Sedimentological and Tectonic Evolution of Tertiary St. Croix

Ivan Gill
Peter MacLaughlin
Dennis Hubbard
Clyde Moore

Converted to digital format by Thomas F. Barry (NOAA/RSMAS) in 2004. Copy available at the NOAA Miami Regional Library. Minor editorial changes may have been made.

Sedimentological and Tectonic Evolution of Tertiary St. Croix

Ivan P. Gill[1], Dennis K. Hubbard[2]. Peter McLaughlin[3], and Clyde H. Moore[3]

[1] Dept. of Geology
Tulane University
New Orleans, LA

[2] West Indies Laboratory
St. Croix, U.S.V.I.

[3] Louisiana State University
Baton Rouge, LA

ABSTRACT

St. Croix is a dominantly sedimentary island in the northeastern Caribbean and its sedimentary development is therefore of considerable relevance to regional tectonic reconstruction. Previous models of the late Tertiary development of St. Croix assume either that the carbonate sediments were deposited in 1) shallow water or 2) entirely within the confines of an insular graben system. Both models presume a static, isolated island with a self-contained sediment source. Evidence from a recent drilling program on St. Croix requires modification of both models of basin evolution. Pelagic and hemipelagic carbonates of the Kingshill Limestone overlie blue pelagic and hemipelagic carbonates of the Jealousy Formation with a sharp, diachronous lower-to-middle Miocene boundary that ranges between planktonic foraminiferal zones N8 and N10. The Jealousy Formation itself is a deep-water limestone indistinguishable from the Kingshill Limestone except by color. Based on all known samples taken from it, the Jealousy Formation is a Miocene unit, not Oligocene, and does not occur in outcrop.

Benthic foraminiferal faunas from drill samples suggest that most of the Neogene section reachable by drilling was deposited in the upper bathyal zone. Pronounced shallowing did not occur until the latest Miocene to early Pliocene. Samples collected from the western side of the basin show no sedimentologic or paleoecologic evidence of shallowing, faulting or a nearby landmass during early Miocene deposition of the Jealousy Formation. However, coarse clastic debris in Kingshill Limestone exposures along the eastern fault zone indicate that faulting and graben formation may have begun at least prior to the latest middle Miocene.

This evidence indicates that the Jealousy Formation and the Kingshill Limestone began deposition prior to graben formation, and that faulting or horst exposure occurred later. A source external to the present structural basin is required to produce the pre-graben, shelf-derived carbonate components; we suggest that they originated from source areas to the north such as Puerto Rico or the Virgin Islands Platform, or to the east such as Anguilla or Saba. It appears likely that St. Croix has migrated and was uplifted in the Neogene, possibly during the opening of the Virgin Islands Basin and the Anegada Passage. The creation of these seismically active features was probably dominated by transtensional movement with a significant left-lateral component of slip.

INTRODUCTION

St. Croix is a sedimentary island located inside the sweep of the Lesser Antilles arc. It is geographically separated from Puerto Rico and the Lesser Antilles by the 4500 m deep Virgin Islands Basin, the Anegada Passage and the St. Croix Basin (Fig. 1). At its widest points, the island is 39 km long and 9 km wide, and covers a total of 207 sq. km. The central plain of the island is the focus of this paper, and lies between the mountainous Eastend and Northside Ranges composed of Cretaceous siliciclastic and intrusive rocks of the Mt. Eagle Group. The central plain is a graben structure containing exposures of alluvium and underlying Tertiary carbonate rocks (Fig. 2) that we will refer to as the Kingshill-Jealousy Basin.

The rock units dealt with in this paper are (Fig. 3):

1) the Cretaceous Mt. Eagle Group that brackets the basin to the east and west, and presumably floors the graben. Details on the Cretaceous section of St. Croix can be found in Speed, this volume.
2) the Miocene Jealousy Formation, consisting of grey-blue, planktonic foram-rich muds.
3) the Miocene Kingshill Limestone; including an upper section of shelf and slope facies, designated as the Mannings Bay Member.
4) the Pliocene Blessing Formation consisting of reef and shelf limestones that unconformably overlie the

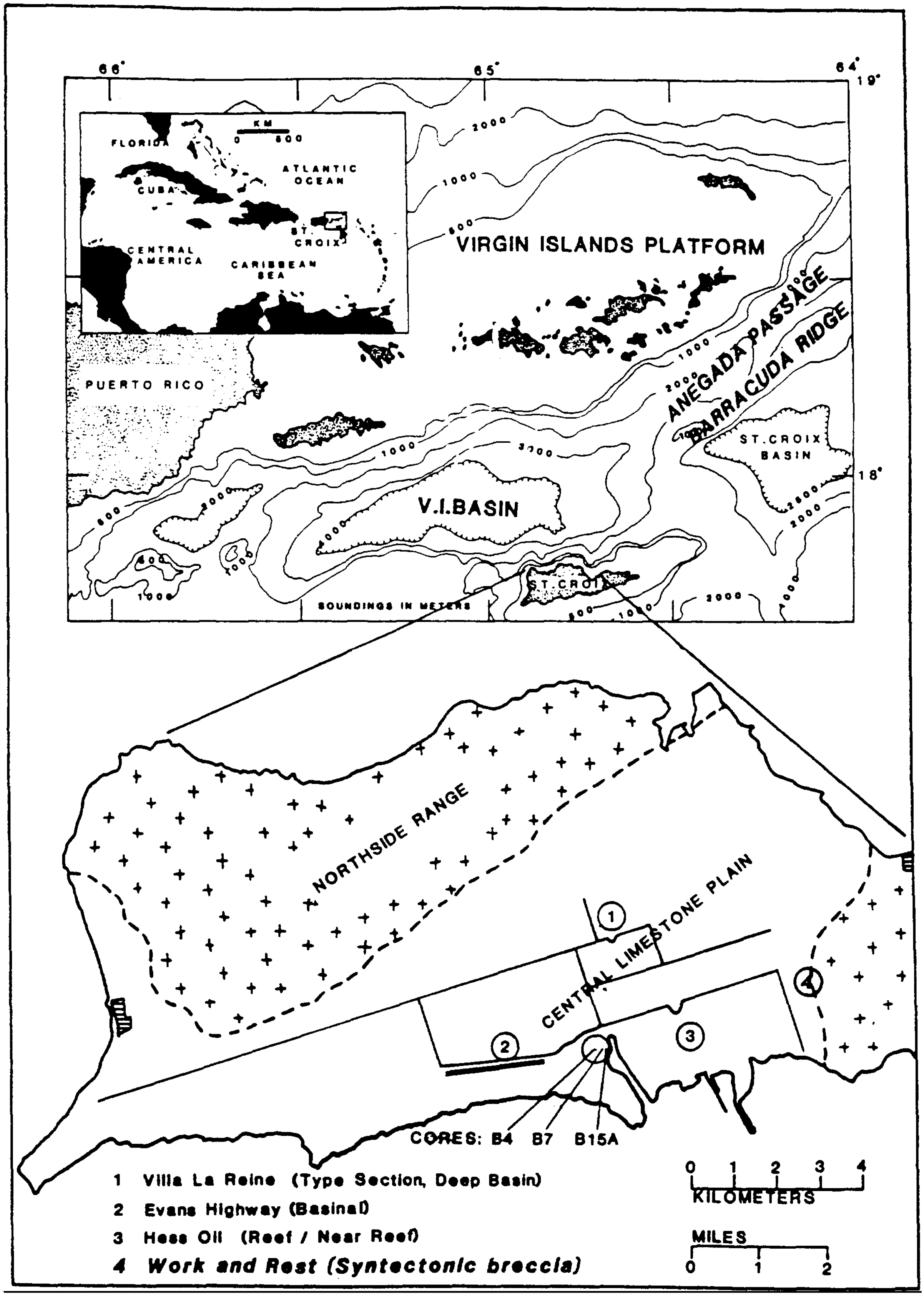


Figure 1. St. Croix location map and study area.

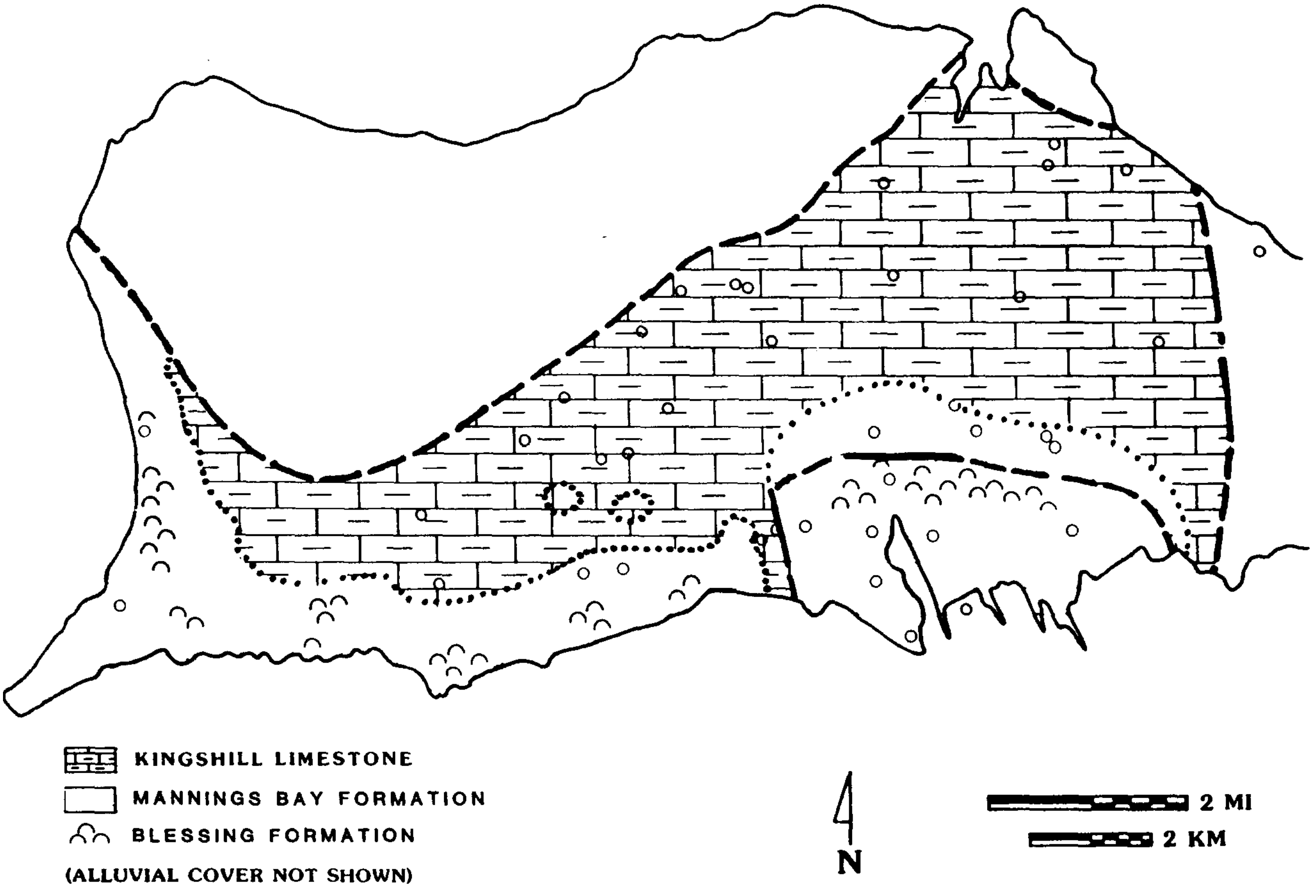


Figure 2. *Generalized geologic map of St. Croix. Exposed strata mapped as Jealousy Formation by Whetten (1966) are re-mapped as Kingshill Limestone in this dissertation.*

Kingshill Limestone along the southern coast (Fig. 3).

These units, and their geologic interpretation, are discussed individually in later sections.

St. Croix's thick sequence of Tertiary carbonates provides a record of Tertiary deposition and uplift at the juncture of the Lesser Antilles geologic provinces. The tectonics of this area are complicated, and remain controversial. To this point, the Tertiary section of St. Croix has been viewed as a self-contained product of an isolated graben system. In the most recent interpretations (Whetten, 1966; Multer *et al.,* 1977; Gerhard *et al.,* 1978), the Tertiary section is either not tied to regional tectonics, or is interpreted to be solely the product of vertical tectonics. Based on outcrop evidence alone, these interpretations offer the simplest reasonable explanations of the development of St. Croix in the Neogene.

A drilling program undertaken in the past several years furnishes some constraints on the motion and timing of faulting on St. Croix, and provides a more detailed picture of St. Croix's sedimentary evolution during the Tertiary. This subsurface information, in conjunction with outcrop data, furnishes structural, sedimentological and paleontological information that allows the testing of several models of basin development.

As a result, it is suggested here that St. Croix was not a static, isolated land mass during the Neogene, and instead required an external source of sediment during much of its development. The details of Neogene basin development bear both directly and indirectly on the tectonics of the region, and these details are discussed in the following portions of this paper. Following the conclusions, a section on outcrops provides lithologic details on rocks that can be examined in the field.

METHODS

Fourteen test holes were drilled during an extensive subsurface exploration project. Samples from these holes, as well as donated samples and well logs from engineering borings and water wells, were used in the construction of stratigraphic cross sections. Samples were taken by split spoon and diamond-bit coring, and were analysed by thin section, x-ray diffraction and micropaleontological separation. Mud-rich samples from below the water table

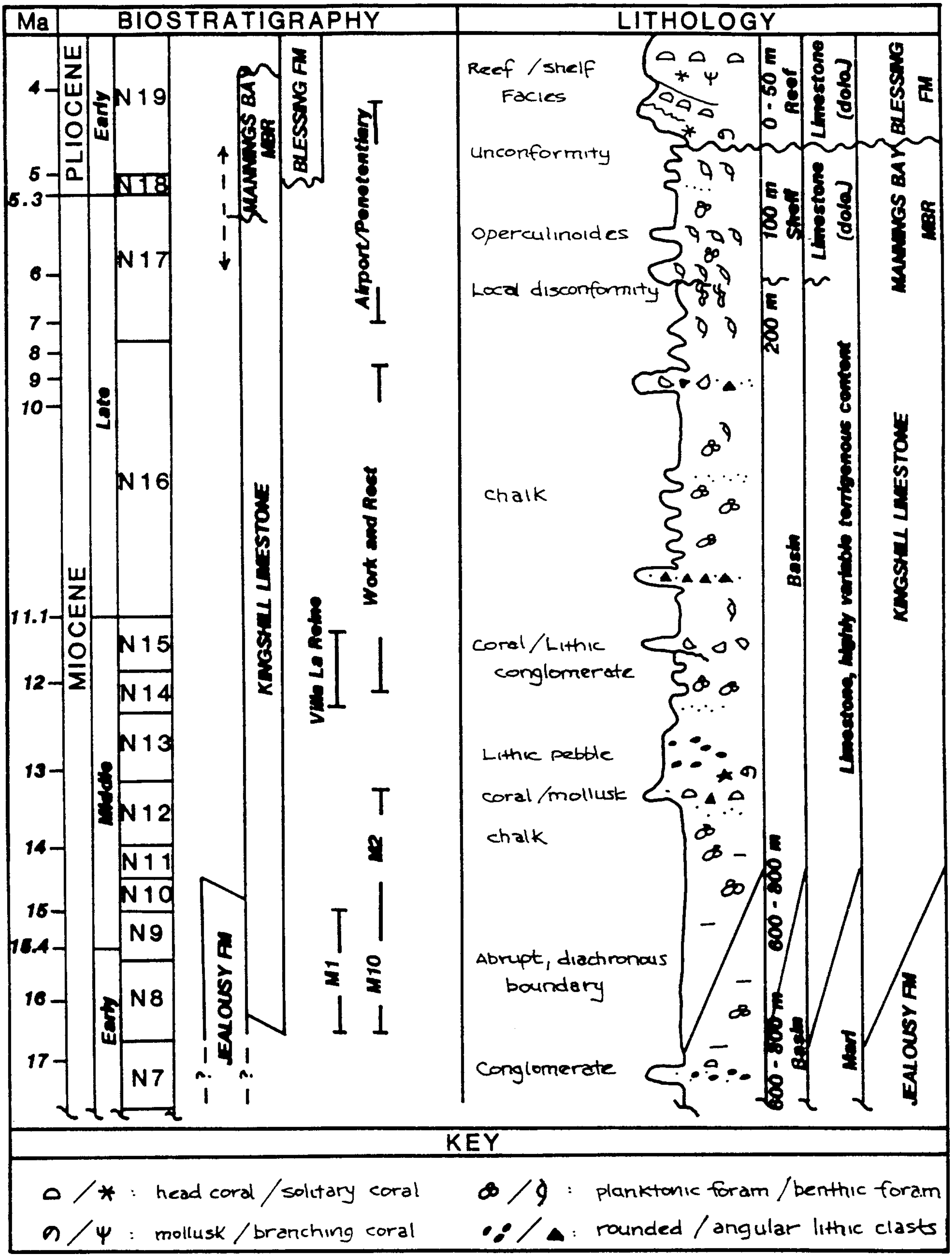


Figure 3. *Expanded stratigraphic column showing the St. Croix Tertiary section, including chronologic, biostratigraphic and lithologic characteristics.*

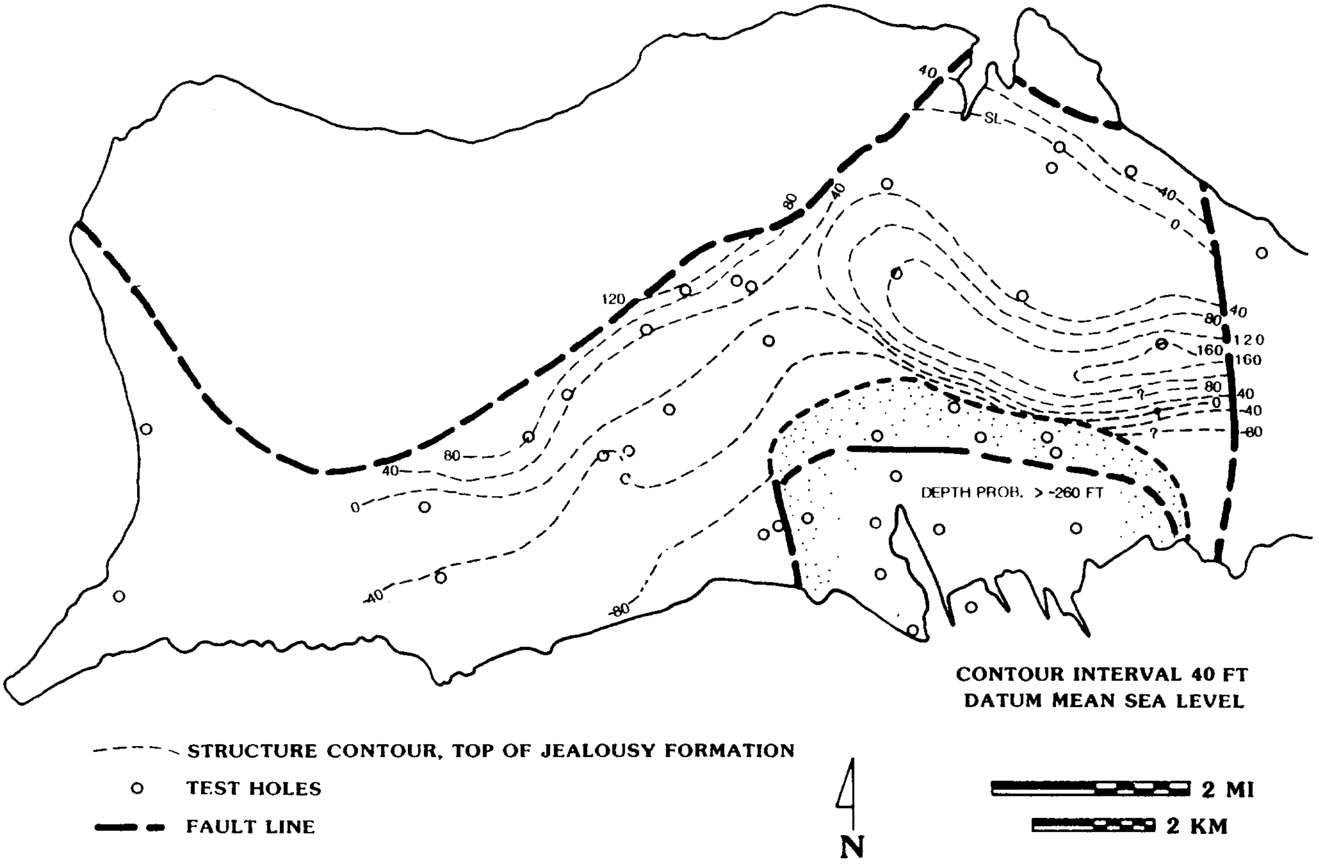


Figure 5. Structure map: top of the Jealousy Formation. Well control is sparse along the eastern fault boundary of the Tertiary limestones. No Jealousy Formation sediments were encountered within the southeastern coastal section of the Central Plain, which is a graben or demi-graben structure. Depth to Jealousy Formation sediments in this area exceeds 80 m.

section sampled. However, no comment can be made on the mineralogy at greater depths than those sampled here.

Based on benthic foraminiferal faunas, the Jealousy Formation was deposited at depths between 600 to 800 m throughout the basin (McLaughlin, Gill and Bold, in prep; Gill, 1989). The subsurface samples taken for this project do not indicate an estuarine environment, or an estuarine source for the Jealousy Formation sediments, and there is no indication of shallowing toward the basin edges.

The surface of the Jealousy Formation is characterized by 1) a marked upbowing of the surface beneath the highlands in the northern section of the central plain; 2) a gentle dip toward the northern and southern coasts of St. Croix; and 3) a pronounced rise of the Jealousy Formation surface close to the fault boundary imposed by the Northside Range (Figs. 5, 6). The depth to the Jealousy Formation surface in the southeastern coastal section is not known due to local faulting, which places the upper surface of the Jealousy Formation beyond 80 m, the maximum penetration of the drill (Fig. 7).

The Jealousy Formation is found in the subsurface throughout the Central Plains region as documented by our drilling program as well as by Cederstrom (1950) and Robison (1972). In addition to the subsurface occurrences, Cederstrom (1950) and Whetten (1966) mapped several areas in the Northside Range as Jealousy Formation. We suggest that these strata are more correctly mapped as Kingshill Limestone, following the suggestion of Gerhard *et al.* (1978), since the exposed units in the Northside Range bear no resemblance to the Jealousy Formation sediments recovered by drilling. They occur at similar altitudes, and contain similar lithologic facies as outcrops of Kingshill Limestone in other parts of the island, and are within the biostratigraphic range of Kingshill Limestone deposition (Bold, 1970; Bold in Gill and Hubbard, 1986; McLaughlin *et al.*, in prep).

Blue clays identified as Jealousy Formation were encountered outside the structural basin in Test Well C26 (Fig. 4) (Cederstrom, 1950). The presence of Jealousy Formation sediments outside of the structural basin boundaries indicates that the Jealousy Formation is not confined to the Kingshill-Jealousy Basin.

Interpretation - We differ from previous interpretations of the Jealousy Formation in several ways. In particular, the Jealousy Formation represents deep basinal accumulation throughout its sampled extent. The

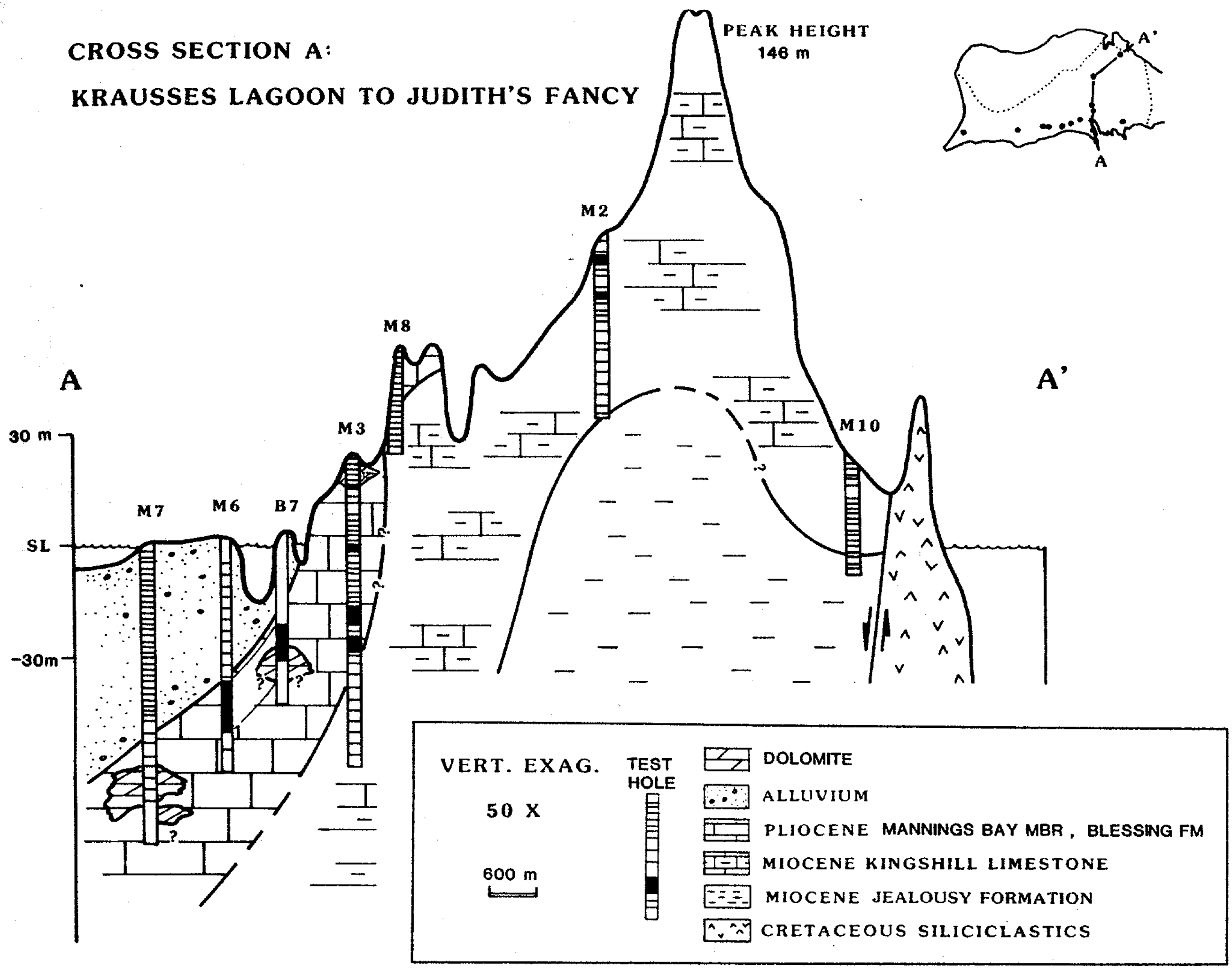


Figure 6. *Cross section A-A': Krause Lagoon to Judiths Fancy. Note that the Jealousy Formation surface roughly follows the topography of the Kingshill Limestone. Sample depths are shown for each test hole. Dark intervals represent diamond-bit coring.*

depth of the basin during the deposition of the Jealousy Formation apparently did not change either 1) over the time range represented by our samples; 2) over the geographic range from the western boundary of the present basin to the center; or 3) along a transect from the southern to the northern coastline. These conclusions are based on the bathyal affinities of the benthic foraminiferal fauna, the dominance of planktonic foraminifera, and the fact that all conglomeratic layers encountered by Cederstrom (1950) are bracketed above and below by pelagic sediments.

Previous workers suggest that the Kingshill-Jealousy Basin formed in the Oligocene as a result of vertical tectonic movement. In particular, Whetten (1966) suggested that the central lowlands on St. Croix subsided in a graben during the Oligocene, following a period of low-rank metamorphism, faulting, folding, igneous intrusion and uplift.

In contrast, we suggest that the present graben boundaries could not have been formed before the end of the early Miocene because early Miocene Jealousy Formation sediments close to the Northside Range show no evidence of basinal shallowing. In addition, Jealousy Formation sediments are Miocene, not Oligocene in age. The existence of Jealousy Formation sediments in Test Well C26 (Cederstrom, 1950) outside the graben boundary suggests that Jealousy deposition was not confined to the graben, and that the horst blocks were not subaerially exposed during Jealousy sedimentation. Deposition of the Jealousy Formation probably preceded basin faulting.

In summary, the Jealousy Formation was deposited in 600 to 800 m of water, and represents deep-marine depositional conditions. Multer *et al.* (1977) envisioned the Northside Range and the Eastend Range as subaerially exposed horst blocks, providing both terrigenous sediments and shelf-derived carbonates. However, for the

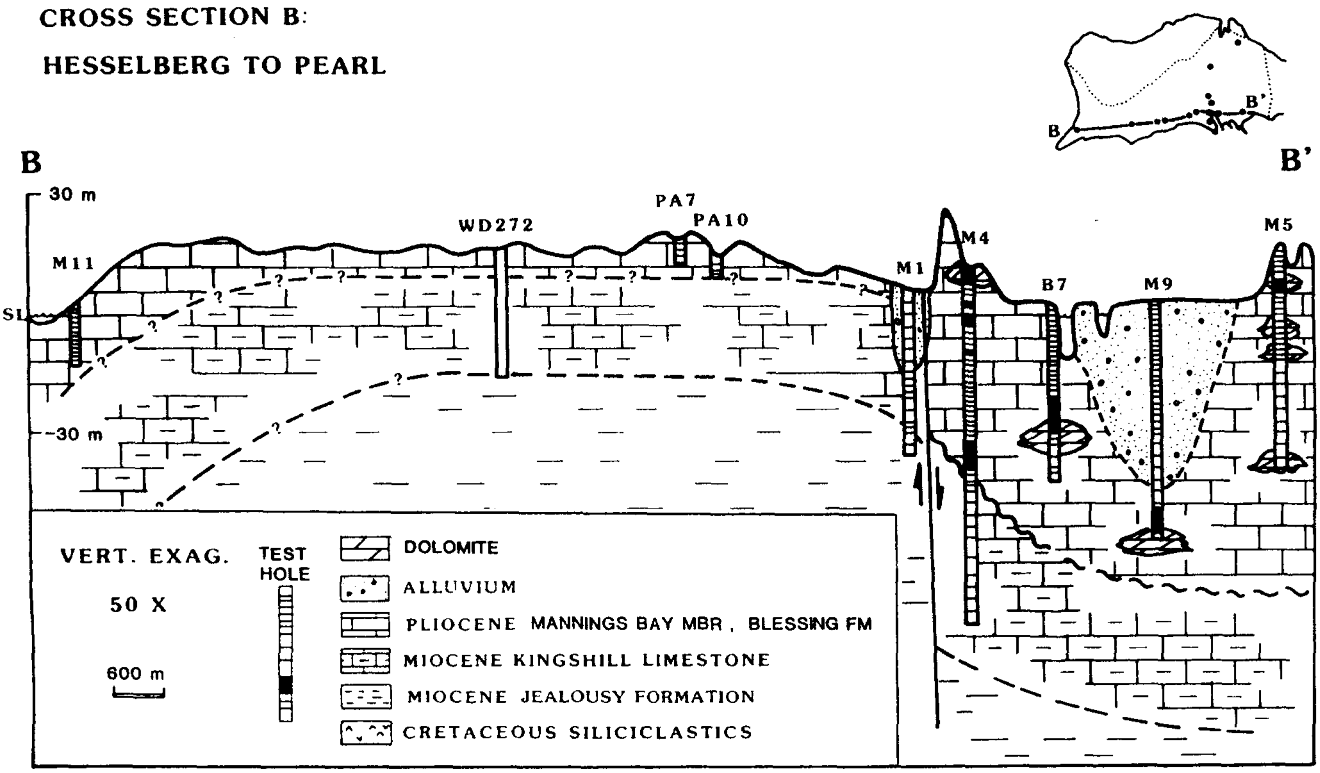


Figure 7. *Cross section B-B': Estate Hesselberg to Pearl. A normal fault forming the western boundary of the subsidiary graben block occurs between test holes Ml and M4. The Jealousy Formation was not reached to the east of this fault. Solid intervals represent diamond-bit coring.*

reasons discussed above, these horst blocks could not have been emergent during the deposition of the lower Jealousy Formation (Fig. 8a), and therefore St. Croix must have been close to a land mass capable of supporting reef growth and supplying clastic materials and must have been deep enough to accumulate pelagic sediment. We feel that Puerto Rico and the Virgin Islands Platform, to the northwest of St. Croix, and Anguilla and Saba, to the northeast, are possible source areas. Either source area requires significant lateral translation of St. Croix.

Kingshill Limestone

Previous interpretations - Gerhard *et al.* (1978) proposed that the lowermost Kingshill Limestone was deposited during a sea-level rise between the Oligocene and the Miocene. Limestone strata exposed close to the northern coastline were interpreted as the transition between strandline environments of the Jealousy Formation and lagoonal environments of the basal Kingshill Limestone. Fault action on the eastern bounding fault caused deepening of the basin floor, followed by continued general deepening throughout the basin (Gerhard *et al.*, 1978). Carbonate and terrigenous sediments were introduced into the basin by turbidity currents and debris flows, primarily from the eastern basin margin. The close of Kingshill Limestone deposition was marked by basinal shallowing, resulting in the deposition of a larger foraminiferal facies representative of shelf environments (Gerhard *et al.*, 1978). The basinal shallowing was the result of continued sedimentation, sea-level rise, or tectonic uplift (Gerhard *et al.*, 1978).

Gerhard *et al.* (1978) separated the Kingshill Limestone into facies representing 1) the transition from strandline and nearshore deposits (molluscan packstone and clastic grainstone facies), 2) deep basinal gravity-flow deposits and pelagic accumulations (polymictic packstone and foraminiferal wackestone facies, respectively), and 3) basinal shallowing and the establishment of extensive foraminiferal banks (foraminiferal grainstone facies). The Kingshill Limestone lithology is highly variable and insoluble residue contents range from less than 5 percent to 99 percent (Gerhard et *al.*, 1978).

Results - Deposition of the Kingshill Limestone, including those portions exposed in outcrop, spans the range from the lower Miocene (N8) to close to the Mio-Pliocene boundary (N17)(McLaughlin *et al.*, in prep; Gill, 1989). The subsurface section sampled in our drilling program spans a narrower range, from lower Miocene (N8) in Wells Ml and M10, to middle Miocene (N12) in the upper parts of Well M2. The contact between the buff-

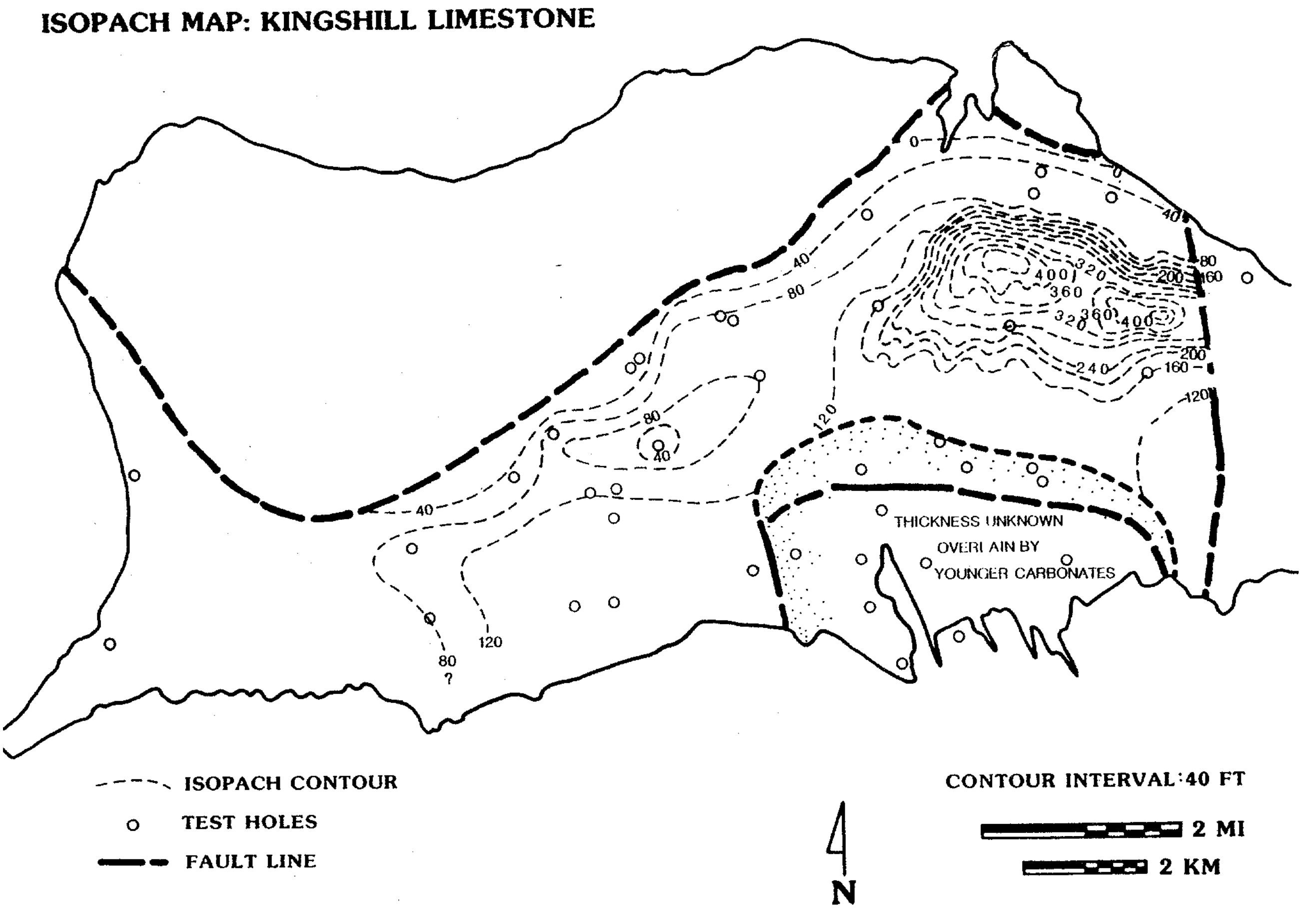


Figure 9. *Isopach map of the Kingshill Limestone; the contoured area represents the Central Limestone Plain region. The thickest known areas of the Kingshill Limestone correspond with areas of high topographic relief. If the hilly limestone areas were produced structurally, they have not existed long enough to be planed down by erosion. Well data are sparse along the eastern fault boundary, and the Kingshill Limestone was not penetrated to its base within the subsidiary graben in the southeastern Central Plain.*

the middle Miocene, since strata in the eastern fault zone can be assigned to zones between N14 and N16 (McLaughlin *et al.*, in prep; Gill, 1989).

Mannings Bay Member of the Kingshill Limestone

Previous interpretations - The Mannings Bay member was included in the Kingshill Limestone as the foraminiferal grainstone and wackestone facies by Gerhard *et al.* (1978), and was interpreted as representing shoaling of the Kingshill-Jealousy basin. These strata are characterized by extensive deposits of larger benthic foraminifera, primarily *Operculinoides* and *Paraspiroclypeus*, derived from shallow carbonate banks. Lidz (1982, 1984) separated this section from the Kingshill Limestone, placing it in the Pliocene with other post-Kingshill limestones. Later biostratigraphic work by Andreieff *et al.* (1986) supported the assignment of these strata to the early Pliocene.

Results - The Mannings Bay member is exposed only in the southeastern section of the Central Plain. Subsurface Mannings Bay strata were also encountered in several of the test wells drilled for this project. The stratigraphic range of the Mannings Bay member is between the top of the upper Miocene (upper N17) and the top of the lower Pliocene (upper N19; McLaughlin *et al.*, in prep; Gill, 1989). It has not been possible to further refine stratigraphic placement due to extensive diagenetic alteration, and for this reason we support a wider biostratigraphic assignment for these strata than the lower Pliocene assignments of Lidz (1982) and Andreieff *et al.* (1986).

The assemblage includes, and is dominated in places by the nummulitid forams *Operculinoides cojimarensis* and *Paraspiroclypeus chawneri* (Behrens, 1976; S. Frost, pers. comm., 1986; Gerhard *et al.*, 1978). In foraminiferal wackestone strata the matrix also includes significant quantities of planktonic foraminifera. Other bioclasts that contribute significantly to the facies are coralline algal crusts and rhodoliths, and echinoid fragments. Minor coral and molluscan debris are represented by external molds and pore space in the cores.

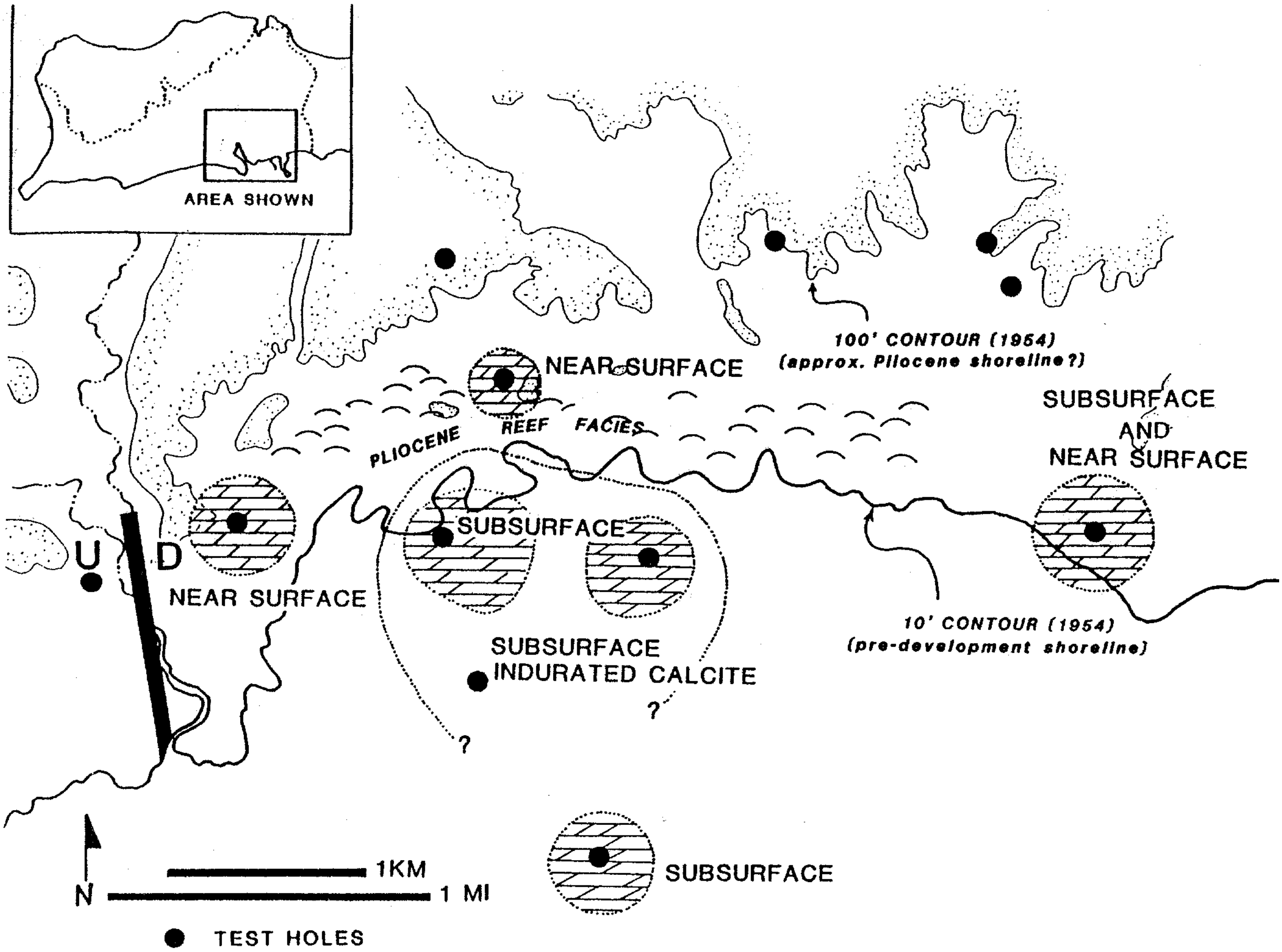


Figure 10. *Facies map: south coast industrial area. Dolomite in the vadose zone or exposed in outcrop is distributed in an arcuate region following the Pliocene reef trend. Dolomite presently in the phreatic zone is found in off-shore facies. The western boundary of the subsidiary graben is well-defined by a normal fault. The northern and eastern boundaries are poorly known, but probably correspond fairly closely with the 100 ft contour.*

4, and outcrops west of the Airport/Evans Highway outcrop are limited to scattered exposures along the southern and western shorelines, including a reef exposure described by Gerhard *et al.* (1978). The maximum thickness of the Blessing Formation west of the fault at Fairplain is estimated to be between 10 and 20 m.

The Blessing and Mannings Bay Formation carbonates show localized dolomitization both in the surface and subsurface (Fig. 10) in an area restricted to a subsidiary graben on the southern coastline. Dolomite distribution is confined to the Pliocene reef tract and fore-reef facies surrounding Krause Lagoon; no dolomite has been detected anywhere else on St. Croix. Based on its stratigraphic position, the dolomitization occurred during or following the Pliocene. The pattern of exposure surfaces in the Blessing Formation strata indicates that the southern shoreline was exposed, possibly repeatedly, during the Pliocene.

Interpretation - Continued shoaling of the Kingshill-Jealousy Basin resulted in the deposition of the Blessing Formation reef tract which apparently extended around the southern and western shorelines of St. Croix (Fig. 8e). The reef tract consisted of interspersed reefs and shelf systems similar to the arrangement of reefs around the southern coastlines of St. Croix today, and apparently formed weakly mounded deposits with little topographic relief. This planar geometry was common in Caribbean Tertiary reef deposits (S. Frost, pers. comm.).

The greatest thickness of reef growth occurred at what is now the industrial area on the south-central coastline, with the geographical distribution suggesting that faulting in the subsidiary graben affected sedimentation in the

Blessing Formation as well as the Mannings Bay Formation, and may have formed antecedent relief upon which reefs colonized. The arcuate distribution of reef and lagoonal facies in this area indicates that the area was an embayment during the establishment of the reefs (Fig. 10) with the size and shape of the embayment controlled by faulting in the Krause Lagoon area.

From a tectonic standpoint, the fault that cuts through the Mannings Bay and Blessing units demonstrates that normal faulting, and therefore a tensional tectonic regime, extends at least into the Pliocene if not later. The orientation of this fault is poorly controlled, but suggests that the mechanism for the faulting may be the same for both the basin boundary faults and the subsidiary south-coast graben. We suggest that the deposition of Kingshill Limestone and post-Kingshill sediments was concentrated in the basin formed by this subsidiary graben, and that the strata were preserved by down-faulting in the graben during island uplift. The incorporation of reworked, cemented planktonic forams from the Kingshill Limestone in the post-Kingshill rocks demonstrates that erosion of the uplands area has removed significant section from the Kingshill Limestone and, by inference, the post-Kingshill rocks as well.

Normal faulting of Blessing Formation sediments indicates that tectonic activity continued on St. Croix through the latest periods of Tertiary deposition, and therefore extended into the Pliocene or later. Uplift continued during the Pliocene, and eustatic variation along with tectonic uplift account for the repeated exposure of Blessing Formation strata. Preferential uplift of the northern part of the island accounts for the more extensive erosion in the northern central plain, and the general southerly dip of Tertiary strata in the Kingshill-Jealousy Basin.

TECTONIC MODEL

We propose that St. Croix was rifted away from a pre-existing mainland by left-lateral faulting. This idea was suggested by Hess (1933, 1966) among others, but was rejected by Whetten, Hess' doctoral student, in his dissertation on the geology of St. Croix (Whetten, 1966). The idea is resurrected here because it best explains the characteristics of structure and sedimentation in the Tertiary section of St. Croix, and is far more consistent with regional tectonics and seismicity than a static basin model. We suggest that St. Croix was rifted away from Puerto Rico by oblique left-lateral faulting, and that the Virgin Islands Basin is a strike-slip basin (Fig. 11). Similar left-lateral faulting could have occurred between St. Croix and the Anguilla/Saba Bank area to the northeast. However, the structural and bathymetric relations in the St. Croix Basin (Fig. 1) are less clear than those in the Virgin Islands Basin.

Rifting north of St. Croix is indicated by the steep northern coast and island slope (Meyerhoff, 1927) as well as escarpments observed on ALVIN dives along the northern coast (Dill, 1977; Hubbard *et al.,* 1981). In addition, seismic activity in the northern wall of the Virgin Islands Basin has been observed historically (Reid and Tabor, 1920) and is occurring today (Frankel *et al.,* 1980). This evidence indicates that rifting may have occurred north of St. Croix, but does not indicate its orientation.

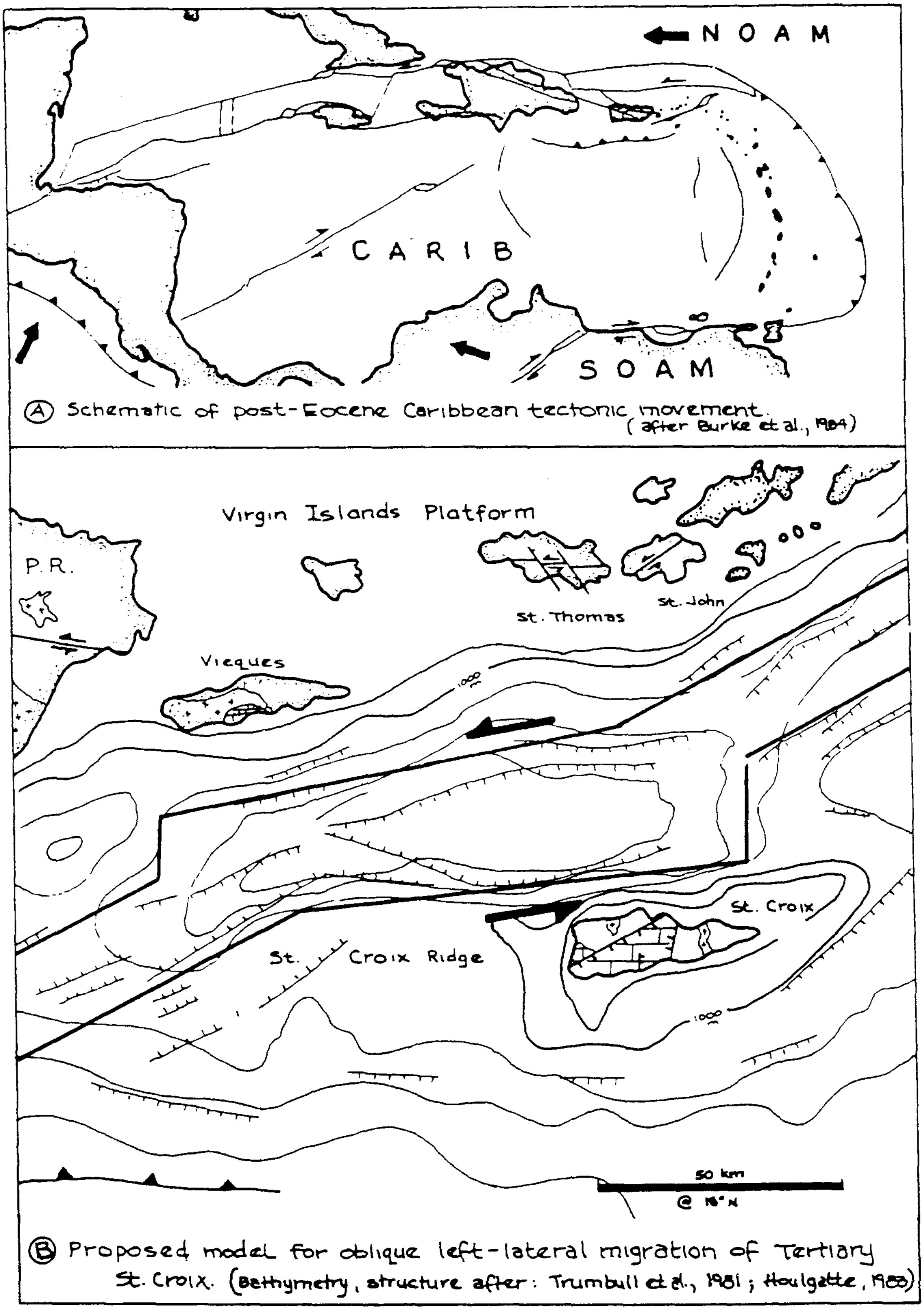
A sinistral transtensional model for the Virgin Islands Basin and the Anegada Passage is most consistent with the structural and sedimentological characteristics of St. Croix. Such a model satisfies structural evidence on St. Croix such as the consistent northeast-southwest orientation of the normal fault system, as well as the requirement for an extrabasinal source of sediments. In addition, a left-lateral motion is consistent with the position of the fault scarps in the Virgin Islands Basin, sinistral faulting in St. John and St. Thomas, as well as the location of the closest likely sediment source. From a regional standpoint, a sinistral-motion model provides the simplest explanation for the kinematics of the northeastern Caribbean region and is consistent with recent work defining the Puerto Rico microplate (e.g. McCann *et al.,* 1987).

Dextral slip in the Anegada Passage is supported by several recent papers (e.g. Houlgatte, 1983; Mauffrey *et al.,* 1986; Stephan *et al.,* 1986; Jany *et al.,* 1987), but lacks the support of structural evidence. Seismic sections across the Virgin Island Basin (Fig. 12) confirm ubiquitous normal faulting, but do not show evidence of strike slip movement. In addition, such a model requires several complicating *ad hoc* assumptions to make it fit the known characteristics of the area, including a mechanism for reversing the direction of slip in the fault zone, and some unspecified means of translating compressional stress along the length of the Muertos Trough. While it is certainly possible that a reversal of slip direction has occurred since the Pliocene, such a reversal has not been recorded by deformation in the Tertiary strata of St. Croix.

Our position, from the context of St. Croix geology, is that St. Croix was initially part of the Virgin Islands Platform and that motion along the Anegada Passage was left-lateral and transtensional throughout most of the Tertiary. Whether subsequent motion in the Virgin Islands Basin was right-lateral remains neither proved nor disproved, and proof awaits earthquake fault-plane solutions or better seismic sections. However, from our perspective, a fault-movement reversal without producing compression in the Virgin Islands Basin or on St. Croix is unlikely.

CONCLUSIONS

1) St. Croix is not a product of vertical tectonic motion alone, and has not remained stationary throughout the Tertiary. Instead, we suggest that St. Croix has been separated from a larger land mass by transtensional faulting. Puerto Rico and the Virgin Islands Platform, as well as Saba Bank and Anguilla are possible source



Ⓐ Schematic of post-Eocene Caribbean tectonic movement. (after Burke et al., 1984)

Ⓑ Proposed model for oblique left-lateral migration of Tertiary St. Croix. (Bathymetry, structure after: Trumbull et al., 1981; Houlgatte, 1983)

Figure 11. *Left-lateral plate motion model. A NOAM = North American Plate; SOAM = South American Plate; CARIB = Caribbean Plate. B Oblique left-lateral model for St. Croix and the V. I. Basin. Note that major Tertiary faults on St. Croix are aligned at roughly 30 and 60 degrees to the orientation of the V.I. Basin. Normal faults on St. Croix Ridge parallel those on the island.*

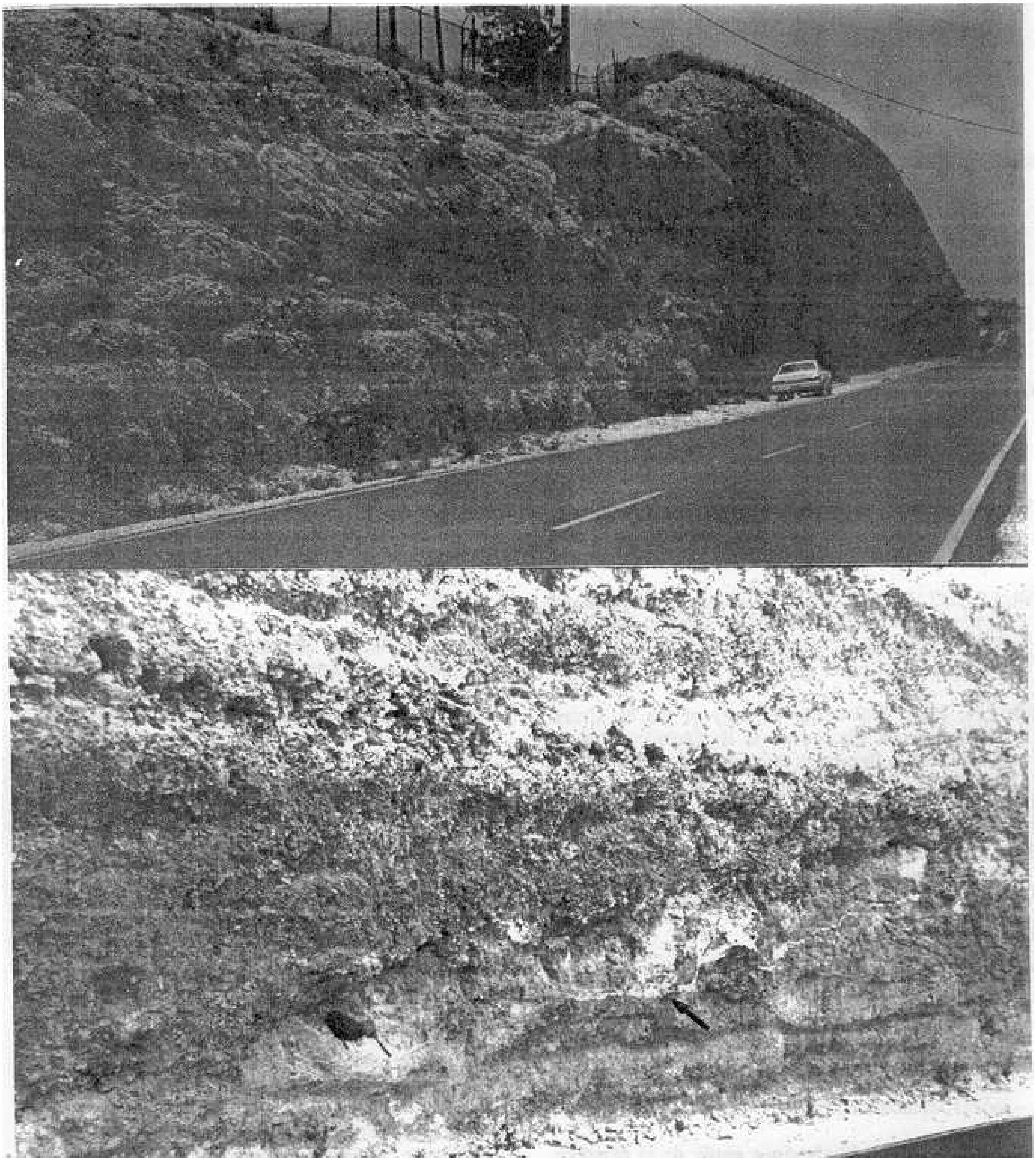


Figure 16. Photographs of the Hess Cut outcrop. Upper photo: oblique view looking north-northwest, rent-a-wreck for scale. Apparent "bedding" dipping from upper left to lower right is actually bulldozer scarring. Lower photo: Hardground and exposure surfaces in the Blessing Formation reef tract. Rock hammer and field book for scale.