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# Biostratigraphy, paleoenvironments and stratigraphic evolution of the Neogene of St. Croix, U.S. Virgin Islands

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**ABSTRACT:** Analysis of the microfauna of the Jealousy Formation and Kingshill Limestone from four cored wells, two water wells, and ten outcrops in the Kingshill basin of St. Croix allows a comprehensive reconstruction of the Neogene stratigraphic evolution of the island. This study results in the first precise biostratigraphic zonation and paleoenvironmental evaluation of these Neogene units in the subsurface as well as a re-evaluation of the age and correlation of outcropping strata. The Jealousy Formation is an entirely subsurface unit of dark, plankton-rich marls which contains planktonic foraminifera indicative of the lower part of the middle Miocene (*Praeorbulina glomerosa* Zone to the *Globorotalia fohsi fohsi* Zone) and a middle bathyal benthic microfauna. The Kingshill Limestone conformably and diachronously overlies the Jealousy Formation and is subdivided into two members, both of which occur in outcrops and the subsurface. The lower of these, the La Reine Member, is characterized by buff pelagic limestones and marls with an upward increasing proportion of intercalated shelf-derived debris. It ranges from the basal part of the middle Miocene (*Praeorbulina glomerosa* Zone) to the upper part of the uppermost Miocene (*Globorotalia humerosa* Zone), and exhibits a transition from middle bathyal (600-800m) to upper bathyal (200-300m) environments. The uppermost part of the Kingshill Limestone, the Manning's Bay Member, is made up of skeletal debris-rich carbonate slope deposits and is placed near the Miocene-Pliocene boundary.

Biostratigraphic control indicates activation of the St. Croix graben fault system and formation of the Kingshill basin at the beginning of the late Miocene. The Neogene section records deposition in an open-marine setting at middle bathyal depths during the early middle Miocene, shoaling gradually to upper bathyal depths in the late middle and late Miocene and more rapidly to a shallow-marine setting at the beginning of the Pliocene. Shoaling was accompanied by an increasing proportion of transported shallow marine sediments. Subsidence analysis for the section indicates more than 400 m of tectonic uplift between 10.5 and 3.5 Ma. Two depositional shifts in the Kingshill Limestone may be tied chronostratigraphically to postulated major global sea-level falls. An interval of carbonate debris in the type section of the Kingshill Limestone may record a fall at 10.5 Ma, and a disconformity at the base of the Mannings Bay Member may be tied to a fall at 5.5 Ma.

## INTRODUCTION

St. Croix is the southernmost of the U.S. Virgin Islands, located on the crest of an east-west oriented submarine platform near the eastern end of the northern Caribbean plate boundary zone. The central plain of the island is underlain by a northeast-southwest trending sedimentary trough (Gerhard et al. 1978; Whetten 1966), here referred to as the Kingshill basin (text-fig. 1), and bounded by the mountainous East End and Northside Ranges.

Most studies of the Kingshill basin have been based on outcrop data and considered the Tertiary carbonate succession to record deposition in an isolated graben system (Whetten 1966; Multer et al. 1977; Gerhard et al. 1978; Lidz 1984). These strata have been assigned a wide range of ages in past studies, ranging from middle Oligocene (Vaughan 1923) to early Pliocene (Lidz 1982) (Table 1). However, exposures are limited in number and predominantly represent the upper part of the section.

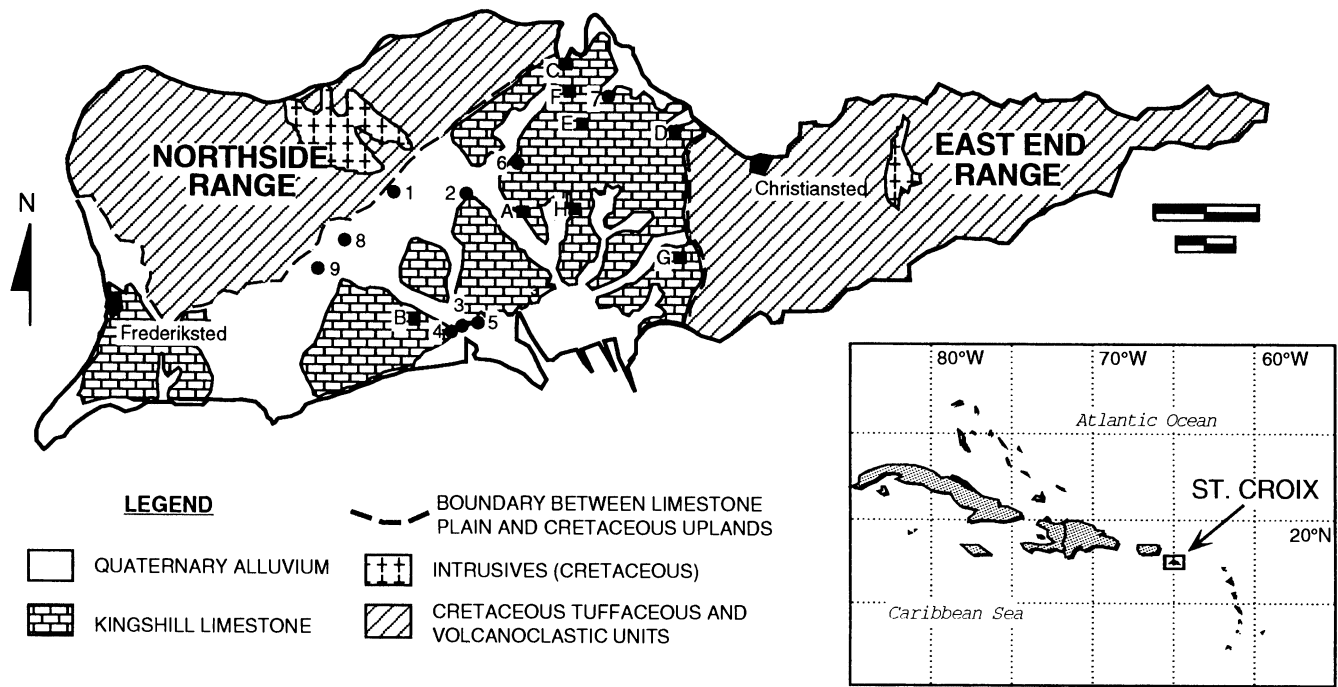
A drilling program undertaken in the mid-1980's has allowed us to conduct a more comprehensive study of the Neogene stratigraphy of the island and better constrain the nature and timing of the tectonic events affecting the evolution of the Kingshill basin. This study focuses on foraminiferal and ostracode faunas present in cores collected during this drilling program and in outcrop samples collected during field studies. The goals of this study are to: (1) to establish an accurate age and environmental framework for the

Neogene strata of St. Croix; (2) to resolve surface-subsurface correlations of these strata; and (3) to outline the stratigraphic evolution of the Kingshill basin and its implications for the Neogene tectonics of the structurally complex region at the eastern end of the northern Caribbean plate boundary zone.

## Geologic setting

The Neogene carbonate section of the Kingshill basin is subdivided into three formations (text-fig. 2): the blue-gray marls of the Jealousy Formation; marls and limestones of the Kingshill Limestone; and reefal limestones of the Blessing Formation. Only the lower two of these units are examined in this study. Scattered segments of these strata crop out in the central plain of the island and are estimated to total at least 700 m thick.

Well-lithified, deep-water, Late Cretaceous tuffaceous and volcaniclastic sedimentary rocks of the Mt. Eagle Group are exposed in graben bounding fault blocks that make up the mountainous eastern and western ends of the island (text-fig. 1) (Whetten 1966; Speed et al. 1979). Evidence in outcrop and in well penetrations in the basin indicates that Kingshill basin is a graben. Gerhard et al. (1978) suggested that this graben may be "hinged" along the western boundary, with the largest fault displacement occurring in the southeast.



TEXT-FIGURE 1

Map of the study area in central St. Croix (after Whetten 1966). Well locations are designated by numbered circles: 1. Well 39; 2. Well 41; 3. Well 45a; 4. Well M1; 5. Well M4; 6. Well M2; 7. Well M10; 8. Water well GP-41; 9. Water well PL-149. Outcrop locations are designated by lettered squares: A. Villa La Reine and Fredensburg Quarry; B. Airport/Penitentiary; C. Salt River valley; D. Five Corners; E. Rattan-Belvedere; F. Morningstar; G. Estate Work and Rest; H. Centerline Road.

Along the eastern fault boundary of the basin (text-fig. 1), outcropping Tertiary sediments contain angular clasts of reworked terrigenous material and dip more steeply than those found in the central part of the basin (Gill 1989; Gill et al. 1989). Along the western boundary of the basin, an abrupt fault contact between Tertiary carbonates in the graben and Cretaceous rocks outside it is exposed in the northern section of the Northside Range. Nearby exposures of Tertiary limestones contain chaotic and steeply dipping strata (Gill 1989). The greatest thickness of shallow-water limestones of the Manning's Bay Member and the Blessing Formation occurs in a subsidiary graben on the southern coast of the island. The western fault boundary of this graben is well documented by drilling and shows a displacement of 50 to 80m (Gill et al. 1989). Its other boundaries are not well documented.

### Previous studies

Most previous biostratigraphic studies of the Tertiary of St. Croix have been based on outcrops (Vaughan 1923; Bold 1970; Multer et al. 1977; Frost and Bakos 1977; Lidz 1982; Andreieff et al. 1986 1987) (table 1). Only two previous biostratigraphic studies have examined material from the subsurface. Cushman (1946) studied smaller benthic foraminifera found in cuttings from three test wells drilled during the winter of 1938-1939; the planktonic foraminifera in these wells were later described by Todd and Low (1976).

Re-evaluation of these studies is critical to establishing a consistent Neogene chronostratigraphic framework for the island. Age interpretations differ significantly among recent studies, even for the same outcrop. Nannofossils reported from the Kingshill Limestone type section at Villa La Reine have placed this unit as low as the middle of the lower Miocene (Multer et al. 1977) and as high as

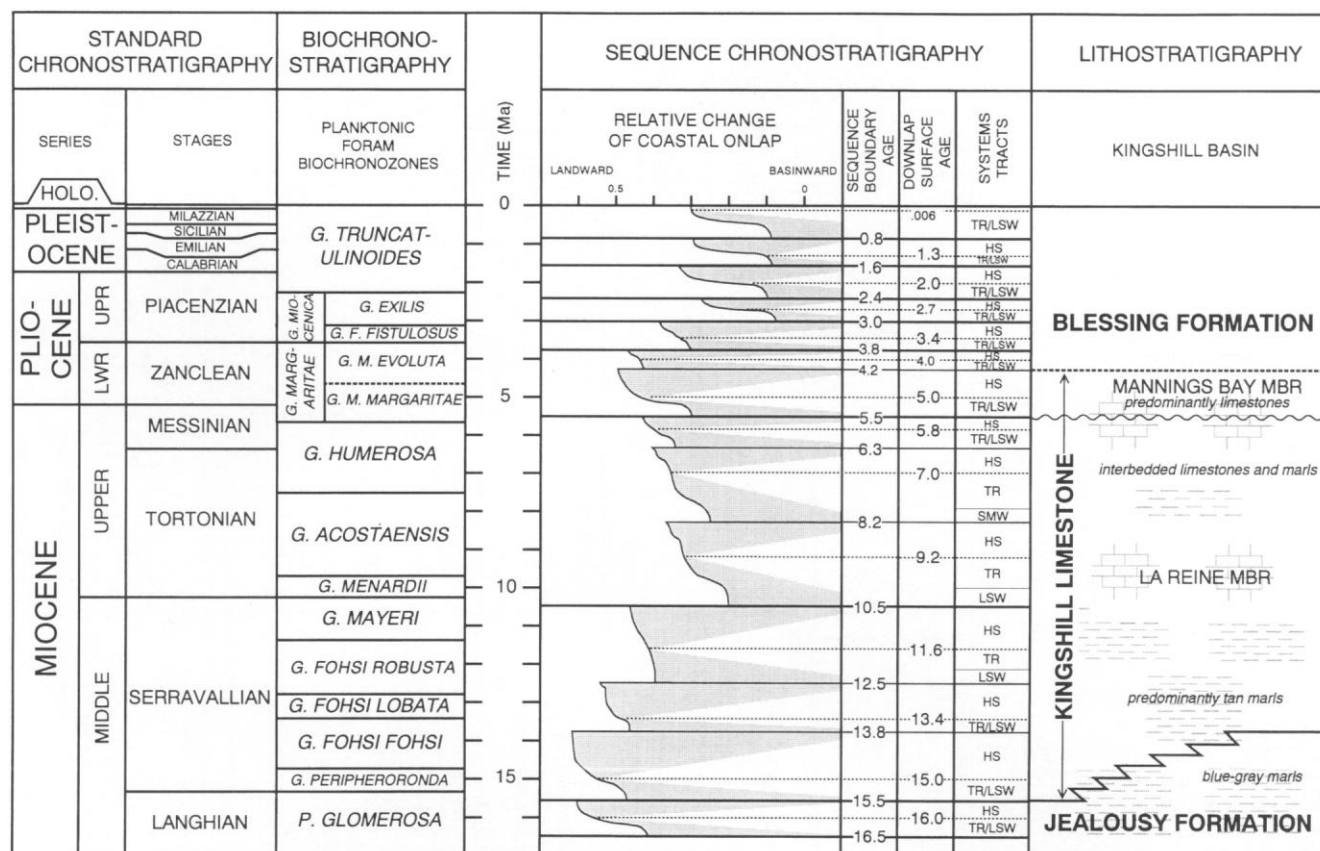
near the middle Miocene-upper Miocene boundary (Andreieff et al. 1986). From the same outcrop, planktonic foraminiferal determinations have ranged from lower middle Miocene (Frost and Bakos 1977; Multer et al. 1977) to near the top of the upper Miocene (Lidz 1982).

### Methods and materials

We have examined the microfauna in cores from four test wells drilled in the central plain of St. Croix between 1984 and 1986, cuttings from the bottom of two water wells, and surface samples from ten outcrops (text-fig. 1). Friable or unconsolidated sediments were sampled at five- or ten-foot intervals with a split-spoon sampler; lithified strata were sampled with a diamond-bit core barrel. Samples were disaggregated with a Calgon solution and washed in a 63  $\mu$ m sieve.

The biostratigraphy of the Jealousy Formation and Kingshill Limestone is based on the occurrences of 44 species or subspecies of planktonic foraminifera (text-figs. 4, 5; Plates 1-4) and on the composition of shallow-marine ostracode assemblages. The planktonic foraminiferal zones and corresponding species ranges are taken from Bolli and Saunders (1985) (text-fig. 3); their chronostratigraphic positions are based on Haq et al. (1988). Correlations to the Blow N-Zones (Blow 1969; 1979) cited in other studies are taken from Bolli and Saunders (1985). The ostracode zones recognized are those defined in the Caribbean by Bold (1983).

Paleobathymetric estimates are for the most part based on the depth-distributions of benthic foraminifera in present-day low-latitude ocean settings (tables 2, 3). Although the watermass properties of the Caribbean Sea in the Miocene were not identical to those of



TEXT-FIGURE 2

Stratigraphic column and chronostratigraphic framework for the Neogene of St. Croix. Planktonic foraminiferal zonation based on Bolli and Saunders (1985). Chronostratigraphy, coastal onlap curve, and eustatic cycles after Haq et al. (1988).

modern low-latitude settings, they were probably similar enough to permit the same foraminiferal associations to be used for approximate paleobathymetric estimates (see, for example, Van Morkhoven et al. 1986). The foraminiferal data are augmented by ostracode data (table 4). Some of the paleoenvironmentally significant benthic foraminiferal species are Text-figured on Plates 5 and 6. Benthic foraminiferal percentages cited are based on sample counts of approximately 300 specimens.

## LITHOSTRATIGRAPHY

### Jealousy Formation

The Jealousy Formation includes the lowest strata recovered in the Kingshill basin. This unit is generally uniform in lithology, composed of blue-gray marls rich in planktonic foraminifera. It was originally described from the subsurface of St. Croix by Cederstrom (1950); although we consider this unit to be restricted to the subsurface, some past workers have mapped this unit on the surface as well. Jealousy Formation blue marls were reached during drilling of wells M1, M2 and M10 for this study, and additional samples were taken from water wells in Grove Place (GP-41) and Plessen (PL-149) (text-fig. 1). No bedding or grading was noted in core material. The samples average 89% silt and clay size sediment, with the sand fraction of each sample dominantly composed of planktonic foraminiferal tests (89%). Non-carbonate components ranged from 1 to 19% within the sand-size fraction. Deep drilling in the 1930's established the presence of a number of conglomeratic beds

and thin layers of limestone at depths not reached in our drilling program (Cederstrom 1950).

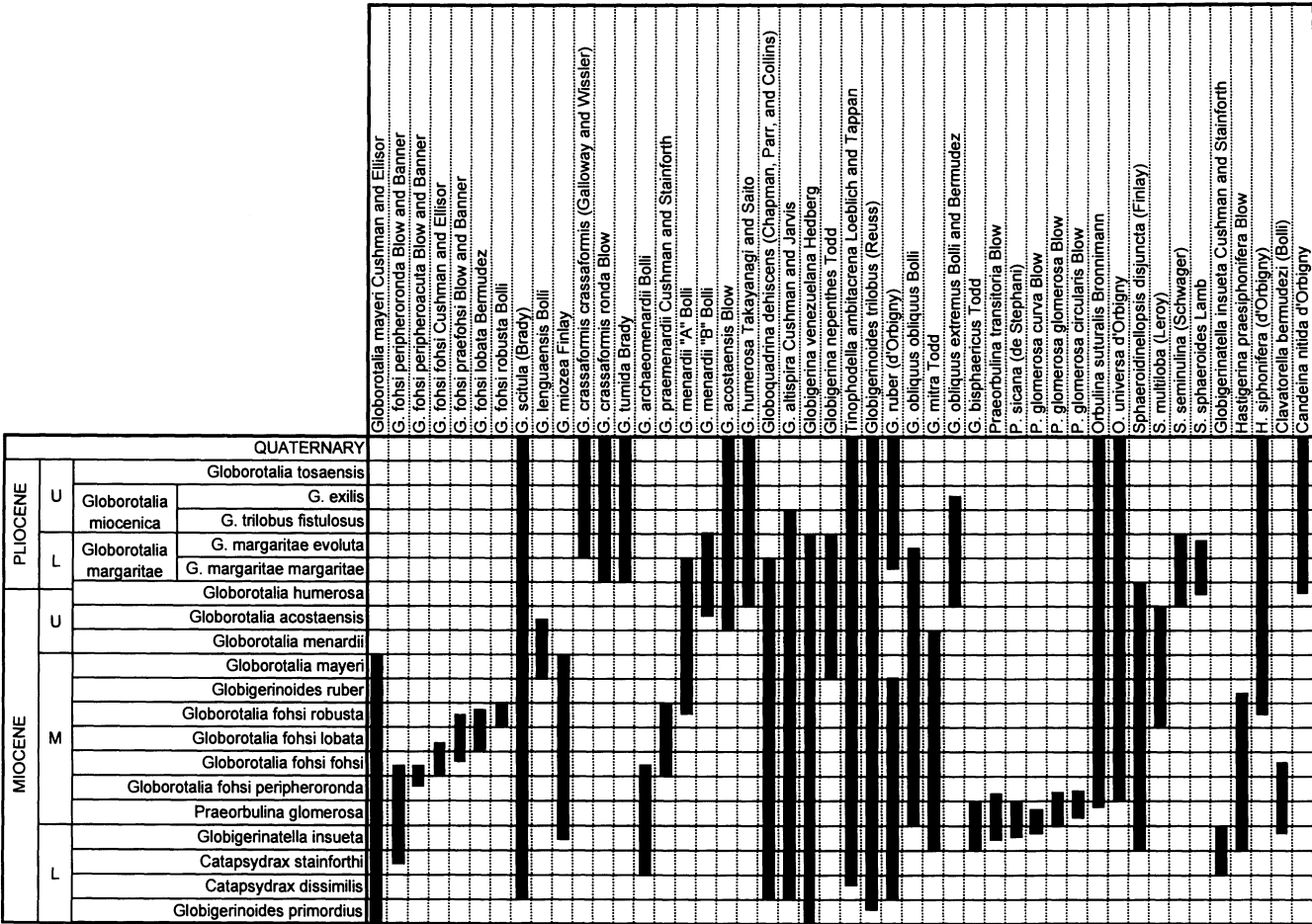
A maximum thickness of 450m (1400 ft) has thus far been documented for the Jealousy Formation (Cederstrom 1950). Although the entire thickness of the Jealousy Formation has never been penetrated by the drill in the middle of the basin, Shurbert et al. (1956) estimated a total thickness of over 1800m (6000 ft) based on gravity surveys. On the northwestern edge of the basin, the contact between the Jealousy Formation and the underlying Cretaceous Mt. Eagle Series was reached in Well 39 (text-fig. 1) near Jealousy (Cederstrom 1950). The contact is unconformable and has been estimated to slope south-southeastward at 33 degrees (Cederstrom 1950; Whetten 1966).

Scattered small outcrops in the Salt River valley (text-fig. 1) have been placed in the Jealousy Formation by some workers (Cederstrom 1950; Whetten 1966; Lidz 1982; Andreieff et al. 1986). These outcrops are typically muddy conglomerates with some zones rich in skeletal debris. On the basis of biostratigraphic and paleoenvironmental evidence discussed later in the paper, we place these strata within the Kingshill Limestone following Gerhard et al. (1978).

### Kingshill Limestone

The Kingshill Limestone overlies the Jealousy Formation and is recognized in both subsurface samples and in outcrops from throughout the Kingshill basin. It is composed of limestones and





TEXT-FIGURE 3  
Planktonic foraminiferal criteria used in the zonation of the St. Croix Tertiary sequence.

buff pelagic marls with an upward-increasing proportion of shelf-derived sediment gravity-flows. Its type section was defined at Villa La Reine by Gerhard et al. (1978). The lithofacies are predominantly polymictic packstones (Gerhard et al. 1978) characterized by interbedded basinal marls and shallow-marine debris. The formation is subdivided into two members (Gill et al., in press): the La Reine Member, which is characterized by interbedded planktonic foraminifera-rich marls and shallow-water limestone debris; and the Manning's Bay Member, which is characterized by heavily burrowed limestone dominated compositionally by sediment-gravity flows of larger benthic foraminifera and other bioclasts.

**La Reine Member**

The La Reine Member of the Kingshill Limestone is a rhythmically bedded unit, generally characterized by marls and limestones rich in planktonic foraminifera, alternating with flows of terrigenous and shelf-derived sediments. The middle of the member, which is exposed at Villa La Reine (text-fig. 1) and along Centerline Road, is characterized by polymictic packstones (Gerhard et al. 1978). Deeper water facies present include planktonic foraminiferal chalks and marls; significant volumes of down-slope transported materials are also present, including boulder-sized coral heads in cobbles of terrigenous material. Similar lithologies occur at Fredensburg Quarry and Estate Work and Rest, but the latter also includes breccia beds of predominantly terrigenous material presumably

derived from the Cretaceous Mt. Eagle Series. Outcrop sections in the lower part of the member at Five Corners, Rattan-Belvedere, and Morningstar have lithologies generally to the Villa La Reine section similar but include less down-slope transported debris.

In the subsurface, the lower part of the La Reine Member is dominated by planktonic foraminiferal packstone, with less common are lithic-pebble or foraminifera-rich wackestones. The boundary between it and the underlying Jealousy Formation is marked by a distinct color change from tan above to blue-gray below. However, the exact significance of this change is unclear; based on sedimentological and micropaleontological evidence, it does not reflect any notable change in lithology, mineralogy, or depositional environment, nor is any hiatus evident. The color difference is strongest in fresh core material but in most cases weakens with exposure to air (Gill 1989).

The stratigraphically highest part of the La Reine Member is exposed in the Airport/Penitentiary section along the Melvin Evans Highway (text-fig. 1). The outcrop can be divided into two parts, separated by a disconformity that forms the boundary between the La Reine Member and overlying Manning's Bay Member. Here the La Reine Member is characterized by regularly bedded intercalations of softer, planktonic foraminifera-rich beds and more indurated, graded beds of shelf-derived debris. The quantity of

SAMPLE		Globorotalia mayeri Cushman and Ellis G. fohsi peripheronata Blow and Banner G. fohsi perpherocuta Blow and Banner G. fohsi fohsi Cushman and Ellis G. fohsi praefohsi Blow and Banner G. fohsi lobata Bermudez G. fohsi robusta Bolli G. scitula (Brady) G. miozea Finlay G. tumida Brady G. archaeomenardii Bolli G. praemenardi Cushman and Stainforth Globotruncana dehiscens (Chapman, Parr, and Collins) G. altipira Cushman and Jarvis Globigirina venezuelana Hedberg Tinophodella ambitracena Loeblich and Tappan Globigerinoides trilobus (Reuss) G. ruber (d'Orbigny) G. obliquus obliquus Bolli G. mitra Todd G. obliquus extremus Bolli and Bermudez G. bisphaericus Todd Praeorbulina transitoria Blow P. sicana (de Stephani) P. glomerosa curva Blow P. glomerosa glomerosa Blow P. glomerosa circularis Blow Orbulina suturalis Bronnemann O. universa d'Orbigny Sphaerolinellopsidis disjuncta (Finlay) Globiginatella insuetta Cushman and Stainforth Hastigerina praesiphonifera Blow	FORMATION	ZONE
M10	16.8	x x x	L	peripheroronda
	22	x x x		
	24.7	x x x	J	glomerosa
	25.9	x x		
	26.5	x x		
	30.5	x x		
	32	x x		
M4	21.8	R ?	M	humeroso-fistulosus
M2	3.4	x x x	L	robusta
	6.1	x x x		
	11.1	x R		
	11.3	x R		
	15.7	x x x		
	21.8	x x		
	22.9	x R		
	24.8	x x		
	27.9	x x		
	30.9	x x x		
	50.3	x x x		
	50.8	x x x	J	fohsi
M1	32	x x x	L	peripheroronda
	35.1	x x x		
	38.1	x x x	J	glomerosa
	41.6	x x		
	44.2	x x		
GP41	32	x x	J	glomerosa
PL149	24.3	x x	J	glomerosa

TEXT-FIGURE 4

Planktonic foraminiferal occurrences in studied well samples. Core sections are those that penetrated the Jealousy Formation; numerical sample numbers are in terms of sample depth in meters below land surface. "R", reworked; "?", tentative identification. Stratigraphic units: M, Manning's Bay Member of the Kingshill Limestone; L, La Reine Member of the Kingshill Limestone; J, Jealousy Formation.

shelf-derived sand is greater than lower in the member, and burrowing appears to be more pervasive.

The La Reine Member in the St. John/Judith's Fancy area includes beds of calcareous conglomerate composed of rounded terrigenous gravel and a fauna of shallow-water echinoids and benthic foraminifera. These outcrops were interpreted by Gerhard et al. (1978), Lidz (1982) and Andreieff et al. (1986) as shelf and lagoon deposits. However, the conglomerate beds are overlain in outcrop

and underlain in Well M10 by planktonic foraminiferal packstones. Therefore, we interpret them as allochthonous beds occurring within a succession of typical La Reine Member deep-water strata.

Cederstrom (1950) and Whetten (1966) mapped these and other nearby exposures of calcareous conglomerate in the Northside Range as Jealousy Formation based on their similarity to a conglomerate encountered in the Jealousy Formation in CCC Test well 39. However, we consider these strata to fall within the range of

SAMPLE		Globorotalia mayeri Cushman and Ellisor G. fohsi lobata Bermudez G. scitula (Brady) G. linguatensis Bolli G. miozea Finlay G. crassaformis crassaformis (Galloway and Wissler) G. crassaformis ronda Blow G. praemenardii Cushman and Stainforth G. menardii "A" Bolli G. menardii "B" Bolli G. acostaensis Blow/G. humerosa Takayanagi and Saito Globobulimina dehiscens (Chapman, Parr, and Collins) G. altispira Cushman and Jarvis Globigerina venezuelana Hedberg G. nepenthes Todd Tinophodella ambicrenata Loeblich and Tappan Globigerinoides trilobus (Reuss) G. ruber (d'Orbigny) G. obliquus obliquus Bolli G. mitra Todd G. obliquus extremus Bolli and Bermudez Orbulina suturalis Bronnimann O. univulsa d'Orbigny Sphaeroidinellopsis disjuncta (Finlay) S. multiloba (Leroy) S. seminulina (Schwager) S. sphaeroides Lamb Hastigerina praesiphonifera Blow H. siphonifera (d'Orbigny) Clavatobulimina bermudezi (Bolli) Candeiina nitida d'Orbigny																	FORMATION	ZONE
EH	O																		M	humerosa?-
	N	x			?	?														margaritae
	C	x																		
	A	x																		humerosa
FR	2/1																		L	?
WR	A/4																		L	mayeri-acostaensis
EMS	89/4																		L	menardii
CR	89/8b	R																	L	menardii
	89/8a																		L	menardii
VR	K		x																L	mayeri-menardii
	H	x	x	x																
	D																			
	C																			mayeri
	A																		L	
MS	89/7	x	x		x														L	lobata
RB	89/6	x	x																L	lobata
FC	89/3																		L	fohsi (lower part)
SR	89/5b																		L	?

TEXT-FIGURE 5

Planktonic foraminiferal occurrences in studied outcrop samples. "R", reworked; "?", questionable identification. Sections: EH, Evan's Highway Airport/Penitentiary section; FR, Fredensborg Quarry; WR, Estate Work and Rest; EMS, east side of Morningstar; CR, Centerline Road; VR, Villa La Reine shopping center; MS, entrance road to Tradewinds subdivision, Morningstar; RB, Rattan-Belvedere; FC, Five Corners; SR, Salt River valley. Stratigraphic units: M, Manning's Bay Member of the Kingshill Limestone; L, La Reine Member of the Kingshill Limestone; J, Jealousy Formation.

facies recognized in outcrops of the La Reine Member. The calcareous conglomerates in question bear no resemblance to the Jealousy Formation sediments recovered by drilling for this project (Gill and Hubbard 1987). Placement in the Jealousy Formation is also unlikely based on structural relationships. These exposures occur at similar altitudes as outcrops of the La Reine Member only a few kilometers away; for them to be placed in the Jealousy Formation would require faulting to raise the stratigraphically lower Jealousy beds to the same elevation as the nearby La Reine. No evidence of such faulting is known.

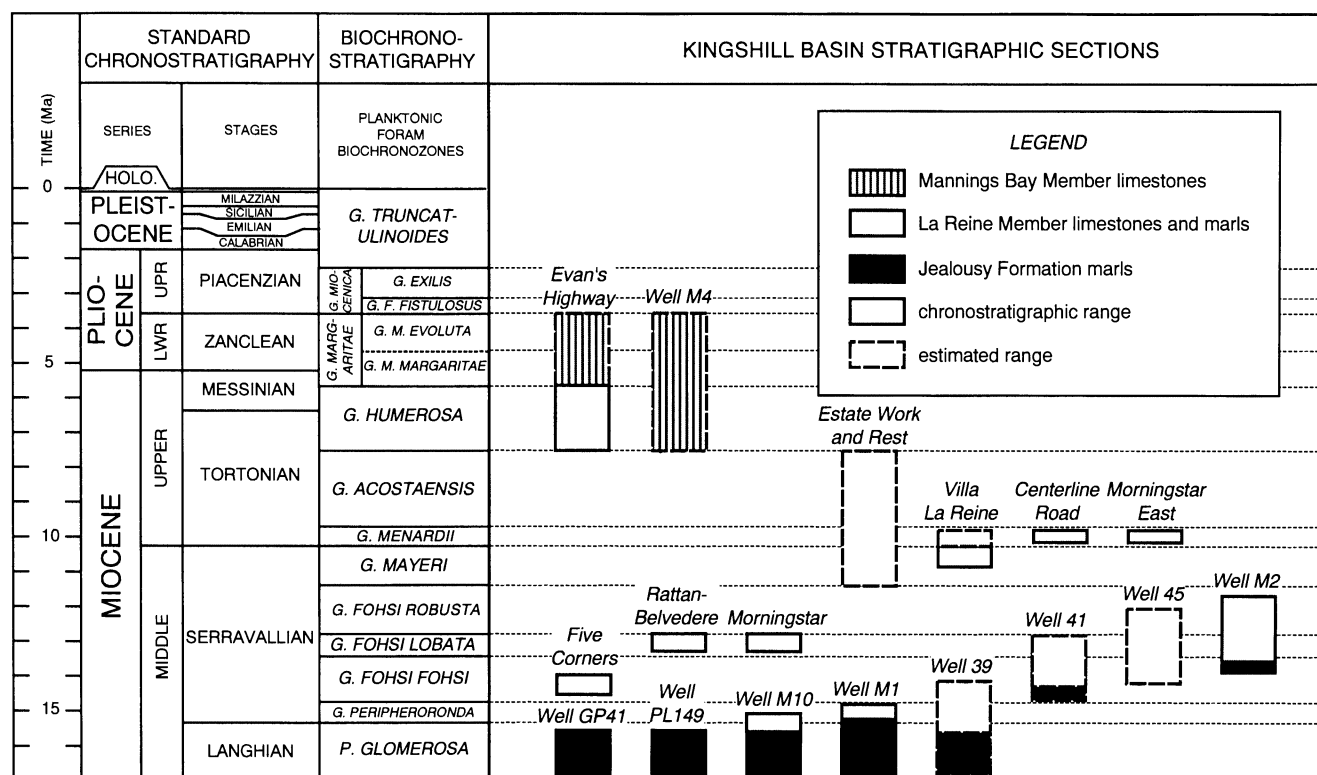
Overall, the abundance of downslope-transported debris in the La Reine Member increases from the middle of the formation upsection. This increase may reflect the onset of basinal faulting and the initial exposure of the Northside and East End ranges as horst blocks.

### Manning's Bay Member

The Manning's Bay Member of the Kingshill Limestone is characterized by channelized beds of grainstones rich in shelf debris interbedded with softer wackestones and packstones containing poorly preserved planktonic foraminifera. The grainstones contain abundant *Operculinoides cojimarensis* and *Paraspiroclypeus chawneri* (Behrens 1976; S. Frost, pers. comm. 1986; Gerhard et al. 1978). Many specimens show signs of transport or reworking, such as fracturing, abrasion, and imbrication and were probably deposited from sediment-gravity flows. The foraminiferal wackestones and the softer packstones also include significant quantities of planktonic foraminifera, including *Orbulina univulsa* and *Globigerina* spp.

The Manning's Bay Member rests disconformably on the La Reine Member, from which it was distinguished by Gill (1989; Gill et al.,





TEXT-FIGURE 6  
Stratigraphic distribution of studied sections.

in press) based on high abundance of shallow-water carbonate material. These strata were previously referred to as a "benthic foraminiferal wackestone and grainstone facies" in the upper Kingshill Limestone by Gerhard et al. (1978) and separated from the Kingshill Limestone facies at Villa La Reine (our La Reine Member) as post-Kingshill limestones by Lidz (1982) and Andreieff et al. (1986). At the Airport/Penitentiary section, the disconformity is a scour surface with more than one meter of relief. Lidz (1984) cited this surface as evidence of basinal shallowing caused by eustatic fall at the end of the Miocene. However, there is no direct evidence for subaerial exposure at this surface. Lithologic evidence supports formation of the disconformity by submarine erosion caused by flows of shelf-derived sediment.

## BIOSTRATIGRAPHY

### Jealousy Formation

**Well samples:** Rich planktonic foraminiferal assemblages are present in subsurface samples from the Jealousy Formation. The top of the formation lies in the lower part of the middle Miocene but is diachronous, ranging across three planktonic foraminiferal zones (text-fig. 6).

Core samples from the lower parts of wells M1 (41.6, 44.2m) and M10 (26.5, 30.5, 32.0m) and cuttings from the bottom of water wells GP-41 (32.0m) and PL-149 (24.3m) comprise the oldest material studied (text-fig. 4). Co-occurrence of *Praeorbulina glomerosa* subsp. and *Globigerinatella insueta* places these samples near the base of the middle Miocene in the *Praeorbulina glomerosa* Zone.

The top of the Jealousy Formation falls near the top of the *Praeorbulina glomerosa* Zone in Well M10. However, in Well M1 the Jealousy extends slightly higher into the middle Miocene (text-fig. 6) because a sample taken from just below the top of the formation (38.1m) contains the lowest occurrences of *Orbulina universa* and *Globorotalia fohsi peripheroacuta*, suggesting equivalence to the *G. fohsi peripheroronda* Zone. The stratigraphically highest Jealousy sample was recovered from the bottom of Well M2, in the middle Miocene *Globorotalia fohsi fohsi* Zone; it includes the nominate taxon, but apparently lies below the lowest occurrence of *Globorotalia fohsi lobata*.

Ostracodes in core samples from the upper part of the Jealousy Formation indicate a lower to middle Miocene placement. These forms (table 4) have been described from various parts of the Antilles, including the Montpelier Formation of Jamaica (Steineck 1981), the Cipero Formation of Trinidad (Bold 1972), and the Kingshill Limestone of St. Croix (Bold 1970).

**Comparison to previous studies:** The only previous study to examine the planktonic foraminifera of the Jealousy Formation was that of Todd and Low (1976). Their study was based on the re-examination of cutting samples studied by Cushman (1946) in his investigation of Tertiary smaller benthic foraminifera of three wells (their Test wells 39, 41, and 45a) from St. Croix. Todd and Low (1976) reported two faunal associations in the subsurface section: the first, in the lower part of the wells which includes Jealousy and lower Kingshill strata, was a fauna assigned to the lower part of the middle Miocene (N9 to N11); and the second, in the Kingshill strata of the upper part of the wells, was a fauna assigned to the middle part of the middle Miocene (N12 or N13).



TABLE 1

Summary of the results of previous biostratigraphic studies on St. Croix. The age determinations given are either those of the respective authors, or are interpreted from their publications, and do not necessarily agree with this study. \*referred to as post-Kingshill limestones in Lidz (1982) and Andreieff et al. (1986). \*\*referred to as Kingshill Limestone in these studies.

Author	Study	Fossil Type	Manning's Bay Mbr*	La Reine Mbr**	Jealousy Fm
Vaughn (1923)	outcrop	corals, molluscs, larger foraminifera	—	middle Oligocene	—
Cushman (1946)	subsurface	smaller foraminifera	—	Miocene	Oligocene to Miocene
Bold (1970)	outcrop	ostracodes, planktonic foraminifera	—	Middle Miocene ( <i>G. fohsi fohsi</i> to <i>G. fohsi robusta</i> Zone)	late early Miocene
Todd and Low (1976)	subsurface	planktonic foraminifera	—	lower middle Miocene (N9 to N11) to middle middle Miocene (N12 or N13)	lower middle Miocene (N9 to N11)
Frost and Bakos (1977); Multer et al. (1977)	outcrop	planktonic foraminifera	—	middle Miocene ( <i>G. fohsi fohsi</i> Zone)	—
Multer et al. (1977)	outcrop	calcareous nannoplankton	—	middle lower Miocene ( <i>Discoaster druggi</i> and <i>Sphenolithus belemnus</i> Zones)	—
Lidz (1982)	outcrop	planktonic foraminifera	lower Pliocene (upper N18 and N19)	middle to upper Miocene (N10 to N18)	—
Andreieff et al. (1986)	outcrop	calcareous nannofossils	upper Miocene to lower Pliocene (NN11 to NN14/15)	middle to upper Miocene (NN5 to NN11)	NN5
Andreieff et al. (1986, 1987)	outcrop	larger foraminifera	lower Pliocene ( <i>Paraspirocyclus chawneri</i> Zone)	—	—

We have re-interpreted their data using only the highest occurrence of each species, because of apparently extensive downhole contamination. On the basis of this data, we recognize the *Praeorbulina glomerosa* and *Globorotalia fohsi fohsi* Zones in the Jealousy Formation in these wells, similar to those in our samples (text-fig. 6).

In Test well 39, the Jealousy Formation may be correlated to the *Praeorbulina glomerosa* Zone, possibly extending lower. This placement is constrained by the highest occurrence of *Globigerinatella insueta* which was recovered at 27.4m depth in Test well 39 just above the top of the Jealousy Formation (27.7m), and the apparent presence of *Praeorbulina glomerosa* in the lower part of the well (reported as *Orbulina suturalis* in Todd and Low 1976, Plate 11, Text-fig. 12).

In Test well 41, the Jealousy Formation was encountered from the bottom of the well at 459m up to 33m. We place the lower part of this section in the *Praeorbulina glomerosa* Zone or lower based on the highest reported occurrence of *Globigerinatella insueta* at 152.4m. This is supported by a sudden downhole increase of *Globigerinoides bisphaericus* and *Praeorbulina transitoria* reported at the same depth. The top of the Jealousy Formation (33m) is estimated to lie in the *Globorotalia fohsi fohsi* chronozone, based upon the presence of *G. fohsi lobata* from the top of the well downward and the 22.9m maximum thickness of the *G. fohsi lobata* Zone in Well M2.

Although the third well, Test well 45a, penetrated the Jealousy Formation, the depths of samples reported by Todd and Low (1976) suggest that only the Kingshill Limestone portion of the well was studied.

#### La Reine Member

Planktonic foraminifera are abundant and well preserved in core and outcrop samples from the lower and middle parts of the La

Reine Member and permit clear biostratigraphic assignment (text-figs. 4, 5). The fauna recovered from outcrop samples in the upper part of the member are not as rich nor as well preserved but are nevertheless useful. These occurrences indicate that the La Reine Member extends from the upper part of the basal middle Miocene *Praeorbulina glomerosa* Zone to the upper part of the upper Miocene *Globorotalia humerosa* chronozone.

**Well samples:** La Reine Member samples from the wells represent the lower part of the formation (text-fig. 4); the oldest strata were encountered in Well M10 (text-fig. 6). The lowest sample (25.9m) contains *Praeorbulina glomerosa curva* and *Globigerinatella insueta*, diagnostic of the *Praeorbulina glomerosa* chronozone (text-fig. 4). Higher samples in M10 (16.8, 22, 24.7m) lie in the *Globorotalia fohsi peripheroronda* Zone, as do both La Reine Member samples in Well M1 (32, 35.1m). These include the lowest occurrences of the nominate taxon and of *Orbulina universa*.

The stratigraphically highest subsurface samples were taken from Well M2, where the La Reine Member extends from the *Globorotalia fohsi fohsi* Zone to the *G. fohsi robusta* Zone (text-fig. 4). Across this interval, the development of the *Globorotalia fohsi* lineage can be traced from *G. fohsi fohsi* to *G. fohsi praefohsi* to *G. fohsi lobata* to *G. fohsi robusta*. Anomalous occurrences of older Miocene species are noted in several samples from Well M2 (11.1, 11.3, 22.9m), suggesting that submarine erosion reworked older middle Miocene pelagic sediments during the middle of the middle Miocene.

Twelve shallow-marine ostracode species occur in the lower part of the La Reine Member in these wells. Six of these species are also found in an outcrop of conglomerate previously placed in the Jealousy Formation (Bold 1970) (table 4). *Loxococoncha runa*, which was present in Jealousy Formation core samples, is absent

TABLE 2

Benthic foraminifera used in the bathymetric interpretation of the Kingshill/Jealousy Basin. Key to references:

- |                                 |                               |  |
|---------------------------------|-------------------------------|--|
| 1. Bandy and Rodolfo (1964)     | 7. Ingle (1980)               | 13. Phleger, Parker and Peirson (1953) |
| 2. Bandy and Arnal (1957)       | 8. Morkoven et al. (1986)     | 14. Phleger and Soutar (1973)          |
| 3. Berggren and Haq (1976)      | 9. Natland (1933)             | 15. Poag (1981)                        |
| 4. Berggren et al. (1976)       | 10. Parker (1954)             | 16. Sen Gupta, Lee and May (1981)      |
| 5. Boltovskoy and Wright (1976) | 11. Pflum and Frerichs (1976) | 17. Smith (1964)                       |
| 6. Hasegawa (1984)              | 12. Phleger (1951)            |  |

Taxon	Bathymetry and remarks
1. <i>Bolivina</i> spp.	Abundant small <i>Bolivina</i> are often associated with nutrient-enriched or low-oxygen environments which may be related to upwelling (2, 5, 14, 16).
2. <i>Bulimina alazanensis</i>	Ranges from the upper bathyal zone to abyssal depths, most common between 500 and 100m (10, 11, 12).
3. <i>Cassidulina subglobosa</i>	Wide ranging bathymetry, found up to 75m, more common and larger @>200m (11) in the Gulf of Mexico; characteristic of >130m, mostly 500-700m, in the Pacific off Central America (17).
4. <i>Cibicides wuellerstorfi</i>	Reported >500m (10) and 700m (12), but most common below 3000m; >630m in the North Atlantic (3, 4, 14).
5. <i>Cibicidoides bradyi</i>	Inhabits >450m in the Gulf of Mexico (11).
6. <i>Cibicidoides cicatricosus</i>	Upper bathyal to abyssal (8).
7. <i>Cibicidoides incrassatus</i>	Most common outer neritic to upper bathyal, found to lower bathyal depths (8, 11 as <i>Anomalina corpulentus</i> ).
8. <i>Cibicidoides pachyderma bathyalis</i>	<i>Cibicidoides pachyderma</i> is most common at upper bathyal depths (3, 8); <i>C. p. bathyalis</i> has been reported (as <i>C. "floridanus" bathyalis</i> ) to be common in slope facies of the Gulf of Mexico (15).
9. <i>Cibicidoides robertsonianus</i>	Reported >450m in the Gulf of Mexico (11, 12); specimens noted in this study are transitional towards <i>Cibicidoides bradyi</i> , generally with 9 chambers in the last whorl.
10. <i>Epistominella</i> sp. cf. <i>E. exigua</i>	<i>E. exigua</i> is characterized as occurring below 180m and most common near 500m (>2%) in the Gulf of Mexico (10, 11). Reported in 30-60m deep water off the coast of El Salvador (17). Specimens noted in this study are nearly identical with <i>E. exigua</i> but are very small (0.1mm).
11. <i>Karreriella brady</i>	150-800m in the Gulf of Mexico (11), 100 to 3000m in the North Atlantic (3, 4, 13)
12. <i>Laticarinina pauperata</i>	Reported from >205m (12) and 300m (10), most common in lower bathyal zone, in the Gulf of Mexico; middle and lower bathyal forms are larger (3mm) than the specimens noted here (11); >200m, mostly 550-3000m in North Atlantic (3,4,14); >200m, mostly 1200-3500m off California (3,4).
13. <i>Melonis pompilioides</i>	Specimens identified are inflated <i>M. pompilioides</i> (= <i>soldanii</i> ) of Morkhoven et al. (1986), closer to forma <i>sphaeroides</i> than to the compressed <i>M. barleeianum</i> form; they probably inhabited the upper bathyal zone in the Miocene (6) rather than the greater depths it characterizes today.
14. <i>Oridorsalis umbonatus</i>	In the Gulf of Mexico, >65m, mostly >80m (12); in the North Atlantic, >60m, predominantly 150-300m (3, 4, 14); characterize s 1300-3200m range off El Salvador (17).
15. <i>Osangularia culter</i>	Found at >600m in the Gulf of Mexico (11,12).
16. <i>Planulina ariminensis</i>	Outer neritic to middle bathyal, with greatest abundances 300-500m (3, 8); found up to 50m, can be common in shelf facies in the Gulf of Mexico (11).
17. <i>Planulina arenzi</i>	Characterized as an upper bathyal species in Tertiary deposits of the Caribbean region (8).
18. <i>Pullenia bulloides</i>	Predominantly middle-lower bathyal; >65m in Gulf of Mexico (11, 12); >150m in the North Atlantic, mostly 500-2500m (3, 4, 13); >175m off California, 2000-2600m in Catalina Channel (9), mostly 1200-3500m (3, 4); found below 1300m off Panama (2) and El Salvador (17).
19. <i>Pyrgo murrhina</i>	In the Gulf of Mexico, noted as >45m (10), mostly middle bathyal (600m) to abyssal (8); deeper than 200m off the western coast of Mexico (2).
20. <i>Rectuvigerina multicostata</i>	Fossil species considered a bathyal indicator (8).
21. <i>Siphonina tenuicarinata</i>	Characterized as outer neritic to middle bathyal, most commonly bathyal, UDL estimated at about 100m (8). Similar to modern carinate <i>Siphonina bradyana</i> which is found at 45-700m in the Gulf of Mexico (13).
22. <i>Sphaeroidina bulloides</i>	Small specimens up to 100m in Gulf of Mexico (11) and North Atlantic, most commonly middle - upper bathyal (8).
23. <i>Stilostomellids</i>	Significant numbers (>5%) of <i>Stilostomella</i> noted typical of lower bathyal depths (1, 3); ornamented forms have been associated with the lower middle bathyal-middle bathyal transition.
24. <i>Uvigerina carapitana</i>	Fossil species interpreted as bathyal, 200-2000m (8).
25. <i>Uvigerina hispida</i>	Characterized as >1000m in the Gulf of Mexico (11), or as a bathyal species, 200-2000m (8).

TABLE 3

Benthic foraminifera recognized in this study. MB = Mannings Bay Member of the Kingshill limestone; RU = top La Reine Member; RM = middle part of La Reine Member; RL = lower part of La Reine Member, outcrops; RC = lower part of La Reine Member, core samples; JC = Jealousy Formation, core samples. \* = in allochthonous clay clasts.

Benthic foraminiferal species	MB	RU	RM	RL	RC	JC
<i>Planulina ariminensis</i> d'Orbigny	X	X				
<i>Cibicidoides incrassatus</i> (Fichtel and Moll)	X		X			
<i>Fursenkoina</i> sp.	X					
<i>Siphonina pulchra</i> Cushman	X				X	
<i>Amphistegina</i> sp.	X			X*		
<i>Discorbis</i> sp.	X					
<i>Rosalina</i> sp.	X					
<i>Liebusella soldanii</i> (Jones and Parker)		X				
<i>Uvigerina carapitana</i> Hedberg		X				
<i>Laticarinina pauperata</i> (Parker and Jones)		X	X		X	X
<i>Cibicidoides pachyderma bathyalis</i> Poag		X	X		X	
<i>Cassidulina subglobosa</i> H.B. Brady		X	X		X	X
<i>Karreriella bradyi</i> (Cushman)		X	X	X	X	
<i>Stilostomella/Siphonodosaria</i> spp.		X	X	X	X	X
<i>Planulina renzi</i> (Cushman and Stainforth)		X		X		X
<i>Cibicides wuellerstorfi</i> (Schwager)			X	X	X	X
<i>Archais</i> sp.				X*		
<i>Elphidium</i> spp.				X*		
<i>Pyrgo murrhina</i> (Schwager)				X		
<i>Cibicides cicatricosus</i> (Schwager)				X	X	
<i>Sphaeroidina bulloides</i> d'Orbigny				X	X	
<i>Melonis pompilioides</i> (Fichtel and Moll)					X	
<i>Bolivina</i> spp. (>25% of >63µm fauna)					X	X
<i>Bulimina alazanensis</i> Cushman					X	X
<i>Cibicidoides bradyi</i> (Trauth)					X	X
<i>Epistominella</i> sp. cf. <i>E. exigua</i> (Brady)					X	X
<i>Oridorsalis umbonatus</i> (Reuss)					X	X
<i>Osangularia culter</i> (Parker and Jones)					X	X
<i>Pullenia bulloides</i> (d'Orbigny)					X	X
<i>Rectuvigerina multicostata</i> (Cushman and Jarvis)					X	X
<i>Siphonina tenuicarinata</i> Cushman					X	X
<i>Uvigerina hispida</i> Schwager					X	X
<i>Cibicidoides robertsonianus</i> (Brady)						X

in the lower part of the La Reine Member. This species normally has its highest occurrence in the planktonic foraminiferal *Globorotalia fohsi peripheroronda* Zone.

**Outcrop samples:** The lowest exposed strata of this unit crop out on the northern side of the central plain in the Salt River valley (text-fig. 1) and were previously placed in the Jealousy Formation (Bold 1970; Cederstrom 1950; Whetten 1960; Lidz 1982; Andreieff et al. 1986). Ostracodes were recovered in clasts of greenish clay contained within a conglomerate bed. The stratigraphic ranges of the species present in the clay (table 4) and the absence of *Puriana gatunensis* restrict the age of this sample to between the *Globigerinatella insueta* and *Globorotalia fohsi peripheroronda* Zones, around the lower Miocene - middle Miocene boundary (Bold 1970). This ostracode fauna is completely different from that of the subsurface Jealousy Formation, but contains several species in common with the lower part of the La Reine Member collected in the drilling program. Samples from this area were reported by Andreieff et al. (1986) as basal middle Miocene based on calcareous nannoplankton indicative of zone NN5. They also noted in one sample the presence of reworked planktonic foraminifera and radiolaria indicative of lower Eocene zone P9 or middle Eocene zone P10. Based partly on this evidence, we consider these outcrops

to represent an interval of shelf-derived debris flow deposits within the La Reine Member.

Faunas diagnostic of the middle part of the middle Miocene were recovered from several other outcrops on the northern side of the island. At Five Corners (text-fig. 1), the La Reine Member (sample 89/3) is placed in the lower part of the *Globorotalia fohsi fohsi* Zone based on the presence of *Clavatorella bermudezi*, *Globigerinoides mitra*, and *Globorotalia praemenardii*. Samples from Rattan-Belvedere (89/6) and from the Tradewinds Subdivision entrance road, near Morningstar (89/7), are placed slightly higher, in the *Globorotalia fohsi lobata* Zone.

In the middle of the island, samples from the type section of the Kingshill Limestone at Villa La Reine (text-fig. 1) yielded rich planktonic foraminiferal faunas diagnostic of the upper part of the middle Miocene. *Globorotalia mayeri* is present in two samples in the section (samples D and H, Text-fig. 5), *Globorotalia linguaensis* is in one (sample H, Text-fig. 5), *Globigerina nepenthes* is in the highest and lowest samples (samples A and K, Text-fig. 5), and *Globorotalia menardii* is present throughout the section. These occurrences, combined with the absence of *Globorotalia acostaensis* (pre-appearance), indicate that this section

TABLE 4

Ostracodes recovered from core samples of the upper Jealousy Formation (column J), from the lower part of the La Reine Member (column R), and from an outcrop of conglomerate of the La Reine Member previously placed in the Jealousy Formation (column C). Note absence of *Loxoconcha runa* in the La Reine Member core samples (latest occurrence in N9) and the absence of *Puriana gatunensis* in the La Reine Member conglomerate outcrop (earliest occurrence in zone N9). Asterisk (\*) denotes shallow marine species occurring in the lower part of the La Reine Member; six of these species also occur in the conglomerate bed, supporting its placement in the La Reine Member of the Kingshill Limestone rather than in the Jealousy Formation.

Ostracode species	J	R	C
<i>Abyssocypris pykna</i> (Bold)	X	X	
<i>Abyssocypris tipica</i> Bold	X	X	
<i>Agrenocythere hazelae</i> (Bold)	X	X	
<i>Ambocythere</i> sp. aff. <i>A. caudata</i> Bold	X		
<i>Argilloecia</i> sp. 1, Bold, 1971	X	X	
<i>Argilloecia</i> sp. 2, Bold, 1971	X	X	
<i>Argilloecia</i> sp. 3, Bold, 1971		X	
<i>Argilloecia</i> sp. Bold, 1970		X	
<i>Argilloecia suavis</i> Lubimova and Sanchez	X	X	
<i>Bairdia condylus</i> Bold			X
<i>Bairdia oarion</i> Bold	X		
<i>Bairdia</i> sp., Bold, 1970		X*	
<i>Bairdoppilata cassida</i> (Bold)	X	X	
<i>Bradleya johnsoni</i> Benson	X	X	
<i>Bythocypris</i> sp. cf. <i>B. bosquetiana</i> (Brady)	X	X	
<i>Cytherella perpolita</i> Lubimova and Sanchez	X	X	
<i>Cardobairdia glabra</i> Bold	X		
<i>Caudites nipeensis</i> Bold		X*	
<i>Caudites sacer</i> Bold		X*	
<i>Costa cubana</i> Bold	X	X	
<i>Cytherella</i> sp. aff. <i>C. gracilis</i> Lienenklaus			X
<i>Cytherella</i> sp. aff. <i>C. vulgata</i> Ruggieri	X		
<i>Cytherella perpolita</i> Lubimova and Sanchez	X	X	
<i>Cytheroma</i> sp. Bold, 1970			X
<i>Henryhowella</i> ex gr. <i>asperrima</i> (Reuss)	X	X	
<i>Krithe morkhoveni</i> Bold	X	X	
<i>Krithe proluxa</i> Bold	X	X	
<i>Krithe reversa</i> Bold	X	X	
<i>Krithe trinidadensis</i> Bold	X	X	
<i>Krithe vandenboldi</i> Steineck	X	X	
<i>Krithe lambi</i> Bold	X	X	
<i>Legitimo cythere acanthoderma</i> (Brady)	X	X	
<i>Loxoconcha</i> ( <i>Loxoconcha</i> ) sp. aff. <i>L. (L.) forda</i> Bold		X	
<i>Loxoconcha</i> ( <i>Loxocorniculum</i> ) <i>antillea</i> Bold		X*	X
<i>Loxoconcha</i> ( <i>Palmoconcha</i> ) <i>banesensis</i> Bold	X	X	
<i>Loxoconcha runa</i> Bold			X
<i>Messinella jamaicensis</i> Bold	X		
<i>Neocaudites macertus</i> (Stephenson)		X*	
<i>Orionina vaughani</i> (Ulrich and Bassler)		X*	X
<i>Paracypris</i> sp. B, Bold, 1970			X
<i>Paracytheridea tschoppi</i> Bold	X	X	
<i>Parakrithe vermunti</i> (Bold)	X	X	
<i>Paranesidea antillea</i> (Bold)		X*	X
<i>Perissocytheridea alata</i> Bold			X
<i>Procythereis ?calhounensis</i> (Smith)	X	X	
<i>Procythereis ?deformis</i> (Reuss)		X*	X
<i>Propontocypris vaga</i> (Lubimova and Sanchez)			X
<i>Puriana gatunensis</i> (Coryell and Fields)		X*	
<i>Quadracythere antillea</i> (Bold)		X*	X
<i>Quadracytheresparpa</i> Bold		X*	X
<i>Sclerochilus</i> sp., Bold, 1970			X
<i>Trachyleberidea mammidentata</i> (Bold)	X	X	
<i>Xestoleberis</i> sp. C, Bold, 1946			X
<i>Xestoleberis</i> sp. E, Bold, 1946 = <i>X.</i> sp. B, Bold, 1970			X



belongs in the *Globorotalia mayeri* Zone, possibly extending into the *Globorotalia menardii* Zone towards the top. Nearby outcrops along Centerline Road are slightly higher stratigraphically. The presence of *Globorotalia menardii* and *Globigerina nepenthes*, the absence of middle Miocene taxa such as *Globorotalia mayeri* present at Villa La Reine, and the absence of younger late Miocene taxa, such as *Globorotalia acostaensis*, place this section in the basal upper Miocene *Globorotalia menardii* Zone. Well preserved, relatively diverse faunas were present in less resistant recessed beds (89/8b), but resistant beds (89/8a) are dominated by damaged specimens of robust-tested *Sphaeroidinellopsis multiloba*, with steinkerns and recrystallized tests of other species reworked from older, probably middle Miocene, strata. A similar *Globorotalia menardii* Zone fauna was recovered from sample 89/4, taken from an outcrop on the east side of Morningstar (text-fig. 1) on the northern side of the island.

Further to the south, the Estate Work and Rest section (text-fig. 1) is also placed tentatively in the *Globorotalia menardii* Zone. The planktonic foraminiferal fauna is poorly preserved in these samples, with a usable fauna recovered from only one. The presence of *Globigerina nepenthes* and *Sphaeroidinellopsis multiloba* and the absence of *Globorotalia mayeri* and of *Globorotalia acostaensis* suggest placement in the *Globorotalia menardii* Zone, but this placement is tentative due to possible diagenetic control on absences in this poorly preserved sample.

Faunas are also poorly preserved in samples from Fredensburg Quarry. *Globigerina nepenthes* is the only stratigraphically diagnostic occurrence, indicating placement between the uppermost middle Miocene (*Globorotalia mayeri* Zone) and lower Pliocene (top of the *Globorotalia margaritae* Zone).

The highest strata of the La Reine Member were sampled at the Airport/ Penitentiary section (text-fig. 1). The presence of the zonal marker *Globorotalia humerosa* and of *Candeina nitida* and the lack of Pliocene marker species such as *Globorotalia margaritae* and *Sphaeroidinella dehiscens* place the strata below the unconformity in the upper part of the upper Miocene *Globorotalia humerosa* Zone. The absences of the latter two species appear to be due to the chronostratigraphic position of these samples rather than ecologic or diagenetic effects, based on two criteria: the presence of species that dwell in the upper part of the water column, such as *Globigerinoides* (Bé 1977), as well as forms considered to be deeper dwellers, such as *Globorotalia* and *Sphaeroidinellopsis* (Bé 1977; Keller 1985); and secondly, the good to fair preservational state of the fauna.

**Comparison to previous studies:** Todd and Low (1976) reported lower (N9 to N11) and upper (N12 to N13) planktonic foraminiferal associations in subsurface Kingshill Limestone intervals that we would now place in the La Reine Member. Our re-evaluation of their data suggests that the intervals included in their study range from the *Praeorbulina glomerosa* to the *Globorotalia fohsi robusta* chronozone.

In Test well 39, the La Reine Member is present from the uppermost samples to 27.7m. We re-interpret this interval to lie, for the most part, in the lower part of the middle Miocene, equivalent to the *Globorotalia fohsi peripheroronda* or *G. fohsi fohsi* chronozone; the basal portion of this unit appears to lie in the top of the basal middle Miocene *Praeorbulina glomerosa* chronozone. These determinations were based on the highest occurrence of *Globigerinatella insueta* at 27.4m, just above the base of the La Reine Member, and the probable presence of *Globorotalia fohsi peripheroacuta* from the top of the well downward. Todd and Low

(1976) Text-figured both keel-less "*G. fohsi*" (their Plate 12, Text-fig. 4), which we would interpret as *G. fohsi peripheroacuta*, and keeled forms more typical of *G. fohsi fohsi*; because of the stratigraphic proximity of the "*G. fohsi*" occurrences in this well to the highest occurrence of *Globigerinatella insueta*, these forms are likely the older subspecies, *G. fohsi peripheroacuta*.

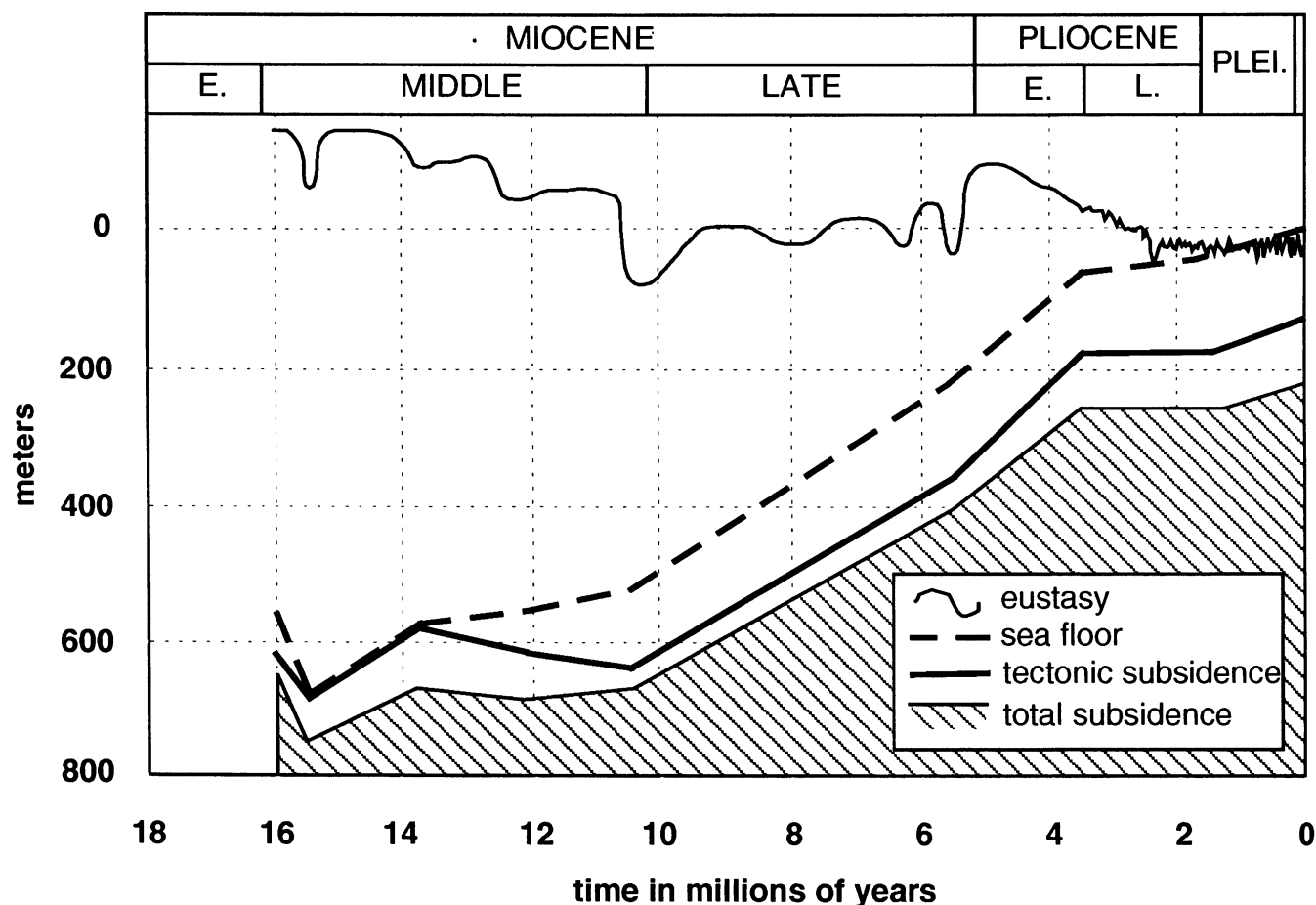
The La Reine Member in Test well 41 can be assigned to the middle part of the middle Miocene. The presence of *Globorotalia fohsi lobata* from the top of the well downward and the absence of *Globorotalia menardii* and *Globorotalia fohsi robusta* indicate that the strata in the top of the well are equivalent to the *Globorotalia fohsi lobata* Zone. Given the 22.9m maximum thickness of the *Globorotalia fohsi lobata* Zone in the other wells studied, the basal portion of the Kingshill Limestone is interpreted to lie in the *G. fohsi fohsi* chronozone.

In Test well 45a, the La Reine Member is re-interpreted to range from the base of the *Globorotalia fohsi fohsi* chronozone to the middle of the *G. fohsi robusta* chronozone. The upper limit for this interval is placed in the middle of the *Globorotalia fohsi robusta* Zone based on the last-appearance datum of the *Globorotalia archeomenardii* - *Globorotalia praemenardii* group and on the absence of *Globorotalia menardii*. *Globorotalia archeomenardii* is reported by Todd and Low (1976) throughout the cuttings from Test well 45a; however, the form Text-figured in their Plate 12, Text-figure 5 appears to be *Globorotalia praemenardii*, so their reports of *G. archeomenardii* may represent either species. The presence of *Globorotalia fohsi fohsi* sets a lower limit for this interval at the base of the *Globorotalia fohsi fohsi* Zone. In addition, *Globorotalia fohsi lobata* is noted at 30.5m, suggesting that the *G. fohsi lobata* Zone is represented in part of the cored interval.

A variety of biostratigraphic determinations have been made for the La Reine Member at the Kingshill Limestone type section at Villa La Reine. Andreieff et al. (1986) assigned the lower one-third of the section to planktonic foraminiferal zone N14 and the upper two-thirds to N15, which agrees closely with our results. In contrast, a younger late Miocene (N17) assignment for was made for this same section by Lidz (1982). The difference with our results and those of Andreieff et al. (1986) may be explained by difficulties in the identification of two key species, namely *Globorotalia humerosa* and *Globorotalia plesiotumida*. Juvenile specimens of *Globoquadrina altispira* may resemble *Globorotalia humerosa*, as may be the case for the specimens identified as *G. humerosa* in Text-figures 57 to 59 of Lidz (1982). The aperture on the figured specimen appears to be umbilical with a small tooth, in contrast to the narrow umbilical-extraumbilical aperture more typical of *G. humerosa*. *Globorotalia plesiotumida* may be difficult to differentiate from other menardiform species. Members of the *Globorotalia merotumida* - *plesiotumida* group were noted by Banner and Blow (1965) as being more convex and tumid than *Globorotalia menardii*, but juvenile middle and late Miocene specimens of *Globorotalia menardii* "A" are also usually much more convex and tumid than their adult forms.

Our results also differ with the interpretations of Frost and Bakos (1977) and Multer et al. (1977), which place the Villa La Reine section in the lower middle Miocene *Globorotalia fohsi fohsi* Zone. Some of the figured specimens of key index taxa in Frost and Bakos (1977) may actually be assignable to other taxa: *Globorotalia archeomenardii* appears to be *Globorotalia scitula* in Plate III, Text-figure 5 and *Globorotalia menardii* "A" in Plate III, Text-figure 6; *Globorotalia fohsi fohsi* in Plate III, Text-figures

## ST. CROIX, U.S.V.I. - KINGSHILL BASIN



TEXT-FIGURE 7

Subsidence analysis for the Neogene of the central plain of St. Croix. Accurate subsidence calculations rely heavily upon micropaleontologic data. Input includes ages for age-depth pairs derived from biostratigraphy, and paleobathymetry for subsidence calculations derived from paleoenvironmental analysis of the microfauna. Tectonic subsidence is calculated from total subsidence by removing the effects of sediment and water loading and calculating the decompacted thickness of the strata based on lithology. Eustasy is from Haq et al. (1988). The sea floor line represents the position of the sea bottom based on paleobathymetry with eustatic contributions removed. Upward trend of tectonic subsidence curve indicates uplift beginning at approximately 10.5 Ma. This uplift may reflect initiation of fault activity along the graben boundaries, driven by left-lateral movement along the northern Caribbean plate boundary zone.

1-4, appears to be *Globorotalia menardii* "A"; and *Globigerinoides diminutus*, in Plate II, Text-figure 8 appears to be *Globigerinoides trilobus trilobus*. The biostratigraphic significance of taxa in this revised species list is consistent with our placement of this section in the *Globorotalia mayeri* and *Globorotalia menardii* Zones.

Calcareous nannoplankton determinations by Hay (in Multer et al. 1977) suggest a lower Miocene placement for the Villa La Reine section, in the *Discoaster druggi* and *Sphenolithus belemnoides* Zones. This nannofossil determination points to a stratigraphic position considerably lower than our planktonic foraminiferal determinations and those of previous studies (Multer et al. 1977; Lidz 1982; Andreieff et al. 1986). Frost and Bakos (1977) noted that only *Cyclocargolithus floridanus* is abundant in their samples from the La Reine Member; in dozens of samples, only a few specimens of *Discoaster* were found, mostly *D. deflandrei*. Reworking of older sediments may be responsible for the difference between the nannofossil and planktonic foraminiferal age determi-

nations. We noted some reworking of older early and middle Miocene planktonic foraminifera in this section; because calcareous nannoplankton are more easily transported than planktonic foraminifera, the nannofloras would be expected to be more significantly affected.

#### Manning's Bay Member

Planktonic foraminifera were recovered from the Manning's Bay Member in Well M4 and at the Airport Penitentiary section. The zonation of this interval is based only on species present; species absences in this part of the section are unreliable because they may be due to either unfavorable ecological or diagenetic factors. The abundance of shallow-marine larger foraminifera suggests an environment poorly suited to planktonic forms, and the generally poor state of preservation of the planktonic foraminifera suggests that dissolution-resistant taxa were preferentially preserved.

**Well samples:** The biostratigraphic significance of samples from Well M4 is not clear and only tentatively defined. The sample at

21.8m includes a poor fauna containing six species. *Globorotalia fohsi peripheroronda* is present, reworked from older Miocene strata. Specimens of *Globoquadrina altispira*, *Globigerinoides trilobus* subsp., and *Globigerinoides obliquus extremus* suggest placement near the Miocene-Pliocene boundary, between the base of the upper Miocene *Globorotalia humerosa* chronozone and the middle of the Pliocene *Globorotalia miocenica* chronozone (top of *Globigerinoides trilobus fistulosus* subchronozone). If the tentative identification of one small menardiform specimen as *Globorotalia tumida* is correct, the sample may lie in the Pliocene portion of this interval.

**Outcrop samples:** The interval above the unconformity in the Airport/Penitentiary section (text-fig. 1) appears to lie in the lower Pliocene *Globorotalia margaritae* chronozone. The lower limit is based on several specimens from just above the unconformity (sample N) tentatively identified as *Globorotalia crassaformis* and *Globorotalia crassaformis ronda*. The upper limit is derived from the presence of *Globigerina nepenthes* (text-fig. 5).

**Comparison to previous studies:** Strata above the unconformity at the Airport/Penitentiary section were also assigned to the lower Pliocene by Lidz (1982) and Andreieff et al. (1986), based mainly on the absence of *Globoquadrina dehiscens*. Although both authors considered this taxon to range only to the top of the Miocene, Bolli and Saunders (1985) place the last-appearance datum of this species in the Pliocene, at the top of the *Globorotalia margaritae margaritae* subzone, so we do not consider its absence to be indicative of Pliocene age.

Andreieff et al. (1986 1987) also noted the presence of the planktonic foraminifera *Globigerinoides conglobatus* and the

co-occurrence of the larger foraminifera *Paraspiroclipeus chawn-eri* and “*Operculinoides*” *cojimarensis* above the unconformity as diagnostic of the lower Pliocene.

#### Discussion - planktonic foraminiferal chronostratigraphy

The distribution of *Sphaeroidinellopsis* in Well M1 clarifies the biostratigraphic significance of the first-appearance datum (FAD) of that genus. Bolli and Saunders (1985) set the FAD of the first species of this genus, *S. disjuncta*, at the base of the *Globorotalia fohsi peripheroronda* Zone. However, its occurrence with *Globigerinatella insueta* in the lowest part of Well M1 supports a lower Miocene FAD; this is consistent with that reported by Kennett and Srinivasan (1983) in zone N7 (approximately equal to the *G. insueta* Zone).

The range of *Globigerinoides mitra* can also be clarified by its occurrences in St. Croix. Bolli and Saunders (1985) place the appearance of this species at the base of the middle Miocene *Globorotalia fohsi peripheroronda* Zone. However, the presence of this species in the basal middle Miocene (*P. glomerosa* Zone) fauna at 26.5m in Well M10 supports an earlier FAD for *G. mitra*. Kennett and Srinivasan (1983) reported the FAD of the species in lower Miocene zone N7 (approximately the *Globigerinatella insueta* Zone).

#### PALEOENVIRONMENTS

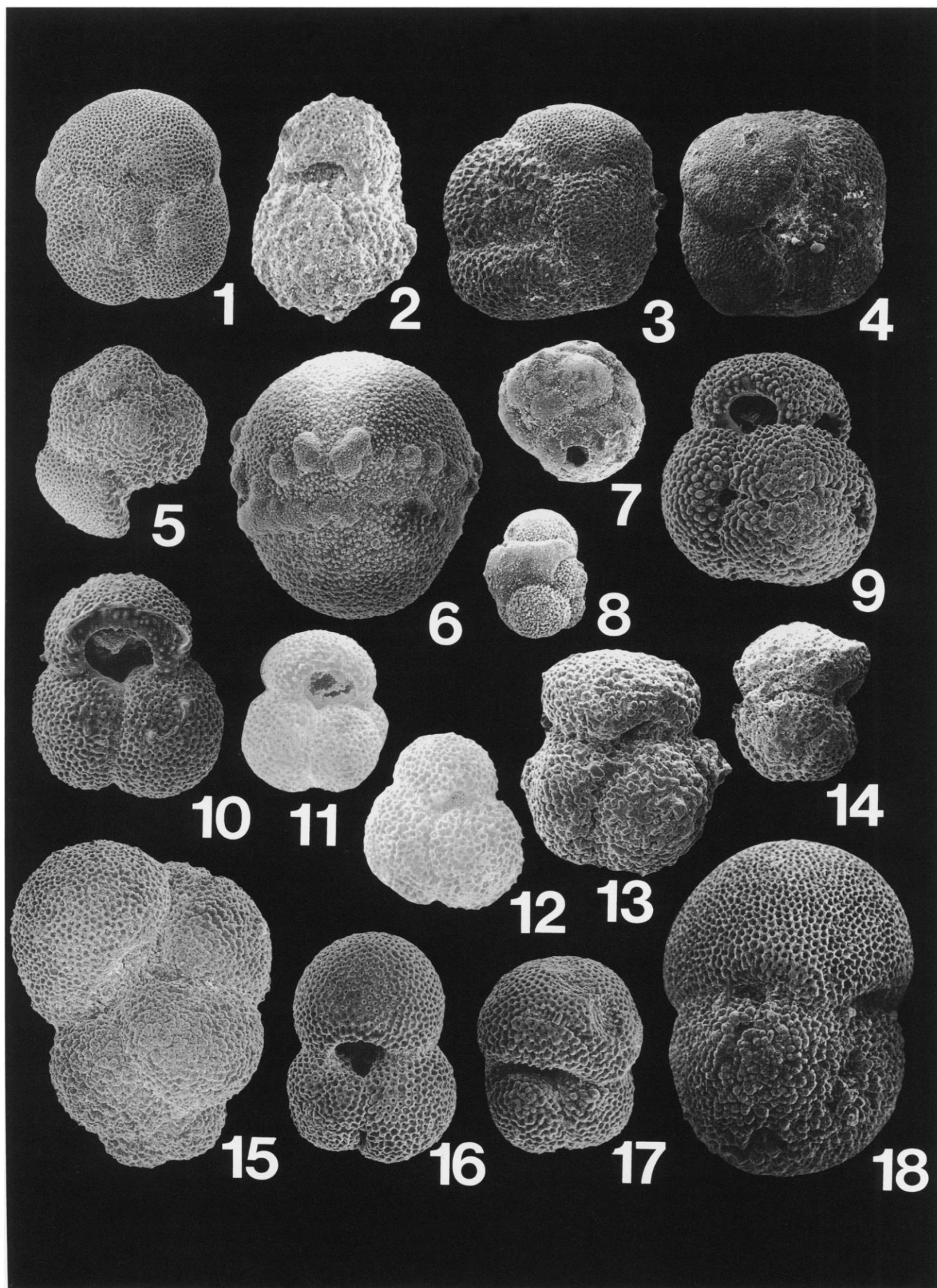
##### Jealousy Formation

**Well samples:** The Jealousy Formation contains benthic foraminiferal species generally associated with both middle and upper bathyal environments in modern assemblages. We interpret the relative abundance of four species present (*Cibicides wueller-*

#### Plate 1

- |     |   |       |  |
|-----|---|-------|--|
| 1   | <i>Globigerina venezuelana</i> Hedberg. Dorsal view, x91. Jealousy Formation (M1-38.1).   | 9,10  | <i>Globigerinoides ruber</i> (d'Orbigny). 9, dorsal view, x91; 10, ventral view, x100. Jealousy Formation (M1-44.2).               |
| 2   | <i>Globigerina nepenthes</i> Todd. Ventral view, x91. La Reine Member (VLR-A).  | 11,12 | <i>Globigerinoides obliquus obliquus</i> Bolli. 11, ventral view, x91; 12, dorsal view, x100. Jealousy Formation (M1-38.1).        |
| 3,4 | <i>Globoquadrina dehiscens</i> (Chapman, Parr, and Collins). 3, dorsal view, x100; 4, ventral view, x91. La Reine Member (M2-22.9). | 13,14 | <i>Globigerinoides obliquus extremus</i> Bolli and Bermudez. 13, ventral view, x100; 14, dorsal view, x91. La Reine Member (EH-C). |
| 5   | <i>Globoquadrina altispira</i> Cushman and Jarvis. Lateral view, x91. Jealousy Formation (M1-38.1).                                 | 15    | <i>Globigerinoides mitra</i> Todd. Lateral view, x91. La Reine Member (M10-25.9).  |
| 6   | <i>Globigerinatella insueta</i> Cushman and Stainforth. Lateral view, x91. Jealousy Formation (M10-26.5).                           | 16    | <i>Globigerinoides trilobus</i> (Reuss). Dorsal view, x91. Jealousy Formation (M1-44.2).   |
| 7   | <i>Candeina nitida</i> d'Orbigny. Dorsal view, x91. La Reine Member (EH-A).   | 17    | <i>Globigerinoides bisphericus</i> Todd. Ventral view, x91. Jealousy Formation (M1-44.2).  |
| 8   | <i>Tinophodella ambitacrena</i> Loeblich and Tappan. Ventral view, x91. Jealousy Formation (M10-26.5).                              | 18    | <i>Praeorbulina transitoria</i> Blow. Lateral view, x91. Jealousy Formation (M10-26.5).  |







*storfi*, *Cibicidoides bradyi*, *Cibicidoides robertsonianus*, and *Osangularia culter*, see Plate 6) to indicate a middle bathyal setting. *Cibicides wuellerstorfi*, a species whose modern representatives are closely associated with the North Atlantic Deep Water (Sen Gupta 1988), occurs in low percentages (0.4 to 2.4%) in several samples. Although it has been found at upper bathyal depths, it is most common in middle bathyal and deeper environments (Parker 1954; Phleger 1951; Morkhoven et al. 1986). *Osangularia culter* is an uncommon species in several Jealousy Formation samples and has an upper depth limit (UDL) of approximately 600m in the Gulf of Mexico (Phleger 1951). *Cibicidoides bradyi* and *Cibicidoides robertsonianus*, both of which occur most commonly below 450m in the Gulf of Mexico (Pflum and Frerichs 1976), are also present. Stilostomellids such as *Stilostomella* and *Siphonodosaria*, which are most typical of middle to lower bathyal depths (Bandy and Rodolfo 1964; Berggren and Haq 1976), are common in the lower Miocene of Wells M1, M10, and PL-149, comprising up to 17% of the fauna, but are less significant constituents (%) of the middle Miocene Jealousy Formation strata of Well M2. *Pullenia bulloides* is rare, never comprising more than 0.5% of the fauna.

A number of species indicative of upper bathyal and greater depths are also present in the Jealousy Formation (table 2): *Bulimina alazanensis*, *Cassidulina subglobosa*, *Planulina renzi*, *Epistominella* sp. cf. *E. exigua*, *Laticarinina pauperata*, *Oridorsalis umbonatus*, *Rectuvigerina multicostata*, *Uvigerina hispida*, and *Siphonina tenuicarinata* (Plates 5 and 6). All are uncommon in the samples, with the exception of *Cassidulina subglobosa* and *Epistominella* sp. cf. *E. exigua*. Pflum and Frerichs (1976) noted that *E. exigua* increases in abundance below the top of the middle bathyal zone in the modern Gulf of Mexico, reaching values of over 2%.

The ostracode faunas of the upper part of the Jealousy Formation are clearly of bathyal character (table 4). The presence of *Krithe reversa* in the upper Jealousy strata suggests that this part of the formation was deposited in water as deep as 1000m or more. Neritic species are completely absent in this interval.

From these faunal data, the Jealousy Formation strata sampled in our drilling program reflect deposition in the upper part of the middle bathyal zone (600-800m). The fauna is dominated by forms typical of upper bathyal and greater depths in the present-day ocean and includes several species not commonly found above the middle bathyal zone.

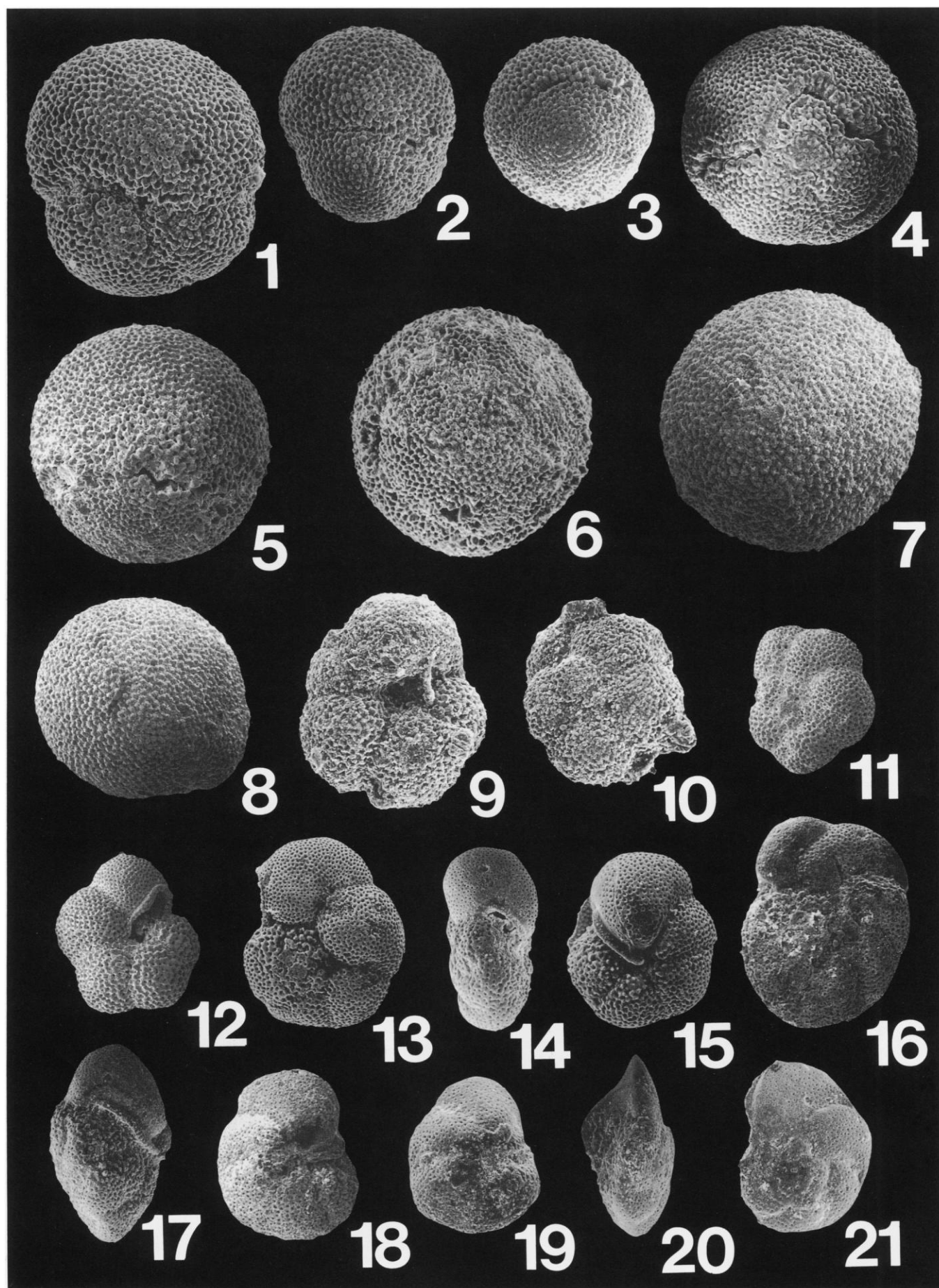
#### La Reine Member

**Well samples:** The benthic foraminiferal faunas of the lower part of the La Reine Member in Wells M1, M2, and M10 differ little from those of the underlying Jealousy Formation. *Melonis pompilioides* and *Sphaeroidina bulloides* are present, but have not been noted in the underlying Jealousy strata. *Cibicidoides robertsonianus* and *Planulina renzi*, which are present in the Jealousy Formation, are absent in the La Reine Member well samples. However, these minor faunal differences do not reflect any significant environmental shifts from the setting of the Jealousy Formation. Hasegawa (1984) has suggested that *Melonis pompilioides* was probably most typical of upper bathyal settings in the Miocene, and *Sphaeroidina bulloides* is most common at middle and upper bathyal depths (Morkhoven et al. 1986). Therefore, the lower part of the La Reine Member appears to have been deposited in the upper part of the middle bathyal zone (table 2).

**Outcrop samples:** The ostracode and foraminiferal faunas recovered in the Salt River Valley outcrops suggest a totally different environment than those from the subsurface Jealousy Formation and La Reine Member. The ostracode fauna is of a nearshore nature,

#### Plate 2

- |   |   |
|---|---|
| <p>1 <i>Praeorbulina sicana</i> (de Stephani). Lateral view, x93. Jealousy Formation (M1-41.6).</p> <p>2,3 <i>Praeorbulina glomerosa curva</i> Blow. 2, lateral view, x93; 3, bottom view, x93. Jealousy Formation (M1-41.6).</p> <p>4,5 <i>Praeorbulina glomerosa glomerosa</i> Blow. 4, bottom view, x93; 5, lateral view, x93. Jealousy Formation (PL149-24.3).</p> <p>6 <i>Praeorbulina glomerosa circularis</i> Blow. Bottom view, x93. Jealousy Formation (M10-32).</p> <p>7 <i>Orbulina universa</i> d'Orbigny. x93. La Reine Member (VLR-A).</p> <p>8 <i>Orbulina suturalis</i> Brönnimann. x93. Jealousy Formation (M10-32).</p> | <p>9,10 <i>Globorotalia humerosa</i> Takayanagi and Saito. 9, ventral view, x93; 10, dorsal view, x93. La Reine Member (EH-A).</p> <p>11,12 <i>Globorotalia mayeri</i> Cushman and Ellisor. 11, dorsal view, x93; 12, ventral view, x93. Jealousy Formation (M1-38.1).</p> <p>13-15 <i>Globorotalia fohsi peripheroronda</i> Blow and Banner. 13, dorsal view, x93; 14, lateral view, x93; 15, ventral view, x93. Jealousy Formation (M1-44.2).</p> <p>16-18 <i>Globorotalia fohsi peripheroacuta</i> Blow and Banner. 16, dorsal view, x93; 17, lateral view, x93; 18, ventral view, x93. La Reine Member (M1-32).</p> <p>19-21 <i>Globorotalia fohsi fohsi</i> Cushman and Ellisor. 19, ventral view, x93; 20, lateral view, x93; 21, dorsal view, x93. Jealousy Formation (M2-50.8).</p> |
|---|---|





very similar to that of the Anguilla Formation of Anguilla and the Lowlands Formation of St. Martin. However, the absence of *Hemicyprideis* and *Peratocytheridea* indicates that the ostracodes were probably derived from a reefal environment instead of the lagoonal environment represented in the otherwise similar Anguilla fauna. The foraminiferal faunas of some samples are similar to those of Recent Caribbean reefs, dominated by *Archaias* and miliolids (SC-5 of Bold 1970); other samples (89/5b) include taxa typical of inner neritic and lagoonal areas of carbonate coastlines, such as *Elphidium* and *Amphistegina*. These findings are similar to those reported in Lidz (1982) from the Salt River valley, which cited the presence of *Archaias* sp. and *Amphistegina* spp. as indicative of a low-energy lagoon or shoal shelf environment. These strata have been mapped as sediments of the Jealousy Formation (Cederstrom 1950; Whetten 1966) or shallow lagoonal or strandline deposits of the basal Kingshill Limestone (Gerhard et al. 1978; Lidz 1982; Andreieff et al. 1986). An in-place interpretation would indicate the presence of a very shallow-marine environment in northern St. Croix in the earliest middle Miocene contemporaneous with middle bathyal environments indicated in the nearby Well M10 (text-fig. 1). Because of the extremely steep gradient that would be required to explain these occurrences if the faunas are in-place, downslope transport of shallow-marine material into a deep basin seems a more likely explanation.

In stratigraphically higher outcrops of the lower part of the Kingshill Limestone (*Globorotalia fohsi fohsi* and *G. fohsi lobata* Zones), the benthic foraminiferal fauna suggests a setting near the middle bathyal - upper bathyal boundary (approximately 600m). *Planulina renzi*, *Cibicides wuellerstorfi*, *Cibicides cicatricosus*, *Pyrgo murrhina*, and *Sphaeroidina bulloides* are present in these samples from the Five Corners, Rattan-Belvedere, and Tradewinds outcrops. The specimens of *Sphaeroidina bulloides* are large, approaching 1m, suggesting nearly middle bathyal depths (Pflum and Frerichs 1976). The flat morphology, less hooked sutures, and smooth surface (indistinct pores) exhibited by specimens of *Cibicides wuellerstorfi* in these samples suggests a setting near the upper depth limit of this species (top of the middle bathyal zone); Bandy (1967) reported that forms with smoother, less hooked sutures tend to occur at water depths shallower than 1000m.

Benthic foraminifera from higher in the Kingshill Limestone at the Villa La Reine type section (*Globorotalia mayeri* Zone, possibly

extending into the *Globorotalia menardii* Zone) suggest deposition in the lower part of the upper bathyal zone (400-600m). Stilostomellids (such as *Stilostomella* and *Siphonodosaria*) are common throughout the section. *Karreriella bradyi*, *Cassidulina subglobosa*, *Cibicidoides incrassatus* and *Cibicidoides pachyderma bathyalis* are also present, all common constituents of upper bathyal assemblages. Rare specimens of *Laticarinina pauperata* and *Cibicides wuellerstorfi* were found in this section. The specimens of *Laticarinina pauperata* are relatively small, mostly near 1mm in diameter, suggesting a setting in the upper part of its typical depth range (Pflum and Frerichs 1976). *Cibicides wuellerstorfi* also exhibits a morphology more typical of the upper part of its bathymetric range (lower part of upper bathyal zone), with a flatter test and less distinct pore development on the test surface. Shallow-water forms such as *Amphistegina* are much more common in the Villa La Reine samples than in the core samples. Combined with the volume of coral rubble evident at the outcrop, this reflects an increased influx of sediment gravity flows near the end of the middle Miocene. Benthic foraminiferal faunas are similar in the nearby Centerline Road outcrop (89/8b).

Sample material placed in the *Globorotalia menardii* Zone from the east side of Morningstar has a very rich, diverse fauna composed of middle to upper bathyal forms with a component of shallow-marine downslope contaminants (e.g. *Amphistegina*). *Laticarinina pauperata*, *Osangularia culter*, *Planulina renzi*, *Cibicides wuellerstorfi*, *Cibicides cicatricosus*, *C. incrassatus*, *Karreriella bradyi*, *Sphaeroidina bulloides*, stilostomellids, and *Vulvulina* sp. are some of the bathyal taxa present.

Below the unconformity at the Airport/Penitentiary section, benthic foraminiferal evidence suggests shoaling upward from the Villa La Reine section. The assemblage is typical of the upper part of the upper bathyal zone (200-300m) with *Planulina renzi*, *Planulina ariminensis*, *Uvigerina carapitana*, *Stilostomella* spp., *Liebusella soldanii*, *Cassidulina subglobosa*, *Cibicidoides pachyderma bathyalis*, and very small specimens of *Laticarinina pauperata*. Shallow-water contaminants such as *Amphistegina* are generally more abundant here than in the Villa La Reine samples.

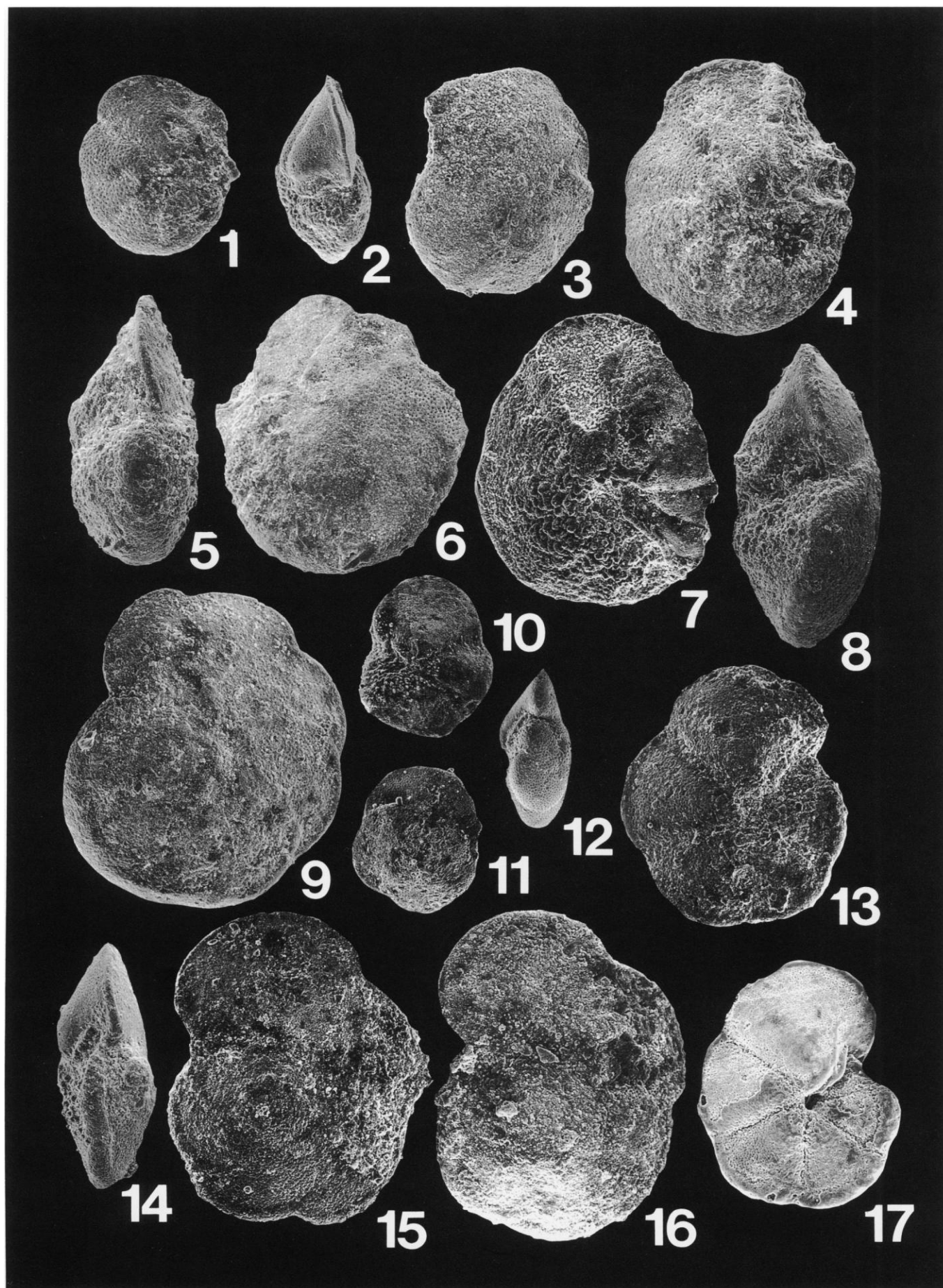
#### Manning's Bay Member of the Kingshill Limestone

**Outcrop samples:** - The fauna of the basal part of the Manning's Bay Member is a mixture of outer neritic species and forms

### Plate 3

- |   |   |
|---|---|
| <p>1-3 <i>Globorotalia fohsi praefohsi</i> Blow and Banner. 1, ventral view, x82; 2, lateral view, x82; 3, dorsal view, x82. La Reine Member (M2-50.3).</p> <p>4-6 <i>Globorotalia fohsi lobata</i> Bermudez. 4, ventral view, x82.5; lateral view, x82; 6, dorsal view, x82. La Reine Member (M2-21.8).</p> <p>7-9 <i>Globorotalia fohsi robusta</i> Bolli. 7, ventral view, x82; 8, lateral view, x82; 9, dorsal view, x82. La Reine Member (M2-6.1).</p> | <p>10-12 <i>Globorotalia archaeomenardii</i> Bolli; 10, ventral view, x82. 11, dorsal view, x82; 12, lateral view, x82. Jealousy Formation (M1-41.6).</p> <p>13-15 <i>Globorotalia praemenardii</i> Cushman and Stainforth. 13, ventral view, x82; 14, lateral view, x82; 15, dorsal view, x82. La Reine Member (M2-6.1).</p> <p>16, 17 <i>Globorotalia menardii</i> "A" Bolli; 16, dorsal view, x82. 17, ventral view, x82. La Reine Member (VLR-H).</p> |
|---|---|







associated with reef complexes. The outer neritic assemblage includes *Cibicidoides incrassatus*, *Siphonina pulchra*, *Planulina ariminenensis*, *Fursenkoina* sp., and a small, flattened variety of *Oridorsalis* sp. cf. *O. ecuadorana*. The reef complex forms are mostly poorly preserved, abraded specimens of *Amphistegina* and of *Discorbis* or *Rosalina*, and appear to be transported.

#### Discussion of the benthic foraminiferal faunas

Microfaunal evidence indicates an upward shoaling trend in the Kingshill Limestone. Within the La Reine Member, a gradual shoaling is evident from middle bathyal in the core samples of marls of the lower part of the member to uppermost bathyal in the limestones of its uppermost portion at the Airport/Penitentiary section. This shoaling is accompanied by an increasing proportion of shallow-water faunal contaminants. A distinct environmental shift is recorded at the Airport/Penitentiary section unconformity, with the bathyal fauna of the La Reine Member passing immediately into the neritic fauna of the Manning's Bay Member.

The subsurface samples of the Jealousy Formation and La Reine Member of wells M1, M2, and M10 are notably rich in *Bolivina*, suggesting that high-productivity or oxygen-poor conditions prevailed during parts of the middle Miocene. The percentage ranges from a low of 14% in the Jealousy Formation to a high of 38% in the La Reine Member. Overall, *Bolivina* is most abundant in the middle part of the middle Miocene (*Globorotalia fohsi fohsi* and *G. f. lobata* Zones) in Well M2, averaging 31.5% of the fauna. In the lower part of the middle Miocene (*Praeorbulina glomerosa* and *Globorotalia fohsi peripheroronda* Zones), higher *Bolivina* percentages are noted in the southern part of the Kingshill basin than in the northern part, averaging 30% in Well M1 versus 21% in M10. High proportions of *Bolivina* are known in low oxygen environments (Boltovskoy and Wright 1976; Phleger and Soutar 1973) and nutrient-enriched settings associated with upwelling (Sen Gupta, Lee, and May 1981). In a review of benthic foraminifera of oxygen-poor settings, Sen Gupta and Machain-Castillo (1993) indicated that a low-diversity fauna dominated by a few hyaline species (such as *Bolivina*, *Bulimina*, *Uvigerina*, *Epistominella*, and *Cassidulina*) is typical of bathyal oxygen-minimum zones.

In addition, more subtle temporal differences can be identified in the bathyal faunas of the lower part of the section. *Epistominella* sp. cf. *E. exigua*, *Cassidulina subglobosa*, and the stilostomellids are significant components lowermost middle Miocene deposits (*Praeorbulina glomerosa* and *Globorotalia fohsi peripheroronda* Zones) in wells M1 and M10, but are generally much less common in the higher middle Miocene strata (*Globorotalia fohsi fohsi* and *G. f. lobata* Zones) of Well M2. This trend may reflect temporal oceanographic changes associated with a significant drop in bottom water temperatures in the early part of the middle Miocene (Savin et al. 1975).

#### NEOGENE DEPOSITIONAL HISTORY

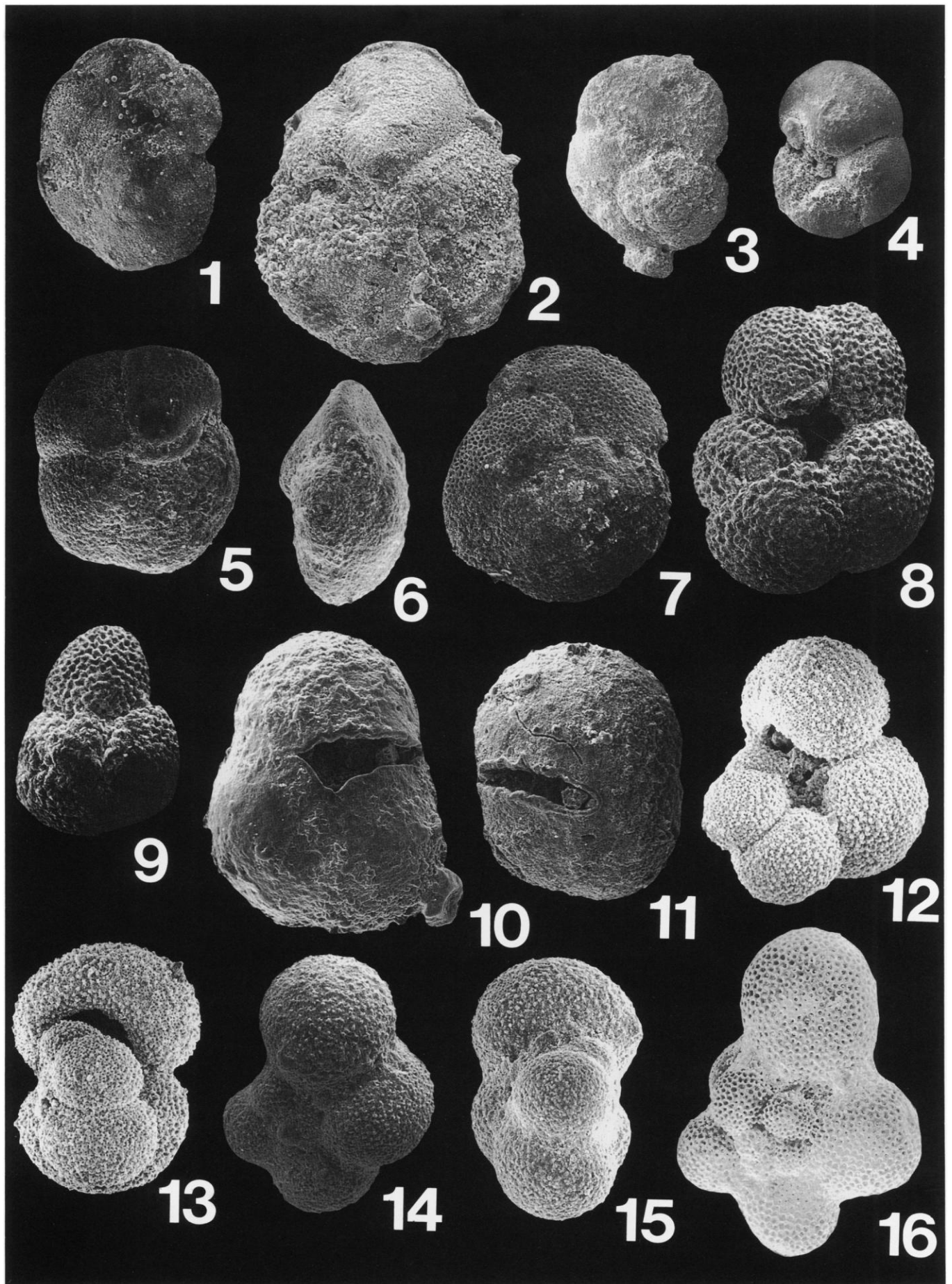
The Neogene depositional history of St. Croix records a major increase in tectonic activity at the beginning of the late Miocene. Lithofacies and biofacies indicate St. Croix was characterized by tectonically quiescent, deep-marine deposition for most of the middle Miocene. The end of the middle Miocene marks the onset of an episode of significant uplift and shoaling, with normal faulting producing the Kingshill basin graben.

The oldest strata known in the Kingshill basin are pelagic-rich blue clays of the Jealousy Formation and tan marls of the lower part of the La Reine Member deposited during the early part of the middle Miocene. Deposition appears to have taken place at middle bathyal depths (>600m) in a tectonically quiescent, low-relief setting with little terrigenous influence at least through the *Globorotalia fohsi fohsi* Zone.

The contact between these blue clays and tan marls is a significant boundary that separates the Jealousy Formation from the Kingshill Limestone, but its precise significance is difficult to determine. The contact is diachronous, ranging from basal middle Miocene *Praeorbulina glomerosa* chronozone to the lower middle Miocene *Globorotalia fohsi fohsi* chronozone. Within the resolution of the planktonic foraminiferal biostratigraphy, no detectable chronostratigraphic break is evident at the boundary. The benthic foraminiferal faunas reveal no discernible paleobathymetric shift. The only clear change is in color, but no changes in bulk mineralogy have been detected (Gill 1989). The diachroneity of this boundary may reflect the extension of several tongues of Kingshill Limestone facies into

#### Plate 4

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|-----|--|-------|--|
| 1,2 | <i>Globorotalia menardii</i> "B" Bolli. 1, dorsal view, x92; 2, ventral view, x92. La Reine Member (EH-A).                     | 11    | <i>Sphaeroidinellopsis sphaeroides</i> Lamb. Ventral view, x92. La Reine Member (EH-C).                              |
| 3,4 | <i>Globorotalia scitula</i> (Brady). 3, dorsal view, x92; 4, ventral view, x92. La Reine Member (EH-A).                        | 12,13 | <i>Hastigerina siphonifera</i> (d'Orbigny). 12, frontal view, x92; 13, lateral view, x92. La Reine Member (VLR-A).   |
| 5-7 | <i>Globorotalia miozea</i> Finlay. 5, ventral view, x92; 6, lateral view, x92; 7, dorsal view, x92. La Reine Member (M2-50.3). | 14,15 | <i>Hastigerina praesiphonifera</i> Blow. 14, frontal view, x92; 15, lateral view, x92. Jealousy Formation (M2-50.8). |
| 8,9 | <i>Sphaeroidinellopsis multiloba</i> (LeRoy). 8, ventral view, x92; 9, dorsal view, x92. La Reine Member (VLR-A).              | 16    | <i>Clavatorella bermudezi</i> (Bolli). Dorsal view, x92. Jealousy Formation (M1-38.1).                               |
| 10  | <i>Sphaeroidinellopsis seminulina</i> (Schwager). Ventral view, x92. La Reine Member (EH-C).                                   |       |  |





the basin, possibly associated with global eustatic falls at 15.5 and 13.8Ma (of Haq et al. 1988). However, because no clear textural or mineralogical change has yet been documented across this formation boundary, it may have been produced by diagenetic changes not detected in the mineralogical analyses or by other factors not at all related to eustasy; these possibilities will be pursued in future studies.

The onset of Neogene tectonism in St. Croix appears to be represented in the earliest late Miocene sediments of the Kingshill Limestone type section at Villa La Reine. Foraminifera in this section indicate the start of significant shoaling, with forms typical of upper bathyal depths (400-600m) contrasting with the middle bathyal (600-800m) faunas present lower in the La Reine Member. The shoaling is accompanied by an influx of large volumes of shallow-marine and terrigenous debris, including coral heads and lithic boulders similar to the Cretaceous Caledonia Formation, which is exposed in the fault-block highlands bounding the Kingshill basin (Gerhard et al. 1978). Gill (1989) has suggested that fault relations between the Kingshill Limestone and the Cretaceous strata on the eastern boundary fault of the basin indicate that faulting post-dates the beginning of Kingshill Limestone deposition; these relationships, as well as the large influx of carbonate debris and Cretaceous lithics, indicate that graben fault activity began near the end of the middle Miocene. The age of the Villa La Reine section and the large volume of debris suggests deposition might also be related to the major terminal Serravallian global sea level drop (10.5 Ma) proposed by Haq et al. (1988).

The unconformity at the Airport/Penitentiary section between the La Reine Member and the Manning's Bay Member marks another abrupt shift in depositional setting. The strata below the unconformity are regularly bedded turbidites with benthic foraminiferal assemblages indicative of the upper part of the upper bathyal zone

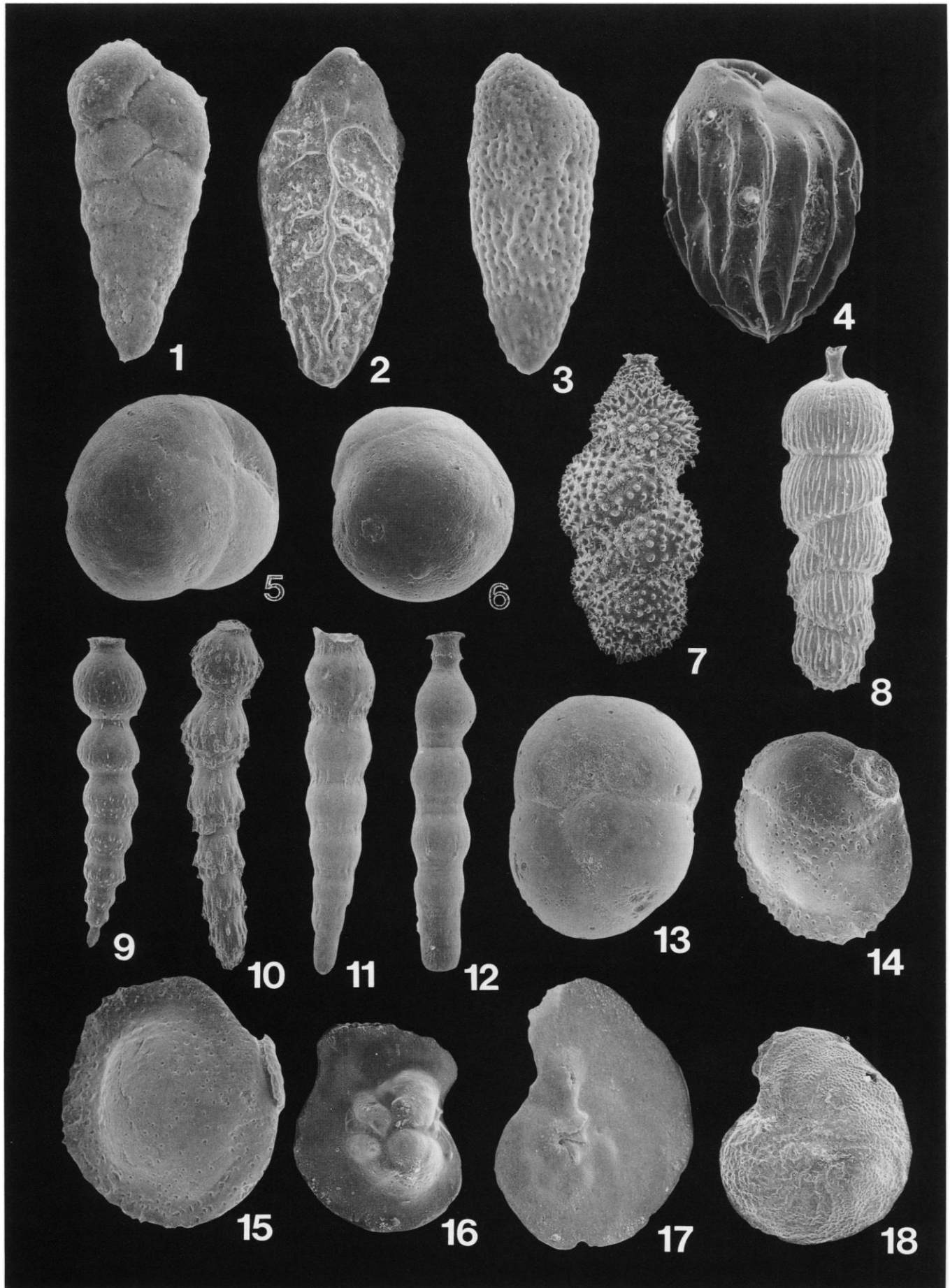
(200-300m). The overlying disconformity is an undulating scour surface with relief of one meter or more. Above this break, the strata are irregularly bedded and contain transported inner neritic larger foraminifera, outer neritic benthic foraminifera, and only rare planktonic foraminifera. Identification of the Miocene-Pliocene boundary in this section is beyond the resolution of the biostratigraphic data available, but larger foraminifera suggest that the strata above the break are Pliocene (Andreieff et al. 1986). This break may be associated, then, with a global terminal Miocene sea level fall, as previously suggested by Lidz (1984), and correspond to the 5.5 Ma sequence boundary of Haq et al. (1988). However, we find no evidence for subaerial exposure at this disconformity (Gill 1989; Gill et al. 1989) and suggest that the cause was submarine erosion by sediment gravity flows.

Our middle Miocene reconstruction contrasts with depositional histories proposed by Cederstrom (1950), Multer et al. (1977), and Lidz (1984, 1988). These authors concluded that the Jealousy Formation was deposited in a marine seaway bounded by emergent mountain blocks of the Northside and East End Ranges. However, our well penetrations reveal no significant contribution of shelf-derived sediment, as would be expected within such a steep-sided marine seaway. Jealousy Formation samples from two water wells (PL-149 and GP-41) within 0.5km of the western boundary of the basin show deep-marine foraminiferal assemblages similar to those in the other Jealousy samples studied, with no significant component of transported shallow-water forms.

Lidz (1982, 1984) interpreted molluscan packstones in the Salt River valley to represent lagoonal-shelfal deposits on the north rim of this seaway. These lie within a trend of calcareous conglomerates along the western boundary of the graben that have been described as shallow-marine and strandline deposits of the Jealousy Formation in previous studies (Cederstrom 1950; Whetten 1966). Ceder-

## Plate 5

- |     |  |        |   |
|-----|--|--------|---|
| 1   | <i>Bolivina</i> sp. A. Lateral view, x 248. La Reine Member (M1-32)  | 10     | <i>Stilostomella</i> sp. cf. <i>S. spinea</i> (Cushman). Lateral view, x47. La Reine Member (M1-32).                          |
| 2   | <i>Bolivina</i> sp. B. Lateral view, x149. Jealousy Formation (M2-50.8).                                   | 11     | <i>Siphonodosaria</i> sp. cf. <i>S. paucistriata</i> (Galloway and Morrey). Lateral view, x55. La Reine Member (PL149-80).    |
| 3   | <i>Bolivina</i> sp. C. Lateral view, x275. La Reine Member (M1-32).  | 12     | <i>Siphonodosaria</i> sp. cf. <i>S. verneuili</i> (d'Orbigny). Lateral view, x50. La Reine Member (M1-32).                    |
| 4   | <i>Bulimina alazanensis</i> Cushman. Lateral view, x149. Jealousy Formation (M1-44.2).                     | 13     | <i>Sphaeroidina bulloides</i> d'Orbigny. Dorsal view, x55. La Reine Member (M2-50.3).   |
| 5,6 | <i>Cassidulina subglobosa</i> Brady. 5, ventral view, x55; 6, dorsal view, x50. La Reine Member (M2-50.8). | 14, 15 | <i>Siphonina tenuicarinata</i> Cushman. 14. Ventral view, x66, 15. Dorsal view, x83. Jealousy Formation (M10-32).             |
| 7   | <i>Uvigerina hispida</i> Schwager. Lateral view, x61. Jealousy Formation (M1-44.2).                        | 16, 17 | <i>Laticarinina pauperata</i> (Parker and Jones). 16, ventral view, x88; 17, dorsal view, x110. Jealousy Formation (M2-50.8). |
| 8   | <i>Rectuvigerina multicostata</i> (Cushman and Jarvis). Lateral view, x83. La Reine Member (M1-32).        | 18     | <i>Planulina renzi</i> (Cushman and Stainforth). Dorsal view, x22. La Reine Member (PL149-80).                                |
| 9   | <i>Stilostomella</i> sp. cf. <i>S. curvatura</i> (Cushman). Lateral view, x61. La Reine Member (M1-32).    |        |   |





strom (1950) identified these strata as lithic and bioclastic conglomerates cemented with carbonate mud and correlated these to conglomerates penetrated in the Jealousy Formation in Well 41 and Well 39. As a result, paleogeographic reconstructions for the early and middle Miocene of St. Croix, such as that of Lidz (1984), suggest that these strata represent a marginal to shallow-marine Jealousy shelf on the flank of an ancestral Northside Range.

We believe, however, that the Jealousy Formation is a strictly subsurface unit and that these packstones and conglomerates are sediment gravity flow deposits in the La Reine Member of the Kingshill Limestone. Numerous conglomerates, which appear to have been deposited by sediment gravity flows of lithic material and shallow-water carbonate debris, have been described from both subsurface and outcrop portions of the La Reine Member. The microfauna present in these beds contain shallow-water forms, and could represent either a coastal setting or downslope transport into a deeper marine setting. Considering the proximity of age-equivalent deep marine facies of the La Reine Member in well M10, we infer deep-water deposition by shelf-derived sediment-gravity flows. In addition, the shallow-water ostracode faunas in samples collected from these outcrops have greater affinities with that in our lower La Reine Member samples than Jealousy Formation core samples.

Subsidence analysis indicates increased tectonism at the end of the middle Miocene (text-fig. 7), with more than 400m of tectonic uplift calculated between 10.5 and 3.5 Ma (input to the subsidence analysis include age-thickness pairs derived from biostratigraphy, paleobathymetric estimates derived from analysis of the benthic microfauna, and lithologic content of each unit; tectonic subsidence/uplift is calculated from total subsidence by removing the effects of sediment and water loading and calculating decompacted stratal thicknesses based on lithologies). This uplift is reflected in a gradual shoaling trend through the middle Miocene followed more rapid emergence in the late Miocene and Pliocene. The timing of this tectonism suggests that St. Croix was affected by the same plate movements that have influenced evolution of a number of other basins along the northern Caribbean plate boundary zone.

Distinct increases in tectonic activity have been identified at about 10 Ma in Hispaniola (Mann et al. 1991; McLaughlin and Sen Gupta 1991; McLaughlin et al. 1991) and Jamaica (Burke et al. 1980; Mann and Burke 1980; Mann et al. 1985). Late Miocene counterclockwise rotation of Puerto Rico has been identified on the basis of paleomagnetic data from the island's north coast carbonate sequence (Reid et al. 1991). Scanlon and Masson (1988) and Speed and Larue (1991) have suggested that this rotation of the Puerto Rico-Virgin Islands terrane would cause extension on its southeastern side relative to St. Croix, giving a mechanism for the opening of the Anegada Passage.

## SUMMARY

Data from cores collected during the 1984-1986 stratigraphic drilling program on St. Croix provide the first accurate biostratigraphic framework for the Jealousy Formation and the lower part of the La Reine Member of the Kingshill Limestone. Combined with our study of ten outcrops on the island, we are able to use this new subsurface data to refine previous biostratigraphic interpretations for the Neogene of St. Croix and to resolve several stratigraphic correlation problems.

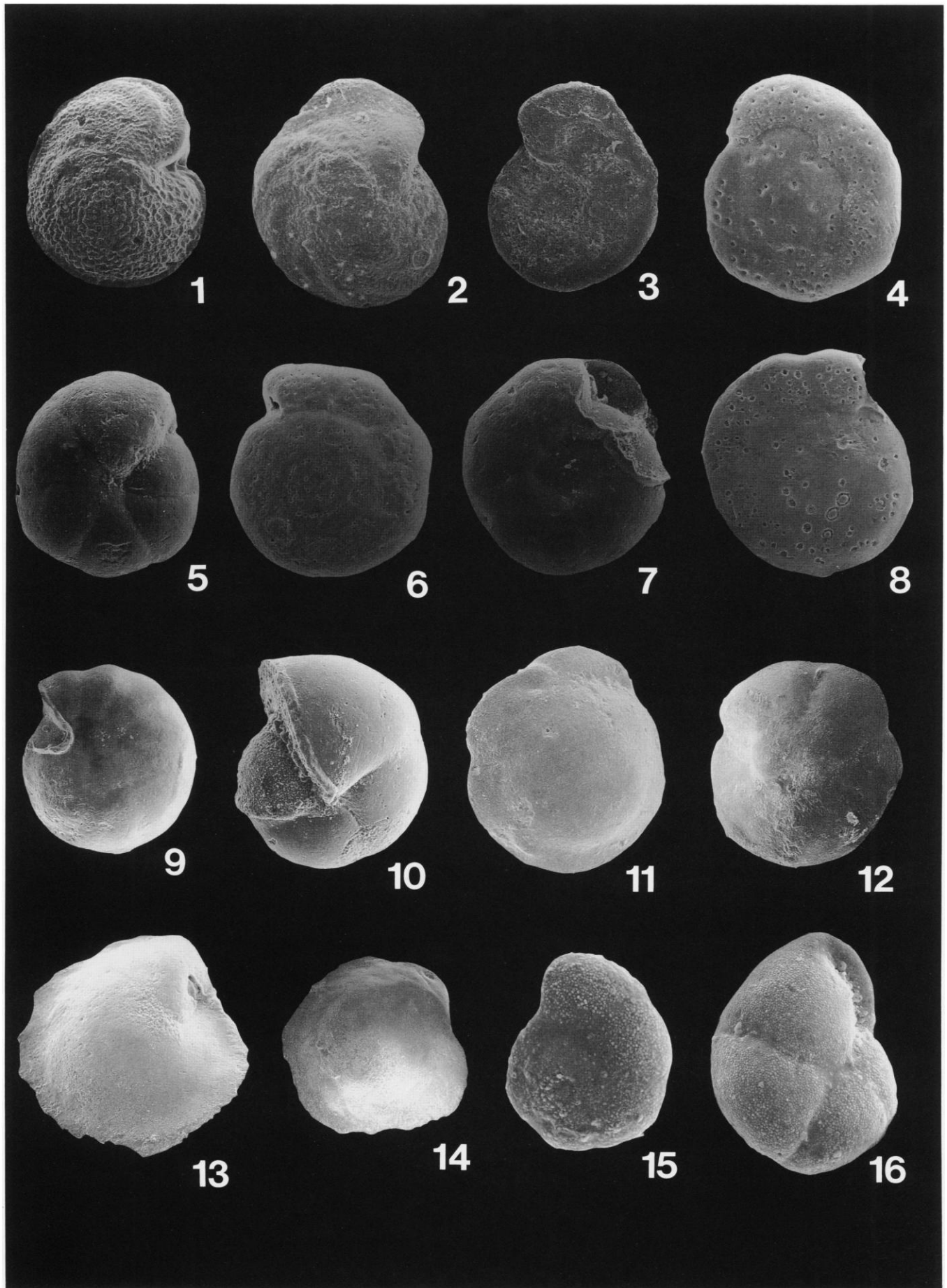
Our results, and a re-evaluation of older data, permit the depositional history of the lower Neogene formations to be summed up as follows:

*Jealousy Formation:* The oldest strata recovered in our boreholes are stratigraphically equivalent to the basal middle Miocene *Praeorbulina glomerosa* Zone. The top of the formation is diachronous, ranging from within the *P. glomerosa* chronozone (in Well M10) to the lower part of the lower middle Miocene *Globorotalia fohsi fohsi* chronozone (in Well M2).

*La Reine Member of the Kingshill Limestone:* This unit extends from basal middle Miocene at its base up to approximately the top of the uppermost Miocene *Globorotalia humerosa* Zone below the unconformity in the Evans Highway section.

## Plate 6

- |     |  |       |  |
|-----|--|-------|--|
| 1   | <i>Planulina renzi</i> (Cushman and Stainforth). Ventral view, x47. La Reine Member (M1-32).                               | 10    | <i>Pullenia bulloides</i> (d'Orbigny). Frontal view, x93. La Reine Member (PL149-80).  |
| 2,3 | <i>Cibicides wuellerstorfi</i> (Schwager). 2, ventral view, x82; 3, dorsal view, x70. La Reine Member (M2-50.8).           | 11,12 | <i>Oridorsalis umbonatus</i> (Reuss); 11, dorsal view, x70. 12, ventral view, x58. La Reine Member (M2-50.3).                    |
| 4,5 | <i>Cibicidoides bradyi</i> (Trauth); 4, dorsal view, x146. 5, ventral view, x128. La Reine Member (M1-35.1).               | 13,14 | <i>Osangularia culter</i> (Parker and Jones). 13, ventral view, x55; 14, dorsal view, x32. Jealousy Formation (M10-26.5).        |
| 6,7 | <i>Cibicidoides bradyi</i> / <i>robertsonianus</i> . 6, dorsal view, x99; 7, ventral view, x99. La Reine Member (M1-35.1). | 15,16 | <i>Epistominella</i> sp. cf. <i>E. exigua</i> (Brady). 15, dorsal view, x251; 16, ventral view, x251. La Reine Member (M1-35.1). |
| 8,9 | <i>Cibicidoides robertsonianus</i> (Brady). 8, dorsal view, x105; 9, ventral view, x82. Jealousy Formation (M10-26.5).     |       |  |



**Manning's Bay Member of the Kingshill Limestone:** These shallow-marine limestones are exposed above the unconformity in the Evans Highway section, where poor planktonic foraminiferal faunas indicate placement between the upper part of the upper Miocene *Globorotalia humerosa* Zone and the top of the lower Pliocene *Globorotalia margaritae* Zone. Larger foraminifera present suggest a Pliocene age (Andreieff et al. 1986).

The new subsurface geologic data resolve several critical points on stratigraphic correlation, as follows:

(1) The Jealousy Formation is an entirely subsurface unit of deep-marine sediments. Lithological comparison of material recovered from the Jealousy Formation in our cores to reported exposures of Jealousy strata reveals little in common. The outcrop material is compatible with the range of lithologies included in the La Reine Member of the Kingshill Limestone and field relationships suggest correlation to surrounding well sections through the La Reine Member.

(2) The boundary between the Jealousy Formation and the La Reine Member of the Kingshill Limestone is distinct and abrupt, with blue marls of the lower unit capped by tan marls of the overlying unit. However, this boundary is diachronous, ranging from the basal part of the middle Miocene in Well M10 (*Praeorbulina glomerosa* Zone) to higher middle Miocene in Well M2 (*Globorotalia fohsi* Zone). The boundary does not appear to indicate any significant paleoenvironmental change.

The Neogene stratigraphic record of the central plain of St. Croix reflects the island's tectonic and eustatic history. Late Miocene uplift and faulting along the margins of the graben can be related to increased activity of the northern Caribbean plate boundary zone elsewhere in the Caribbean at the same time. A record of global eustatic changes appears to be superimposed on the tectonic signal, with sedimentary shifts that may be related to major sea level falls in the middle and late Miocene.

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## APPENDIX 1

### Locations of outcrops studied.

Evan's Highway Airport/Penitentiary section (EH sample series). This outcrop of the Kingshill Limestone is located in highway cut along Melvin Evans Highway (Rt. 66) approximately 1km west of intersection with Airport Road (Rt. 64). The location is due north of Alexander Hamilton airport on the north side of Mannings Hill facing the penitentiary, which lies in the flat, low valley plain to the north. Samples designated La Reine Member were collected from below the marked disconformity, and those designated Mannings Bay Member were collected above the unconformity.

*Fredensburg Quarry (FR)*. Exposure of Kingshill Limestone (La Reine Member) chalks and marls in an active limestone quarry approximately 0.5km north of Centerline Road (Rt. 70) near the Kingshill Church. The quarry can be reached via a dirt road that joins Centerline Road 0.8km west of its intersection with Northshore Road (Rt. 75). The quarry exposure faces east across the broad valley between Fredensborg and the Villa La Reine shopping center.

*Estate Work and Rest (WR)*. Exposures of Kingshill Limestone (La Reine Member) along a driveway excavation in a housing development northwest of the intersection of Rts. 83 and 62. This site can be reached by following Rt. 83 1.1km north of its intersection with Rt. 62, turning left and continuing 0.6km to the apex of a 180 degree turn in the road.

*East side of Morningstar (EMS)*. Exposures of Kingshill Limestone (La Reine Member) in east-west oriented driveway excavations on the east side of Morningstar. From Five Corners, follow Rt. 74 approximately 0.35km to the first oblique right turn, then 0.65km WNW to a complex junction; from the right angle bend to the left at this junction, proceed approximately 0.1km SW up the steep incline between Estate Bellvue and Estate Rattan-Belvedere to housesites. Shallow-water carbonate debris-rich turbidite sandstones and interbedded marls of the Kingshill Limestone comprise this exposure.

*Centerline Road (CR)*. Location in south-facing roadcut through La Reine Hill on Centerline Road (Rt. 70) 0.3km east and uphill of intersection with Rt. 75. Interbedded marls and limestone-debris

turbidite deposits are similar to those at the Villa La Reine type section of the Kingshill Limestone (La Reine Member) 0.3km to the southwest.

*Villa La Reine shopping center (VR)*. Type section of the Kingshill Limestone (La Reine Member) in parking lot excavation behind Villa La Reine shopping center in west-facing exposure cut into La Reine Hill, near intersection of Centerline Road (Rt. 70) and Rt. 75.

*Entrance road to Tradewinds subdivision, Morningstar (MS)*. Low exposures of Kingshill Limestone (La Reine Member) on Evening Road, the eastern entrance road to Tradewinds subdivision. Evening Road intersects Rt. 75 approximately 0.8km east of its intersection with Rt. 80, and the exposures are 0.3–0.5km south of Rt. 75 on Evening Road. Exposures are predominantly interbedded turbidite sandstones and marls and include a pebble bed.

*Rattan-Belvedere (RB)*. White chalk sampled from Kingshill Limestone (La Reine Member) exposures in north-facing house construction site excavations along steep escarpment that rises up from St. John-Judith Fancy area to Rattan-Belvedere. Site reached via gravel road that intersects Rt. 79 from east 0.2 south of intersection of Rt. 75 and Rt. 79. Excavation is approximately 50m upslope of first right-angle bend in gravel road.

*Five Corners (FC)*. This Kingshill Limestone (La Reine Member) exposure is located in excavation at house construction site near Little Princess. From the complex intersection of Rts. 74, 75, and 83, the house site is located 0.15km to the east on Rt. 74, then 0.15km up the slope on the south side of the road.

*Salt River valley (SR)*. Exposure along unpaved road on the east side of Triton Bay in the Salt River valley, in low roadcut next to driveway 0.35km south and uphill of intersection with Rt. 751. Outcrop is a conglomerate that was placed in the Jealousy Formation in some previous studies but is now placed in the Kingshill Limestone (La Reine Member). The conglomerate is composed of igneous clasts, coral fragments, oysters, and mudstone clasts. Sample taken from a rounded green claystone clast.