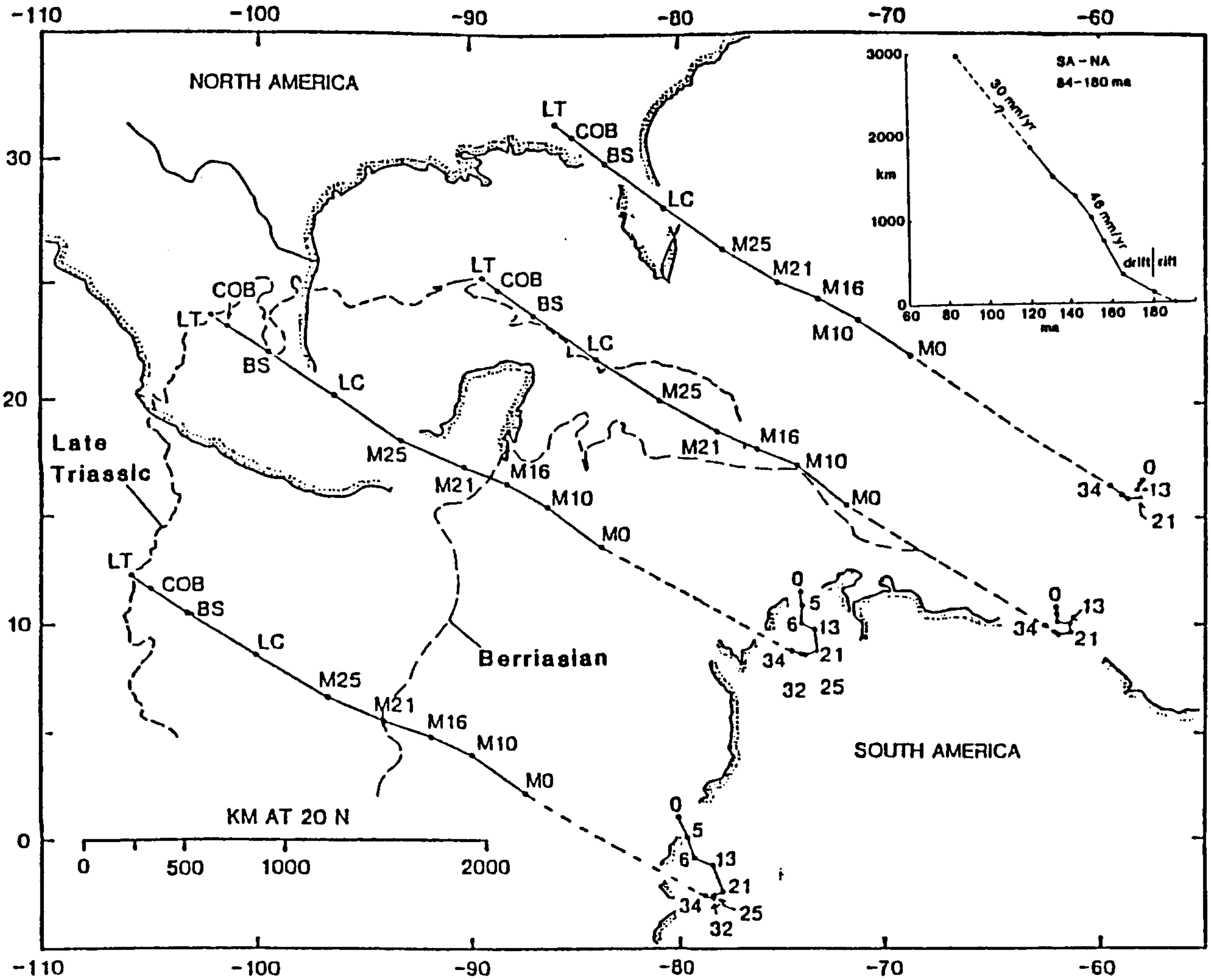

Figure 2. *Displacement-time paths of four points attached to the South American plate relative to North American plate from the breakup of Pangea to the present (calculated by Pindell et al., 1988). Lt: late Triassic, COB: onset of central Atlantic drifting, BS: Blake Spur anomaly, LC: late Callovian (170 ma), M: pre-quiet interval magnetic anomalies, M21: Berrasian, MO: early Aptian (119 ma), LA: late Albian (Linear interpolation), numbers: post quiet interval magnetic anomalies, 34: Cenomanian (84 ma), 25: late Paleocene (50 ma).*

Antilles implies generally EW, left-lateral strike slip for the Greater Antilles, and this could be either concentrated at a single fault or distributed more broadly across the ridge. The epicenter distributions of teleseisms (Fig. 5a) and local shocks (Fig. 5b) are irregular and imply, by clustering, the existence of sites of active deformation, but not of long EW strike-slip faults. Hypocenters of network data (which have better depth control) have been interpreted as indicating the top of a south-dipping slab, presumably North American oceanic lithosphere, that reaches 140 km below St. Croix (Fig. 5b; Frankel *et al*., 1980; McCann and Sykes, 1984). Neither the epicenter distribution nor the updip end of the proposed slab has an evident association with major structures of the eastern Greater Antilles, namely the Puerto Rico Trench and the Anegada Gap (Figs. 3, 5).

At the center of the problem is the uncertainty over how the North American plate adjusts its subsurface configuration around the northeastern corner of the Caribbean plate (or plate assembly) from a west-dipping slab below the northern Lesser Antilles to a transform boundary in the Cayman Trough. One principal model for this is a hinge (Molnar and Sykes, 1969) where the east-verging thrust of the Lesser Antilles ends to the north at a hypothetical EW-striking transform with hinged motion (rotational slip) in a region of the mutual fault tips. A second model is that the North American slab bends in continuity from the Lesser Antilles, north around the

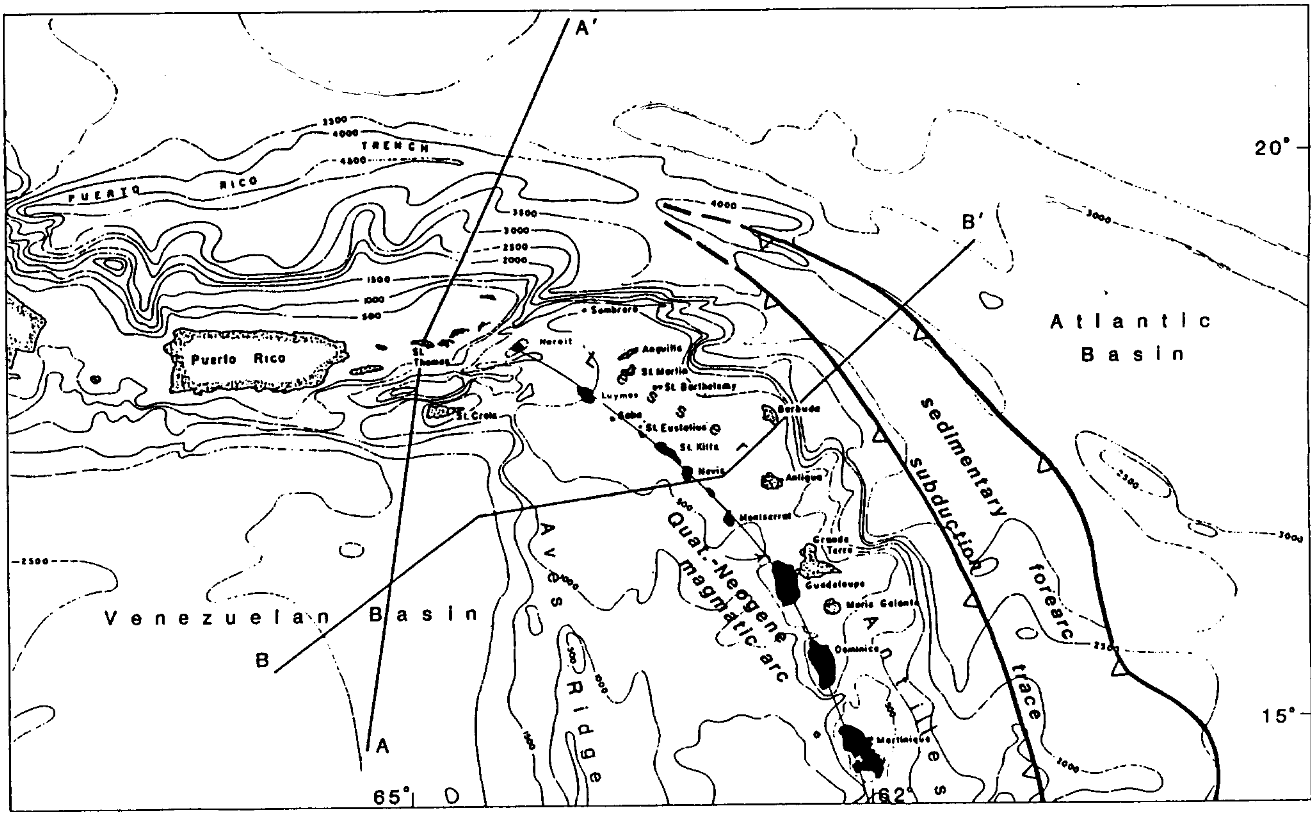

Figure 3. Regional features of the northeastern Caribbean. Bathymetric contours in meters (from Pinet et al., 1985). Black spots are volcanoes of the Neogene Magmatic arc. Traces AA' and BB' are cross sections of Figure 4.

northeastern corner of the Caribbean, and shallows irregularly westward through the Greater Antilles toward the Cayman Trough. The second model implies that the top of the dipping slab has strike-slip motion in the Greater Antilles. The continuity of structural contours of the top of the downgoing siesmic zone around the bend (Fig. 5b) supports the second model (McCann and Sykes, 1984).

Tectonic features - The principal active or Cenozoic tectonic features of the eastern Greater Antilles are the Puerto Rico Trench, Muertos Trough, Anegada Gap, onland faults that strike WNW in Puerto Rico, basins with subsidence as much as 10 km, and the Virgin Island and St. Croix platforms (Fig. 6). The Puerto Rico Trench, up to 8 km deep on the north side of the eastern Greater Antilles, is an atypical deep-sea trench because it has no shallow seismicity (it is north of such activity) and there is no associated arc volcanism. Eastward, the Puerto Rico Trench is physiographically continuous with the lithospheric plate boundary of the Lesser Antilles (Fig. 3). The Trench, or its precursory structure, almost certainly was a plate boundary in the past (before early Miocene) because the crustal structure and lithic columns differ substantially across it (Fig. 4) (Officer *et al.,* 1959; Bunce, 1966; Perfit *et al.,* 1980). It is contested, however, whether the Trench is currently a principal locus of Ca-NA relative movements and what the orientation of such motions might be. The existence of oblique convergence below the Trench's southern wall is suggested by McCann and Sykes (1984) based on the deformed and presumably accreted but undated forearc sediments fronting the southern wall, and from the apparent continuity of the Trench floor and the deformed sediment belt with the subduction trace of the Lesser Antilles (Fig. 3). In contrast, the structure of the present Trench floor (i.e. broad, flat, bounded by steep, normal-faulted walls, and covered by 1-2 km of undeformed, onlapping pelagic sediments, Perfit *et al.,* 1980) indicates it is a graben of extensional origin. Moreover, the strata on the slope between Puerto Rico and the Puerto Rico Trench show northward increasing subsidence, as much as 3.5 km since the early Miocene (Fox and Heezen, 1975). Such subsidence is most readily interpreted as being due to rotation (roll-over) of the hanging wall of a south-dipping, low-angle, normal or oblique-normal fault. The normal-fault hypothesis jointly explains the graben form of the Puerto Rico Trench, subsidence of the southern slope, and lack of convergence, i.e. typical seismicity and volcanism. The implications of extension across the Puerto Rico Trench for at least Neogene and Quaternary times are that its motion is transtensional if a strike-slip component exists, and that an ESE direction of Ca-NA motion is probable in the eastern Greater Antilles and northern Lesser Antilles. It is still a question, however, whether

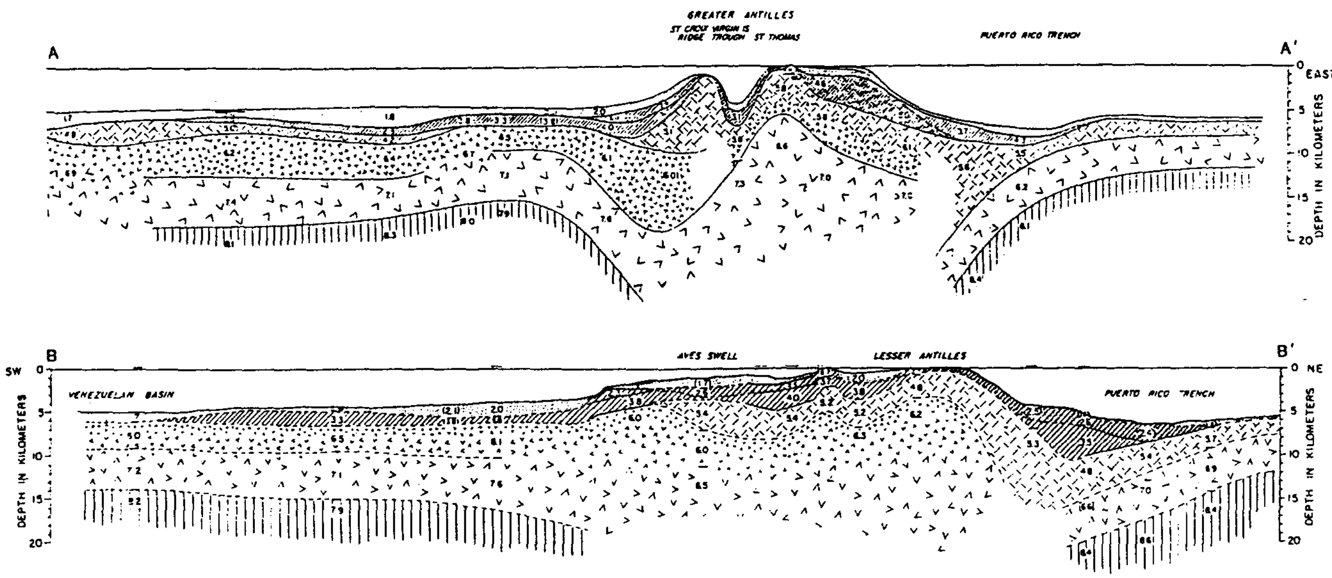

Figure 4. *Refractor sections AA' and BB' located in Figure 3. Numbers are p-wave velocities in lon/sec., (from Officer et al., 1959).*

the south-dipping seismic zone interpreted below the Puerto Rico-Virgin Islands (PR-VI) platform by McCann and Sykes (1984) is 1) convergent, or 2) divergent and a deep extension of the postulated low-angle normal fault. It is reasonable to suppose that before Miocene time, the south-dipping zone was convergent and that later, the downdip component has been normal, reflecting plate-tectonic changes. Moreover, a downgoing slab below the PR-VI platform may be detached from the NA plate at the modem Puerto Rico Trench.

The Muertos Trough fronts the southern margin of the Greater Antilles and can be traced as a bathymetric depression south of Puerto Rico nearly to the longitude of St. Croix (Fig. 6). It is coupled with an accretionary forearc which lies above the downgoing Venezuelan Basin lithosphere (Fig. 4; Garrison *et al.,* 1972; Ladd and Watkins, 1978; Ladd *et al.,* 1981). The thinness or lack of undeformed sediment cover on the Muertos forearc suggests that subduction is active or only recently inactive. In contrast, the lack of associated seismicity implies that subduction is inactive or so slow as to be taken up by creep. The lack of associated volcanism implies that the slab does not penetrate deeply. The structure and extent of the Muertos subduction zone are obscure east of St. Croix. It appears, therefore, that oceanic slabs have extended below the eastern Greater Antilles from both the north and south in the Cenozoic, but it is not clear whether they converged simultaneously or not, and whether any convergence occurs currently.

The Anegada Gap is a sinuous trough of varied amplitude that crosses the Antilles from approximately the eastern tip of the deep Puerto Rico Trench to basins between Puerto Rico and St. Croix (Figs. 3, 6). Its northern reach has been commonly taken as the divide between the Greater and Lesser Antilles, a postulate recently given support by the discovery of post-Neogene submarine volcanoes of the Lesser Antilles chain as far north as the brink of the Anegada Gap (Bouysse, 1988). It occupies a seismic gap between the Lesser Antilles Benioff zone and the irregular epicentral distribution of the Greater Antilles (Fig. 5): Whether this means the Anegada Gap is inactive and storing elastic strain, or is creeping is uncertain (Fig. 5). Nevertheless its morphology implies recent faulting. Motions across the Anegada Gap are not clear; most authors assume it is a left-lateral strike-slip fault zone from plate-tectonic reasoning (Donnelly, 1966; Garrison *et al.,* 1972) whereas Stephan *et al.* (1985) believe it to be right lateral. If the Ca-NA velocity direction is ESE, left-oblique normal faulting is predicted for the Anegada Gap. This is consistent with recent stratigraphic data on St. Croix for the Tertiary (Gill *et al.,* this volume).

Modern platforms or banks in the northeastern Caribbean include the Puerto Rico-Virgin Islands (PR-VI), St. Croix, and Anguilla platforms, and Saba Bank (Figs. 3, 6). The central regions of the PR-VI, St. Croix, and Anguilla platforms have all undergone tectonic unroofing of modest amplitude, perhaps up to a few kilometers. The Saba Bank has not been unroofed. The platforms are separated by steep-walled bathymetric basins or troughs that are almost certainly fault-bounded, with one exception. The Kallinagro Trough (Fig. 6) which is between the active volcanic chain and the Anguilla Bank to the east, seems to be a subsiding forearc trough without faults according to seismic sections of Pinet *et al.* (1985). The basins between the PR-VI and St. Croix platforms are on trend with the Anegada Gap, and are probably related to it kinematically. The large basin below the south wall of

Figure 5. *Epicentral distribution in the northeastern Caribbean. Upper map (5a) shows teleseismic events from 1950-1979; Lower map (5b) shows events located by local network during 1977-1980; magnitude 3 or greater; contours of hypocentral depth in km. Epicenters on both maps from McCann and Sykes, 1984.*

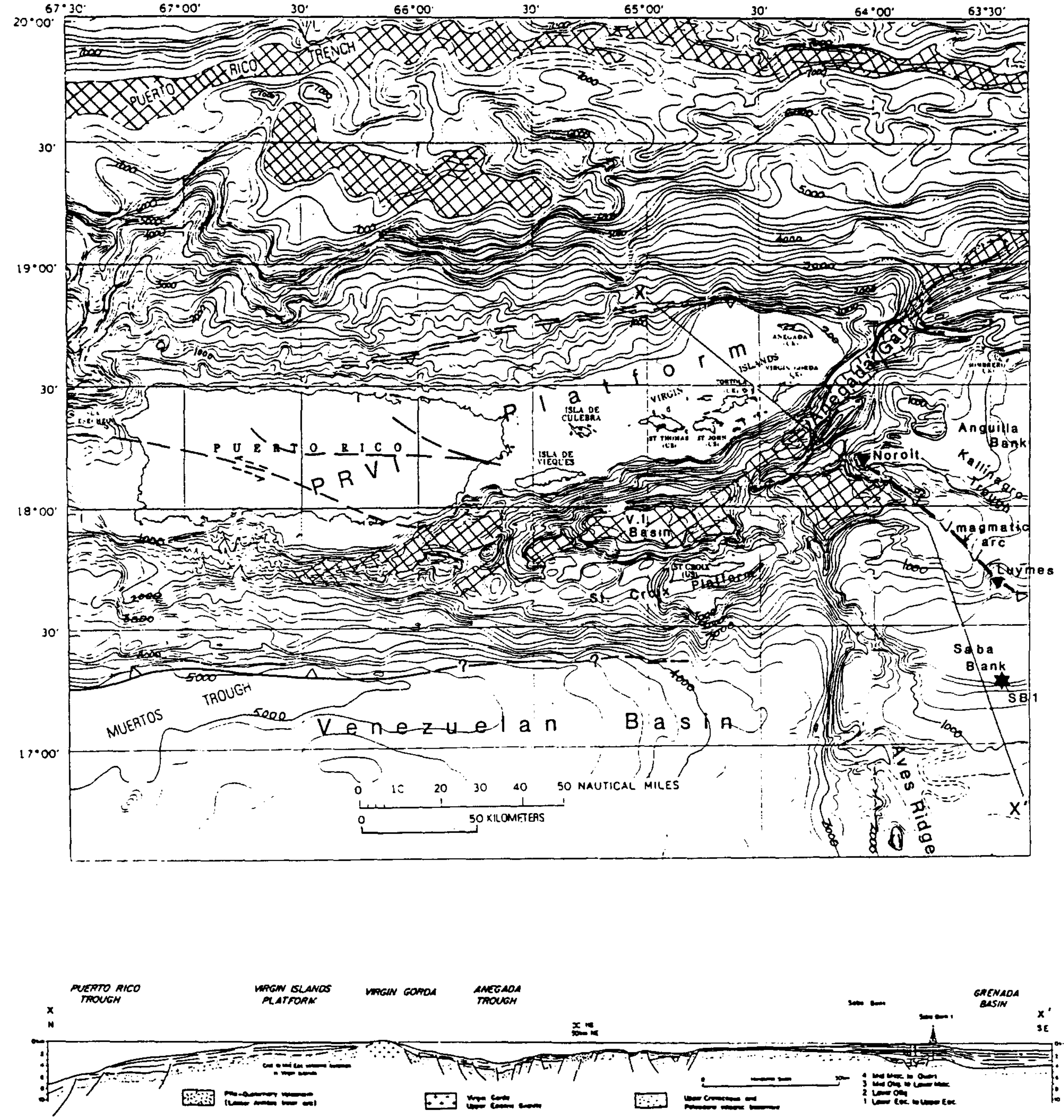

Figure 6. *Bathymetric map of northeastern Caribbean; contours in meters. Crossed-line pattern shows deep basin floors within the Greater Antilles. Double-dashed line with teeth is updip end of dipping seismic zone of Figure 5. SB is Saba 1 well. Cross section from Pinet et al., 1985.*

the Puerto Rico Trench (cross-hatched in Fig. 6) could be extensional or alternatively, a forearc basin as proposed by McCann and Sykes (1984) that is probably inactive at present.

Onland faults of long trace length, WNW strike, and left or left-oblique slip exist on Puerto Rico (Fig. 6; see Perfit *et al.,* 1980; Garrison *et al*., 1972). These cut rocks that are as young as Eocene but their ages of last movement are probably pre-Miocene.

To hypothesize on neotectonics of the northeastern Caribbean it is suggested that the region of transitional lithosphere of the eastern Greater Antilles and northern Lesser Antilles west of the active volcanic chain (Fig. 7) has undergone transtensional breakup since at least some time in the Miocene. The idea, which explains most of the features discussed, is based on the evident active extension in the Aves Ridge and northern Grenada Basin (Speed *et al.,* 1984; Bouysse, 1988). The generally

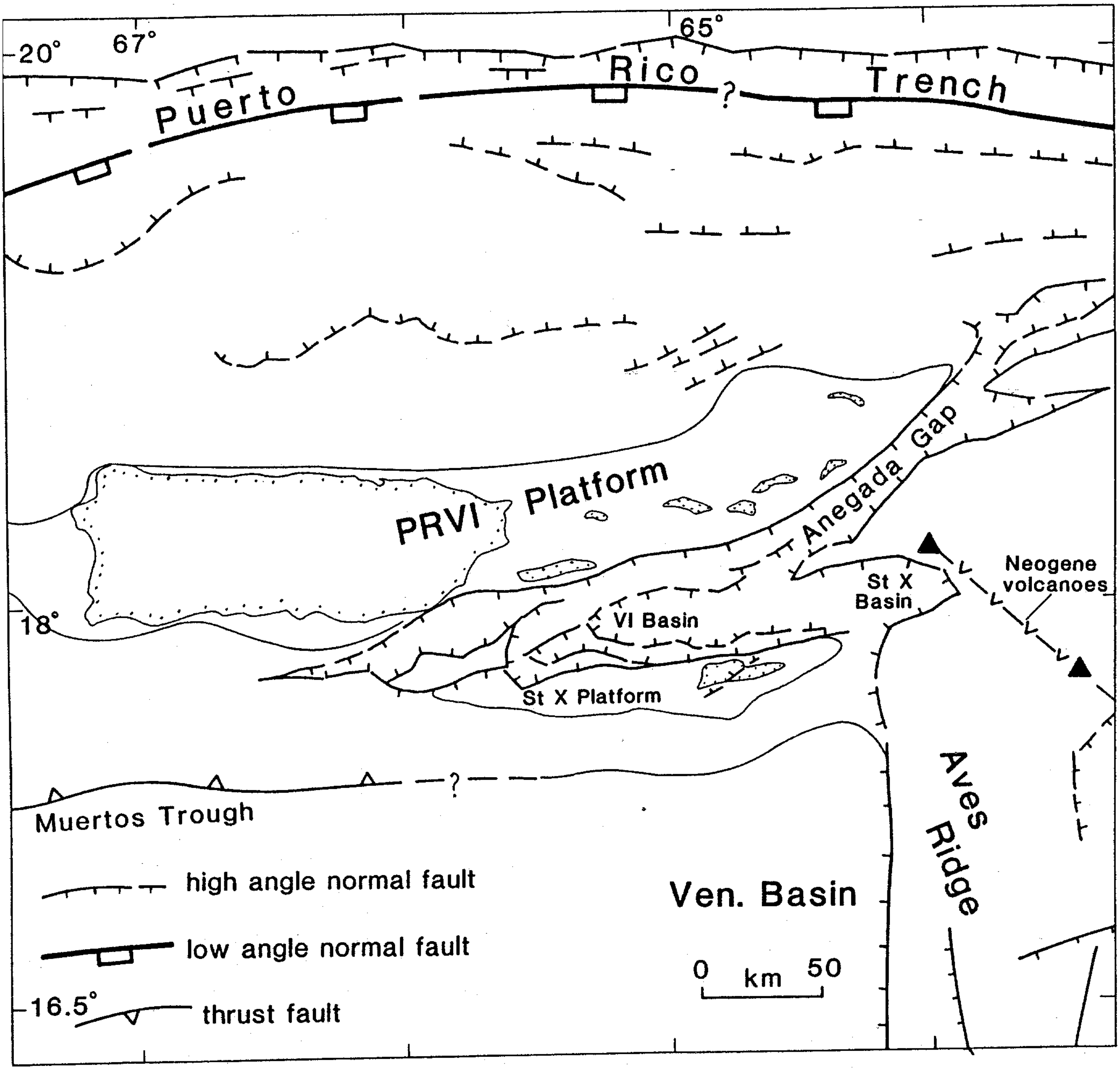

Figure 7. *Tectonic interpretation of the area of Figure 6.*

aseismic extension in the Aves Ridge and Grenada Basin is indicated by basin-range topography, young normal faults resolved by seismics, and anomalously high heat flow. Such extension is probably a backarc phenomenon related to Late Cenozoic subduction, and may pass north around Saba Bank (Bouysse, 1988) to the Anegada Gap and related basins to the southwest. These collectively form an end-arc extensional zone. The PR-VI platform may be a large, coherent block moving WNW from the Anegada breakaway zone (Fig. 7). In this scheme, oceanic lithosphere of the North American plate may be moving WNW with respect to the PR-VI block, causing extensional faulting at the former convergent boundary of the Puerto Rico Trench. The slab below the PR-VI platform may either be similarly extending, producing a south-dipping seismic zone, or alternately the slab may be detached from North America at the Puerto Rico Trench and still sinking obliquely below the PR-VI platform. The Muertos Trough and adjacent forearc, in this idea, would have formed before transtensional breakup.

TECTONIC EVOLUTION OF ST. CROIX

The oldest rocks exposed on St. Croix are entirely sedimentary and occupy a tectonic complex of Cretaceous age. Their depositional ages are known to be Late Cretaceous (ranging from Cenomanian or Turonian to Maastrichtian) at a half dozen sites (Whetten, 1966; Speed *et al.,* 1979; Andreieff *et al.,* 1986; Speed and Joyce, this volume). Because of lithic similarities, they are probably Late Cretaceous throughout, although it is possible that older rocks may exist. The sediments are volcanigenic (with occasional carbonates) sediment-gravity flows that are mainly turbiditic, together with minor siliceous pelagic deposits. They were probably sub-CCD accumulations on a basin floor fronting an active, shoaled island arc. The Cretaceous strata of St. Croix contain no lava or pyroclastic intercalations. These strata underwent major deformations and tectonic imbrication by late Maastrichtian time (Speed *et al.,* 1979). The horizontal contraction of such deformations was oriented between NE-SW and NS, and imbrication was south-vergent. Foliations, extensive quartz veining, and low-grade metamorphism (prehnite-pumpellyite and/or low greenschist facies) developed at deeper levels of the tectonic complex.

The major assembly of the tectonic complex and deformation of its contents was followed by island-wide shallow intrusion of mafic dikes, sills, and plutons in late Maastrichtian time (Speed *et al.,* 1979; Speed and Joyce, this vol.). The igneous rocks are almost certainly of island-arc type (i.e. strongly porphyritic, clinopyroxene ± hornblende rich).

Seismic-refraction data suggest that rocks with velocities of about 5 km/sec extend from the surface to about 8 km below in a body that pinches out to the north and south below the walls of the St. Croix platform (Fig. 4A). Such velocity is appropriate for a composite mass of deformed metasediment and intrusive rock. The implication is that the upper 8 km of the St. Croix platform (which contained metamorphosed and tectonized rocks together with late Maastrichtian diorite), is an assemblage not unlike that at St. Croix's surface (Bouysse *et al.,* 1985). Outcrops on the steep northern face of St. Croix at a depth of 3100 m are similar in lithology to the Cretaceous rocks exposed on St. Croix (Hubbard *et al.,* 1982). The refraction layers of St. Croix (fig. 4A) below 8 km may be Venezuelan Basin crust which underrode St. Croix in the Cenozoic below the Muertos Trough and/or Late Cretaceous arc crust.

The structure and probable great thickness of the tectonic complex implies it is of accretionary origin (Speed and Joyce, this vol.). The Cretaceous sediments were imbricated in thin-skinned thrust sheets at the deformation front of a forearc above a downgoing oceanic plate. Upon accretion, the sediments were progressively flattened by folding and foliation and subjected to low-grade metamorphism within the accretionary prism. The range of known stratigraphic ages in the sediments, 14 to 30 ma, permits interpretations either that 1) subduction occurred for all or part of that interval if sediments were accreted shortly after deposition as in a trench wedge or 2) an incoming stratal section had at least that age range.

The Maastrichtian igneous bodies that invade the prism may be from the same island arc that was the source of volcanigenic debris of the accreted sediments, but which migrated seaward from its earlier position, as if the slab progressively steepened. Alternatively, the Maastrichtian magmatism may represent a newly-formed and short-lived (~5 ma) arc. Because arc-derived debris was fed to-the depositional sites of Cretaceous sediments on St. Croix over a significant time span that ended with a pulse of arc magmatism, it is probable that subduction below the same arc occurred for at least 14 to 30 ma before the end of the Cretaceous. The downgoing slab dipped northerly to northeasterly if St. Croix is now in its original orientation but more westerly in the Cretaceous if St. Croix rotated clockwise in the Cenozoic as is apparently the case in Puerto Rico (Elston and Krushensky, 1982).

A late phase of contractile deformation affected the Cretaceous strata, as indicated by macroscopic folds of foliation (Speed, 1974; Speed and Joyce, this vol.). Axial planes of such folds imply horizontal contraction between NS and NW-SE. This phase occurred between late Maastrichtian, (the age of foliation development) and early Miocene (the oldest known age of little-deformed cover strata).

The Tertiary sedimentary cover on St. Croix (Mutter *et al.,* 1977; Gerhard *et al.,* 1978; Andreieff *et al.,* 1986; Lidz, 1984; 1988; Gill *et al.,* this vol.) provides further clues to Cenozoic tectonics of St. Croix. Exposures and shallow wells indicate the cover is hemipelagic and carbonate-turbiditic beds whose oldest well-documented age is early Miocene (between 17 and 22 ma) (Multer *et al.,* 1977) and youngest is Pliocene (Gill *et al.* this volume). Such strata accumulated at least partly on an unconformable surface on the Cretaceous tectonic complex at substantial water depths (Gill *et al.,* this volume). Deposition of at least part of the Miocene cover was concurrent with normal faulting (Whetten, 1966), and the basin is probably an ENE-striking halfgraben with northwesterly downthrow (Fig. 1 of Speed and Joyce, this volume). The strike of the halfgraben indicates a component of NNW-SSE extension but does not reveal the existence of a strike-slip component. The Miocene cover is said to exist thickly on the north-dipping slope of the St. Croix platform (Lidz, 1984).

The existence of thick Cenozoic sediments below the Miocene beds in the deep reaches of the halfgraben is implied by a local negative gravity anomaly which suggests a modal thickness of about 1.5 km (Whetten, 1966). Further, the occurrence of many species of resedimented planktic forams of Eocene and Oligocene ages in the Miocene beds, especially those concentrated in a single mudball (Lidz, 1984; Andreieff *et al.,* 1986), supports the idea that buried Paleogene cover could exist in the St. Croix graben. The oldest resedimented foram ranges from late early to early middle Eocene, about 46-50 ma (Lidz, 1984). The source of carbonate debris in the Miocene beds, however, is uncertain and probably lies outside the area of St. Croix's current exposure (Gill *et al.,* this volume). Therefore, it remains unclear whether the halfgraben contains buried sediments of Paleogene age or a very thick early Miocene section, and whether or not St. Croix could have been widely covered by Paleogene sediments that were eroded before early Miocene deep-water deposition. It is clear, however, the the source region for allochthonous sediment of the Miocene beds had a Paleogene pelagic cover at least as old as middle Eocene and that it shoaled during late Miocene through early Pliocene time.

Post-Miocene tectonic events on St. Croix include tectonic uplift, tilting, and minor folding. The deeper-water Miocene beds are overlain unconformably by shoalwater early Pliocene carbonate rocks, implying substantial tectonic uplift during the Miocene because sea level rose markedly at this time. This was accompanied by continued normal faulting at least partly through Pliocene time (Gill *et al.,* this volume). The Miocene beds are shallowly south-tilted and openly folded with south-plunging axes (Gerhard *et al.,* 1978) which may be a product of growth faulting within the halfgraben or oblique-slip tectonics. The absence of younger onland strata suggests St. Croix has been emergent for the last 3-4 ma, and the existence of raised coastal deposits indicates it is still rising relative to sea level.

IMPLICATIONS FOR TECTONIC EVOLUTION

St. Croix's Neogene and Quaternary history of tectonic subsidence and uplift associated with normal faulting with a component of NNW-SSE extension supports the idea presented earlier of late Cenozoic extension in the Anegada Gap and a broader region of the eastern Greater Antilles and northern Aves Ridge. St. Croix's record implies that extension in the region began at least as far back as the end of the Early Miocene (16-18 mybp). The existence of over 1 km of buried cover rocks on St. Croix permits an older onset to be considered, but it is uncertain what their ages are and whether or not their deposition was fault-controlled.

If extension in the northeastern Caribbean is in fact related to back- and end-arc tectonics, the duration of extension on St. Croix indicated that magmatism at the northern end of the arc (St. Kitts and to Noroit Bank, Fig. 3) has been going on at least 10 ma longer than dating of arc volcanics suggests (maximum age 7 ma, Briden *et al.,* 1979; Bouysse *et al.,* 1985). If, however, the extension is due only to regional transtension across the eastern Greater Antilles, no such implication is warranted.

The event preceding extension on St. Croix, with horizontal contraction oriented between NS and NNW-SSE suggests convergence across the eastern Greater Antilles in Paleogene or latest Maastrichtian time. Such convergence may have been due to subduction at the Puerto Rico Trench or Muertos Trough. It is important to note that this late contraction was almost certainly not due to simple shear on an EW-striking transform system unless the strain were extreme. Given such strain, the contraction direction might fit a right-lateral system but not the left-lateral one predicted by Ca-NA plate motions.

Comparison of magmatic histories indicates that St. Croix and the Saba Bank (Fig. 3; Bouysse, 1988) apparently were similar in having their last igneous phase in latest Maastrichtian time. Puerto Rico also had Maastrichtian magmatism, but its last intrusion and its extrusive phase was of late Eocene age (about 40 ma; Cox *et al.,* 1977). The eastern Virgin Islands platform and the Anguilla platform were the site of copious Eocene volcanigenic sedimentation (the age of some of these is only inferred to be Eocene), followed by mainly intrusive magmatism whose rocks give mainly late Eocene and Oligocene K-Ar mineral ages (Cox *et al.,* 1977; Briden *et al.,* 1979) for their last igneous event. The K-Ar data are not sufficient to interpret a sequencing of magmatism with position.

The northern islands of the northeastern Caribbean, therefore, underwent Paleogene magmatism whereas its southern region, St. Croix and Saba Bank, did not. Further, Saba Bank and perhaps, St. Croix and/or the source region of resedimented Paleogene particles in its cover were the sites of mainly non-volcanigenic sedimentation after Maastrichtian magmatism. Such conditions argue that subduction giving rise to Paleogene magmatism occurred on the north side of the Greater Antilles, probably at the precursor to the Puerto Rico Trench.

The Cretaceous tectonic complex of St. Croix has no evident equivalent on islands of the northeastern Caribbean. Volcanigenic sediments of comparable age range occur on Puerto Rico (Glover, 1971; Cox *et al.,* 1977) and of Cenomanian age in the northern Virgin Islands (Donnelly, 1966), but these appear not to have had similar depositional, deformational, or metamorphic histories as those of St. Croix. St. Croix's tectonic complex, however, is probably not greatly exotic with respect to Puerto Rico if the Maastrichtian magmatism of both islands is related. The differences may be explained as follows. The Late Cretaceous rocks of Puerto Rico and the northern Virgin Islands were arc platform and intra-arc basin accumulations. Those of St. Croix were derived from the same arc but were deposited on an oceanic floor and/or in a trench fronting the south side of the Late Cretaceous arc of the eastern Greater Antilles. The tectonic complex of St. Croix arose due to accretion, tectonic stacking, and forearc contraction whereas Late Cretaceous strata of the arc platform were relatively little deformed. The locus of magmatism then moved seaward in the Maastrichtian and invaded the forearc complex in St. Croix, as discussed earlier.

The postulated north-dipping subduction zone below the south wall of the eastern Greater Antilles in the Late Cretaceous expired by the end of Cretaceous time, and in the Paleogene, convergence was taken up at the south-dipping subduction zone in the precursor to the Puerto Rico Trench. If true, St. Croix was switched from a forearc position in the Late Cretaceous to a backarc one in the Paleogene. It was again in a forearc during subduction at the Muertos Trough, but the age of this unknown.

Late Cretaceous north-dipping subduction occurred during a time when the North American and South American plates were either in the waning phase of /or had completed their divergent movement (Fig. 2). This implies either that 1) the convergence was accommodated by intra-Caribbean extension, 2) the downgoing plate was propelled by spreading in the Pacific, or 3) the complete Antillean subduction system underwent transport from the Pacific since Late Cretaceous time. Each is currently a plausible solution. The oceanic lithosphere that was downgoing below the eastern Greater Antilles in the Late Cretaceous may or may not have been that of the Venezuelan Basin. For example, the Muertos Trough may be at a reactivated convergent boundary between the Venezuelan Basin and the Greater Antilles. Alternatively, the Muertos Trough could have inherited a long EW transform fault of large displacement. The first case implies that the Greater Antilles have mainly overridden the Venezuelan Basin through time whereas the second case implies that a different oceanic lithosphere could have underridden the Greater Antilles in the Late Cretaceous.

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