Sedimentological and Tectonic Evolution of Tertiary St. Croix

Ivan Gill
Peter MacLaughlin
Dennis Hubbard
Clyde Moore

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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

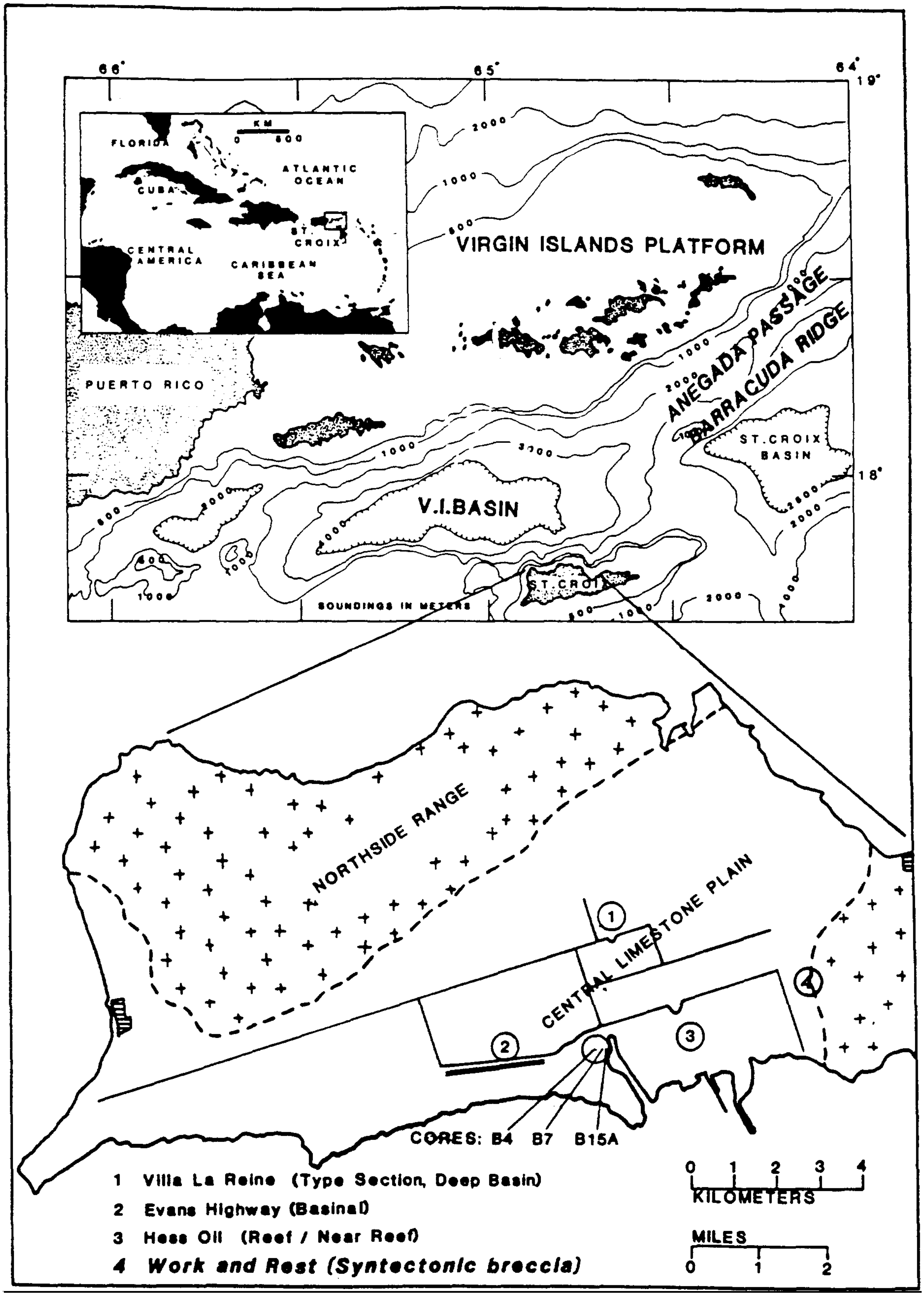

Figure 1. St. Croix location map and study area.

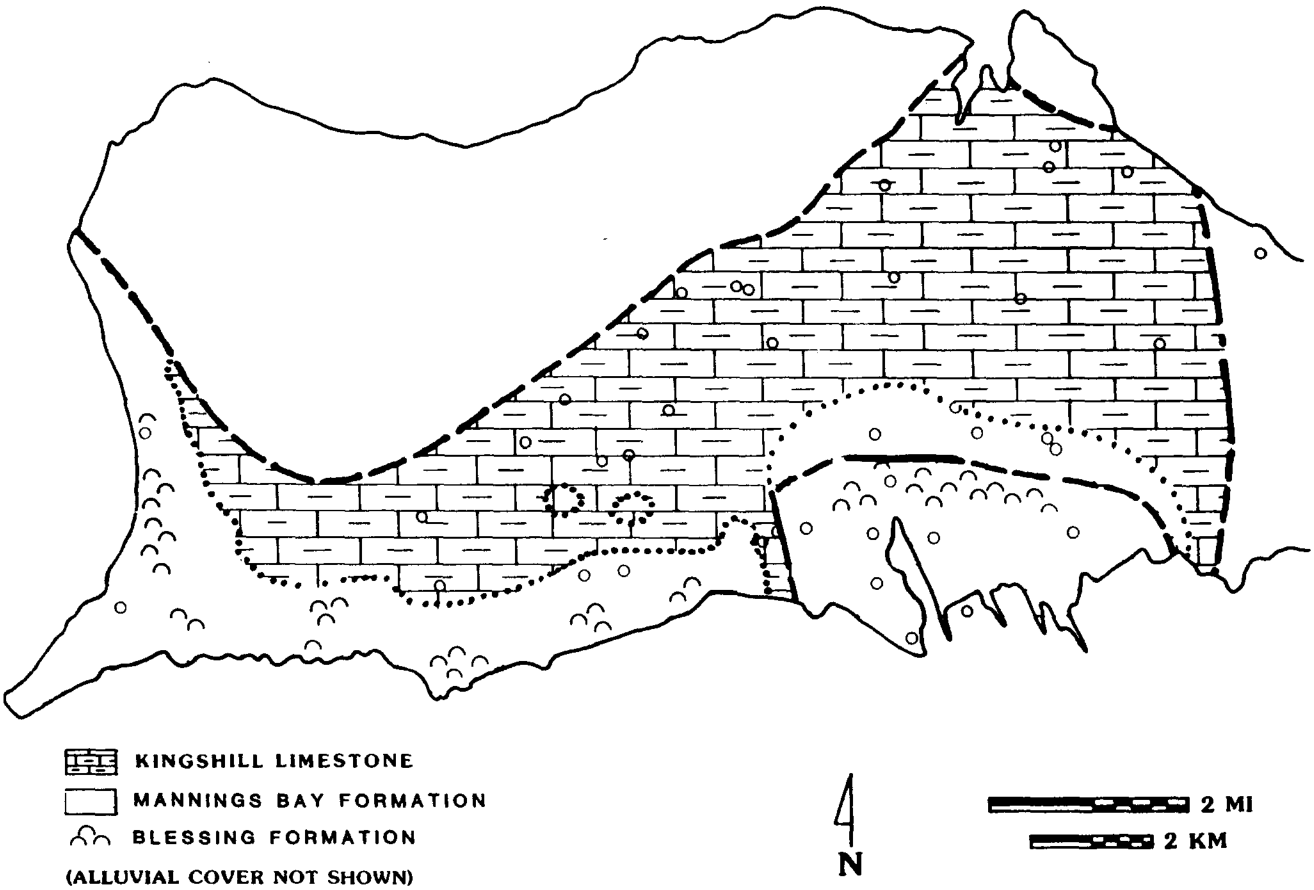

Figure 2. *Generalized geologic map of St. Croix. Exposed strata mapped as Jealousy Formation by Whetten (1966) are re-mapped as Kingshill Limestone in this dissertation.*

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

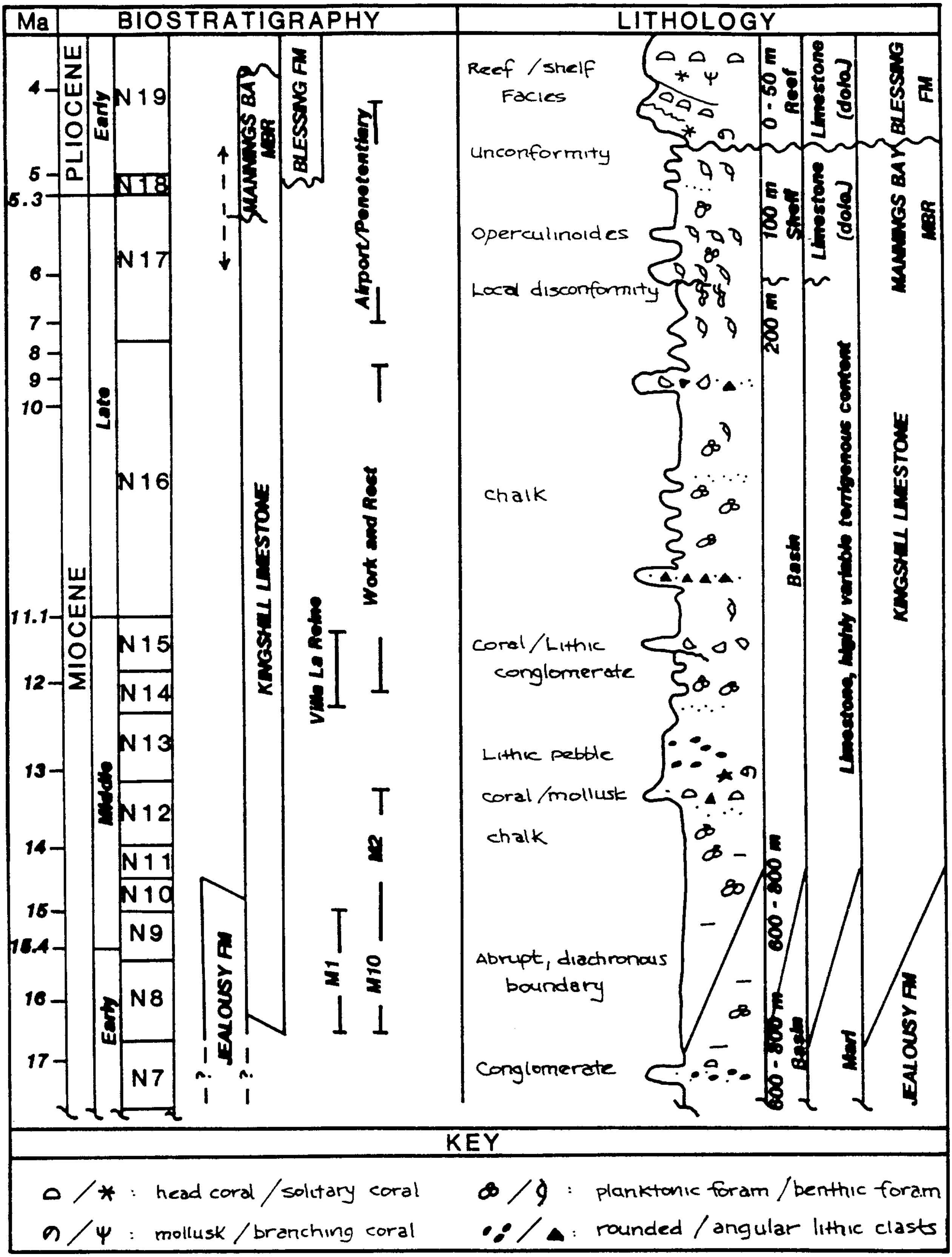

Figure 3. *Expanded stratigraphic column showing the St. Croix Tertiary section, including chronologic, biostratigraphic and lithologic characteristics.*

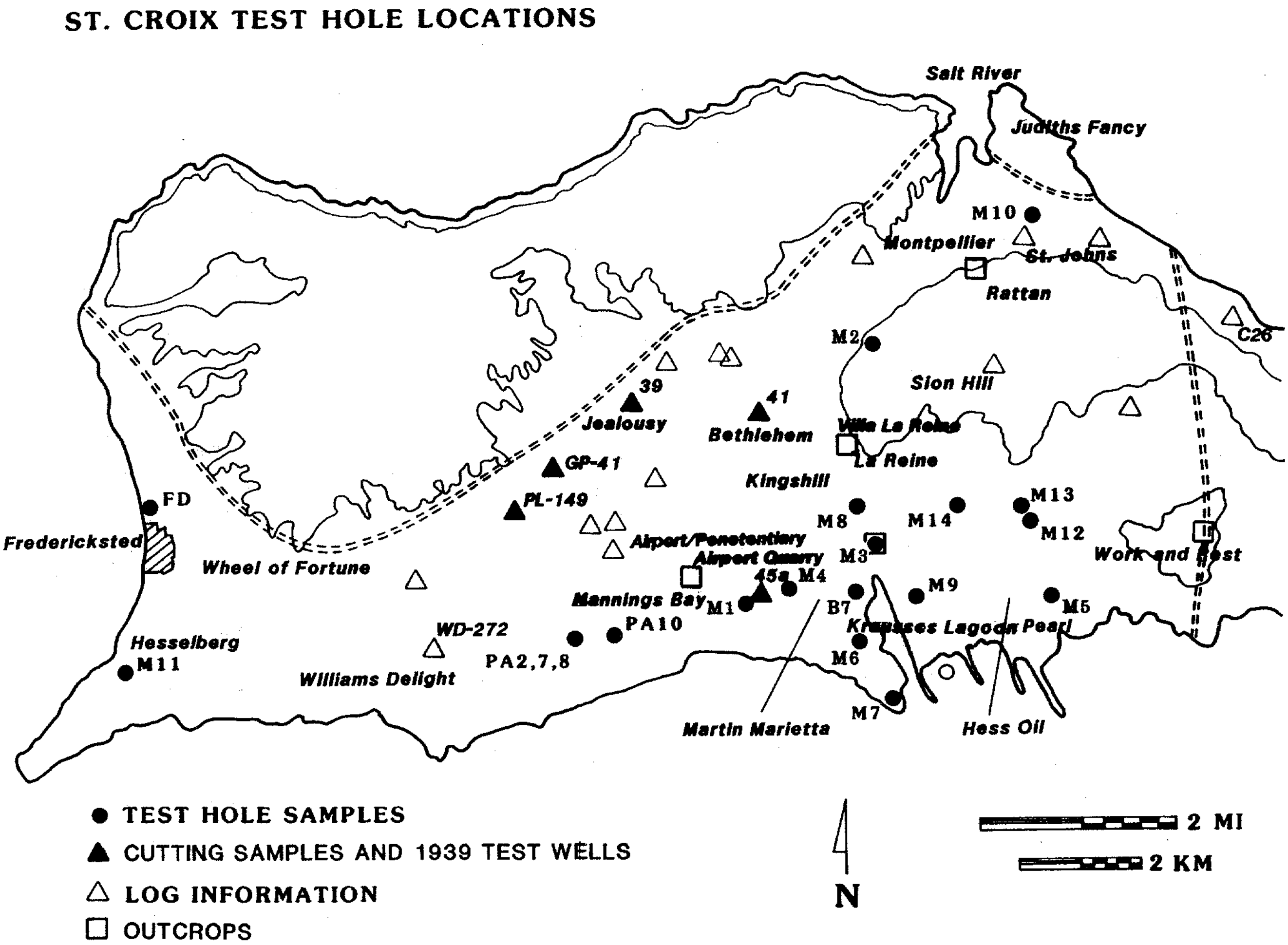

Figure 4. *Locations of outcrops, test holes and water wells used in the stratigraphic cross sections.*

were essentially unlithified, and the samples used for benthic and planktonic foraminiferal analysis contained nearly pristine tests.

LITHOLOGY AND BIOSTRATIGRAPHY

Jealousy Formation

Previous interpretations - The type section for the Jealousy Formation is defined as the interval penetrated by the deepest test well drilled by the Civilian Conservation Corps in 1939 (Test Well 41, Fig. 4). This well penetrated more than 426 m of Jealousy Formation sediments (Cederstrom, 1950), which gravity surveys indicate may be as much as 2000 m thick (Shurbet *et al.*, 1956). The Jealousy Formation type section was described by Cederstrom (1950, p 19) as 1398 ft of dark, blue-grey clayey strata interupted by calcareous conglomeratic deposits of Mt. Eagle Group volcanics.

Multer *et al.* (1977) interpreted the Jealousy Formation as an Oligocene estuarine deposit. The sediment source for the Jealousy Formation was assumed to be the exposed horst blocks of the Northside and Eastend Ranges, then exposed as two islands (Multer *et al.*, 1977; Gerhard *et al.*, 1978). However, Gerhard *et al.* (1978) noted the possibility that an external sediment source may have been required to account for the great thickness of the Jealousy Formation.

Results - The age of the Jealousy Formation has been overstated. Samples from the Jealousy Formation range from upper lower Miocene (N8) to lower middle Miocene (N10). Since no documented Jealousy Formation strata extend beyond the early Miocene, the Jealousy Formation is most accurately referred to as a Miocene and not an Oligocene unit. However, it is likely that the Jealousy Formation extends into the Oligocene or earlier, given a potential thickness of 1800 m (Shurbet *et al.*, 1956).

Jealousy Formation samples were uniformly blue-grey, planktonic-foraminiferal muds, and are still unlithified. In all of our samples, Jealousy Formation sediments are dominantly calcite, with significant components of quartz, feldspars and clay minerals. Insoluble residues from the Jealousy Formation range from 30 to 51%, and powder-mount x-ray diffractograms from the Jealousy Formation are indistinguishable from diffractograms from the immediately overlying Kingshill Limestone described below. Based on these preliminary data, the mineralogy of the Jealousy Formation does not change within the basin, or within the stratigraphic

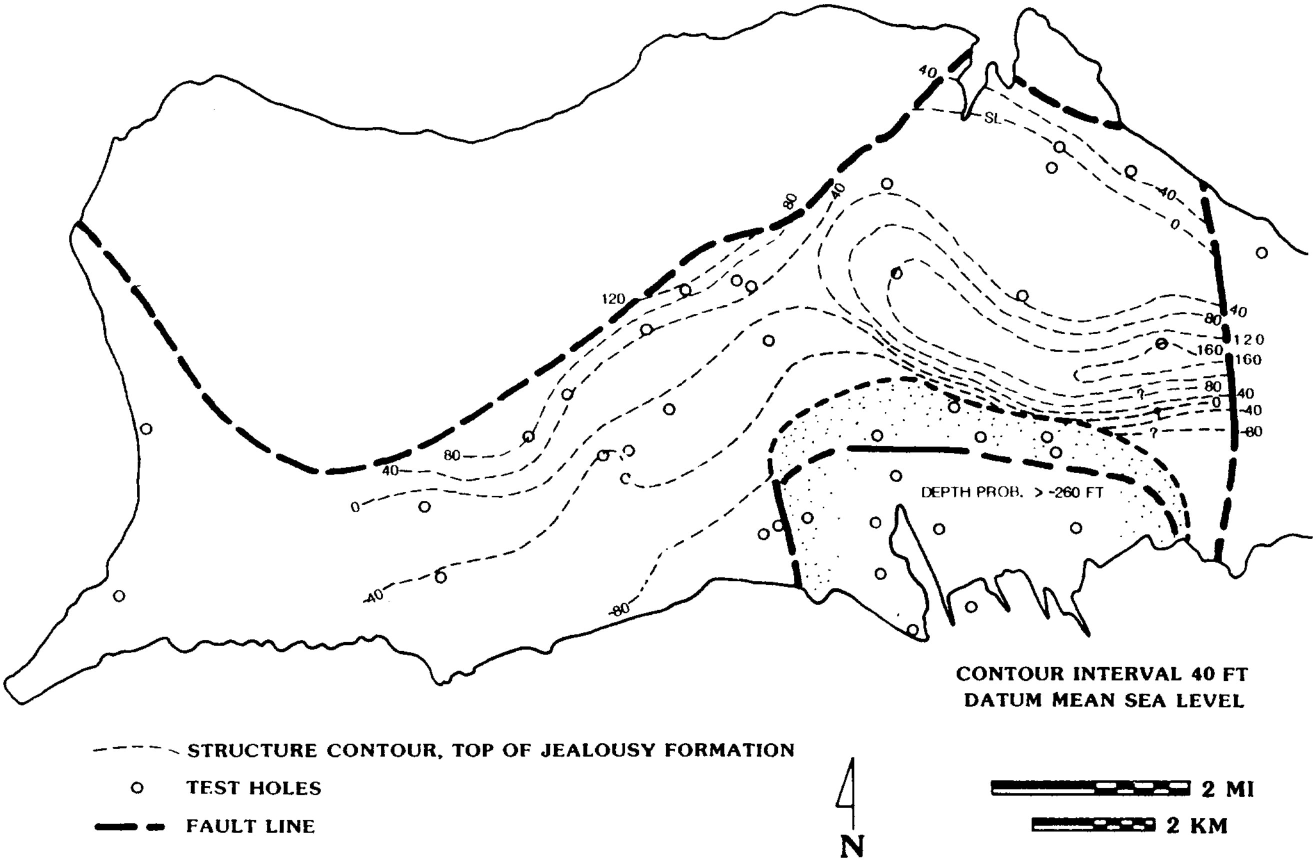

***Figure 5.** Structure map: top of the Jealousy Formation. Well control is sparse along the eastern fault boundary of the Tertiary limestones. No Jealousy Formation sediments were encountered within the southeastern coastal section of the Central Plain, which is a graben or demi-graben structure. Depth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

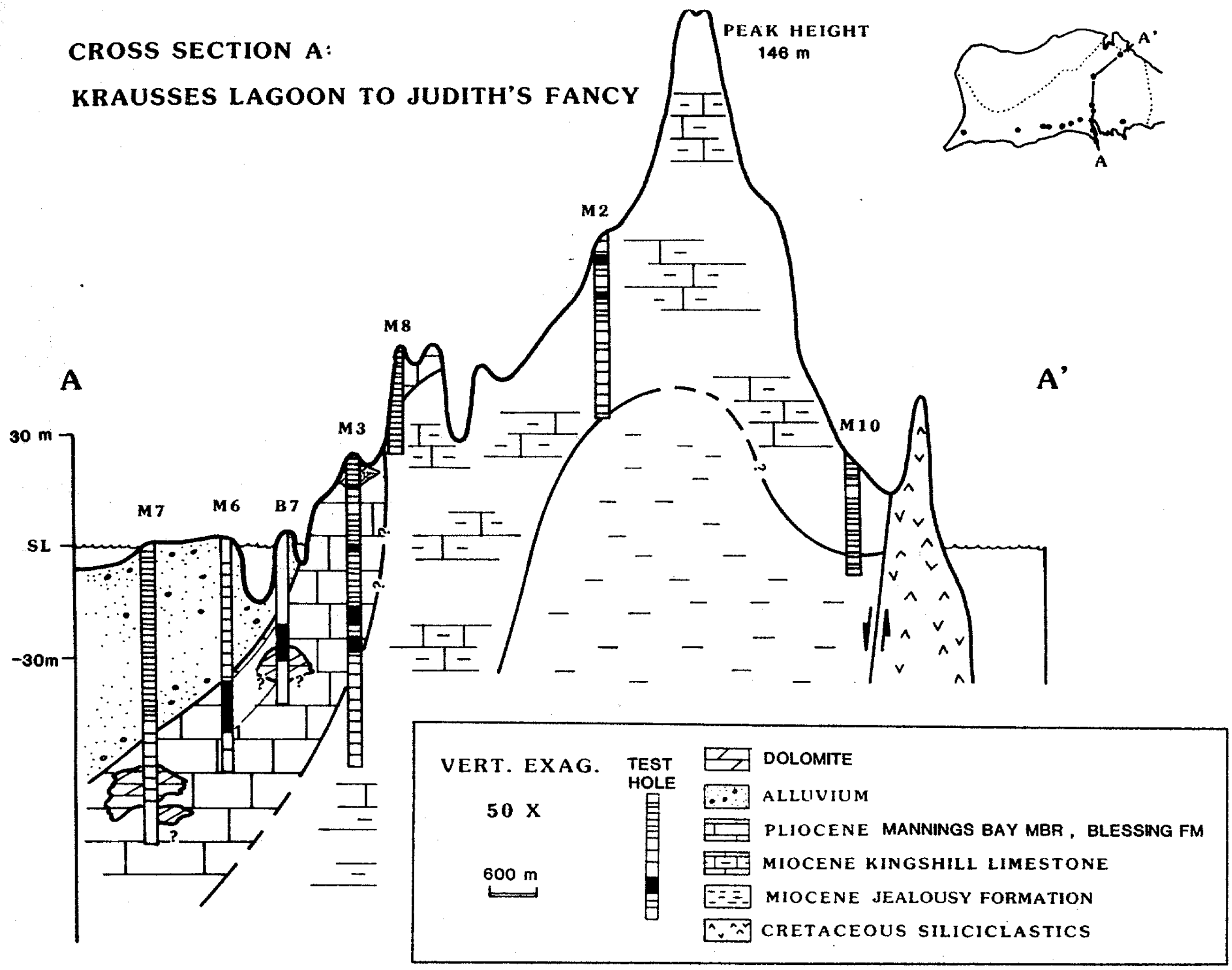

Figure 6. *Cross section A-A': Krause Lagoon to Judiths Fancy. Note that the Jealousy Formation surface roughly follows the topography of the Kingshill Limestone. Sample depths are shown for each test hole. Dark intervals represent diamond-bit coring.*

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

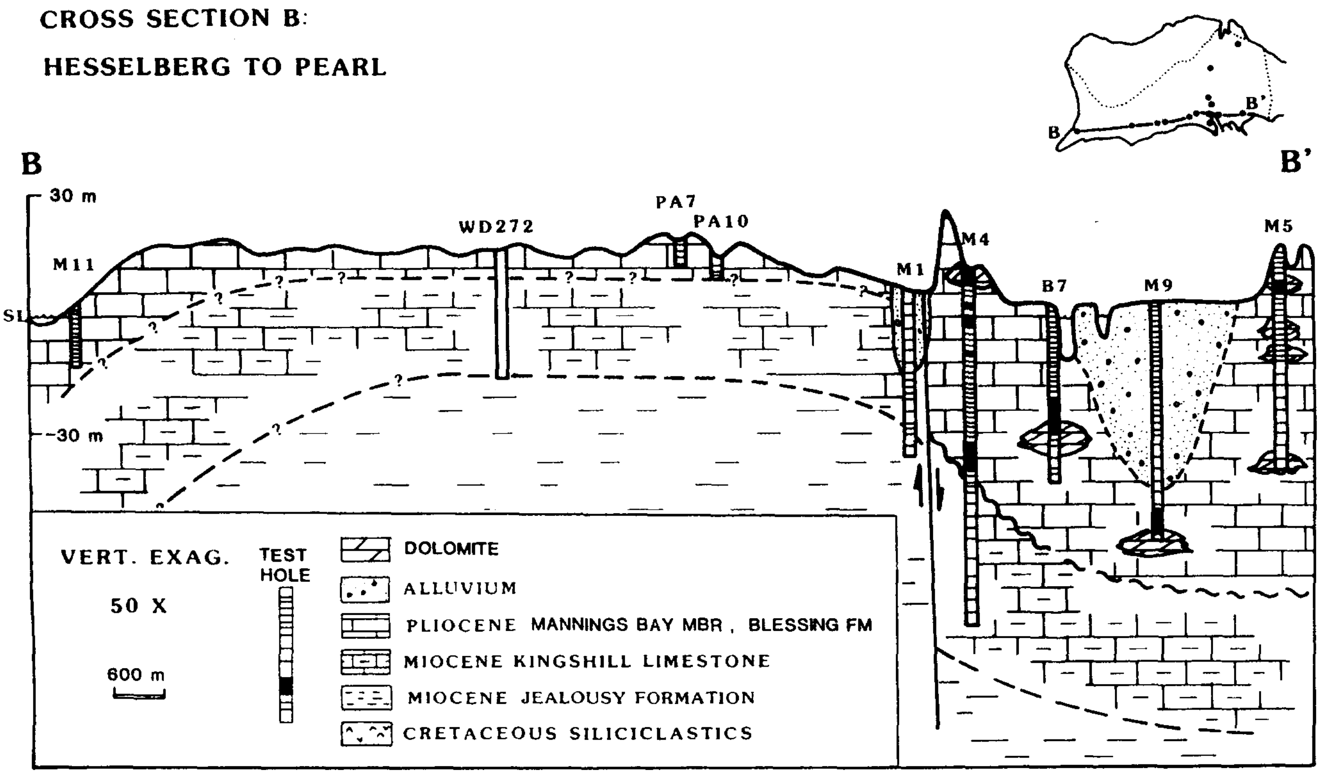

Figure 7. *Cross section B-B': Estate Hesselberg to Pearl. A normal fault forming the western boundary of the subsidiary graben block occurs between test holes Ml and M4. The Jealousy Formation was not reached to the east of this fault. Solid intervals represent diamond-bit coring.*

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-

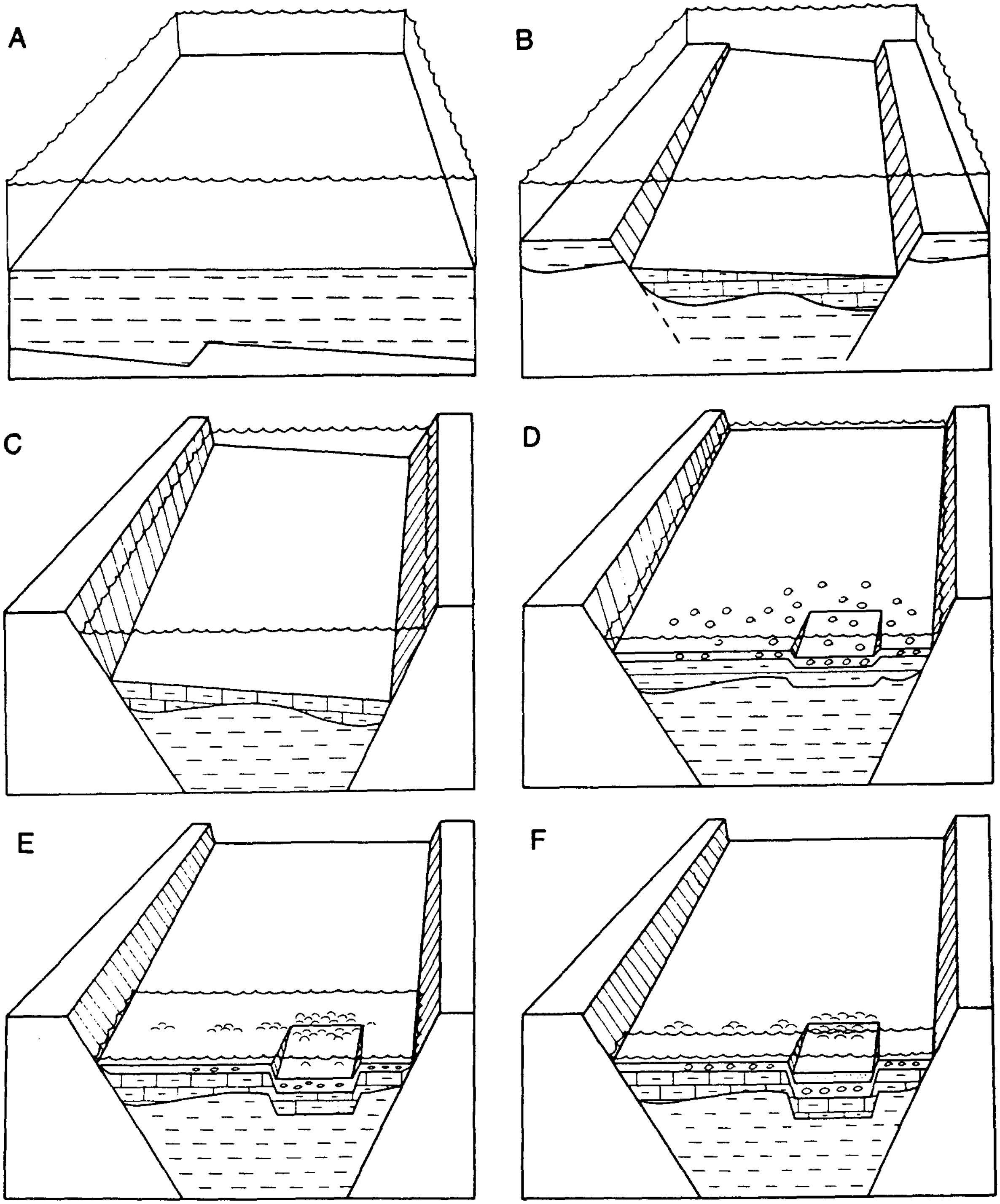

Figure 8. *Block models of St. Croix during the early Miocene.* ***A*** *. Deposition of the Jealousy Formation in the early Miocene prior to formation of the graben system.* ***B*** *Deposition of the lower Kingshill Limestone in the latest early Miocene shortly after initiation of graben faulting. Note Jealousy Formation sediments on the horst blocks.* ***C*** *Deposition of the Kingshill Limestone in the middle Miocene.* ***D*** *Deposition of the Mannings Bay Formation foraminiferal banks in the latest Miocene to early Pliocene and initiation of faulting in the subsidiary graben along the southern coastline. E. Establishment of the Blessing Formation Reef Tract, early Pliocene.* ***F*** *Emergence and resubmergence of the Blessing Formation reefs.*

colored Kingshill Limestone and the blue-grey Jealousy Formation is abrupt but diachronous.

Based on powder-mount x-ray difractograms, the mineralogy of the lowermost Kingshill Limestone is not detectably different from that of the immediately underlying Jealousy Formation. The marked color contrast between the upper Jealousy Formation and the lowermost Kingshill Limestone does not reflect a significant change in either age, depositional pattern or mineralogy. The two units represent a continuous record of deposition, and the cause and significance of the color change between the Kingshill Limestone and the Jealousy Formation is unknown.

The lower Kingshill Limestone in the St. John/Judiths Fancy area has been interpreted by Gerhard *et al.* (1978), Lidz (1982) and Andreieff *et al.* (1986) as shelf and lagoon deposits. These interpretations were based on the presence of rounded terrigenous gravel, as well as a shallow-water fauna that includes molluscs, corals, echinoids and benthic forams. However, these deposits are bracketed above in outcrop, and below in Test Well M10 (Fig. 4), by pelagic and hemipelagic carbonates.

The benthic foraminifera of the Kingshill Limestone in Test Wells M1, M2, and M10 differ little from those of the underlying Jealousy Formation, and do not reflect any significant environmental shifts. Like the Jealousy Formation, the Kingshill Limestone was deposited in the upper part of the middle bathyal zone, between 600 and 800 m. Significant basinal shallowing does not occur until close to the top of the formation at the Mannings Bay member boundary. A more complete description of the benthic foraminiferal faunas can be found in McLaughlin *et al.* (in prep.) and Gill (1989).

The maximum thickness of Kingshill Limestone encountered during this project is about 140 m (Fig. 6) which is less than the 180 m maximum extrapolated by Cederstrom (1950). Isopach patterns reveal three major trends: 1) pinching out toward the north and northwest margins of the basin; 2) pronounced thickening in the carbonate highlands close to the northern coast of St. Croix; 3) gentle thickening toward the south of the basin, interrupted by post-depositional faulting along the south coast (Fig. 9). In general, Kingshill Limestone thickness patterns follow the trends shown by the Jealousy Formation structure map (Fig. 5).

Stratigraphic relationships are illustrated in Figure 7. The Jealousy Formation underlies the Kingshill Limestone across most of the south coast of St. Croix. The position of the Kingshill Limestone/Jealousy Formation contact is unknown west of Estate Williams Delight due to poor core control, and east of Test Hole Ml in Estate Anguilla due to faulting within the Tertiary section between Test Holes Ml and M4 (Figs. 4, 7).

The contacts between the Kingshill Limestone and the underlying Cretaceous rocks are interpreted as faults by Whetten (1966) and Multer *et al.* (1977). The northwestern contact in the Northside Range is mostly obscured by alluvial cover (Fig.2) and Gerhard et *al.* (1978) suggest that there was less displacement here than along the eastern basin margin.

Interpretation - The lowermost strata of the Kingshill Limestone recovered in core samples were deposited in the same bathyal conditions as the immediately underlying strata of the Jealousy Formation (Fig. 8b). There are no changes in sediment character, and no changes in basin depth. Tectonic or eustatic changes, if they occurred in this period, either were not substantial enough to be detectable, or cancelled each other out. The origin of the sharp color change between the two formations remains undetermined, but may reflect differences in clay mineralogy or diagenetic effects.

Gerhard (1978), Lidz (1982), and Andreieff *et al.* (1986) called for extensive shallow-water environments to prevail during deposition of Kingshill sediments in the St. John and Salt River areas (Fig. 4). However, we disagree with this interpretation because these sediments are over- and underlain by deep basinal Kingshill sediments, and lie in close proximity to other obviously transported sediments close to the fault in the Northside Range. It is more reasonable to assume that the Kingshill Limestone deposits in the St. John/Salt River areas are allochthonous, and deposited at bathyal depths. To interpret these outcrops as *in situ* shelf accumulations would require a 600-m shallowing from bathyal depths to shelf conditions, followed by a drop back to bathyal depths. This tectonic history is complex, and is not documented anywhere else in the basin.

Shallowing of the Kingshill-Jealousy Basin only becomes apparent upsection at the southern edge of the Central Plain. Here the Kingshill Limestone contains increasing quantities of shelf-derived sand, is burrowed, and is capped by an intraformational disconformity that underlies the Mannings Bay member. These features are discussed in more detail in the section on the Airport/Penetentiary outcrop. The presence of a planktonic foraminiferal fauna that includes both shallow- and deep-water forms implies that the deposition of the uppermost Kingshill Limestone occurred in approximately 200 m of water (McLaughlin *et al.,* in prep; Gill, 1989).

The fault relations between the Kingshill Limestone and the Cretaceous strata on the eastern boundary fault indicate that the Kingshill Limestone existed prior to basin faulting (Gill and Hubbard, 1986; 1987). We suggest that initiation of the St. Croix normal-fault system occurred after the late early Miocene, on the basis of evidence discussed earlier (Fig. 8b). However, it is not clear that the basin fault boundaries had formed during the deposition of the Kingshill Limestone, or that the bounding horst blocks were exposed during this time. Gerhard *et al.* (1978) supported the exposed horst model by interpreting exposures along the eastern fault boundary as syntectonic breccias. If the terrigenous clasts in the Kingshill are indeed derived from Mt. Eagle Group strata, then the graben boundaries must have formed no later than

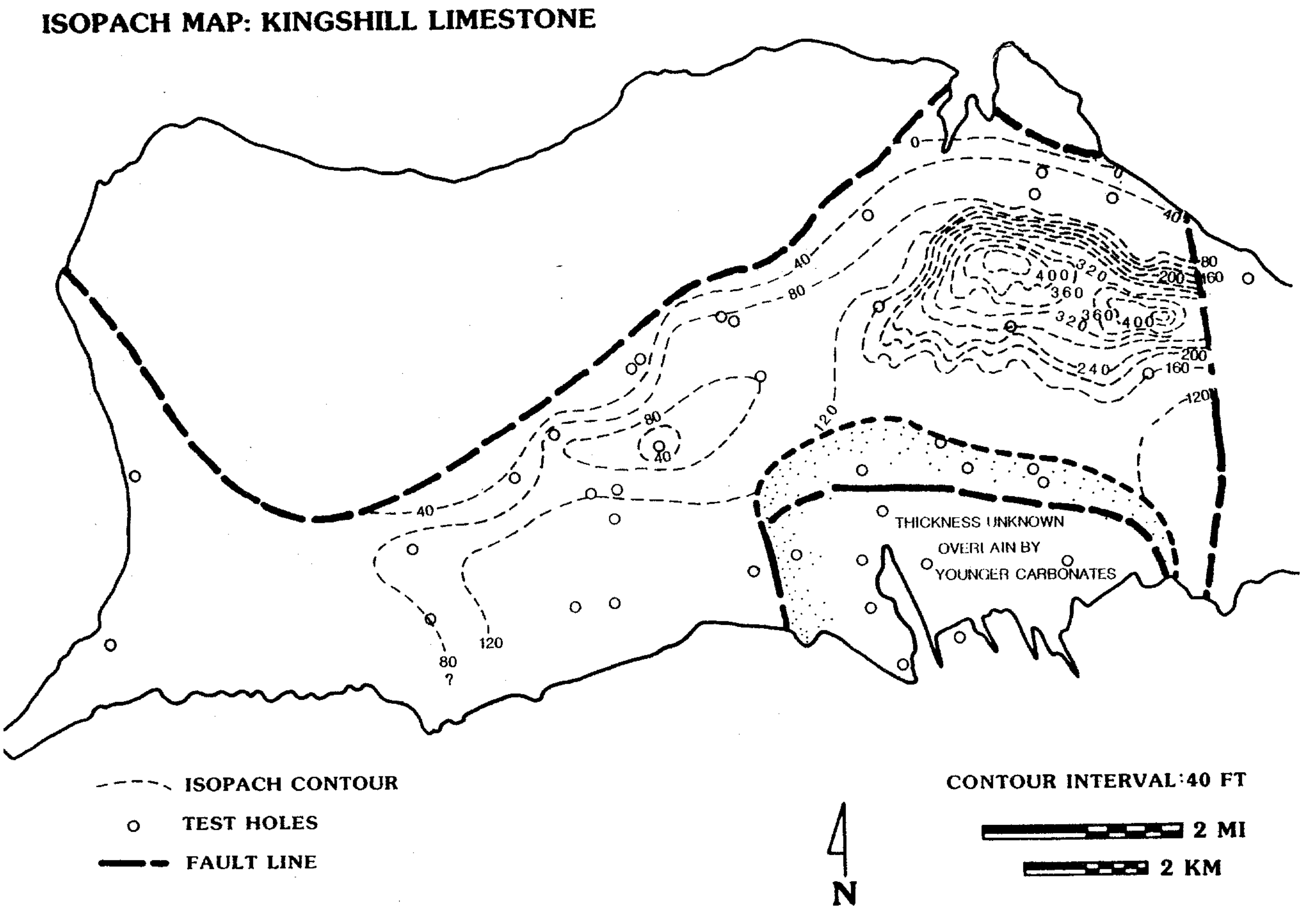

Figure 9. Isopach map of the Kingshill Limestone; the contoured area represents the Central Limestone Plain region. The thickest known areas of the Kingshill Limestone correspond with areas of high topographic relief. If the hilly limestone areas were produced structurally, they have not existed long 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.

The presence of both shallow planktonic foraminifera as well as poorly developed deep-water forms suggests deposition in approximately 100 m of water (McLaughlin *et al.,* in prep; Gill, 1989).

The Mannings Bay member unconformably overlies the lower strata Kingshill Limestone in one outcrop, and underlies the reef and lagoon facies that comprise the Blessing Formation. Large thicknesses of Mannings Bay strata are preserved in a small down-dropped block (Gill and Hubbard, 1986, 1987). The western margin of this block is marked by a normal fault between Test Holes Ml and M4, with a minimum vertical displacement of approximately 30 m. (Fig. 7). The actual vertical displacement may be as high as 80 m, based on correlating the Kingshill/Mannings Bay boundary in outcrop and in Test Hole M4. However, the boundaries between the Kingshill Limestone and the Mannings Bay member are difficult to locate with precision in core material.

Interpretation - The unconformable contact between the underlying Kingshill Limestone and the Mannings Bay member signals both basin shallowing and the development of a shallow-water source of larger benthic forams, in particular *Operculinoides cojimarensis* and *Paraspiroclypeus chawneri..* However, due to the lack of karsting, soil development or significant missing section, we do not agree with Lidz' (1984) suggestion that the disconformity is caused by subaerial exposure. Rather, it represents submarine erosion caused by the deposition of coarse, shelf-derived gravity deposits.

The nummulitid foram-algal facies of this member marks a period of deposition when shallow-water carbonate production was dominated by benthic forams and coralline algae at the expense of scleractinian communities. These deposits mark basin shallowing from bathyal depths to outer platform or upper slope environments of around 100 m water depths (Fig. 8d).

The amount of shallowing indicated by the Mannings Bay member is too large to be explained by either basinal fill or eustatic change alone, and must have been caused primarily by tectonic uplift. Neglecting eustatic variation, the Kingshill-Jealousy Basin shallowed from approximately 750 m of water depth in the middle Miocene to approximately 100 m water depth in the lower Pliocene (N17). The rate of uplift suggested by these estimates is 650 m of vertical movement over roughly 9 million years. This translates to a mimimum uplift of 72 m/Ma, or slightly less than 0.1 mm/y.

These calculations assume even uplift from bathyal depths between the middle Miocene and the early Pliocene, and that the foraminiferal biozones on St. Croix are equivalent to the biozones established elsewhere in the Caribbean. This uplift culminated in the establishment of a Pliocene reef tract represented by the Blessing Formation.

Blessing Formation

Background and previous interpretations - The Blessing Formation, as described in this paper, has not had the detailed published discussion of the underlying units. Behrens (1976) described this section as two formations, the Annaberg and the Blessing Formations. We feel that Behrens' (1976) two formations are better described as individual facies within one formation. Multer *et al.* (1977) and Gerhard *et al.* (1978) briefly describe the lithology and the paleontology of the strata that overlie the Kingshill Limestone, and interpret the unconformity between the Blessing Formation strata and the underlying Mannings Bay Formation as indicative of exposure. Lidz (1982) and Andreieff (1986) assigned strata immediately below the Blessing Formation to the lower Pliocene.

Since the work of Gerhard *et al.* (1978) and Multer *et* al. (1977), much of the exposed Blessing Formation section has been removed by industrial development. The remaining exposures are concentrated in the Hess Oil and Martin Marietta industrial areas, with scattered, sparse outcrops to the west and in the town of Frederiksted. These exposures are assigned to the Blessing Formation on the basis of lithological and macrofaunal similarity, but biostratigraphic correlation by planktonic foraminifera has not been possible (McLaughlin *et* al., in prep).

Results - Deposition of the Blessing Formation occurred in the lower Pliocene (Lidz, 1982; Andreieff et al.,1986; McLaughlin *et al.,* in prep). This assignment is based on planktonic foraminifera and is further supported by stratigraphic position of the Blessing Formation relative to underlying units, and the occurrence of larger benthic forams and scleractinians.

Exposures and core samples of the Blessing Formation contain a macrofaunal assemblage represented by external molds of scleractinians, gastropods and pelecypods, as well as skeletal debris from forams, coralline algae and a wide variety of shallow-water invertebrates. The scleractinians include several extant genera *(Agaricia, Diploria, Montastrea, Siderastrea,* among others) as well as extinct solitary corals such as *Stylophora* spp., *Teliophyllia* sp. and *Thysanus* sp. In general, the different faunal assemblages within the Blessing Formation represent co-existing reef, forereef, and lagoon environments that extended along the southern and western coastlines of St. Croix.

The greatest accumulation of Blessing Formation sediments is found in the subsurface to the east of the Fairplain fault mentioned in the previous section. The thickness of the Blessing Formation in this area may reach 30 m and indicates that the fault activity controlled both the accumulation and preservation of reef facies. It should be noted that towards the western end of St. Croix, core control is poor and outcrop exposures are sparse. For this reason the age and nature of the reef facies in this area are speculative. Test hole locations are shown in Figure

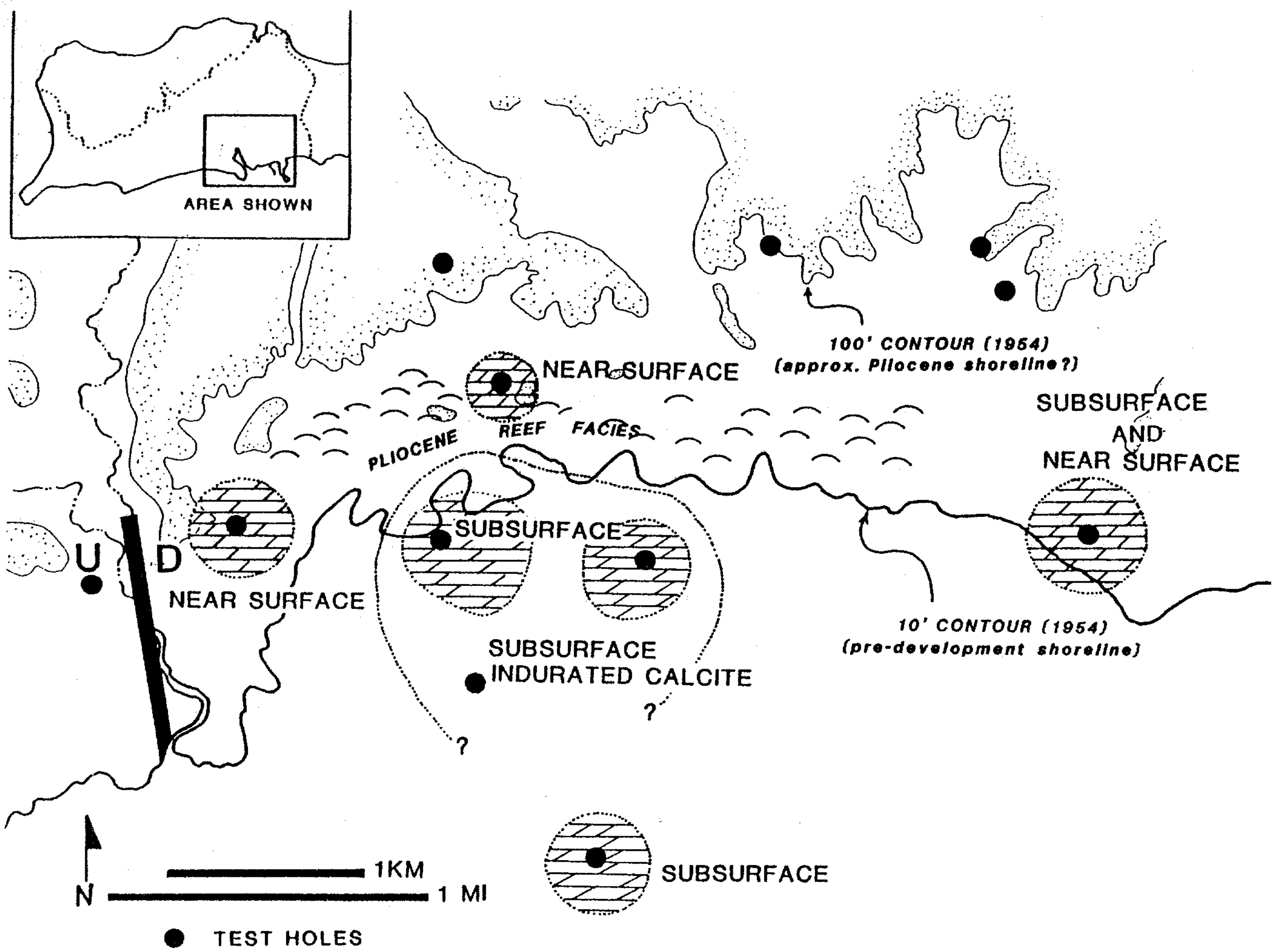

Figure 10. Facies map: south coast industrial area. Dolomite in the vadose zone or exposed in outcrop is distributed in an arcuate region following the Pliocene reef trend. Dolomite presently in the phreatic zone is found in off-shore facies. The western boundary of the subsidiary graben is well-defined 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 fades 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

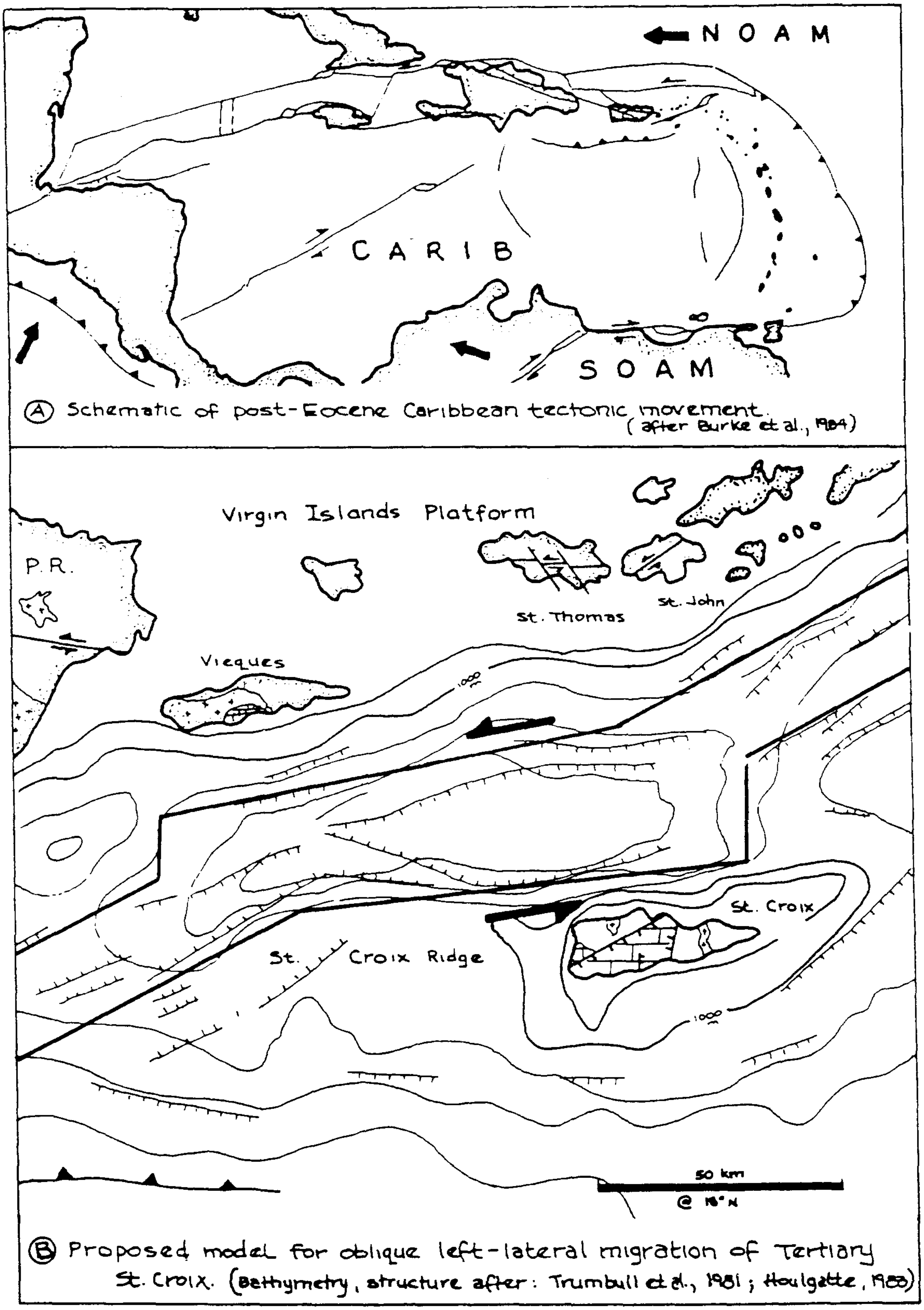

Figure 11. *Left-lateral plate motion model. A NOAM = North American Plate; SOAM = South American Plate; CARIB = Caribbean Plate. B Oblique left-lateral model for St. Croix and the V. I. Basin. Note that major Tertiary faults on St. Croix are aligned at roughly 30 and 60 degrees to the orientation of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

areas for the coarse, shelf-derived clasts in the lower Kingshill Limestone and the Jealousy Formation.

2) The Virgin Islands Basin is a strike-slip structure formed by sinistral faulting that rifted St. Croix away from the mainland along the Anegada Passage. Horizontal rifting rates were between 3 and 21 mm/y, but were probably close to 6 mm/y.

3) The Tertiary Kingshill-Jealousy Basin on St. Croix records bathyal deposition throughout its known sedimentary record until extensive shallowing occurred in the late Miocene to early Pliocene. Vertical uplift rates for St. Croix are estimated at between 0.1 and 0.2 mm/y. The Kingshill-Jealousy Basin was probably not a trough-like seaway until late in the Neogene, if at all.

4) Faulting did not occur in the boundary graben faults until the beginning of the middle Miocene at the earliest, but may have begun by the end of the middle Miocene. The horst blocks of the basin could not have been available as a sediment source for the Jealousy Formation, and an external source for these sediments was required.

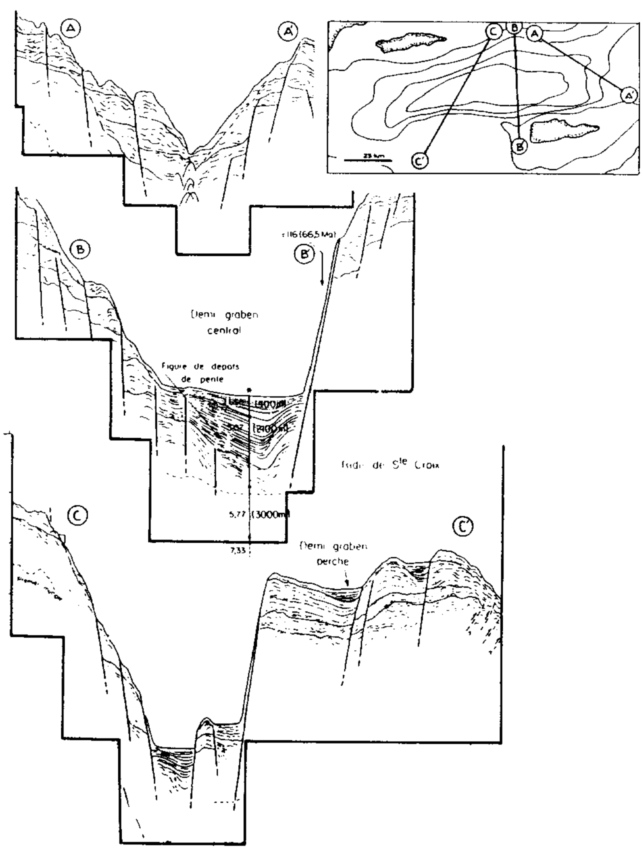

Figure 12. Seismic sections of varied orientation, showing the dominance of normal faulting within the Virgin Islands Basin (from Houlgatte, 1983).

5) The Jealousy Formation, which includes the majority of the sampled Tertiary section, is a Miocene unit that does not outcrop. The Jealousy Formation may extend into the Oligocene or earlier due to its thickness, but no Jealousy Formation samples older than the Miocene have been documented.

6) The Jealousy Formation is composed dominantly of deep-water planktonic foram tests and was deposited in water depths between 600 and 800 m. The Jealousy is not a shallow, estuarine unit.

7) The transition between the Jealousy Formation and the Kingshill Limestone is abrupt and distinct, but is time-transgressive and does not indicate any major bathymetric or other environmental change. There is no apparent paleontological or lithological difference between the lower Kingshill Limestone and the Jealousy Formation.

8) Recently suggested dextral strike-slip faulting for the origin of the Virgin Islands Basin, if it occurred, is not supported by structural or sedimentological evidence on St. Croix.

9) St. Croix had acquired its present shoreline configuration by the Pliocene, and an extensive reef and lagoon tract had established itself along the present western and southern shorelines.

10) Structural control of the coastline in the form of a subsidiary graben or demi-graben allowed the accumulation and preservation of reef and platform Pliocene sediments. Normal faulting has continued on St. Croix at least into the Pliocene.

KEY OUTCROPS ON ST. CROIX

Lower Kingshill Exposures

Kingshill Limestone strata occur in exposures in the Judith Fancy, St. John and Salt River areas. Most of these exposures are relatively poor, but contain rounded lithic pebbles and fossils with shallow-marine affinities (Gerhard *et al.,* 1978). The contact between the Kingshill Limestone and the underlying Cretaceous rocks is visible close to Judiths Fancy and on Scenic Road east. As discussed earlier, the carbonate rocks exposed in the Northside Range are probably best mapped as Kingshill Limestone rather than Jealousy Formation (Gerhard *et al.,* 1978; Gill and Hubbard, 1986).

In these locations, the Kingshill Limestone was interpreted to be deposited in lagoonal, littoral and patch reef environments (Gerhard *et al.,* 1978; Lidz, 1982; Andreieff *et al.,* 1986). However, these exposures are bracketed stratigraphically between deep basinal deposits in outcrop and Test Well M10. Barring undetected fault displacement, these exposures are probably best interpreted as allochthonous deposits, transported into deep water down steep slopes close to the northern terminus of the Kingshill-Jealousy basin. More extensive Kinghsill Limestone exposures have recently been created by construction of a subdivision in the Morningstar area.

Villa La Reine Outcrop

This outcrop was designated as the type section for the Kingshill Limestone by Gerhard *et al.* (1978), and exposes close to 23 m of Kingshill Limestone section (Fig. 13). The majority of the depositional facies and subfacies of the Kingshill Limestone are exposed behind the Villa La Reine shopping center and in nearby outcrops. The beds exposed here display rhythmic alternation between poorly consolidated chalks and thin *marly* and sandy beds (foraminiferal packstone and impure quartz arenite subfacies, respectively, of Gerhard *et al.*, 1978). The marly units tend to weather more easily, producing protruding chalk beds and inwardly eroded marls. This alternation is interupted at several locations by debris flows of lithic clasts and large coral heads with sharply defined bases (coral-lithic packstone subfacies of Gerhard *et al.*, 1978).

The debris flows erode into the underlying sediments and contain clasts that range from sand to boulder size. Many of the coral heads within the flows are well preserved and lack evidence of significant abrasion, prompting Gerhard *et al.* (1978) to suggest that the corals were alive immediately before deposition. The corals are preserved as recrystallized calcite, a mode of preservation common throughout the Kingshill Limestone, but in sharp contrast to the external molds and cavernous porosity that is typical for the corals in the Pliocene reef tract of the Blessing Formation. The extensive cementation of the coral heads and debris in the flows causes these facies to resist erosion and stand out as ledges throughout the central part of St. Croix.

The lithologic subfacies present in the Villa La Reine outcrop are common throughout the northern and central parts of the Kingshill-Jealousy depositional basin, but decrease in importance upsection, to the south. The large quantity of coral debris in the Kingshill Limestone in the central part of the basin prompted Cederstron (1950) and Whetten (1966) to interpret the Kingshill Limestone as a coral-reef deposit. However, deposits throughout the depositional basin contain benthic foraminifera indicative of bathyal depths between 600 and 800 m (McLaughlin *et al.*, in prep; Gill, 1989), and the outcrop relations indicate that the corals are allochthonous and deposited in deep, basinal conditions. The lenticular cross sections of the coral-head debris flows in the Villa La Reine section suggest channelization (Mutter *et al.*, 1977). However, similar beds occur throughout the basin as planar features up to 1 m thick, indicating that channelization was neither ubiquitous in the basin, nor necessary for transport of the coarse material.

The biostratigraphic placement of the type section has been interpreted differently by several authors. Based on planktonic foraminiferal data, we assign the Villa La Reine section to the upper middle Miocene (Fig. 3), in agreement with the conclusions of Andreieff *et al.* (1986), but differing significantly from the upper Miocene assignment of Lidz (1982). Details on the biostratigraphy of the St. Croix carbonate section can be found in McLaughlin *et al.* (in prep).

The Villa La Reine section has been interpreted as a deep basinal deposit in which pelagic sedimentation was interupted at intervals by shelf-derived sediment-gravity flows originating in the exposed Eastend Range (Gerhard *et al.*, 1978). The depostion of the sediment gravity flows was probably triggered by tectonic events or major storms (Muller *et al.*, 1977; Gerhard *et al.*, 1978). While this interpretation is not illogical, there is no compelling evidence to suppose that exposure had occurred by the middle Miocene either. Furthermore, given that the depth of the basin during deposition of the type section was between 600 and 800 m, the sides of the depositional basin would have been extremely steep, and could not have supported the reef systems required to supply the

***Figure 13**. Photograph of the Villa La Reine outcrop, type section of the Kingshill Limestone. Dr. Arnie Miller for scale.*

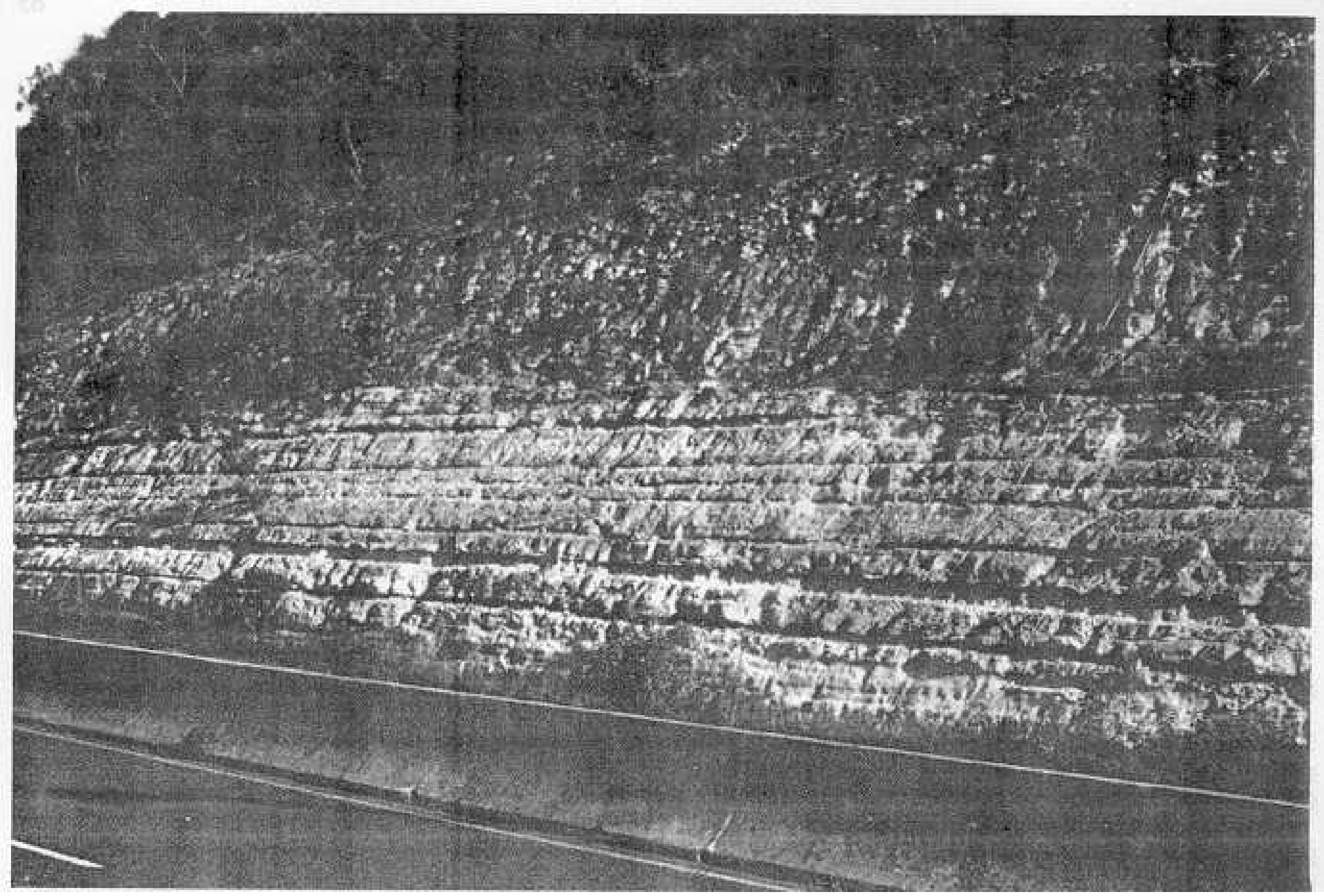

Figure 14. Photograph of the Airport/Penetentiary outcrop. Note the disconformity about midway up the outcrop (approx. 7 m above road level) corresponding to the Kingshill Limestone/Mannings Bay member contact.

volume of reefal sediment in the basin. We therefore propose that the Northside Range was not exposed during the late early Miocene deposition of the Jealousy Formation.

Evans Highway/Penetentiary Outcrop

This outcrop exposes the upper part of the Kingshill Limestone section as described by Gerhard *et al.* (1978). An unconformity in this outcrop separates the rhythmically bedded Kingshill Limestone from overlying, thinner-bedded limestones that were separated from the Kingshill Limestone by Lidz (1982) and are referred to here as the Mannings Bay member of the Kingshill Limestone (Fig. 14). The lower part of the exposure displays the ledge-and-reentrant weathering profile displayed in the Villa La Reine type section except that protruding beds in this outcrop are often graded with sharp, sandy bases. Also, the well-defined relationship between grain types and weathering characteristics of the La Reine outcrop is not obvious here.

Below the unconformity, the Kingshill strata display extensive bioturbation (Lidz, 1982) preserved primarily as sole marks of tracks and trails on the underside of protruding beds. Above the disconformity, the bedding is thinner, more convoluted and becomes massive toward the top of the exposure. Selective algal discoloration of the strata above the disconformity likely indicates a subtle lithological change. Beds containing abundant larger forams become thicker and commonplace above the unconformity. In addition, the simultaneous occurrence of *Operculinoides* and *Paraspiroclypeus* is noted only above the disconformity, interpreted as evidence of Pliocene deposition by Andreieff *et al.* (1986).

The Kingshill Limestone strata were assigned to the latest Miocene by Lidz (1982) and Andreieff *et al.* (1986), with the disconformably overlying Mannings Bay strata assigned to the early Pliocene. We suggest that the strata above the disconformity may be assigned to the Pliocene or to the uppermost Miocene, since the Pliocene assignment of Lidz (1982) is based primarily on planktonic foraminiferal absence criteria and may not be reliable in highly altered strata. Due to the difficulties in resolving the biostratigraphic placement of the section, the timing of this disconformity cannot accurately be restricted to the Miocene/Pliocene boundary or a Messinian eustatic drop. Additional detail on the biostratigraphy of these strata can be found in McLaughlin *et al.* (in prep) and Gill (1989).

The disconformity in this outcrop was interpreted by Lidz (1984) as evidence of exposure caused by basinal shallowing during a eustatic fall at the end of the Miocene. However, there is no evidence of subaerial exposure. Instead, the disconformity appears to be the result of submarine erosion caused by flows of shelf-derived sediment. The amount of missing section represented by the disconformity may not be significant, and the corresponding hiatus is not resolveable by biostratigraphy (McLaughlin *et al.,* in prep; Gill, 1989).

This exposure indicates that the Kingshill-Jealousy basin had shallowed to around 100 m since the deposition of Villa La Reine type section. The thick deposits of coral debris in the Villa La Reine cut are missing here, and are replaced in the upper part of the section by sediment-gravity flows of larger forams. Shallowing of the basin was caused primarily by tectonic uplift, which allowed the establishment of banks of *Operculinoides* and *Paraspiroclypeus* forams.

Airport Quarry Outcrop

This outcrop is located on the eastern end of Manning Hill just north of the Alexander Hamilton Airport runway, and exposes approximately 30 m of the Mannings Bay member and Blessing Formation strata (Fig. 15) (Behrens, 1976). We suggest this outcrop as a reference section for the Mannings Bay member of the Kingshill Limestone. These strata are the upsection continuation of the rocks exposed in the Airport/Penetentiary cut on the north side of Mannings Hill, just discussed. Operculinoid forams weather out of thin beds of Mannings Bay strata, and are the dominant clast in many of the beds. These strata are unconformably overlain by well-lithified Blessing Formation rocks. The Blessing Formation rocks contain scattered molds of molluscs, solitary corals such as *Teliophyllia* sp. and *Antillea* sp. as well as rhodoliths. The environment of deposition was shallow shelf, behind or between scattered reefs such as those exposed in the Hess Outcrop discussed below.

The contact between the Mannings Bay Formation and the Blessing Formation in this outcrop is marked by a disconfonnity, but it is not clear that there was subaerial exposure. The presence of Kingshill Limestone clasts in rhodolith cores within the Blessing Formation, as well as the geometry of the deposits, led Gerhard *et al.* (1978) to interpret the unconformable contact as subaerial.

This section reflects the continued shallowing of the Kingshill-Jealousy depositional basin. Basinal shallowing resulted in the establishment of shelf environments favorable to the growth of operculinoid forams, which were subsequently replaced by near-reef environments inhabited by molluscs, coralline algae, and sediment-tolerant corals. It is possible that subaerial exposure occurred between the establishment of these two environments. Outcrops exposing the Mannings Bay and Blessing Formation strata also exist to the east, along Evans Highway to the east of Airport road as it cuts through a hill on the way to Martin Marietta and the Hess Refinery.

Hess Oil Outcrop

This outcrop is more than 400 m long, and is the largest exposure of the Blessing Formation Pliocene reef tract (Fig. 16). Other nearby exposures of the reef tract exist within the Martin Marietta plant to the west, and reveal that reef growth was extensive within the area now occupied by the Hess Oil Refinery and the Martin Marietta plant. Extensive reef outcrops existed within the Hess Oil Refinery, but these have been removed by subsequent industrial development (Gerhard *et al.,* 1978; Frost, pers. comm., 1984). Further evidence of extensive reef growth within the area now occupied by the Hess Refinery are the boulders of well-cemented reef material that were excavated from the refinery during construction. These boulders now form much of the seawall and jetty structures on the eastern side of the refinery.

To the west, outcrops of reef and shallow shelf facies exist on the top of Manning Hill in the airport outcrop and in scattered meager exposures on the newly completed extension of Evans Highway and in Frederiksted. Test Hole M3 penetrates through the Blessing Formation strata in the Hess Outcrop from near the highest point of the outcrop to 85 m subsurface (58 m below sea level). Similar strata exist in Test Well M11 in West End Salt Pond (Fig. 4), indicating that reef growth extended along the western shoreline as well (Fig. 2).

Bedding in the Hess Outcrop is massive, and facies relations have become obscured by weathering as the exposure ages. Excavation artifacts -- bulldozer scars -- are common in this outcrop, and are easily confused with natural bedding. Natural surfaces within the outcrop represent 1) subaerial exposure 2) submarine pavements or hardgrounds and 3) unconformity and onlap. The first type of surface is characterized by a convolute, undulating surface with deep pits. These "karst pits" (Lidz, 1982) are generally filled with fine micrite, presumably the product of vadose weathering. The exposure surface is marked by a well-cemented layer of calcite that shows a sharp, stable isotopic deviation toward light values of both carbon and oxygen.

The bedding planes interpreted as submarine pavements are characterized by inclined surfaces marked with spherical to hemispherical voids ranging from 10 to around 25 cm in diameter (Fig. 16). The interiors of the hemispherical voids display external molds of head coral calyxes, some of which can be identified to genus. Fine details are rapidly being lost to weathering, but these layers represent growth surfaces and thin reef veneers that supported head coral growth during development of the Pliocene reef tract. The surfaces dip to the south at varying angles, with dips increasing generally toward the northern end of the outcrop. It is not possible to separate tectonic from depositional dip, and these surfaces reflect both the general southerly dip of St.Croix due to differential uplift, as well as reef and forereef progradation. The direction of progradation was toward the south, and the Pliocene shoreline was to the north of this outcrop.

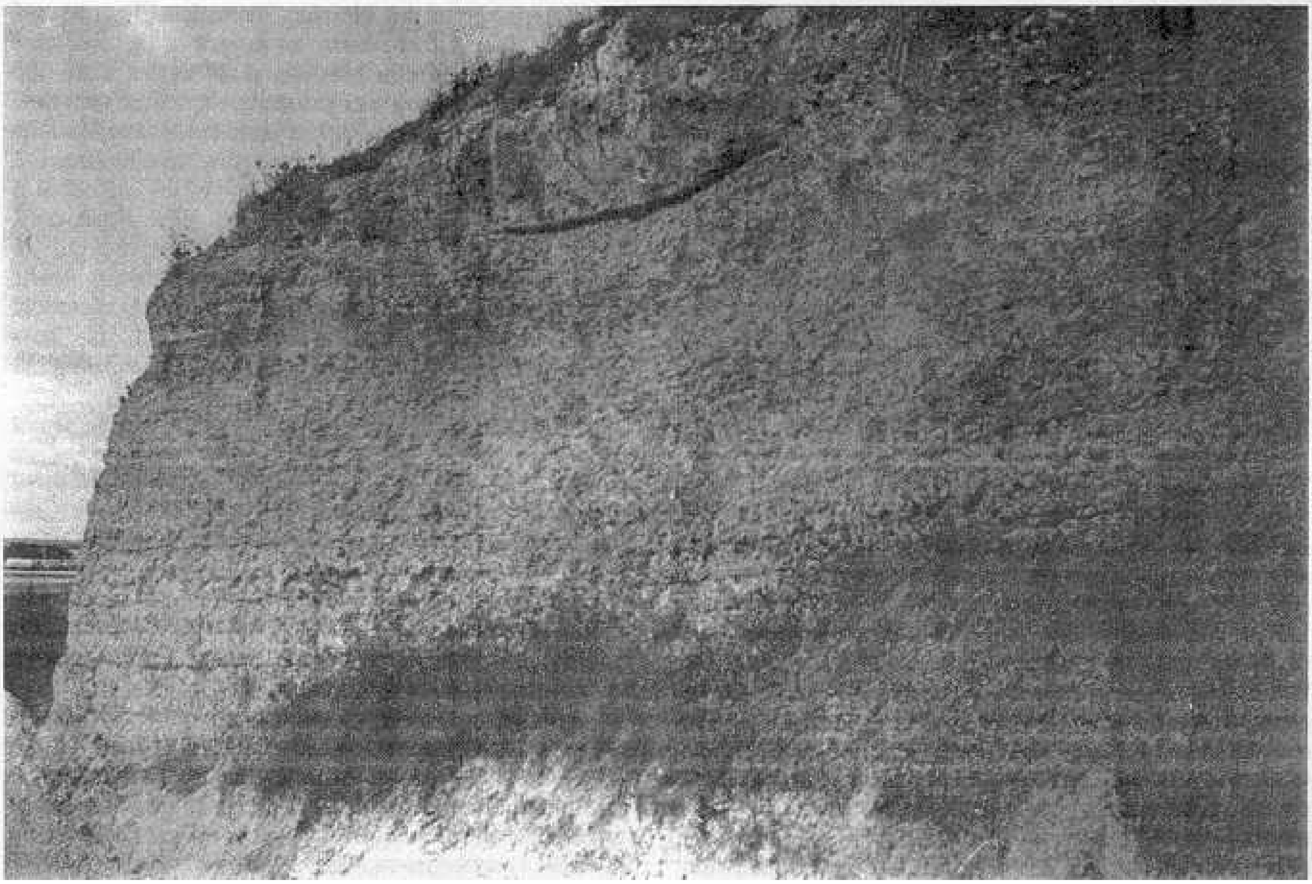

Figure 15. Photograph of the Airport Quarry outcrop. The unconformity at the top of the photo marks the Mannings Bay Member/Blessing Formation contact.

An erosional unconformity intersects many of the underlying surfaces in the outcrop, and the bedding above the unconformity suggests an on-lap surface (Fig. 16). Above the unconformity, shallow marine sedimentation is locally replaced by a diverse reef assemblage, indicating the establishment of a stable reef community. The reef was roughly planar rather than lenticular in cross-section, a morphology that is apparently common to Tertiary Caribbean reefs (S. Frost, pers. comm. 1986). Patchy dolomitization occurs at several locations within the Hess Outcrop, with the dolomitization taking place in Krause Lagoon after deposition of the reef complex.

The Hess Outcrop displays evidence for at least one period of Pliocene exposure and resubmergence, and several periods of reef growth. Evidence from exposure surfaces in surrounding outcrops, including one that has been removed by industrial development (Behrens, 1976; Frost, pers. comm. 1986) indicates that the southern shoreline of St. Croix was exposed several times in the Pliocene. The episodes of emergence were controlled by eustatic variation, by continued uplift of St. Croix, and by activity along the subsidiary fault that bounds Krause Lagoon.

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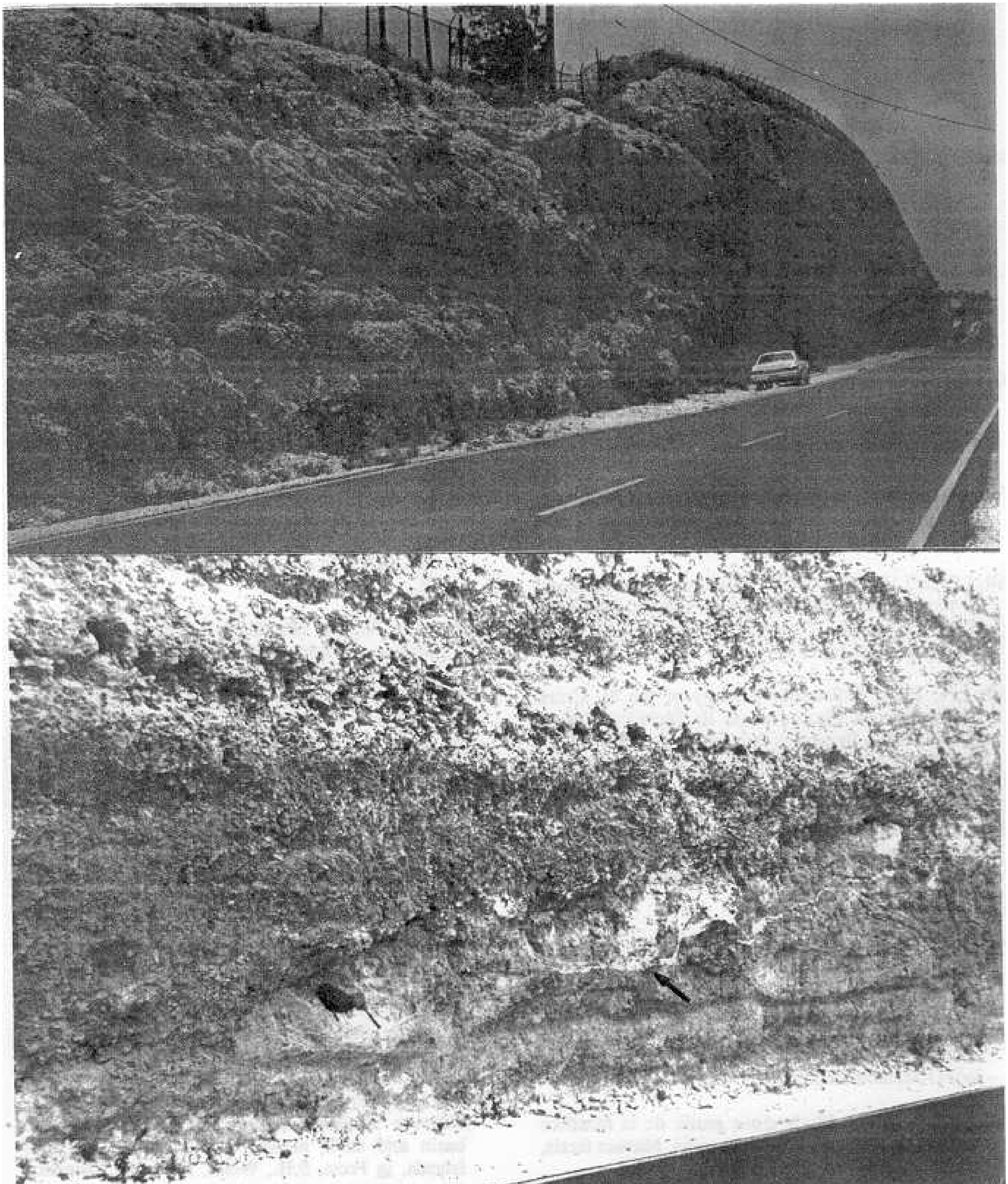

Figure 16. *Photographs of the Hess Cut outcrop. Upper photo: oblique view looking north-northwest, rent-a-wreck for scale. Apparent "bedding" dipping from upper left to lower right is actually bulldozer scarring. Lower photo: Hardground and exposure surfaces in the Blessing Formation reef tract. Rock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

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