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Stratigraphy and Depositional Setting, Kingshill Limestone, Miocene, St. Croix, U.S. Virgin Islands[1]

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Abstract The Kingshill Limestone of St. Croix, U.S. Virgin Islands, was deposited during a transgressive-regressive cycle of the early and middle Miocene. Depositional bathymetry ranged from shallow lagoon and patch-reef environments to basin slopes, probably representing strandline to water about 500 m deep. Younger facies reflect a shoaling to probable subaerial exposure. Depositional processes included turbidity current movement of shallow-water sediments and benthic organisms into deep water, especially along the eastern margin of the depositional basin. Current indicators suggest that transport was largely toward the southwest or west.

Sedimentation took place in a partly downfaulted basin that resulted from early Cenozoic vertical structural movements in the Caribbean. The basin now is the low-lying central plain of the otherwise mountainous island.

Although the Kingshill has not been demonstrated to contain hydrocarbons, a relatively complete, albeit restored, stratigraphic section may aid in defining potential exploration targets in nearby areas of the Caribbean.

INTRODUCTION

Petroleum potential of eastern Caribbean islands and banks only recently has received public attention by way of bona-fide exploration programs (Hatfield et al, 1975) in several areas, including a proposed seismic program for St. Croix, U.S. Virgin Islands, and an exploratory well to be drilled on Saba Bank, east of St. Croix. Little information about Cenozoic carbonate rocks of the region has been reported.

Study of the carbonate rocks of St. Croix, U.S. Virgin Islands, has revealed the existence of four rock units of Cenozoic age, whereas only two units had been recognized previously. Depositional environments of these rocks range from basin slope and reefs to strandlines; their ages are Oligocene to Pliocene. The major exposed rock unit of this group is the Miocene Kingshill Marl (Kemp, 1926), which heretofore has been considered to comprise the entire Cenozoic carbonate rock section of St. Croix (Whetten, 1966). This paper reports the stratigraphy, tectonic setting, and depositional history of the Kingshill Marl (hereafter referred to as the "Kingshill Limestone") and suggests restriction of the name "Kingshill" to the lower part of the total Cenozoic carbonate section.

St. Croix is the largest of the U.S. Virgin Islands, located at lat. 17°44′N and long. 64°42′S, about 65 km south of St. Thomas and 130 km east-southeast of Puerto Rico (Fig. 1). Its climate is subtropical, but rainfall variations have created environments ranging from tropical desert to remnant rain forest (Forman, 1974). Most of the island has a heavy vegetative cover. In consequence, exposures are few and these are highly weathered. Most exposed carbonate rocks are highly micritized or chalky. Exceptions to these are fresh and deep construction cuts, active quarry faces, and a few shoreline exposures. No single complete section of the Kingshill Limestone is exposed; consequently a composite section is described (Fig. 2).

Cenozoic rocks are restricted to the relatively flat and low-lying plain and hills occupying the center and southwestern part of the island. The mountainous eastern and northwestern parts of St. Croix are underlain largely by Cretaceous sed-

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The writers' investigations of the Kingshill rocks were instigated by H. G. Multer, who first interpreted the Villa La Reine section. Many other people have contributed to our studies of the Kingshill. Rick Haack helped determine sediment transport directions and John French studied the foraminiferal wackestone facies. Jonathon Fuller was a valuable field companion and sounding board for early ideas. Richard Holt made many thin sections and acetate peels. R. F. Dill pointed out the newest exposures and freely discussed interpretations with us. We also thank John Wray who reviewed our manuscript and made many helpful suggestions for its improvement. Facilities of the West Indies Laboratory, St. Croix, were used extensively during this study. The North Dakota Geological Survey provided drafting and manuscript-preparation facilities and time as part of its continuing study of carbonate petroleum reservoir development in the Williston basin.

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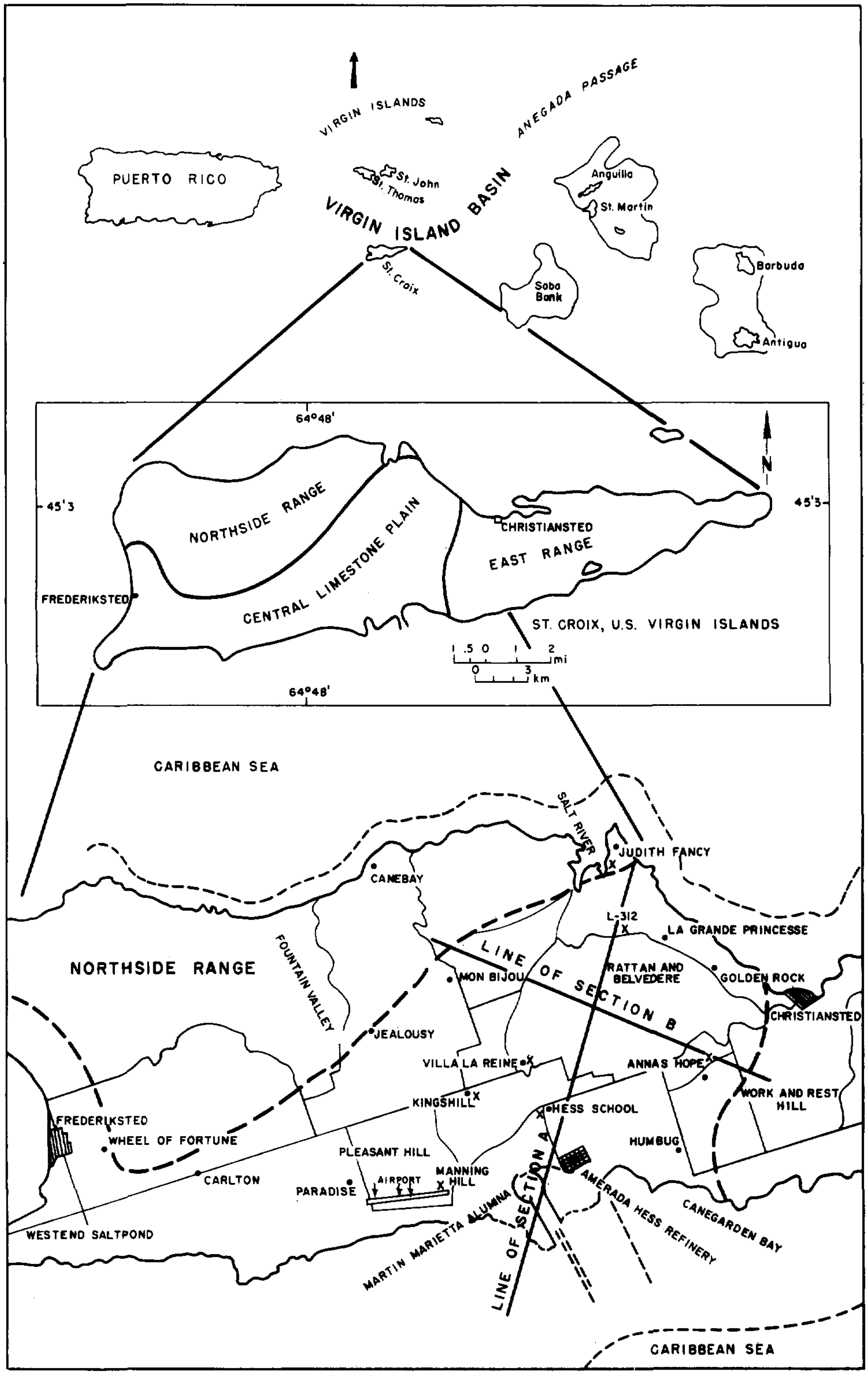
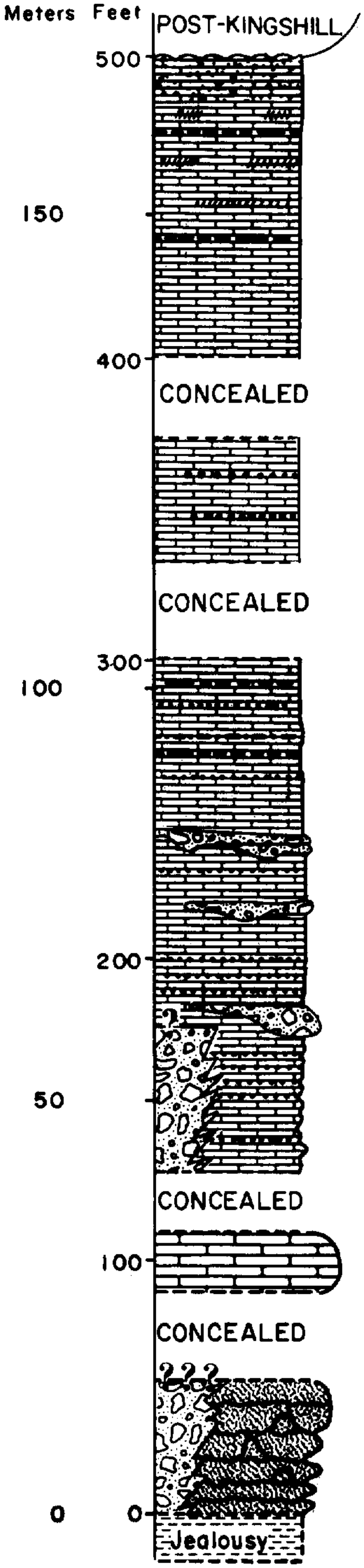


FIG. 1—Location maps showing St. Croix, St. Croix features, and field localities cited in text. Lines of section are for Figure 3.



FORAMINIFERAL GRAINSTONE FACIES. Benthic foraminiferal "coquina" with mollusks, echinoid plates, and spines; rare algae and corals. Shelf-edge bank environment.

FORAMINIFERAL WACKESTONE FACIES. Planktonic Foraminifera in matrix of broken Foraminifera tests, coccoliths, and other micrite and clay grains. "Floods" of larger benthic Foraminifera. Basin-slope environment, shoaling upward.

POLYMICTIC PACKSTONE FACIES. (Based largely on type section at Villa La Reine.)

FORAMINIFERAL PACKSTONE SUBFACIES. Planktonic Foraminifera and coccoliths with other skeletal grains, clay. Basin-slope environment.

CORAL LITHIC PACKSTONE SUBFACIES. Large corals, benthic and planktonic Foraminifera, various other skeletal grains with lithic clasts, boulder to sand size. Shelf-edge debris flows in basin-slope environment.

QUARTZ ARENITE SUBFACIES. Quartz sand and other detrital grains plus some Foraminifera in thin beds intercolated with other subfacies. Graded bedding common. Turbidites of shelf sands in basin-slope environment.

LITHIC FORAMINIFERAL GRAINSTONE FACIES. Quartz sand, lithic gravel and sand, benthic Foraminifera and red algae. Shelf and shelf-edge environments.

Right: MOLLUSCAN PACKSTONE FACIES. Mollusk foraminiferal, algal, coral packstones with scattered lithic clasts and quartz sand. Strandline, lagoon, patch-reef, and shallow-shelf environments represented.

Left: LITHIC FORAMINIFERAL PACKSTONE SUBFACIES of polymictic packstone facies. Planktonic Foraminifera and lithic clasts with scattered corals. Base of tectonic shelf-edge environment. Upper limit not established. Parts of subfacies probably equivalent to parts of Villa La Reine section (type section).

FIG. 2—Generalized stratigraphic column for Kingshill Limestone, St. Croix. This composite section illustrates facies described in paper. Concealed parts of section are assumed to be transitions between facies. Polymictic packstone facies includes type section of Kingshill Limestone.

imentary rocks (Fig. 1; Cederstrom, 1950; Whetten, 1966). Early geologic studies have been summarized by Cederstrom (1950) and Whetten (1966). Of particular interest to the present study are the works of Vaughan (1923), who described fossils collected from the Kingshill; Kemp (1926), who first used the name Kingshill (Kingshill Series); Cederstrom (1941, 1950), who used the name Kingshill Marl and studied the underlying, unexposed Jealousy Formation; and Whetten (1966), who detailed earlier general geologic maps of St. Croix and described the Cretaceous rocks, intrusive rocks, and tectonic history of St. Croix in detail.

More recently, abstracts and progress reports by Multer (1972), Curth et al (1974), and Multer et al (1974) have presented ideas for a shelf-margin deep-water interpretation for part of the Kingshill. Multer et al (1977) recognized the greater complexity of Kingshill lithologies described herein, and described a possible modern analog for the polymictic packstone facies of this paper. Frost and Bakos (in press) have analyzed pelagic biogenic sediment production and diagenesis.

TECTONIC SETTING

St. Croix is separated from the northern Virgin Islands by the Anegada Passage and Virgin Islands basin (Fig. 1). The northern Virgin Islands are largely volcanic in origin, except for Anegada, which is one of the "Limestone Caribees." St. Croix basement rocks are highly deformed, but largely unmetamorphosed Cretaceous turbidites.

Major island structures are an east-plunging anticline forming the framework of the Northside Range, two gabbroic intrusive masses (Fountain Valley intrusive in the Northside Range and Southgate intrusive in the East End Range), and a series of north-south folds in the East End Range. Superimposed on these structures is a triangular central, Cenozoic sediment-filled valley (Fig. 1; Whetten, 1966).

Deposition of the Cretaceous sediment apparently occurred as distal turbidites from volcanic centers located on the margin of the north-moving early Caribbean plate (Whetten, 1966; Edgar et al, 1971; Malfait and Dinkleman, 1972). Available radiometric and fossil dates suggest a Late Cretaceous age (Campanian) for these rocks and an Eocene age for the intrusions; a recent fossil date for the lowest exposed part of the Caledonia Formation (R. C. Speed and L. C. Gerhard, in prep.) suggests a Cenomanian-Turonian age for the lower part of the Caledonia. Deformation of these rocks apparently was related to northward movement of the Caribbean plate. A change to eastward movement of the plate changed tectonic style for St. Croix. Most Cenozoic structural movement has been vertical rather than compressional, and has been controlled by transform motions along the Puerto Rico Trench (Edgar et al, 1971; Malfait and Dinkelman, 1972).

Kingshill rocks have been gently folded into a large south-plunging syncline with several small cross folds. Younger rocks appear to have undergone only island-wide uplift. The Jealousy Formation appears to conform in structure to the Kingshill, on the basis of subsurface data on which the Kingshill-Jealousy surface is mapped (Robison, 1972). No data are available to describe the nature of the sub-Jealousy valley floor, although the floor may be as much as 5,000 ft (1,600 m) below sea level (Whetten, 1966).

Eustatic sea level changes also may have played a substantial role in the deposition of Cenozoic carbonate materials on St. Croix. Major cycles of sea level changes may be responsible for post-Kingshill unconformities, several younger carbonate rock units, and both subaerial and submarine terraces. A general transgressive rise from late Oligocene through middle Miocene times may have effected deposition of the Jealousy and Kingshill in conjunction with vertical tectonic movements (P. R. Vail, written commun.; Vail, 1975).

STRATIGRAPHY

The Kingshill Limestone is composed of about 550 ft (185 m) of foraminiferal skeletal micrites, chalk, thin calcareous detrital sandstone, skeletal grainstone, packstone, and wackestone mixtures of coral, coarse detrital conglomerates and skeletal mudstone, and mudstone. This disparate group of lithologies is divided into five major facies representing the major depositional environments interpreted for the Kingshill Limestone. The Kingshill is of early middle Miocene age (Multer et al, 1977).

Underlying the Kingshill Limestone is the Jealousy Formation of Oligocene age (Cederstrom, 1941, 1950) and above the Kingshill is an unnamed limestone of apparent Pliocene age. Where the Jealousy Formation is absent, the Kingshill Limestone is in contact with Cretaceous rocks.

Older Rock Units

Jealousy Formation (Cederstrom, 1941)—The Jealousy lithology is largely clay with a few thin streaks of limestone; the unit is entirely subsurface. Conglomerates of detrital rocks cemented by carbonate mud are exposed along the southern edge of the Northside Range. These conglomerates may be Jealousy or Kingshill beach deposits. Highly weathered exposures show apparent conformity and gradational lithologies between the conglomerates and true Kingshill, so we suggest that the exposed conglomerates be included in the Kingshill Limestone.

Cederstrom (1950) and Whetten (1966) considered the Jealousy to be of Oligocene age, on the basis of foraminiferal studies by Cushman (1946). Cushman's study clearly demonstrates a marine-shelf origin for the Jealousy. In a recent paper, Todd and Low (1976) assigned an Oligocene age to the oldest planktonic Foraminifera from the wells studied by Cederstrom (1941).

Younger Rock Units

An algal-foraminiferal limestone containing a few solitary corals and mollusks overlaps the eroded margin of a syncline in the Kingshill Limestone north of the St. Croix airport, along the "new airport road" and (prior to recent excavations which have removed the exposure) at the Hess VIRCO refinery on the south shore. Rocks of similar lithology are exposed at or near sea level at Westend Saltpond. These rocks are rich in rhodolites and red algal crusts, apparently deposited as a "hardground" facies. There is no direct physical evidence to determine whether the contact unconformity is submarine or subaerial; however, geometry of exposures suggests a subaerial origin. Basal beds of the overlying limestone contain abundant clasts of Kingshill Limestone, and rhodolites in the younger rocks commonly have Kingshill Limestone clasts as central cores.

Areal Distribution of Kingshill Limestone

Previous geologic maps of St. Croix have portrayed extensive areas of the southwestern plain as being outcrop areas of Kingshill Limestone (Whetten, 1966). Restriction of the term "Kingshill" to those rocks typified by the exposure at the type locality as outlined in this paper considerably limits the areal distribution of the Kingshill Limestone. Generally, topographic prominences on the southwestern plain of 200-ft (67 m) elevation or greater have Kingshill Limestone present, and the Kingshill probably underlies much of the southwestern plain. However, most of the southwestern plain appears to be veneered with carbonate rocks somewhat younger than the Kingshill. These rocks are of varied texture, ranging from micritic chalk (probably the result of extensive weathering) to in situ fossil coral reefs (Estate Carleton; Hess VIRCO Refinery; Martin-Marietta Aluminum Co.). The farthest west unequivocal exposure of Kingshill Limestone is at Pleasant Hill, north of the ruins of Paradise.

STRATIGRAPHIC NOMENCLATURE—TYPE SECTION

The name "Kingshill" was used first in 1923 by J. F. Kemp, in an informally published report cited in his later compiliation of geologic literature of the Virgin Islands region (Kemp, 1926). Kemp used the term "Kingshill series" to encompass all of the Tertiary limestone of St. Croix.

No type section was designated at that time, nor has one been established subsequently. Kemp (1926) suggested that the exposures at Annas Hope, near the eastern margin of the basin, were significant, but this exposure is remote from the geographic locality of Kingshill.

A more formal name, Kingshill Marl, was used by Whetten (1966) after the usage of Cederstrom (1950). Cederstrom referred to the carbonate rocks above the Jealousy Formation specifically as the "Kingshill marl."

In none of those papers were the carbonate rocks studied in any detail, nor were there any attempts to define a stratigraphic sequence. This paper suggests that the term "Marl" be replaced by the term "Limestone" in formal usage, and thus the formation herein described be named the "Kingshill Limestone." Further, the exposures of the polymictic packstone facies at Villa La Reine (a shopping center) are designated as the type section of the Kingshill Limestone (Fig. 2). Over 70 ft (23 m) of section is exposed at Villa La Reine, including the roadcut exposure on the hill east of the intersection of Northshore Road and Centerline Road. Reference localities for other facies are suggested in the facies descriptions.

The Villa La Reine locality was selected because it is the best exposure of typical Kingshill Limestone, is easily accessible, and is proximal to Kingshill (which lies less than 1 mi or 1.6 km west). None of the younger limestones are exposed at this locality.

PETROLOGY AND FACIES DESCRIPTION

The Kingshill Limestone includes five major facies. Geometric relations between these facies are obscure because of poor exposures, but appear to reflect both synchronous and time-transgressive environmental changes (Fig. 2). All five major facies are limestone, although terrigenous-derived clastic grains are common in three of the five. Major differences in biotic constituent particles are the major basis for differentiation of facies and are a result of differing physical environments, communities, and depositional processes. Fabrics, biotic constituents, mineralogy, and sedimentary structures are the basis for interpretations of depositional environments.

Facies descriptions have been arranged in an apparent base-to-top order from field localities present from north to south. This is not to say that lateral changes in environments could not produce the identical set of lithologies; however, the northernmost exposure is in contact with older rock units and the southernmost exposures are overlain disconformably by younger rocks, suggesting that a vertically successive "stack" is represented by the restored composite section (Figs. 2, 3).

Fossil age dates of the Kingshill are early middle Miocene (Multer et al, 1977). The age is based on planktonic and benthic forams, corals, and coccoliths.

Molluscan Packstone Facies

The apparent lowest unit of the Kingshill Limestone is the molluscan packstone facies (Fig. 4a), exposed in north-central St. Croix in the vicinity of Judith Fancy (Fig. 1). Exposures are generally poor, but excavations for house foundations have provided numerous blocks for study. In roadcuts the beds are generally highly weathered, but stratigraphic relations are still discernible. A contact between the Judith Fancy Formation (Cretaceous) and the Kingshill Limestone is exposed by the road leading south along the east shore of the Salt River estuary. Cretaceous rocks are in a nearly vertical attitude; the basal exposed Cenozoic rocks appear to lap against a small cliff of Judith Fancy Formation, but the contact could be faulted (Whetten, 1966). These younger rocks are conglomerates with a carbonate-mud matrix, containing clasts of Cretaceous rocks, other limestones, and andesite porphyry, similar to the conglomerates described by Cederstrom (1950) as being both basal Jealousy and basal Kingshill. The exposure has been cut by a series of small faults which make stratigraphic interpretation difficult; nonetheless, the apparent vertical sequence from these basal beds upward contains progressively smaller and fewer grains of lithic clasts and increases in primary carbonate content. About 7 m upsection from the exposed contact (also about 50 m horizontally from that exposure), the limestones are molluscan packstones containing appreciable amounts of quartz sand, red algae, codiacean algae, forams, and echinoids. Exposures are very poor. Blocks excavated for new home foundations (and saved by owners because of spectacular fossil content) show some corals in growth position and at least one patch reef has been excavated.

Lithic and quartz grains are rounded to subangular and constitute up to 10% of the rock; near the base of the facies lithic content does increase to over 75% of the total rock. All of the

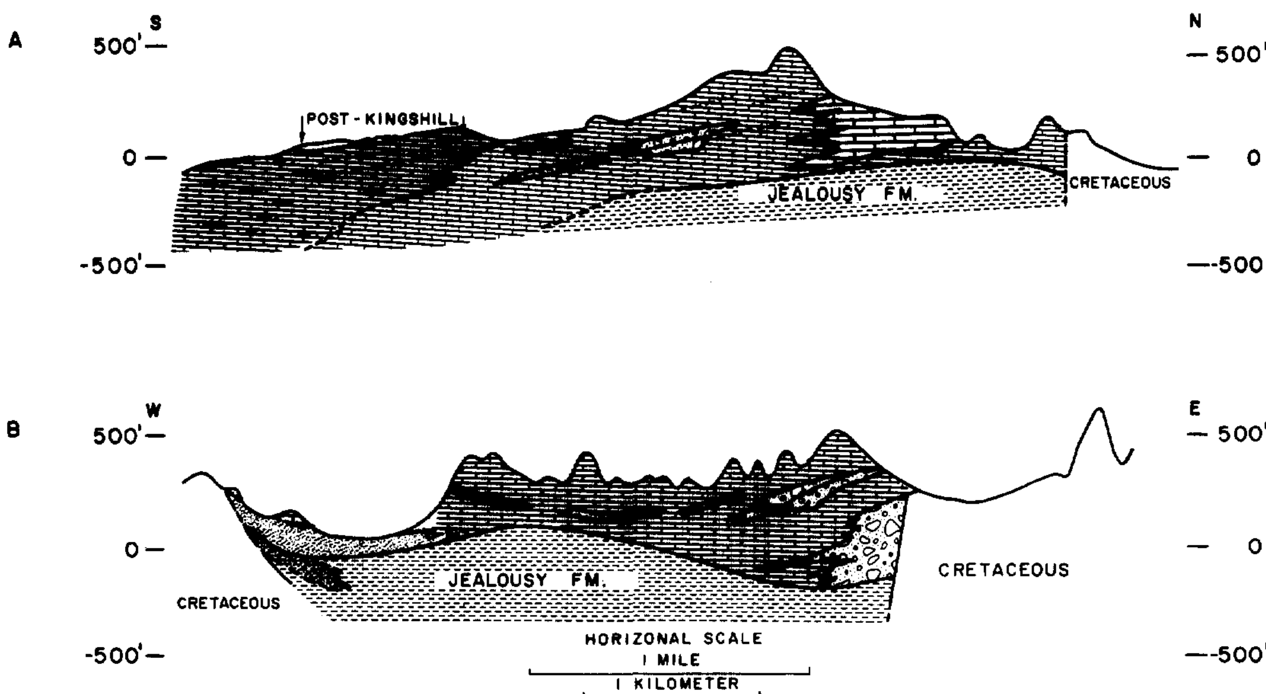


FIG. 3—Interpretive cross sections through Kingshill Limestone. A, north-south section; B, east-west section. See Figure 2 for pattern explanation, Figure 1 for lines of section.

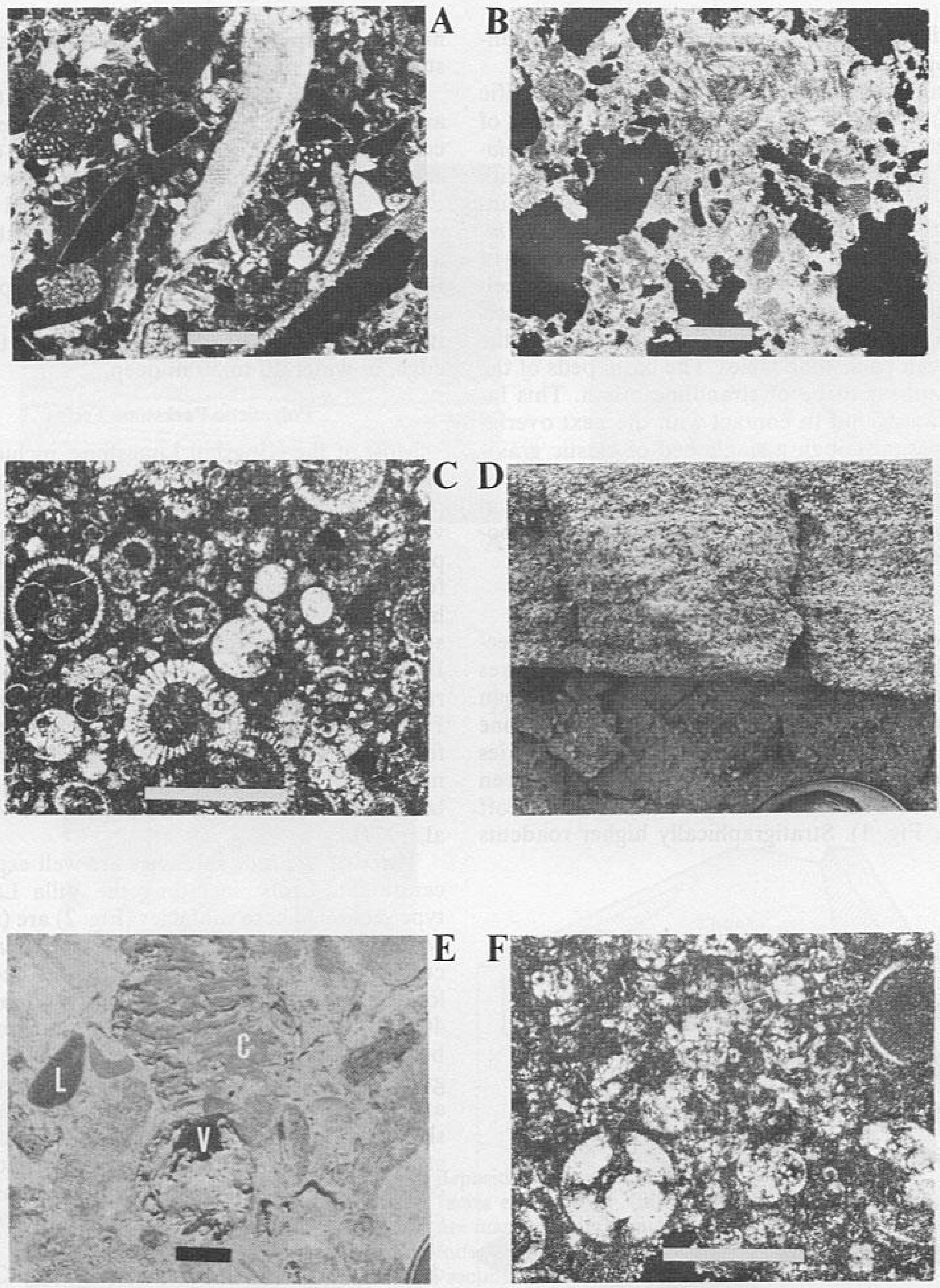


FIG. 4—Kingshill Limestone facies.

A, Photomicrograph of molluscan packstone facies showing mollusks, foraminifers, and codiacean algae. Bar represents 0.5 mm.

B, Photomicrograph of lithic foraminiferal grainstone facies, showing micritized carbonate, foraminifers, and detrital grains. Black areas are voids. Bar represents 0.5 mm.

C, Photomicrograph of foraminiferal packstone and facies of polymictic packstone facies, showing pelagic foraminifers (*Orbulina* and *Globorotalia*) in micrite matrix. Bar represents 0.5 mm.

D, Quartz arenite subfacies of polymictic packstone facies, showing typical bed thickness and graded character. U.S. dime is scale.

E, Coral lithic packstone subfacies of polymictic packstone facies, showing coral, *C*; coral void, *V*; and lithic grains, *L*. Bar represents 0.33 cm.

F, Photomicrograph of foraminiferal wackestone facies, showing mixed benthic (*Operculinoides*) and pelagic foraminifers. Bar represents 0.5 mm.

lithic clasts could have been derived from the underlying Judith Fancy Formation.

Fossil biota of this facies is varied and prolific (Fig. 5). Cederstrom (1950) reported 12 genera of pelecypods and 6 genera of gastropods plus *Stylophora* (coral) and *Sorites* (foram) from the Judith Fancy area; we have found additional fossils including *Strombus*, echinoids, other forams (*Amphistegina*, miliolid), and corals. Preservation of algae (*Halimeda, Amphiroa,* and *Jania*) is excellent and supports a shallow lagoon or shelf interpretation for the depositional environment of the molluscan packstone facies. The basal beds of the facies appear to be of strandline origin. This facies is not found in contact with the next overlying facies, although a single bed of clastic grainstone perhaps representing the overlying facies, about 0.5 m thick, is intercalated with molluscan packstones in the uppermost part of road exposures overlooking Salt River estuary.

Clastic Grainstone Facies

Structural restoration of the stratigraphic section of the Kingshill Limestone places exposures of a clastic grainstone facies above the molluscan packstone facies. Like the molluscan packstone facies, exposures of the clastic grainstone facies are very poor. This facies was exposed between LaGrande Princesse and the Salt River turnoff (L-312, Fig. 1). Stratigraphically higher roadcuts

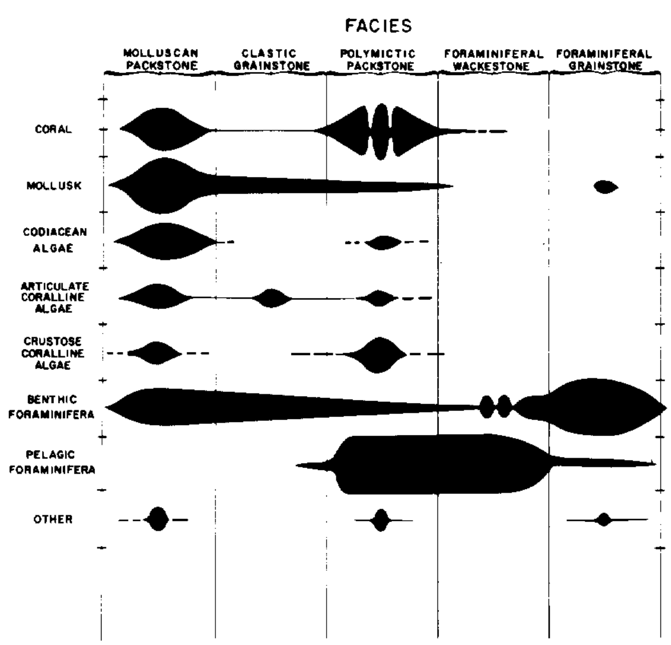


FIG. 5—Diagram depicting relative abundance of major organism groups identifiable in various facies of Kingshill Limestone. Base of Kingshill is on left, top on right.

near this exposure expose foraminiferal packstones of the next overlying facies.

Constituent particles of this facies are lithic and quartz sand (up to about 45%, forams, and coralline algae (Fig. 3b). Micritization of most carbonate grains prevents a detailed description of the fossil biota, but *Amphistegina* and various miliolid forams are present and both crustose and articulate coralline algae appear to be present. Beds are about 15 cm thick; the total exposure is about 7 m thick and discontinuous. This facies is interpreted to be a sand deposited near the shelf edge, in water 10 to 50 m deep.

Polymictic Packstone Facies

Most of the Kingshill Limestone, including the designated type section, can be categorized in a polymictic packstone facies. This facies is subdivided into four genetically related subfacies comprising a somewhat heterogeneous assemblage of foraminiferal packstones, quartz arenite, coral-lithic packstones. and lithic-foraminiferal packstones. Graded bedding is common to this facies. Insoluble-residue content varies by subfacies, but ranges from a little less than 0.5% to over 80%. Planktonic Foraminifera (see Multer et al, 1977, for biostratigraphy and faunal zones) are common to all subfacies and the subfacies are intercalated with each other (Curth et al, 1974; Multer et al, 1977).

Three of the four subfacies are well exposed in central St. Croix, including the Villa La Reine type section. These subfacies (Fig. 2) are (a) poorly indurated foraminiferal packstone (chalk), occurring as white, massive, continuous beds, with local graded bedding in the lowest parts (Fig. 4C); (b) impure quartz arenite in thin continuous beds 2 to 6 cm thick, composed largely of mineral grains derived from Cretaceous rocks. The quartz arenite has calcareous cement, contains a few skeletal grains, and exhibits grading and flame structures (Fig. 4D); (c) coral-lithic packstones composed of large corals, mollusks, forams, calcareous algae, echinoid fragments, an occasional shark tooth, and detrital grains from clay to boulder size, with a micritic matrix (Fig. 4E). Grading, when present, is limited to a few centimeters of foraminiferal-clastic packstone directly overlying the main rock mass. This subfacies is lenticular, commonly cutting out finer grained lower beds (Fig. 6A). Large detrital grains are angular to rounded and corals are only in part abraded, suggesting that some were alive immediately before deposition.

Lithic-foraminiferal packstone is the fourth subfacies. It is characterized by small to large blocks of Cretaceous Caledonia Formation im-

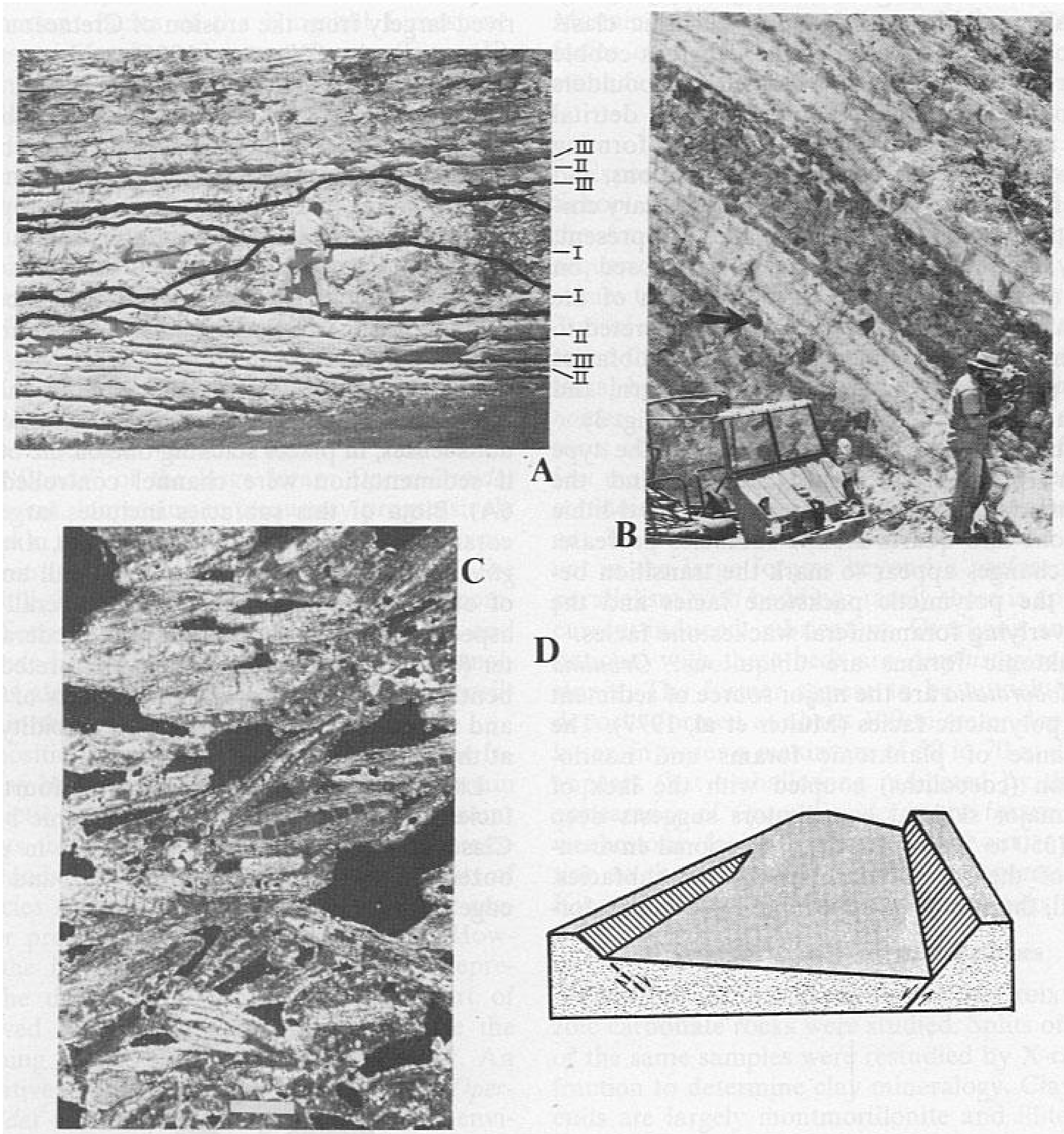


FIG. 6—Kingshill Limestone facies and depositional-basin structural model.

A, Photograph of polymictic packstone facies exposure at Villa La Reine near center of St. Croix. Debris flows (coral-lithic packstone) are massive units (contacts outlined, labeled *I*) irregularly interspersed with thick-bedded foraminiferal packstones (such as *II*) and thin quartz beds (such as *III*). This is newly designated type section of Kingshill Limestone.

B, Photograph of Kingshill Limestone at Work and Rest Hill, showing syntectonic breccia. Dark beds are clastics eroded from Cretaceous rocks, light-colored beds are foraminiferal packstone. Clasts are angular; arrow points to pebble lens. Dip is interpreted as partly original. Locality is at faulted east margin of the Kingshill depositional basin.

C, Photomicrograph of foraminiferal grainstone facies. *Operculinoides* is most abundant foram. Bar is 0.5 mm long.

D, Block diagram illustrating manner in which floor of Kingshill depositional basin is envisioned to have subsided. Fault on west side is not established.

bedded in foraminiferal packstones. Dip of this unit is up to 70°, and structural relations suggest that some of the high dip angles are initial dip along an eastern margin (at Work and Rest Hill). Generally, pebble- and granule-size lithic clasts are subrounded to well rounded, whereas cobble sizes are subangular to subrounded and boulders commonly are angular. Some lenses of detrital clasts are obviously current bedded, forming "shadows" around larger clasts, imbrications, and incipient cross-laminations (Fig. 6B). Solitary coral clasts of boulder size and smaller are present, usually abraded. This subfacies is exposed on Work and Rest Hill, the eastern margin of the Kingshill depositional basin, and is interpreted to interfinger with the preceding described subfacies which are exposed in the central, northern, and eastern parts of the depositional basin (Fig. 3).

Stratigraphically above and south of the type section foraminiferal chalk increase and the amount and thickness of the lenticular coral-lithic packstone and quartz arenite subfacies decrease. These changes appear to mark the transition between the polymictic packstone facies and the next overlying foraminiferal wackestone facies.

Planktonic forams are ubiquitous; *Orbulina* and *Globorotalia* are the major source of sediment in the polymictic facies (Multer et al, 1977). The abundance of planktonic forams and nannoplankton (coccoliths) coupled with the lack of other major skeletal contributors suggests deep water (350 to 500 m) for the depositional environment of the foraminiferal packstone subfacies. Overall, the subfacies appears to have been a foraminiferal-coccolith ooze, deposited in a basin-slope environment or a small, deep basin (see also Frost and Bakos, in press).

Quartz arenite subfacies sediments were derived largely from the erosion of Cretaceous sedimentary rocks (Whetten, 1966), and apparently were transported from the east and northwest (Fig. 7). Graded bedding predominates in beds of this subfacies and there seems little doubt that turbidity-current movement of basin-margin, shallow-water sands into the deeper water pelagic oozes was the major sedimentary process in the deposition of the quartz arenite subfacies. Composition of the detrital grains reflects the composition of the Judith Fancy and the Caledonia Formations.

Coral-lithic packstones crosscut older, but unlithified, sediments of the facies and are discontinuous lenses, in places stacking one on the other as if sedimentation were channel controlled (Fig. 6A). Biota of this subfacies includes large head corals (e.g., *Porites trinitatus, Halimeda, Amphistegina, Mesophyllum,* mollusks, and small amounts of other skeletal components. The overall biotic aspect is one of mixed shallow and moderate water (0 to 70 m); the subfacies is interpreted to be benthic skeletal grains and lithic clasts of fluvial and strandline origin deposited by turbidity flows at the base of steep shelf edges.

Lithic foraminiferal packstone, the fourth subfacies, is interpreted to be a syntectonic breccia. Clasts of Cretaceous rocks imbedded in pelagic oozes, a few corals, steep initial dip, and basin-edge position support this hypothesis.

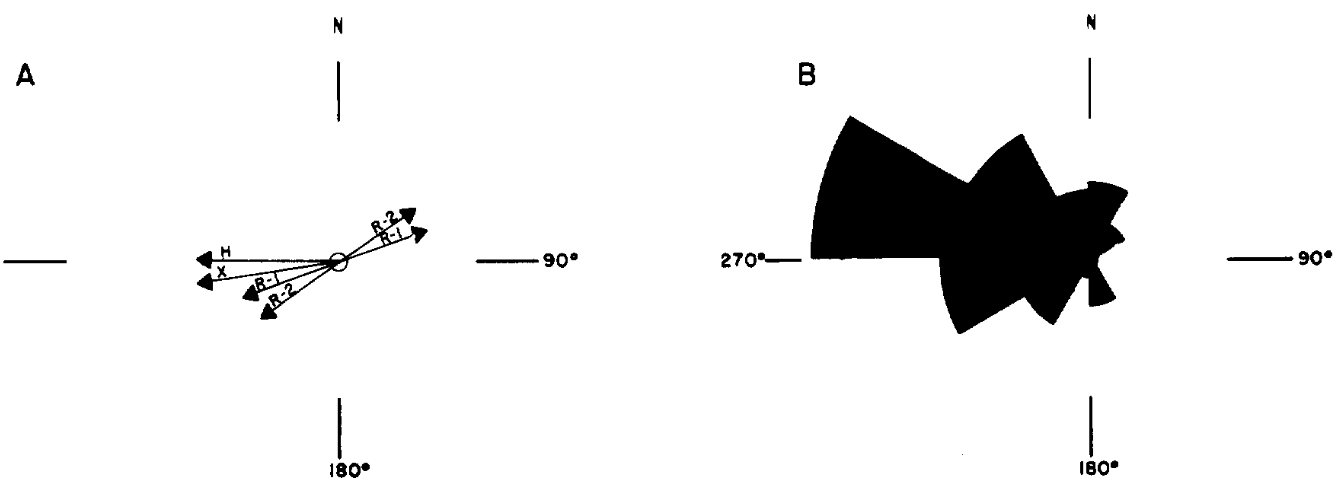


FIG. 7—Directions of sedimentary particle transport at Villa La Reine, A, and Manning Hill, B.

A, *H* = Pebble halo around boulder; *X* = direction of inclination of cross-lamination set; *R-1* and *R-2* are strike of normal to sets of oscillation ripples (polymictic packstone facies).

B, Directions of current based on imbrications of large benthic foraminifers, based on 42 measurements, plotted in 30° arcs (foraminiferal wackestone facies).

Foraminiferal Wackestone Facies

Overlying and transitional with the polymictic packstone facies is the second most volumetrically important facies of the Kingshill Limestone, the foraminiferal wackestone facies (Fig. 4F). Constituent skeletal particles are tests of *Orbulina* and *Globorotalia*, as in the polymictic packstone facies, but disintegrated foram tests and coccoliths are volumetrically more important, forming a wackestone fabric in most samples. Coral-lithic and quartz arenite lithologies of the lower polymictic packstone facies are not present. The best exposures of this facies are in a quarry cut northeast of the Alexander Hamilton Airport main runway, where a continuous section of about 22 m of Kingshill is exposed, including the top of the formation.

Two lithologic varieties occur in this facies. First, "floods" of the large foram *Operculinoides* are present, increasing in frequency progressively upward in the section, culminating (in other exposures) in the last and youngest facies of the Kingshill. Imbrications of these forams is common. Second, several continuous brown silt and clay beds 1 to 2 cm thick are present. X-ray analysis has identified quartz, calcite, and montmorillonite in these thin beds.

Deposition of the foraminiferal wackestone facies may be both distal to and later than the main polymictic facies (Fig. 3). Lack of detrital grains suggests the distal environment, but the increasing "floods" of large forams in the upper part of the facies suggest either a shallowing of the seaway or progradation to effect shallowing. However, the foraminiferal wackestones may represent the deepest and farthest seaward part of preserved Kingshill sediments and indicate the beginning of the shallowing of the seaway. An alternative explanation is that the floods of *Operculinoides* result from changing shoreward environments which caused down-canyon or downslope transportation of the forams. R. F. Dill (West Indies Lab., personal commun., 1975) has suggested that these facies are submarine distributary-fan deposits.

Origin of the thin but continuous brown silts and clays is not settled. Two possible origins for these beds are: (1) distal parts of turbidity flows from which coarser fractions already had been sedimented, and (2) volcanic ash falls. Weathering has eliminated any possible glassy shards or other direct evidence for ash falls. Clay minerals of other Kingshill turbidites have illite and, commonly, kaolinite in addition to montmorillonite. We suggest that the silt and clay beds are most likely of volcanic origin because of the differences in clay minerals from those in other Kingshill rocks derived from local island sources (Fig. 8). The disconformity between the Kingshill and overlying younger limestones is preserved in the Manning Hill exposure; however the uppermost facies of the Kingshill, the foraminiferal grainstone facies, is not present.

Foraminiferal Grainstone Facies

Exposures at the road intersection by the Hess School and in a cut that formerly existed inside the Amerada Hess Refinery (Fig. 1) comprise a sequence of thick-bedded foraminiferal grainstones terminated by a disconformity. Only about 3 m of section is exposed, but these beds appear to be the youngest exposed Kingshill Limestone. Basal beds of the exposures are largely *Operculinoides*—and *O. (Paraspiroclypeus)* with admixtures of *Orbulina* and *Globorotalia* (Fig. 6C). A few mollusk fragments, an occasional pelecypod, echinoid spines, or echinoid plates are also present. No particular orientation seems to be apparent in the large forams beyond a preference for parallelism with bedding; rarely there is apparent current-induced imbrication. Overlying and gradational with these beds are *Amphistegina* grainstones. The former appear to be autochthonous deposits formed at about 100-m water depth, the latter, in water a maximum of 50 to 70 m deep. It appears that a shallowing indicated by the first appearance of *Operculinoides* in the foraminiferal wackestone facies progressed without interruption to the time of unconformity separating the Kingshill Limestone from overlying rocks.

Clay Minerals and Insoluble Residues

Over 350 acetic acid residues of St. Croix Cenozoic carbonate rocks were studied. Splits of many of the same samples were restudied by X-ray diffraction to determine clay mineralogy. Clay minerals are largely montmorillonite and illite, with variable amounts of kaolinite.

Two separate source areas are indicated by clay mineralogies (Fig. 8). Clay mineral suites are independent of the sample's position in the section, indicating that major depositional facies are not distinguished by their clay mineral suites, but that the clay mineral suites are related to source rocks of the Northside Range and the East End Range. These clay mineral suites, and structural evidence for subsidence of a Cenozoic central St. Croix basin (Fig. 6D), help establish the presence of at least two islands during the deposition of the Kingshill Limestone.

Clay mineral and insoluble residue suites of southern and southwestern St. Croix limestone are clearly different from suites in central St.

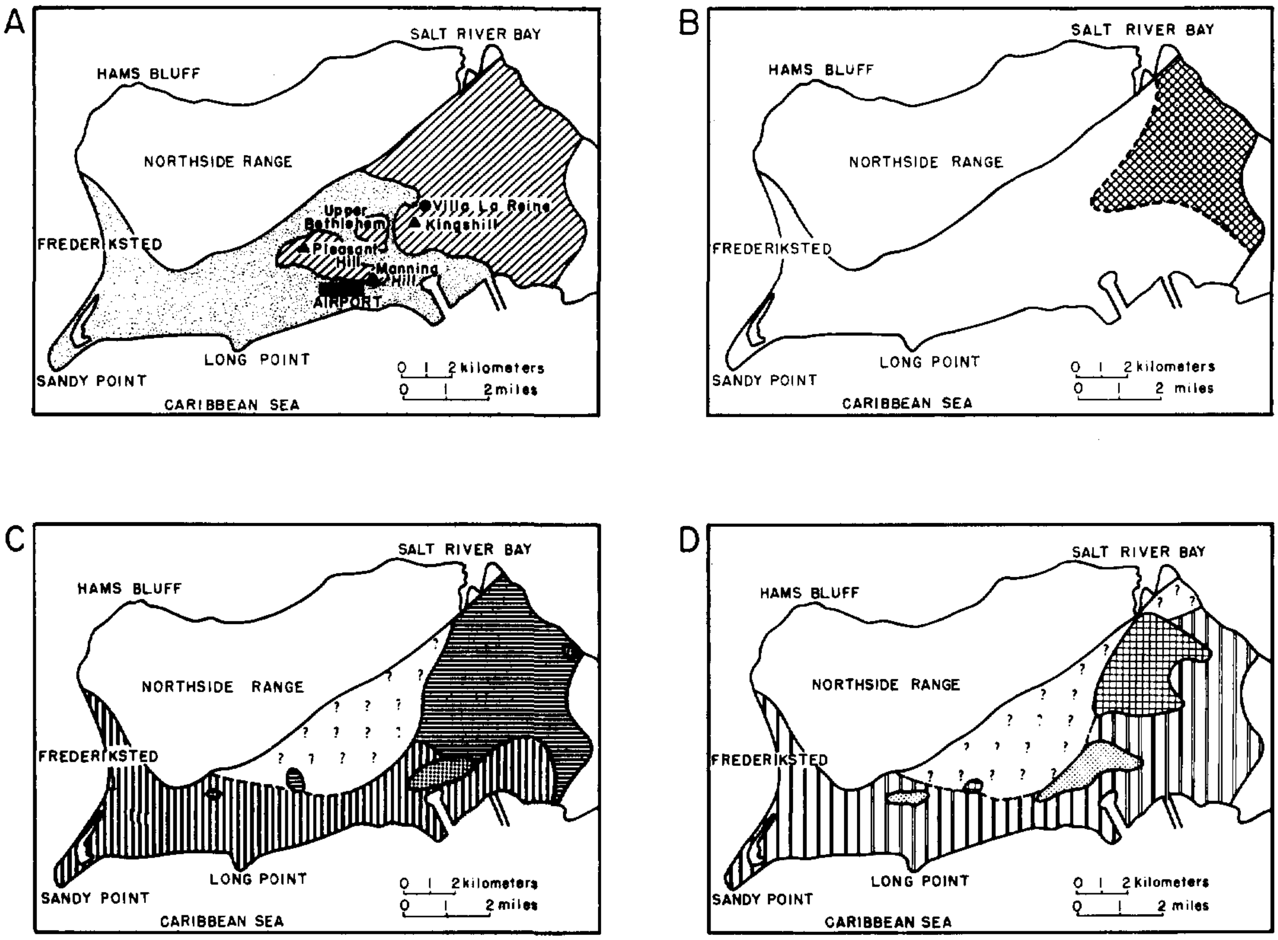


FIG. 8—Distribution of Kingshill Limestone and its noncarbonate components.

A, Distribution of surface exposures of Kingshill Limestone. Surface exposures are ruled diagonally. Dot-patterned area represents carbonate rocks younger than Kingshill.

B, Cross-pattern is area in which clasts of older rocks greater than 4 mm in diameter are present in Kingshill Limestone. Contribution of Northside Range (left) appears to be less than East End Range (right of patterned area).

C, Insoluble residue content of St. Croix limestones. Dotted pattern = less than 5% insoluble residues, vertical ruled pattern = 5 to 25% insoluble residues, and horizontal ruled pattern = extreme variability in insoluble residue content ranging from 13 to 99%. Queries are in areas of insufficient data. Insoluble percentages for Kingshill Limestone are extremely varied compared to younger limestones.

D, Clay mineral facies map of St. Croix limestones. Cross-hatched pattern = low or no kaolinite with montmorillonite, illite, and mixed-layer material; vertical ruled pattern = kaolinite (poorly crystallized), illite, and montmorillonite; stippled pattern = kaolinite (better crystallized), illite, and montmorillonite. Queries are in area of insufficient data. Distribution of clays appears to be more related to source rock (Judith Fancy Formation = low kaolinite; Caledonia Formation = kaolinite, poorly crystallized) than depositional units.

Croix limestone samples; coarser insoluble residues are present only in trace amounts in the former rocks and are abundant in the latter and in eastern exposures. These data clearly support the restriction of the Kingshill Limestone from the mapped extent of Cederstrom (1950) and Whetten (1966) to the restricted section and distribution suggested in this paper. Insoluble residues are of little use in making primary distinctions of the various facies of the Kingshill, although they support distinctions made on biota and fabric criteria and aid in distinguishing Kingshill Limestone from younger limestones.

Limestone samples from north-central St. Croix are low in kaolinite compared with those from other areas of exposure. Samples from this area also are characterized by a variable, but usually high (13 to 99%), insoluble residue content. The combination of low kaolinite content and high insoluble residue content suggests a Northside Range source (Judith Fancy Formation plus other rock units) and that the samples are from true Kingshill Limestone.

Samples from the more easterly exposures have the same insoluble residue percentages, but contain appreciable amounts of kaolinite (although it appears to be poorly ordered). An easterly source, the East End Range, is inferred for the detrital grains in those samples (Caledonia Formation).

Well-crystallized kaolinite with low (5% or less) insoluble residues is characteristic of the limestone directly overlying the Kingshill. Younger, reef-tract limestones are characterized by poorly crystallized kaolinite and an intermediate percentage of insolubles (5 to 25%).

Mineralogy of the nonclay insoluble residues does not vary significantly. Quartz, plagioclase, and hornblende are common and also show up in X-ray patterns. At the level of this study, the most useful variable in the clay minerals and insoluble residue minerals is the abundance and crystallization of kaolinite. The percentage of insoluble residues is also useful for separation of rock units.

Lithic clasts of Cretaceous source rocks are most common in the northeastern exposures. Although the distribution of large lithic clasts suggests a northeasterly source, this may be illusory because the exposures from which these samples were collected are largely in the more detrital lower and middle parts of the stratigraphic section. The higher parts of the section, which are low in detrital grains, are also exposed nearer the center of the limestone plain.

DEPOSITIONAL HISTORY OF KINGSHILL LIMESTONE

A composite section (Fig. 2), cross sections (Fig. 3), and interpreted block diagrams (Fig. 9) summarize the framework of facies relations interpreted for the Kingshill Limestone. Several alternative models for facies relations have been considered by the writers but have a lesser degree of "fit" with the available data.

A Cenozoic marine sedimentation was initiated in the Kingshill depositional basin at least by Oligocene time (Jealousy Formation). Much of the Jealousy appears to have been deposited on open shelves at depths up to 200 m, according to foraminiferal identification (Cushman, 1946). Sediment sources during Jealousy deposition must have been two islands now comprising the mountains of the present island of St. Croix. The great thickness of sediment suggested by gravity data (Shurbet et al, 1956) may require an additional source not now connected to St. Croix.

Kingshill deposition was initiated gradually, carbonate sediments mixing with the more typical clays of the Jealousy. Conglomerates exposed on the western margin have been referred to the Jealousy by Whetten (1966) and Cederstrom (1950). Because these conglomerates are similar to those that appear to be basal Kingshill at Judith Fancy, perhaps they mark a transition from strandline to lagoonal environments during the sea level rise between deposition of the Jealousy and Kingshill lithologies.

Oldest Kingshill deposits now exposed were lagoonal sediments, patch reefs, and near-strandline sands (molluscan packstone facies), which probably interfinger with deeper shelf deposits and basin-slope deposits. Dropping of the basin floor along the eastern boundary fault created the deeper water basin-slope environments and provided the tectonic setting for generation of clastic blocks introduced into pelagic oozes at the base of the fault scarp (Fig. 9).

Continued deepening of water forced fringing reefs and shallow-water environments farther up the slopes of the eastern and western islands (now the East End and Northside Ranges, respectively). Carbonate sand mixed with clastic sand was deposited on the northern shelf area, in part covering the earlier shallow-water sediment (clastic grainstone facies).

Detritus was continually introduced along the eastern margin, perhaps also along the southwestern margin of the basin. Much of this coral reef debris and sand was transported as turbidity flows, constructing submarine fans along the eastern escarpment. Intervals between storm or earthquake events that could drive turbidity currents were marked by deposition of pelagic oozes (*Orbulina* and *Globorotalia* with coccoliths) in the basin. A model for such an island fringe–ocean basin setting has been proposed by Multer et al (1977); the proposed analog has much deeper wa-

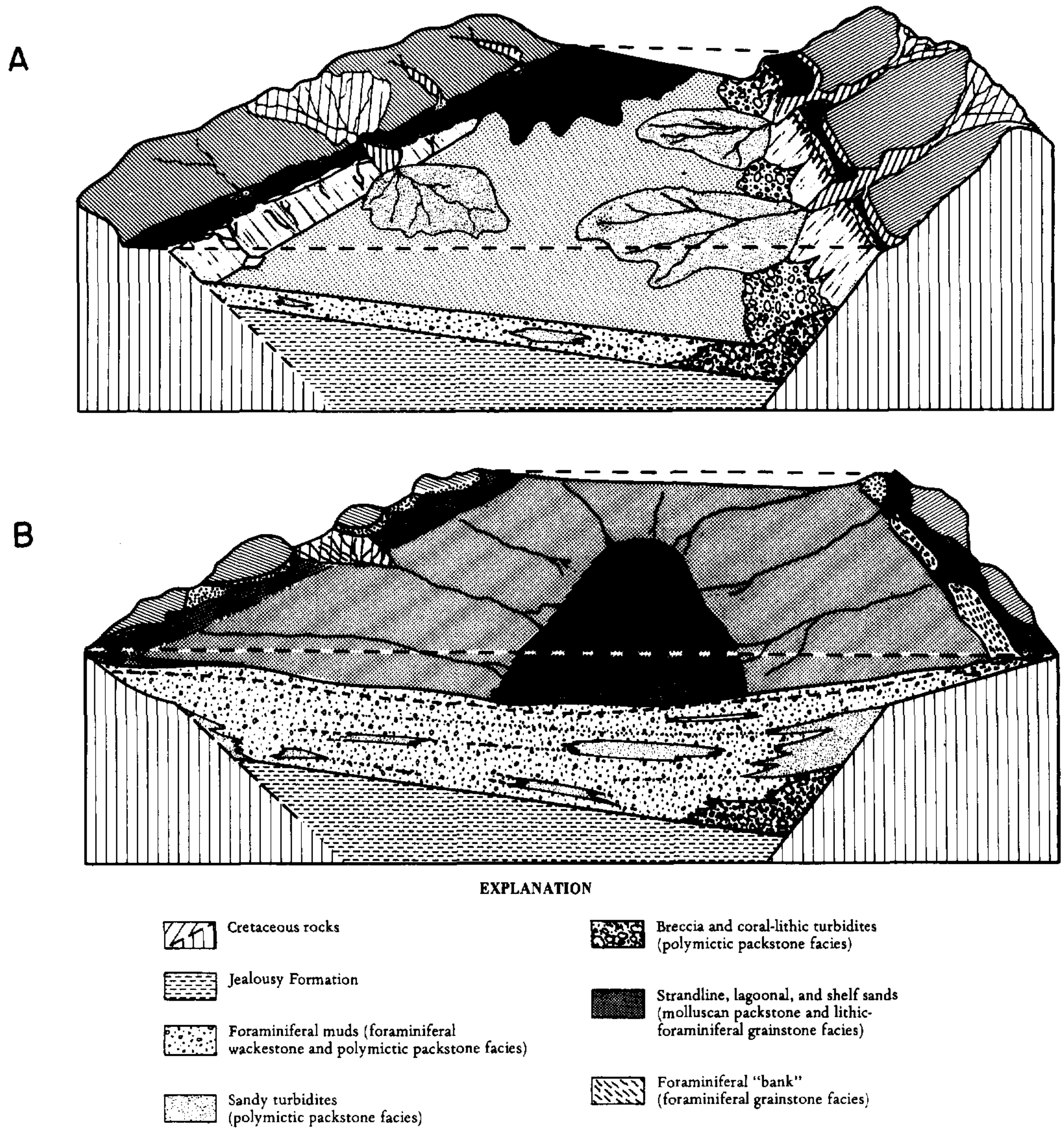


FIG. 9—Diagrammatic restorations of Kingshill depositional basin.

A, During deposition of major part of Kingshill Limestone. Molluscan packstone, lithic-foraminiferal grainstone, and polymictic packstone facies are being deposited.

B, Near close of deposition, showing *Operculinoides* banks as source for "floods" of benthic foraminifers in upper part of basinal rocks and as in situ source of foraminiferal grainstones. Foraminiferal banks or biostromes would become closer to basin center with reduction in water depth.

ter (greater than 2,000 m) than that proposed for the Kingshill in this paper, although the processes are the same.

Maximum transgression and stable sedimentation conditions are recorded by the foraminiferal wackestone facies. Very little detrital material was added during this time, although volcanic ash falls may be preserved in this facies as thin, continuous, clayey beds.

Termination of deposition of the Kingshill Limestone is marked by the appearance of floods of *Operculinoides* into the pelagic oozes, culminating in pure foraminiferal grainstone facies. This facies appears to be remnants of foraminiferal banks formed at a depth not exceeding 100 m (Fig. 9).

It is unclear whether basin filling, tectonic lifting, or eustatic lowering of sea level was responsible for the shoaling of water that marks the end of Kingshill deposition. Vail (1975) suggested a worldwide drop in sea level in late Miocene after a middle Miocene highstand. However, a vertical tectonic uplift of the St. Croix block could explain the unconformity between the Kingshill Limestone and overlying units just as well as a eustatic sea-level change.

Faulting on the east side of the basin is readily apparent, but only the nearly vertical nature of the few contact exposures in the north part of the west side suggests any structural discontinuity on that basin margin. It is suggested that the basin may be a hinged block, downdropped most on the southeast and least at the northwest (Fig. 6D).

Current directions during Kingshill deposition are largely inferred from the geometry of the structural basin of deposition. Measurements of ripples, sand halos, and one set of cross-laminations at the Villa La Reine exposures suggest east-to-west current motions (Fig. 7). Measurements on imbricated large forams in the upper part of the section (foraminiferal wackestone facies) indicate the same relative current motion but with a more northerly component. The absence of north-south current indicators may be because only bottom-current indicators were preserved or because circulation in the depositional basin was truly restricted at the north.

RESERVOIR POTENTIAL

The Kingshill Limestone on St. Croix is a freshwater producer, and no hydrocarbon shows have been reported from any rocks on the island. However, St. Croix is structurally separated from other similar blocks which have not been tested. Similar rock facies appear to be present on Antigua, Anegada is on a carbonate platform, and various other Limestone Caribbees are part of an island-arc system that ends southward in Trinidad and Tobago, where petroleum production is well established. Potentially significant are shallow submarine areas that may have a Cenozoic limestone section, have not been flushed by fresh water, and may be more structurally favorable for hydrocarbon occurrence. Such areas are Saba Bank, lying about 90 km east of St. Croix, the Barbuda-Antigua platform, the St. Martin–Anguilla platform, and the Anegada platform (the latter are all named after the low-lying carbonate islands which project upward from the platforms themselves).

Porosity development in the Kingshill has been controlled largely by intratest voids in planktonic forams, differential solubility of the various aragonite skeletal grains, the degree of cementation of clastic units, and solution at unconformable surfaces. In general, interparticle porosity is best developed in the molluscan packstone, clastic grainstone, and foraminiferal grainstone facies. Permeability appears quite high. All of these facies are potential reservoirs.

Permeability in the polymictic packstone and the foraminiferal wackestone facies is poorly developed in the foraminiferal chalk lithology. It is well-developed in the quartz arenite subfacies which is generally poorly cemented, coarse grained, and exceedingly permeable. Unfortunately, these are usually very thin beds. Porosity in the coral-lithic subfacies appears to be a result of secondary solution of large skeletal grains (coral and mollusk) after primary cementation had taken place around finer grains. Molds of mollusks and corals are common. Permeability appears to be low.

Destruction of primary porosity appears to be related to postdepositional flushing by meteoric water, during which fine-grained aragonite and magnesium calcite were replaced by calcite, and calcite cement filled primary pore spaces. A second stage of aragonite solution is demonstrated by the large number of coral and mollusk molds present in both the coral-lithic packstone subfacies and the molluscan packstone facies. In each of these units, borings and surface ornamentation are faithfully preserved whereas the skeletal grain itself is represented by a void space. Geopetal calcite is not uncommon as a partial filling or coating in voids.

This stage of diagenetic alteration may be synchronous with the development of cavernous porosity and terra rossa at the top of the Kingshill which is preserved in a few localities such as at the Hess VIRCO refinery (where caves 1 to 2 m across are present).

This study has not attempted to define a possible hydrocarbon source. It must be pointed out, however, that highly organic sediments of both older (Jealousy) and modern age are known from the island or its surrounding basin. Heat necessary for hydrocarbon conversion during early diagenesis could have been provided, at least in the Saba Bank and other platform areas, by volcanic and seismic activity (Saba Island, for example, is volcanic). Although we have not been able to establish the actual presence of hydrocarbons in these eastern Caribbean Cenozoic rocks, they appear to be attractive exploration targets.

SUMMARY

Potential reservoir rocks are present in the Kingshill Limestone of Miocene age on St. Croix, U.S. Virgin Islands. These rocks are of variable lithology, but can be divided into five major facies on the basis of fabric, fossils, and clastic content. Although there is no fully exposed section of these rocks, a composite section drawn from six localities relates these facies to a cycle of marine transgression and regression. Water depths at onset of sedimentation were strandline to about 30 m, maximum depths appear to be no greater than 500 m, and water depths shoaled to about 30 to 50 m by the end of deposition of preserved sediments.

Deposition took place in a triangular basin that was hinged in the northwest corner, downfaulted along the east, and possibly downfaulted along the northwestern side. Clastic sources lay both east and northwest of the basin. Transport of grains by turbidity currents or other currents appears to have been from east to west or northeast to southwest from the eastern clastic source area.

A type section has been designated for the Kingshill Limestone. Restriction of use of the name to the lowest major limestone rock unit on the island is suggested.

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