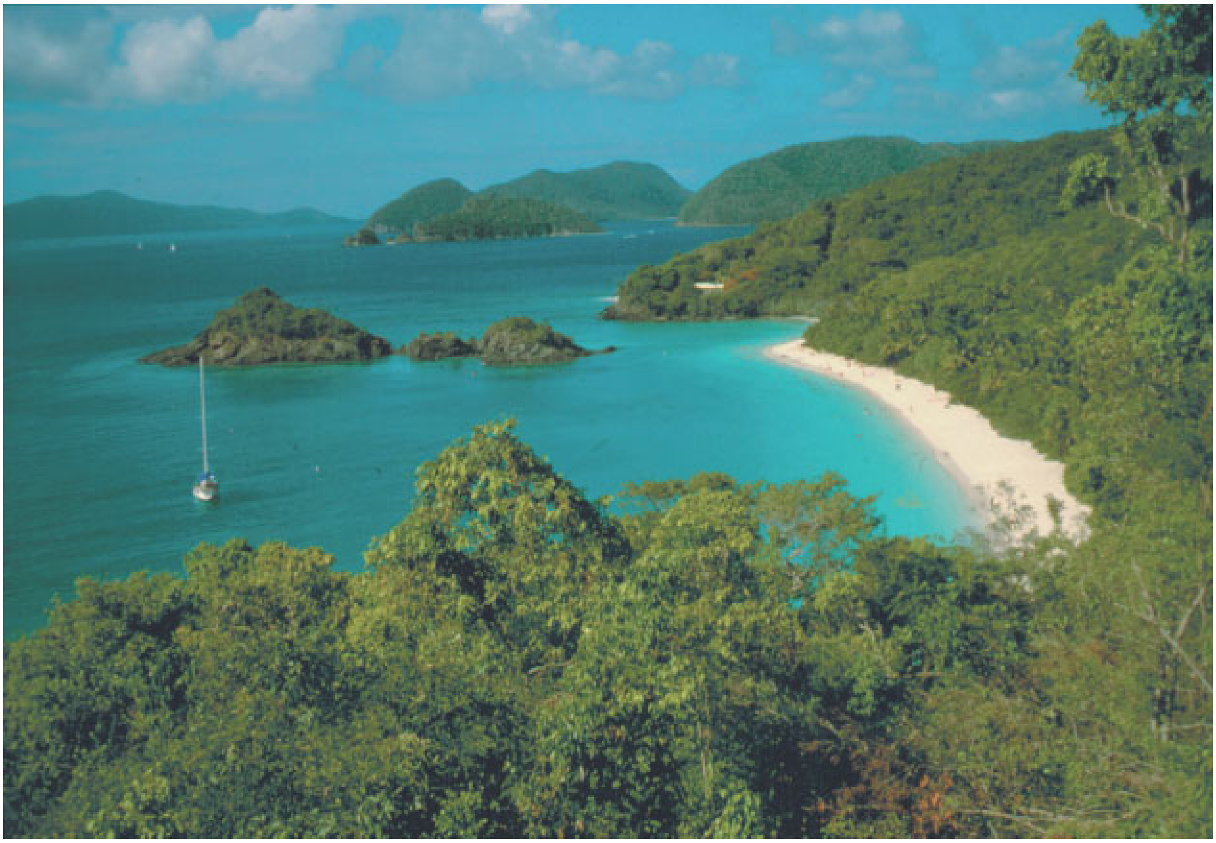
U.S. Department of the Interior
U.S. Geological Survey

Geology of St. John, U.S. Virgin Islands

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1631



Prepared in cooperation with the
National Park Service

USGS
science for a changing world

Cover. View of Trunk Bay on the northern coast of St. John, U.S. Virgin Islands. Trunk Cay is located just to the left of the shoreline. Along the skyline, from left to right, are Jost Van Dyke and Great Thatch Islands of the British Virgin Islands, and Mary Point, which is to the northeast on St. John.

U.S. Department of the Interior
U.S. Geological Survey

Geology of St. John, U.S. Virgin Islands

By Douglas W. Rankin

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1631

Prepared in cooperation with the
National Park Service

Stratigraphy, structure, and geologic history of St. John as related to the evolution of the northeastern corner of the Caribbean plate

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 2002

Published in the Eastern Region, Reston, Va.
Manuscript approved for release March 26, 1998.

Copies of this report are for sale by:

U.S. Geological Survey
Information Services
Box 25286, Federal Center
Denver, CO 80225

or call the toll-free telephone number
1–888–ASK–USGS

Library of Congress Cataloging in Publication Data

Rankin, Douglas W.,
Geology of St. John, U.S. Virgin Islands / by Dougls W. Rankin.
p. cm. — (U.S. Geological Survey professional paper ; 1631)
Includes bibliographical references.
1. Geology—Virgin Islands—Saint John. I. Title. II. Geological Survey professional paper ; 1631.

QE75 .P9 vol. 1631
[QE226.V]
557.3 s—dc21
[557.297'22]

00-052820

CONTENTS

PLATE

[Plate is in pocket]

FIGURES

TABLES

METRIC CONVERSION FACTORS

Multiply	By	To Obtain
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)

GEOLOGY OF ST. JOHN, U.S. VIRGIN ISLANDS

By Douglas W. Rankin[1]

ABSTRACT

The rocks of St. John, which is located near the eastern end of the Greater Antilles and near the northeastern corner of the Caribbean plate, consist of Cretaceous basalt, andesite, keratophyre, their volcaniclastic and hypabyssal intrusive equivalents, and minor calcareous rocks and chert. These rocks were intruded by Tertiary mafic dikes and tonalitic plutons. The oldest rocks formed in an extensional oceanic environment characterized by abundant keratophyre and sheeted dikes. Subduction-related volcanism of the east-west-trending marine Greater Antilles volcanic arc, began on St. John near the transition between the Early and Late Cretaceous. South-directed compression, probably caused by the initial collision between the Greater Antilles arc of the Caribbean plate and the Bahama platform of the North American plate, deformed the Cretaceous strata into east-west-trending folds with axial-plane cleavage. Late Eocene tonalitic intrusions, part of the Greater Antilles arc magmatism, produced a contact aureole that is as much as two kilometers wide and that partly annealed the axial-plane cleavage. East-west compression, possibly related to the relative eastward transport of the Caribbean plate in response to the beginning of spreading at the Cayman Trough, produced long-wavelength, low-amplitude folds whose axes plunge gently north and warp the earlier folds. A broad north-plunging syncline-anticline pair occupies most of St. John. The last tectonic event affecting St. John is recorded by a series of post-late Eocene sinistral strike-slip faults related to the early stages of spreading at the Cayman Trough spreading center and sinistral strike-slip accommodation near the northern border of the Caribbean plate. Central St. John is occupied by a rhomb horst bounded by two of these sinistral faults. Unlike other parts of the Greater Antilles, evidence for recent tectonic movement has not been observed on St. John.

[1]Scientist Emeritus, U.S. Geological Survey, Reston, VA, 20192.

INTRODUCTION

St. John is one of three major islands of the U.S. Virgin Islands. St. Thomas lies about 4 km to the west of St. John and St. Croix about 60 km to the south. The British Virgin Islands lie north and east of St. John across the Sir Francis Drake Channel, which is as narrow as 1 km immediately north of St. John where the channel is called The Narrows. The British Virgin Islands, St. John, St. Thomas, and Puerto Rico are subaerial topographic highs on the Puerto Rico Bank, a submerged platform generally defined by the 183-m-depth contour (Rogers and Teytaud, 1988). During the Pleistocene low stand of sea level, a continuous subaerial landmass extended eastward from Puerto Rico across the British Virgin Islands. Today, a drop in sea level of about 30 m would reestablish a land bridge between St. Thomas and Puerto Rico, about 60 km to the west (National Oceanic and Atmospheric Administration (NOAA) Chart 25650, 1983). Deep water and steep slopes surround the Puerto Rico Bank. The Puerto Rico Trench, with water depths as great as 9,166 m, is to the north; the Virgin Islands Basin, with water depths commonly in excess of 2,500 m (NOAA Chart 25641, 1983), separates St. John from St. Croix to the south.

St. John is an irregularly shaped island covering about 48 km^2 that is characterized by steep slopes and relief of as much as 390 m. Slopes in excess of 30 percent cover more than 80 percent of the island (CH2M Hill, 1979). Bedrock is well exposed in outcrops and cliffs along the irregular shoreline, in some of the water courses (locally called guts), along some ridge crests, and in roadcuts. Cliffs are commonly interrupted by deep cuts caused by the erosion of nearly vertical dikes. In places, cliffs drop into deep water and the cliff-dry forest interface above is typically exceedingly thorny. Elsewhere, exposures are limited and, in numerous places, contacts are mapped based on float. Vegetation in the dry forest that covers much of the island is thorny and where thorny vines are abundant, the dry forest is essentially impenetrable. The guts, however, are largely vegetation free because of flash floods (Rankin, 1984, fig. 4B). Much of the island was cleared for sugar plantations in colonial times. Narrow, rock-walled terraces are still present on some of the steep, forest-covered slopes. The Virgin Islands National Park covers much of the island and includes substantial offshore area as well.

The islands of St. Thomas and St. John and nearby cays (islands) were mapped at a scale of 1:24,000 between 1983 and 1988 with brief visits in 1990 and 1995. Most of the time spent in the field, starting in 1985, was spent on St. John. The mapping began as part of a U.S. Geological Survey (USGS) program to assist the government of the U.S. Virgin Islands (USVI) by providing it with a modern geological data base. Initial funding was provided by the Office of the Assistant Secretary for Territorial and International Affairs of the Department of the Interior. Major- and trace-element analyses (including rare-earth element, or REE, analyses) of about 100 samples from St. Thomas and St. John were made in the USGS laboratories as part of this geologic mapping project. An extended discussion of the chemistry of these rocks is not in order here, but reference will be made to the data set as appropriate. Although the base-map elevations are in feet, all other scientific measurements are in metric units (see conversion table in the Contents section).

ACKNOWLEDGMENTS

I would like to thank Thomas W. Donnelly (State University of New York at Binghamton) for numerous discussions that helped to introduce me to the geology of St. Thomas and St. John and for encouragement to pursue the study. I also acknowledge helpful discussions with Henry V. Alminas, who shared with me the geochemical data generated as part of the mineral-resource assessment; with Richard D. Krushensky on the geology of Puerto Rico; with E-an Zen on prehnite-pumpellyite identification; and with Thomas R. Armstrong on numerous aspects of the geology and mineralogy. Michael J. Kunk made $^{40}Ar/^{39}Ar$ determinations for four samples. Charles D. Blome studied Radiolaria from two samples, both from St. Thomas. An early version of the geologic map and explanation was reviewed by William C. Burton and Avery A. Drake, Jr. The revised geologic map and accompanying text were reviewed by William C. Burton and Arthur P. Schultz. Personnel of the Virgin Islands National Park were helpful in many ways during the fieldwork. I particularly thank Caroline Rogers, now with the U.S. Geological Survey, and Ranger Bernard Stoffel. Some assistance was provided in the later part of the fieldwork by the Island Resources Foundation. The friendship of Angela and Michael Ebner made life on St. John even more enjoyable. Finally, I thank my wife, Mary Louise, for her help as a volunteer field assistant under conditions that were not always pleasant.

GEOLOGIC SETTING

The Virgin Islands constitute the eastern extremity of the Greater Antilles. The Puerto Rico Bank is the geomorphic expression of the Puerto Rico-Virgin Islands microplate located within the northern boundary zone between the Caribbean and North American plates. The Caribbean plate is bounded on the east and west by subduction zones, and on the north and south by strike-slip faults. Current thinking is that the Caribbean plate began as an oceanic plateau of overthickened oceanic crust of Jurassic and Cretaceous age in the Pacific Ocean and moved into the gap between North and South America formed by the opening, about 170 Ma, of the North Atlantic Ocean (Burke and others, 1978; Pindell, 1990; Pindell and Barrett, 1990; Montgomery and others, 1994; Draper and Pindell, 1995). According to Hall (1995), the Caribbean plate entered the Atlantic about 75 Ma and since then has been moving roughly eastward with respect to both North and South America. In response to the relative eastward movement of the Caribbean plate, west-dipping subduction of the North American plate has produced magmatism preserved as a continuous record from the Late Cretaceous to Paleogene in the submarine Aves Ridge volcanic-arc complex and from the Eocene to Holocene in the Lesser Antilles arc (Pindell, 1990). The active Lesser Antilles arc terminates at the island of Saba, about 160 km southeast of St. John. Calc-alkaline basalt dated at 4 Ma has been dredged from the Noroit Seamount about 110 km north of Saba at the Anegada Passage, which is the eastern boundary of the Puerto Rico-Virgin Island microplate northeast of the Virgin Island Basin (Bouysse and others, 1985). The seamount is interpreted to be the extinct north end of the Lesser Antilles arc.

The following overview is taken largely from Pindell and Barrett (1990). The Greater Antilles, including the Virgin Islands, are interpreted to be part of the same magmatic arc, which is probably built on oceanic crust. Subduction-related magmatism began in the Early Cretaceous and continued until the Eocene. The early polarity of this arc is not known. In places, Jurassic to Early Cretaceous oceanic crust, much of it thought to be samples of early oceanic crust of the Caribbean plate, has been tectonically emplaced in the Greater Antilles (and in northern South America and La Desirade, a small island east of Guadeloupe). The Bermeja Complex in southwestern Puerto Rico is one such body interpreted to be serpentinized upper mantle rocks and metamorphosed Caribbean oceanic crust (Mattson, 1973; Schellekens and others, 1990; Evans and others, 1997) tectonically interleaved with radiolarian chert ranging in age from Early Jurassic (Pliensbachian) to Late Jurassic (Tithonian) (Montgomery and others, 1994). Mattson (1973) and Mattson and Pessagno (1979) interpreted the complex to have been obducted above a south-dipping subduction zone prior to the Campanian. After the

Santonian or Campanian, however, the Greater Antilles arc was definitely north-facing in Cuba and Hispaniola (Pindell and Barrett, 1990).

Donnelly and Rogers (1980) recognized two major magma series in the northeastern Caribbean island arcs and elsewhere in the greater Caribbean area. They called the older one (of which the Water Island Formation of the northern Virgin Islands was the initial example) the "primitive island arc (PIA) series;" it is characterized by low thorium (Th) and uranium (U) contents and low Th/U ratios. The PIA also included the Louisenhoj Formation of the northern Virgin Islands and rocks older than the Robles Formation of Puerto Rico. Many of the PIA series rocks have been called spilites and keratophyres. The younger series was called the "calc-alkaline (CA) series" which, in places, included high-potassium (K) units near the base. In Puerto Rico, the CA series began with rocks of the Robles Formation and Rio Orocovis Group (Albian, possibly extending upward to the Turonian according to Donnelly and others, 1990) and extended upward to the youngest (Eocene) volcanic rocks in Puerto Rico. The dominant rock type is andesite. The relationship of the current work to these observations will be discussed later.

Aspects of plate motion thought to be important for this study are summarized from Pindell and others (1988). From the Late Triassic(?) to the Late Cretaceous, South America moved relatively southeastward away from North America, opening a gap into which the Caribbean plate moved progressively. Since the Campanian, no significant deformations of the Caribbean plate can be attributed to relative motions of North and South America. Although the northern boundary of the Caribbean plate with the North American plate is complex and has probably shifted in location through time, it is essentially a sinistral strike-slip fault for much of its length. The Puerto Rico-Virgin Islands microplate, at the northeast corner of the Caribbean plate, is in the transition region between west-dipping subduction of the North American plate beneath the Lesser Antilles arc and strike-slip motion along the northern plate boundary. Speed and Larue (1991) argue that motion along the Caribbean-North American plate boundary zone here has been left transtensional for the past 15 to 20 m.y., resulting in a boundary-normal component of extension that is the principal cause of the Puerto Rico Trench. Their model uses a vector of motion across the boundary of N. 82°-83° W., 1.1 to 1.5 cm/yr. Additional consequences of this vector are a counterclockwise rotation of the Puerto Rico-Virgin Islands microplate, south-directed thrusting in the Muertos Trough (south of Puerto Rico), and the opening of the Virgin Island Basin by extension. The fault pattern in southwestern Puerto Rico supports the model of counterclockwise rotation of the microplate (Meltzer and others, 1995). However, Deng and Sykes (1995) argue strongly that the azimuth of plate motion along most of the northern boundary of the Caribbean plate is S. 70°±4° W. (95 percent confidence) and therefore do not accept an extensional component of motion in the Puerto Rico Trench; they suggest that Puerto Rico and the northern Virgin Islands are moving with the main Caribbean plate rather than as a separate microplate.

PREVIOUS WORK

The only previous detailed geologic mapping of St. John was by Donnelly (1966) as part of a Ph.D. dissertation at Princeton University under the guidance of Harry H. Hess, one of the pioneers of modern Caribbean geological research. Donnelly's 1:62,500-scale map covers both St. Thomas and St. John and is based on field work done mostly in 1956 and 1957. Fragmentary earlier work is well summarized by Donnelly (1966). The British Virgin Islands were mapped by Helsley (1960, 1971), another Hess student. Longshore (1965) studied the chemical and mineralogical variations of the Virgin Islands batholith and wall rocks. Hekinian (1971) did a petrologic and geochemical study of spilites of the Water Island Formation from a core hole drilled near Ram Head, St. John. The petrology and geochemistry of Caribbean volcanic rocks, including rocks of the northern Virgin Islands, are described by Donnelly (1963, 1972), Donnelly and Rogers (1978, 1980), and Donnelly and others (1971). Griscom and Geddes (1966) published a 1:2,500,000-scale aeromagnetic map of Puerto Rico, the Virgin Islands, and a large offshore area. The results of a mineral-resource assessment of the Virgin Islands were published by Alminas and others (1994) prior to the completion of the new geologic maps. As part of the mineral-resource assessment, Tucker (1987) made a geochemical study of St. John.

STRATIGRAPHY

Basalt, andesite, keratophyre, and their volcaniclastic equivalents make up most of St. John as well as St. Thomas and the offshore cays. Calcareous rocks and cherts are minor but important components. Stratified rocks, except the surficial deposits, are of latest Aptian or Albian to late Turonian or late Santonian (late Early Cretaceous to Late Cretaceous) age; at least most of the section is marine. The stratified rocks are several kilometers thick. The oldest volcanic rocks (Water Island Formation) are of oceanic affinity emplaced in an extensional environment. Volcanic rocks higher in the section (Louisenhoj Formation and higher), are increasingly of island-arc affinity. Hypabyssal intrusive rocks related to the Water Island Formation are common. All pre-surficial stratified rocks are intruded by dikes and small plutons ranging in composition from gabbro to gran-

Table 1. Stratigraphic nomenclature used previously and in this report for St. Thomas, St. John, and the British Virgin Islands.

Donnelly (1966) (St. Thomas and St. John)	Helsley (1971) (British Virgin Islands)	This report (St. John)
Virgin Island Group	Virgin Island Group	
	Necker Formation	
	Tortola Formation	
	Shark Bay Member	
	Sage Mountain Member	
Hans Lollik Formation	Hans Lollik Member	
	possible unconformity	
Tutu Formation	Tutu Formation	Tutu Formation
		Mandal Member
Congo Cay Limestone Member	Congo Cay Limestone Member	Congo Cay Limestone Lens
		Picara Member
conformity	unconformity	conformity
Outer Brass Limestone	Outer Brass Limestone	Outer Brass Limestone
Louisenhoj Formation	Louisenhoj Formation	Louisenhoj Formation
unconformity	unconformity	conformity
		Lameshur Volcanic-Intrusive Complex
Water Island Formation	Water Island Formation	Water Island Formation and Careen Hill Intrusive Suite

ite. Some of the plutons are as young as late Eocene and have contact metamorphic aureoles. In northern and eastern St. John, the contact effects extend out a few kilometers from the small exposed plutons, suggesting that larger plutons, including The Narrows pluton and the Virgin Gorda batholith, underlie The Narrows and the Sir Francis Drake Channel. Surficial deposits include beach deposits, beachrock, bay-mouth bars, playa deposits, alluvium, boulder fields, and artificial fill. Only the alluvium is likely to contain material as old as Pleistocene.

For the most part, the stratigraphic units established by Donnelly (1966) were found to be valid in the course of the new geologic mapping. Table 1 compares the formal stratigraphic units of Helsley (1971) and Donnelly (1966) with revisions developed during the current work. As will be discussed later, I do not use the terms Virgin Island Group or Hans Lollik Formation. The latter was not mapped on St. John by Donnelly (1966), but my reassignment of the rocks at the type locality on Hans Lollik Island to the Louisenhoj Formation has bearing on the regional structural interpretation.

Donnelly (1966) defined the Water Island Formation, the oldest unit recognized in the northern Virgin Islands, as a heterogeneous unit of keratophyre (80 percent), spilite, and radiolarian chert along with hypabyssal intrusive rocks. He established the age as Albian or older, but probably late Early Cretaceous, and selected Water Island in the harbor of Charlotte Amalie, St. Thomas as the type locality. More recently Emile A. Pessagno, Jr. (University of Texas at Dallas) dated the top of the Water Island (just north of Haypiece Hill, Central St. Thomas quadrangle) at probably late Aptian or earliest Albian based on Radiolaria (*in* Donnelly and others, 1990; oral commun., March 1997). Several conventional K-Ar ages for both intrusive and extrusive keratophyre, mapped by Donnelly as the Water Island Formation, were published by Alminas and others (1994). The ages range from 65.8±2.9 Ma to 30.9±0.3 Ma. Some of the rocks probably are devitrified. These whole-rock ages are not considered to be reliable and cannot be reconciled with the geologic history presented here. Detailed field work has shown that intrusive rocks interpreted to be comagmatic with the keratophyres and spilites are more varied and abundant than recognized by Donnelly. The assemblage is here grouped into three stratigraphic units: the Lameshur Volcanic-Intrusive Complex consisting of the Water Island Formation and Careen Hill Intrusive Suite.

LAMESHUR VOLCANIC-INTRUSIVE COMPLEX (HERE NAMED)

The Lameshur Volcanic-Intrusive Complex (Klm) consists dominantly of keratophyre and volcaniclastic rocks derived from them, but also includes basalt, basaltic andesite, an unknown volume of trondhjemite (as defined by Barker, 1979) and gabbro, and minor chert. The igneous rocks are distinctly bimodal in silica content. The terms “keratophyre” and “spilite” are ingrained in the literature of the Water Island Formation of Donnelly (1966) and, as described, are part of the primitive island arc (PIA) series of the Caribbean (Lidiak, 1965; Donnelly, 1966; Donnelly and others, 1971, 1990; Hekinian, 1971; Donnelly and Rogers, 1980). Keratophyre is a name applied to igneous rocks, either intrusive or extrusive, that have an aphanitic or fine-grained groundmass, are silicic (commonly >70 percent SiO_2),[2] and are sodic rather than potassic. Donnelly (1966) used the term “spilite” for the mafic rocks of the Water Island because he observed that the rocks contained albitic plagioclase and other secondary minerals. The term “spilite” also has been used for mafic rocks that are sodic rather than calcic. The initial magmatic chemistry of the mafic rocks is difficult to assess because of the highly amygdaloidal nature of most rocks and the presence of pervasive secondary minerals. Analyses of the least amygdaloidal rocks indicate that they are basalts and basaltic andesites (see also Donnelly and others, 1971; and Hekinian, 1971). Analyses made as part of this study show that in bulk chemistry they are not particularly sodic as opposed to calcic relative to basalts and andesites in general. They do not plot in the field of spilites on a plot of Na_2O against CaO (weight percent) as shown by Mullen (1983). These rocks are called basalts in this report for ease of expression, although (a) they do include some basaltic andesites; (b) in many, the primary igneous mineralogy has been altered; and (c) in the northern part of St. John, the rocks are metamorphosed to grades in the amphibolite facies.

Keratophyre occurs in several varieties that are distinguished by the size and mineralogy of phenocrysts and by the mode of emplacement. Keratophyre occurs as lava flows, breccia, layered tuff, dikes, and small hypabyssal intrusive bodies. In all varieties of keratophyre, quartz phenocrysts (if present) are embayed, and phenocrysts of plagioclase (albite as determined by Donnelly, 1963, 1966) and quartz (if present) form growth aggregates either singly or together. Plagioclase phenocrysts are either not zoned or weakly zoned. The groundmass of the freshest keratophyre is medium grayish blue (5*PB* 4/2) to medium dark gray (*N*4).[3] The rocks become progressively lighter in color as the content of whitish-weathering albite phenocrysts and (or) the degree of weathering increases. The more mafic rocks of the complex occur as pillow lavas, pillow breccias, dikes, and rare small plutons. In the extrusive rocks, phenocrysts are generally inconspicuous. All rocks may exhibit local intense deuteric hydrothermal alteration, which may include silicification, oxidization, and sulfidization. The development of boxwork textures and relict gossan on Bordeaux Mountain are weathering products that formed relatively recently from previously altered rocks.

Figure 1. Water Island Formation, northwest side of Ram Head. Porphyritic keratophyre (Kwp) overlying hyaloclastite (Kws). Person is standing on the contact that strikes 20° and dips 40° SE.

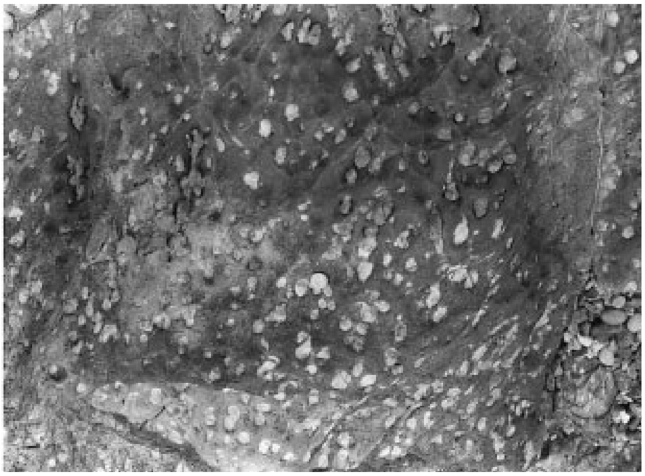
The name Lameshur Volcanic-Intrusive Complex is used in reference to the assembly of comagmatic igneous rocks and the volcaniclastic rocks derived from them. The unit is mapped undivided where the size and mineralogy of phenocrysts in the keratophyre varies over short distances and the distinction between extrusive and intrusive rocks is not readily apparent. The name is taken from the locality of Lameshur in southern St. John. Along the coast of Great and Little Lameshur Bays, a variety of keratophyres (extrusive and intrusive) and basalt are exposed. The complex crops out only on St. Thomas, St. John, offshore cays, and the British Virgin Islands. The complex is thought to have been generated in an oceanic extensional environment. The stratified rocks are interpreted to be submarine deposits (Donnelly, 1966, and this report).

WATER ISLAND FORMATION (REVISED)

The name Water Island Formation is retained for stratified rocks, but is revised from the usage of Donnelly (1966) to exclude intrusive rocks. The unit consists dominantly of extrusive keratophyre and related volcaniclastic rocks (80

[2]Unless otherwise stated, major oxide values are weight-percent normalized volatile free. In general, the rock classification of Le Maitre (1989) is used.

[3]Throughout the text, alphanumeric symbols following color names are taken from the rock-color chart of Goddard and others (1970).



A

B

Figure 2. Nodular phenocryst-poor keratophyre (Kwa) of the Water Island Formation. The nodules are interpreted to be metamorphosed spherulites. *A*, West side of Turner Point north of cobble beach. Kwa is not mapped separately here, but is included in undivided rocks of the Lameshur Volcanic-Intrusive Complex (Klm). Dime for scale. *B*, View looking east at weathered, near-vertical surface perpendicular to foliation. Nodules are oblate spheroids flattened in plane of foliation (85°, dipping 70° N.). Located at elevation of about 150 ft, north of East Base, Coral Bay. Dime for scale.

percent), basaltic lava and breccia (about 20 percent), and minor chert (fig. 1). No internal stratigraphic order has been recognized. In places, mixed blobby masses of keratophyre and basalt indicate that the two lava types were extruded simultaneously. An example may be found in shoreline outcrops at the northeast corner of Limestone Bay, Water Island, Central St. Thomas quadrangle. In other places, clasts of basalt are present in keratophyre, and clasts of keratophyre in basalt.

The various units of the Water Island Formation are interlayered and any lithology may be in contact with any other. The attitude of these contacts, along with bedding in the volcanic wacke, flow layering in keratophyre (used cautiously), and "bedding" in pillowed basalt aid in defining the map pattern and overall structure. Donnelly (1966) apparently mismapped numerous younger diabase dikes as extrusive basalt and plotted the trends of these dikes as layering in the Water Island Formation. As a result, our structural interpretations of layering (bedding) in eastern St. John are nearly perpendicular to each other. The base of the Water Island is not exposed, although it is presumably underlain by oceanic crust (Donnelly, 1989, p. 305). A 715-m-deep corehole on Ram Head, thought at the time to have reached lowest stratigraphic level of the formation, bottomed in basalt and keratophyre of the Water Island (Hekinian, 1971). The present mapping shows that Ram Head is structurally isolated and probably not near the base of the formation. On St. John, the Water Island Formation is at least 2 km thick and could be more than twice that.

KERATOPHYRE

The groundmass of the keratophyre is locally spherulitic. Much of the keratophyre on eastern St. John weathers so that ovoid bodies (fig. 2*A*), some as large as 4 cm, stand out on the weathered surface. In thin section, these ovoids are commonly rimmed with limonite-filled fractures. The larger ovoids contain phenocrysts of the same species and in about the same abundance as the rest of the rock. The extremely fine grained quartzofeldspathic material within the ovoids lacks any radial structure and looks identical to the material in the matrix around them. If anything, the ovoids are more homogeneous than the surrounding matrix. The ovoids are interpreted to be spherulites recrystallized by the metamorphism that affected northern and eastern St. John. Typically, these nodular keratophyres of eastern St. John contain fine-grained metamorphic chlorite, muscovite, and brown biotite. Phenocryst-poor keratophyre, without obvious nodules, along the crest of the 320-ft ridge northwest of Haulover contains metamorphic biotite and sillimanite. In places, the ovoids are roughly spherical, but more commonly they are oblate spheroids and the rock has a foliation seen in thin section by the alignment of phyllosilicates. Weathered surfaces of foliated albite-phyric keratophyre (Kwf) between elevations of 100 and 200 ft on the slope north of the East Base horizontal control marker in the town of Coral Bay show that oblate spheroids a few centimeters across make up at least 30 percent of the rock (fig. 2*B*); on fresh surfaces of this rock, the spheroids are nearly invisible.

Figure 3. Flow breccia of plagioclase-phyric keratophyre (Kwf) of the Water Island Formation, head of peninsula (locally known as Yawzi Point) between Little and Great Lameshur Bays. Folding of flow layering is visible in one fragment. Knife is 8.3 cm long.

A

B

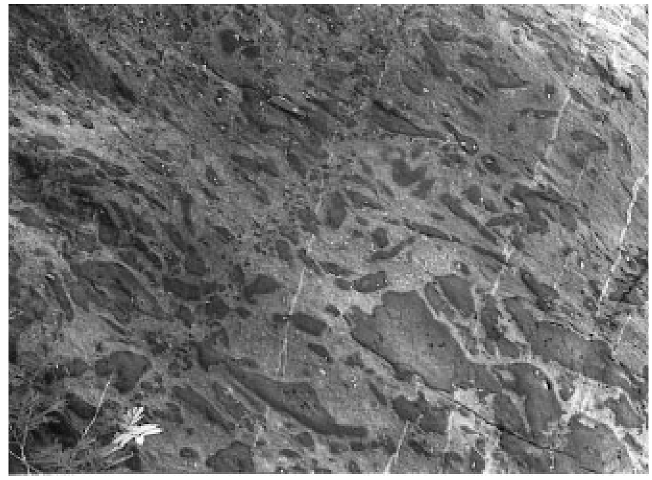
Figure 4. Pillow basalt (Kws) of the Water Island Formation, Harbor Point in Coral Bay. Layering strikes 310° and dips 35° NE. *A,* View looking east. Pillows are as large as a meter across. Pillow asymmetry indicates that layers are right side up. *B*, View looking north shows that pillows in *A* are cross sections of tubes elongated downdip. Hammer is 28.5 cm long.

Several varieties of keratophyre are distinguished by the size and mineralogy of phenocrysts; all have hypabyssal equivalents in the Careen Hill Intrusive Suite. Ash-flow tuffs are notably sparse. Phenocryst-poor keratophyre (Kwa) is characterized by up to 10 percent small phenocrysts (generally less than 2 mm across) of quartz and plagioclase in an aphanitic groundmass. Many outcrops lack visible primary structural features, whereas others display flow layering (Rankin, 1999, fig. 4), flow folds, or brecciation. Lava, flow breccia, some bedded tuff (Rankin, 1999, fig. 5), and volcaniclastic rock, in which the clasts are phenocryst-poor keratophyre, have been recognized. Unit Kwa is the dominant unit of the Water Island Formation on St. John and is well exposed between an elevation of 200 and 350 ft in Fish Bay Gut. Porphyritic keratophyre (Kwp) is characterized by obvious quartz and plagioclase phenocrysts, typically less than 5 mm across, in an aphanitic groundmass. Phenocrysts constitute 10 to 25 percent of the rock. Flow layering was observed in a few outcrops and even fewer outcrops are breccias. Unit Kwp is superbly exposed in a series of cascades (typically dry) between an elevation of 100 and 400 ft in Battery Gut. The mapped distribution is approximate, but the unit appears to constitute less than 10 percent of the Water Island Formation on St. John. Plagioclase-phyric keratophyre (Kwf) contains 5 to 10 percent small (1- to 3-mm-long) plagioclase phenocrysts. The groundmass is commonly a felted mass of flow-oriented aphanitic feldspar laths and interstitial quartz. Flow layering is visible in enough outcrops to conclude that this unit consists mostly of lava flows (fig. 3). Unit Kwf is a minor part of the Water Island Formation on St. John; however, because the phenocrysts are small and sparse, some areas mapped as Kwa could be Kwf. On St. John, Kwf is largely restricted to the area of Great and Little Lameshur Bays.

BASALT

The unit mapped as basalt (Kws) consists of amygdaloidal pillow basalt, pillow breccia, and hyaloclastite; some rocks probably are andesites. Although Donnelly (1966) reported that pillows were uncommon, textural evidence for pillows, pillow breccia, or hyaloclastite is present in most outcrops. Pillows typically are about 1 m across.

Figure 5. Pillow fragment in basaltic pillow breccia (Kws) of the Water Island Formation on headland between Salt Pond and Booby Island. The fragment contains truncated concentric layers of amygdules. Penny for scale at bottom edge of pillow fragment.



A

B

Figure 6. Basaltic hyaloclastite (Kws) of the Water Island Formation. *A*, East side, base of peninsula of Dittlif Point. Knife is 8.3 cm long. *B*, Fragments, deformed while soft, in a carbonate matrix. Dime for scale. Float block on west side of Contant Point.

Amygdules are commonly in concentric shells within the pillows. Interstices between the pillows are, in places, filled with calcite or epidosite. In good exposures, bedding and topping direction can be determined from the pillow asymmetry. Topping directions have been determined from pillowed basalt at Harbor Point (fig. 4*A*), the point between Elk Bay and Haulover (Rankin, 1999, fig. 6), and eastern Red Point, all in eastern St. John. Other excellent exposures of bedding in pillowed basalt are on the southwest side of Dittlif Point on the south coast of St. John, on the point between Saltpond Bay and Ram Head, and on Turner Point in eastern St. John. In places, such as at Harbor Point, some pillows are actually tubes as long as 3 m (fig. 4*B*).

In many outcrops, the basalt is fragmented (Rankin, 1999, fig. 7). The fragments are irregularly shaped and have either angular or rounded edges. Many are molded against one another and some are folded; these fragments were clearly soft when incorporated into the deposit. The fragments range in size from vanishingly small to many centimeters across. These "lumpy greenstones" (a field term) are interpreted to be pillow breccias grading into hyaloclastites. On the south-southeast-trending coast between Saltpond Bay and Ram Head, a bent, tubular mass, of which an area 20 by 60 cm is exposed, has a rounded termination and is enclosed within a large expanse of pillow breccia and hyaloclastite. Several shells of small amygdules parallel the borders of the tube, follow the borders around the bend, and then around the rounded termination. This body is the termination of a small lava tube, now probably isolated as a clast in the breccia. In another part of this outcrop, breccia fragments contain layers of amygdules that are parallel to one margin of the clast but terminate at other margins of the clast (fig. 5). This is further evidence for brecciated pillows.

Other good exposures of pillow breccia and hyaloclastite are found on Dittlif Point (fig. 6*A*) and Contant Point. In loose blocks at Contant Point, deformed breccia fragments are in a limestone matrix (fig. 6*B*). A rudist or solitary coral fossil is present in the limestone matrix of one of the blocks. In the freshest exposures, breccia fragments are commonly reddish brown and the matrix is greenish, yet the color difference, even in the same outcrop, is not restricted to fragmental borders and resulted from rock alteration. Donnelly (1966) and Hekinian (1971) noted the color difference, called the rocks "patchy spilite," and discussed the alteration. In some altered rocks, the clasts have been replaced by epidosite.

Figure 7. Amygdaloidal basalt (Kws) of the Water Island Formation, Kiddel Point, south shore, St. John. Knife in center of photograph is 8.3 cm long.

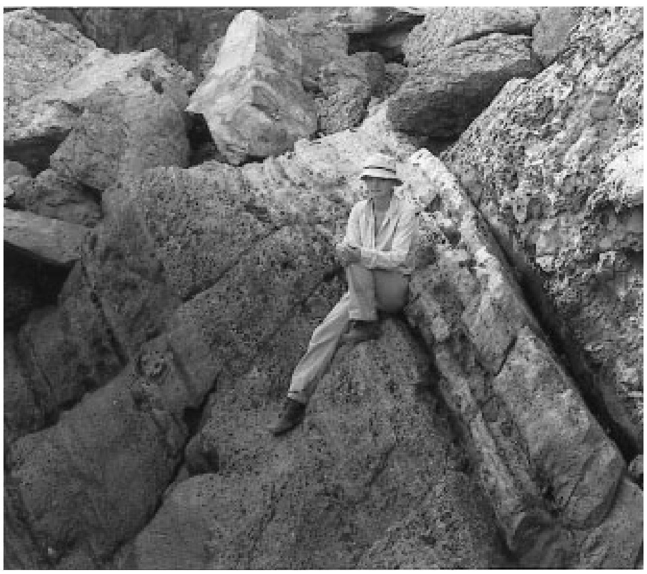


Figure 8. Bedded volcanic wacke, tuff breccia, and tuff (Kww) of the Water Island Formation, Red Point, East End. Clasts include both porphyritic and phenocryst-poor keratophyre. Bedding strikes 330° and dips 60° NE.

In central and southern St. John, the groundmass of the least altered basalt consists of typically randomly oriented plagioclase microlites in a dark mesostasis that, except for opaque dust, is microscopically irresolvable. Phenocrysts are sparse, small (about 1 mm), and consist of plagioclase (typically in growth aggregates) and clinopyroxene. Epidosite segregations are common; in places, pillows have epidosite cores. Secondary minerals in the southern St. John area include prehnite and pumpellyite (both identified optically only), chlorite, calcite, and leucoxene. To the north and east, with increasing intensity of metamorphism, pale amphibole, and then, finally, pleochroic amphibole appear in the groundmass. Clinopyroxene is replaced by epidote and pale amphibole and farther north by pleochroic amphibole. Plagioclase phenocrysts include myrmekitic intergrowths with quartz. Basalt pillow breccia adjacent to the tonalite body at the Please horizontal control marker in the Eastern St. John quadrangle is strongly foliated, the breccia fragments are flattened and elongated downdip, and the metamorphic assemblage includes garnet and diopside in addition to quartz, plagioclase, hornblende, and calcite.

Most of the basalt, including the breccia fragments, is amygdaloidal. On Kiddel Point, flattened amygdules are as long as 10 cm (fig. 7). Some basalt is scoriaceous with small (a few millimeters) amygdules making up 30 percent or more of the rock. Amygdules are filled with various combinations of quartz, calcite, chlorite, epidote, and plagioclase, as well as local prehnite and pumpellyite. Toward the north and east, pale amphibole and clinozoisite in radiating fibers appear in the amygdules.

VOLCANIC WACKE AND BEDDED TUFF

Volcanic wacke and bedded tuff are minor components of the Water Island Formation and constitute unit Kww (fig. 8). Volcanic wacke consists of subrounded to angular clasts of keratophyre of all varieties, basalt, and granitoid in a matrix of comminuted keratophyre that includes xenocrystic quartz and plagioclase. The constituents are poorly sorted, up to more than a meter across, and bedding is commonly poorly defined. Graded beds are rare but present in some of the finer grained rocks between Turner Bay and Contant Point. Generally, the keratophyre clasts have sharp rather than ragged edges, are not pumiceous, and were probably derived from lava. Keratophyre clasts in bedded rocks along the shore between Grootpan and Kiddel Bays on the south coast have wispy ends and are probably pumice; these rocks may be submarine pumice flows. Trondhjemite clasts as large as boulders have been found in two areas on the East End: (1) in the cove along Long Bay about 250 m northeast of Long Point and (2) the easternmost part of Privateer Point. The trondhjemite clasts have granophyric texture and are discussed in the section on the Careen Hill Intrusive Suite. The bedded tuff in unit Kww contains finer grained, better bedded, and better sorted beds of sand- to silt-size material. It is difficult to determine whether the finest material is ash or chert. No shards have been seen in the few thin sections available. Some of the fine-grained beds have slump folds. Unit Kww crops out on the East End from Europa Bay to Saltpond Bay, and forms the top of the Water Island Formation in southwestern St. John.

RADIOLARIAN CHERT

Radiolarian chert (Kwr) is mapped where fossil Radiolaria have been observed. Beds of light-blue-gray to dark-gray chert crop out near Contant Point in unit Kww (but are too thin to show on the map) and on Kiddel Point. On Kiddel Point, where it crops out on the shore of Saltpond Bay, the unit contains well-preserved Radiolaria. They were only observed in thin section after the completion of field work.

CAREEN HILL INTRUSIVE SUITE (HERE NAMED)

The Careen Hill Intrusive Suite consists of hypabyssal trondhjemite, intrusive coarsely porphyritic keratophyre, intrusive equivalents of all of the keratophyre units of the Water Island Formation, and fine-grained gabbro thought to be the intrusive equivalent of basalt of the Water Island. These intrusive rocks are found isolated on islands off St. John and as dikes and small plutons intruding each other and the Water Island Formation. No order of intrusion has been recognized and the intrusions are found throughout the stratigraphic thickness of the Water Island. Coarsely porphyritic keratophyre intrudes the Water Island within about 35 stratigraphic meters of the overlying Louisenhoj Formation northwest of Boatman Point on the south coast. Columnar jointing is typical of the small plutons and dikes and is one of the criteria used to identify a rock body as intrusive. Rocks of the Careen Hill Intrusive Suite have been subjected to the same local hydrothermal alteration as those of the Water Island. The larger keratophyre intrusive bodies form sharp hills along the south coast of St. John and around the harbor of Charlotte Amalie, St. Thomas. The name is taken from Careen Hill, which is held up by intrusive coarsely porphyritic keratophyre (Kcp), in Charlotte Amalie.

INTRUSIVE KERATOPHYRE

Several varieties of intrusive keratophyre have been mapped based on the size and mineralogy of the phenocrysts, as was true for the Water Island Formation. Phenocryst-poor keratophyre (Kca) contains up to about 10 percent small (generally less than 2 mm across) phenocrysts of quartz and plagioclase in an aphanitic groundmass. This unit forms a small pluton that holds up the sharp 272-ft-high hill of Bovocoap Point and forms dikes such as the one at the end of Dittlif Point that is 20 m thick. Porphyritic keratophyre (Kcp) is characterized by about 20 percent conspicuous phenocrysts of quartz and white-weathering plagioclase up to 3 mm across in a medium-dark-bluish-gray (5*B* 4/1), aphanitic groundmass. Unit Kcp forms a small pluton about 140 m across on the 160-ft-high hill at the head of Europa Bay and forms dikes elsewhere. In thin section, the Europa Bay body looks remarkably unaltered except for some secondary sericite and chlorite; yet, the presence of unzoned albite and the alkali ratio suggest metasomatic alteration. Many phenocrysts are in growth aggregates and some quartz has embayments and inclusions of devitrified glass. Plagioclase is twinned, nonzoned, clear albite. Some plagioclase aggregates are surrounded by granophyric intergrowths of quartz and plagioclase. The groundmass consists of randomly oriented plagioclase laths about 0.1 mm long, interstitial quartz, and magnetite dust. Apatite and allanite are sparse accessories. In major element chemistry, the rock consists of 77.9 percent SiO_2, 6.54 percent Na_2O, and 0.15 percent K_2O. Yet, the presence of unzoned albite and the alkali ratio suggest metasomatic alteration. Plagioclase-phyric keratophyre (Kcf) consists of 5 to 15 percent plagioclase phenocrysts (1 to 3 mm long) in a groundmass of typically felted plagioclase microlites and interstitial quartz. This unit forms small plutons on Ram Hill and on the peninsula leading to Dittlif Point, and occurs as dikes. The Ram Hill pluton is a laccolith dipping moderately to the east and is cut off by a fault on the south. Relatively small columnar joints, 10 to 20 cm across and plunging 40° WNW. may be seen just north of the saddle between Ram Hill and Ram Head.

Coarsely porphyritic keratophyre (Kcc) is characterized by prominent quartz and plagioclase phenocrysts, typically 5 to 10 mm across, that constitute 20 to 30 percent of the rock. In some rocks, the groundmass is exceedingly fine grained and similar to that of the extrusive keratophyres; in others, plagioclase laths are up to 0.3 mm long. Toward the north and east where contact metamorphism has affected the rocks, coarse epidote appears in the plagioclase phenocrysts and epidote, pale amphibole, and shreddy olive biotite appear in the groundmass. At an elevation of 320 ft along Center Line Road northwest of Coral Bay, blue-green amphibole is present in the groundmass. Small plutons of Kcc hold up the sharp hills north of Cocoloba Cay, near Hart Bay, and Maria Bluff. Dikes of Kcc are widespread in the Water Island Formation and cut the trondhjemite (Kct) of Flanagan Island, where the groundmass of Kcc consists of granophyric spherulites. The body of Kcc on the east slope of Bordeaux Mountain is interpreted to be a sill or laccolith based on the southwest-plunging columnar joints, and on the map pattern of Kcc, which shows that it extends northeastward downslope, as shown in guts. The northeast dip of the body is consistent with the attitude of the Water Island Formation in eastern St. John. Unit Kcc has no extrusive equivalent.

Unit Kcc is distinguished from the Tertiary Red Hook Tonalite Porphyry (Tr) by the generally smaller size of the quartz phenocrysts, the absence of barrel-shaped biotite phenocrysts, the absence of strong zoning in plagioclase phenocrysts, the absence of a yellowish cast to the rock color, the presence of some secondary epidote, the presence locally of intense hydrothermal alteration, and the trace-element chemistry. The coarsely porphyritic keratophyre, like most of the keratophyres of the Lameshur, has an essentially flat rare-earth element (REE) chondrite-normalized pattern with a small negative europium (Eu) anomaly. In unit Kcc, REE's are enriched 10 to 15 times those in chondrites. Chondrite-normalized light REE's in the Red Hook (only two samples) decrease from 20 to 30 times that of chondrites for lanthanum (La) to 3 to 4 times that of chondrites for terbium (Tb). Heavy REE's are 3 to 4 times that of chondrites; there is no Eu anomaly. The coarsely porphyritic keratophyre that crops out in roadcuts on the steep slope leading down to the northeast side of Hart Bay is unusually fresh. Plagioclase phenocrysts are albite, not zoned, have sharp euhedral borders, and minor sericitic alteration. The groundmass is homogeneous and ultrafine grained (generally less than 0.05 mm), but does contain some secondary calcite, chlorite, and sericite. The major oxides include 76.2 percent SiO_2, 6.25 percent Na_2O, and 0.10 percent K_2O. Volatile components reported in the analysis include 0.81 percent H_2O^+, 0.12 percent H_2O^-, and 0.38 percent CO_2. Again, the unzoned albite and the alkali ratio suggest metasomatic alteration.

Figure 9. Columnar joints in trondhjemite (Kct) of the Careen Hill Intrusive Suite on southwestern shore of Leduck Island. Columns plunge 75° with a bearing of 255°. Dark band to right of person is a northwest-trending diabase dike (Td) dipping 75° to the southwest.

TRONDHJEMITE

Trondhjemite (Kct) is fine to medium grained and commonly porphyritic with phenocrysts of quartz and plagioclase. In the freshest rocks, the plagioclase is albite, nonzoned, and twinned, but with some sericitic alteration. The groundmass is typically a granophyric intergrowth between quartz and albite. Commonly granophyric intergrowths radiate from albite phenocrysts. Chlorite forms 5 to 7 percent of the rocks; in one rock, chlorite is clearly replacing biotite. Trondhjemite forms Leduck Island, where columnar jointing is prominent (fig. 9), and Flanagan Island, where it is not. Trondhjemite also forms a 4-m-thick dike on the small peninsula leading to Blinders Rocks, southwest of Haulover in the Eastern St. John quadrangle. On Leduck Island, the trondhjemite is light bluish gray (5*B* 7/1) and coarsely porphyritic; the groundmass has a less well developed granophyric texture. Albite tends to be subhedral and the quartz is equant; the grain size is about 0.1 mm. The trondhjemite on Flanagan Island is medium bluish white (5*B* 9/1) and contains a few percent clinozoisite in addition to chlorite. The stratigraphic position of the trondhjemite on these two islands cannot be determined directly because of the absence of stratified rocks. Donnelly (1966) and Helsley (1960, 1971) included the trondhjemite on Flanagan Island in the younger suite of plutonic rocks that includes the Virgin Gorda batholith. The trondhjemites are here included in the Careen Hill because of the mineralogy, texture, and chemistry. The chondrite-normalized REE patterns for the trondhjemites are essentially the same as that of the keratophyres in the rest of the Lameshur Volcanic-Intrusive Complex. The consistent, steep, west-southwest plunge of the columnar joints on Leduck Island suggests a tabular body that dips gently east-northeast and is roughly conformable with the bedding in the Water Island Formation around Privateer Bay to the northeast.

Two zones of trondhjemite clasts up to boulder size in volcanic wacke of the Water Island Formation were observed on the East End. One is on the shore of Long Bay, about 250 m northeast of Long Point, and the other is on the easternmost part of Privateer Point. At the latter locality, one boulder clast is more than 1 m across. As mapped, the two zones of clasts are at different stratigraphic levels. Trondhjemites in these clasts are typically porphyritic with phenocrysts of quartz and nonzoned plagioclase in a granophyric crystalline groundmass that contains several percent chlorite, probably after biotite. They are interpreted to be clasts of trondhjemite of the Careen Hill Intrusive Suite. These observations, as well as the outcrops of trondhjemite, indicate that the Lameshur Volcanic-Intrusive Complex includes heretofore unrecognized silicic plutons, and that some of these were either exposed to erosion at the time of volcanism related to the Water Island Formation, or were solidified enough to have survived transport upward through a volcanic vent and subsequent incorporation into a volcanic wacke.

GABBRO

Dark-greenish-gray, fine-grained gabbro (Kcm) forms a small intrusive body on Bovocoap Point in southwestern St. John. The gabbro is porphyritic with small (2 mm or less), subhedral phenocrysts of clinopyroxene and plagioclase in a

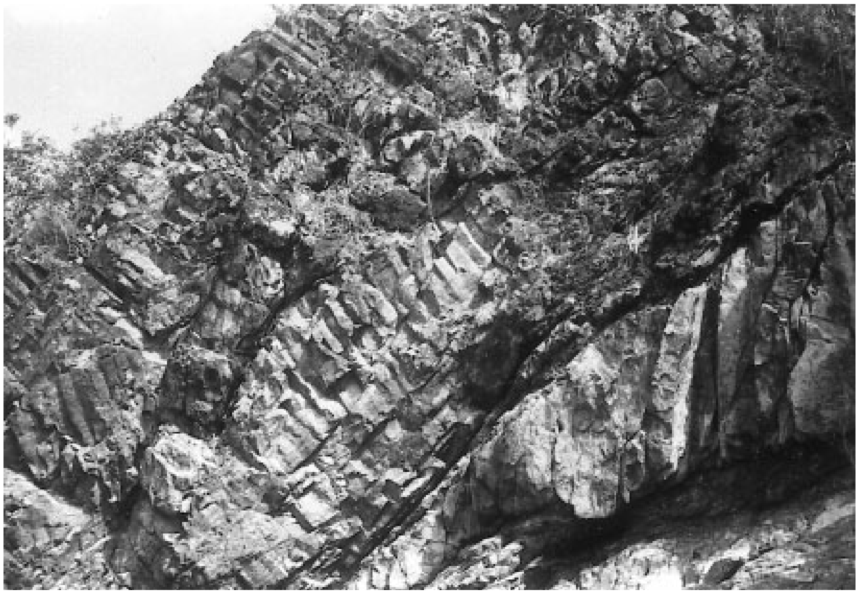


Figure 10. Mafic sheeted dikes of the Careen Hill Intrusive Suite seen in bluff at southwest corner of Saltpond Bay. The dikes display columnar jointing, strike northeast, and dip northwest. The dikes are intruded by a sill of coarsely porphyritic keratophyre also of the Careen Hill Intrusive Suite (lower right) that is 9 m thick at right edge of photograph, and by a younger diabase dike (unit Td) in left center. The diabase dike trends 40° and dips 70° NW.

Figure 11. Bedded, boulder volcanic conglomerate of the Louisenhoj Formation, south end of Trunk Cay. Beds strike 80° and dip 65° N. Hammer resting on largest boulder is 28.5 cm long.

groundmass of randomly oriented plagioclase laths about 0.5 mm long, clinopyroxene, chlorite, leucoxene, and opaque minerals. The gabbro is cut by small plagioclase-pyribole pegmatites. The gabbro has the same REE pattern as the basalts of the Water Island Formation (light REE's enriched 3 to 5 times that of chondrites; heavy REE's enriched 5 to 8 times that of chondrites). The gabbro physically occurs within the area of the Lameshur Volcanic-Intrusive Complex, and is here included within the Careen Hill Intrusive Suite. Some of the mafic dikes associated with keratophyre dike swarms, particularly those that show hydrothermal alteration, are also probably of the Careen Hill Intrusive Suite, but are not mapped separately. Trondhjemite on the southwest coast of Flanagan Island forms a network of veins in a large area of diorite or gabbro. These dark rocks may be mafic rocks of the Careen Hill Intrusive Suite.

SHEETED DIKES

Sheeted dikes were observed at a number of localities on St. John and on St. Thomas (where they are better developed). The sheeted-dike complexes on St. Thomas are unusual in that they consist dominantly of keratophyre but also include diabase. The dikes trend northeast, dip moderately to steeply northwest and include both diabase with columnar jointing and keratophyre. Helsley (1960, 1971) mapped a series of abundant north-northwest-trending porphyry dikes cutting the Water Island Formation on the southern tier of the British Virgin Islands between St. John and Virgin Gorda. The porphyry dikes are not present on the northern tier of the British Virgin Islands where younger strata (Tutu Formation and younger, as mapped by Helsley, 1960, 1971) are present. The dikes are highly altered porphyritic "microgranites" with granophyric texture and are almost completely lacking in mafic minerals (Helsley, 1960; Longshore, 1965). Helsley (1971) interpreted the dikes to be of post-Eocene age and related to the opening of the Anegada Trough. Granite, also mapped on the southern tier of the British Virgin Islands, possibly might be trondhjemite of the Careen Hill Intrusive Suite such as that on Flanagan Island, and the porphyry dikes might be part of the sheeted-dike complex. On St. John, sheeted dikes were observed on the buttress forming the south side of Saltpond Bay (fig. 10) and at Harbor Point.

Keratophyres are not normally a major component of sheeted-dike complexes. An exception is the Canyon Mountain Complex of Oregon, where albite granite and keratophyre dikes locally are dominant in the sheeted-dike unit (Thayer and others, 1981). Avé Lallemant (1976) suggested that, because of the abundance of silicic rocks in the Canyon Mountain Complex, the ophiolite might have formed either near a volcanic island arc or in a spreading marginal basin. The Lameshur Volcanic-Intrusive Complex certainly formed in a marine extensional environment. The REE pattern of the mafic rocks is most similar to that of normal (N-type) mid-ocean ridge basalt (MORB) (Sun and others, 1979; Sun and McDonough, 1989).

VIRGIN ISLAND GROUP (NOT USED)

Donnelly (1966) included the stratified rocks of St. Thomas and St. John that overlie the Water Island Formation in his Virgin Island Group (table 1). He considered the lowest unit of the group, the Louisenhoj Formation, to lie unconformably above the Water Island and to be part of the primitive island arc (PIA) series. The dominant volcanic components of the Louisenhoj and Tutu Formations, however, are distinctly of island arc character, and, except for the lowest basalt flows of the Louisenhoj, contrast with those of the more oceanic Water Island Formation. Because of the different chemistry and interpreted different tectonic settings, I would not include the Water Island and Louisenhoj in the same "series." The stratigraphic contact between the Water Island and Louisenhoj is here interpreted to be conformable. The youngest unit of the Virgin Island Group in the northern U.S. Virgin Islands was named the Hans Lollik Formation by Donnelly (1966). In the northern U.S. Virgin Islands, it crops out only on Hans Lollik Island, Little Hans Lollik Island, and Pelican Cay, all north of St. Thomas. The rocks on these islands are here interpreted to be the Louisenhoj Formation (Rankin, 1997), brought up north of the Leeward Passage on the north limb of a major syncline, as first postulated by Cleve (1882). As stated earlier, the name Virgin Island Group is not used in this report.

LOUISENHOJ FORMATION

Strongly cemented volcanic conglomerate, breccia, volcanic wacke, shale, chert, andesite, basalt, tuff, and rare limestone of the Louisenhoj Formation (Kl) overlie the Water Island with apparent conformity. The rock is known locally as the "blue beach" (Cleve, 1882), or "blue bitch" (Donnelly, 1966). The formation was named by Donnelly (1966) for excellent exposures in roadcuts in the vicinity of Louisenhoj north of Charlotte Amalie, St. Thomas. Volcaniclastic rocks predominate. Primary volcanic rocks, such as lavas and flow breccias, are present but sparse. In weathered exposures or exposures covered with vegetation, distinguishing between epiclastic breccia and aa lava is difficult (for example, in the Camelberg Peak area). Other units of massive conglomerate and breccia consisting of large boulders and slabs of basalt or andesite, such as those at America Point, appear to have been deposited near the source rocks. Conglomerate, breccia, and coarse volcanic wacke are typically pale green, greenish gray, or grayish blue green. The formation is at least 1.5 km thick on the west coast of St. John, but thins to the east. At Leinster Bay, it may be as thin as 0.5 km.

The age of the Louisenhoj cannot be constrained more closely than Albian to Santonian. The latter is the younger age limit of the overlying Outer Brass Limestone (Ko). Donnelly (1966, 1989) considered the Louisenhoj to be of Albian age because of his interpreted Albian age of the Tutu Formation. Helsley (1960, 1971) assigned a Cenomanian age to the Louisenhoj, but did not present any evidence.

Bedding characteristics of the Louisenhoj are heterogeneous. The unit is dominated by thick beds of conglomerate (fig. 11), but these are typically interlayered with sequences a few to several meters thick of silt- to sand-size material and even some laminated radiolarian chert at Dorothea Point and Kastel Point in the Central St. Thomas quadrangle. Graded beds are common (Rankin, 1999, fig. 9), some as thick as 4 to 6 m (fig. 12). Crossbedding is present but less common. Soft sediment deformation and broken-up, finer grained beds were observed locally. Massive beds of unsorted sand- (or smaller) to boulder-size material are tens of meters thick at the point forming the northeastern end of Hawksnest Bay. The larger clasts in the conglomerates tend to be more rounded than the smaller ones. Clasts larger than 0.5 m across are abundant throughout the formation (figs. 11 and 13). The largest subrounded clast observed on St. John is about 3 m across. Breccia fragments may be larger, but these appear to be closely

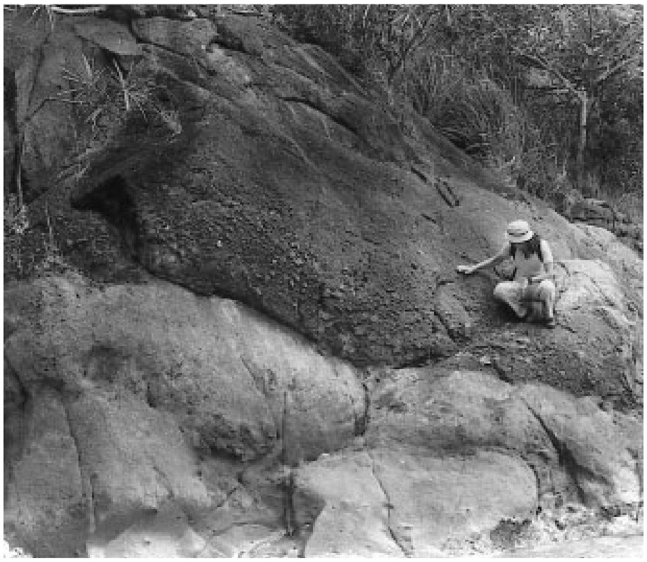


Figure 12. Graded bed 4 m thick showing transition from volcanic conglomerate to wacke of the Louisenhoj Formation, west side, Jumbie Bay. Pyroxene andesite clasts at base are commonly 10 cm and as much as 15 cm across. Matrix contains abundant obvious detrital pyroxene. Beds strike 285° and dip 45° N.; foliation (not obvious in photograph) trends 285° and dips 80° N.

Figure 13. Boulder bed in the Louisenhoj Formation, looking northwest, north shore of St. John on point between Denis and Jumbie Bays. Clasts are andesite. Beds strike 85° and dip 60° N. Hammer is 28.5 cm long.

related to lava flows. The conglomerates may be either clast supported or matrix supported.

Clasts of clinopyroxene andesite and basalt constitute the bulk of the Louisenhoj Formation. Some of these rocks have overgrowths of hornblende on the pyroxene phenocrysts, and a few also have primary hornblende phenocrysts. Small amygdules are pervasive in some clasts. The andesite and basalt clasts in the Louisenhoj are characterized by stubby, zoned plagioclase and clinopyroxene phenocrysts that occur together or singly. In most rocks, the phenocrysts are obvious, constitute about 20 percent of the rock, and commonly attain diameters of 5 to 10 mm. These field characteristics differ markedly from those of the basalts of the Water Island Formation. Large xenocrysts of plagioclase and pyroxene are notable constituents of some of the clastic rocks. Other rocks found as clasts include devitrified andesitic glass (particularly in western St. Thomas), pumice (not common), limestone, keratophyre, phenocryst-poor basalt similar to that of the Water Island Formation. Differences in clast populations suggest local sources. Keratophyre and phenocryst-poor basalt clasts locally are abundant near the basal contact with the underlying Water Island Formation. Limestone clasts occur on Rata and Ramgoat Cays; some of these clasts are fossiliferous with individual identifiable forms as well as fossil hash. Small collections have been made from these limestone boulders. On the west side of Rata Cay, the limestone clasts are in two layers separated along strike by about 0.7 m of conglomerate; they probably represent dismembered beds of limestone. Elsewhere, calcite cement is common in the conglomerate of the Louisenhoj.

In some places, breccia fragments (fig. 14) coalesce into massive andesite (field term, only); in other places, only massive andesite appears to be present. These areas are mapped as porphyritic andesite lava (Kla). The rocks may be vesicular and are characterized by stubby plagioclase and pyroxene phenocrysts. Unit Kla at the north end of Ramgoat Cay is pillowed. Highly brecciated Kla on Camelberg Peak could be aa lava. Chemically, Kla includes basalts as well as andesites (SiO_2 content of six samples ranges from 49.7 to 59.0 percent). The REE contents range from 10 to 30 times that of chondrites for lanthanum (La) to 5 to 15 times that of chondrites for lutetium (Lu). Porphyritic, locally amygdaloidal basalt (Klb) forms the basal unit of the Louisenhoj in the vicinity of Rendezvous Bay and near Ajax Peak. The basalt is included in the Louisenhoj because of the presence of prominent phenocrysts of stubby plagioclase and (or) pyroxene. The basalt is chemically transitional between basalt of the Water Island Formation and andesite of the Louisenhoj. The chondrite-normalized REE pattern is essentially flat and is about 10 times that of chondrites. No evidence has been found to support the idea of Donnelly (1966) that a paleovolcano in Pillsbury Sound between St. Thomas and St. John was the source of the volcanic material in the Louisenhoj Formation.

The lower contact of the Louisenhoj with the Water Island is well exposed in a few places on St. John and can be traced around Contant Point. On the nose of the point, the contact is gradational over about 15 cm from thinly bedded volcanic wacke and chert or ash of the Water Island up into massive conglomerate of the Louisenhoj. The same contact

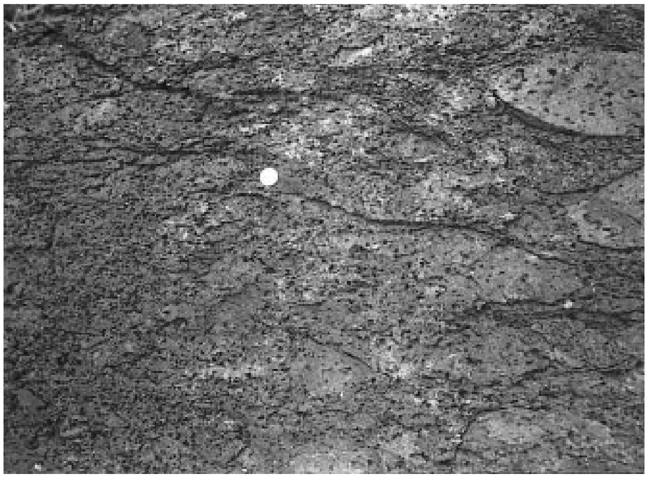


Figure 14. Foliated andesitic tuff breccia of the Louisenhoj Formation, buttress between Jumbie and Trunk Bays. Dark spots are relict clinopyroxene phenocrysts. Dime for scale.

Figure 16. Conformable contact between phenocryst-poor keratophyre tuff (Kwa) of the Water Island Formation below and volcanic conglomerate of the Louisenhoj Formation above, north end Cocoloba Cay. Contact dips 30° NE. Hammer is 28.5 cm long.

Figure 15. Conformable contact between bedded ash or chert and lithic tuff (Kww) of the Water Island Formation below and volcanic sandstone and conglomerate of the Louisenhoj Formation above. The head of the three-pound hammer rests on the contact, which strikes 290° and dips 50° N. Photograph taken in 1986 at a construction site low on the west side of Roman Hill at the head of Great Cruz Bay. The site is now covered by landscaping of a resort hotel.

is sharp at the base of a ledge on the northwest shore of Great Cruz Bay. Graded beds in the Water Island volcanic wacke dip northeast about 30° and are upright. The contact is somewhat irregular and an outlying patch of Louisenhoj conglomerate (Kl) is preserved on a flat exposure of volcanic wacke (Kww) a few meters shoreward of the ledge. At the time of field work in 1986, construction for a new resort hotel at the head of Great Cruz Bay exposed an excellent section across the conformable contact (290°, 50° N.) (fig. 15). The section extends up from amygdaloidal basalt through bedded ash or chert and lithic tuff of the Water Island to conglomerate of the Louisenhoj. A 10-m-thick sill of hornblende lamprophyre intrudes the volcanic wacke (Kww) about 6 m below the contact; a 20-m-thick slightly discordant sill (80°, 70° N.) of fine-grained gabbro intrudes the Louisenhoj above the contact. The contact is now covered by outbuildings and landscaping of the resort. The 200-m sinistral offset of this northeast-dipping contact at sea level, determined by projecting the exposed contact along strike into Great Cruz Bay, was the first evidence developed for the Guinea Gut fault. The contact is again exposed on the peninsula between Monte and Klein Bays where amygdaloidal basalt containing stubby phenocrysts of plagioclase and pyroxene (Klb) overlies volcanic wacke (Kww) containing blobby masses of flow-layered, phenocryst-poor keratophyre. Protrusions of basalt cut down into the volcanic wacke. Finally, a conformable contact between underlying flow-layered, brecciated, phenocryst-poor keratophyre (Kwa) and bedded conglomerate (Kl) is exposed on the north end of Cocoloba Cay (fig. 16). Cobbles of keratophyre are abundant in the lower 3 m of the conglomerate.

As the degree of metamorphism increases to the northeast, biotite, pale amphibole, and epidote appear in the andesite, and epidote, hornblende, and lesser amounts of biotite appear in the basalt. The calcite cement in the conglomerate from Cinnamon Bay eastward also contains epidote, brown anisotropic garnet, and, farthest east, diopside. From central St. John to the north and east, a foliation is present in most rocks, particularly in the finer grained sedimentary rocks and in the matrix of the finer grained conglomerates. Northeast of Cinnamon Bay and particularly

Figure 17. Foliated and contact-metamorphosed volcanic conglomerate of the Louisenhoj Formation, looking east on America Point. Meta-andesite clasts are flattened in a plane striking 285° and dipping 90° and elongated downdip. Knife in center of photograph is 8.3 cm long.

Figure 18. Fluted outcrop of bluish-gray, clean, calcite marble of the Outer Brass Limestone, looking east on nose of ridge at Annaberg ruins. Beds strike 85° and are vertical. Knife is 8.3 cm long.

east of Annaberg Point, the clasts in the conglomerates are distinctly flattened and locally elongated (fig. 17). Flattened boulders can be seen in float blocks of conglomerate of the Louisenhoj along the shore of Leinster Bay at Annaberg Point. Deformation is thought to precede the thermal peak of metamorphism.

OUTER BRASS LIMESTONE

The Outer Brass Limestone (Ko) (fig. 18) is a relatively minor, thin unit on St. John stratigraphically separating the conglomeratic Louisenhoj Formation below from the less conglomeratic Tutu Formation (above). The formation was named by Donnelly (1966) for exposures on the western seacliff side of Outer Brass Island north of St. Thomas. The thin outcrop belt extends from Maho Bay to Brown Bay on St. John. The belt is discontinuous because of numerous faults and it is cut by a Tertiary pluton (Tt) east of Leinster Hill. The map pattern portrayed on Leinster Hill is without field control due to impenetrable vegetation, chiefly a thorny vine known locally as come-along. Neither the base nor the top of the formation is exposed on St. John. The Outer Brass is interpreted to be part of a conformable sequence from the Louisenhoj Formation through the Tutu. The conformable upper contact of the Outer Brass with the Picara Member of the Tutu Formation is exposed on Outer Brass Island. The only exposure of the Outer Brass's lower contact on St. Thomas is a mylonite zone. The Outer Brass is on the order of 100 m thick. Pessagno (1976; oral commun., March 1997) identified planktonic Foraminifera of late Turonian to late Santonian age in thin sections of the Outer Brass from St. Thomas.

Outcrops of the formation on St. John are within the metamorphic aureole of the Tertiary plutons. The Outer Brass Limestone consists of thin-bedded calc-silicate beds of white to blue-gray calcite marble (H_2S odor when broken), and matrix-supported cobble conglomerate consisting of andesite clasts in a carbonate matrix. A unit of clean calcite marble at least 3 m thick and with a fluted weathering surface is exposed on the western nose of the small ridge at the Annaberg Sugar Mill Ruins (fig. 18, this report; fig. 16 of Rogers and Teytaud, 1988, mislabeled as bedded siltstone of the Tutu Formation). Clean calcite marble is also found on the low hill east of Maho Bay and along the trail from Waterlemon Bay to Brown Bay near the 240-ft ridge crest. Heterogeneous calc-silicate rock, exposed in the bluff on Annaberg Point, includes calcite, plagioclase, epidote, brown isotropic garnet, diopside, vesuvianite, and wollastonite in various assemblages. A carbonate matrix conglomerate containing flattened clasts of andesite crops out on the low hill east of Maho Bay and at the Annaberg ruins. Coastal exposures east of Leinster Hill are of tonalite containing abundant calc-silicate xenoliths, which are inferred to be more or less in-place remnants of the Outer Brass Limestone.

TUTU FORMATION

The Tutu Formation (Kt) consists of volcanic wacke, shale, conglomerate, calcareous siltstone, sparse limestone, and rare basalt and andesite or their metamorphosed equivalents. Many rocks are calcareous. The formation was named by Donnelly (1966) for exposures around Tutu Bay on the north shore of St. Thomas, Eastern St. Thomas quadrangle. Donnelly also defined the Congo Cay Limestone Member for exposures on Congo Cay at the west border of the Western St. John quadrangle. In this report, the Tutu is divided into a basal Picara Member and an overlying Mandal Member on the basis of field work on St. Thomas. The Congo Cay has been reduced to a lens within the Mandal Member. Donnelly (1966) concluded that the Tutu was of Albian age on the basis of the faunal assemblage in limestone clasts in a megabreccia exposed at Coki Point, Eastern St. Thomas quadrangle. Young (1972) identified ammonites of early late Albian age in the Tutu of St. Thomas. If the Turonian to Santonian age for the Outer Brass Limestone is correct, the ammonites in the Tutu are probably reworked from an older unit as noted by Pessagno (1976).

The Tutu Formation is more completely exposed on St. Thomas and on the chain of islands that forms the northern border of Pillsbury Sound. The Tutu underlies northernmost St. John and the chain of islands north of Pillsbury Sound that extends into the Western St. John quadrangle. The basal contact of the Tutu with the Outer Brass Limestone is not exposed on St. John, but bedding in adjacent outcrops is essentially parallel. The contact is interpreted to be conformable. The Congo Cay Limestone Lens of the Mandal Member is the youngest stratified bedrock unit in the map area, but stratigraphic contacts are under water. Helsley (1960) portrays the Congo Cay to be within the Tutu on Great Thatch Island and Tortola of the British Virgin Islands. In the map area of this report, the Tutu Formation is within the contact aureole of the Tertiary plutons. Metamorphic recrystallization is most noticeable in the calcareous rocks. Former limestones are now marbles, and calcareous siltstones and sandstones contain obvious garnet, diopside, and, in places, wollastonite.

Graded beds and slump folds are common in the Tutu, as are disrupted slabs of metasandstone and metasiltstone in metaconglomerate (Rankin, 1999, fig. 10). A spectacular example of slump folds in the Mandal Member is exposed in a steeply north dipping bed of interlayered metasiltstone and metasandstone 3 m thick on Thatch Cay, just east of Mother East Point, Eastern St. Thomas quadrangle. Most of the material is thought to have been deposited by turbidity currents. The extent of soft sediment deformation combined with the evidence for turbidity current deposition indicates that the Tutu was deposited on an unstable slope such as a trench wall leading to an accretionary wedge. Tectonism has produced boudins of metasiltstone in marble and of metasandstone in metasiltstone and marble. Tight to isoclinal tectonic folds with axial-plane cleavage also are common. Marble is typically deformed in a plastic manner. Distinguishing between soft sediment and tectonic folds is difficult in places because the two appear to grade into one another.

PICARA MEMBER (HERE NAMED)

The Picara Member (Ktp) on St. John consists of metamorphosed thick- to thin-bedded volcanic wacke, conglomerate, siltstone, limestone, and rare andesite or basalt. Many rocks have a calcareous matrix. The member, minus limestone and basalt, is well exposed on the long peninsula on the north side of St. Thomas that ends in Picara Point, from which it takes its name. The Picara Member on St. John is well exposed in shoreline outcrops around Maho, Leinster, and Threadneedle Points. Clasts in the conglomerate are metamorphosed andesite, basalt, and limestone. In the limited exposures on St. John, pebble and cobble conglomerates are more common than boulder conglomerates. Metasiltstone and fine-grained metawacke are commonly weathered out and produce ribby outcrops. In places, the carbonate content is concentrated in nodules. Marble conglomerate and calc-silicate beds north of Maho Point are shown on the geologic map as Ktpl. Calc-silicate assemblages include plagioclase-biotite-hornblende and plagioclase-hornblende-diopside-calcite. Porphyritic meta-andesite (Ktpv) crops out on the south side of Maho Point and on the hill to the east. Fresh rock is foliated, medium dark gray (*N* 4) and contains relict phenocrysts of glomerophyric plagioclase and prominent clinopyroxene as large as 3 by 6 mm. Metamorphic amphibole replaces the clinopyroxene phenocrysts. Fibrous amphibole and chlorite are abundant in the groundmass and impart a foliation to the rock.

Two calc-silicate layers, 5 and 10 m thick separated by about 4 m of siliceous hornfels, crop out on the west end of Waterlemon Cay. The calc-silicate assemblage includes brown garnet, some of which is anisotropic, diopside, wollastonite, sphene, calcite, monazite, and sulfide. In places, the beds are layered with each layer dominated by one mineral. In other places, the monomineralic layers form concentric zones of lenses of calcareous minerals. A typical sequence within the lens consists of calcite cores surrounded by a layer of garnet, surrounded by a layer of diopside. The garnets may be euhedral and as large as 2 cm; wollastonite blades in sheaves are as long as 2 cm. Some euhedral garnets are multiply zoned and in thin section are seen to consist of alternating shells of garnet and diopside. These observations suggest open-space crystallization; the rocks are probably skarns.

MANDAL MEMBER (HERE NAMED)

The Mandal Member (Ktm) is characterized by finer grained, thinner bedded material than the Picara (fig. 19). The unit is named for rocks on the east side of Mandal Point, Eastern St. Thomas quadrangle, that overlie those of the Picara Member with apparent conformity. The Mandal

Figure 19. Thin-bedded turbidite of the Mandal Member of the Tutu Formation in the zone of contact metamorphism on the north shore of Francis Bay. Bedding strikes 90° and dips 70° N.

Figure 20. Wave-cut notch in the Congo Cay Limestone Lens of the Mandal Member of the Tutu Formation, looking west along southern shore of Congo Cay. Bedding strikes 80° and dips 80° N. Isoclinal folds are visible in beds in foreground.

Member makes up most of Whistling, Lovango, and Congo Cays, Carval Rock, and Mary Point, St. John. The Mandal protoliths were noticeably calcareous in the Western St. John quadrangle. The siltstones were typically calcareous and the sandstones commonly had a calcareous matrix as shown by the present calc-silicate mineralogy. Conglomerates are sparse, but can be as much as 3 m thick; most are composed of limestone (marble) clasts. Areas of limestone conglomerate, abundant calc-silicate beds, and marble are mapped as Ktml on both sides of Fungi Passage. Marble clasts in the conglomerate are composed of calcite, plagioclase, tremolite, brown garnet, epidote, and opaque minerals. Metamorphosed calcareous siltstone and sandstone contain brownish garnet (locally as large as 3.5 cm), diopside, tremolite, plagioclase, calcite, opaque minerals, and minor quartz. Eight meters below a 6-m-thick tonalite dike at the northeast corner of Whistling Cay, garnet-rich, bedded calc-silicate rock contains isotropic reddish garnet, bright-green diopside, plagioclase, wollastonite, phlogopite, sphene, pleochroic amphibole, and quartz. Dark-grayish-red (5*R* 3/2), very fine grained metasandstone contains abundant reddish-brown biotite and cordierite clouded with tiny inclusions. Some metasandstones contain tiny muscovite crystals as well as biotite and cordierite.

CONGO CAY LIMESTONE LENS (REVISED)

The Congo Cay Limestone Lens (Ktmc) consists of vertical beds of calcite marble interlayered with some reddish-brown, siliceous hornfels and calc-silicate rock on Congo Cay (fig. 20) and Carval Rock. The marble is white to medium light bluish gray (5*B* 6/1) and consists of 98 percent calcite plus accessory plagioclase, white mica, and opaque minerals; in other rocks, the accessories are plagioclase, tremolite, wollastonite, sphene, and opaque minerals. The calcite grain size is typically 1 to 3 mm, but the grain size in some marbles is as large as 1 cm. The stratigraphic position of the Congo Cay within the Tutu is not known because the rocks are isolated by water. The Congo Cay is interpreted to be continuous underwater with the calcareous rocks of the Mandal Member (Ktml) on Whistling Cay. Helsley (1960) and Donnelly (1966) interpreted the lens to be continuous underwater with carbonate beds on Great Thatch Island of the British Virgin Islands. The beds on Great Thatch Island could well be the Congo Cay repeated on the north limb of the syncline whose axis passes between Picara Point and Hans Lollik Island, Central St. Thomas quadrangle.

DIABASE, GABBRO, AND DIORITE DIKES

Dikes of diabase, gabbro, and diorite (Td) are abundant. They range in thickness from a few centimeters to several tens of meters. Chilled margins are typical. Some form complex bodies of multiple dikes; some have internal layering parallel to the walls. Most dikes do not display columnar jointing. Color index, grain size, and texture vary; most are diabase or, if thick enough, gabbro with diabasic margins. Some dikes are amygdaloidal. Primary minerals in the dikes are plagioclase, clinopyroxene, commonly hornblende, magnetite, and (or) pyrite, and in some, quartz. The dikes are commonly porphyritic with phenocrysts of plagioclase, clinopyroxene, and (or) hornblende. Thicker bodies commonly contain epidote-quartz (epidosite) nodules and considerable disseminated epidote. Sampled dikes contain secondary pale, commonly fibrous amphibole, chlorite, and epidote. To the north and east, most dikes are progressively metamorphosed to greenschist facies; farther north they are at amphibolite facies.

The dikes intrude all stratified units, are intruded by tonalite (Tt), and pieces of the dikes are xenoliths in the tonalite. Dikes cut clasts in conglomerates of the Louisenhoj and Tutu Formations, which indicates that the dike intrusion occurred after the conglomerates were cemented. In the northern part of the island, many dikes exhibit the same penetrative cleavage as the stratified rocks; some dikes are broken into segments aligned parallel to the cleavage. At Mandal Point on St. Thomas and on the south shore of Thatch Cay, west of Stony Bay in the Eastern St. Thomas quadrangle, segments of mafic dikes as thick as 15 m in the Mandal Member occur as boudins. Many of the northern dikes were affected by the metamorphic aureole of the tonalites. Some dikes appear to have intruded after cleavage formed. Abundant fresh, noncleaved diabase and gabbro dikes cut and are chilled against noncleaved tonalite of unknown age on the Capella Islands, about 3 km south of eastern St. Thomas. Most diabase and gabbro dikes that intrude the Lameshur Volcanic-Intrusive Complex are mapped as unit Td. Those mafic dikes that show the same hydrothermal alteration as the adjacent keratophyre are included in the Careen Hill Intrusive Suite. Some of those Careen Hill mafic dikes have columnar joints.

The dikes mapped as Td are almost certainly of more than one age. No systematic study of the dikes was made and no distinctive field characteristics were noted that could document an age assignment. Some dikes, particularly those that are cleaved, may be intrusive equivalents of the enclosing or overlying stratified units. A few cut hornblende lamprophyre (Tl) and are interpreted to be among the youngest rocks in the map area. Donnelly and others (1971) and Donnelly and Rogers (1980) noted that the diabase dikes on St. John are part of a dike swarm extending from San Juan, Puerto Rico, to St. John. In Puerto Rico, that dike swarm cuts Paleocene strata (Pease, 1968) and is overlain by Oligocene coastal plain strata (Donnelly and Rogers, 1980). Donnelly and others (1971) suggested that the dike swarm was related to the Tertiary plutons (here represented by the tonalite unit, Tl). However, Donnelly and others (1990) later concluded that the dike swarm was an independent magmatic event largely because of its wide distribution and lack of localization around the plutons. A large mass of mafic and intermediate dikes on St. John that (1) generally lack columnar joints and hydrothermal alteration, (2) have chilled margins, (3) are near vertical, and (4) cut folded rocks as young as the Tutu Formation are interpreted to represent an independent magmatic episode older than the tonalite. The tonalite, however, locally grades into gabbro and some dikes may be early phases of the tonalitic magmatism. The dikes, therefore, are grouped into a single map unit and assigned a Tertiary age.

Gabbroic dikes (Td) 3 m or more in thickness are shown on the geologic map where space permits. They are nearly vertical and trend northeast; a subset of gabbroic dikes, also nearly vertical, strikes northwest. Thinner dikes of unit Td are prominent in most coastal exposures; in some exposures, dike complexes occupy as much as 20 percent of the outcrop. The inset map of dike distribution and attitude on plate 1 shows a more complete data set of all dike attitudes, including those assigned to the Careen Hill Intrusive Suite and younger dikes; the dikes are separated into those more than 3 m thick and those less than 3 m thick. The inset map also indicates that, when all dikes are included, attitudes are more varied. Presumably the real density of dikes in the interior is the same as it is on the coast.

BIOTITE-HORNBLENDE TONALITE

Biotite-hornblende tonalite (Tt) is very light gray to medium light gray, medium grained, and nonfoliated. The unit also includes minor gabbro, diorite, granite, and pegmatite. The tonalite (58.8 to 60 percent SiO_2) is composed of interstitial quartz (10 to 15 percent); subhedral strongly and complexly zoned plagioclase; biotite, partly altered to chlorite; hornblende; and magnetite. The gabbro is composed of plagioclase, hornblende, clinopyroxene, apatite, and pyrite and (or) magnetite. The granite (not sampled for chemistry) is very light gray, fine to medium grained, and contains quartz; orthoclase (about 35 percent); strongly zoned plagioclase; biotite, partly altered to chlorite; zircon; and magnetite. The pegmatite is white with a locally greenish copper stain and contains quartz, slightly perthitic orthoclase (poikilitic crystals up to 1.5 cm across), reddish isotropic garnet, and small amounts of diopside, sphene, allanite, and calcite.

Unit Tt crops out for about 2 km along the north shore of Mary Point where it intrudes the Mandal Member of the Tutu. Between Threadneedle Point and Brown Bay, unit Tt is interpreted to intrude the sequence from the Picara Member of the Tutu to the Louisenhoj Formation. The unit also occurs in a smaller area, not shown by Donnelly (1966), at the Please horizontal control marker in the Eastern St. John quadrangle, where it intrudes the Water Island Formation. Granite is found within unit Tt in a small area on the north shore, north of the eastern high point (520 ft) of the ridge on Mary Point. Small pegmatites cut calc-silicate beds of the Mandal Member about 350 m south of the tonalite contact at the west end of Mary Point. The contact of the body on Mary Point with the tightly folded Mandal Member is exposed both at Fungi Passage and at Anna Point. At both localities, the contact is sharp and roughly parallel to the nearly vertical bedding in the Mandal; locally, the contact crosscuts bedding. At both localities, the tonalite is choked with xenoliths, indicating some stoping

Figure 21. Gently dipping (25°, dipping 20° W.) tonalite dike (Tt), 6 m thick, intruding vertical beds (280°, dipping 85° N.) of the Mandal Member of the Tutu Formation at the northeastern corner of Whistling Cay. View looking south from a boat.

during intrusion. At Anna Point, most xenoliths are mica-rich contact rocks of the Tutu; the xenoliths are roughly aligned 290° and dip about 90° as much as 200 m from the contact. Adjacent to Fungi Passage, xenoliths of gray, fine-grained granofels, gabbro, calc-silicate rock, and siliceous hornfels constitute 5 to 10 percent of the tonalite as far as 200 m from the contact. A reaction zone about 5 cm thick separates the tonalite body from bedded calc-silicate rocks of the Tutu Formation. Near the contact, the tonalite is cut by small leucocratic pegmatites and granite veins and the tonalite contains segregations a few centimeters across of large hornblende crystals. Some blocks of bedded calc-silicate rocks in the tonalite are internally tightly folded. Outcrops and float boulders along the western half of the north shore of Mary Point contain numerous masses of pyrite up to 30 cm across, calc-silicate xenoliths, and pockets of limonite-stained skarn. The masses of skarn commonly are zoned and may contain open space. In some, an outer rim of coarse-grained epidote crystals surrounds intergrowths of epidote, brown garnet, and calcite. Toward the center of the skarn bodies are masses of sulfide (mostly pyrite) and free-growing quartz crystals. Some rocks have a green copper stain.

Exposures on the eastern end of Whistling Cay just west of Fungi Passage are useful in working out age relationships. At the northeast corner of the cay, a gently dipping 6-m-thick tonalite dike cuts nearly vertical calc-silicate beds of the Mandal Member (fig. 21). The beds are tightly folded and have a cleavage that is axial planar to those folds; fold axes are subhorizontal. Thermal metamorphism has partly annealed the cleavage. The dike has sharp contacts, is not internally deformed, and contains about 5 percent xenoliths of the country rock. Nearby diabase dikes have been deformed into boudins whose axes are subhorizontal. Locally, thin diabase dikes are offset by cleavage. The sequence of events here is (1) deposition of the Mandal Member of the Tutu Formation, (2) tight folding with the development of axial-plane cleavage, (3) intrusion of nearly vertical diabase dikes in the later stages of this deformation and the development of boudins, and (4) intrusion of tonalite accompanied by thermal metamorphism.

Tonalite and related rocks (Tt) of St. John are part of The Narrows pluton that also crops out on the north side of The Narrows from Great Thatch Island to western Tortola and is hypothesized to underlie much of The Narrows (Helsley, 1960; Donnelly, 1966). The Narrows pluton may or may not be connected to the Virgin Gorda batholith, a composite batholith that underlies eastern Tortola, Virgin Gorda, and adjacent islands. Helsley (1960) states that the batholith has a total land area of only about 34 km^2, but that the total area including the subaqueous parts is on the order of 260 km^2. A major reason for hypothesizing the large size relative to the area of the exposed pluton is the extent of the contact aureole. Certainly this seems valid for The Narrows pluton.

The Narrows pluton intrudes the Mandal Member of the Tutu (Turonian or younger) and is post-kinematic relative to cleavage and tight folding of the Tutu. The Virgin Gorda batholith (*sensu stricto*) in eastern Tortola intrudes the Tortola Formation of middle Eocene age (Helsley, 1971). Published K-Ar ages for rocks of the Virgin Gorda batholith (*sensu lato*) are listed in table 2. As part of this study, several samples of rocks from St. John, including three samples of tonalite and gabbro from The Narrows pluton, were analyzed by the $^{40}Ar/^{39}Ar$ age-spectrum dating technique by Michael J. Kunk (U.S. Geological Survey, written commun., March 1997 and August 1998). Sample VI-85-193 is a medium-grained quartz-plagioclase-hornblende-biotite-magnetite tonalite (59.8 percent SiO_2) collected near the Please horizontal control marker in the Eastern St. John quadrangle. Sample VI-85-218 is a medium-grained quartz-plagioclase-hornblende-biotite-magnetite-pyrite gabbro (53.8 percent SiO_2) collected from the northwestern shore of Mary Point in the Western St. John quadrangle. Sample VI-85-222 is a medium-grained quartz-plagioclase-hornblende-biotite-magnetite tonalite with less than 1 percent potassium feldspar (60.0 percent SiO_2) from the northeastern corner of Mary Point. Plateau ages from hornblende separates from these samples, all close to 39 Ma, also are shown in table 2. These new data, together with most of the other ages in table 2 (except VI-7 and VIJ-451), suggest a late Eocene age for the Virgin Gorda batholith (*sensu lato*) according to the time scale of Harland and others (1989), and is consistent with stratigraphic and structural control of the age of this batholith. The young hornblende age (24.3 Ma) for The Narrows pluton reported by Kesler and Sutter (1979) is the most puzzling anomaly. Their sample came from the north shore of Mary Point about midway between Fungi Passage and Anna Point (Stephen E. Kesler, written

Table 2. Conventional K-Ar ages and three $^{40}Ar/^{39}Ar$ ages from the Virgin Gorda batholith and The Narrows pluton.

SAMPLE NUMBER	ROCK AND UNIT	LOCATION	MINERAL	AGE (Ma)	REFERENCE
V-G-1	Granodiorite, Virgin Gorda batholith	Southern Virgin Gorda	Hornblende	34.2±1.6	Cox and others (1977)
V-G-1	Granodiorite, Virgin Gorda batholith	Southern Virgin Gorda	Biotite	36.4±0.9	Cox and others (1977)
VI-8	Granodiorite, Copper Mine Point pluton, Virgin Gorda batholith	Southern Virgin Gorda	Biotite	32.7±0.4	Kesler and Sutter (1979)
VI-7	Quartz diorite, The Narrows pluton	Mary Point, St. John	Hornblende	24.3±0.3	Kesler and Sutter (1979)
VI 29	Diorite, The Narrows pluton	Fort Recovery, Tortola	Whole rock	42.80±2.14	Vila and others (1986)
TTL 459	Virgin Gorda batholith	Beef Island	Whole rock	38.85±1.94	Vila and others (1986)
VIJ 453	Granite, Virgin Gorda batholith	The Baths, Virgin Gorda	Whole rock	35.37±1.77	Vila and others (1986)
VIJ 451	Gabbro, Virgin Gorda batholith	Near Virgin Peak, Virgin Gorda	Whole rock	60.36±3.02	Vila and others (1986)
VI-85-193	Tonalite (Tt), The Narrows pluton	Please horizontal control marker, Eastern St. John quadrangle	Hornblende, plateau age	38.81±0.14	This report[1]
VI-85-218	Quartz gabbro (Tt), The Narrows pluton	Northwestern shore, Mary Point, Western St. John quadrangle	Hornblende, plateau age	39.29±0.22	This report[2]
VI-85-222	Tonalite (Tt), The Narrows pluton	Northeast corner, Mary Point, Western St. John quadrangle	Hornblende, plateau age	38.67±0.22	This report[2]

[1]Michael J. Kunk, U.S. Geological Survey, written commun., March 1997.
[2]Michael J. Kunk, U.S. Geological Survey, written commun., August 1998.

commun., April 1997). That location is certainly within the body that I map as The Narrows pluton. Pindell and Barrett (1990), presumably referring to this 24.3 Ma age, suggested that Oligocene magmatism in the Virgin Islands might be related to subduction beneath the Lesser Antilles arc rather than beneath the Greater Antilles arc. The problem of the 24.3 Ma age is unresolved.

HORNBLENDE LAMPROPHYRE

Dark, aphanitic dikes characterized by abundant large hornblende phenocrysts (up to 3 by 1 cm) are scattered across both St. Thomas and St. John. They typically contain smaller plagioclase phenocrysts and disseminated magnetite; some contain centimeter-sized clinopyroxene phenocrysts. Some of these dikes have columnar joints. They intrude all stratified units, but have not been observed to cut tonalite (Tt) on St. John. Many cut diabase and gabbro dikes (Td) but a few of the coarsely hornblende-phyric dikes are cut by Td dikes. It is not clear that the coarsely hornblende-phyric dikes represent an independent intrusive event. In places, coarsely hornblende-phyric dikes grade texturally into diabase. Donnelly (1966) recognized the hornblende-phyric dikes and called them lamprophyres, but did not map them except at Haypiece Hill, St. Thomas. These distinctive rocks are here mapped separately as hornblende lamprophyres (Tl). One such dike thick enough to show on the map cuts gabbro of the Careen Hill Intrusive Suite south of Devers Bay. This dike has chilled margins, contains clinopyroxene phenocrysts as well as hornblende up to 3 by 1.2 cm, plagioclase up to 3 mm long, and zones of epidote alteration. Magnetite constitutes about 15 percent of the

Figure 22. Vertical dike 15 to 20 cm thick trending 275° of explosion breccia (Te) intruding hyaloclastite of the Water Island Formation, east side of the middle of the peninsula of Dittlif Point. Dime for scale.

groundmass. The hornblende lamprophyre of Devers Bay is cut by a diabase dike of unknown age, but indistinguishable from those of unit Td.

EXPLOSION BRECCIA

A mafic dike (Te), 15 to 20 cm thick, that contains 60 percent or more xenoliths of keratophyre, greenstone, gabbro, and tonalite intrudes hyaloclastite of the Water Island Formation on the east side of the middle of the peninsula of Dittlif Point (fig. 22). No other occurrence of this unit is known and it is shown only on the inset map of dike distribution and attitude on plate 1. The dike can be traced for about 20 m across the outcrop and cuts a diabase dike that is interpreted to be unit Td, but could be gabbro (Kcm) of the Careen Hill Intrusive Suite.

RED HOOK TONALITE PORPHYRY (HERE NAMED)

The Red Hook Tonalite Porphyry (Tr) consists of dikes and small hypabyssal intrusions of yellowish-gray (5*Y* 7/2), pinkish-gray (5*Y*R 8/1), and grayish-yellow-green (5*GY* 6/2) porphyritic tonalite characterized by large, bipyramidal quartz and barrel-shaped biotite phenocrysts. The groundmass is aphanitic to fine grained and locally spherulitic. Apatite crystals typically are prominent and may be as large as 1 by 0.3 mm. Phenocrysts, in places as abundant as 45 percent, consist of quartz, plagioclase, biotite, and less commonly hornblende. Quartz and plagioclase are commonly in growth aggregates, either singly or together. Plagioclase phenocrysts are complexly zoned with many reversals. Bipyramidal and embayed quartz phenocrysts, commonly 1 cm to as much as 3 cm across, and euhedral, barrel-shaped biotite phenocrysts are distinguishing features of these rocks. Vermiculite is typically a pseudomorph of the biotite. Some coarsely porphyritic keratophyre (Kcc) of the Careen Hill Intrusive Suite resembles the Red Hook (see previous discussion about unit Kcc). The unit takes its name from Red Hook, Eastern St. Thomas quadrangle, where several tonalite porphyry dikes intrude hydrothermally altered keratophyres of the Water Island Formation. At Red Hook, the tonalite porphyry dikes are not affected by the alteration. The Red Hook Tonalite Porphyry intrudes stratified rocks as young as the Mandal Member of the Tutu (on Grass Cay, Eastern St. Thomas quadrangle). On the Capella Islands, Eastern St. Thomas quadrangle, the Red Hook intrudes tonalite that may or may not be biotite-hornblende tonalite (Tt). On St. John, three small bodies of the Red Hook are interpreted to be intruded along the Great St. James fault. A small body of Red Hook crops out just west of the catchment basin above Caneel Bay Plantation, but the large dike of quartz andesite porphyry (Red Hook of this report) mapped by Donnelly (1966) at Caneel Bay could not be located. The Red Hook is assigned a Tertiary age because it intrudes the Late Cretaceous Tutu Formation and may be the youngest bedrock unit on St. John.

STRUCTURE

The rock units on St. John and adjacent cays form a north- or northeast-dipping homoclinal sequence plicated by folds of various degrees of intensity whose axes generally trend roughly parallel to the strike of local segments of the homocline. The structure is complicated by younger long-wavelength, low-amplitude cross folds and faults. The assembly of the structural elements of St. John into a coherent package, indeed even identifying what those elements are, draws heavily on evidence developed on St. Thomas and, to a certain extent, on the British Virgin Islands (Helsley, 1960, 1971). Some of the features mentioned in this discussion are shown on Donnelly's (1966) geologic map or on the generalized geologic maps of St. Thomas (Rankin, 1984) and the northern U.S. Virgin Islands (Rankin, 1999).

FOLDS

Numerous observations of topping directions confirm that the units young to the north or northeast. Deformation increases in intensity northward across St. John. Moderate dips are typical in the southern part of the island; steep dips are common in the northern part. A few outcrop- or map-scale open folds with generally east-west axes, mostly in the

Louisenhoj Formation, were observed or deduced from reversals of bedding attitudes. Most fold axes plunge gently east or west; a few steep plunges were observed. No consistent direction of tectonic transport was determined. The folds are cut by an axial-plane cleavage that typically dips more steeply (most commonly to the north) than the bedding and increases in intensity to the north. Horizontal beds cut by vertical cleavage crop out in the western part of the head of Hawksnest Bay. Graded beds and channels indicate that the beds are upright. Bedding attitudes nearby indicate that the bedding-cleavage intersection in the beachside outcrop is parallel to the axial trace of a syncline that strikes 280°. At places along the north shore from Caneel Bay to Maho Bay, and as far south as just northwest of elevation marked 662 ft on Center Line Road south of Susannaberg, clasts (pumice lumps at the Susannaberg locality) in the Louisenhoj conglomerates are flattened in the plane of cleavage. In a few of those outcrops, the clasts are elongated downdip. In a seacliff outcrop on the east side of Hawksnest Point, boulder conglomerate of the Louisenhoj dips north 60° and is cut by vertical cleavage. Boulders, several as large as 1.5 m across, are aligned in the cleavage. Penetrative cleavage passes through boulders as large as 2 m in the Louisenhoj on the west side of Cinnamon Bay. Boulders flattened in and elongated down the dip of the vertical cleavage may also be seen in steeply north dipping conglomerate beds in coastal outcrops on America Point. Pillows and pillow fragments are flattened and elongated downdip in coplanar, steeply southwest dipping cleavage and layering in metabasalt of the Water Island Formation near the Please horizontal control marker.

Mesoscopic folds, interpreted to be of the same generation as the open folds described above, become tighter to the north. Minor folds in the Outer Brass Limestone and Tutu Formation are tight to isoclinal with axial-plane cleavage that generally dips steeply north and is either parallel to or dips more steeply than bedding, except in the noses of folds. The few observations made suggest a shear sense in which the north side moved up. The geometry of boudins of sandy beds within limy beds of the Mandal Member on the south side of Whistling Cay and of the Outer Brass Limestone on Outer Brass Island also indicate a shear sense of north side up.

The same progressive tightening of folds and the development of axial-plane cleavage is observed northeastward across St. Thomas from Charlotte Amalie to Mandal and Coki Points. The intensity of deformation on St. Thomas increases markedly near the base of the Outer Brass Limestone. At Mandal on Route 42 at the western edge of the Eastern St. Thomas quadrangle, a mylonite forms the base of the Outer Brass. The more intense deformation may extend half a kilometer or so southwest into the Louisenhoj Formation, but outcrops are sparse.

The rocks on St. John and adjacent cays are interpreted to be on the south limb of an east-west syncline as first proposed by Cleve (1882). The axis of the syncline passes between St. Thomas and Hans Lollik Island, probably through The Narrows, and may continue through the Sir Francis Drake Channel. I map the rocks (mostly volcaniclastic conglomerate) on Hans Lollik Island, Little Hans Lollik Island, and Pelican Cay (Central St. Thomas quadrangle) as the Louisenhoj Formation. Donnelly (1966) interpreted these strata to be a continuation of the north-dipping homoclinal sequence and defined them as his youngest stratigraphic unit, the Hans Lollik Formation (table 1). Helsley (1960) included the Hans Lollik as a member in the Tortola Formation and reported middle Eocene fossils in it at an unspecified locality on Jost Van Dyke Island, some 7 km north of Mary Point. The Hans Lollik Formation is not used here as a stratigraphic unit. The conglomerates on Hans Lollik Island are broken up by the intrusion of abundant diabase dikes, and, in most places, bedding is obscure. At the southern end of Hans Lollik Island, however, beds dip 55° to 75° S. and in one outcrop, graded and channeled beds top to the south. Elsewhere, the north limb of the syncline is in the British Virgin Islands. Helsley (1960, 1971) showed that bedding in the southern part of Tortola generally dips steeply to moderately (as gently as 40°) south. He interpreted the beds to be overturned but gave no evidence for this. The only mention of penetrative cleavage in the British Virgin Islands by Helsley (1960) is a statement that schistosity is well developed in metamorphic rocks and is always parallel to bedding. No fold axes are shown on his map. Bedding on Jost Van Dyke Island and in northern Tortola generally dips steeply to moderately north. The internal stratigraphy of the Tortola Formation is poorly constrained because of the lack of throughgoing marker beds or reported topping direction indicators. The bedding attitudes on Tortola indicate a major east-west-trending anticline. The major syncline south of Hans Lollik Island and the major anticline through Tortola are here interpreted to be of the same generation as the minor folds with generally east-west axes on St. John.

The intensity of deformation decreases north of St. Thomas. Conglomerates interpreted to be in the Louisenhoj on Hans Lollik and Little Hans Lollik Islands are deformed in open folds with roughly east-west-trending axes. Dips on Guana Island north of Tortola are mostly moderate to the north, also suggesting a decrease in the intensity of deformation with either time or place.

The east-west fold axes and associated axial-plane cleavage may represent the initiation of the collision between the Caribbean plate and the North American plate in the time interval between the end of the deposition of the Mandal Member (Santonian, about 83 Ma) and the intrusion of The Narrows pluton (about 39 Ma). Further studies of the mafic dikes in the northern U.S. Virgin Islands as well as structures in the British Virgin Islands may help to constrain the time of the initial collision. At least some of the dikes that intrude the Mandal Member were intruded before north-south compression. Other dikes, thought to be related to these, cut clasts in conglomerates of the Louisenhoj and Tutu Formations; those dikes did not intrude unconsolidated sediments. Finally, in Puerto Rico, where penetrative cleavage has not been reported, similar dikes cut Paleocene strata and are overlain by nonconformably Oligocene coastal plain strata. The Puerto Rico Trench is the present boundary between the Caribbean and North American plates in the vicinity of the Virgin Islands. Rocks of the North American plate on the north wall of the Puerto Rico Trench are basalts and serpentinite geochemically similar to oceanic tholeiites (MORB) and ultramafic rocks (Perfit and others, 1980). In the interval between 84 and 39 Ma, however, the Caribbean plate was relatively farther west, and rocks of the Virgin Islands may have been in collision with the crust of the Bahama platform. The available structural information indicates a south vergence; most tight folds and the asymmetry of boudins indicate a north-side-up shear sense and most cleavage dips north. These observations are most compatible with a south-facing arc, following the definition of Pindell and Barrett (1990), whereby a south-facing arc overlies a north-dipping subduction zone. On the other hand, by the Late Cretaceous, the Greater Antilles arc in Hispaniola was north facing (Lewis and others, 1990; Pindell and Barrett, 1990). There, Late Cretaceous to Eocene subduction complexes were thrust over the shelf carbonates of the Bahama bank in the early Paleogene. Given the regional setting, the best guess as to the time of development of penetrative cleavage in the northern Virgin Islands, also interpreted to be the time of collision with the North American plate, is Eocene and prior to intrusion of The Narrows pluton at 39 Ma.

The structures related to the north-south compression possibly are of more than one generation. Although most cleavage on St. John dips north or is vertical, about 25 percent of the recorded cleavages dip to the south. Float blocks of marble and calc-silicate rocks along the shore of Leinster Bay, from below the Annaberg ruins to Annaberg Point, display tight to isoclinal folds with a poorly developed axial-plane cleavage. In some float blocks, the axial surfaces of the isoclines are folded. No folded axial surfaces have been observed in outcrop. Finally, on the east side of Mandal Point, Eastern St. Thomas quadrangle, graded bedding and refracted cleavage show that beds of the Mandal Member of the Tutu Formation that dip 65° S. are overturned (Rankin, 1984, fig. 6). Cleavage in the slaty rocks dips 80° S. Either these outcrops are on limbs of downward-facing folds or the overturning of the beds is not related to the cleavage. The overturning may be related to large-scale slumping, but no other evidence for slumping on that scale was found; the next outcrops to the northeast across strike are several kilometers away across open water and in the British Virgin Islands.

Structures resulting from the north-south compression are warped by long-wavelength, low-amplitude folds whose axes plunge gently north. These folds are most easily seen by the attitudes of bedding in central and western St. Thomas as shown by Donnelly (1966) and Rankin (1984) and by the broad arc of the Tutu Formation from Picara Point on St. Thomas to Mary Point on St. John. The wavelength of these folds ranges from a few to many kilometers. Bedding attitudes in the Water Island and Louisenhoj Formations show that a broad, north-plunging syncline-anticline pair disrupted by later faulting occupies most of St. John. That conclusion reflects my observations that stratigraphic layering (bedding, pillow layering, and flow layering) from Great and Little Lameshur Bays across Bordeaux Mountain to the East End dips northeastward, roughly at right angles to the layering shown by Donnelly (1966) (see discussion of the Water Island Formation in this report). The curvature, concave to the north, of the Sir Francis Drake Passage northeast of St. John may reflect a broad, north-plunging syncline east of St. John. Cleavage related to the north-south compression also is warped across the north-south axes, although in southern St. John, where cleavage is marginally discernible, relations are poorly understood. The age of the north-south folding relative to the age of The Narrows pluton is not known. No north-plunging fold axes have been observed in outcrop nor is there a north-south-striking cleavage. There are, however, numerous north- to north-northeast-striking, nearly vertical, brittle faults of unknown but probably minor displacement. Numerous anastomosing limonite-calcite veins are commonly associated with and subparallel to the faults. In places, north-trending limonite zones are present where there is no apparent fault. Most of these minor brittle faults were not recorded in the field, but may be readily observed on the chain of islands north of Pillsbury Sound.

FAULTS

The two generations of folds are cut by northeast-striking, nearly vertical, brittle faults. Some, such as the ones shown in the southeastern part of St. John, are defined by the distribution of rock units and the fault pattern established farther west. The most convincing evidence for the northeast-striking fault set comes from the offset of the Water Island-Louisenhoj stratigraphic contact as mapped along the highly irregular southwestern coast of St. John. One of the fault zones is exposed in a long, quarry-like exposure of weathered Louisenhoj Formation on the northwest side of Guinea Gut, from which the fault takes its name, about 200 m upstream from Highway 104 (fig. 23). The exposure is parallel to the fault zone, which is at least 2 m thick. The fault zone consists of punky-weathering limonite-stained breccia containing open cavities parallel to the fault zone that are partly filled with calcite. Northeast-trending limonite zones up to 10 cm thick in the country rock parallel the fault zone on the southeast side of the gut. The sense of movement

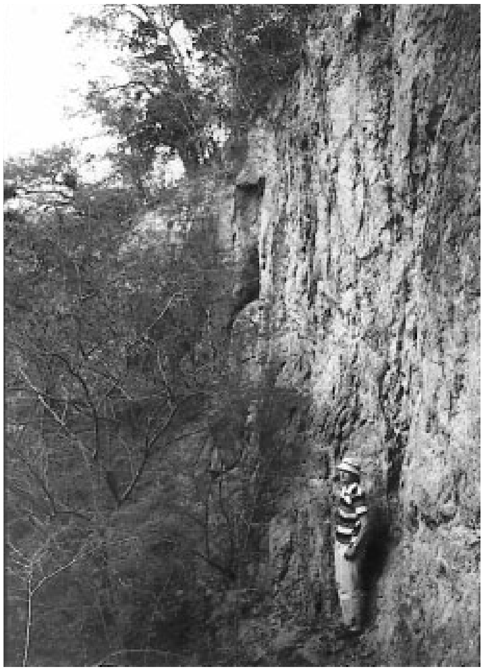


Figure 23. Exposed surface of the northeast-striking, near-vertical, left-lateral, strike-slip Guinea Gut fault in the Louisenhoj Formation, looking southwest on northwest side of lower end of Guinea Gut, where dip symbol is plotted on map (plate 1).

could not be determined. As noted earlier, however, the Water Island-Louisenhoj contact has 200 m of sinistral offset across Great Cruz Bay. Southeast of Great Cruz Bay, the Water Island-Louisenhoj contact is progressively offset to the northeast another 1.5 km, and a series of faults is shown on the geologic map to account for this.

Geologic mapping of central St. John for this report produced a significantly different distribution of units from that shown by Donnelly (1966). The Water Island-Louisenhoj stratigraphic contact reappears south of L'Esperance where it dips northeast parallel to the dip of the contact along the southwestern coast, and it reappears again near Ajax Peak where it dips northwest. Between the southwestern coast and Ajax Peak, three additional contacts between the Water Island and Louisenhoj are interpreted to be high-angle faults with very little deflection of strike across steep topography. The faults southwest of Battery Gut and northeast of Camelberg Peak are upthrown on the northeast. The third fault, southwest of Ajax Peak, is upthrown on the southwest. An attempt to integrate these elements must also accommodate observations from southeastern St. Thomas and adjacent cays where the Water Island-Louisenhoj stratigraphic contact also is offset by a series of northeast-striking, nearly vertical faults. These faults may be dip-slip faults creating a series of graben and horsts as portrayed by Donnelly (1966), or most of them could be strike-slip faults extending the pattern deduced for southwestern St. John. In the Eastern St. Thomas quadrangle, the southeasternmost exposure of the stratigraphic contact is on Great St. James Island where it dips northeast and is cut off on the southeast by a northeast-trending fault. My interpretation is that, between Great St. James Island and Great Cruz Bay, the Water Island-Louisenhoj contact is offset 4 km along a sinistral fault, here called the Great St. James fault after Great St. James Cut (the open water between Great and Little St. James Islands) on the southeast side of Great St. James Island. The Great St. James fault projects into Turner Bay and Enighed on St. John. No fault has been recognized there, yet the Great St. James fault must be a major fault. Farther northeast, this fault projection merges with the fault that I had earlier mapped as a continuation of the Guinea Gut fault. The axis of an open S-style fold that plunges 35° NE in volcanic wacke of the Water Island Formation south of Turner Bay suggests that there was also a dip-slip component to the movement along the Great St. James fault.

Movement along the Great St. James fault appears to decrease toward the northeast. The Outer Brass Limestone is offset by only about 1 km, and Helsley (1960, 1971) shows no fault on Tortola along the projection of the Great St. James. This complex region of faulting in central St. John is essentially bounded on the southeast by the Brown Bay fault, which is named for Brown Bay on the north coast of St. John. The Brown Bay fault is interpreted to be a significant sinistral strike-slip fault that terminates the outcrop belt of the Louisenhoj on St. John. The Brown Bay fault projects northeastward to a northeast-trending stretch of the coast of Tortola that marks the eastern end of the outcrop belt of the Tutu Formation as mapped by Helsley (1960). Movement along the Brown Bay fault appears to decrease southwestward to less than 100 m at Fish Bay on the south coast of St. John. I suggest that this zone, from Great St. James Island through central St. John, represents regional sinistral movement across a block that is bounded by right-stepping, en-echelon, sinistral strike-slip faults, as illustrated by Aydin and Nur (1982, fig. 1) and Ramsay (1987, fig. 23.39). The sinistral movement along each bounding fault decreases along the zone of overlap to no movement beyond the zone of overlap. Rocks within the zone of overlap are uplifted under compression. The northwest-trending faults near Battery Gut and Camelberg Peak, within the zone of overlap, are interpreted to be high angle reverse faults. As shown on cross section *A-A´*, the Water Island-Louisenhoj contact is brought up on the order of 2,700 m along the fault near Battery Gut. A brittle fault within the Water Island Formation is exposed along Center Line Road southwest of Ajax Peak. The fault dips 80° NE., and kinematic indicators suggest downward movement of its northeast side. This fault is interpreted to be the northeastern bounding fault of the zone of overlap between the Great St. James and Brown Bay faults. This fault is shown on the geologic map and on cross section *A-A´* as a high-angle normal fault. An alternative interpretation is that the overall dip of the fault is steeply to the southwest and that it moves the block of overlap up and to the northeast. The change in attitude of the Water Island-Louisenhoj contact between L'Esperance and Ajax Peak is attributed to a broad, north-plunging syncline that formed during the episode of mild east-west compression (discussed earlier) that occurred prior to the strike-slip faulting.

The sinistral strike-slip faulting is the youngest major structural episode recognized on St. John. Two minor northwest-trending faults near Ajax Peak offset the Water Island-Louisenhoj stratigraphic contact. The westernmost fault probably also offsets the Great St. James fault and appears to offset the intrusive contact of The Narrows pluton on Mary Point. These youngest northwest-trending faults are interpreted to be dextral strike-slip faults and probably represent some minor adjustment within the Puerto Rico-Virgin Islands microplate to stress at the northeastern corner of the Caribbean plate.

The age of the late brittle faulting, including the major sinistral strike-slip faulting, is interpreted to be younger than the intrusion of The Narrows pluton. The Red Hook Tonalite Porphyry appears to be intruded along the strike-slip faults. If these interpretations are correct, then the sinistral faulting is younger than The Narrows pluton and older than the Red Hook.

Sinistral strike-slip faulting is widely documented in Puerto Rico, particularly along the North and South fault zones that have been interpreted to divide the island into three structural blocks (Glover, 1971; Mattson and others, 1990). Faults in both zones cut Eocene strata; it is not known how much earlier than Eocene the sinistral faulting may have begun. Both fault zones are covered unconformably by middle Oligocene and younger beds at their northern extremities, but near its southern margin, the South fault zone displaces Oligocene and Miocene rocks (Mattson and others, 1990). Thus, a major episode of sinistral strike-slip faulting took place in Puerto Rico in late Eocene to early Oligocene time, which is compatible with a post-39 Ma (age of The Narrows pluton) timing for the sinistral faulting in St. John. Sinistral strike-slip motion of the northern border of the Caribbean plate relative to the North American plate probably began with the initiation of the Cayman Trough spreading center. Pindell and Barrett (1990) conclude that there has been 1,050 to 1,100 km of offset along the Cayman Trough since the Eocene. Other estimates for the time of initiation of the spreading center and the amount of offset include 1,400 km since 38 Ma (Sykes and others, 1982), 1,100 km since 30±5 Ma (Wadge and Burke, 1983), and a time of initiation of 45 to 50 Ma (Rosencrantz and others, 1988). I suggest that the sinistral strike-slip faulting on Puerto Rico, St. Thomas, and St. John represents strike-slip accommodation near the northern border of the Caribbean plate in the early stages of the Cayman Trough spreading and the transition from an east-west-trending arc to an east-facing arc. Perhaps the gentle folding on north-south axes on St. Thomas and St. John was caused by compression at the earliest stage of Cayman Trough spreading prior to the strike-slip faulting.

Finally, the strike-slip faults in St. John strike northeast to east-northeast, whereas those in Puerto Rico strike east-west to west-northwest. The difference between the average orientation of these Tertiary sinistral faults is about 45°. If the two sets of faults represent conjugate shears, a possible cause of the difference in orientation of these two shear sets is the difference in location of the two islands relative to the curvature of the arc and the vector of plate motion at the time of shearing.

GEOLOGIC HISTORY

The geologic history of St. John began with the eruption of submarine keratophyres and amygdaloidal pillow basalts of the Water Island Formation (at least 2 km thick) in the late Early Cretaceous, probably onto oceanic plateau crust. At that time, the Caribbean plate was in the western Pacific. The submarine volcanism was accompanied by the deposition of radiolarian cherts and by the intrusion of small hypabyssal plutons and abundant dikes of the Careen Hill Intrusive Suite, again mostly keratophyres but including mafic rocks. The presence of sheeted dikes indicates that the igneous activity was in an extensional environment. Presumably, the high Na_2O/K_2O ratio of the high-silica rocks (keratophyres) is secondary; the abundance of the keratophyres in an oceanic environment is problematic. Perhaps the rocks represent a back-arc basin environment, but the high silica content is still a problem. Local deuteric hydrothermal alteration is probably responsible for the metal anomalies reported by Alminas and others (1994) in rocks and outcrop areas of the Lameshur Volcanic-Intrusive Complex.

The igneous compositions changed through a relatively brief interval to more island arc-like clinopyroxene andesite and basalt that are preserved mostly as clasts in the volcaniclastic Louisenhoj Formation (as thick as 1.5 km) which conformably overlies the Water Island. Primary volcanic units are sparingly present and on Ramgoat Cay are pillowed. The variation of clast lithology with location suggests that there were local sources, such as lavas from different vents, for the clasts. No specific sources for the clasts have been identified, but the sources cannot be far away because of the prevalence of boulder-size clasts throughout the formation. The coarser units probably originated as debris flows on relatively steep slopes. Final emplacement was in a submarine environment as indicated by the common grading of even the coarsest material.[4] Radiolarian chert is present, but rare, on St. Thomas. Local submarine pyroclastic flows are indicated by the local abundance of pumiceous clasts. Calcite cement becomes increasingly common in the upper part of the formation and rare fossiliferous limestone beds are present.

A brief interval of volcanic quiescence followed in the late Turonian to late Santonian with the deposition of the Outer Brass Limestone, which includes clean calcite limestone (now marble), calc-silicate rocks, and conglomerate with calcareous cement and clasts of marble and (or) andesite. No structural discordance is seen either at the base or top of the Outer Brass.

Volcanism then resumed as indicated by the deposition of volcaniclastic turbidites and rare pyroxene basalt to andesite flows in the overlying Tutu Formation in Late Cretaceous time. The volcanic source for the Tutu was farther away than for the Louisenhoj because boulder conglomerates in the Tutu are sparse and silt- to sand-size material dominates. Sediments become finer upward from the basal Picara Member to the overlying Mandal Member, suggesting increasingly distal sources. Carbonate cement is typical and limestone beds (now marble and calc-silicate rock) and conglomerate are prominent. Soft sediment deformation throughout the Tutu, including some striking slump folds in the Mandal Member, suggests deposition on an unstable slope, perhaps a trench wall leading to an accretionary wedge.

Volcanism that occurred during the deposition of the Louisenhoj and Tutu is interpreted to be island-arc volcanism that was part of the Greater Antilles arc volcanism. No direct evidence for the polarity of this arc is known on St. John. The Tutu Formation is the youngest stratified unit on St. John. Volcanism continued in the British Virgin Islands into the middle Eocene. Volcanism on St. John was followed by a variety of intrusive activities that began with the intrusion of abundant diabase dikes. The dikes probably are part of the same suite that continues east to Puerto Rico where they are dated stratigraphically as post-Paleocene and pre-Oligocene. The age of the dike swarm on St. John (nearly vertical dikes that trend mostly northeast and northwest) relative to the middle Eocene volcanism on Tortola is not known.

North-south compression followed the major pulse of dike intrusion and produced broad folds that originally had east-west axes. The folds are interpreted to be related to the initiation of the collision between the Greater Antilles arc of the Caribbean plate and the Bahama platform of the North American plate. A synclinal axis north of St. Thomas and St. John accounts for the roughly north-dipping homoclinal sequence from the Water Island to Tutu Formations on those islands. The intensity of deformation related to this north-south compression increases northward across St. John. Tight folds have a penetrative axial-plane cleavage that mostly dips steeply north or is vertical. The asymmetry of both the tight folds and boudins mostly indicates a north-side-up sense of shear.

Intrusion of the dominantly tonalitic The Narrows pluton and Virgin Gorda batholith followed the episode of north-south compression, produced a contact metamorphic aureole a couple of kilometers wide, partly annealed the axial-plane cleavage within the aureole, and probably produced the metal anomalies in the Louisenhoj and younger formations reported by Alminas and others (1994). The Narrows pluton and the Virgin Gorda batholith are part of the Greater Antilles arc magmatism. The age of intrusion of The Narrows plutons is about 39 Ma (late Eocene) based on an $^{40}Ar/^{39}Ar$ plateau age on hornblende.

East-west compression produced long, broad, open folds of bedding and the east-west fold axes on a new set of axes that plunge gently north. Widely spaced, nearly vertical, north- to northeast-striking, brittle fractures associated with anastomosing calcite-limonite veins may be related to these late folds. The age relationship of these late folds to the tonalitic plutons is not known. The broad north-plunging late folds may be related to the relative eastward transport of the Caribbean plate in response to the beginning of spreading at the Cayman Trough. If so, the north-south folds should be younger than The Narrows pluton.

The last major tectonic event recorded on St. John is a series of post-39 Ma sinistral strike-slip faults interpreted to be related to the initiation of spreading at the Cayman Trough center and the sinistral strike-slip accommodation near the northern border of the Caribbean plate. A structural block that extends from Great St. James Island, Eastern St. Thomas quadrangle, northeastward across central St. John is bounded by northeast-trending, right-stepping, en

---

[4] On a field visit in March 2001, Richard S. Fiske (Smithsonian Institution) noted the similarity of the Louisenhoj Formation graded sequences to those of the Pliocene Shirahama Group of the Izu Peninsula, Japan (Fiske, 1986). There, larger lithic clasts in proximal deposits, like those in the Louisenhoj, are better rounded than associated finer ones and finer ash matrix is sparse. Fiske suggested that major parts of both units might have been generated by shallow submarine explosive eruptions such as were observed during the 1952–1953 eruption of Myojinsho, 420 km south of Tokyo, Japan. Myojinsho exploded 1000 times during that eruption (Fiske and others, 1998). The products of those explosions are below present-day sea level and have never been observed, but are likely to consist of thick sequences of graded beds on the volcano's submarine flanks. The many breccias and conglomerates of the Louisenhoj Formation are interpreted to have been produced by shallow submarine explosive eruptions from numerous centers. The volcanic clasts in the Louisenhoj therefore are interpreted to be primary (or only slightly) reworked volcanic products.

echelon, sinistral strike-slip faults. The zone of overlap between the bounding faults is uplifted on at least two northwest-trending, high-angle reverse faults that dip northeast. The structure is thus the inverse of a pull-apart basin (that is, a rhomb horst, a term introduced by Aydin and Nur, 1982). The stratigraphic contact between the Water Island and Louisenhoj Formations is sinistrally offset 5.7 km across this block. The Water Island-Louisenhoj contact is brought up about 2.7 km on one of the high-angle reverse faults within the block in the zone of overlap. The amount of uplift on the second high-angle fault cannot be determined.

Unlike other parts of the Greater Antilles, evidence for recent tectonic movement has not been observed. I have seen no uplifted beaches, no uplifted wave-cut platforms, and no fault scarps. Hypocenters of shallow earthquakes (depth <50 km) are mostly associated with the Puerto Rico Trench and the north wall of the Virgin Islands Basin (Frankel and others, 1980). Sea level appears to have been roughly at the same level since the Pleistocene. Most bays are blocked by bay-mouth bars consisting of modern reef debris that entraps a salt pond or playa landward. Much of the cliffy shoreline of Congo Cay is undercut by a wave-cut notch at sea level (fig. 20).

Finally, two geomorphic features are worthy of mention. First, on the north side of Congo Cay toward its eastern end, a relict sinkhole is exposed at the top of a sea cliff. The sinkhole formed after the beds on Congo Cay had been deformed into their nearly vertical orientation and erosion had reduced the region to roughly the present topography. The lower part of the sinkhole is filled with disoriented blocks of marble and hornfels in reddish-orange caliche showing horizontal stratification. The rest of the country rock (marble) in which the sinkhole formed has been eroded away. Second, isolated pillars and blocks of gossan are present on the wooded summit of Bordeaux Mountain. The gossan presumably formed from weathering of hydrothermally altered Water Island Formation more recently than the time of the deuteric alteration.

REFERENCES CITED

Alminas, H.V., Foord, E.E., and Tucker, R.E., 1994, Geochemistry, mineralogy, and geochronology of the U.S. Virgin Islands: U.S. Geological Survey Bulletin 2057, 36 p.

Avé Lallemant, H.G., 1976, Structure of the Canyon Mountain (Oregon) ophiolite complex and its implication for sea-floor spreading: Geological Society of America Special Paper 173, 49 p.

Aydin, Atila, and Nur, Amos, 1982, Evolution of pull-apart basins and their scale independence: Tectonics, v. 1, p. 91–105.

Barker, F., 1979, Trondhjemite: Definition, environment and hypotheses of origin, *in* Barker, F., ed., Trondhjemites, dacites, and related rocks; Developments in petrology 6: New York, Elsevier, p. 1–12.

Bouysse, P., Baubron, J.C., Richard, M., Maury, R.C., and Andreieff, P., 1985, Evolution de la terminaison nord de l'arc interne des Petites Antilles an Plio-Quaternaire: Bulletin de la Société Géologique de France, sér. 8, t. I, no. 2, p. 181–188.

Burke, Kevin, Fox, P.J., and Sengör, A.M.C., 1978, Buoyant ocean floor and the evolution of the Caribbean: Journal of Geophysical Research, v. 83, no. B8, p. 3949–3954.

CH2M Hill, Inc., 1979, A sediment reduction program: Report to the Department of Conservation and Cultural Affairs, Government of the U.S. Virgin Islands, St. Thomas, U.S. Virgin Islands.

Cleve, P.T., 1882, Outline of the geology of the northeastern West India Islands: Annals of the New York Academy of Science, v. 2, p. 185–192.

Cox, D.P., Marvin, R.F., M'Gonigle, J.W., McIntyre, D.H., and Rogers, C.L., 1977, Potassium-argon geochronology of some metamorphic, igneous, and hydrothermal events in Puerto Rico and the Virgin Islands: U.S. Geological Survey Journal of Research, v. 5, p. 689–703.

Deng, Jishu, and Sykes, L.R., 1995, Determination of Eulerpole for contemporary relative motion of Caribbean and North American plates using slip vectors of interplate earthquakes: Tectonics, v. 14, p. 39–53.

Donnelly, T.W., 1963, Genesis of albite in early orogenic volcanic rocks: American Journal of Science, v. 261, p. 957–972.

———1966, Geology of St. Thomas and St. John, U.S. Virgin Islands, *in* Hess, H.H., ed., Caribbean geological investigations: Geological Society of America Memoir 98, p. 85–176.

———1972, Deep-water, shallow-water, and subaerial island-arc volcanism: Example from the Virgin Islands, *in* Shagam, R., and others, eds., Studies in earth and space sciences: Geological Society of America Memoir 132, p. 401–414.

———1989, Geologic history of the Caribbean and Central American, *in* Bally, A.W., and Palmer, A.R., eds., The geology of North America—An overview: Boulder, Colo., Geological Society of America, The Geology of North America, v. A, p. 299–321.

Donnelly, T.W., Beets, Dirk, Carr, M.J., Jackson, Trevor, Klaver, Gerard, Lewis, John, Maury, Rene, Schellekens, Hans, Smith, A.L., Wadge, Geoffrey, and Westercamp, Denis, 1990, History and tectonic setting of Caribbean magmatism, *in* Dengo, Gabriel, and Case, J.E., eds., The Caribbean region: Boulder, Colo., Geological Society of America, The Geology of North America, v. H, p. 339–374.

Donnelly, T.W., and Rogers, J.J.W., 1978, The distribution of igneous rock suites around the Caribbean: Geologie en Mijubouw, v. 57, p. 151–162.

———1980, Igneous series in island arcs: The northeastern Caribbean compared with worldwide island-arc assemblages: Bulletin Volcanologique, v. 43, p. 347–382.

Donnelly, T.W., Rogers, J.J.W., Pushkar, Paul, and Armstrong, R.E., 1971, Chemical evolution of the igneous rocks of the eastern West Indies: An investigation of thorium, uranium, and potassium distributions, and lead and strontium isotopic ratios, *in* Donnelly, T.W., ed., Caribbean geophysical, tectonic, and petrologic studies: Geological Society of America Memoir 130, p. 181–224.

Draper, Grenville, and Pindell, James, 1995, The Caribbean—Perspectives on a plate's progress [abs.]: Geological Society of America Abstracts with Programs, v. 27, p. A152.

Evans, Amanda, Danihel, J.P., Jolly, W.T., and Lidiak, E.G., 1997, Petrology of the Monte del Estado Peridotite (Bermeja Complex), southwestern Puerto Rico [abs.]: Geological Society of America Abstracts with Programs, v. 29, p. 44.

Fiske, R.S., 1986, Shallow marine volcanic field in the Mio-Pliocene Shirahama Group, Izu Peninsula, Japan [abs.]: Geological Society of America, Abstracts with Programs, v. 18, no. 6, p. 602.

Fiske, R.S., Cashman, K.V., Shibata, A., and Watanabe, K., 1998, Tephra dispersal from Myojinsho, Japan, during its shallow submarine eruption of 1952–1953: Bulletin of Volcanology, v. 59, no. 4, p. 262–275.

Frankel, Arthur, McCann, W.R., and Murphy, A.J., 1980, Observations from a seismic network in the Virgin Islands region: Tectonic structures and earthquake swarms: Journal of Geophysical Research, v. 85, no. B5, p. 2669–2678.

Glover, Lynn, III, 1971, Geology of the Coamo area, Puerto Rico, and its relation to the volcanic arc-trench association: U.S. Geological Survey Professional Paper 636, 102 p.

Goddard, E.N., Trask, P.D., DeFord, R.K., Rove, O.N., Singewald, J.T., Jr., and Overbeck, R.M., 1970, Rock color chart: Boulder, Colo., Geological Society of America.

Griscom, Andrew, and Geddes, W.H., 1966, Island-arc structure interpreted from aeromagnetic data near Puerto Rico and the Virgin Islands: Geological Society of America Bulletin, v. 77, p. 153–162.

Hall, S.A., 1995, Oceanic basement of the Caribbean basins [abs.]: Geological Society of America Abstracts with Programs, v. 27, p. A153.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1989, A geologic time scale 1989: Cambridge, Cambridge University Press, 263 p.

Hekinian, Roger, 1971, Petrological and geochemical studies of spilites and associated rocks from St. John, U.S. Virgin Islands: Geological Society of America Bulletin, v. 82, p. 659–682.

Helsley, C.E., 1960, Geology of the British Virgin Islands: Princeton, N.J., Princeton University, unpublished Ph.D. dissertation, 219 p.

———1971, Summary of the geology of the British Virgin Islands, *in* Mattson, P.H., ed., Transactions of the Fifth Caribbean Geological Conference, St. Thomas, U.S. Virgin Islands, 1968: New York, Queens College Press, p. 69–76.

Kesler, S.E., and Sutter, J.F., 1979, Compositional evolution of intrusive rocks in the eastern Greater Antilles island arc: Geology, v. 7, p. 197–200.

LeMaitre, R.W., ed., 1989, A classification of igneous rocks and glossary of terms: Oxford, Blackwell Scientific Publications, 193 p.

Lewis, J.F., Draper, G., Bowin, C., Bourdon, L., Maurrasse, F., and Nagle, F., 1990, Hispaniola, *in* Dengo, Gabriel, and Case, J.E., eds., The Caribbean region: Boulder, Colo., Geological Society of America, The Geology of North America, v. H, p. 94–112.

Lidiak, E.G., 1965, Petrology of andesitic, spilitic, and keratophyric flow rocks, north-central Puerto Rico: Geological Society of America Bulletin, v. 76, p. 57–88.

Longshore, J.D., 1965, Chemical and mineralogical variations in the Virgin Islands batholith and its associated wall rocks: Houston, Tex., Rice University, unpublished Ph.D. dissertation, 94 p.

Mattson, P.H., 1973, Middle Cretaceous nappe structures in Puerto Rican ophiolites and their relation to the tectonic history of the Greater Antilles: Geological Society of America Bulletin, v. 84, p. 21–39.

Mattson, P.H., Draper, G., and Lewis, J.F., 1990, Puerto Rico and the Virgin Islands, *in* Dengo, Gabriel, and Case, J.E., eds., The Caribbean region: Boulder, Colo., Geological Society of America, The Geology of North America, v. H, p. 112–120.

Mattson, P.H., and Pessagno, E.A., 1979, Jurassic and Early Cretaceous radiolarians in Puerto Rican ophiolite—Tectonic implications: Geology, v. 7, p. 440–444.

Meltzer, A.S., Schoemann, M.L., Dietrich, C., Almy, C.C., and Schellekens, Hans, 1995, Characterization of faulting: Southwest Puerto Rico [abs.]: Geological Society of America Abstracts with Programs, v. 27, p. A227–A228.

Montgomery, Homer, Pessagno, E.A., Jr., and Pindell, J.L., 1994, A 195 Ma terrane in a 165 Ma sea: Pacific origin of the Caribbean plate: GSA Today, v. 4, no. 1, p. 2–6.

Mullen, E.D., 1983, $MnO/TiO_2/P_2O_5$: a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis: Earth and Planetary Sciences Letters, v. 62, p. 53–62.

Pease, M.H., Jr., 1968, Cretaceous and lower Tertiary stratigraphy of the Naranjito and Aguas Buenas quadrangles and adjacent areas: U.S. Geological Survey Bulletin 1253, 57 p.

Perfit, M.R., Heezen, B.C., Rawson, Michael, and Donnelly, T.W., 1980, Chemistry, origin, and tectonic significance of metamorphic rocks from the Puerto Rico Trench: Marine Geology, v. 34, p. 125–156.

Pessagno, E.A., Jr., 1976, Middle Cretaceous planktonic foraminiferal biostratigraphy of the Antillean-Caribbean region and eastern Mexico: Musée d'Histoire Naturelle de Nice, Annales, Tome 4, p. 176–182.

Pindell, J.L., 1990, Geological arguments suggesting a Pacific origin for the Caribbean plate, *in* Larue, D.K., and Draper, Grenville, eds., Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S. V.I.: Miami, Fla., Miami Geological Society, p. 1–4.

Pindell, J.L., and Barrett, S.F., 1990, Geological evolution of the Caribbean region; A plate-tectonic perspective, *in* Dengo, Gabriel, and Case, J.E., eds., The Caribbean region: Boulder, Colo., Geological Society of America, The Geology of North America, v. H, p. 405–432.

Pindell, J.L., Cande, S.C., Pitman, W.C., III, Rowley, D.B., Dewey, J.F., LaBrecque, John, and Haxby, William, 1988, A plate-kinematic framework for models of Caribbean evolution: Tectonophysics, v. 155, p. 121–138.

Ramsay, J.G., 1987, Folds and fractures, v. 2 *of* Techniques of modern structural geology: New York, Academic Press, p. 309–700.

Rankin, D.W., 1984, Geology of the U.S. Virgin Islands, a progress report, *in* Gori, P.L., and Hays, W.W., eds., A

Workshop on "Earthquake hazards in the Virgin Islands region," April 9–10, 1984, St. Thomas, Virgin Islands: U.S. Geological Survey Open-File Report 84–762, p. 83–96.

———1997, Geologic maps of St. John, U.S. Virgin Islands: U.S. Geological Survey Open-File Report 97–472, 14 p., 1 sheet, scale 1:24,000.

———1999, Geology of the northern U.S. Virgin Islands, *in* Davis, John, Brannon, G.R., and Santiago, Carmen, Soil Survey of the United States Virgin Islands: Washington, D.C., U.S. Department of Agriculture, Natural Resources Conservation Service.

Rogers, C.S., and Teytaud, Robert, 1988, Marine and terrestrial ecosystems of the Virgin Islands National Park and Biosphere Reserve: St. Thomas, U.S. Virgin Islands, National Park Service Biosphere Reserve Report 29, 112 p.

Rosencrantz, Eric, Ross, M.I., and Sclater, J.G., 1988, Age and spreading history of the Cayman Trough as determined from depth, heat flow, and magnetic anomalies: Journal of Geophysical Research, v. 93, no. B3, p. 2141–2157.

Schellekens, J.H., Montgomery, Homer, Joyce, James, and Smith, A.L., 1990, Late Jurassic to Late Cretaceous development of island arc crust in southwestern Puerto Rico, *in* Larue, D.K., and Draper, Grenville, eds., Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S. V.I.: Miami, Fla., Miami Geological Society, p. 268–281.

Speed, R.C., and Larue, D.K., 1991, Extension and transtension in the plate boundary zone of the northeastern Caribbean: Geophysical Research Letters, v. 18, p. 573–576.

Sun, S.S., and McDonough, W.F., 1989, Chemical and isotopic systematics of ocean basalts—Implications for mantle composition and processes, *in* Saunders, A.D., and Norry, M.J., eds., Magmatism in the ocean basins: Geological Society Special Publication 42, p. 313–345.

Sun, S.S., Nesbitt, R.W., and Sharaskin, A.Y., 1979, Chemical characterstics of mid-ocean ridge basalts: Earth and Planetary Science Letters, v. 44, p. 119–138.

Sykes, L.R., McCann, W.R., and Kafka, A.L., 1982, Motion of Caribbean plate during last 7 million years and implications for earlier Cenozoic movements: Journal of Geophysical Research, v. 87, no. B13, p. 10,656–10,676.

Thayer, T.P., Case, J.E., and Stotelmeyer, R.B., 1981, Mineral resources of the Strawberry Mountain Wilderness and adjacent areas, Grant County, Oregon: U.S. Geological Survey Bulletin 1498, 67 p.

Tucker, R.E., 1987, A geochemical study of St. John, U.S. Virgin Islands: Golden Colo., Colorado School of Mines, unpublished Ph.D. dissertation, 404 p.

Vila, Jean-Marie, Andreieff, Patrick, Bellon, Hervé, and Mascle, Alain, 1986, Tectonique de collage le long d'un accident décrochant, ante oligocéne, est-ouest, dans les Iles Vierges septentrionales (Antilles): Comptes Rendus Académie des Sciences, Paris, Tome 302, série II, no. 3, p. 141–144.

Wadge, G., and Burke, K., 1983, Neogene Caribbean plate rotation and associated Central American tectonic evolution: Tectonics, v. 2, p. 633–643.

Young, Keith, 1972, Ammonites from Puerto Rico and St. Thomas, *in* Petzall, Cecily, ed., Memorias de la VI Conferencia Geologica del Caribe, Margarita, Venezuela, July 6–14, 1971: New York, Queens College Press, p. 469.

APPENDIX A

DESCRIPTION OF MAP UNITS

[Dikes 3 m or more in width are shown where space permits. Alphanumeric symbols following color names are taken from the rock color chart of Goddard and others (1970). Minerals are not necessarily listed in order of abundance.]

Qs **Surficial deposits (Quaternary)**—Alluvium, swamp deposits, beach deposits, beachrock (sedimentary rock formed in tidal zone), and artificial fill. Only alluvium is likely to contain material as old as Pleistocene

Tr **Red Hook Tonalite Porphyry (new name) (Tertiary)**—Dikes and small hypabyssal intrusions of yellowish-gray (5*Y* 7/2), pinkish-gray (5*YR* 8/1), and grayish-yellow-green (5*GY* 6/2) porphyritic tonalite characterized by large bipyramidal quartz and barrel-shaped biotite phenocrysts. Groundmass aphanitic to fine grained and locally spherulitic. Phenocrysts, as abundant as 45 percent, of quartz, plagioclase, biotite, less commonly hornblende, and prominent apatite. Quartz and plagioclase commonly in growth aggregates, either singly or together. Bipyramidal and embayed quartz phenocrysts commonly 1 cm to as much as 3 cm across. Plagioclase phenocrysts complexly zoned with many reversals. Biotite typically completely replaced by vermiculite. Named for prominent dikes at Red Hook, Eastern St. Thomas quadrangle, where dikes are intruded along late brittle faults

Te **Explosion breccia (Tertiary?)**—Mafic dike 15 to 20 cm thick contains 60 percent or more xenoliths of keratophyre, greenstone, gabbro, and tonalite. Observed only on east side of Dittlif Point where it can be traced for about 20 m across outcrop of Water Island Formation. Cuts diabase dike that is interpreted to be unit Td but could be unit Kcm. Shown only on inset map showing dike distribution and attitude on plate 1

Tl **Hornblende lamprophyre (Tertiary)**—Dark, magnetite-bearing, aphanitic dikes with prominent hornblende phenocrysts as large as 3 cm by 1 cm and, in places, clinopyroxene phenocrysts as large as 1 cm. Typically smaller plagioclase phenocrysts are present. Most Tl dikes are younger than dikes of unit Td, but some Td mafic dikes cut Tl

Tt **Biotite-hornblende tonalite (Tertiary, late Eocene)**—Very light gray to medium-light-gray, medium-grained, nonfoliated biotite-hornblende tonalite and minor gabbro, diorite, granite, and pegmatite. Tonalite composed of interstitial quartz (10 to 15 percent); subhedral, strongly and complexly zoned plagioclase; biotite partly altered to chlorite; hornblende; and magnetite. Gabbro composed of plagioclase, hornblende, clinopyroxene, apatite, and pyrite and (or) magnetite. Granite is very light gray, fine to medium grained and contains quartz, orthoclase (about 35 percent), strongly zoned plagioclase, biotite altering to chlorite, zircon, and magnetite. White pegmatite contains quartz, slightly perthitic orthoclase (poikilitic crystals up to 1.5 cm across), reddish isotropic garnet, and minor diopside, sphene, allanite, and calcite. Shows copper stain. Contains many xenoliths of stratified country rock (gray, fine-grained granofels, siliceous hornfels, and calc-silicate) and gabbro (unit Td?); also contains pockets of skarn with massive sulfide and copper stain. Sharp contacts; post-kinematic to tight folding and cleavage in country rock. Produces contact-metamorphic aureole as wide as 2 km

Td **Diabase, gabbro, and diorite (Tertiary)**—Nearly vertical dikes ranging in thickness from a few cm to several tens of meters and complex bodies of multiple dikes, some with internal layering parallel to dike walls. Chilled margins typical; columnar jointing not typical. Color index, grain size, and texture vary; mostly diabase or gabbro with diabase margins. Amygdules present locally. Primary minerals include plagioclase, clinopyroxene, commonly hornblende, magnetite, and (or) pyrite, and, in some rocks, quartz. May be porphyritic with phenocrysts of plagioclase, clinopyroxene, and (or) hornblende. Thicker bodies commonly contain epidosite nodules and disseminated epidote. Secondary, pale, commonly fibrous amphibole, chlorite, and epidote are common. In northern half of St. John, progressively metamorphosed to amphibolite-facies assemblages. Also toward the north, many dikes carry the same penetrative cleavage as the enclosing stratified rocks; some broken into segments aligned parallel to cleavage. Other dikes are post-cleavage. Dikes intrude all stratified units except surficial deposits and are intruded by tonalite (Tt). Probably includes dikes of more than one age. Some may be intrusive equivalents of extrusive rocks in enclosing or overlying stratified units. Others may be part of tonalite (Tt) intrusive cycle, and a very few cut hornblende lamprophyre (Tl). Most interpreted to be part of early Tertiary pre-tonalite (Tt) magmatic cycle, as suggested by Donnelly and others (1990)

Tutu Formation (Upper Cretaceous, upper Turonian, upper Santonian, or younger)—Volcanic wacke, shale, conglomerate, calcareous siltstone, sparse limestone, and rare basalt and andesite or their metamorphosed equivalents. Many rocks are calcareous. All rocks are within contact aureole of tonalite (Tt); hornfels, calc-silicate rock, and marble common. Clasts in conglomerate dominantly basalt and andesite; limestone clasts locally abundant; clasts of plutonic rocks rare, but present. Graded beds, slump folds, and disrupted slabs of metasandstone and metasiltstone in metaconglomerate indicate deposition by turbidity currents on an unstable slope, perhaps a trench wall. Tight tectonic folds with axial-plane cleavage also present, as well as boudins of competent thermally metamorphosed sandstone and silt beds in marble. Distinguishing between soft-sediment and tectonic folds difficult in places where cleavage is not apparent. Basal contact not exposed; in apparent conformity with underlying Outer Brass Limestone (Ko)

Ktm Mandal Member (new name)—Medium- to thin-bedded, metamorphosed sandstone, siltstone, shale, and limestone. Siltstone typically calcareous and sandstone commonly with a calcareous matrix. Sparse conglomerate, mostly limestone conglomerate in beds as thick as 3 m. Marble contains calcite, plagioclase, tremolite, brown garnet, epidote, and opaque minerals. Metamorphosed calcareous siltstone and sandstone contain brownish garnet (locally as large as 3.5 cm), diopside, tremolite, plagioclase, calcite, opaque minerals, and minor quartz. On Whistling Cay, bedded, garnet-rich calc-silicate rock contains isotropic reddish garnet, bright-green diopside, plagioclase, wollastonite, phlogopite, sphene, pleochroic amphibole, and quartz. Dark-grayish-red (5*R* 3/2), very fine grained metasandstone contains abundant reddish-brown biotite and cordierite clouded with tiny inclusions. Named for exposures on the east side of Mandal Point, Eastern St. Thomas quadrangle. About 750 m exposed on St. John

Ktmc Congo Cay Limestone Lens—Tightly folded, vertical beds of marble, calc-silicate rock, and siliceous hornfels exposed on Congo Cay and Carval Rock. Dominantly white to medium-light-bluish-gray (5*B* 6/1) marble that is 98 percent calcite and either accessory plagioclase, white mica, and opaque minerals, or accessories plagioclase, tremolite, wollastonite, sphene, and opaque minerals. Calcite grain size typically 1 to 3 mm, but may be as large as 1 cm. Stratigraphic position of rocks on Congo Cay within the Tutu Formation (Ktm) not known. Here correlated with similar rocks on Whistling Cay and Mary Point that are within the Mandal Member

Ktml Marble, calc-silicate rock, and marble conglomerate

Ktp Picara Member (new name)—Thick- to medium-bedded, metamorphosed volcanic wacke, conglomerate, siltstone, limestone, and rare andesite or basalt. Locally calcareous. Clasts in conglomerate of metamorphosed andesite, basalt, and limestone. Pebble and cobble conglomerate more common than boulder conglomerate. Ribby outcrops of metasiltstone and metawacke common; calcareous nodules locally present. Named for exposures on the peninsula of Picara Point, Central St. Thomas quadrangle. About 600 m thick on St. John

Ktpl Marble conglomerate and calc-silicate-rich beds north of Maho Point—Calc-silicate assemblages include plagioclase-biotite-hornblende and plagioclase-hornblende-diopside-calcite. Two layers of marble and calc-silicate rock on Waterlemon Cay not mapped separately. Assemblage there includes brown garnet (some anisotropic and as large as 2 cm), diopside, wollastonite (blades as long as 2 cm), sphene, calcite, monazite, and sulfide

Ktpv Medium-dark-gray (*N*4), porphyritic meta-andesite south of Maho Point—Contains relict phenocrysts of glomerophyric plagioclase and prominent clinopyroxene as large as 3 by 6 mm. Metamorphic amphibole replaces clinopyroxene; fibrous amphibole and chlorite abundant in groundmass and impart foliation

Ko **Outer Brass Limestone (Lower Cretaceous, upper Turonian to upper Santonian)**—Thin-bedded calc-silicate rock, beds of white to blue-gray calcite marble (H_2S odor when broken) as thick as 3 m, and metamorphosed, matrix-supported cobble conglomerate with andesite clasts in carbonate matrix. Heterogeneous calc-silicate at Annaberg Point includes, in various assemblages, calcite, plagioclase, epidote, brown isotropic garnet, diopside, vesuvianite, and wollastonite. About 100 m thick

Kl **Louisenhoj Formation (Cretaceous, Albian to Turonian or Santonian)**—Strongly cemented volcanic conglomerate, breccia, volcanic wacke, shale, chert, andesite, basalt, tuff, and rare limestone. Overlies Water Island Formation with apparent conformity. Detrital units dominantly volcaniclastic. Lavas and flow breccias present but sparse. Conglomerate, breccia, and coarse sandstone typically pale green, greenish gray, or grayish blue green. Matrix may be calcareous.

Xenocrysts of plagioclase and pyroxene are notable constituents of some clastic rocks. Dominated by thick, clast- or matrix-supported conglomerate beds typically interlayered with sequences a few to several meters thick of siltstone and sandstone. Graded beds as thick as 6 m; some crossbedding. Soft sediment deformation and rafts of broken, finer grained beds common. Clasts larger than 0.5 m abundant throughout the formation; largest subrounded clast 3 m across. Breccia blocks may be as large as tens of meters. Clasts of porphyritic clinopyroxene andesite and basalt constitute bulk of formation. Typically contain about 20 percent prominent phenocrysts, commonly 5 to 10 mm across, of clinopyroxene and stubby, zoned plagioclase, either singly or together. In some rocks, pyroxene phenocrysts overgrown by hornblende; a few rocks have hornblende phenocrysts as well. Small amygdules pervasive in some clasts. Other clast lithologies include pumice (not common), limestone, keratophyre, and phenocryst-poor basalt like that in Water Island Formation. Differences in clast populations suggest local sources. Keratophyre and phenocryst-poor basalt are locally abundant near basal contact. Limestone clasts, some fossiliferous, on Rata and Ramgoat Cays. Metamorphism increases to the northeast. Biotite, pale amphibole, and epidote appear in andesite; epidote, hornblende, and lesser amounts of biotite appear in basalt. From central St. John to the north and east, most rocks are foliated. At least 1.5 km thick on west coast of St. John; may be as thin as 0.5 km at Leinster Bay

Kla Porphyritic, locally vesicular andesite lava—Phenocrysts of stubby plagioclase and pyroxene. Pillowed on Ramgoat Cay. Highly brecciated on Camelberg Peak and could be aa lava. May be more abundant than shown on map because of difficulty in the field distinguishing between conglomerate/breccia and homogeneous lava

Klb Porphyritic, locally amygdaloidal basalt and pillow basalt—Abundant (as much as 40 percent) stubby plagioclase phenocrysts, typically 3 to 4 mm but as much as 15 mm long; and less abundant clinopyroxene. Near Ajax Peak, recrystallized to greenschist-facies assemblages. Appears to be restricted to base of formation

Lameshur Volcanic-Intrusive Complex (new name) (Lower Cretaceous, Aptian to lowermost Albian)—Includes Water Island Formation and Careen Hill Intrusive Suite

Klm **Undivided**—Dominantly keratophyre and volcaniclastic rock derived from it, but includes basalt and basaltic andesite, an unknown volume of trondhjemite and gabbro, and minor chert. Several varieties of keratophyre distinguished by size and mineralogy of phenocrysts and mode of emplacement. Keratophyre occurs as lava flows, breccia, layered tuff, dikes, and small hypabyssal intrusive rocks. In all varieties, quartz phenocrysts embayed, if present, and phenocrysts of plagioclase (albite as determined by Donnelly, 1963, 1966) and quartz form growth aggregates, either singly or together. Plagioclase phenocrysts not zoned or weakly zoned. Groundmass medium grayish blue (5*PB* 4/2) to medium dark gray (N*4*). Keratophyres become progressively lighter colored as content of albite phenocrysts and (or) weathering increases. Mafic rocks occur as pillow lava, pillow breccia, dikes, and rare small plutons. All rocks may exhibit local intense, deuteric, hydrothermal alteration, which may include silicification, oxidation, sulfidization, and development of boxwork textures and, locally, gossan. Named for locality of Lameshur on the southern coast of St. John. Mapped where size and mineralogy of phenocrysts vary over short distances and distinction between extrusive and intrusive rocks is not readily apparent

Careen Hill Intrusive Suite (new name) (Early Cretaceous)—Hypabyssal trondhjemite (Kct), coarsely porphyritic keratophyre (Kcc), intrusive equivalents of all keratophyre units of Water Island Formation, gabbro and sheeted dikes intrusive into the Water Island Formation or isolated on islands. No sequence of intrusion recognized. Except for some bodies of Kct and Kcc, columnar jointing characterizes keratophyre and is used as one criteria for mapping these bodies as intrusive rocks. Larger keratophyre intrusive bodies form sharp, isolated hills along south coast of St. John and around harbor of Charlotte Amalie, St. Thomas. Name is taken from Careen Hill in Charlotte Amalie

Kct Trondhjemite—Fine- to medium-grained, commonly porphyritic with quartz and twinned, nonzoned albite phenocrysts. Groundmass typically granophyric intergrowth between quartz and albite. Common granophyric intergrowths radiate from albite phenocrysts. Forms Leduck Island (where columnar jointing is prominent) and Flanagan Island. Also occurs as clasts in tuff breccia of Water Island Formation in eastern St. John. On Leduck Island, is light bluish gray (5*B* 7/1) and coarsely porphyritic with less well-developed granophyric texture in groundmass that contains subhedral albite and equant quartz. Grain size is about 0.1 mm. On Flanagan Island, is medium-bluish-white (5*B* 9/1); contains a few percent clinozoisite and chlorite

Kcc Coarsely porphyritic keratophyre—Consists of 20 to 30 percent prominent quartz and plagioclase phenocrysts, typically 5 to 10 mm across. Groundmass varies from exceedingly fine grained, similar to extrusive keratophyre, to coarser grained with plagioclase laths up to 0.3 mm long. At higher metamorphic grade, coarse epidote appears in plagioclase phenocyrsts and epidote, pale amphibole, and shreddy biotite appear in groundmass. Blue-green amphibole is in groundmass along Center Line Road at elevation of 320 ft. Widespread as dikes in Water Island Formation; cuts tonalite (Kct) of Flanagan Island. Plugs form sharp hills of Maria Bluff, northeast of Chocolate Hole and north of Cocoloba Cay

Kcp Porphyritic keratophyre—About 20 percent conspicuous quartz and albite phenocrysts up to 3 mm across in a medium-dark-bluish-gray (5*B* 4/1), aphanitic groundmass of randomly oriented plagioclase laths 0.1 mm long, interstitial quartz, and magnetite dust. Accessory apatite and allanite. Glomerophyric plagioclase surrounded by granophyric intergrowths. Forms small unaltered plug west of Lameshur and sparse dikes

Kca Phenocryst-poor keratophyre—May contain up to 10 percent small (generally less than 2 mm across) phenocrysts of quartz and plagioclase. Forms small pluton north of Bovocoap Point and sparse dikes

Kcf Plagioclase-phyric keratophyre—Consists of 5 to 15 percent plagioclase phenocrysts, 1 to 3 mm long, in groundmass of typically felted plagioclase microlites and interstitial quartz. Forms small plutons on Ram Hill and on peninsula of Dittlif Point, and sparse dikes

Kcm Gabbro—Dark-greenish-gray, fine-grained, porphyritic, with small (2 mm or less) subhedral phenocrysts of clinopyroxene and plagioclase in groundmass of randomly oriented plagioclase laths about 0.5 mm long, clinopyroxene, chlorite, leucoxene, and opaque minerals. Forms intrusive body on Bovocoap Point; some mafic dikes in Water Island Formation are probably unit Kcm. May be more abundant than shown on map

See Plate 1 for pattern Sheeted dike complex—Dominantly keratophyre, but includes diabase as well. Dikes trend northeast (as does the diagrammatic overprint pattern) and dip moderately to steeply northwest. Mapped southwest of Salt Pond and at Harbor Point. Better developed on St. Thomas than on St. John. (Shown in magenta on plate1)

Water Island Formation (Lower Cretaceous)—Dominantly (80 percent) extrusive keratophyre and volcaniclastic rock derived from it; about 20 percent basaltic lava, breccia, and hyaloclastite; minor radiolarian chert. No internal stratigraphic order recognized. Groundmass of keratophyre commonly spherulitic. With increasing metamorphic grade to the north and east, spherulites are recrystallized and stand out as ovoids, some as large as 4 cm, on weathered surface. Lower contact of formation not exposed. Interpreted to have been deposited on oceanic plateau crust. Upper contact conformable and is exposed at several localities in southwestern St. John and nearly exposed south of Ajax Peak. Thickness at least 2 km. Several varieties of keratophyre distinguished by size and mineralogy of phenocrysts; all have intrusive equivalents in Careen Hill Intrusive Suite. Ash-flow tuffs notably absent

Kwp Porphyritic keratophyre—Consists of 10 to 25 percent conspicuous quartz and plagioclase phenocrysts, typically less than 5 mm across, in aphanitic groundmass. Flow layering present locally. Mapped distribution is approximate; appears to constitute less than 10 percent of formation on St. John

Kwa Phenocryst-poor keratophyre—May contain up to 10 percent small (generally less than 2 mm across) phenocrysts of quartz and plagioclase. Some rocks are aphyric on the scale of thin section. Many outcrops untextured but may display flow layering and flow folds. Includes lava, flow breccia, some bedded tuff, and some volcaniclastic rock. Dominant unit of Water Island Formation on St. John

Kwf Plagioclase-phyric keratophyre—Consists of 5 to 10 percent plagioclase phenocrysts 1 to 3 mm long in groundmass that is commonly felted mass of oriented aphanitic feldspar laths. Flow layering visible in some outcrops. Exposed in vicinity of Great and Little Lameshur Bays. Because phenocrysts are small and sparse, some areas mapped as phenocryst-poor keratophyre (Kwa) could be Kwf

Kws Basalt and basaltic andesite—Amygdaloidal pillow lava, pillow breccia, and hyaloclastite. Called spilite by Donnelly (1966). Na_2O and CaO contents, however, are in the range of basalt. Pillows typically about 1 m across. Tubular bodies as long as 3 m have been observed. Amygdules commonly in concentric shells within pillows. Interstices between pillows filled with calcite or epidosite. Bedding and topping direction determined from pillow asymmetry at Harbor Point, peninsula between Elk Bay and Haul Over, and eastern Red Point, all in eastern St. John. Bedding, but no topping direction, observed at several other localities. Excellent exposures of pillow breccia and hyaloclastite found in coastal outcrops between Saltpond Bay and Ram Head and on Dittlif and Contant Points. Fragments of breccia are commonly deformed against one another. Groundmass of least altered basalt consists of plagioclase microlites (typically randomly oriented) and opaque dust in a cryptocrystalline mesostasis. Small (millimeter range), sparse phenocrysts of glomerophyric plagioclase and clinopyroxene. Epidosite segregations common and, in places, pillows have epidosite cores. Secondary minerals in southern St. John include prehnite and pumpellyite (identified optically only), chlorite, calcite, and leucoxene. Zeolites probably the result of burial metamorphism. To the north and east toward Tertiary plutons, pale amphibole and finally pleochroic amphibole appear in groundmass. Clinopyroxene replaced by epidote and pale amphibole; farther north by pleochroic amphibole. Metamorphic assemblage adjacent to tonalite at Please horizontal control marker, north of More Hill in eastern St. John, includes quartz, plagioclase, hornblende, diopside, garnet, and calcite. Most basalt, including breccia fragments, is amygdaloidal; some is scoriaceous (amygdules a few millimeters across make up 30 or more percent of rock). Flattened amygdules on Kiddel Point are as long as 10 cm. Amygdules filled with combinations of quartz, calcite, chlorite, epidote, and plagioclase, as well as local prehnite and pumpellyite; at higher grade, filled with pale amphibole and clinozoisite in radiating sheaves

Kww Volcanic wacke and bedded tuff—Volcanic wacke consists of subrounded to angular clasts of keratophyre of all varieties, basalt, and trondhjemite in a matrix that is probably comminuted keratophyre but includes xenocrysts of quartz and plagioclase. Constituents poorly sorted and up to more than 1 m across; bedding may be poorly defined. Graded bedding rare but present. Pumiceous keratophyre clasts rare except between Grootpan and Kiddel Bays where submarine pumice flows may be present. Trondhjemite clasts up to boulder size, thought to be from Kct, found in cove 250 m northeast of Long Point and easternmost Privateer Point. Bedded tuff locally; no shards seen in the few thin sections available. Difficult to distinguish between tuff and chert in the field

Kwr Radiolarian chert—Light-blue-gray to dark-gray, bedded chert containing Radiolaria. Mapped where Radiolaria have been observed, such as at Kiddel Point on the shore of Saltpond Bay