# GEOLOGY OF THE BRITISH VIRGIN ISLANDS

by

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ABSTRACT

The British Virgin Islands are a group of small islands in the northeastern Caribbean about 70 miles east of Puerto Rico. They are underlain by keratophyres and spilites of unknown age, andesitic pyroclastics of Cenomanian and middle Eocene age, and granitic rocks of middle or post-middle Eocene age, all of which have been mildly metamorphosed and deformed.

The oldest rocks are named the Water Island Formation and consist of keratophyres and spilites with a few radiolarite units. This formation was apparently deposited on the sea floor prior to the Cenomanian and marks the beginning of the development of the island arc. Throughout most of the area the formation has been contact metamorphosed by the later intrusives to the epidote-amphibolite or hornblende-hornfels facies.

Uplift and erosion of the Water Island formation preceded the deposition of the andesitic pyroclastics of Cenomanian to middle Eocene age, which constitute the Virgin Island group. The oldest formation in this group is the Louisenhoj Formation which is comprised of up to 15,000 feet of augite-andesite breccias and tuffs with a few interrelated conglomerates. These pyroclastic rocks were deposited on the northern slope of a geanticlinal rise during the Cenomanian.

The _Outer Brass Limestone_ overlies the Louisenhoj formation and consists of a carbonaceous, silicified, radiolarian limestone with minor tuffaceous material, apparently deposited in several hundred feet of water.

Unconformably overlying the Outer Brass limestone is the _Tutu Formation_ consisting of about 9,000 feet of volcanic wackes and a few limestone breccias derived from the Louisenhoj formation and Outer Brass limestone. Near the top of the unit is a limestone about 500 feet thick, the _Congo Cay Limestone_. Limestone breccias within this formation have been dated as probably Cenomanian in age.

Conformably overlying the Tutu formation is the _Tortola Formation_ of middle Eocene age. This formation is subdivided into three members: the _Hans Lollik_ augite-andesite breccia member, the _Sage Mountain_ member consisting of pyroxene-free andesite breccias and volcanic sandstones, and the _Shark Bay_ member which consists of pyroxene-free andesite breccias and tuffs with abundant glass fragments, and includes a limestone lentil, the _Mount Healthy Limestone_. These pyroclastic rocks were derived from at least three cones and were deposited on a northward sloping surface.

Overlying the Tortola formation in apparent conformity is the _Necker Formation_, of possible middle Eocene age, which consists of welded tuffs, breccias, and tuffs, all of which contain free quartz. This formation includes fragments of granitic rocks derived from the batholith and thus post-dates the intrusion of the batholith.

The eastern portion of the area is underlain by a composite batholith, the Virgin Gorda Batholith, of probable middle Eocene age. The rocks within it vary systematically from olivine gabbro to granite with the bulk of the batholith being diorite, tonalite and granodiorite.

Following the emplacement of the batholith the Virgin Island group was deformed into a northward dipping homocline, in many areas overturned, with an approximate east-west axis. This has subsequently been further deformed by northwest-trending dextral and northeast-trending sinstral strike-slip faults and by north-south faults with both normal and strike-slip components. This faulting probably accompanied the development of the Anegada trough. Near surface intrusives were emplaced during this faulting and are characterized by quartz-andesine and andesine-hornblende porphyrites.

All the rocks in the British Virgin Islands have undergone contact metamorphism by the batholith, varying in intensity from the zeolite facies to the pyroxene-hornfels facies. Shearing and dynamo-thermal metamorphism are also present in the lower portion of the section.

# INTRODUCTION

This thesis presents a geological description and interpretation of the British Virgin Islands.

The British Virgin Islands consist of about forty small islands totaling about 65 square miles spread over an area of about 800 square miles, the largest of which are Tortola, Virgin Gorda, Anegada, and Jost van Dyke. These are located at the junction of the Greater and Lesser Antilles and (1) provide information concerning the relations between these chains of islands, (2) provide a well exposed yet relatively mildly deformed and contact metamorphosed section of Cretaceous through Eocene pyroclastic and sedimentary rocks, and (3) afford excellent outcrops of a composite quartz diorite batholith and its associated contact metamorphic rocks.

The field work was carried out during the summers of 1958 and 1959. A total of 28 weeks were spent in the area with a distribution among the various islands as follows: Tortola and neighboring small islands, 15 weeks; Jost van Dyke, 1 week; Virgin Gorda and vicinity, 7 weeks; with the other small islands accounting for the remaining five weeks. Approximately a week was spent in the American Virgin Islands in correlating the work of Donnelly (1959) with the present work and another week was spent on the Cretaceous and Eocene volcanics in Puerto Rico.

A base for field mapping was provided by aerial photographs loaned to the author by the British Virgin Island government. These were on several scales varying from 1/5,000 to 1/30,000. The field data recorded on these was transferred to topographic sheets (1/25,000 scale) provided by the Directorate of Overseas Surveys in the fall of 1959. These in turn were compiled and reduced to a final map scale of 1/40,000 (See Plate 1).

Exposures throughout the islands vary from excellent on the cliffs along the shores to extremely poor in the brush-covered interior. As a result most of the observations were made along the shoreline and along the few well-used trails in the interior. Road cut exposures are non-existent except in a few places along the southern shore of Tortola. Because of the lack of exposure away from the shore, as well as the general similarity of rock types, very few units could be traced inland more than a few hundred feet. As a result many structural problems were left unsolved and the structural interpretation shown is only a best guess.

Laboratory study of about 350 of the nearly 1,000 field samples was made with the facilities and equipment of the Geology Department at Princeton University. Petrographic and mineralogical descriptions were made of some 250 thin sections, including 77 Rosiwal analyses of about 1,000 points each on the granitic rocks. In addition to the thin section slides, x-ray studies were made of about 100 of the fine grained volcanic and metamorphic rocks. Polished sections were made for study of the opaque minerals in each of the major granite rock types.

An attempt was made to use x-ray peak intensity for general mode of many of the very fine grained intrusive and extrusive rocks. Feldspar compositions were determined by measurement of $N_x$ on suitably oriented grains removed from uncovered thin sections where precise composition seemed necessary; and by use of maximum extinction angles, optic sign and 2V where a lesser accuracy seemed sufficient. In addition an estimate of the plagioclase composition of the fine grained pyroclastics was made by using the spacing of the (131),($1\bar{3}1$) peaks after a calibration curve had been prepared from plagioclase whose composition had been determined by oils from coarser grained rocks of similar origin. The composition of the pyroxenes was determined by measurement of $N_y$ and 2V after the method of Hess (1949).

## Acknowledgements

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A project involving the geology of a number of small islands is virtually impossible without the assistance and co-operation of numerous local inhabitants. Their help in providing food, lodging and transportation is acknowledged with a great sense of indebtedness. Particular thanks are to be given to A. D. Fraser for providing a house on Virgin Gorda; to A. D. Watts and Miss Eileen Carter of West End, Tortola, for food and lodging and numerous helpful discussions; and to the Trellis Bay Club for the loan of a small boat during the summer of 1958.

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## Previous Work

The earliest geological work in the islands was done by William Maclure (1817). He pointed out the general NW-SE strike and dark color character of the rocks. He states (Kemp, 1926, p. 7): "The rocks consist of a variety of aggregates resembling the transition (Paleozoic), some of which when fresh have the appearance of hornblende rocks. . . ." The first comprehensive work on the British Virgin Islands was that of Robert H. Schomburgk (1837) who gives a remarkably accurate and penetrating account of the general geology of the islands, including some comments on their origin that showed much insight, considering the status of geology in 1837. Most of the rock types described by Schomburgk were found by the present author, but many of his descriptions are incorrect in the light of our current knowledge of petrology.

The next significant contribution to the geology of the British Virgin Islands was made by Per Teodor Cleve (1871) who studied the Virgin Islands in detail in 1868 and 1869. Cleve was the first to describe the andesitic volcanic rocks in detail. He also correctly dated some of them as Cretaceous in age. Another major contribution he made, in addition to his geologic interpretation, was six chemical analyses of the various granitic rock types on the islands. These have been used in this thesis.

Cleve (1881) was the first to mention a synclinal fold in the Virgin Islands with its axis running approximately east-west between St. John and Tortola. He states:

> The Cretaceous formation . . . consists . . . of volcanic rocks, often stratified and associated with large eruptive masses of a light colored diorite. . . . Their strike is generally east to west and their dip very strong, which proves that they have been elevated and bent by a great pressure, acting from north or south. . . . On studying in detail . . . I found . . . a synclinal fault [fold]* . . . in the continuation of Sir Francis Drake's Channel."

He believes this deformation to have begun in the Turonian, to have continued into the Eocene and to have ceased by the Miocene.

Some twenty years after Cleve's descriptive and chemical work in the islands Högbom (1905) published petrographic descriptions of the major rock types reported by Cleve. The location from which many of these came is uncertain, however, and little use can be made of these descriptions.

In 1924 I. W. Earle, who was at the time the British government geologist of the Leeward Islands, published a more complete and up to date paper on the general geology and

*Brackets by author; apparently Cleve used the German word <u>faulte</u> for fold instead of the English word.

structural history of the British Virgin Islands. In this paper he elaborated on the petrographic work done by Högbom and presented a more coherent synthesis of the geology of the islands. Nevertheless, many areas were not visited or otherwise studied, and he attempted little or no interpretation of his additional information.

In 1926 Kemp reviewed the geology of the Virgin Islands but added little new information. At the same time Meyerhoff discussed the physiography of the group of islands and pointed out several interesting geomorphic features that are probably controlled by major structural breaks.

In addition to the above mentioned men many other geologists have visited the islands briefly and have published short papers and notes on them. The most important of these are Hovey (1839), Hornbeck (1840, 1846), Knox (1852), Quin (1907), Böggild (1907, 1908), Vaughan (1916, 1919, 1923), Lobeck (1922), Kemp (1923), Davis (1924, 1926).

Donnelly (1959) made a thorough study of the geology of the American Virgin Islands and frequent reference will be made to his work throughout this paper.

The most recent published work in the British Virgin Islands is Martin-Kaye's study of the bedrock geology and its relation to water supply problems. A brief summary of this work was published in 1960. In addition to this published report, an unpublished report was made by Martin-Kaye to the Administrator of the British Virgin Islands concerning the general geology of the islands.

Geography and Physiography

The British Virgin Islands are located in the north eastern Caribbean Sea between Latitude 18°18'N and 18°45'N and Longitude 64°19'W and 65°52'W. These islands can be divided into four geographic (and geologic) groups which are: (1) Anegada, a flat island about 10 miles north of Virgin Gorda; (2) Virgin Gorda and neighboring islands of Necker, Prickly Pear, Mosquito, Eustatia, and Fallen Jerusalem; (3) a southern chain of islands between Virgin Gorda and St. John, namely, Round Rock, Ginger, Cooper, Salt, Peter, and Norman; and (4) Tortola and its satellite islands of 'Guana, Great Camanoe, Little Camanoe, Beef, Scrub, Frenchmans Cay, Little Thatch and Great Thatch. The fourth group can also be considered to contain Jost van Dyke and surrounding islands even though they are a considerable distance away since they are both geologically and geomorphically very similar to Tortola. In addition to the larger islands mentioned above there are many smaller islands varying from hardly more than a rock above the waves to islands of several acres.

The vegetation of the islands is quite variable, varying from dense forests resembling the drier rain forests of Puerto Rico to a sparce ground cover of cactus and small thorny brush much like that found in the Southwestern United States. There is a noticeable difference in temperature and humidity, and thus vegetation, between east and south facing slopes and those facing north and west with the latter being more densely overgrown and also being warmer and more humid since they are exposed to the sun but not to the trade winds that come from the east. The type of vegetation, and its direct effect on quality and number of exposures can be divided into three zones: (1) above about 1,300 feet there is heavy forest with little or no undergrowth and thus exposures, though poor, are moderately easy to find; (2) heavy, dense thorny brush below an elevation of 1,300 feet and above 100 feet to 400 feet (north and west slope and east and south slopes, respectively), with very few outcrops and extremely slow traversing; and (3) a zone between sea level and 100 to 400 feet in which the most noticeable plants are cactus and very thorny low brush--this part of the slope has numerous outcrops but their observation is a very painful process and thus they were not exploited to the maximum extent. The equilibrium of these three zones has been disturbed by recent farming and in some areas considerable overlap is present.

Inasmuch as Meyerhoff has discussed the physiographic development of the Virgin Islands in considerable detail only a short review will be given here.

The British Virgin Islands are an eastward extension of the Greater Antilles located along the axis of a long welt on the seafloor. The Puerto Rico trench lies a hundred miles to the north and the Anegada trough, with a minimum depth of over 1,000 fathoms, lies a few miles to the south and east.

The islands are located on a broad platform with a maximum depth of less than 35 fathoms and several well developed surfaces of lesser depths. The islands rise above this platform to a maximum elevation of 1,710 feet. Many of the islands are moderately rugged or even mountainous with about 50 percent of the shoreline consisting of cliffs 10 to 250 feet high. An example of one of the more rugged islands is Jost van Dyke. The center of this island is about 4,000 feet wide, yet its maximum elevation at this position is 1,070 feet. Tortola is the most rugged of the Virgin Islands and also has the greatest relief. Much of the western half of the island is above 1,000 feet and many of the slopes are in excess of 30 degrees.

Meyerhoff recognizes a three cycle erosional history. The oldest surface is between 900 and 1,200 feet above sea level; the second and third surfaces are at elevations of 225 to 450 feet above sea level and at 100 to 180 feet below sea level, respectively. These three surfaces are thought by Meyerhoff to have been formed entirely by subaerial processes with wave action having very little effect. This is not believed to be the case by the present author for there are indications of pronounced wave cutting along the present shorelines (See Fig. 1). Moreover several of Meyerhoff's submerged erosional surfaces are believed to be coral banks and not an erosional surface.

An interesting ridge suggesting growth of a coral reef during the late Pleistocene rise of sea level is that along the northern edge of the Anegada trough. This submerged

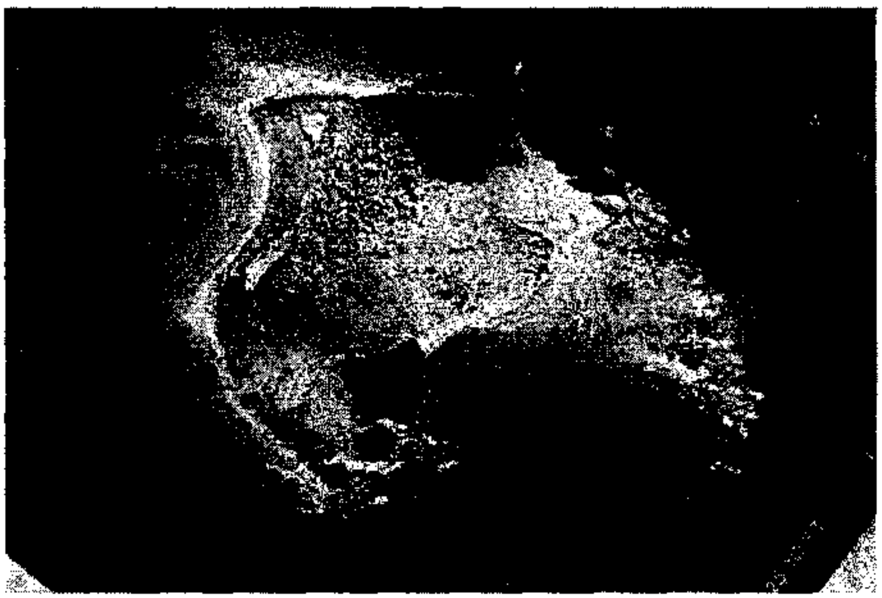


Figure 1. Aerial photograph of Dead Chest Island showing a wave-cut surface in the lower right corner and a prominent beach ridge in the upper left corner.

ridge at a depth of 11 to 20 fathoms (See Plate 2) is continuous from a point 8 miles south of the eastern end of St. Thomas to a point east of Virgin Gorda where it merges with the reef extending south from Anegada; a total length of more than 50 miles. To the south the depth of water increases very rapidly to a depth of over 1,000 fathoms; to the north the water depth increases to 30 to 35 fathoms and then rises again to an average depth of about 16 fathoms in the vicinity of the islands.

Even though the author believes that the Virgin Island platform may have been developed predominately by wave action during lowering of the sea level in the Pleistocene, it must have been above sea level for some time for there is a well developed stream drainage pattern on the detailed bathymetry of the platform. Areas of less resistant rock have been weathered to broad (now submerged) valleys with a predominant east-west orientation. The controlling feature for the development of these valleys appears to have been the presence of large bodies of granitic rock that weathered more rapidly than the surrounding amphibolites and skarns of the contact zone.

One of the more prominent physiographic features is the northwest-southeast trend of shorelines and ridges which is not controlled by lithologic variations as the strike is nearly east-west. The most probable explanation of these features is that this is the orientation of a major fracture or fault set. Abundant fractures or faults with this orientation are seldom seen, but this may in part be due to the fact that they are sufficiently weathered to make their recognition on a small scale very difficult. The latter is born out by the fact that outcrops tend to be very poor wherever there is a prominent northwest trending topographic low.

The shoreline of the islands is quite irregular, consisting of alternating cliffs and coves, some of which have very nice sand beaches. As mentioned above, about 50 percent of the shoreline consists of cliffs varying in height from 10 to 250 feet; these are most pronounced along the north shore of the northern islands and along the south shore of the southern islands. The eastern shore of Virgin Gorda is also very precipitous. The cliffs have developed or at least been accentuated by wave erosion, with most of the erosion taking place during times of heavy swells, known locally as "ground seas," which occur most frequently during the winter months and may last for several days before subsiding. This swell at times has amplitudes of over 12 feet and in many places it may break as high as 150 feet up on the cliffs. Very little of the energy in the wave is expended prior to reaching the cliff face since most of the cliffs continue below the water to a depth of 40 to 70 feet.

The coves along the exposed shore of islands normally consist of gravel or boulder beaches with no sand present unless there is a reef offshore both to provide the sand and to provide a small barrier to prevent the storm waves from removing the sand so readily. Along the more protected coasts sand beaches have developed in most of the coves. The sand consists for the most part of shell and coral fragments with some quartz or feldspar in areas of granitic outcrops. The reefs which usually protect the sand beaches from storm waves appear to have developed as a result of both the growth of coral and the accumulation of detritus removed from the neighboring cliffs. This material removed from the cliffs is often combined with large broken fragments of coral and accumulated into beach ridges up to 20 feet high. Notable examples of this type of beach ridge are at the southern end of South Sound, Virgin Gorda; at the southern end of The Sound, Salt Island (See Plate 3); and along the north shore of Dead Chest (See Fig. 1)

Numerous reefs, composed of several species of coral, four of which are prominent reef framework builders, are present throughout the islands and provide not only excellent examples of the development of fringe reefs but also provide good harbors in some places, while in others they provide no more than a serious obstacle to navigation. Many of these reefs form a barrier at a considerable distance from shore and thus they often form a deep (up to 25 feet), moderately well protected harbor. These reefs apparently began to grow during the latter part of the eustatic rise in sea level after the Wisconsin Glaciation and have continued to keep pace with this rise to the present day.

## GENERAL GEOLOGY

The Virgin Islands are the erosional remnants of a thick section of deformed pyroclastics which were deposited on the northern slope of a geanticlinal rise. The major episodes of volcanic activity were: Pre-Cenomanian, Cenomanian to Turonian, and Middle Eocene.

The earliest episode of volcanic activity deposited the Water Island sequence of spilites and keratophyres which underwent mild folding and erosion prior to the deposition of the Virgin Island group which includes the Cenomanian to Turonian, and middle Eocene volcanic sequences.

The Virgin Island group has been divided into five formations, namely: the Louisenhoj formation (up to 15,000 feet of augite andesite pyroclastics), the Outer Brass limestone (up to 600 feet of siliceous limestone), the Tutu formation (up to 6,000 feet of volcanic wackes with two limestone members), the Tortola formation (about 20,000 feet of andesite and augite-andesite pyroclastics), and the Necker formation (over 6,000 feet of andesite pyroclastics). The Tortola formation, of middle Eocene age, has been subdivided into four members based upon lithologic differences.

Following the deposition of the Tortola formation a composite diorite to granodiorite batholith was emplaced in in the eastern portion of the area. The emplacement of the batholith accompanied or slightly preceded the deposition of the Necker formation which is of middle or post-middle Eocene age.

In post-middle Eocene time the area was sharply tilted to form a northward dipping homocline which is overturned throughout much of the area. The strike varies from N65W to N55E with the most common strike being about N85W. Dips vary systematically south to north from 55S (overturned) to 70N except in the northernmost exposures of the Necker formation where dips of 20N to 40N are the most common. The batholith has been rotated to about the same extent. Additional deformation of about 20 degrees about a north-south axis took place in post-Miocene to pre-Recent times as evidenced by a calcarenite in Rogue's Bay.

Faulting, both normal and strike slip, followed the deformation and was probably related to the development of the Anegada trough.

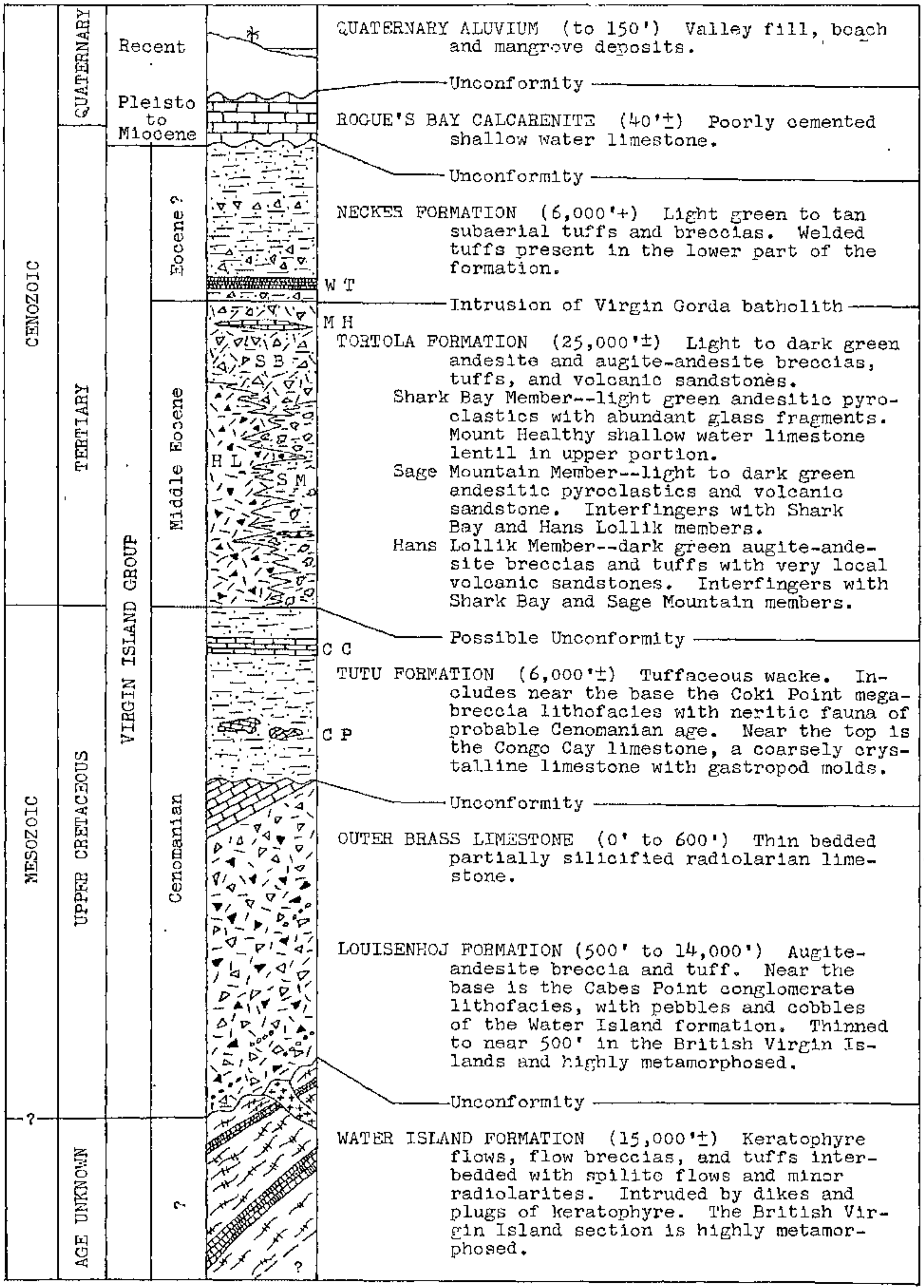



Figure 3. Stratigraphic section of the Virgin Islands, modified from Donnelly (1959)

# STRATIGRAPHY

## Introduction

The stratigraphy of the Virgin Islands has been discussed by several workers, notably Vaughan (1923) and Donnelly. These works have not included the British Virgin Islands and thus only form a guide for the present work as discussed below. The work of Donnelly in the American Virgin Islands established a stratigraphic sequence that, with certain modifications, seems to be valid for the British Virgin Islands and thus his nomenclature will be followed for the most part.

The stratigraphic section will be discussed as a composite section of all the islands, however this involves serious problems of correlation between widely separated island groups. This method is used because it enables a closer comparison with the section of Donnelly since the change in character of the sediments along strike is much easier to follow and understand.

Serious difficulty in correlation between islands, or even between opposite sides of a point arises because of the lack of reliable distinguishing features in the pyroclastics of approximately the same composition. In addition to the fact that there are few differences between rock types the recognizable units are very lenticular and change very rapidly along strike;

for example, several apparently mappable units, such as volcanic sandstones, were observed to disappear or became indistinguishable from the surrounding units within less that 300 yards.

In spite of these difficulties a stratigraphic sequence can be established (Fig. 3) that can be recognized and used in the field interpretation of structural problems. This section is based on the more general aspects of the rock units and allows considerable internal variation.

The only terminology in need of explanation is the use of the term reworking. Unless otherwise stated this term is used to convey the idea that originally subaerially deposited material has been transported, abraided, and in some cases sorted, in a dilute water suspension.

## Summary of the Stratigraphy of the British Virgin Islands

The oldest unit in the area is the pre-Cenomanian Water Island formation described by Donnelly. It consists of interbedded keratophyre flows and breccias and spilite flows which have subsequently been intruded by keratophyre plugs. The formation crops out along the southern shores of the Virgin Islands; in the British Virgin Islands on Peter, Norman, Salt and Cooper Islands. Its maximum thickness is in excess of 15,000 feet.

Overlying the Water Island formation with a marked angular unconformity is the Virgin Island group described by Donnelly. This group consists of four major units: the

Louisenhoj formation composed of 200 to 14,000 feet of augite andesite breccias and tuffs with a discontinuous conglomerate member at the base; the Outer Brass limestone, varying from 200 to 600 feet in thickness, consisting of a fine grained, dark grey, silicified, radiolarian-bearing limestone with a few (10%±) interbedded fine grained tuff lenses; the Tutu formation which comprises tuffaceous wackes (6,000'+), limestone and volcanic megabreccias and a 400± foot gastropod bearing limestone, the age of which is Cenomanian; and the Hans Lollik formation, now considered part of the Tortola formation, consisting of a maximum of more than 10,000 feet of augite andesite breccias and tuffs of probably Eocene age.

In addition to the Virgin Island group as defined by Donnelly, two other formations are present. These are: the Tortola formation of middle Eocene age having a maximum thickness of about 20,000 feet which includes both pyroxene and non-pyroxene bearing silicified andesite breccias (of which the Hans Lollik formation of Donnelly is considered a member) and tuffs of a light green color; and the Necker Formation of middle Eocene or younger age consisting of light green to tan breccias, tuffs and a few volcanic sandstones, all of which contain free quartz, and having a maximum thickness of more than 4,500 feet.

The thickness of sediments in any one section is not the composite thickness of several partial sections, which would be in excess of twelve miles. Instead, it is probably something in excess of five miles.

WATER ISLAND FORMATION

## Introduction

The Water Island formation of unknown age was named by Donnelly and consists of keratophyre flows, breccias and tuffs interbedded with spilite flows and local radiolarites. The type locality is along the shores of Water Island, an island of about one square mile at the entrance to Charlotte Amalie harbor in St. Thomas, American Virgin Islands.

In the British Virgin Islands this formation is exposed along the shores of Cooper, Salt, Peter and Norman Islands and neighboring small Cays and rocks. The exposures generally are excellent along the shore but are very poor inland. Thus most of the work on these islands was confined to a narrow belt along the shore.

## Description

In the excellent exposures at the type locality along the shore of Water Island and on numerous other points of southern St. Thomas and St. John, the Water Island formation is predominately light tan to reddish brown keratophyres interbedded with thin flows of dark green to almost black spilites. The total stratigraphic thickness throughout St. Thomas and St. John appears to be in excess of 15,000 feet, although no one continuous section of this thickness has been observed.

In hand specimen a fresh quartz keratophyre is dark grey in color and except for the large (3 mm) beta quartz phenocrysts it is very fine grained. Normally a flow banding is present but this may be very obscure unless weathering has accentuated it. Most specimens are weathered to some degree which produces a light tan to reddish brown stain throughout the rock. The mineralogy of the keratophyres is quartz (phenocrysts) and albite (as both phenocrysts and small laths) with accessories of magnetite, chlorite, hematite and/or pyrite. Micas may be present in small amounts but these are probably an alteration product from original glass.

In hand specimen the spilites consist of a fine grained green mineral (chlorite) with a few phenocrysts of plagioclase and augite. Amygdules are common but not present in all specimens. Little or no texture is to be seen. When observed under the microscope the rock is seen to consist of a few plagioclase (labradorite or labradorite replaced by albite) and augite phenocrysts surrounded by a groundmass of chlorite, albite laths, and magnetite. The amygdules contain quartz, calcite, prehnite, and epidote. Many specimens contain irregular patches of epidote that appear to have been formed deuterically.

In the British Virgin Islands, in contrast to the American Virgin Islands, the formation has undergone greater metamorphism. The rocks described above are now amphibolites and quartz mica schists. This is true of the whole section except for one intrusive keratophyre plug that does not appear to have reacted to the metamorphism, its only changes having been fracturing with the formation of a very few flakes of sericite along the fractures and the addition of fine grained silica to the rock giving it a "sugary" appearance on a freshly broken surface.

Inasmuch as these metamorphosed rocks are no longer recognizable as spilites and keratophyres, except for their stratigraphic position, their petrography will be discussed in the section on metamorphism (page 132).

## LOUISENHOJ FORMATION

### Introduction

In the southern part of the British Virgin Islands on Salt and Cooper Islands some amphibolites contain very elongate fragments of keratophyre resembling stretched cobbles in a conglomerate interbedded with normal breccia units. Since keratophyre pebbles are known elsewhere only in the Cabes Point conglomerate lithofacies, of the Louisenhoj formation (Donnelly, p. 59) this part of the section has been correlated with the basal part of the Louisenhoj formation. However, it may be a basal conglomerate that developed locally at the base of the Tutu formation which is less than 2,000 feet (stratigraphically) above the keratophyre pebble-bearing member.

Exposures of this unit are not very good. The only definitive exposures occur along the western shore of Cooper Island for an interval of about 2,000 feet, part of which is covered and part of which is an intrusive body. Some metamorphic rocks with unusual mineralogy occur in an equivalent position on Salt Island but the keratophyre pebbles were not recognized.

### Description

At the type locality near Louisenhoj on the hill above Charlotte Amalie, St. Thomas, the Louisenhoj formation consists of as much as 15,000 feet of coarse augite-andesite breccias interbedded with finer tuffs. This unit thins both eastward and westward and has a thickness of near 4,000 feet on eastern St. John. Considerable evidence of slumping and flowage of the units is present suggesting that it may have been originally deposited on an unstable slope. The basal contact shows a moderate angular unconformity with respect to bedding in the Water Island formation and locally is marked by a well developed conglomerate, the Cabes Point conglomerate, consisting of keratophyre and spilite clasts. These are moderately well rounded but not size sorted and probably represent a beach deposit much like those seen along some of the present shores. The upper limit of the formation is the Outer Brass limestone. The break in deposition between the Louisenhoj formation and the Outer Brass limestone is sharp with no mixing where exposed on St. Thomas.

In the British Virgin Islands the thickness and the very existence of the unit is somewhat in doubt as was mentioned above. At the southern extremities of Salt and Cooper Islands the rocks are definitely equivalent to those of the Water Island formation. Proceeding northward on Salt Island (Plate 3), one continues to be in the Water Island formation until the intrusive occupying the narrowest portion of the island is reached. North of the intrusive the rocks are in general amphibolites (see descriptions S-32 and S-20 under metamorphism for details), but no longer are interbedded with metamorphosed keratophyres and are generally coarser grained than those derived from spilites. However, the texture of a meta-breccia was never observed.

At the northern edge of Salt Island, particularly on the eastern and westernmost points, one encounters amphibolitic schists, graphitic schists, and a unit that appears to have been a calcareous tuff or breccia (now garnet, diopside, hornblende and calcic-plagioclase). This is most likely equivalent to the Coki Point megabreccia lithofacies of the Tutu formation but might be an equivalent of the graphitic Outer Brass limestone. However, this limestone is quite thin on the northern shore of St. John (in comparison to its thickness on St. Thomas) and has probably been entirely eroded away in the vicinity of Salt Island. This view is further supported since the Outer Brass limestone is nowhere observed to contain appreciable volcanic material and the development of the rock observed on Salt Island would require a considerable amount of volcanic material. Furthermore, it may have been a breccia, i.e., garnet and diopside occur in patches resembling in outline some of the breccia fragments seen in the Coki Point megabreccia, and thus the conclusion that it is not equivalent to the Outer Brass limestone. This in turn leads to the conclusion that there is no direct evidence that any portion of the Louisenhoj formation exists on Salt Island since all of the rocks seen can be assigned to either the Water Island formation or the Tutu formation. On the other hand some of the section, not more than 500 feet, could possibly belong to the Louisenhoj formation since it really has no exact equivalent in the Tutu formation or the Water Island formation.

On Cooper Island one finds much the same problem since the same intrusives obscure much of the section and the only three definitive rock types are the "calcareous breccia," the stretched keratophyre pebble conglomerate and the Water Island formation of interbedded amphibolites and mica schists. However, one additional piece of information is present, namely, the Congo Cay limestone can be identified about 900 feet stratigraphically above the calcareous breccia and this is about what one would expect if the latter were equivalent to the Coki Point megabreccia lithofacies. The first appearance of keratophyre pebbles is 1,000 to 2,500 feet stratigraphically below the calcareous breccia, the uncertainty being due to a sill-like intrusive having a thickness of about 1,500 feet. The keratophyre-pebble-bearing conglomerates are interbedded with metabreccias of the Louisenhoj type and also with amphibolites probably equivalent to the finer tuffaceous units in the Louisenhoj. This sequence continues for nearly 2,000 feet (stratigraphically) along the southwestern shores of Cooper Island. The southernmost point of the island is again interbedded meta-keratophyres and amphibolites. A strongly disturbed zone of variable attitudes and lithology forms a contact zone of about 500 feet in thickness. This probably represents a slumped megabreccia, of probable landslide origin, of both Water Island and Louisenhoj lithologies.

The conglomerates are interesting in that, although very strongly deformed, three distinct textural and compositional variants can be recognized. These are spilites (containing amygdules), keratophyre fragments, and cobble sized clasts having much the same appearance as contact metamorphosed fragments from the Louisenhoj or Hans Lollik formations as exposed in the American Virgin Islands. This, and the fact that the conglomerates are interbedded with amphibolites and more usual non-keratophyre bearing breccias suggests that these were all deposited in Louisenhoj time and that the Water Island fragments represent the coarse clastics derived from a nearby high on the pre-Louisenhoj surface. If it is true that these coarse materials were partially derived from a nearby high, then one might expect an appreciable angle of repose to have developed much like those associated with shoreline conglomerates of today. This seems to be the case in that dips in this section are about ten to twenty degrees steeper than those in the overlying fine grained material or than in finer material along strike, although an observation such as this should not carry much weight since the section has been rotated through at least 120 degrees during later deformation.

The above observations and arguments provide a picture of the depositional environment of the Louisenhoj formation.

Since no structural complications of more than a few hundred feet can be seen post-intrusives and no evidence has been found for pre-intrusive structures it is assumed that the observed thickness on Salt and Cooper Islands are both actual. This implies a thickening of over 1,500 feet in about a mile along strike as well as a marked facies change. This requires a 25 percent slope (minimum) on the original depositional surface. The presence of the mega-breccia moreover suggests considerably greater relief. Thus the Louisenhoj formation is thought to have been deposited upon a surface of considerable relief, with the andesitic volcanics having been deposited over most of the surface and subsequently transported short distances, by slumping or stream transport, to local basins of deposition. These depositional sites were most likely sub-aqueous at least part of the time since the conglomerates show some degree of sorting; they are also rounded but this could be only apparent rounding due to stretching during metamorphism.

## Petrography

The petrography of the original rocks has been extensively altered and little, if any, of the original textures or mineralogy survived the metamorphism. As a result these subjects will be discussed under metamorphism where it will be more obvious that any original microscopic textural relations are mostly guesses. Likewise the mineralogy will also be discussed under metamorphism as all of the minerals appear to have been formed during metamorphism.

## OUTER BRASS LIMESTONE

### Introduction

A marked depositional change occurred at the end of Louisenhoj time. Most of the islands appear to have been submerged, possibly several hundred feet, and a carbonaceous radiolarian bearing limestone was deposited. Volcanic eruptions in the area seem to have subsided or stopped altogether; the only volcanic additions to the limestone were fine grained. The limestone varies from 0 to 600 feet in thickness and is named for its typical exposures on Outer Brass Island north of St. Thomas.

### Description

At the type locality the Outer Brass limestone consists of about 600 feet of thin bedded, dark grey, carbonaceous limestone with numerous radiolarian tests. A few fine grained tuff beds are present but at no place do they amount to more than ten percent of the unit.

To the east the unit becomes thinner and is apparently missing in the vicinity of Salt and Cooper Islands. In the vicinity of Mary Pt., St. John, wollastonite is developed in the limestone near the contact with the Narrows pluton.

The formation is nowhere exposed in the British Virgin Islands and, since exposures are present in the interval in which it should occur, it probably never was deposited in the British Virgin Islands. However, it could have been removed by erosion prior to or during part of Tutu time since the Tutu section is also thin.

TUTU FORMATION

## Introduction

The volcanic wackes outcropping along the north shores of St. Thomas and St. John and on the islands just offshore were designated as the Tutu formation by Donnelly. These rocks are also present on the western portion of Tortola. In addition to the major lithology of the unit, two marked variants occur in the vicinity of the type section. These are the Coki Point megabreccia lithofacies, named by Donnelly for its typical development in the vicinity of Coki Point, St. Thomas, and the Congo Cay limestone, named for its type locality on Congo Cay, north of St. John.

## Description

At the type locality the Tutu formation apparently lies conformably on the Outer Brass limestone and consists of thin bedded fine grained tuffaceous wackes interbedded with coarser grained materials of about the same character. Graded bedding is present in the finer units but is reported to be absent from the coarser units. Considerable variation is present in both size of material, varying from silt to cobbles, and in thickness of individual beds, varying from less than an inch in the finer wackes to more than thirty feet in conglomeratic units. Numerous fragments of limestone and of underlying beds are incorporated in the finer sediments suggesting the presence of currents capable of carrying large fragments of material originally formed or deposited nearer to the shore. Slump structures are present showing transport to the north and indicating deposition on a northward sloping surface. Donnelly has suggested that this deposit was formed from reworked material transported by turbidity currents and deposited on a gently sloping surface in moderately deep water (several hundred feet).

The Coki Point megabreccia consists of large (some greater than 100 feet long) blocks of shallow water limestone mixed with andesitic volcanics (of possible flow origin) and tuffaceous wackes of the surrounding Tutu formation. This unit is believed to have been formed by landslide slumping of nearshore and subaerial deposits into the deeper water characteristic of the depositional site of most of the Tutu formation.

The second distinctive rock unit in the Tutu formation is the Congo Cay limestone which is now a coarsely crystalline, fetid marble at all exposures in the Virgin Islands. A few megafossil molds have been recognized but preservation is so poor that accurate identification is impossible. The unit varies somewhat in thickness with the usual thickness being about 400 feet in the western portion of Tortola.

In addition to the 6,000± feet of section described by Donnelly and reviewed above, there are on the western portions of Tortola about 3,500 feet of similar rocks not present in the American Virgin Islands. Although most of this section is moderately metamorphosed (amphibolite facies) some of the original sedimentary characters of the rock are present and will be described below.

A section about 1,500 feet thick is exposed stratigraphically beneath the Congo Cay limestone in the British Virgin Islands that is not exposed in the American Virgin Islands. However, this section has undergone a high degree of metamorphism and very few of the original sedimentary features can be recognized. Most of the exposures are now garnet-diopside-calcite rocks which, of course, have undergone complete recrystallization. Interbedded with these are hornblende hornfelses and quartz biotite schists suggesting that the original section was an interbedded sequence of calcareous and silicious tuffaceous wackes having a considerable range of composition.

The unit about 500 feet in thickness immediately beneath the Congo Cay limestone consists of fine grained, thin bedded amphibolites with calcareous tuffs and thin limestones(?). In about the middle of this unit (about 200 feet below the Congo Cay limestone) is a chiastolite-bearing graphite schist varying in thickness from fifteen to thirty feet. Locally more than one of these graphite rich units may be present.

Chiastolite is not present at all localities nor is the amount of graphite present constant, varying from near one percent to as much as forty percent in samples of hand specimen size. This graphite rich zone probably represents a swamp or lagoonal deposit behind a protective reef along the margin of the remnants of the Louisenhoj volcanic cones, probably much like some of the larger mangrove swamps in the islands today. There is no evidence that volcanic activity occurred during deposition of this graphitic unit as no coarse volcanic material or even feldspar crystals were recognized.

In the 2,000 feet of section above the Congo Cay limestone, the sediments are much the same except that the center of volcanic activity appears to have been closer as evidenced by the numerous thin, lenticular, breccia-like units, now seen as epidote amphibolites and hornblende hornfelses with a breccia-like texture. It is possible, however, that these are conglomerate units like those in the Tutu formation at the type locality. Most of the section is thin bedded, fine grained and apparently well sorted volcanic wackes or tuffaceous volcanic sandstones. No primary sedimentary features were observed, other than bedding, except in one siliceous volcanic wacke near Havers on the south shore of Tortola. Here a weak current cross-bedding is developed in a fine grained volcanic sandstone consisting of plagioclase, magnetite and a very small amount of quartz. Minute grains of epidote or diopside, probably diopside, are also present. This unit has several garnet bearing massive amphibolites within it, probably representing coarse ash deposits, as a weak fragmental texture can be seen on a weathered surface. Secondary reworking by burrowing organisms was observed in one sample from near the top of the section, indicating deposition in a subaqueous environment for this unit. Since this fine grained unit appears to be no different than other fine grained units in the section, it suggests that much of the section may have been deposited subaqueously.

About 150 feet stratigraphically above the Congo Cay limestone is a marble unit about fifteen feet thick in which numerous irregular amphibolite fragments are present. These are not bedded and are interpreted here as being volcanic fragments or bombs deposited in a lime mud. This inference is further born out by the fact that they are more abundant near the upper surface of the marble unit which is overlain by a massive amphibolite. This is in turn overlain by thin bedded amphibolites. No primary structures are preserved in this overlying amphibolite and thus one cannot determine whether or not they were originally lapilli tuffs or volcanic wackes.

Beneath this thin marble are thin bedded amphibolites which pass downward into massive to thin bedded garnet-diopside rocks that apparently were calcareous tuffs or tuffaceous wackes. These continue downward to the contact with the Congo Cay limestone and probably represent the deposition of tuffaceous or volcanic material simultaneously with the dying phases of the Congo Cay bank which was eventually buried in volcanically derived material, either tuffs or reworked tuffaceous material.

In the remaining portion of the Tutu formation above the Congo Cay limestone no limestone or carbonate rich material was observed and, although most of the rocks are still fine grained and thin bedded, they may no longer represent entirely subaqueously deposited material. The lenticular character of many of the thin interbedded breccia-like units suggests subaerial deposition, and much of the formation may represent fine tuffs deposited to the east of the volcanic center from which the Hans Lollik augite-andesite breccias, with which the upper Tutu formation appears to interfinger, were derived.

Petrography

Only one petrographic description will be given here since most of the thin sections no longer are representative of the sediments but rather their metamorphic equivalents and as such will be described under metamorphism.

T-301 In hand specimen the sample is a dark grey, fine grained metamorphosed tuff or tuffaceous wacke. The unit is thin bedded to laminated with a suggestion of grading in some of the thin beds. The sample shows reworking by burrowing organisms. In thin section it consists of:

Hornblende: metamorphic, possibly replacing pyroxene crystals.
Actinolite(?): fine needles developed in groundmass and in plagioclase crystals during metamorphism.

Plagioclase: the composition is about calcic andesine, ($An_{47\pm5}$).
Magnetite: embayed crystals.

The sample is thin bedded and has undergone metamorphism equivalent to about the hornblende hornfels facies. Very little metamorphic foliation has been developed, however most of the original textures (other than macroscopic ones) have been removed or masked by the recrystallization accompanying the metamorphism.

From the grain size, bedding characteristics (i.e., slight grading of thin bedded fine grained sediments), and evidence of reworking by bottom dwelling organisms, the rock was deposited in water of shallow to moderate depth at a moderate distance from a source of coarse clastic material. No evidence of lithic fragments were seen, suggesting masking by metamorphism or more likely their absence to begin with. This would support the interpretation that the depositional environment was at some distance from the source of clastic materials. Probably no volcanic activity was present in the immediate vicinity during the deposition of this unit. The sample is probably best described as a fine grained volcanic wacke.

## Depositional Environment

The Tutu formation was probably deposited along the flanks of an active volcano or volcanic chain beginning in water of moderate depth at a considerable distance from the nearest volcanic source. As deposition continued the water became shallower, probably due to accumulation of sediments, and at the same time the addition of pyroclastic material or clastics derived from volcanics decreased. This process continued until a broad, shallow, and possibly partially subaerial, platform was built up. At this time the carbonaceous (now graphitic) rocks were deposited with the addition of small amounts of strongly weathered (i.e., highly aluminous) material.

Following the deposition of the carbonaceous unit a thin sequence of tuffs or tuffaceous wackes were deposited either subaerially or subaqueously. The area was then submerged a few tens of feet and the Congo Cay limestone was deposited. Very little tuffaceous material was added during the deposition of the 400 feet of limestone in the vicinity of Western Tortola, however the limestone appears to be interbedded with tuffs (now amphibolites) farther east on Ginger Island thus evidencing volcanic activity, or possibly only proximity to a source of clastics, to the east of the area. To the west the Congo Cay limestone is not exposed but the thinness of the section of fine grained sediments suggests either non-deposition or at least decreased deposition. After the deposition of the Congo Cay limestone, either renewed erosion of the neighboring highlands took place or the volcanic centers moved closer, probably the latter because of the amphibolite blocks within the thin marble overlying the Congo Cay limestone. Some of the upper part of the formation is probably subaerial since the units are very lenticular and bedding is often poorly developed. To the west of Tortola the Hans Lollik member of the Tortola formation may have been deposited at the same time as the uppermost portions of the Tutu formation; thus the two formations may represent the cone and near cone deposits and those accumulating at the flanks of a volcanic cone by both reworking of the cone deposits and by direct airborne additions.

## TORTOLA FORMATION

### Introduction

Overlying the Tutu formation is a sequence of about 20,000 feet of andesitic breccias, tuffs and reworked tuffaceous sediments which is here named the Tortola formation for its excellent exposures on the northwestern portion of the island of Tortola. The formation is also well exposed on Jost van Dyke, and the small islands surrounding it, and on the southeastern shore of Tortola, although here it has been moderately to highly metamorphosed by the Narrows pluton. In addition to the major lithologies mentioned above several limestone and limestone breccia units are present that have yielded foraminifera of Eocene age.

### Description

The Tortola formation consists of at least four separate facies or lithologies between which there is considerable mixing, both vertically and laterally. For this reason it will be convenient to think of the formation as consisting of mixtures of somewhat idealized end members each of which represents one of these major rock types. Some of the mixtures, however, could reasonably be considered as valid end members by themselves. The four end members that are seen in a nearly pure form in the field are: (1) breccias and lapilli tuffs, (2) fine grained tuffs, (3) volcanic sandstones, and (4) limestone. Actually a fifth class, volcanic flows, is present but has not been included because it does not mix with the other four.

A brief description of each of the four end members is as follows:

(1) Breccia. Deposits termed breccias are characterized by an abundance of large angular fragments and rare bombs of pyroclastic origin incorporated in a matrix of finer grained pyroclastic material. Sorting is very poor or lacking and fragments with diameters over 32 mm constitute much of the volume. Bedding is very rarely present and when it is observed it is very irregular. Slumping is common and often deforms the underlying units and locally has incorporated large fragments of them within the main breccia mass.

Pyroclastics with an average particle size ranging from 4 mm to 32 mm have been termed lapilli tuffs and are considered to be a part of the breccia end member in that they represent deposits laid down near the volcanic source and are thus much more closely allied to the breccias than to the tuff which may have been transported in the air for considerable distances before deposition.

(2) Tuff. These rocks include all pyroclastic material finer than 4 mm that shows little or no reworking other than local slumping evidenced by contorted bedding. In

thin section these tuffs consist of accumulations of (a) angular and usually broken crystals of plagioclase or pyroxene or (b) angular rock fragments or (c) a mixture of both incorporated in a fine grained microscopically crystalline groundmass of irregular thin shard-like fragments probably representing devitrified glass. These thin plate- or shard-like fragments usually show a preferred orientation that is parallel to bedding when the latter is present. Some units show an obscure grading which is probably primary but may have been formed during reworking. If the latter is the case, no other characteristics of reworked sediments, such as rounded grains, were developed. An average grain size of 1/4 mm was used to subdivide the tuffs into coarse and fine tuffs.

(3) Volcanic sandstone. This name has been used for all sediments consisting of pyroclastic volcanic material in which evidences of appreciable reworking were present. The macroscopic evidence of reworking most commonly found were cross-bedding, ripple marks, sorting and graded bedding when accompanied by other features of reworking, and to a lesser degree development of bedding planes, especially evidences of erosion of the underlying bed. In thin section the best criterion was the rounding of lithic or crystalline fragments, especially when the abrasion had removed corners of zoned plagioclase crystals. Size sorting was also used as evidence of reworking particularly when its development was marked or accompanied by abrasion of the grains. In many of the finer

grained sediments without large fragments considerable difficulty was experienced in determining reworking and in many cases they were called either volcanic sandstones or tuffs on the basis of the character of the surrounding sediments.

Several units of a conglomeratic nature were also observed and are considered members of this facies since they have the common denominator of having undergone considerable reworking.

(4) Limestone. The limestones form a separate and distinct class of very local development. They are fine grained and rich in algal remains as well as numerous foraminifera and a few macrofossils. Little mixing took place between this facies and the others at the time of deposition in that only rare clastic fragments are seen. However, after deposition of the limestone, considerable reworking took place as will be discussed later.

Considerable mixing between the four end members has taken place and in several areas units were observed to change from a nealy pure end member such as a lapilli tuff into an end member such as a volcanic sandstone in a few hundred yards with the intervening area being either a mixture of both end members or else an irregular interbedded and interfingering sequence of both end members. Where exposures are poor little can be said about either the average or the detailed character of the sediments except that they are pyroclastics or reworked pyroclastics.

The Tortola formation, when viewed in a broader sense, is composed of four major lithologic units, three of which have been given member status. The two most obvious members, based upon composition, are the Hans Lollik augite-andesite breccia, which was described as a formation by Donnelly, and the Mount Healthy limestone. The remaining portion of the section can be divided into two parts in the field on the basis of color, abundance of lithic lapilli tuffs and stratigraphic position above a thin bedded fine grained sequence of tuffs and volcanic sandstones, but when either detailed field examination or microscopic examination is undertaken, no single definitive character is found that would distinguish these two members of the formation. Part of this confusion is due to the fact that the exposed lower portion of the Tortola formation has undergone metamorphism to the hornblende hornfels facies and thus has lost much of its detailed sedimentary character. In addition the mineralogy has been profoundly altered so that the composition and textures of the original minerals have been masked or lost entirely. Nevertheless, it will be worthwhile to discuss each of these members in detail even though their separation may not be possible in all cases.

The lower of these two members is the Sage Mountain member which interfingers both laterally and vertically with the Hans Lollik member. The upper member has been designated as the Shark Bay member. It interfingers slightly with both the Hans Lollik and Sage Mountain members.

## HANS LOLLIK AUGITE-ANDESITE BRECCIA MEMBER

### Introduction

Although the breccias that crop out on the islands of Hans Lollik and Little Hans Lollik north of St. Thomas have been described and named by Donnelly (p. 82), additional mapping of the British Virgin Islands by the author has shown that breccias and tuffs having all the characteristics of the Hans Lollik formation are interbedded with the tuffs and volcanic sandstones of the Sage Mountain member throughout a considerable stratigraphic interval (about 10,000 feet on Tortola). Discontinuous lenses of augite-andesite are also present within the Sage Mountain member and probably represent outliers of the Hans Lollik member. On the island of Jost van Dyke breccia units of similar character are abundant on the southern half of the island but are present only as local lenses along the north shore where they are interbedded with the Shark Bay member of the Tortola formation. Since the augite-andesites of the Hans Lollik member are widely distributed as a unit interbedded with units of different characteristics throughout about 15,000 feet of section, it is considered to be a member of a more extensive formation which consists of the pyroclastics derived from several cones. The original name has been retained since there is no doubt that the most continuous and best exposed section is on Hans Lollik Island and also that the petrographic character at the original type locality is characteristic of all of the studied lenses of augite-andesite breccias and tuffs.

Description

The thickness of the Hans Lollik member, none of which was recognized east of Road Harbor on Tortola, increases from east to west at the expense of the Sage Mountain member with the sum of the two stratigraphic intervals increasing slightly to the west. In the vicinity of western Jost van Dyke to the southern extremity of Hans Lollik Island massive augite-andesite breccias and tuffs comprise about eighty percent of the exposed stratigraphic section. This thickening, or rapid increase in relative amount, to the west is thought to indicate a nearby center of pyroclastic activity which probably was located very near the Hans Lollik Islands, most likely to the south and east. This center of volcanic activity was apparently competing with one farther east, possibly in the vicinity of Virgin Gorda, which contributed the pyroclastics of the Sage Mountain member.

Petrography

The Hans Lollik augite-andesites are very similar to the coarser Louisenhoj augite-andesites as exposed on St. Thomas. They consist of pyroxene, plagioclase and magnetite phenocrysts in a groundmass of chlorite and plagioclase probably developed as the devitrification products of an andesite glass. A shard-like texture is present in some of the finer-grained samples, but contact metamorphism associated with nearby intrusives has obscured this texture in most specimens. Where metamorphism has been slight the plagioclase phenocrysts of andesine to labradorite composition show considerable patchy or irregular vein-like replacement by albite. Where the grade of metamorphism is higher some of the phenocrysts of plagioclase are more homogeneous and have a composition of oligoclase to sodic labradorite depending upon the degree of metamorphism. However, many relic phenocrysts of labradorite remain even where highly metamorphosed.

The phenocrysts of pyroxene range up to 5 mm in length and are usually euhedral although occasionally subhedral. Their composition is shown in Figure 4. When metamorphosed they show replacement by hornblende and rarely by epidote or chlorite. Low grade metamorphism normally has had no effect on the pyroxene with the exception showing marginal alteration to chlorite. Higher grades of metamorphism produce replacement of the pyroxene by strongly pleochroic hornblende either as patches and rims or as replacement of the whole crystal. Patchy replacement by epidote was also observed.

The groundmass is most readily altered by metamorphism and rapidly loses its tuffaceous texture. An amphibole resembling actinolite replaces the chlorite in the higher

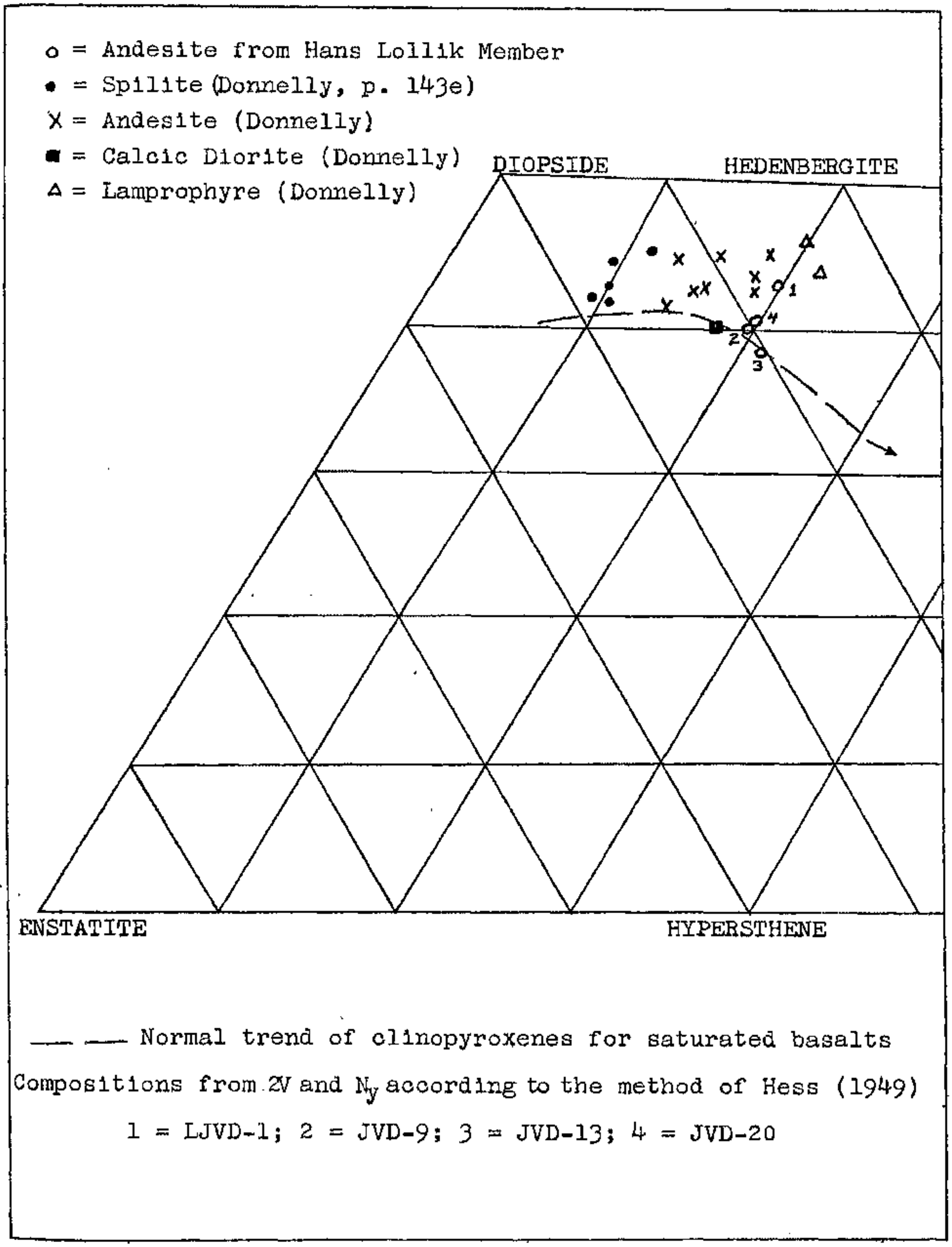



Figure 4. Composition of Clinopyroxenes

Figure 5. Polished slab of a lithic-lapilli tuff (LJVD-2) showing the wide variation of textural types within the upper part of the Hans Lollik member.

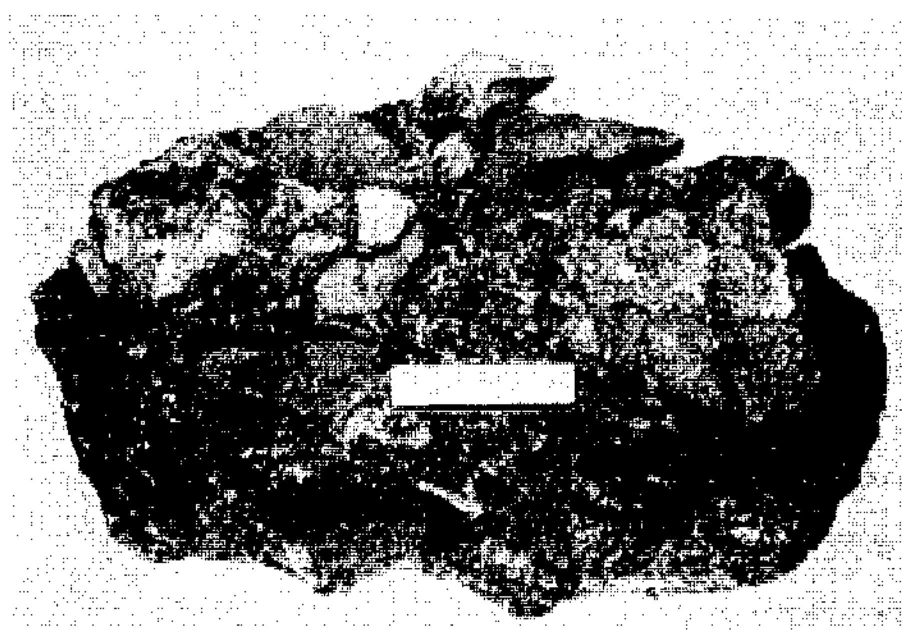


Figure 6. Hand specimen of JVD-22 showing the weathered surface of a limestone-bearing augite-andesite breccia of the Hans Lollik member. All of the fragments in the upper portion of the picture are limestone.

grades of metamorphism while epidote has replaced the groundmass chlorite and plagioclase at lower grades.

The fragments within the Hans Lollik member are extremely variable with respect to both size and texture. Blocks in excess of four feet in the largest exposed dimension occur in several of the breccias on Jost van Dyke. Normally the largest fragments in an outcrop are less than one foot in maximum dimension. The minimum sized particles are submicroscopic. In texture the fragments vary from porphyritic augite-andesites to amygdular aphanitic andesites and occasionally fragments of pilotaxitic andesite or felsite with virtually no ferromagnesian minerals. These three textural types are not the only ones present as gradational mixtures between them have been observed in most specimens. A few fragments of detrital origin have also been observed suggesting reworking of previously deposited breccias and tuffs.

Coral and limestone fragments were found in three breccia units of the Hans Lollik member and have yielded foraminifera of Eocene age as discussed later.

The petrographic descriptions of individual samples of the Hans Lollik member are given in Appendix A. Sample T-170 was collected from one of the thin lenses lower in the section and interbedded with the Sage Mountain member. The other samples were collected from near the top of the Hans Lollik member (upper 2,000 feet).

Most of the samples are mixtures of the breccia and

and tuff end members. Several limestone fragments were observed in the breccias showing the presence of the limestone end member, however from a quantitative point of view this end member is not very important. The remaining end member, volcanic sandstone, was also recognized, however only one sample (JVD-15) was studied in thin section and its description is included in Appendix A. The field occurrence is in a thin bedded to massive tuffaceous volcanic sandstone sequence about 45 feet in thickness. This is the only definitely reworked material found in the Hans Lollik member, however part of this may be only an apparent scarcity since the fine grained sediments are normally poorly exposed.

Depositional Environment

The augite andesites of the Hans Lollik member of the Tortola formation were deposited on the flanks of a volcanic cone which was probably located in the vicinity of the Hans Lollik Islands. Some of the massive breccias of the Tobagos and Hans Lolliks may be remnants of the cinder cone. Most of the member, however, was deposited on the gently sloping flanks of the volcanic cone or in basins surrounding it and was probably carried there by mudflows or other mass movements. Eastward from the maximum development of the breccias the fragments rapidly decrease in size and the units become thin tongues or lenses of augite-andesite breccias, tuffs and tuffaceous volcanic sandstones interbedded or locally intermixed with the Sage Mountain member, thus suggesting that this pyroclastic debris accumulated at the same time as the pyroclastic debris that had a source farther to the east. The limestone and coral fragments, but no beds of limestone, indicates that these breccias were deposited at depths of over 200 feet after having incorporated limestone fragments as they were transported, probably in the form of mudflows, over (or through) the reefs surrounding the subaerial cone. The cone may not have been subaerial during all of its history but at least the later portions of it were, for these are the portions that contain the shallow water coral and limestone fragments.

Age

Thin sections of a limestone fragment from the Shark Bay member, JVD-14, include foraminifera belonging to the Eocene. Dr. W. Storrs Cole (personal communication, 1960) states: "JVD 14 . . . seemingly could be regarded as middle Eocene. I recognize *Asterocyclina* sp., *Pseudophragmina* sp., and *Eoconuloides* sp."

A description of the limestone fragment containing the fossils is given below.

JVD-14 The sample consists of a fragment of limestone about three inches in diameter incorporated in a lithic lapilli tuff probably belonging to the Shark Bay member, but interbedded with the Hans Lollik member. The fragment has an irregular but slightly rounded outline and appears to have been broken during transport. Several other smaller limestone fragments were also found.

In thin section the sample consists of calcareous algae and foraminiferal remains, some of which are broken, in a fine grained cryptocrystalline groundmass of calcite. Plagioclase and epidote were the only clastic fragments observed. The more porous areas have been silicified with the formation of radiating pore fillings of chalcedony. This is most pronounced near the edges of the fragment.

A sample of coral (JVD-7) about six inches in diameter was found in a volcanic breccia about 1,000 feet stratigraphically below sample JVD-14. Dr. J. W. Wells (personal communication, 1960) identified it as follows:

> ". . . JVD 7 . . . [is] a new species of Stylophora, a genus that ranges from Lower Eocene to Miocene in the West Indies. . . . it is a species not closely related to any of the Oligocene forms. It may well be the same as that represented by a couple of very badly preserved specimens of this genus I have seen from the Lower Eocene Richmond formation of Jamaica."

The above information leaves little doubt as to the minimum middle Eocene age of the upper part of the Hans Lollik augite-andesite breccias. The beginning of the volcanic activity is not dated, but it is probably also Eocene, even though there are about 20,000 feet of pyroclastics between the top and bottom of the member. Supporting evidence for this interpretation comes from work in the Coamo area of Puerto Rico where E. A. Pessagno (Princeton PhD thesis 1960) has described a section of marine sediments including pyroclastics which has a thickness of about 17,000 feet. He has shown that this section was deposited during a small portion of the late middle Eocene. The Hans Lollik member is thus thought to be restricted to the Eocene, probably to the middle Eocene, rather than representing a large fraction of the time between Turonian and middle Eocene.

## SAGE MOUNTAIN MEMBER

### Introduction and Description

The Sage Mountain member of the Tortola formation, as described here, includes all of the pyroclastics and reworked pyroclastics above the fine grained Tutu formation and below the lapilli tuffs of the Shark Bay member of the Tortola formation, exclusive of the augite-andesite breccias and tuffs described under the Hans Lollik member. It is the time equivalent of the Hans Lollik member since it interfingers with it but is lithologically separate because it is composed of the pyroxene-free pyroclastics derived from an eastern source, probably in the vicinity of Virgin Gorda. The upper boundary of the Sage Mountain member is somewhat arbitrary but is usually recognizable by the abrupt change from light tan to brown fine grained volcanic sandstones and tuffs to lithic lapilli tuffs generally light or whitish green in color. The name is derived from Sage Mountain, on the slopes of which are typical exposures of both the interfingering and intermixing of the Hans Lollik and Sage Mountain members. Excellent, but discontinuous, exposures are also present around Road Harbor and a moderately metamorphosed but well exposed section is present along the shore from Road Harbor to Paraquita Bay. No one well exposed section is available.

The distinction between the Sage Mountain member and the Hans Lollik member is locally difficult to make as there is considerable mixing of the two rock units as well as interfingering both vertically and horizontally. This, together with poor exposures over most of the area and contact metamorphism by the neighboring intrusives, leaves considerable doubt as to the exact relation between these two members in many localities.

Petrography

The lower portion of the Sage Mountain member is predominately tuffs, both coarse and fine grained, and volcanic sandstones, many of which have some reworked augite-andesite breccias incorporated in them. Several breccia and lapilli tuff units are also present, but these have been sufficiently altered by the metamorphism to remove all evidences as to their original nature. All the breccias in this part of the section which have not been strongly metamorphosed apparently belong to the Hans Lollik member.

In the upper portion of the member similar tuffs and volcanic sandstones are present, interbedded with lapilli tuffs and breccias, some of which become thicker and coarser eastwards. These breccias consist of fragments of andesite with an absence of pyroxene crystals. A large variety of textural types is present in the fragments with the most prominent being aphanitic andesite, andesite porphyries, amygdular andesite and pilotaxitic andesite. No megascopic

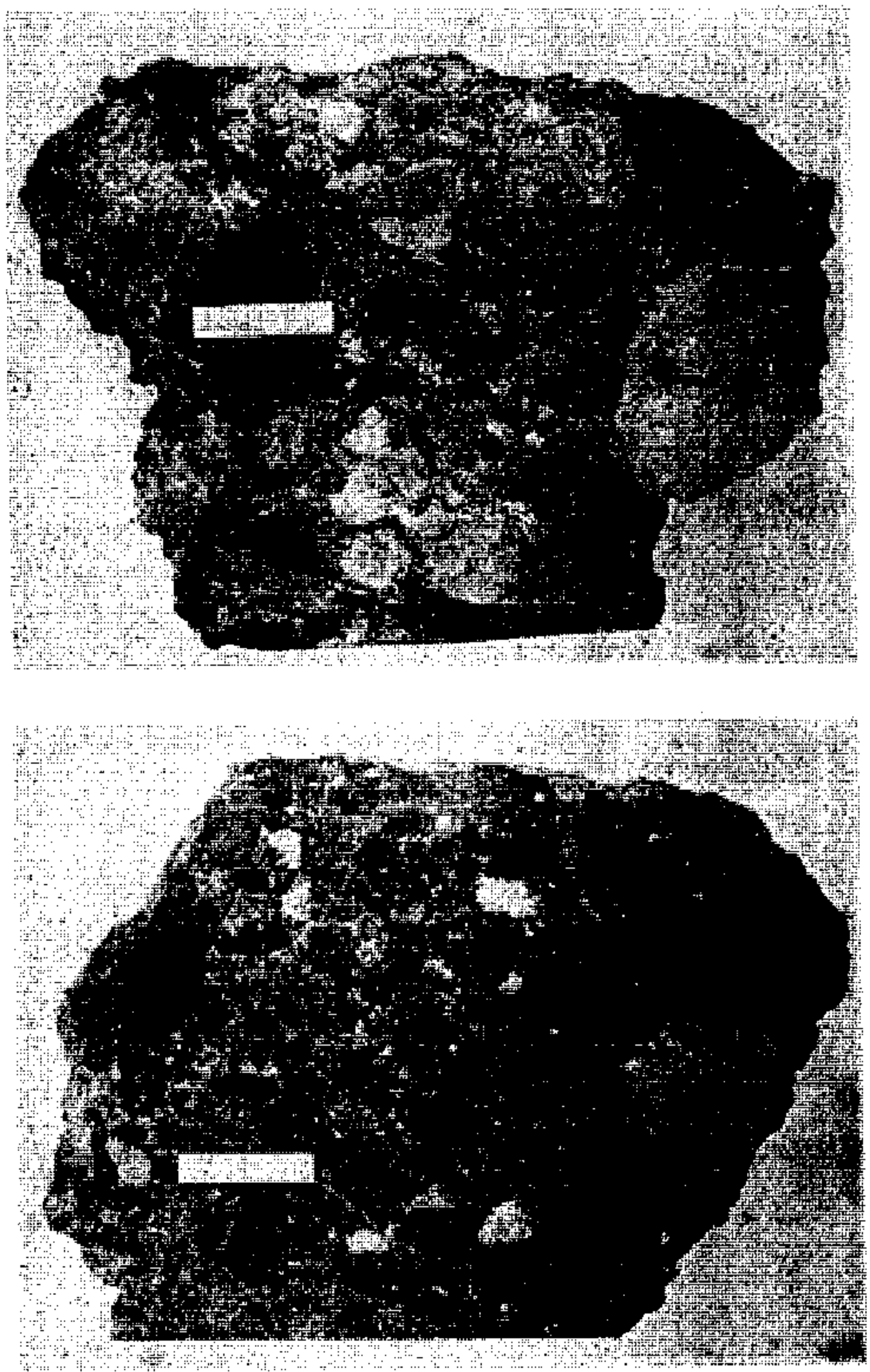


Figure 7. Sample of mildly metamorphosed breccia from the upper part of the Sage Mountain member. The upper photograph shows the weathered surface; the lower photograph shows the polished slab. The light colored fragments have been partially replaced by epidote.

Figure 8. Metamorphosed volcanic sandstone (T-99) from the lower portion of the Sage Mountain member showing poor sorting and slight grading.

glassy fragments are present. Fragments are rarely more than six inches in diameter in any of the exposures of the member.

The volcanic sandstones have been considerably reworked as indicated by rounded grains, cross-bedding, ripple marks and sharp bedding planes in relatively coarse sediments. Sorting is usually fair but is probably somewhat skewed toward the finer sizes. No conglomerates were observed; several units were described in the field as coarse wackes, actually volcanic sandstones, and probably represent the coarsest of the reworked material.

The tuffs show a typical groundmass of shard-like material surrounding both euhedral plagioclase crystals and angular lithic fragments. Sorting is poor except in the finest tuffs which are moderately well sorted.

For detailed descriptions of samples from the Sage Mountain member see Appendix B.

## Depositional Environment

The Sage Mountain member was deposited in the basin or basins between two or more volcanic cones. The pyroclastics from one of these cones were entirely augite-andesites and constitute the Hans Lollik member. The pyroclastics and reworked volcanic debris from the other volcanic center or centers, one of which was to the east in the vicinity of Virgin Gorda, constitute the Sage Mountain member. About half of the Sage Mountain deposit has been reworked by waves or currents. The remainder consists of pyroclastic deposits, which show little or no reworking, and breccias that were probably transported as mudflows. The coral and shallow water limestone fragments found in the slumped breccias in the upper portions of the Hans Lollik member indicate that these breccias incorporated shallow water limestone prior to deposition. These breccias probably were originally deposited on the slopes of a subaerial cone and acquired the limestone fragments during transport through or over the reefs surrounding the cone. Since the Sage Mountain member interfingers with these breccias it probably is also in part subaqueous in origin. The presence of ripple marks and evidences of abrasion and sorting also indicate a probable subaqueous origin. The lack of calcareous material is somewhat puzzling however, unless the member was deposited in several hundred feet of water.

## Age

No fossils were found in this member, but, since it interfingers with the Hans Lollik member, it probably is the same age, namely middle Eocene for the upper portions.

## THE SHARK BAY MEMBER

### Introduction and Description

In the upper part of the Sage Mountain member several thin lenses of breccia and lapilli tuffs of a markedly different character, were observed interbedded with the tuffs and volcanic sandstone. Just above the tuffs and volcanic sandstones of the Sage Mountain member a thick sequence of these breccias and lapilli tuffs is present. They have a characteristic whitish green color and abundant fragments of dark green glassy material not observed elsewhere in the Tortola formation. These breccias and their associated finer grained pyroclastics have been named the Shark Bay member of the Tortola formation for their excellent exposures in the vicinity of Shark Bay on the northwestern corner of Tortola. The member conformably overlies and interfingers with the Sage Mountain and Hans Lollik members of the Tortola formation. It is overlain by the Necker formation, but the upper contact is nowhere exposed. The member is recognizable over a large area extending from the northwest portion of Jost van Dyke to the eastern end of Tortola. In addition, it is possibly present as highly metamorphosed blocks incorporated in the Virgin Gorda batholith.

Examined in detail the Shark Bay member is seen to consist of massive to thin bedded lapilli tuffs and coarse tuffs. Breccias with fragments up to 10 cm in diameter were seen in the vicinity of Shark Bay but were not seen farther to the east except higher in the section in the exposures on Rogue's Point and the neighboring headlands. The section on northern Jost van Dyke, Little Jost van Dyke and Green Cay is predominately breccia and lapilli tuffs with virtually no finer grained tuffs. This is probably due to the fact that the exposures were limited to massive units and the intervening covered areas may have contained the finer grained tuffs. The thicknesses and directional increase in particle size in the breccias and lapilli tuffs in the lower portion of the member indicate a source to the west of Tortola. Those higher in the section are not exposed sufficiently well along strike to permit detailed description to say much other than coarse material is found in all exposures. Slump structures showing northward transport and the wide spread distribution of approximately the same size pyroclastics make it quite probable that the source of these pyroclastics was south of the present outcrops rather than east or west as was assumed for the previous members.

In the vicinity of Jost van Dyke the Shark Bay breccias are interbedded with breccias of the Hans Lollik member. Interfingering of the two members indicates that the source of the Shark Bay breccias was not the same as that of the Hans Lollik breccias.

## Petrography

The Shark Bay breccias and tuffs consist of fragments of wide variety of textural types including devitrified glass fragments with relic perlitic structures not found elsewhere in the formation. Similar structures, however, were

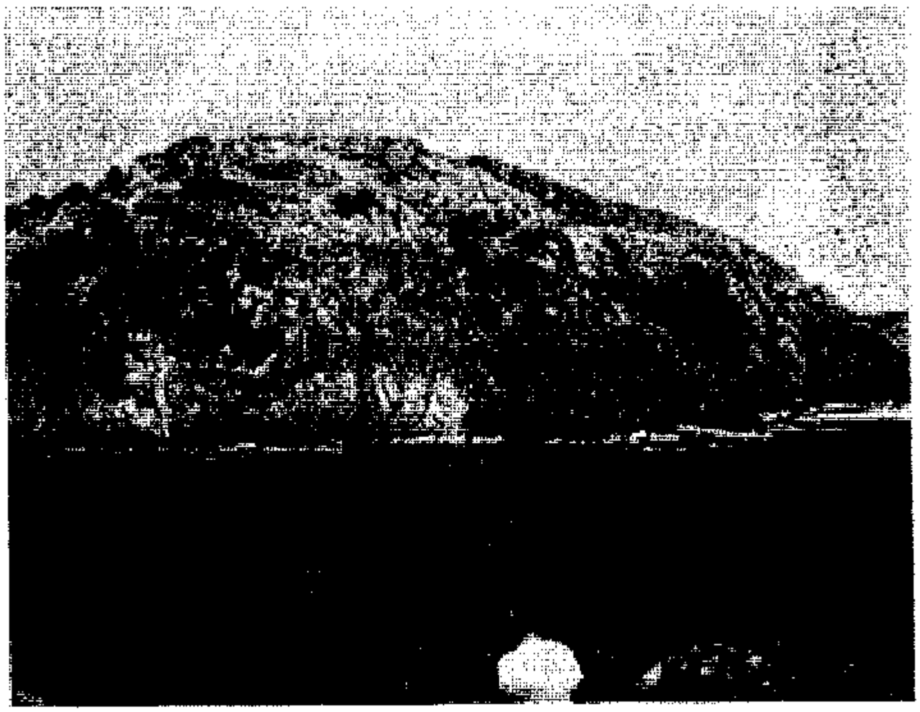


Figure 9. View of the eastern end of Little Jost van Dyke showing northward dipping bedding in lapilli tuffs and breccias at the right and left edges of the photograph. Several near vertical dikes are also present.

Figure 10. Cut slab of breccia taken from the boulder in the right foreground of Figure 9. Note the small bomb in the lower right corner and the alteration of the fragments. The dark fragments are glassy.

Figure 11. Light colored lithic lapilli tuff from the central portion of the Shark Bay member showing an indistinct alignment of fragments. The dark fragments are devitrified glass.

Figure 12. View of a breccia unit in the Shark Bay member as exposed on the north shore of Tortola.

reported by Donnelly (p. 65) from a few occurrences in the Louisenhoj formation. No pyroxene crystals, either free or in fragments, were noted in the Shark Bay member. Plagioclase phenocrysts are present in most of the fragments and are also present as free crystals in the groundmass. The composition of the plagioclase is quite variable but consistantly less calcic than that of the augite-andesites. Patchy replacement of intermediate plagioclases by albite is common and probably represents a deuteric or diagenetic alteration. Epidote and chlorite are common throughout the section; the former being due to mild metamorphism or possibly deuteric alteration, and the latter forming as the result of the devitrification of original glassy material. The four descriptions included in Appendix C are typical of the Shark Bay andesite tuffs and breccias.

## Age

No fossils were found in the Shark Bay member itself, but it interfingers with, and overlies, the upper portion of the Hans Lollik formation which is of middle Eocene age, and also includes a limestone lentil, the Mount Healthy limestone lentil to be discussed below, that has been dated as definitely Eocene, probably middle or upper Eocene.

## Depositional Environment

The environment of deposition of this member was not much different from that of other members of the Tortola formation except for the presence of the Mount Healthy limestone lentil which indicates a shallow, moderately quiet water environment for part of the formation. The lower breccias and tuffs are probably airborne material and mudflows which were deposited subaqueously while the upper part of the section most likely represents subaerial deposits. This is further supported by the highly weathered breccias in the vicinity of Rogue's Point, which probably were weathered subaerially shortly after deposition while the subaqueously deposited pyroclastics lower in the section do not show this strong weathering.

## Mount Healthy Limestone Lentil

In the saddle just north of Mount Healthy on northwestern Tortola a limestone about 50 feet thick is interbedded with the breccias and tuffs of the Shark Bay member of the Tortola formation. This light tan to brown limestone has been named the Mount Healthy limestone. It consists of algal material, pelecypod fragments, and foraminifera in a fine grained calcite matrix. It has been mildly sheared and locally recrystallized and altered with the introduction of iron hydroxide staining. Very few fragments of clastic material were observed, the few present being plagioclase and epidote crystals. The sample has been selectively silicified, a process which has destroyed some of the foraminifera.

In addition to the outcrops in the vicinity of Mount Healthy, the limestone crops out on Rogue's Point; and is probably also present farther to the east near the contact with the batholith where a garnet, diopside, epidote, hematite skarn has developed.

Two other lentils of limestone, now marble, were noted in the Tortola formation but probably have no relation to the Mount Healthy limestone. These two occurrences are on the northern shore of Sandy Cay and on the southeastern point of Little Tobago. The outcrops on Little Tobago are large marble blocks included within an amphibolite and probably represent a deposit much like the Coki Point megabreccia lithofacies discussed earlier (p. 32).

Samples of the Mount Healthy limestone were sent both to Dr. W. Storrs Cole and to Dr. P. Bronnimann. Dr. Bronnimann (personal communication, 1959) reported as follows:

T-221 <u>Lith</u>: Limestone, fragmental, brownish.
<u>Text</u>.: Groundmass cryptocrystalline to microcrystalline, showing stress.
Mollusk and echinoderm fragments.
Orbitoidal Foraminifera.
<u>Fauna</u>: Discocyclina sp., large Rotaliids.
<u>Strat</u>. <u>Det</u>.: <u>Eocene</u>.

Dr. W. Storrs Cole (personal communication, 1960) said: "T-221 contains only a few specimens of <u>Asterocyclina</u> sp. It could be either middle or upper Eocene, but I would favor middle Eocene on the slight evidence available."

Although there is no doubt as to the Eocene age of the unit, its position in the Eocene is somewhat questionable. Most likely it is virtually contemporaneous with the limestone fragment JVD-14 and thus should be considered to be middle Eocene in age.

A brief description of the Mount Healthy limestone at its type locality is as follows:

T-219 and T-221. Light brown, cloudy, very finely crystalline limestone showing considerable shearing and staining by iron hydroxides. Local patches show recrystallization to coarser grained clear calcite. Pelecypods(?), foraminifera, algal material, and other organic fragments are present. The weathered surface indicates a slight silicification of the sample. No clastic fragments are visible in hand specimen.

* * *

Flows Within the Tortola Formation

Along the shore between Road Harbor and Paraquita Bay there are several exposures of flows. One of these shows a brecciated zone about 18 inches thick at the upper contact and red staining of the sediments beneath it. Although these rocks are metamorphosed to the hornblende hornfels facies, a relic flow structure with a few amygdules is still present.

On the ridge west of Road Harbor in the vicinity of Meyers several massive amygdular units were observed, but

Figure 13. Hand specimen (T-160) of the brecciated top of one of the metamorphosed flows in the Tortola formation. The light areas are epidote. No amygdules are present in the brecciated portion of the flow.

their contact relations were not exposed. In thin section these look similar to the previously mentioned flows and since the two occurrences are approximately on strike the units in the vicinity of Meyers have also been classified as flows. An intrusive origin is possible, however, and thus their classification as flows is tenuous.

For petrographic descriptions of these flows see Appendix D.

## Resume of the Tortola Formation

The Tortola formation of probably middle Eocene age consists of four distinct lithologic units. These units embrace considerable textural variation and are mixed with one another on a local scale. The three major members consist of pyroclastic debris from at least three sources that varied in importance in both space and time. The Hans Lollik center was the first to develop and is characterized by pyroclastics of an augite-andesite composition. Shortly thereafter a center of volcanic activity developed to the east in the vicinity of Virgin Gorda. This center assumed an increasingly important role in supplying the pyroclastics for the unit and supplied virtually all of the observed pyroclastics just prior to Shark Bay time. The Shark Bay pyroclastics were derived from a moderately close source, probably located south of the line joining the other two sources. This source rapidly gained prominence, probably due to its proximity to the depositional sight, and continued to be the most prominent, and at times sole, source of pyroclastics until the close of Tortola time.

Volcanic activity was continuous during most of Tortola time, but several periods of reduced activity are represented by fine grained volcanic sandstones in the Sage Mountain member and by the Mount Healthy limestone lentil in the Shark Bay member.

## NECKER FORMATION

### Introduction

The fine grained tuffs, interbedded with a few breccias and tuffaceous volcanic sandstones, that crop out on the small islands north of Virgin Gorda, and on the islands of 'Guana and Great Camanoe are named the Necker formation for their typical development and excellent exposures on Necker Island. The complete range of the rock types included within this formation is not exposed on Necker Island and thus the type section is extended to include the breccias on Prickly Pear Island and the welded tuffs exposed of 'Guana Island.

The exposures, though excellent, are very discontinuous since the outcrops are restricted to eleven widely spaced small islands. Accordingly no attempt was made to place the rocks into a continuous stratigraphic sequence, nor to subdivide them into members, even though considerable variation is present. Instead the formation is described as three island groups within which the outcrops are sufficiently concentrated to enable local stratigraphic sections to be developed.

### Description

The formation is exposed on three distinct island groups which have little relationship to one another. These island groups are: (1) the islands north of Virgin Gorda (Mosquito, Prickly Pear, Eustatia, Little Saba and Necker); (2) the islands of 'Guana and Great Camanoe; and (3) the Seal Dogs, Cockroach Dog and George Dog. The latter group forms a connecting link between the first two, however exposures are poor and some of the outcrops show considerable metamorphism; as a result they are of no use in developing a stratigraphic section.

## The Necker Formation North of Virgin Gorda

In some ways the pyroclastic rocks on the five islands north of Virgin Gorda resemble the upper Tortola formation their major difference being that they are predominately fine tuffs rather than breccias and are much less deformed; the maximum dip being about 40 degrees and the average being near 20 degrees instead of nearly 90 degrees as in the Tortola formation. Metamorphism has been slight with epidote being the only possible metamorphic mineral and this probably was formed at relatively low temperatures.

The basal part of the exposed section is on Prickly Pear Island where about 1,700 feet of section is exposed. The basal 500 feet consists of light blue green to green very fine tuffs with poorly developed bedding. These fine tuffs are interbedded with a few moderately well sorted, green lithic coarse tuffs which have an alignment of tabular fragments

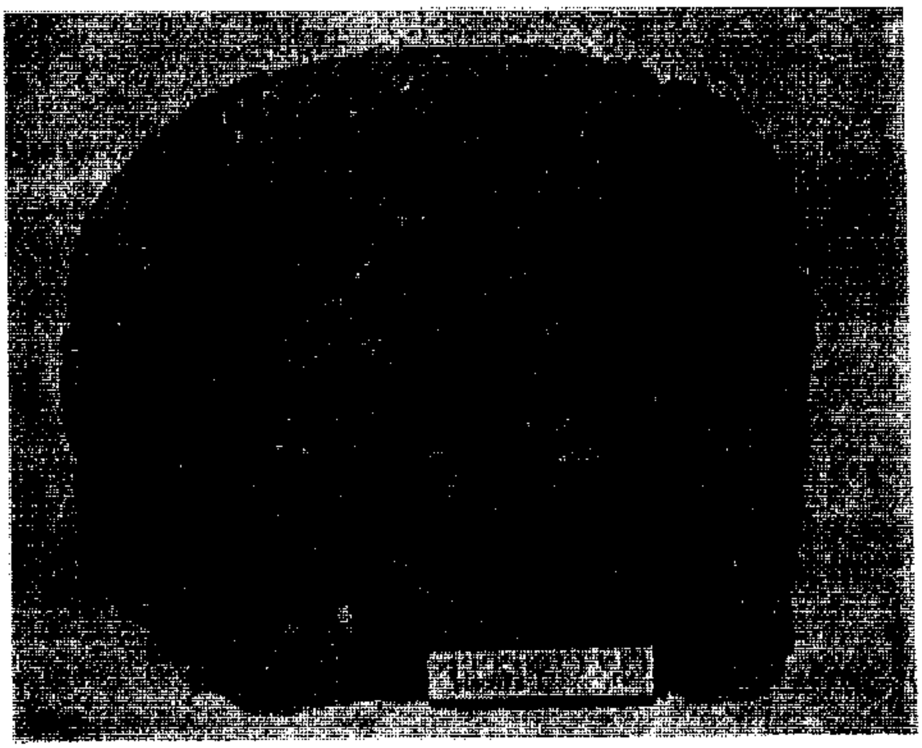
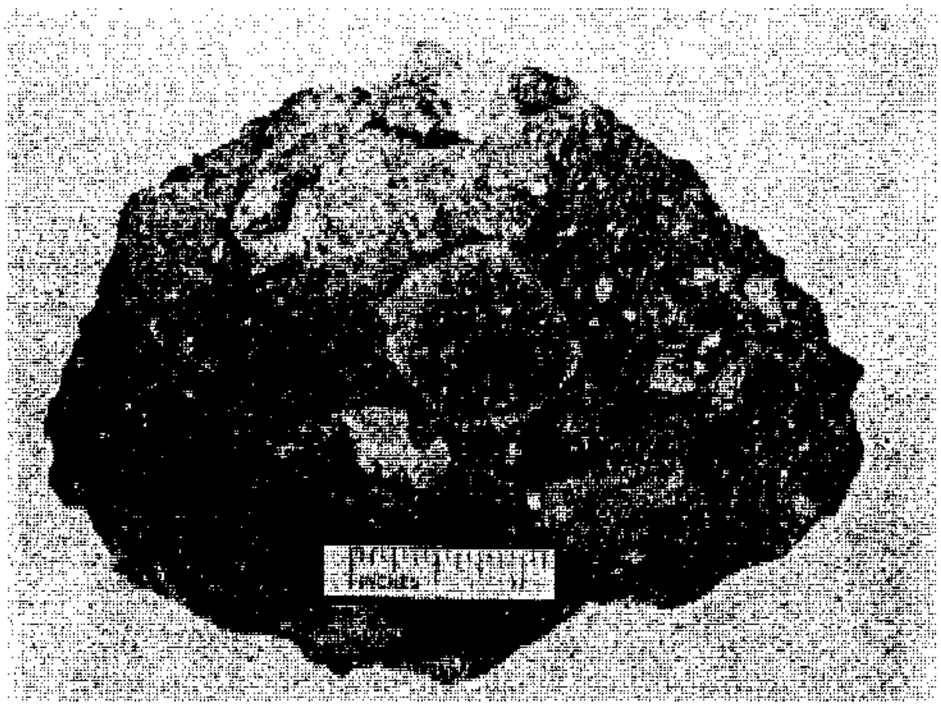


Figure 14. Hand specimen (PP-10) from a lithic coarse tuff interbedded with fine tuffs in the basal 500 feet of the Necker formation north of Virgin Gorda. The small dark fragments are glass or devitrified glass.



a

b

Figures 15(a) and 15(b). Lithic lapilli tuffs from outcrops on the northern half of Prickly Pear Island. The granophyre and diorite fragments mentioned in the text were collected from a breccia associated with these lapilli tuffs.

parallel to bedding which is probably due to primary orientation of fragments and not to later reworking. The rocks were probably deposited as a subaerial ash which was later mildly altered or metamorphosed. No evidence of reworking or slumping is present.

The upper 1,200 feet exposed on Prickly Pear consists of lithic coarse tuff and lithic lapilli tuff with a few interbedded units of breccia and vitric(?) fine tuffs. The coarse tuffs and lapilli tuffs are green colored, varying from whitish green to dark green, and consist predominately of andesitic and felsitic fragments with a wide variety of textures. Numerous dark green chloritic fragments, which probably were originally glass, are also present. Three fragments (samples PP-4 and PP-9) of unusual character were collected and will be described more fully in Appendix E. These are: (1) a fine grained diorite fragment about 2 cm in diameter, (2) a quartz - plagioclase - orthoclase granophyre fragment about 15 cm in diameter and (3) a metasediment, probably a metamorphosed andesite breccia, in which hornblende is present in the fragment but not in the breccia around it. These three fragments, the only ones of their types found in the Virgin Islands, indicate that the batholith had been at least partly emplaced prior to the deposition of the Necker formation.

The section on Mosquito Island is a continuation of that on Prickly Pear, possibly with a slight (200-300 feet) amount of overlap between the two sections. Most of the island consists of light green to brown lapilli tuffs and breccias. All the rocks on Mosquito Island have undergone considerable alteration with clay minerals and epidote having been formed throughout both the groundmass and fragments. Fragment boundaries are very indistinct, probably as the result of the extensive alteration. Bedding is poorly developed in these tuffs and breccias and where it is present it is moderately deformed and contorted suggesting that most of the deposit has slumped, probably to the north. Several units of coarse and fine tuffs are present, which are light olive green and show little bedding. At one locality a sandstone "dike" of the overlying(?) lapilli tuff intrudes fine tuff. This dike is not of volcanic origin. An unusual rock type occurring on Mosquito is a white to brown (when limonite stained along fractures) rock that may be a devitrified and altered lithic or vitric tuff or it may be a very fine grained felsite flow. In thin section no flow texture was observed and only few highly altered felsic fragments are present in an otherwise very fine grained interlocking groundmass of plagioclase and quartz(?).

Eustatia Island is very similar to the upper portion of the section exposed on Prickly Pear and consists entirely of lapilli tuffs and breccias.

Necker Island contains the uppermost section exposed in the Virgin Islands. A covered interval probably exists between the uppermost rocks exposed on Mosquito Island and the lowermost rocks exposed on Necker Island. However, since three miles of water deparates these two islands, this is only a suggestion based upon the amount of section that could be accounted for by the one mile of water between Prickly Pear and Necker Islands.

The section on Necker Island consists of about 1,300 feet of thin bedded to massive tuffs with a few interbedded lapilli tuffs and breccias. Little of the section has been reworked. One sample on the north shore may be a deposit much like a fanglomerate, since it has some sorting and an indistinct bedding formed by varying amounts of coarse fragments. The fragments, however, are very angular and probably have undergone little reworking.

The units in the central portion of the island have undergone slumping and in the vicinity of the easternmost point of the island, slump structures are seen to be overturned to the south, indicating transport to the south, the first time this has been noted in any of the Virgin Islands. The section has undergone little metamorphism, the only alteration being subaerial weathering and possible diagenetic alteration to form epidote from the glass shards in the tuffs. The epidote may have been developed in the outermost metamorphic halo surrounding the Virgin Gorda batholith which lies several miles to the south.

On Necker Island lithic lapilli tuffs and breccias are restricted to the basal 500 feet of the exposed section. Most units show moderate sorting and some have very poor bedding. Very angular fragments (to 10 cm) and plates of chlorite-like material, possibly an alteration of glass shards, are present in all coarse grained samples and do not appear to have been abraded by reworking.

Fine tuffs form most of the upper 800 feet of the section. These tuffs are probably vitric tuffs and have undergone recrystallization to form an intergrown network of epidote, plagioclase and quartz. They are well sorted and poorly, yet distinctly, bedded. No ripple marks, crossbedding, or other current features were observed. The tuffs were probably deposited subaerially, yet show no signs of weathering . The interbedded breccias, however show iron staining throughout which has been interpreted as subaerial weathering shortly after deposition. It is possible that this weathering was restricted to the coarser units because of greater porosity and permeability but is more probably due to their higher content of mafic materials.

The Necker formation is intruded by numerous porphyritic basalt dikes and sills several of which are present on Mosquito Island and one columnar jointed example of which is present on southern Necker Island.

Petrography: Necker Formation North of Virgin Gorda

Under the microscope the presence of quartz as distinct fragments of crystals is a very distinctive feature not observed in the lower members of the Virgin Island group. Previously, quartz has been noted as amygdule fillings and as a major constituent in the quartz keratophyres. In several specimens of the upper Tortola formation, as well as in the Outer Brass limestone, chalcedony was observed but only rarely have fragments of quartz been observed. This presence of fragments of quartz is significant in two respects. Firstly, it provides a means of distinguishing the breccias of the lower part of the Necker formation from those of the Shark Bay member of the Tortola formation. Secondly, it most likely provides additional evidence that the batholith had been emplaced and at least partially cooled prior to the deposition of the Necker formation. The porphyritic andesite clasts do not have modal quartz, except as a fine grained replacement or as a chalcedonic amygdule filling, and thus cannot have supplied the quartz fragments observed elsewhere in the rock. The only possible source seems to be the quartz diorites of the batholith. It is strange however, that so few granitic fragments were found in the breccias--the only two having been those in sample PP-4.

The mineralogy of this portion of the section is quartz, plagioclase, epidote, chlorite and possibly glass. Magnetite is also present in some samples. The plagioclase is quite variable in composition from calcic andesine, which probably is characteristic of the unaltered plagioclase, to albite which has been produced by alteration of pre-existing plagioclase phenocrysts and from original glass. Most of the samples cluster at both ends, i.e., albite and andesine, with a few determinations indicating a sodic oligoclase composition. The epidotes are of two forms. Those nearer to the batholith have a light green color and high dispersion while those farther from the batholith have a yellow to yellow green color and much less dispersion. The latter may have been formed under virtually diagenetic conditions slightly above normal temperatures while the former may represent epidotes that are more truly of metamorphic origin.

For detailed descriptions of some of the rock types see Appendix E.

The Necker Formation: Vicinity of "The Dogs"

The exposures of this portion of the Necker formation are limited to three islands, namely, Cockroach Dog: all exposures are amphibolite and virtually no original textures or structures remain; George Dog: all exposures are amphibolite, however the rocks are probably fine tuffs interbedded with breccias or lapilli tuffs; and the Seal Dogs which are mildly metamorphosed. The rocks exposed on the Seal Dogs will be discussed below.

The presence of fragments of quartz crystals, which were observed in two specimens and a dioritic fragment, very similar in macroscopic appearance to one of the fine grained intrusives on West Dog, is the slight evidence available for grouping these rocks with the Necker formation. Other than this and their position in the islands, these rocks have closer relationships with the Tortola formation and may actually belong with it. This correlation is based upon their degree of metamorphism, never otherwise observed in the Necker formation, and on the presence of a pyroxene bearing basalt or basaltic-andesite flow. However, this flow contains the dioritic fragment mentioned above and thus must be later than the batholith which is observed to cut all of the Tortola formation. Thus, the rocks in the vicinity of "The Dogs" are assigned to the Necker formation.

The exposed section on the Seal Dogs consists of breccias and lithic lapilli tuffs, most of which show evidence of some reworking especially in the form of large scale slumping as evidenced by large blocks, several over ten feet long, of fine grained thin bedded tuffs incorporated within lapilli tuff. Bedding is very poorly developed to non-existent. Much of the section is quite altered, with epidote having developed throughout the section, probably as a result of being near the upper contact of the batholith.

The following five descriptions indicate the detailed character of the rock. These are not necessarily typical examples, however.

SD-1 is a grey to grey green crystal-lithic coarse tuff. Numerous dark green glassy patches are present probably consisting of chlorite after original glass. The maximum fragment size is about 4 mm.

Sericite: as alteration of plagioclase.
Epidote: alteration of groundmass and plagioclase; present as single crystals and aggregates of crystals.
Chlorite: probably replacing glass.
Plagioclase: $An_{20-30}$; broken crystals, however the angularity is not great
Magnetite
Calcite: alteration of groundmass.
Quartz
Rock fragments are of a trachitic nature.

The sample has undergone some reworking as is evidenced by the rounding of the plagioclase grains and lithic fragments. Textural variation between the groundmass and the lithic fragments is very small and has been partially obscured by the alteration that produced the epidote and calcite, most likely associated with the intrusion of the Virgin Gorda batholith. The tuffaceous character of the rock is inferred from the presence of plagioclase crystals and lithic fragments and not from observed shard-like or angular fragments. Its field association also suggests an origin as a tuff or slightly reworked tuff. Sorting is very poor with grain size up to 2 mm common and with some fragments more than 5 mm long. A weak planar structure is present formed by mineralogic orientation parallel to bedding or flowage directions. Chlorite patches and mineral aggregates in the groundmass also have this orientation. This planar structure is thought to have developed by slumping of the tuffaceous ashes.

SD-12 is a thin bedded, slightly graded crystal-lithic fine tuff. Bedding is poorly developed, being represented by bands with lithic fragments in excess of 1 mm in an otherwise fine grained green matrix.

Epidote: alteration of plagioclase and as patches in groundmass.
Plagioclase
Magnetite
Quartz(?)
Sericite: alteration of plagioclase.
Calcite

The sample has been slightly reworked. However, the broken plagioclase crystals are still very angular thus the reworking, evidenced by sorting and bedding, has been very slight. Poorly developed graded bedding is present as is a "flow-like" orientation of crystals parallel to bedding. The structures parallel to bedding are probably primary, representing orientation by settling of tabular shard-like masses, as slumping is very unlikely considering the very thin parallel bedded character of the sample in the field.

SD-6 The sample is a light green lithic lapilli tuff in general appearance very similar to the breccias exposed on Prickly Pear and Mosquito Islands. A slight banding, probably developed during slumping, is present and is formed by the orientation of tabular fragments. Some fragments look very similar to SD-1. Large (10 mm) dark green chlorite aggregates are present throughout the sample. Most fragments are very angular and have not undergone reworking. Several fragments in excess of 60 mm are present.

SD-13 is a light tan thin bedded to laminated fine tuff showing possible slight reworking by water. The sample is from a large block (over six feet long) of fine tuff incorporated by slumping in a breccia similar to SD-6.

Quartz: fine crystals in the groundmass and as fragments.
Plagioclase: calcic oligoclase; $An_{28\pm5}$.
Epidote: throughout groundmass and as replacement of plagioclase.
Chlorite: replacement of ferromagnesians(?) or as replacement of large glass fragments.
Hematite: after magnetite(?).

This sample is a fine grained crystal-vitric(?) tuff composed of plagioclase crystals up to 1 mm in length imbedded in a very fine grained dirty brown groundmass of quartz, plagioclase, epidote and hematite that has probably been derived from the devitrification of glass shards. The sample is very thin bedded, being marked by abundant plagioclase crystals and by a variation in the size and amount of epidote formed as a replacement of the groundmass. The sample has probably been mildly metamorphosed giving rise to the epidote in the groundmass.

SD-7 is a dark grey to dark purple grey porphyritic flow with numerous lithic fragments. Some of these fragments appear to be altered fine grained granitics with large quartz crystals. These granitic fragments probably were derived from the upper portions of the batholith and appear to be very similar to samples collected on West Dog. A pronounced flow banding is present on the weathered surface.

Pyroxene: elongate euhedral crystals up to 1 mm; partially replaced by chlorite.
Plagioclase: $An_{45\pm5}$; euhedral phenocrysts up to 2 mm, mildly zoned, some broken.
Magnetite: euhedra up to 0.5 mm; associated with pyroxene and some within plagioclase phenocrysts.
Epidote: in fractures along with chlorite and quartz; also as alteration of plagioclase.
Chlorite: as alteration of pyroxene or else second ferromagnesian phase.

Quartz: fracture fillings and in included rock fragments.
Glass: dark brown and partially devitrified, showing strong flow banding around phenocrysts and lithic fragments; several glass fragments are also present and have fewer phenocrysts within them.
Rock fragments up to 1 cm.

The rock is a porphyritic lithic-vitric basaltic-andesite flow or very near surface intrusive, most likely the former. Included fragments of vitric material, much like the flow itself, and lithic material, foreign to the flow itself, are present suggesting both normal flow and flow breccia characteristics. This unit was not recognized as a flow in the field and is described as such from its thin section characteristics.

In addition to the above, one sample having undergone high grade metamorphism is included and is considered to be representative, in mineralogy at least, of the metasediments on George Dog and Cockroach Dog.

CD-1 is a dark green amphibolite. Large fragments are visible on the weathered surface along with amygdules, plagioclase phenocrysts(?) and porphroblasts(?) of hornblende. The rock appears to have been a lithic lapilli tuff or breccia.

Mineralogy: quartz, plagioclase, hornblende, and magnetite.

The rock is a metamorphosed fine grained crystal-lithic tuff. The grade of metamorphism is between epidote amphibolite and hornblende hornfels facies. Other than for the fragmental nature of the rock with its suggestion of bedding, no original textures are present. Very little metamorphic foliation has developed, the predominate change being the recrystallization of the groundmass and fragments.

## The Necker Formation: 'Guana Island Section

The 'Guana Island portion of the Necker formation consists of a wide variety of rock types all of which were deposited subaerially with the possible exception of one thin bedded to laminated very fine grained porcellaneous tuff, which may have been either a subaqueous or a subaerial deposit. The breccias, lapilli tuffs and tuffs were all weathered shortly after deposition without reworking, except for probable slumping. Some of the breccia units could be mudflow deposits, however. Several flow units were recognized varying from extensive welded tuffs with columnar jointing to flow breccias of very local development.

The entire section, including the later porphyritic basalt dikes and sills, has undergone considerable alteration with replacement of the original rocks by quartz, chlorite, calcite, epidote and sericite. Calcite, chlorite, and quartz are found as replacements throughout the section while epidote and sericite are restricted to local units. The sericite is restricted to the welded tuffs, flows and late basaltic intrusives and may in part be related to metamorphism by the batholith and/or the basaltic intrusives. At least some of this widespread alteration is later than the basaltic intrusives, which cut the entire section, and thus the alteration is probably associated with late magmatic and hydrothermal activity associated with the intrusion of the batholith rather than with the basaltic intrusives themselves. Some of the alteration probably took place very shortly after deposition particularly in the case of the welded tuffs which are much more altered than the surrounding lithic tuffs.

The entire section has been considerably deformed with the older southern units showing overturning with dips as low as 65 degrees in several localities. To the north the deformation rapidly becomes less intense with the northernmost portion of the island being gently folded and showing dips of 10 to 20 degrees in both north and south directions. No unconformity was observed between the two ends of the island, yet the differing degree of deformation suggests that one may exist. However, this strong deformation in the lower portion of the section is probably local deformation associated with the batholith which lies less than a mile to the south. No discontinuity in lithology or degree of alteration is present between the strongly and mildly deformed sections suggesting that the local deformation interpretation is most likely the correct one.

Due to the complex structure developed in the lower portion of the section and the scarcity of good outcrops, no detailed stratigraphic sequence could be deciphered. In general, the lower portion of the section consists of about 2,000 feet of welded tuffs interbedded with lithic lapilli and coarse tuffs. The welded tuffs show indistinct irregular bedding and a thin, highly contorted internal lamination. All the rocks are highly altered and weathered and no unaltered material could be found. In thin section the welded tuffs consist of oriented and highly altered plagioclase phenocrysts in an aphanitic groundmass which has been replaced by calcite and silica. Numerous flattened irregular amygdules are present and are responsible for the development of some of the

Figure 16. View of the southeastern shore of 'Guana Island showing massive to poorly bedded breccias and coarse tuffs (right side of picture) which are cut by many andesitic dikes (right center).

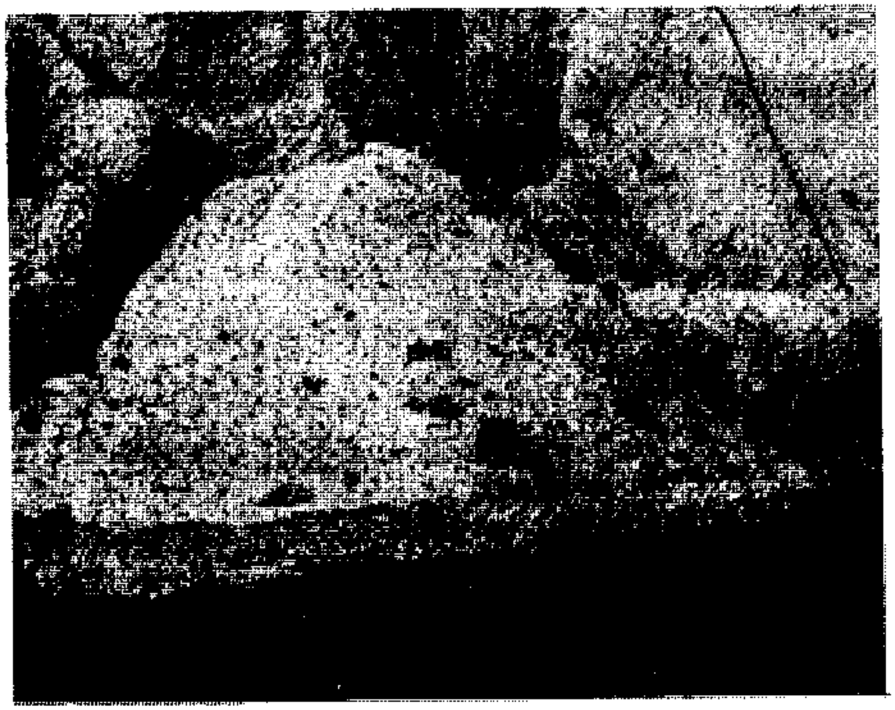


Figure 17. View of tuff breccia as exposed on the western shore of Great Camanoe. Note the disseminated large fragments in the coarse tuff.

Figure 18. Polished slab of the coarse tuff portion of the tuff breccia shown in Figure 17. All fragments have been highly altered to clay minerals and epidote.

lamination of the weathered surface. The alteration, with the formation of chalcedony, calcite, and sericite, was post-compaction, and may have been associated with the deformation since fractures in the rock have about the same mineralogy as the alteration products.

Overlying the lower welded tuff unit is a sequence of breccias and tuffs about 3,000 feet thick with at least one and probably two welded tuff units within it. This sequence has been moderately deformed with dips varying from 30 to 90 degrees. A section very similar in appearance to this is also exposed on Great Camanoe Island, but precise correlation of this section and 'Guana Island section is impossible.

The breccias in the portion of the section overlying the welded tuffs are quite distinctive in that they consist of large blocks, some over a foot in diameter, imbedded mostly in a coarse tuff and rarely a lapilli tuff. All gradations exist between normal breccias, consisting predominately of large fragments, to normal coarse lithic tuffs with only rare large blocks. Except for the two welded tuff units, all of this portion of the section exposed on the eastern half of 'Guana Island and all of the section exposed on Great Camanoe Island consists of this mixture of breccia and coarse tuff. Bedding is very rare, partly because it has been destroyed by slumping and partly because very little developed due to the poor sorting of the pyroclastics. These breccias vary in color from green to brown to purple.

The welded tuffs interbedded with these breccias resemble those lower in the section. However they have been so thoroughly altered that this may only be an apparent similarity and not a real one. One of them, G-23, shows columnar jointing in the field and has a flow banding much like G-24, yet it is so altered to clay minerals and calcite that its original internal textures have been entirely lost except for the radiating chalcedony spherulites that were also noted in G-24. The other occurrence of welded tuff in this portion of the section, G-12, has more of the features of the G-24 type and if both were unaltered they would probably be the same in all respects.

The remaining portion of the section consists of tuffs, both coarse and fine, lapilli tuffs, and a few breccias. Typical examples of these upper units are very well exposed along the north and western shores of 'Guana Island. Although sorting is better and bedding is more extensively developed than in the breccias above the lower welded tuffs, these tuffs and breccias appear to have been deposited as subaerial ashes. No evidence of water reworking or transport were seen and several units, such as G-5, which contains tuffaceous mudballs, could only have been formed subaerially. In addition, the tuffs seem to have weathered prior to their exposure to present day weathering, an interpretation which is supported by their deeply weathered nature even on sea cliff exposures where most other rock in the Virgin Islands is very fresh.

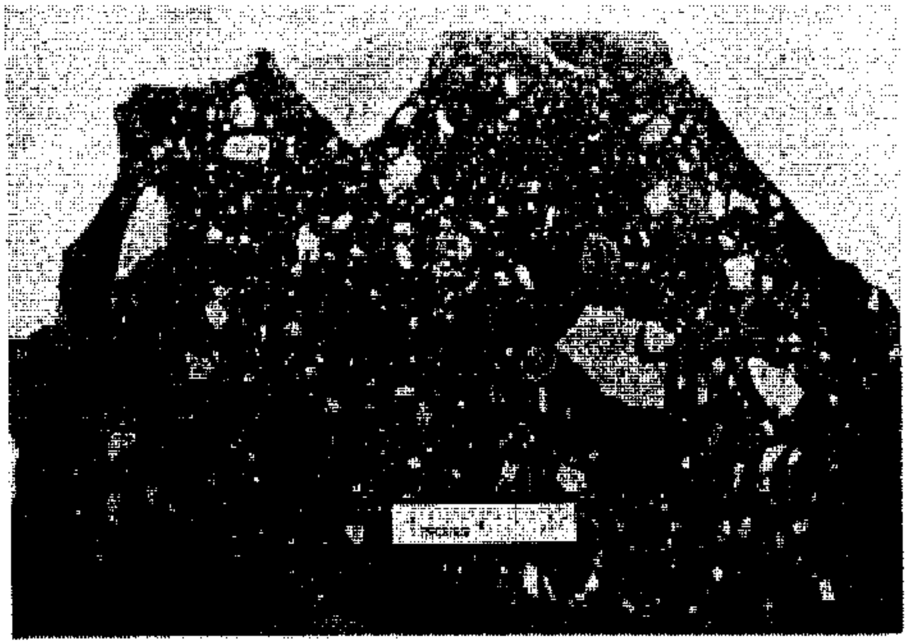


Figure 19. Polished slab of a flow breccia (G-33) from the central portion of the 'Guana Island section of the Necker formation. The fragments are predominately felsites and have been partially replaced by calcite.

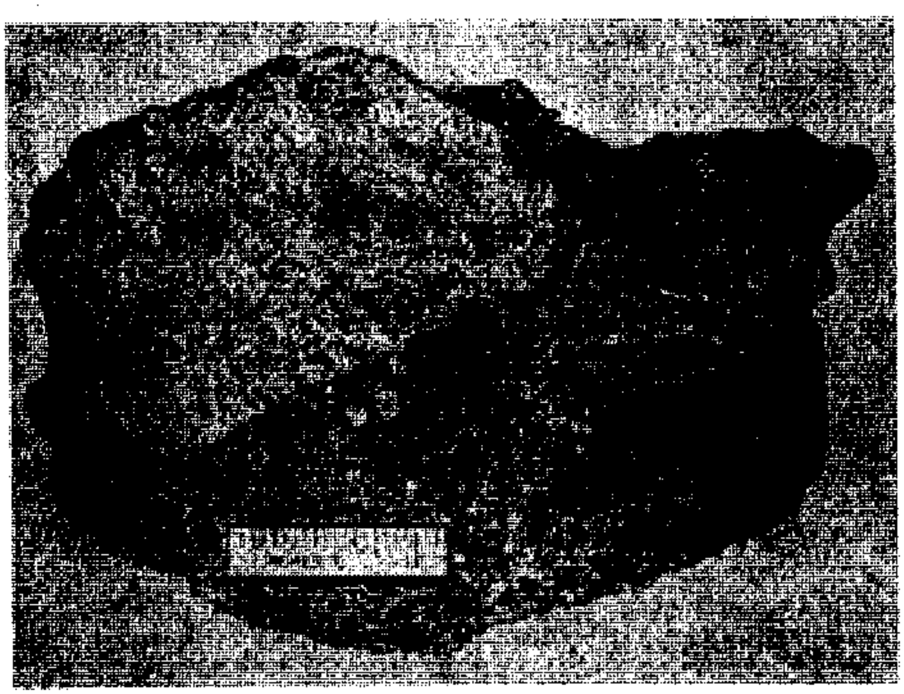
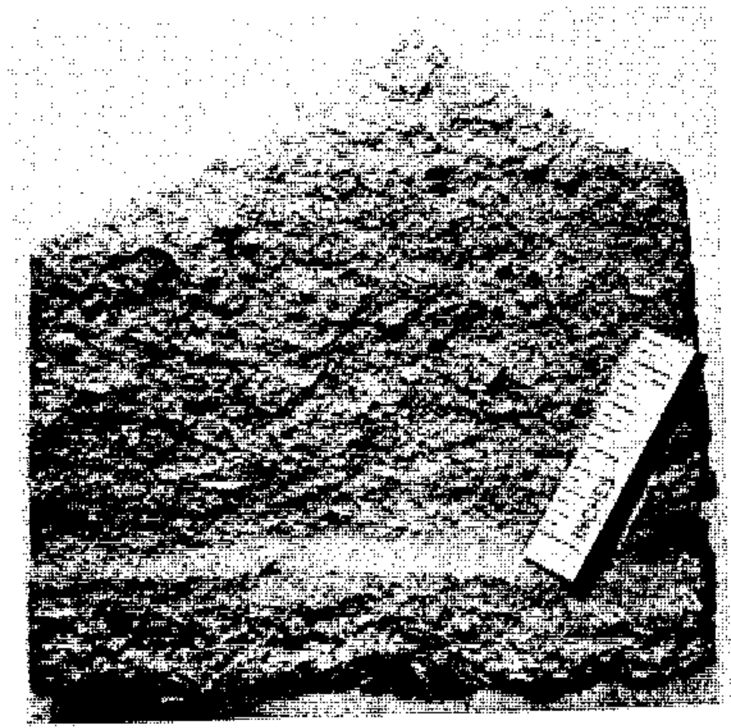
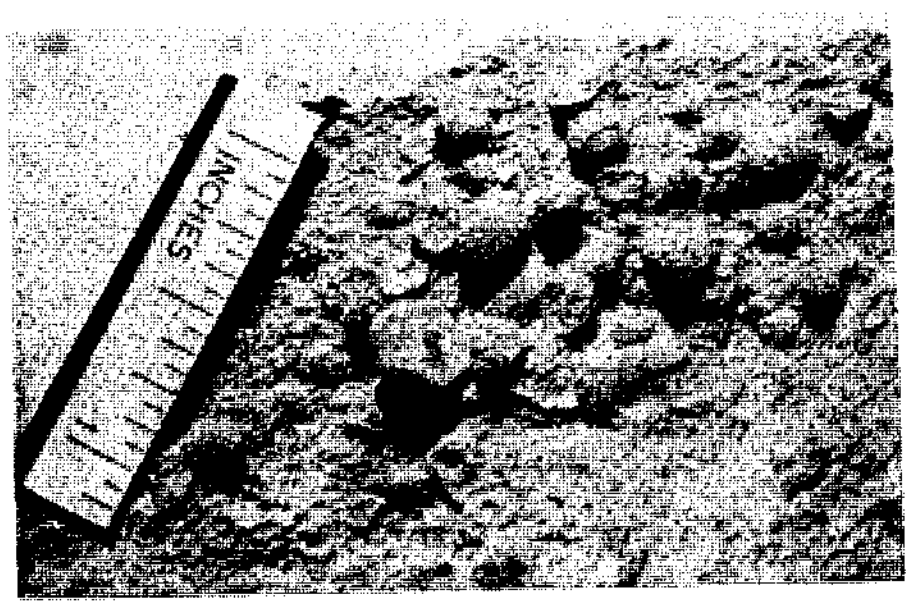


Figure 20. Cut slab of breccia (G-4) from the upper portion of the 'Guana Island section of the Necker formation. Note the large variety of fragment types.




<u>Figure 21</u>. Two views of the hand specimens of G-5 (see <u>description</u> in Appendix F) illustrating the tuffaceous "mud balls". The upper photograph shows numerous slightly flattened pellets while the lower photograph illustrates their spherical form.

For detailed descriptions of the samples mentioned above, as well as others of the typical rock types present, see Appendix F.

## Age of the Necker Formation

The age of the Necker formation is not known for no fossils were found nor are any likely to be found since the entire section appears to have been deposited subaerially. The formation apparently overlies the middle Eocene Shark Bay member of the Tortola formation, but as a result of lack of continuous outcrop this relationship is only inferred. Most likely the formation is of middle or upper Eocene age.

The upper portions contain fragments of granophyre and fine grained diorite, both of which were most likely derived from the Virgin Gorda batholith and, since the granophyre was one of the later phases of the batholith to develop, they indicate the presence of the batholith prior to the deppsition of the upper Necker formation. The lower portions are mildly metamorphosed and may indicate deposition either prior to intrusion of some of the batholith or deposition on a very thin cover over the cooling batholith with most of the evidence tending to support the latter suggestion.

Its age with respect to the deformation is also somewhat questionable since it may have been deposited both before and during deformation or it may have been entirely before deformation with the northward decrease in degree of deformation reflecting only milder folding to the north and not deposition after some of the folding had taken place. As will be discussed in more detail later, deposition prior to deformation is favored by the author.

Resume of the Necker Formation

The Necker formation is composed of predominately subaerially deposited pyroclastics and a few welded tuffs. One of the centers of volcanic activity was in the vicinity of 'Guana Island and another source of pyroclastics was most likely located to the east of Virgin Gorda. However evidence for this is very meager.

The formation was probably deposited during and slightly after the intrusion of the major portion of the Virgin Gorda batholith as fragments of the later intrusive phases of the batholith were observed in the breccias of the Necker formation. The welded tuffs may also represent the extrusive equivalent of portions of the batholith, however they are so altered that they cannot be shown to be exactly equivalent in composition to any portion of it.

Structurally the formation is significant in that the earlier portions of it probably were deposited prior to the major deformation while the later units could have been deposited after some of the deformation had taken place since they are only mildly deformed.

The age of the Necker formation is unknown except that it must be middle Eocene or younger. It should probably be included in the middle or upper Eocene, based upon its regional relations.

## ROGUE'S BAY CALCARENITE

At the eastern edge of Rogue's Bay on the north shore of Tortola a calcarenite, here named the Rogue's Bay calcarenite, crops out over an area of about 10,000 square yards. The calcarenite dips to the west 15 to 20 degrees and has a maximum elevation of about 65 feet above sea level. It also continues below sea level for at least 10 feet. The total thickness is between 30 and 40 feet.

The calcarenite consists of well sorted, 1 mm in diameter, shell fragments of pelecepods, gastropods and large foraminifera, mainly peneroplids. These fragments have been reworked and are moderately well rounded. They are cemented with calcite to form a limestone with about 10 percent porosity. Very few grains of silicates are present, the only ones observed being plagioclase and epidote, which form considerably less than one percent of the rock.

The age of this unit is late Miocene to Recent and thus it is not of much use in determining structural history. The fact that it dips away from the batholith is significant in that it shows that the eastern portion of the area has risen, with respect to the central portion of the area, through an angle of about 15 degrees, since the late Miocene. This indicates at least regional warping considerably later than the major folding which most likely took place in the late Eocene.

## INTRUSIVE ROCKS

### Introduction

Intrusive rocks crop out on all the British Virgin Islands except Anegada and can be subdivided into three groups, according to their age, as follows: (1) pre-batholith intrusives, (2) intrusives forming the batholith and (3) post-batholithic dikes. The pre-batholith intrusives crop out wherever pyroclastics are present and represent intrusives associated in time with the deposition of the pyroclastics. This group comprises dikes and sills and are probably represented as extrusives in the flows of the Tortola formation and as fragments throughout the pyroclastics.

The batholithic rocks are predominately tonalites and consist of many compositional and textural variants. They crop out on Virgin Gorda, eastern Tortola and on the small islands between Virgin Gorda and Tortola and they probably have considerable underwater extension between Virgin Gorda and Tortola and to the south of Tortola. They appear to be later than most of the pyroclastics; however, the welded tuffs in the Necker formation, as well as the granophyre and diorite fragments, indicate that some of the pyroclastics are younger than the batholith. The welded tuffs of the Necker formation are probably the extrusive equivalents of some portions of the batholith.

The third group consists of dikes and sills, some of which are associated with late magmatic activity and some of which were intruded considerably later and are apparently associated with the development of the Anegada trough.

## Early Intrusives

Most of the early intrusives represent intrusive equivalents of the pyroclastics. They are most commonly observed as thin andesite or augite-andesite dikes. They are micro-crystalline, occasionally porphyritic, and are concentrated in local areas, the intervening areas having relatively few dikes. The best exposed example of these dike swarms is on the northern shores of Jost van Dyke and Little Jost van Dyke. Numerous examples were also observed on southern Jost van Dyke and throughout Tortola, but since most of these exposures have been moderately metamorphosed and the dikes are now difficult to recognize, many probably went unnoticed. Their petrography is very similar to the pyroclastics, except that they are slightly coarser grained; three examples, JVD-4, JVD-6 and JVD-56, are discussed in Appendix G.

Several andesite dikes have a marked banding parallel to the walls which is represented by alternating bands of aphanitic and porphyritic aphanitic andesite which were probably produced by movement of the magma during crystallization. These bands are from 2 to 6 inches thick and are continuous for distances up to 20 feet along the dike.

Besides the andesite dikes mentioned above, several metamorphosed basalt and porphyritic basalt dikes are present. One of these has inclusions of quartz diorite in it which indicates that it is later than at least part of the batholith. In addition to the metamorphosed basalt dikes, several unmetamorphosed porphyritic basalt dikes with columnar jointing intrude the upper portion of the Necker formation--these intrusives are thus thought to be later than the batholith. The only basalt dikes known to be pre-batholith have been at least mildly metamorphosed so that their original character is at least partially obscured; three descriptions, T-96, T-131 and JVD-20, of these dikes are included in Appendix G. These are virtually equivalent in composition to the porphyritic basalts to be described later under post-batholithic dikes.

Several other minor variants were also observed in the pre-batholithic dikes. Most notable of these is a felsite dike outcropping on the hill west of Road Town, Tortola. This dike which was the only one of its type observed, may represent the intrusive equivalent of some of the pyroclastics of the Shark Bay member of the Tortola formation. Its description, T-177, is included in Appendix G.

## VIRGIN GORDA BATHOLITH

### Introduction

Granitic rocks are moderately well exposed throughout much of the eastern half of the British Virgin Islands, and are here named the Virgin Gorda batholith after the island of Virgin Gorda which consists almost entirely of granitic rocks and constitutes the largest exposed granitic mass in the islands. Although actual exposures or land areas underlain by the granitic rocks are only about 13 square miles, the logical subsea extensions and connections between islands total over 100 square miles and thus the term batholith has been applied.

In order to develop a general feeling for the heterogeneous yet systematic variation within the batholith it will first be described in general terms. This general description will be followed by detailed descriptions of some of the typical rock types.

### General Description

The major exposures of the Virgin Gorda batholith are on the islands of Virgin Gorda, Great Dog, George Dog, West Dog, Fallen Jerusalem, Scrub, Great Camanoe, Little Camanoe, Beef, and eastern Tortola. Portions of the batholith also are exposed along the shores of Ginger, Cooper, and Salt Islands and on eastern St. John and western Tortola. Other plutons are present but probably not directly connected with the batholith. Two of these are on Ginger, Cooper, Salt, Peter and Norman Islands and a third is west of Tortola between Jost van Dyke and Great Thatch Islands. This latter pluton was never seen, however, and its position and size can only be estimated from the metamorphic halo surrounding it.

The Virgin Gorda Batholith has a total land area of 13.2 square miles, including several large screens. However, it is quite certain that the batholith has considerable underwater extensions and if these are also considered, a conservative estimate of its area is about 102 square miles, including 22 square miles of its western extension, the Narrows pluton. The other major plutons can be estimated to have areas of 38 square miles for the Jost van Dyke pluton; 10 square miles for the Peter Island pluton; and one square mile for the Cooper pluton.

Tonalite is the most abundant rock type in the batholith, with considerable variation in both texture and composition. No sharp contacts between textural or compositional phases were seen in the course of field mapping in the central portion of the batholith. However each of the textural types could be distinguished on a broad scale. The contact zones between compositional or textural phases appear to be gradational over distances of tens to hundreds of feet; the only exceptions are the late pegmatites and granite dikes which have sharp borders with the tonalites, granodiorites, and gabbros which comprise the batholith. A few members in the northern part of the batholith also have sharp contacts. However the textural variations in this portion of the batholith are so frequent that they were of little use in determining age relations. This lack of sharp contacts made the field determination of the sequence of intrusions virtually impossible. However the granites and granophyres, and one of the granodiorites were seen to be later than the tonalites and gabbros. The irregular distribution of the gabbros also suggests that they were an early phase which has later been intruded by many other rock types as would be expected if the rocks in the Virgin Gorda batholith have followed a crystallization trend similar to other calc-alkaline series.

Contacts with the surrounding meta-pyroclastic rocks are present in the central portions of Virgin Gorda, on Tortola along the eastern and southern margins, and on the chain of islands between Virgin Gorda and St. John. Wherever observed these contacts are steeply dipping, usually having approximately the same attitude as the surrounding metapyroclastics. Numerous inclusions are present along these contacts; those in the lower portions of the batholith have been drawn out and now appear as schlieren. This results in a streaked and foliated border zone in which the exact position

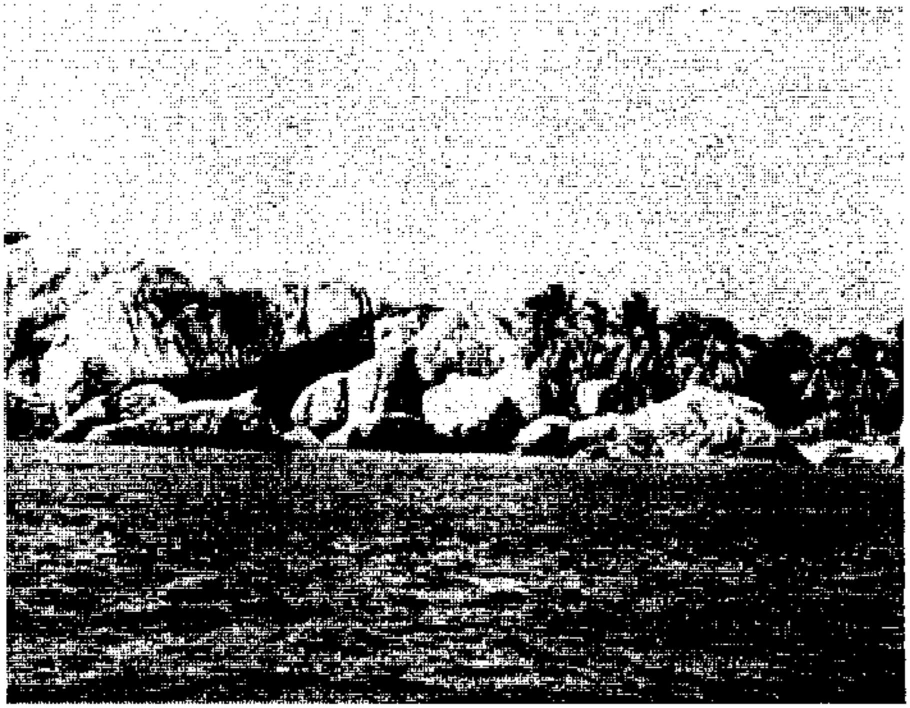


Figure 22. Typical exposure of granodiorite boulders along the southwestern shore of Virgin Gorda.

Figure 23. Anastomosing granite dikes cutting amphibolites on northwestern Salt Island. Considerable shearing is evidenced in these amphibolites and a weak foliation is present in the granite dikes.

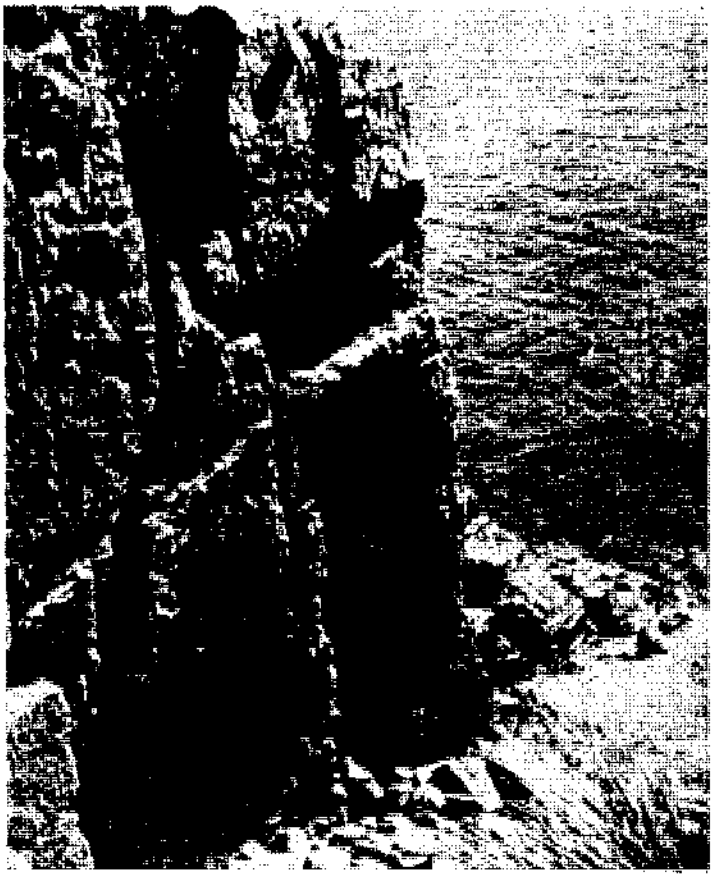


Figure 24. View of inclusion rich tonalite along the northern border of the batholith. This is a view of a 150 foot cliff on the western shore of West Dog Island.

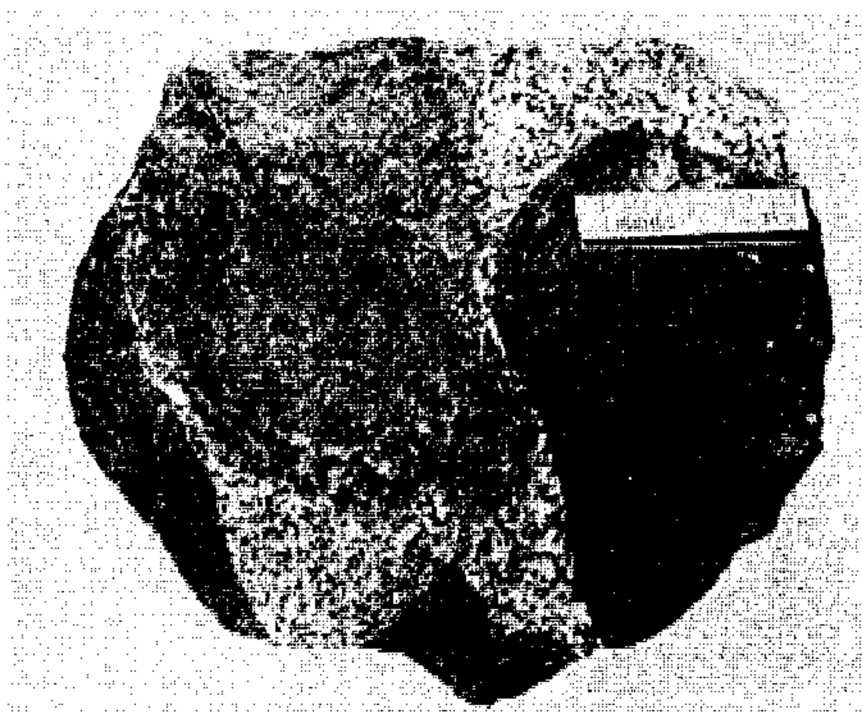


Figure 25. Hand specimen from an inclusion rich tonalite similar to that in Figure 24. The sample is from near Josiah Bay on Tortola.

of the contact between the intrusive and the wall rock is uncertain. The inclusions in the upper portion of the batholith occur as angular to rounded blocks with sharp borders. The contact between intrusive and wall rock in this position of the batholith is sharp and near vertical, as is the dip of the metasediments. The contact is not conformable, however, since it crosscuts bedding along strike.

Many of the individual plutons within the batholith are much less than one square mile in extent and mapping on a scale such that these individual plutons would be adequately delineated was deemed impractical considering the time available. No major structural features within the batholith were able to be mapped due to the irregular and indistinct nature of the contacts. Several minor fault displacements have been postulated on the basis of the offsetting of otherwise very continuous lamprophyre dikes. These displacements are only conjectural, as the actual fault planes or displacements were never directly observed.

Toward the northern border of the batholith, the contacts become sharper and the grain size decreases, which reflects the proximity of the margin of the batholith, in this case the top, where cooling was more rapid. Along with this decrease in average crystal size, an increase in the amount of local textural variation occurs, as the result of local concentration of volatiles and reheating by subsequent intrusion. This increase in local textural variation obscures the added definition produced by increased sharpness of contacts and as a result very little detailed mapping could be accomplished. Textural features are seldom similar for more than a few adjacent outcrops and the apparent composition, based upon mode of weathering as well as mineralogy, also changed over short distances. All this leads to the recognition of over 40 apparently different plutons, each restricted to about two dozen outcrops at the most, in an area of less than two square miles in the vicinity of North Sound, Virgin Gorda. Consequently it was decided to map this portion of the batholith as one unit with the only unit within it being large masses of metasediments.

On Virgin Gorda, samples were taken whenever the rock type appeared to change; additional samples were taken if the rock type continued for some distance. A total of 246 samples were taken on Virgin Gorda. On the other islands fewer samples were taken, the general rule being to take a representative sample whenever major change in either texture or composition took place.

The samples were then compared and about 120 thin sections were made from the total of about 300 samples. An attempt was made to make at least one section for each textural or compositional type with as little duplication as possible. Of these 120 sections 77 were selected for Rosiwal analyses, of 1,000 points each. These selected 77 sections were no longer entirely representative of all the rocks

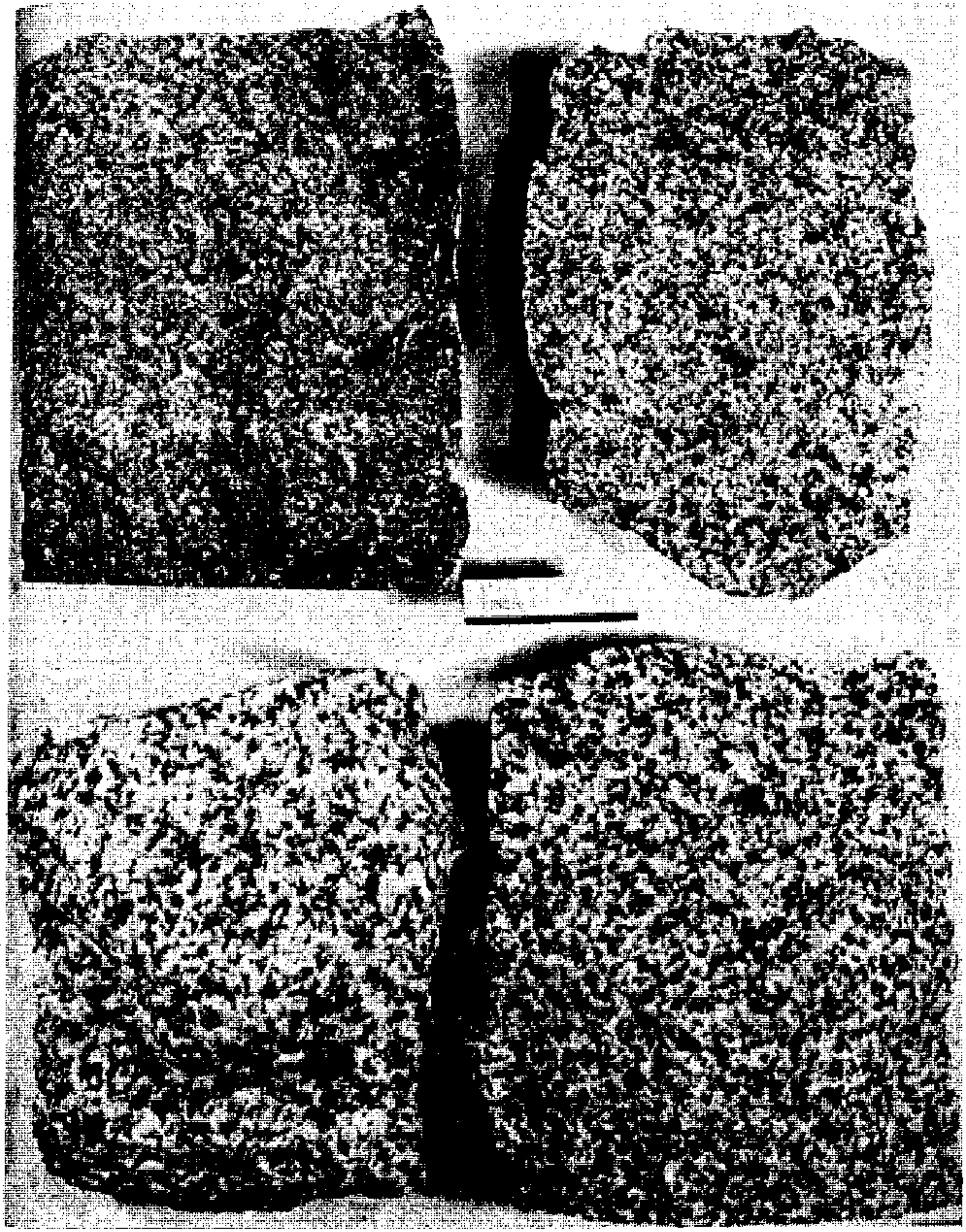


Figure 26. Typical specimens of the coarse grained portions of the batholith.

| | | | |
|---|---|---|---|
| VG-110 | Coarse olivine gabbro | VG-116 | Coarse gabbro |
| VG-15 | Coarse tonalite | B-21 | Coarse diorite |

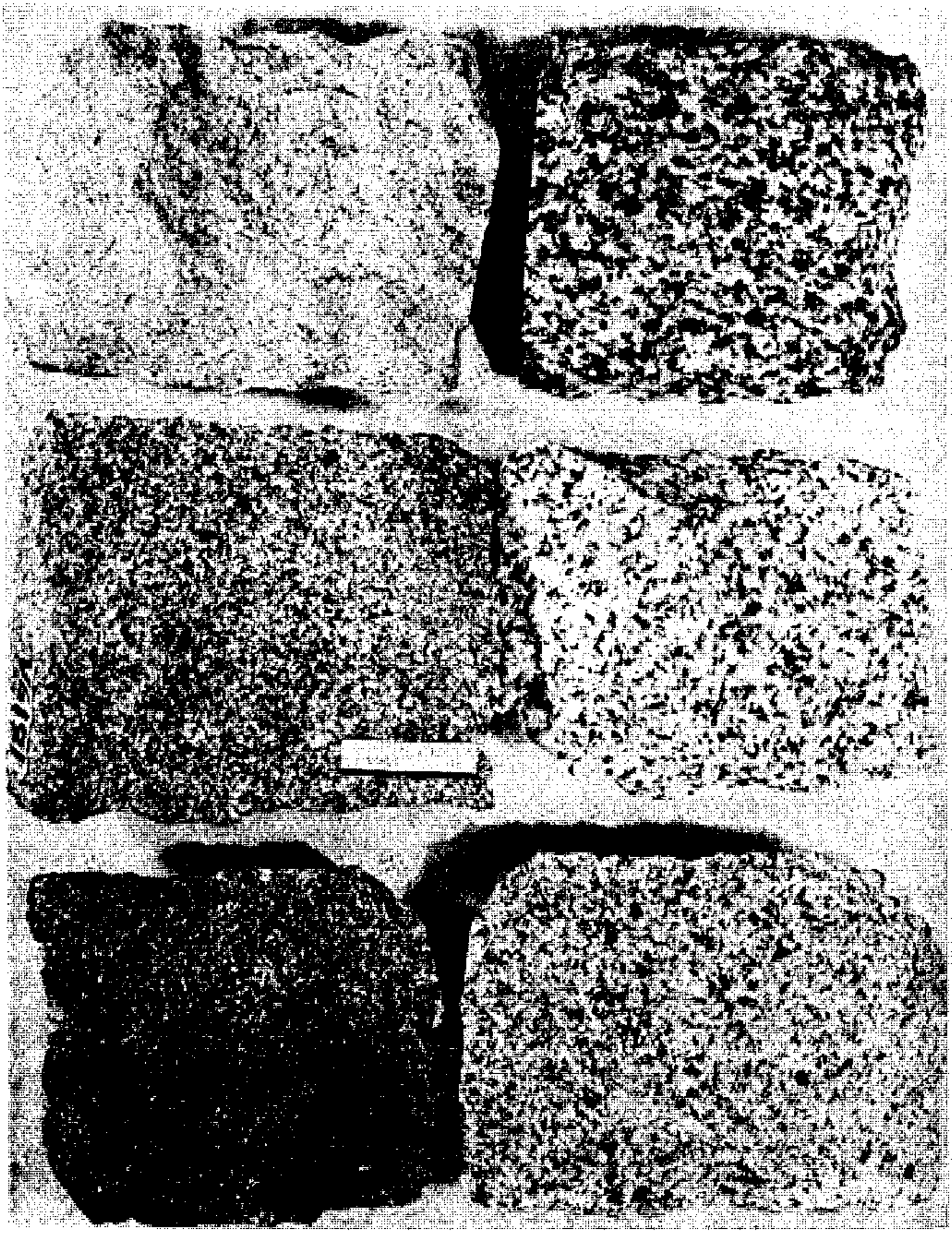


Figure 27. Typical specimens of the finer grained portions of the batholith.

| | | | |
|---|---|---|---|
| T-207 | Granite dike | C-11 | Coarse tonalite |
| VG-181 | Fine tonalite | VG-19 | Granodiorite |
| VG-29 | Fine diorite | VG-41 | Fine granodiorite |

in the batholith since many of the sections that were rejected were either very fine grained or granophyric. Since the granophyres represent the most potassium rich portion of the batholith other than the later pegmatites and granite dikes, insufficient evidence regarding late crystallization trends was gathered. This can be readily observed on the accompanying diagram (Figure 36).

The names used to describe the rocks of the batholith are based upon the color index and quartz percentages and not upon the composition of the plagioclase or the type of ferromagnesian mineral. It closely follows that given by Hatch, Wells and Wells (1949). Thus a rock consisting of 16% quartz, 59% andesine and 22% diopside has been called a pyroxene-tonalite even though a tonalite should have hornblende and/or biotite present. Likewise a rock consisting of 46% calcic bytonite and anorthite, olivine, hypersthene, and augite has been classified as an olivine-hypersthene gabbro even though it should be called a eucrite.

The percentages of mineral constituents given in the descriptions are all volume percentages. The plagioclase composition was determined by $N_x$ in oils where plus or minus values are reported. The other compositions are based upon 2V and twinning measurements on the U-stage and have an uncertainty of about $An_{x \pm 7}$.

Petrography

Granitic rocks in the British Virgin Islands consist of three textural types: (1) medium to coarse grained foliated granitic rocks in the lower portions of the batholith, (2) medium grained, equigranular, homogeneous granitic rocks in the central portion of the batholith, and (3) fine grained to porphyritic granitic rocks in the upper part of the batholith. These textural variations are a function of the depth of burial at the time of crystallization. The depths being as follows: (1) depths greater then five miles, (2) depths between one and five miles, and (3) depths less than one mile. Local exception to these general zones exist, but are not common. The depths given are taken from areas surrounding the major portion of the batholith as very little structural control is present within the batholith itself.

Inclusions are rare in the upper and lower zones of the batholith but are common in the central portion, particularly near the contacts with the metasediments. These inclusions have been completely recrystallized, however their petrography suggests that their bulk chemistry has undergone only slight change. Most contain no free quartz although the rock which encloses them may have up to 40% quartz. Inclusions are most abundant in the tonalitic and granodioritic portions of the batholith. Their size varies from fractions of an inch to about 18 inches. Near the margins of the batholith the inclusions locally constitute upwards of 60 percent of the rock (See Figures 24 and 25 ). In the lower portion of the batholith they have undergone a higher degree of disintegration and are now seen as schlieren, parallel to the foliation in the enclosing granitic rocks. All of these inclusions are metasediments, most of them having been derived from the andesitic volcanics and volcanic wackes comprising the Tortola and Tutu formations. In addition several inclusions consisting entirely of garnet and diopside and apparently derived from calcareous tuffs were noted as float blocks on Virgin Gorda near Collison Point.

The granitic rocks of the batholith are equigranular, light colored rocks (the color index is generally less than 30), except for the schistosity and inclusions and a few porphyritic granodiorites in the upper 5,000 feet of the batholith and the gabbros which account for only about 10 percent of the batholith. The general range of composition is given in Figures 35 and 36.

The plagioclase in the batholith varies in composition from about $An_{95}$ to near $An_0$. The variation in zoned crystals in any one rock is no more than half and usually about one third of this range. The more basic rocks, i.e., the gabbros, diorites and some tonalites show a marked zoning of the plagioclase, usually in several distinct compositional intervals, rather than a gradual series from calcic to more sodic plagioclase. In each of the rock types the plagioclase is more calcic than is to be expected. These compositional ranges, including zoning, are $An_{70-95}$ for gabbro, $An_{50-80}$ for diorite, $An_{40-70}$ for tonalite, $An_{20-50}$ for granodiorite and $An_{0-25}$ for the granitic end members. In the gabbros and diorites the plagioclase is subhedral or euhedral and in several samples shows a strong dimensional orientation. In the less basic rocks the plagioclase is subhedral or anhedral.

Pyroxene is present in about half of the gabbros, diorites and tonalites studied. It has been highly altered to form hornblende (amphibole with green to brown pleochroism) and/or a light green to colorless amphibole, possibly actinolite, or cummingtonite, in some cases prior to complete crystallization. Both hypersthene ($Mg_{70-75}Fe_{25-30}$) and augite were recognized. Exsolution intergrowths between the two was not seen, possibly due to the uralitization present in these samples.

Olivine ($Fo_{75-80}Fa_{20-25}$) is present in a few of the most basic gabbros.

The descriptions below present in detail some of the textures of the more abundant rock types comprising the batholith. Their order is basic to acid, but this does not necessarily represent the order of intrusion as they come from widely separated portions of the batholith, between with there is little correlation.

Typical of the most basic of the gabbroic rocks is VG-110. Its description is followed by descriptions of two slightly more acid varieties, VG-239 and VG-131, which show a moderate to strong dimensional orientation of the plagioclase crystals, indicating that they may be a product of differentiation by crystal settling and thus not be directly related to VG-110 which is an olivine-hypersthene gabbro (eucite).

VG-110 The sample is a dark grey olivine-hypersthene gabbro consisting of plagioclase, olivine, hypersthene, augite, several amphiboles, magnetite and ilmenite.

The olivine, $Fo_{78}Fa_{22}$ ($-2V = 87^o$), was the first ferromagnesian to crystallize and is now largely replaced by magnetite and serpentine. It occurs as irregular fractured grains within large hypersthene crystals, the fractures having been sites of alteration to serpentine and magnetite. The hypersthene, $Mg_{75}Fe_{25}$ ($-2V = 68^\circ$), has in turn been largely replaced by at least three varieties of amphibole and possibly also by some augite with which it locally has intergrown edges.

Plagioclase, which makes up 46 percent of the rock, began to crystallize shortly after the olivine or may have been crystallizing simultaneously with it. The early plagioclase is seen as small euhedral grains within the hypersthene associated with olivine but never in contact with it. Most of the plagioclase is in the form of euhedral to subhedral crystals varying in size from 0.5 to 6 mm. The larger of these crystals are slightly zoned and have a composition varying from $An_{94}$ to $An_{84}$, the smaller early crystals being more calcic than the later larger crystals. Many crystals have a very thin rim of more sodic plagioclase around their borders.

The opaques are always anhedral, some being interstitial to plagioclase, and appear to have crystallized during the alteration of the olivine to hypersthene.

Augite (+2V = 52°) began to crystallize after most of the hypersthene was formed. The augite has subsequently been largely replaced by hornblende.

The amphiboles occur as three distinct types. The most abundant form is a somewhat fibrous green uralite that has formed as an alteration of interstitial augite and to a lesser extent after the larger crystals of augite. The second most abundant form of amphibole is a brown hornblende that always occurs as well crystallized, interstitial crystals in areas adjacent to hypersthene. This form of hornblende is a primary constituent of the rock and was not found as an alteration of pre-existing minerals. The third form of amphibole is probably a member of the cummingtonite series and occurs as a late alteration of the hypersthene crystals.

No evidence of dimensional orientation of crystals is present in the thin section suggesting that the sample was not formed by crystal accumulation.

<u>VG-239</u> The sample is a coarse grained pyroxene gabbro in which most of the pyroxene, an augite, has been altered

to hornblende, probably prior to final crystallization since the hornblende does not have a uralitic texture. The plagioclase ranges in composition from about $An_{70}$ to $An_{90}$ with most grains having a composition near $An_{78\pm3}$. The larger grains (to 5 mm) are subhedral to euhedral while the smaller crystals are anhedral and are present in interstitial areas between the larger grains. No appreciable change in composition is present between large and small crystals. Magnetite and ilmenite (determined in polished section) are present in subhedral to euhedral grains enclosed within hornblende. Several euhedral grains are enclosed within the outer portions of large plagioclase crystals. The hornblende is restricted to anhedral masses usually filling interstitial areas between large plagioclase crystals; a few hornblende crystals are subhedral to euhedral, but always enclosed within larger anhedral hornblende crystals.

A slight preferred orientation is present in the large crystals indicating that they may have accumulated by crystal settling, however no evidence of this was observed in the field.

VG-131 The sample is a grey medium grained gabbro consisting of 66% plagioclase, 12% hypersthene, 7% augite, 12% amphibole and 3% magnetite and ilmenite. A trace of biotite is also present.

Plagioclase occurs as euhedral crystals up to 3 mm in diameter and with an average between 1 and 2 mm. The composition varies from $An_{68\pm3}$ for the cores to $An_{40}$ for the rims of the more strongly zoned crystals. A very strong dimensional orientation is present in the plagioclase crystals, even within large poikilitic hypersthene crystals, suggesting orientation by crystal settling. However, no megascopic evidence of this was observed.

All the other minerals are anhedral and occur as interstitial fillings between the euhedral plagioclase crystals. The hypersthene has a composition of $Mg_{70}Fe_{30}$ ($-2V = 62^{\circ}$) otherwise the compositional, textural, and time relationships are exactly the same as in VG-110, including the three types of amphibole alteration.

Tonalites are the most common rock type in the batholith and have a very large textural and compositional variation. Typical of the coarse grained tonalites is GeD-2. VG-26 is coarse grained but intermediate in composition between the tonalites and granodiorites. VG-194 is an uncommon type of pyroxene-tonalite that occurs at several localities in the upper portion of the batholith.

GeD-2 The sample is a medium grained tonalite consisting of mildly zoned subhedral plagioclase crystals ($An_{55\pm5}$) 1 to 2 mm in length with interstitial quartz and biotite. Euhedral to subhedral hornblende (to 2 mm) and anhedral magnetite (to 0.7 mm) are also present and either crystallized earlier than or along with the plagioclase. Accessories include sphene and apatite.

The quartz is present as large (to 4 mm) rounded grains showing considerable breakage and surrounding small euhedral plagioclase crystals. Several examples are present in which interstitial quartz is optically continuous over areas greater than 6 mm.

The biotite is always anhedral against plagioclase and fills interstitial areas, but it is euhedral against quartz suggesting it crystallized prior to the quartz.

The crystallization sequence is: plagioclase, magnetite, hornblende, biotite, quartz, with considerable overlap between plagioclase and the others. The mode shows 60% plagioclase, 27% quartz, 9% biotite, 2% hornblende, 1% magnetite and traces of chlorite, calcite, sphene, and apatite. Chlorite occurs as an alteration of biotite which is restricted to the margins of the biotite or to thin septa along the cleavage in the biotite. No orthoclase is present.

<u>VG-26</u> is very similar to GeD-2 above except that 3 percent interstitial orthoclase is present; hornblende is also present in more abundance and in larger crystals (up to 4 mm). The hornblende is much more anhedral and some crystals apparently have cores of replaced pyroxene. This sample is from a portion of the batholith intermediate in composition between tonalite of GeD-2 type and granodiorite of VG-226 type (p. 101).

<u>VG-194</u> The rock is a very light green pyroxene-tonalite consisting of 59% plagioclase, 16% quartz, 22% diopside, 2% sphene, and 1% sericite as a alteration of the plagioclase. The diopside ($+2V = 56^{\circ} \pm 0.5^{\circ}$, $Z \wedge C = 41^{\circ}$) is diseminated throughout the sample as small (up to 2 mm, average 0.6 mm) anhedral grains. The sphene is always associated with or incorporated within aggregates of diopside. No other oxides are present.

Plagioclase is present as anhedral to euhedral grains (to 2 mm), the more euhedral of which show strong zoning with the central core largely replaced by sericite. The composition of the less strongly zoned grains is about $An_{52}$ for most of the crystals with a composition near $An_{40}$ for the outer zones.

Quartz is present as anhedral interstitial grains between the plagioclase and diopside crystals. It shows no undulatory extinction and has not been fractured.

The above samples are typical of the coarse grained tonalitic portions of the batholith. Fine grained tonalites are present in the upper portion of the batholith in the vicinity of North Sound, Virgin Gorda; however these show considerable replacement by quartz and K-feldspar. This replacement is virtually restricted to the upper five to seven thousand feet of the batholith and is thought to represent alteration by solutions given off by later tonalites and granodiorites lower in the batholith.

Granodiorites are less abundant than tonalites yet they comprise about 25 percent of the batholith. As in the tonalites, considerable variation in both composition and texture is present between the various rocks classified as granodiorites. VG-226 is a typical example of a coarse grained granodiorite occurring in the lower part of the batholith, particularly on southern Virgin Gorda, while VG-188 is representative of the fine grained equigranular granodiorites of the upper part of the batholith. In addition to the coarse and fine grained granodiorites several other textural variations are present, the most common being a porphyritic granodiorite represented by VG-164 which crops out near the top of the batholith.

VG-226 is a sample of the tonalitic to granodioritic rock exposed on the southern peninsula of Virgin Gorda. The sample is coarse grained granodiorite composed of 32% quartz, 47% plagioclase, 8% orthoclase, 3% hornblende, 7% biotite, 1% magnetite and alteration minerals consisting of sericite and chlorite. Traces of epidote and sphene are also present. The plagioclase consists of subhedral to euhedral crystals (to 4 mm) having a composition varying between $An_{58\pm3}$ in the core to $An_{28\pm3}$ at the borders. The plagioclase crystals are enclosed in quartz (to 4 mm), which is fractured but shows no undulatory extinction; in biotite (to 1 mm), which is replaced along the borders and cleavage by chlorite; and in interstitial orthoclase that is optically continuous over areas greater than 6 mm in diameter. The crystallization sequence was plagioclase, hornblende, quartz, magnetite, biotite, orthoclase with considerable overlap between neighbors.

VG-188 The sample is a granodiorite consisting of 31% quartz, 51% plagioclase, 11% orthoclase, 4% biotite, 3% magnetite and traces of chlorite, sphene, sericite and zircon.

The plagioclase crystals ($An_{35\ to\ 15}$, core to rim) average about 1 mm in length and consist of anhedral crystals, most of which contain a well twinned, slightly zoned, euhedral core. It has been slightly altered to sericite along cleavage planes; and some of it has been replaced by orthoclase which normally occurs as interstitial fillings between quartz and plagioclase crystals. Sericite and albite are also replacing the cores of some plagioclase crystals.

Biotite, some of which has been altered to chlorite, sphene and magnetite is diseminated throughout the sample as anhedral grains smaller than 0.5 mm, most of which are associated with the orthoclase in interstitial areas.

Quartz is present interstitial to plagioclase but crystallized earlier than ortholclase and is probably later than, or equivalent to, the accessories of magnetite, sphene and biotite. It has replaced plagioclase along the borders of many grains possibly to an extent of about 5 percent of the rock. It is highly fractured and shows undulatory extinction.

VG-164 The sample is a porphyritic granodiorite, consisting of 38% quartz, 49% plagioclase, 8% orthoclase, 2% biotite, 2% amphibole, 1% magnetite along with traces of chlorite, zircon, apatite, and sericite.

The quartz occurs as small (to 0.5 mm) crystals in a fine matrix surrounding the large plagioclase and quartz phenocrysts. Many of the large (to 5 mm) quartz crystals are polygonal in outline, indicating that they were originally $\beta$-quartz; some are six sided, others four sided, and some triangular, all with an irregular over-growth of later quartz which is delineated by plagioclase inclusions parallel to the original margins of the crystal.

The plagioclase phenocrysts (to 4 mm) also show quartz and plagioclase inclusions parallel to zoning which is moderately to well developed. The composition varies from about $An_{65}$ to $An_{15}$ from core to rim. Most of this change occurs in the last 10 percent of the crystal, the interior portion being weakly zoned and of very near the same composition throughout. The plagioclse phenocrysts continued to grow until very late in the crystallization history as their outer zones include quartz and plagioclase belonging to the groundmass. Most of the groundmass plagioclase probably has a composition near $An_{20}$ with more calcic cores than margins. The quartz and plagioclase of the groundmass are equigranular and always anhedral.

The amphibole is fibrous and occurs in subhedral aggregates associated with magnetite. It probably is an alteration of an earlier ferromagnesian mineral such as pyroxene. Some of the amphibole may also be primary in that it does not have the patchy appearance associated with the above aggregates. This latter amphibole has a green pleochroism.

Biotite is also associated with magnetite and may also represent a late alteration. However, most of it has been altered to chlorite obscuring the original textures. Nevertheless, it was formed prior to the plagioclase and orthoclase of the groundmass, but after much of the quartz.

Orthoclase is present in interstitial areas in the fine grained portion of the sample, and is replacing the borders of the plagioclase with which it is in contact.

Late sericitic alteration is present in several of the plagioclase phenocrysts and is restricted to the fractured portions of the rock, indicating that it formed after deformation and not as a simple deuteric alteration.

Extensive silicification is present in many portions of the batholith, particularly in the upper 7,000 feet. The best examples of this silicification occur in the vicinity of North Sound, Virgin Gorda. In some cases the silicification is restricted to fractured zones within otherwise unsilicified rocks. However the usual case is for quartz to have replaced the borders, and in some cases central portions, of plagioclase crystals which were in contact with pre-existing quartz. Several examples were noted in which an amaeboid mass of plagioclase, representing one original large crystal of plagioclase, was entirely enclosed within a large quartz grain. Two examples of this silicification are shown in Figures 28 and 29.

The only granites in the British Virgin Islands occur as dikes or as a fine grained phase of a pegmatite. They occur in thin, rarely more than 20 feet thick, dikes usually dipping about 20 to 30 degrees to the north or northwest. Principle exposures are on the islands of Cooper, Salt, Dead Chest, Great Thatch and on Belmont Point on Tortola. Several granitic and pegmatitic dikes are also present on northwestern Beef Island and on northern Virgin Gorda. Most outcrops of the granites and pegmatites were in the amphibolites surrounding the batholith; only a few cases were noted where they actually cut the batholithic rocks. The dikes are very continuous and in the vicinity of Salt Island individual dikes were recognized for distances of several miles.

In thin section these dikes consist of 30% quartz, 30% plagioclase (oligoclase) and 40% microcline. The only minerals present other than the essential constituents are traces of magnetite and biotite, their sum always being less than 1 percent of the rock. A very small amount of microperthite is present in some of the microcline crystals accounting for less than 1 percent of the mineral. Myrmekite and patch perthite are also present along the borders of the plagioclase grains. Most of the plagioclase crystals show a slight alteration to sericite and to very fine grained clay minerals. A foliation has developed in these dikes, produced by a preferred orientation of the long axes of microcline crystals and aggregates. This foliation was not noted in the field so its relation to the dike walls is unknown.

All of the grains are mildly fractured, the feldspars usually being fractured parallel to the foliation while the quartz, which shows undulatory extinction, has been fractured at right angles to the foliation.

In the shallower and more pegmatitic dikes the above mentioned myrmekite apparently changes to a graphic intergrowth which is present between both orthoclase and quartz and plagioclase and quartz. This graphic texture becomes very fine grained in the shallowest intrusives of this type which have been classified as granophyres. The amount of plagioclase present in the shallower, more pegmatitic dikes is much less than in the granite dikes, being about 15% vs. 27%. The quartz to K-feldspar ration is about the same. In the granophyres the amount of K-feldspar seems to be about the same as or slightly less than in the granite dikes although this is by no means certain due to the extremely finely intergrown character of the granophyres.

## Layered Gabbro

In addition to the gabbros mentioned above an unusual variant occurs on the point south of Plum Tree Bay on north-

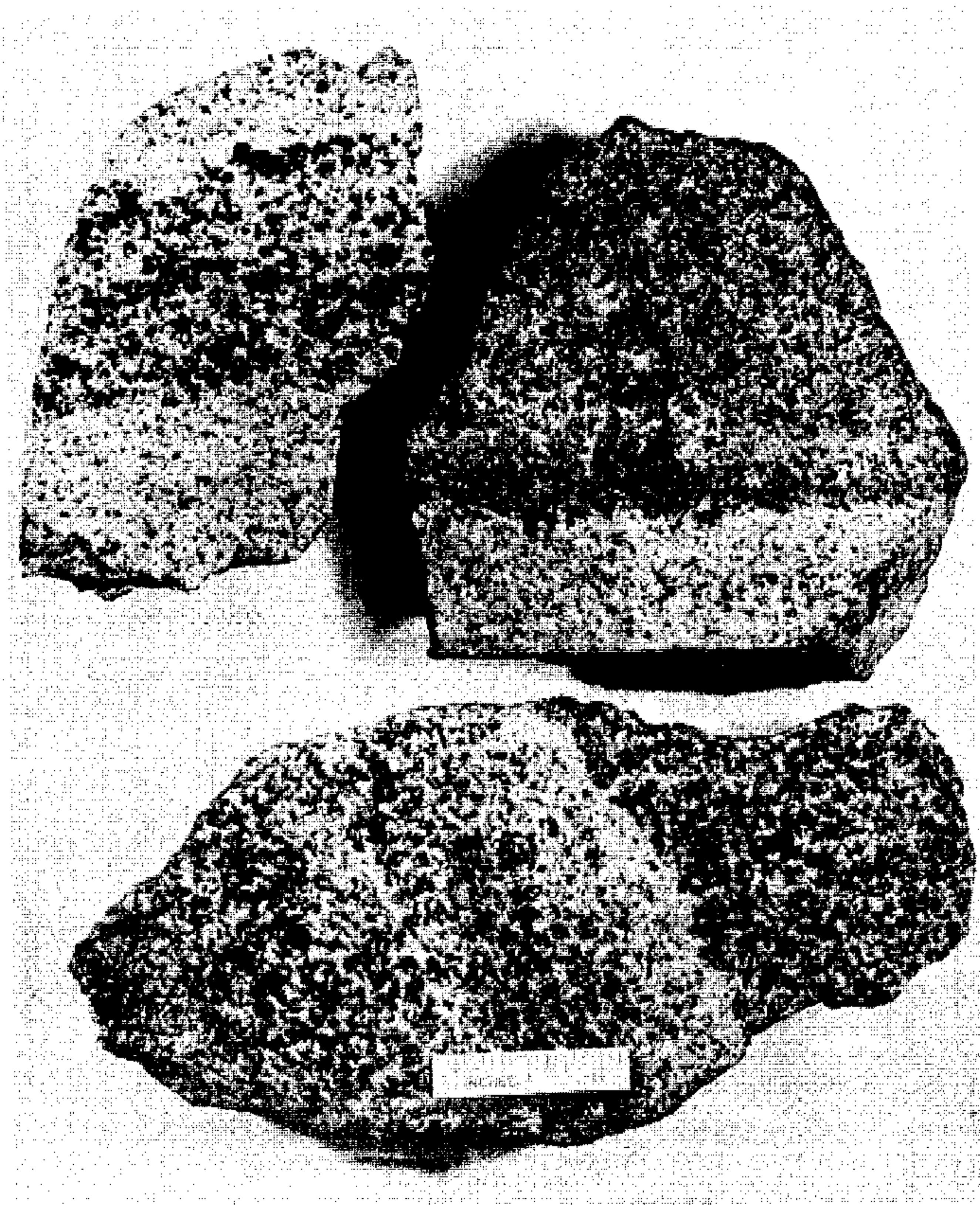


Figure 30. Hand specimens of layer gabbro (VG-112) showing pronounced banding and grading.

Figure 31. Beach boulder of layered gabbro (VG-112) showing weak grading and a pronounced scour channel (just above pencil).

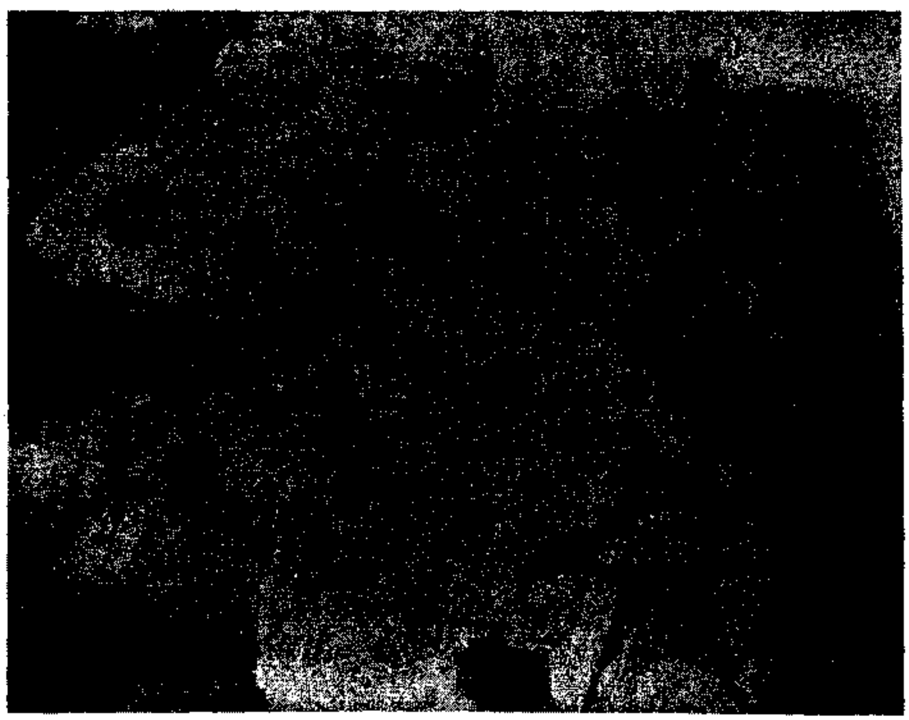


Figure 32. Layered gabbro from southern Salt Island showing weak grading and scour channels.

western Virgin Gorda. This gabbro is layered with the layering varying from 1/2 inch to 4 or more feet. It consists of alternate bands of anorthositic gabbro (some containing about 95 percent plagioclase) and gabbro containing less than 40 percent plagioclase. Numerous examples of grading are present (See Figures 30 and 31) with hornblende and pyroxene being concentrated at the base of the layer immediately above a sharp contact with the plagioclase rich portion of the previous layer. The abundance of dark minerals decreases upwards, as does the average grain size of the plagioclase, until the uppermost portions of the layer consist of plagioclase with a very little hornblende and magnetite as interstitial fillings between the plagioclase crystals. Structures such as cross-bedding and scour channels are also present in some portions of the layered sequence (See Figure 31). A petrographic description of this occurrence is given below. Two other examples, VG-239 and VG-131, showing a strong dimensional orientation of plagioclase crystals but no megascopic banding, were described with the gabbros (pp. 96 and 97).

VG-112 is a dark grey coarsely crystalline stratified anorthositic quartz gabbro. The composition is variable from an anorthosite consisting of 94% plagioclase, 4% hornblende, 1% magnetite and ilmenite and 1% quartz to a gabbro consisting of 55% plagioclase, 25% augite, 12% hornblende, 7% magnetite and ilmenite and 1% quartz.

The plagioclase is strongly zoned with a core of labradorite, $An_{68\pm3}$, followed by a zone consisting of labradorite of composition near $An_{54}$ which is in turn surrounded by andesine of composition about $An_{41}$. The first two zones are euhedral. However the thin outer zone is intergrown with neighboring plagioclase crystals.

Augite, along with magnetite and ilmenite, occurs as anhedral interstitial crystals. Most of the augites are twinned, many polysynthetically. Their composition is unknown as the grains have been largely replaced by hornblende. This replacement is not restricted to the margins but occurs as a very fine intergrowth or uralitization throughout the pyroxene crystals.

In polished section magnetite and ilmenite both show exsolution of hematite lamellae. The ilmenite also has exsolved rutile and possibly other titaniferous minerals. Magnetite is more abundant in the massive gabbroic portions of the sample while ilmenite is predominate in the anorthositic layers. In the gabbroic layers the ilmenite has "sandwich" structures with the magnetite and appears to have exsolved from it. If so, the original oxide was about 40 percent, by volume, ilmenite.

The long axes of the plagioclase crystals show a strong preferred orientation parallel to the megascopic banding in the hand specimen. This, along with the compositional banding, suggests an origin by crystal settling.

Several other examples of this type of rock are present in the British Virgin Islands, notably on Salt Island. These examples are near a fault and have been crushed and somewhat altered. In addition to the plagioclase, hornblende, augite and quartz observed in VG-112 these samples from Salt Island have about 3 percent orthoclase formed during the alteration of the biotite. A megascopic banding with indistinct cross-bedding (See Figure 32) is also present in these rocks. However the microscopic dimensional orientation has been obscured by fracturing and is at best only a suggestion.

## Composition

Cleve (1871) made several analyses of granitic rocks from the Virgin Islands. These analyses (Figure 33), along with one from Donnelly (p. 142a), have been plotted on a variation diagram (Figure 34) using the method of Larsen (1938). In addition these analyses were recalculated to norms and plotted along with the modal data in an attempt to determine what the original rocks had been, as no petrographic data nor precise localities were given by Cleve. From this, analyses 3, 8 and also possibly 6 appear to be unusual variants not directly related to the main crystallization trend and thus they have been weighted less in placing smooth curves through the points on the variation diagram. These analyses could, however, be in error only in $SiO_2$ and $Al_2O_3$ which are seen to vary antipathetically in all cases while the other oxides show little variation. If some $Al_2O_3$ and $SiO_2$ were

| | 1. Diorite George Dog B.V.I. | 2. Felsite Virgin Gorda B.V.I. | 3. Diorite Mary Pt., St. John A.V.I. | 4. Quartz Diorite Beef Is. B.V.I. | 5. Diorite Ginger Is. B.V.I. | 6. Anorthite Diorite Beef Is. B.V.I. | 7. Calcic Diorite Frenchman's Cap, A.V.I. | 8. Quartz Diorite Buck Is. A.V.I. |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 71.60 | 69.33 | 59.24 | 61.35 | 53.85 | 44.60 | 42.61 | 64.71 |
| $TiO_2$ | - - | - - | - - | - - | - - | 0.92 | 0.61 | - - |
| $Al_2O_3$ | 13.63 | 12.77 | 18.16 | 15.39 | 17.15 | 15.38 | 22.32 | 15.09 |
| $Fe_2O_3$ | 3.03 | 2.19 | 3.26 | 4.41 | 4.08 | 8.50 | 5.51 | 2.56 |
| FeO | - - | - - | 3.56 | 3.40 | 6.95 | 8.03 | 5.49 | - - |
| MgO | 0.94 | 1.03 | 2.84 | 3.32 | 5.29 | 6.82 | 6.02 | 1.16 |
| CaO | 3.37 | 7.23 | 6.31 | 6.60 | 8.99 | 14.50 | 15.51 | 4.51 |
| $Na_2O$ | 4.54 | 4.75 | 4.00 | 3.87 | 3.01 | 0.33 | 0.93 | 5.29 |
| $K_2O$ | 1.31 | 0.42 | 1.31 | 0.95 | 0.24 | 0.01 | 0.20 | 1.38 |
| $H_2O$ | 0.63 | 1.47 | 0.87 | 0.58 | 0.58 | 0.56 | 0.37 | 4.86 |
| Total | 99.06 | 99.19 | 99.55 | 99.87 | 100.14 | 99.65 | 99.57 | 99.56 |
| Norms | | | | | | | | |
| Q | 32.5 | 29.1 | 12.1 | 17.5 | 6.9 | 5.5 | - - | 19.3 |
| or | 7.8 | 2.2 | 7.8 | 5.6 | 1.1 | - - | 1.0 | 8.3 |
| ab | 38.2 | 39.8 | 34.1 | 32.5 | 25.2 | 2.6 | 7.3 | 44.5 |
| an | 12.8 | 10.0 | 27.2 | 22.0 | 32.8 | 40.6 | 52.0 | 13.3 |
| di | 3.2 | 5.6 | 3.8 | 8.6 | 9.8 | 25.2 | 14.9 | 6.3 |
| hy | 1.2 | - - | 9.3 | 6.7 | 17.7 | 11.4 | 0.6 | - - |
| ol | - - | - - | - - | - - | - - | - - | 15.3 | - - |
| mt | - - | - - | 4.6 | 6.5 | 6.0 | 12.3 | 7.4 | - - |
| ilm | - - | - - | - - | - - | - - | 1.7 | 1.1 | - - |
| hem | 3.0 | 4.7 | - - | - - | - - | - - | - - | 2.6 |
| wo | - - | 7.8 | - - | - - | - - | - - | - - | 0.4 |

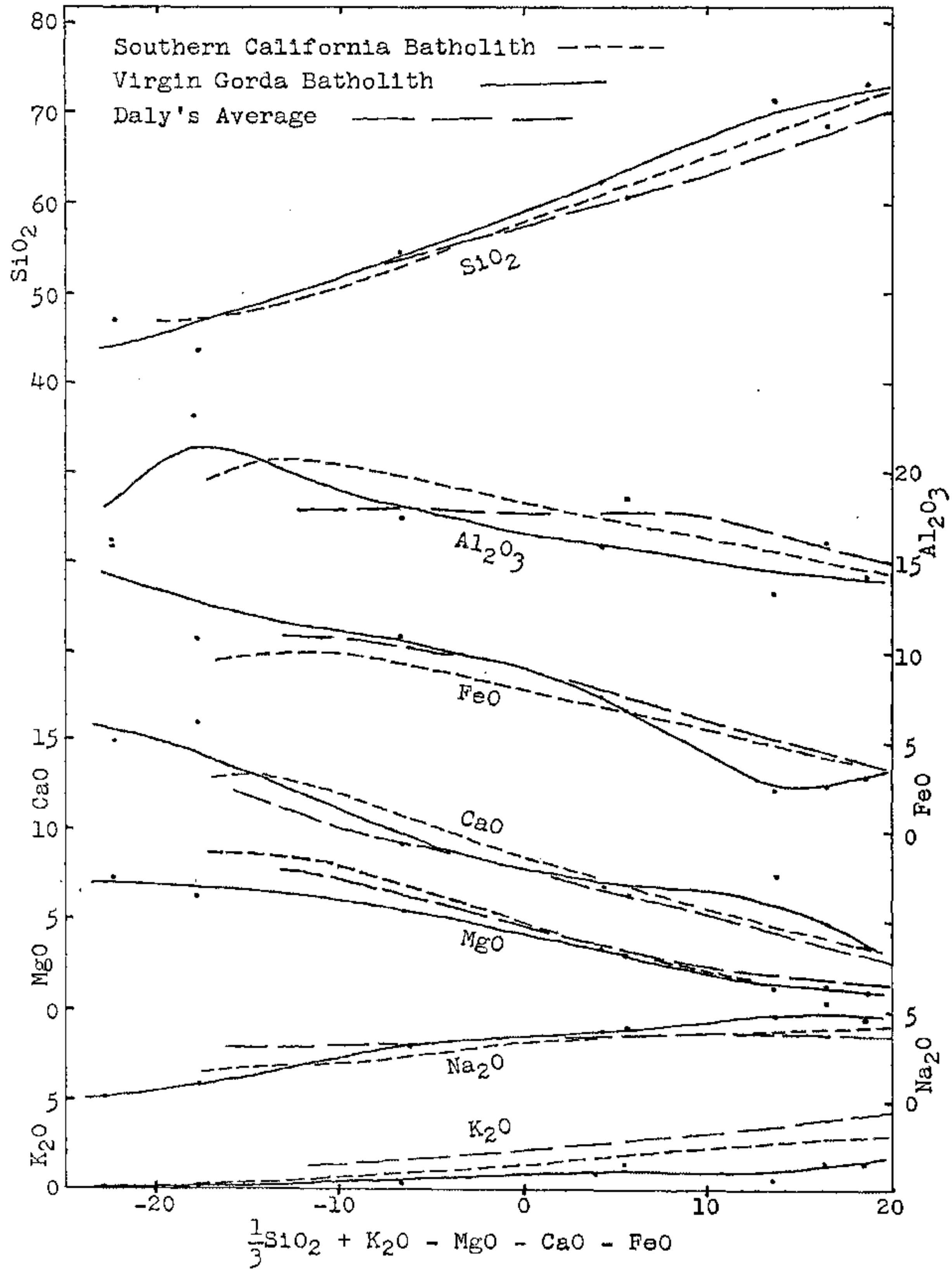
Figure 33. Chemical Analyses of granitic rocks from the British Virgin Islands
Analysis 7 is from Donnelly (p. 142a), all others are from Cleve (1871)

interchanged so as to put them on the smooth curves between the neighboring analyses, then this would also have the effect of moving the norms nearer to the crystallization trend given by the modes.

For purposes of comparison two sets of curves have been superimposed upon the curves for the Virgin Gorda batholith. These are the sequence, average gabbro to average granite (Daly, 1933) and the Southern California batholithic rocks as given by Larsen (1948). The first of these two examples has no particular significance to the present work in itself but is included here strictly for comparison, because it represents an abstract average of continental rocks. The second is a well studied real example close to that average which may be significant to the present work in that it may represent a nearly equivalent set of rocks that were emplaced along the margin of a continent rather than in an oceanic area.

The three curves have about the same shape and approximate position (See Figure 34 ) in the range -8 to +5 on the abscissa which is the sum $1/3SiO_2 + K_2O - MgO - CaO - $ total iron as FeO. The more basic portions of the curves, i.e., abscissa values less than -8, have considerable variation which is due in part to the problems of analyzing rocks which may have undergone varying degrees of crystal settling. The most noticeable divergence in this range in rocks from the British Virgin Islands is that they are considerably

Figure 34.




Variation diagram for the granitic rocks from the British Virgin Islands lower than average in MgO and $Na_2O$ while having excesses of FeO and to some extent CaO and possibly $Al_2O_3$. As mentioned above some of these divergences are probably the result of sampling strongly differentiated or contaminated units that don't really fall on the general crystallization trend; e.g., an oxide rich anorthositic gabbro. However, some of this could be due to real differences in the composition of the original magma as will de discussed later.

The only noticeable difference in the three curves in the middle of the range is that the $K_2O$ content is considerably below the other curves and the FeO content is slightly higher. This may indicate that the magma from which the Virgin Gorda batholith was derived was unable to assimilate any potassium-rich material since it had no continental crust through which to intrude. This divergence in $K_2O$ becomes more marked as the rock becomes more acid.

For compositions in the range above +5 on the abscissa considerable divergence from the other two curves is present. The most important variations are that $K_2O$ is 1% to 2% low throughout the range while $Na_2O$, and to a lesser extent, CaO, are considerably above the other curves. $SiO_2$ is also slightly higher and FeO is considerably lower than the other curves. MgO interestingly enough has remained about the same.

In summary these variation diagrams seem to indicate that: (1) the magma was unable to either get or keep sufficient MgO until the more acid phases which required very little MgO; (2) the magma was unable to get or keep sufficient $K_2O$ at any stage in its history, probably not even in the pegmatitic phases; and (3) considerable variation is present in the magma probably as the result of two processes, namely assimilation and crystal settling. Assimilation had its greatest effect on the more acid members while crystal settling is probably the cause of much of the variation in the basic portions of the curves.

In order to gain some idea of the crystallization and compositional trends within the batholith the 77 modal analyses mentioned above were plotted on two triangular diagrams with the vertices being plagioclase, quartz, and K-feldspar in one case and feldspar (plagioclase + K-feldspar), quartz and total dark minerals in the other case. These are shown in Figures 35 and 36 respectively. As was mentioned earlier, the potassium rich portions have very few points on the diagrams for two reasons: first, the batholith is consistently low in $K_2O$ with respect to other composite batholiths; second, the sections that did have appreciable K-feldspar were so fine grained or were so granophyric that the Rosiwal analyses were thought likely to be in considerable error and thus were not included.

The diagrams show a continuous variation from gabbros to diorites to tonalites to granodiorites to granophyric adamellites and finally to granite pegmatites which are not included because they were much too coarse grained to be

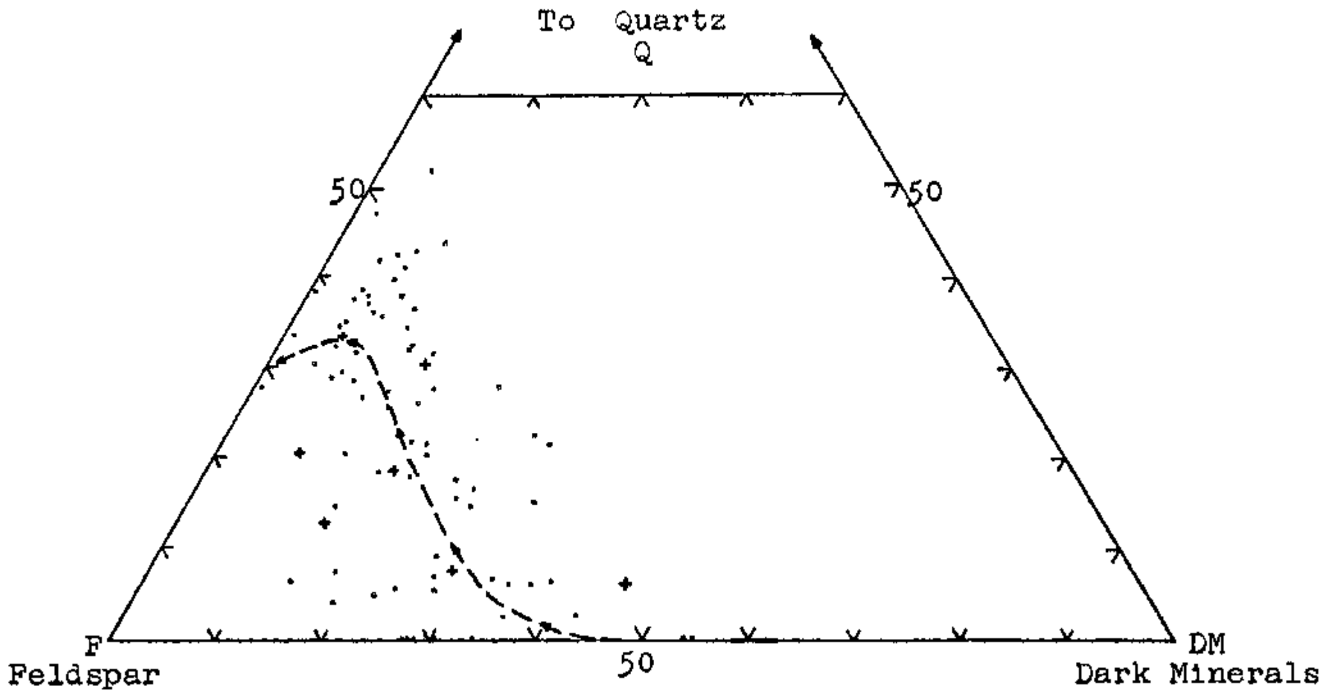



Figure 35.

Composition of granite rocks from the British Virgin Islands

• = mode + = norm

The dashed curve indicates postulated crystallization trends

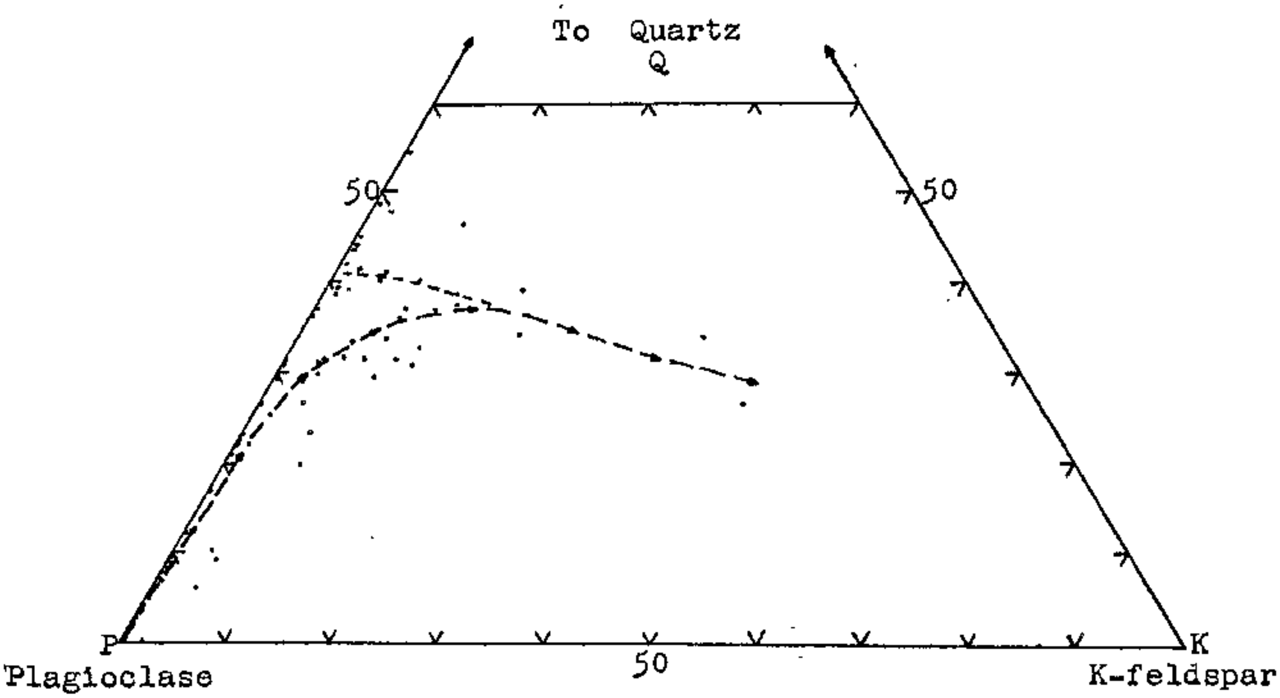



Figure 36.

Composition of granite rocks from the British Virgin Islands

• = mode

The dashed curve indicates postulated crystallization trends counted accurately. This continuous sequence is well substantiated as far as the granodiorites with a large break present between the granodiorites and the adamellites. This break would be considerably narrowed if the finer grained samples were included as their approximate modes fall in this range and in the range between the adamellites and the granite pegmatites which contain less than 30% plagioclase and 30 to 40 percent quartz.

In the tonalite to granodiorite range two separate compositional trends are present, particularly on the plagioclase-quartz-K-feldspar diagram. One of these starts at $P_{60}Q_{40}K_{0}$ and joins the main compositional trend at about $P_{45}Q_{37}K_{18}$. Most of these samples show replacement by quartz and thus it is likely that they all represent samples that have had up to 8% quartz added since crystallization.

The more basic end, in the gabbro to diorite range, Figure 35, shows a rather broad yet systematic variation between a composition of $F_{55}DM_{45}Q_{0}$ to a point near $F_{61}DM_{6}Q_{33}$ where a sharp bend is present indicating the granodiorite to granite sequence. The same group of samples that appeared to have undergone silica addition in Figure 36 has not been considered since the addition of silica has removed them from the major trend. The most basic end of the curve has very little control yet seems to swing toward the dark mineral end member indicating a continuous crystallization sequence between the diorites and gabbros. Several samples showing evidences of crystal settling plotted in the vicinity of $F_{70}DM_{30}Q_0$ and have produced an excessive broadening of the basic portions of the plot. These examples were not considered in drawing the trend line since they don't represent a magmatic trend but rather are unusual variants representing the first crystallized fraction of the magma.

## Age of the Virgin Gorda Batholith

The upper portions of the batholith were intruded after deposition of the middle Eocene Tortola formation and prior to the deposition of the upper half of the Necker formation which contains fragments of granophyre and fine grained diorite that are found in the upper 5,000 feet of the batholith. The welded tuffs in the lower portion of the Necker formation probably represent extrusive equivalents of the batholith. Unfortunately the precise age of the Necker formation is unknown, however as discussed earlier, it is most likely within the Eocene. Thus, at least the major portion of the batholith, and probably all of it, is younger than middle Eocene and probably older than uppermost Eocene.

## Mechanism of Emplacement

The Virgin Gorda batholith could have been emplaced by numerous methods or combinations of methods, the most important of which are: (1) stoping, (2) melting and assimilation, and (3) forceful emplacement by vertical or horizontal movement of the walls. Little evidence of large scale stoping was observed except for the large masses of metasediments on Virgin Gorda. However, these are probably septa between successive intrusions which have been moderately deformed during emplacement. Smaller scale examples of these septa are also present on southern Tortola which may in part represent stoped blocks. Evidence of small scale stoping, i.e., of small blocks, is abundant in the form of angular to rounded inclusions in the central portions of the batholith.

Assimilation of wall rock by the magma can account for only very small portions of the batholith. This is obvious when one considers the composition of the pyroclastics versus that of the batholith. The metasediments contain little, or in some cases, no, free silica in either the mode or norm. Thus, if they were assimilated they would tend to dilute the free silica present in the magma and since this is in excess of 30 percent for much of the batholith it is very unlikely that much assimilation took place.

By far the most important process of emplacement has been displacement of the walls of the batholith both by doming or warping and by faulting. All of the major plutons that have their contacts with metasediments exposed have the shape of very large, slightly crosscutting sills. These have only mild deformation around their margin, and seem to have been emplaced by doming of the roof accompanied by slight faulting. In some cases the floor has been bowed downward to a greater extent than the roof has been raised. Nearer to the batholith horizontal and/or vertical displacement has been more important and probably accounts for most of the space needed by the batholith. At no place have the borders of the batholith been strongly sheared or otherwise deformed. In all cases the deformation has been restricted to warping and minor faulting.

One of the more important factors influencing the emplacement probably was the density difference between the magma and the surrounding sediments. Whenever this came near to being zero the magma would spread out. Since the contact metamorphics would be more dense than the original sediments, due mainly to loss of porosity, the next intrusive, even though it might be the same density, would be emplaced at a higher position in the section. This will also account for the sills dipping away from the main intrusive center since as they left the metamorphic aureole they would be stable, with respect to density, at greater depths.

A second factor influencing the position and shape of the batholith was the relative mobility of the various rock units. Thus the large Narrows pluton was partially controlled by the fine grained Tutu tuffs and the Congo Cay limestone within them. In addition, later intrusions appear to have been emplaced next to or within previous ones which, judging from the lack of distinctive contacts and the wide zone of intermediate composition, were not entirely crystallized. This helped to develop the high degree of hybridization seen on Virgin Gorda as well as to localize the composite portions of the batholith and, for the same reason, the sills that came off from the main intrusive are much more homogeneous than are the main portions of the batholith.

## LATE IGNEOUS ACTIVITY

The post-batholith ingeous rock can be divided into four groups: (1) pegmatites and aplites, (2) lamprophyres, (3) porphyritic basalt dikes and (4) quartz- and hornblende-andesine porphyries. The first group is directly related to the batholith and has been discussed with it. The second crops out in three localities closely associated with the batholith and probably should be considered as late intrusives derived from the batholith. The third group occurs as columnar jointed dikes and sills within the Necker formation. Members of the fourth group are most common on southern Tortola and on the islands between Virgin Gorda and St. John and probably are associated with volcanic activity accompanying the development of the Anegada trough.

### Porphyritic Basalts

The porphyritic basalt dikes and sills are most abundant on the northern half of 'Guana Island and on Mosquito and Necker Islands. They have a fine gained groundmass enclosing phenocrysts of plagioclase and pyroxene. Their color varies from dark grey in unweathered samples to olive green in weathered samples. They show no metamorphism. However some examples have been altered with the development of epi- and calcite. One example is described below.

M-4 The sample is a dark grey porphyritic basalt containing phenocrysts of plagioclase and pyroxene. A very weak columnar jointing is present in the field.

Plagioclase: phenocrysts, $An_{66\pm5}$, up to 2 mm; partially replaced by calcite and chlorite.

Augite: twinned crystals up to 1 mm; replaced by chlorite.

Magnetite: pheoncrysts to 1 mm and as specks throuthout the groundmass.

Calcite and Chlorite: present as replacement of plagioclase and pyroxene.

Sericite: replacing plagioclase.

Serpentine: replacing possible olivine or hypersthene.

Groundmass: plagioclase, magnetite, and (?)epidote.

A pilotaxitic texture with a slight flow orientation of the plagioclase laths in the groundmass is present.

A porphyritic basalt similar to this on southern Jost van Dyke shows little metamorphism, probably only deuteric alteration, and contains large (over 6 inches in diameter) fragments of quartz diorite, probably derived from the Jost van Dyke Pluton.

Porphyries

Numerous porphyritic dikes and plugs crop out on southern Tortola and on the islands between Virgin Gorda and St. John. Similar rocks are present on St. John and St.

Thomas and have been described by Donnelly (pp. 97-102). A larger variety of dikes is present in the British Virgin Islands than is reported from the American Virgin Islands by Donnelly, however, no detailed work has been attempted on most of these samples. Only two types have been studied in detail, these being quartz-andesine porphyrites and hornblende-andesine porphyrites both from the small islands east of St. John. They occur as numerous parallel NNW trending vertical dikes varying from 10 to 50 feet in thickness with the hornblende-andesine porphyrites forming most of the thicker dikes. These dikes have probably been intruded along extensional fractures assosiated with the Anegada trough. Many of them have undergone considerable alteration, probably deuteric, which has developed calcite, sericite, and clays as replacements of the original fine grained groundmass and to a lesser extent of the phenocrysts of plagioclase. The quartz-andesine dikes are more altered than the hornblende andesites, probably as the result of a higher volatile content which promoted deuteric alteration.

The wall rocks show no effects of alteration by the dikes or their volatiles. This may be because they already had been metamorphosed to the epidote amphibolite or hornblende hornfels facies and thus had a mineral assemblage that was not readily affected by the dikes.

These dikes were intruded at shallow depths as evidenced by their fine grained porphyritic texture. Since these dikes are intruded in a portion of the section that has a conservative stratigraphic depth of six miles, they indicate that a large amount of folding and erosion had taken place prior to their intrusion. This suggests that they are not related to the intrusive sequence involved in the formation of the batholith, which was intruded prior to folding, but rather are related to a later event, probably the development of the Anegada trough. This interpretation is supported by their distribution along its northern border and also by the trend which is about at right angles to the trough axis.

The quartz-andesine porphyrites consist of phenocrysts of bipyramidal quartz and highly altered zoned crystals of plagioclase having a composition varying between $An_{48\pm5}$ and $An_{32\pm5}$. The zoning is oscillatory with alternate layers of plagioclase having compositions of about $An_{45}$ and $An_{35}$. Aggregates of plagioclase phenocrysts are abundant and show similar zoning in all crystals. The more highly altered rocks show replacement of the plagioclase phenocrysts by albite, calcite and sericite with the replacement being controlled by fractures and original zonal boundaries.

No primary mafic minerals are present and only a few altered patches containing calcite and epidote suggest that they were ever present.

The groundmass is very fine grained and consists of quartz, plagioclase, calcite and sericite.

In marked contrast to the quartz-andesine porphyrites are the hornblende-andesine porphyrites. These dikes have abundant (up to 30%) hornblende in euhedral phenocrysts but no quartz phenocrysts. Strongly zoned but only slightly altered andesine phenocrysts comprise another 30 percent of the rock. The remaining portion is a fine grained groundmass consisting of plagioclase, quartz, hornblende and magnetite, all of which occur as very fine grained anhedral crystals. The above percentages are for the "average" specimen as considerable variation in the amount and species of phenocrysts is present. Some dikes probably are transitional between the hornblende-andesine and the quartz-andesine porphyrites in that they have a few hornblende and quartz crystals along with abundant zoned andesines in a fine grained groundmass.

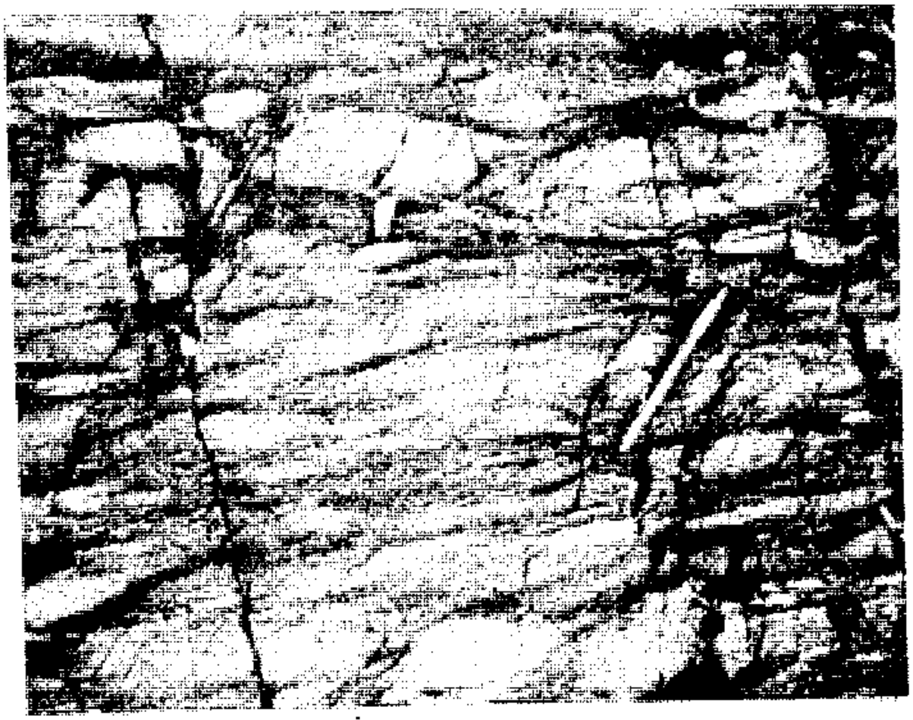
The hornblende is always fresh and unaltered while the plagioclase phenocrysts have been selectively altered along their margins with the formation of calcite, sericite and (?)clays. The groundmass is similarly altered. This alteration is probably the result of deuteric processes.

## METAMORPHISM

The distribution of metamorphic rocks in the British Virgin Islands is shown on Plate 4. This metamorphism has been largely of contact origin, surrounding the granitic rocks of the batholith, nevertheless the width of the contact aureole suggests that some regional metamorphism may have taken place prior to the emplacement of the granitic rocks. This presumed regional metamorphism was not greater than the albite-epidote-chlorite facies as no evidence of regional actinolite is present. Chlorite and epidote were formed as deuteric and/or diagenetic minerals throughout the section and thus cannot be used to show metamorphism. The only evidence suggesting more than contact metamorphism is the width of the aureole surrounding the intrusive which suggests that regional temperatures were somewhat elevated, especially in the lower portions of the section (compare the width of the aureole on St. John vs. Jost van Dyke, Plate 4). It is unlikely that these wide aureoles can be explained by underground extension of the plutons since wherever observed their contacts with the surrounding metasediments were near vertical. Since the presence of regional metamorphism cannot be proved, all further discussion will concern the contact metamorphics.

All formations in the British Virgin Islands, with the possible exception of Necker formation, have undergone metamorphism, most of them to at least the hornblende hornfels facies. Several areas on southern Tortola and Salt Island probably have reached the pyroxene hornfels facies. This metamorphism was predominately thermal and in many places did not deform the original features of the rocks. In some areas, however, the dynamic effects have been large and either no original textures remain or else they have been highly deformed. A striking example of this is on Cooper Island where keratophyre, spilite and andesite fragments have been highly flattened and stretched with flattening ratios of near 8:1 (See Figure 37). Other outcrops nearby show strong lineations of plagioclase and hornblende crystals which also indicate dynamo-thermal metamorphism. Further evidence of some dynamic component in the metamorphism is given by the keratophyres and spilites on Peter Island and Dead Chest where all outcrops consist of strongly foliated amphibolites and quartz biotite schists. On western Tortola and Great Thatch Island coarse grained amphibolites are present, interbedded with fine grained, even granular amphibolites. The coarse grained amphibolites are possibly the result of shearing, but most likely are the result of original grain size and porosity differences rather than shearing.

The metamorphism was nearly isochemical, based upon the thin section and field relations. No chemical work has yet been undertaken to provide a more firm basis for this observation. The indications of isochemical metamorphism present



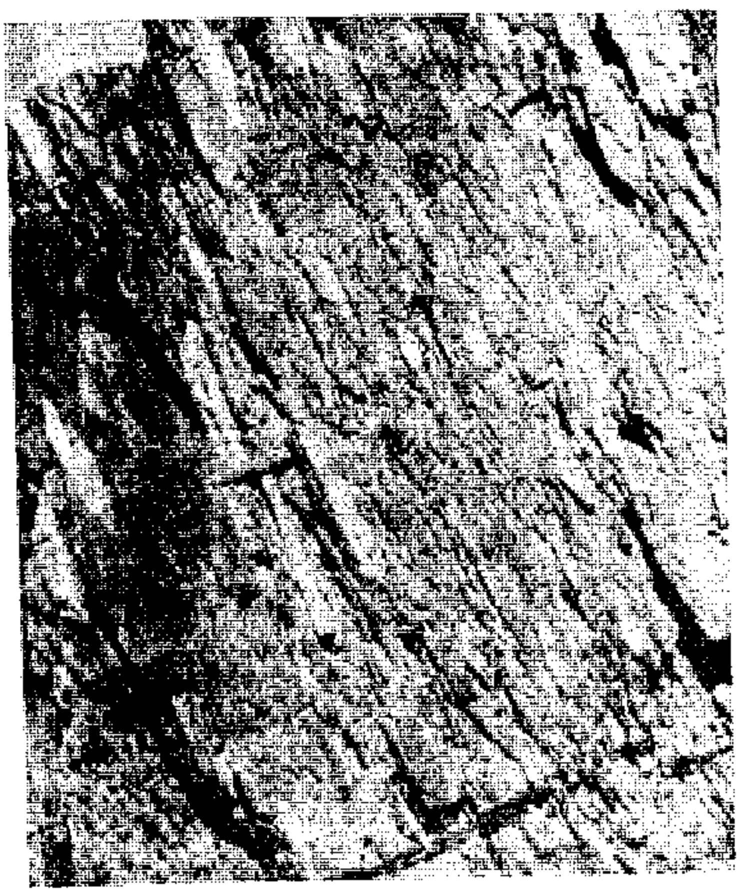


Figure 37. Two views of the stretched fragments present on southwestern Cooper Island. This unit is probably equivalent to the Cabes Point conglomerate lithofacies of the Louisenhoj formation. The light colored clasts are keratophyres, the darker ones spilites and andesites.

Figure 38. Examples of the higher grade metamorphics.

| | | | |
|---|---|---|---|
| G-110 | Coarse amphibolite | T-203 | Coarse amphibolite |
| T-193 | Graphitic andalusite schist | F-5b | Calc-silicate hornfels |
| P-14 | Quartz biotite schist (meta-keratophyre) | T-53(6) | Amphibolite (meta-breccia) |

in the thin sections and the field are the presence of recrystallized amygdules chemically different from the matrix material and the presence of diverse mineralogy and composition between fragments in the breccias. In most cases the contacts between these fragments or amygdules and the matrix are sharp and show no evidence of reaction. Field contacts between units of different composition have also remained sharp even where shearing took place.

Equilibrium was not obtained in most samples since a large number of minerals are present; some of them are relic and others were developed during the metamorphism. Phenocrysts of plagioclase are well preserved with respect to both shape and composition, even where moderately strong shearing has taken place. The large phenocrysts usually have a composition near labradorite while the stable metamorphic plagioclase would be either albite or oligoclase. The groundmass plagioclase and the smaller plagioclase phenocrysts have been recrystallized and are now of a composition suitable to their metamorphic facies, wherever they were large enough to be determined.

The depth at which this metamorphism took place is variable between a few thousand feet and more than 30,000 feet if the evidence for the batholith being pre-folding is correct. Donnelly (p. 106) made the assumption that the metamorphism had taken place at shallow depths, however numerous lines of evidence from the islands east of St. John show that this assumption was incorrect. The most important of these is the foliation in the granitic rocks. This is similar to that developed in mesozonal batholiths and thus suggests that some of these intrusives were emplaced at a depth of more than four miles and thus their contact metamorphics must have been formed at depths at least this great.

Three, and in some areas four, metamorphic assemblages were recognized, however these are not readily placed within the accepted facies as given by Fyfe, Turner and Verhoogen (1958). Rocks belonging to their albite-epidote hornfels facies and hornblende-hornfels facies are definitely present and possibly also some belonging to the pyroxene hornfels facies. The calcium content of the plagioclase determines the facies to which the rock belongs in Fyfe, Turner and Verhoogen's classification and since many unreacted phenocrysts are present in these rocks this classification breaks down. Thus, a classification along much the same lines as that developed by Donnelly (p. 107) has been used. It is based upon the presence or absence of chlorite and actinolite. Epidote has normally not been considered as it has developed throughout the section, both during progressive and retrogressive metamorphism, as well as possibly during deuteric and/or diagenetic processes. This classification is not applicable to the limestones or the keratophyres but these are always interbedded with tuffs or spilites so that these grades can always be determined. The present classification differs from Donnelly in that it contains a classification in which both chlorite and actinolite are present.

The characteristics of the metamorphic assemblages or grades used in this study are (from lowest to highest): (1) the presence of chlorite, usually with some epidote, but no actinolite; (2) the presence of both chlorite and actinolite: (3) the presence of actinolite and/or hornblende but no chlorite; and (4) the presence of pyroxene and calcic plagioclase. These have been designated as the albite-chlorite-epidote assemblage, the chlorite-actinolite assemblage, the amphibole assemblage and the pyroxene hornfels assemblage respectively. The distinction between albite-chlorite-epidote assemblage and the unmetamorphosed sediments is virgually impossible to make, and thus this grade of metamorphism must be assumed to lie outside the rocks of the chlorite-actinolite assemblage, however the thickness of rock that has been involved remains unknown. Pyroxene hornfels occurs only in the immediate vicinity of the contact with the plutons and is not included on Plate 4. The high grade metamorphics can often be broken into two sub-assemblages, the lower one characterized by actinolite with hornblende as replacement of pyroxene crystals and the higher one characterized by the presence of hornblende but no actinolite. All assemblages are within the albite-epidote hornfels facies of Fyfe, Turner and Verhoogen except the hornblende sub-assemblage of the amphibole assemblage, which probably belongs to their hornblende hornfels facies and the pyroxene hornfels assemblage which of course belongs to their pyroxene hornfels facies.

Plagioclase compositions are quite variable, as mentioned above, and are not suitable for use in determining the metamorphic grade. Relic phenocrysts are present in all grades of metamorphism and generally have their original composition. A few examples show patchy replacement by albite; however, this has usually only involved about half of the crystal. Where altered plagioclase concentrates were examined by means of x-ray, some samples gave two (131) peaks which corresponded to the composition of the original and the altered composition. In all cases of double peaks these gave labradorite for the original and andesine for the altered plagioclase. Samples of the hornblende sub-assemblage gave the most consistent results by both optical and x-ray methods, their compositions varying between calcic oligoclase and sodic andesine ($An_{20}$ to $An_{40}$). More altered samples of the albite-chlorite-epidote assemblage were also consistant in giving compositions of about $An_5$. These samples always had abundant epidote. Other less altered samples within the albite-chlorite-epidote and chlorite-actinolite assemblages contain labradorite being replaced by albite.

The amphibole provides both a handy indicator to grade of metamorphism and also a serious problem in that the optical difference between an actinolite and an aluminous hornblende is very slight. Thus they provide qualitative isograd for the appearance of actinolite but are of little help in attempting to determine the hornblende isograd which is the division between the actinolite and the hornblende sub-assemblages of amphibole assemblage. In practice this division was made whenever the predominate amphibole in the rock became very strongly pleochroic, or when the mineral had a light brown color. A small amount of fine grained actinolite may well have been overlooked in several cases. In the field or in hand specimen the hornblende sub-assemblage rocks are quite distinctive in that they are coarser grained, dark grey to black rocks rather than fine grained and dark green as in the case of the actinolite bearing hornfelses.

Extremely low grade metamorphism or diagenetic alteration, probably equivalent to some of the zeolite facies described by Coombs (1959), is present in even the uppermost stratigraphic units. This has formed chlorite (in several cases after perlitic glass), prehnite, epidote, laumontite, analcime, albite and in some cases calcite. This is no longer strictly load metamorphism as these rocks have undoubtedly been affected by the higher thermal gradients associated with the batholith. Nevertheless, load metamorphism is probably present and is responsible for the development throughout the section of chlorite, epidote, and albite, after the glass and some of the phenocrysts. This metamorphism or alteration probably took place both before and after the intrusion of the batholith.

The following comments and descriptions are included as examples of the various grades of metamorphism described above and as descriptions of some of the more unusual metamorphic types not fitting into the above classification.

<u>Metamorphism of the Water Island Formation</u>

Spilites

The lowest grade of metamorphism observed in the spilites in the British Virgin Islands was the albite-chlorite-epidote assemblage, however this example (C-7) has undergone retrograde metamorphism and is not typical of the metamorphic grade of the rocks surrounding it. In all samples the pyroxene phenocrysts have been replaced by hornblende and in most cases the groundmass chlorite and plagioclase have also been altered to hornblende or, in some cases, only to moderately pleochroic actinolite. Some of the plagioclase has been reconstituted, however most of the plagioclase closely reflects the composition of the original phenocrysts. In general the spilites in the British Virgin Islands seem to be much more calcic than their lesser metamorphosed equivalents in the American Virgin Islands. The maximum grade of metamorphism reached by any of the spilites is probably pyroxene hornfels as evidenced by S-20. This is a somewhat peculiar rock and probably represents a metamorphosed weathered horizon at the base of the Louisenhoj formation and thus will be included later.

P-8 This is a sample of a metamorphosed amygdular spilite flow. In thin section it consists of prismatic crystals of moderately pleochroic hornblende forming a decussate aggregate. Over 90 percent of the matrix consists of this hornblende; the ramaining portion being minute crystals of plagioclase. The amygdules have been recrystallized and now contain plagioclase ($An_{30\pm5}$), hornblende, magnetite, quartz and an unknown isotropic mineral. A slight schistosity is present in both hand specimen and thin section.

P-22 is probably a contaminated keratophyric tuff but could be a low ferromagnesian spilite. It is not typical of other keratophyres in the area and thus is included with the spilites. The sample has a strong compositional banding. It consists of a strongly pleochroic, slightly poikiloblastic hornblende with inclusions of pyroxene(?) surrounded by a matrix of plagioclase ($An_{38\ to\ 50}$) and quartz. Minor amounts of magnetite, sphene, apatite, epidote and K-feldspar are also present.

P-10 is a schistose hornblende hornfels containing plagioclase ($An_{60\pm3}$), hornblende, magnetite, and biotite.

C-7 is a highly deformed spilite(?) that has undergone retrograde metamorphism with the formation of chlorite after hornblende. Shearing and flowage are very pronounced and appear to have been later than the maximum metamorphism but prior to some of the retrograde chlorite. The minerals present are:

Hornblende: large and small crystals showing strong schistosity (or lineation) now almost entirely replaced by chlorite and some epidote and calcite.

Plagioclase: large (to 8 mm) phenocrysts ($An_{80 \pm 5}$) showing an extension parallel to flow direction.

Quartz: fine grained crystals in groundmass and fractures.

Magnetite: large crystals (to 1 mm) with strain shadows of chlorite on vertical stream edges. Many large grains are fragmented but only slightly displaced. Fine crystals in the groundmass are extremely drawn out, parallel to the schistosity formed by the hornblende crystals.

Sericite: alteration of plagioclase along fractures and cleavage.

Calcite: alteration of groundmass and in fractures.

Epidote: small crystals as alteration of hornblende and plagioclase(?).

Keratophyres

The keratophyres in the British Virgin Islands have all undergone metamorphism to a grade comparable with the amphibole assemblage described above. Biotite has been developed in most specimens and usually produces a strong foliation. Considerable variation in mineralogy is present due to their original hererogeneity. Sample P-22 above is probably representative of one of the more contaminated keratophyre units. The more typical keratophyres are now present as quartz-biotite-schists with the biotite forming both a foliation and a schistosity in the rock.

P-21 is a well foliated quartz plagioclase schist, formerly a quartz keratophyre. The mineralogy is:

Quartz: 70± % of the rock; present as fine crystals in the groundmass and as coarse crystals that may have been phenocrysts.

Plagioclase: 25%; untwinned, $An_{20\pm5}$; some of the above groundmass quartz may be plagioclase.

The remaining 5% of the rock is hornblende, magnetite, biotite, zircon, and K-feldspar.

The K-feldspar occurs in elongate patches. The rock has been sheared but has recrystallized post shearing, since many of the grains have sutured boundaries.

P-14 is a strongly foliated quartz-plagioclase-biotite-schist typical of most of the metamorphosed quartz keratophyres. It consists of:

Quartz: large recrystallized and broken relic phenocrysts and as fine crystals in the groundmass.

Plagioclase: large recrystallized and broken relic phenocrysts; $An_{20\pm5}$; and as fine crystals in the groundmass.

Biotite: large recrystallized plates possessing a strong foliation.

Muscovite: aggregates of plates showing a schistosity but not as well developed as in biotite.

K-feldspar: small grains in the groundmass and in interstitial fillings in quartz and plagioclase relic phenocrysts.

P-11 is a quartz biotite schist similar to P-14 which has undergone retrograde metamorphism.

Quartz: relic phenocrysts and in very fine crystals in the groundmass.

Plagioclase: predominately very fine grained in the groundmass; a very few relic phenocrysts are also present. X-ray composition is $An_{31}$.

Biotite: strong foliation; has been altered to sericite, chlorite, magnetite(?), and K-feldspar.

Magnetite: small euhedral crystals throughout rock.

Hematite: alteration of magnetite.

Sphene: after ilmenite; associated with magnetite.

Chlorite: after biotite; no schistosity; shows radial alignment of crystals.

Sericite: minor alteration of plagioclase.

K-feldspar: associated with chlorite and magnetite, probably after biotite.

S-36 is a quartz biotite schist and probably represents the highest grade of metamorphism reached by any of the quartz keratophyres studied in thin section. It consists of:

Quartz: relic phenocrysts with a polygonal outline and as fine crystals in the matrix.

Plagioclase: $An_{32\pm3}$; occurs as fine crystals in the groundmass.

K-feldspar: as interstitial crystals; most abundant near the large quartz crystals.

Biotite: altering to chlorite with a yellow to green pleochroism.

Chlorite: alteration of biotite.

Magnetite: large grains mantled by biotite or chlorite.

Calcite: interstitial and as vein fillings.

Garnet: scattered crystals.

Possible pyroxene in very small high relief grains.

## Metamorphism of the Louisenhoj Formation

Rocks belonging to the Louisenhoj formation crop out on the islands of Cooper and Salt and, except for their petrology, have been discussed under stratigraphy (p. 23). All exposures have undergone high grade metamorphism which has obscured contact relations. The three samples described below come from what is believed to be the Louisenhoj formation as exposed in the British Virgin Islands. Sample S-20 is unusual and probably represents a weathered horizon at the Louisenhoj-Water Island contact. Sample S-32 could well be from the Tutu formation.

C-9 is from a poorly exposed, metamorphosed breccia on the eastern shore of Cooper Island. It has been strongly sheared but still contains recognizable breccia fragments.

It consists of strongly twinned and broken plagioclase ($An_{84\pm5}$), set in a matrix of garnet, augite, hornblende and magnetite. Alteration and retrogressive metamorphic products include sphene, calcite, chlorite, epidote, and sericite. In addition quartz is present in several fractures cutting through the sample.

The rock was a crystal-lithic lapilli tuff or breccia in which some of the original textures have been preserved, particularly in the fragments. The thin section shows that the schistosity was formed by shearing rather than plastic flowage.

S-32 is an augen-gneiss possibly belonging to the Tutu formation. It consists of:

Quartz: in veins and aggregate patches, often associated with large plagioclase crystals.

Plagioclase: large broken porphyroblasts with complex twinning and many inclusions; also small crystals in the groundmass and in hornblende.

Hornblende: large poikiloblastic grains showing little orientation, smaller more poikiloblastic grains show strong preferred orientation.

Magnetite: large crystals, a few of which show strain shadows of hornblende and numerous small crystals aligned with flow.

The large plagioclase crystals are sheared and hornblende has grown in the fractures. The shearing is approximately parallel to foliation while extensional fractures are perpendicular to foliation. The small magnetite crystals are restricted to the groundmass and to fractures in the plagioclase crystals.

The "porphyroblasts" are aggregates of large plagioclase crystals and small quartz and plagioclase crystals. Flow banding is not present within these masses. Stream lines bend sharply around the porphyroblasts. The porphyroblasts do not appear to have grown in place after deformation but rather grew pre- or during deformation.

S-20 is a sample from the highly metamorphosed Louisenhoj or Water Island formation from an exposure about 200 yards from the contact with a fine grained dioritic intrusive. It consists of:

Magnetite: subhedral to anhedral crystals occur in "streams" parallel to foliation.

Biotite: formed post deformation; colorless or very pale brown to light brown pleochroism.

Tremolite: as fibrous mineral in groundmass and as rims on pyroxene; strongly foliated.

Hypersthene: $Mg_{80}Fe_{20}$ ($-2V = 70^{o}$); small foliated masses of grains associated with the tremolite(?).

Plagioclase: $An_{90\pm2}$; seriate grains and glomero-porphyroblasts up to 2 mm throughout the sample.

Quartz: seriate grains up to 2 mm throughout the sample, sometimes in elongate masses parallel to foliation.

The glomero-porphyroblasts of plagioclase formed prior or during deformation. The biotite was formed after deformation, probably during later fracturing or mild deformation--many crystals are generally aligned but at an angle of near 60 degrees to the main foliation. The rock appears to have been thinly bedded (now seen as slightly compositional banding with bands 1/8" to 1/2" thick).

## Metamorphism of the Tutu Formation

All outcrops of the Tutu formation in the British Virgin Islands are in the immediate vicinity of the Narrows pluton, a large westward extension of the batholith. Wherever observed they have been metamophosed to the hornblende sub-assemblage of the amphibole assemblage described earlier which is this case corresponds to Fyfe, Turner and Verhoogen's hornblende hornfels, and possibly also to their pyroxene hornfels, facies. The metamorphism of these rocks was not studied in detail and the examples below are only intended to give a general idea of their metamorphic character.

The following are brief descriptions of some of the lime-silicates of the middle part of the Tutu formation:

F-2 Very fine grained; foliated; consists of scapolite, calcite, diopside, pyrite, wollastonite, and garnet.

F-4b Very fine grained, weakly foliated, consists of: wollastonite, diopside (poikiloblastic), scapolite, quartz, and plagioclase.

F-5b Fine grained, no foliation, consists of: garnet, diopside, wollastonite, and an unknown. See Figure 38.

F-9 Fine grained, no foliation, consists of: garnet, diopside, and scapolite.

F-14 Very fine grained, no foliation, consists of: diopside, scapolite, and pyrite.

GT-5 Fine grained, weak compositional banding, consists of: scapolite, diopside, plagioclase, biotite (fox-red), magnetite, sphene(?), and calcite.

GT-19 Coarse grained calc-silicate hornfels, no foliation, consists of: garnet, diopside, calcite, scapolite(?), and an unknown.

GT-23 Fine grained graphitic chiastolite schist, strong foliation, consists of: tourmaline (pleochroism orange to colorless), quartz, plagioclase, andalusite (chiastolite), muscovite (sericite), graphite, rutile(?), and garnet(?).

LT-7 Fine grained, slight foliation, consists of: garnet, diopside, scapolite (mizzonite), calcite, quartz, and sphene.

The following descriptions are from the hornblende hornfelses from the section of the Tutu formation above the Congo Cay limestone:

GT-14 Fine grained schist without pronounced foliation, consists of: biotite, hornblende, quartz, plagioclase ($An_{25\pm5}$), magnetite, sphene, and apatite.

T-203 A coarse grained, grey, mildly sheared amphibolite (Figure 38) consisting of:

Hornblende: strongly pleochroic.

Biotite: pleochroic light tan to brown.

Plagioclase: $An_{45\pm5}$; entirely of metamorphic origin, no phenocrysts remain.

Pyroxene: altering to hornblende, probably an augite.

Magnetite, apatite and sphene: occur as accessories.

The mineral assemblage in this sample is entirely of metamorphic origin with the exception of the pyroxene which is probably a relic. A strong foliation developed during metamorphism and all microscopic evidences of the original nature of the sample have been eliminated.

T-137b A fine grained, moderately sheared amphibolite consisting of:

Hornblende: strongly pleochroic; occurs as fine grained aggregates forming large composite masses showing a moderate foliation, and also as large individual grains possibly after pyroxene.

Scapolite(?)

Quartz: small crystals interstitial to the hornblende.

Diopside: (+)2V about $60^\circ$.

Plagioclase: relic labradorite crystals having a subhedral shape; also metamorphic andesine(?).

Garnet

The rock is a tuff that has undergone high grade metamorphism, probably equivalent to the pyroxene hornfels facies. A strong foliation has been developed in the amphiboles with the diopside aggregates and garnet also reflecting this foliation. Some hornblende grains are not oriented and could possibly represent grains that formed after deformation. This sample may be from a unit in the Hans Lollik member of the Tortola formation.

GT-2 The sample is a dark grey porphroblastic amphibolite consisting of:

Quartz and plagioclase: very fine grains (0.01 mm) in the matrix and as larger porphroblasts (about 0.20 mm in diameter).

Biotite: pleochroic, from colorless or pale green to red-brown (fox-red); weakly foliated, predominately as aggregates along fracture surfaces.

Sphene

Magnetite: small crystals associated with the aggregates of biotite.

Tourmaline(?)

Apatite

The rock is extremely fine grained (maximum size about 0.2 mm, average size less than 0.5 mm). Foliation is poorly developed, however shearing is present throughout the sample and the aggregates of biotite have developed along these fracture surfaces.

In addition to the lime silicates touched upon above, two other rocks worthy of mention are present in the section below the Congo Cay limestone (marble). They are:

T-193 is a graphitic andalusite schist (Figure 38) very limilar to GT-23 described earlier. In thin section it consists of:

Graphite: a fine clouding throughout the slide, locally concentrated into patches showing strong foliation.

Andalusite: does not show the crosses of chiastolite as does sample GT-23. Occurs as ragged crystals up to 0.2 mm in diameter, and may also occur as a fine grained mass in the matrix.

Muscovite: an alteration(?) of the andalusite.

Hematite

Quartz: as a fracture filling; probably post metamorphism.

The sample has been highly sheared with some of the matrix material having the appearance of a mylonite. The andalusite grains are deformed and fractured along their edges. The muscovite is associated with the andalusite and usually forms a deformed sheath surrounding it.

C-10 is from a dark grey calcareous breccia (See Figure 39) possibly equivalent to the Coki Point megabreccia exposed

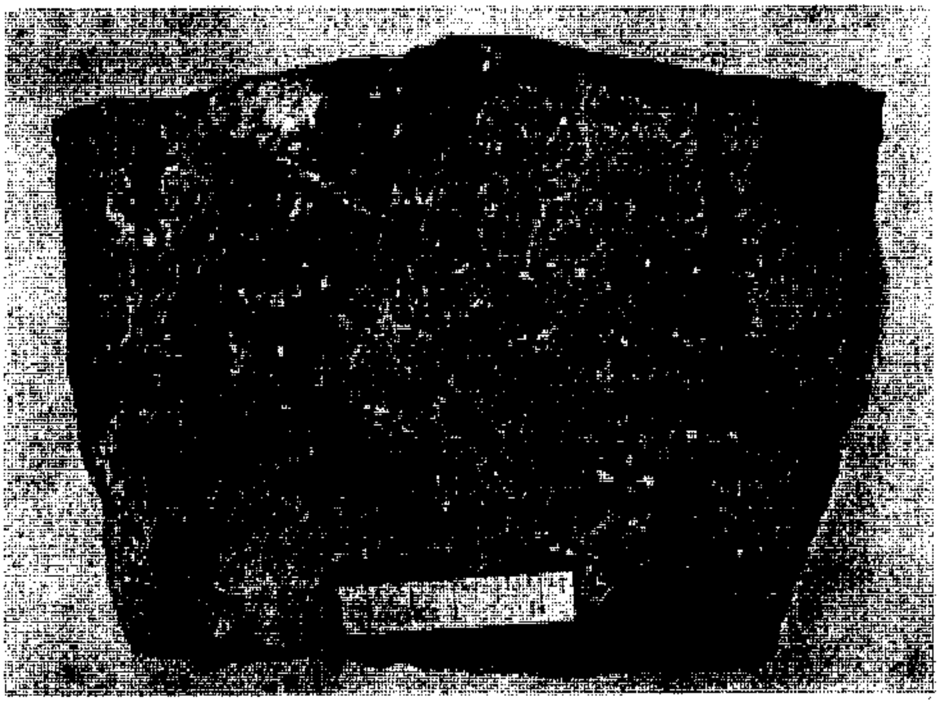


Figure 39. Hand specimen of a calcareous breccia possibly equivalent to the Coki Point megabreccia lithofacies of the Tutu formation. The dark areas are amphibolite; the light areas are lime-silicates.

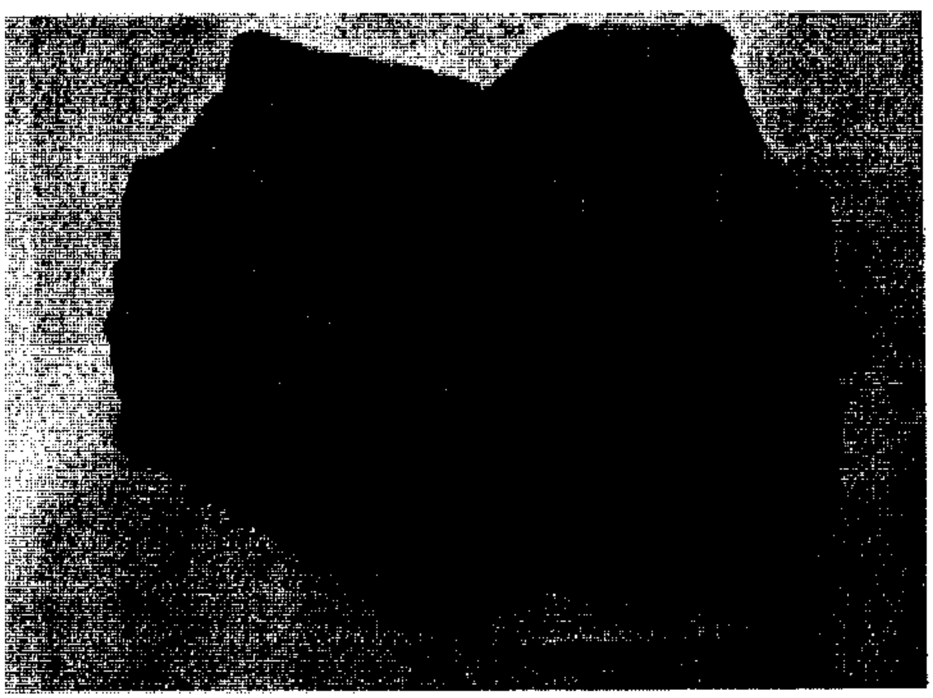


Figure 40. Polished slab of garnet-diopside-wollastonite hornfels developed at the contact of the Congo Cay limestone and the batholith on eastern Cooper Island.

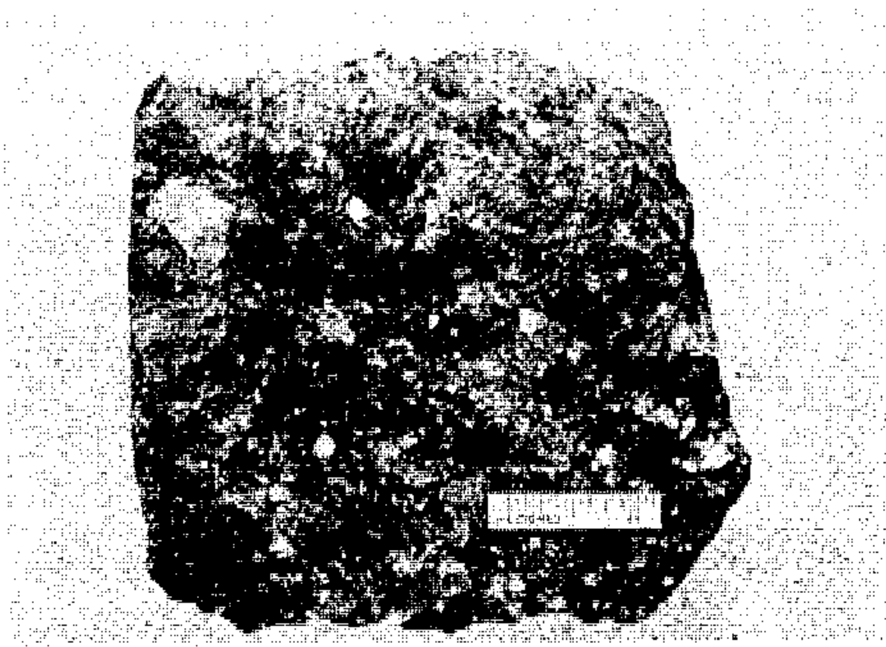


Figure 41. Hand specimen of metamorphosed and silicified augite-andesite breccias from the Hans Lollik member of the Tortola formation.

Figure 42. Meta-breccia from South Sound, Virgin Gorda, showing undeformed fragments although the sample has undergone metamorphism to the hornblende-hornfels facies.

on the north shores of St. Thomas. In thin section it consists of:

Plagioclase: broken phenocrysts, $An_{65?}$.

Hornblende: strongly pleochroic.

Garnet: pinkish brown.

Diopside: (+)2V about 60°.

Calcite: along borders of garnet.

Magnetite: rare; as very small crystals associated with the hornblende.

Epidote is also probably present.

The plagioclase and the hornblende show a moderate alignment parallel to the general compositional banding in the hand specimen; a foliation is not developed, however. The rock is now a garnet diopside amphibolite.

## Metamorphism of the Tortola Formation

Since all the members of the Tortola formation consist of andesitic material (except the Mount Healthy limestone), they will be considered to represent only one composition as far as the metamorphism is concerned. The descriptions of the low grade metamorphics have been grouped with these of the unmetamorphosed rocks and have been included under the petrography of the various members of the Tortola formation. Thus, only the more highly metamorphosed samples will be discussed here.

Other than T-226 no samples of high grade metamorphic rocks definitely belonging to the Tortola formation were sectioned. However, field samples very similar in appearance to T-203 and T137b of the Tutu formation are present. Thus, pending further work, the description of samples T-203 and T-137b (p. 142) are considered to be representative of the highest grade of metamorphism reached by any rocks in the Tortola formation. Sample T-226 is probably equivalent to these samples in metamorphic grade but the retrograde metamorphism it has undergone has made this uncertain.

T-226 is a coarse lithic tuff that has undergone metamorphism equivalent to the hornblende hornfels facies and then has subsequently undergone retrograde metamorphism. It consists of:

Hornblende: strongly pleochroic; weakly foliated; some replaced by chlorite, has a decussate texture.

Plagioclase: $An_{40-50}$; crystals have a brownish tinge; many occur as compound relic phenocrysts surrounded by hornblende; maximum size about 2 mm.

Epidote: retrograde after hornblende and plagioclase.

Magnetite: small grains in and associated with hornblende.

Sphene: associated with hornblende.

Little shearing is present although a weak foliation has been developed during the metamorphism.

Descriptions JVD-42(5) and T-213 below are typical of the rocks in the lower portion of the high grade metamorphics, i.e., those with actinolite as well as hornblende.

JVD-42(5) is a dark greenish grey fine grained tuff which consists of:

Hornblende: strongly pleochroic pseudomorphs after pyroxene.

Actinolite: weakly pleochroic decussate crystals throughout the sample.

Plagioclase: slighly recrystallized relic phenocrysts, $An_{50\pm5}$; also as fine crystals throughout the groundmass.

Magnetite: very small grains.

Pyroxene: almost entirely altered to hornblende.

No shearing or foliation has been developed. The sample has undergone recrystallization, however its original tuffaceous character is still present.

T-213 is a dark greenish grey, fine grained amphibolite possessing a relic tuffaceous texture. It consists of:

Plagioclase: as relic phenocrysts and also as small porphyroblasts; the composition is variable from oligoclase to calcic andesine.

Hornblende: strongly pleochroic, some after pyroxene.

Actinolite: small decussate crystals throughout the rock.

Biotite: associated with hornblende and quartz, possibly as an alteration of pyroxene.

Muscovite (sericite): alteration of the plagioclase and as discrete crystals in the groundmass.

Epidote: retrograde.

Magnetite: scattered original large grains; also a few younger blade-like crystals (hematite?).

Quartz: added during metamorphism.

Many rock fragments are present having a considerable variation in texture (amygdaloidal to pilotaxitic andesites). Many plagioclase phenocrysts are also present and show little alteration.

The metamorphism has produced a weak schistosity that has masked the finer sedimentary features. Potassium was added during metamorphism to form the biotite which developed throughout the rock in all fragment types as well as the matrix.

Metamorphism of the Necker Formation

Only in the vicinity of "the dogs" has the Necker formation undergone appreciable metamorphism. On these islands it has been metamorphosed to the hornblende hornfels facies at the contact with the batholith and decreases within a few hundred yards to a grade equivalent to the albite epidote hornfels facies or less. All other portions of the Necker formation show no appreciable metamorphism even on outcrops only a few hundred yards from the batholith. This very mild metamorphism, verging on diagenetic alteration, has been discussed in the descriptions of the sediments (p. 63).

## HYDROTHERMAL ACTIVITY

Donnelly (p. 123) has described the hydrothermal alteration of the spilites and keratophyres on southern St. Thomas and on St. John where this form of alteration is widespread. In the British Virgin Islands the only rocks that show extensive hydrothermal alteration are some of the keratophyres on the westernmost portions of Peter and Norman Islands.

The alteration is most conspicuous in the keratophyres where it has produced an extensive boxwork of limonitic stain in the otherwise white keratophyre. It is localized along fracture and fault zones having a N50-70W trend and is apparently later than all of the intrusives, although the hornblende-andesine intrusives show virtually no alteration or offset along these zones and thus may be later than the alteration. This alteration is probably related to the strike-slip faulting of the area which was probably accompanied by the intrusion of the quartz-andesine porphyries.

The chemical and mineralogical alteration accompanying the hydrothermal activity was the addition of potash to form both sericite and K-feldspar and the addition of pyrite which was altered to limonite during later weathering. Quartz was also added along these fractured zones. Donnelly (p. 127) has also shown that in some cases considerable soda was removed during the alteration.

In addition to the alteration discussed above numerous north-south trending alteration zones are present. No displacement occurred along these fractures, the only change being the formation of calcite, limonite, quartz and in some cases barite along fractures roughly parallel to the altered zone which is usually six to ten feet wide. These alteration zones occur throughout the Virgin Islands and may be related to east-west extensional stresses accompanying the development of the Anegada trough.

North-south trending quartz veins varying in width from two inches to six feet are present on southern Virgin Gorda. One of these contains copper and molybdenum mineralization and is discussed under economic geology. The development of these quartz filled fractures does not appear to be related to the batholith. Again, they may be related to later deformation possibly accompanying the development of the Anegada trough.

## STRUCTURE

The most prominent structural feature in the Virgin Islands is a northward dipping homocline (See Plate 1) which involves all of the exposed rocks. Throughout most of the British Virgin Islands this homocline has been overturned and it now has dips of 65 to 85 south. Previous workers, except Donnelly, have always assumed that Cleve (1881) was correct in postulating an overturned, almost isoclinal syncline with an axis running east-west through the Narrows. The author's study has definitely shown that this is not the case. The mistake the earlier workers made was to correlate the siliceous Outer Brass limestone with the non-siliceous Congo Cay marble. The similarity between parts of the Tortola formation and the Louisenhoj formation also lead the earlier workers to assume that these were the same formation. The present work has shown that the Tortola formation is upper Eocene in age and thus Cleve's assumption can no longer be accepted.

The structural history of the Virgin Islands began prior to the Cenomanian with the development of a geanticlinal rise in the sea floor. The Water Island spilites and keratophyres were deposited upon this rise in water at depths of less than 15,000 feet, otherwise the explosive activity necessary to form keratophyric tuffs could not have taken place. Most likely the water was much shallower than 15,000 feet.

The first tectonic activity for which there is direct evidence occurred after the deposition of the Water Island formation but prior to the deposition of the Louisenhoj which is probably Cenomanian. This deformation consisted of moderate folding about north-south axes followed by regional uplift and erosion which developed a surface with at least 2,000 feet of relief upon which the Louisenhoj was deposited. Some northward tilting may have also taken place but this is virtually impossible to distinguish from the later post-middle Eocene deformation.

Regional tilting to the north took place sometime in the Cenomanian post-deposition of the Outer Brass limestone and prior to the deposition of the Tutu formation. Uplift appears to have been greater in the eastern British Virgin Islands as the Outer Brass limestone is no longer present, apparently having been eroded away, and the Tutu formation is much thinner. This suggests that the axis of tilting may have had a northeast or east-northeast attitude.

The Virgin Gorda batholith was intruded after the deposition of the Tortola formation of middle Eocene age and was accompanied by doming and warping of the pyroclastics. Minor faulting may have also taken place but is not well exposed in the contact aureole. The Necker formation, the lower portions of which are probably contemporaneous with the batholith, has locally been strongly deformed, probably as a result of subsidence accompanying emplacement of later portions of the batholith. This deformation is best shown in the folding present on 'Guana Island (See Plate 1).

Strong regional folding about an east-west axis followed the emplacement of the batholith. The axis of this folding varies systematically from N70W to N60E from west to east, but later warping may be responsible for part of this attitude change. The amount of rotation varies from about 15 degrees in southern St. Thomas to about 130 degrees on Salt and Cooper Islands. From south to north in the British Virgin Islands the dip systematically varies from 50°S (overturned) to 70°N. The Tortola formation, which comprises about half of the section, usually has dips between 80°S (overturned) and 80°N. The Necker formation, which forms the outcrops on the northernmost islands, has quite variable attitudes. These have a general east-west strike but the dip varies from 45°S (overturned) to 15°N. A few outcrops also show east or west dips of about 15° but these apparently are only local distortions of an otherwise uniform trend with an east-west strike.

The batholith has undergone folding with the country rocks for the following reasons: (1) the batholith was intruded in the form of large sheets parallel to bedding, probably representing sills, (2) stratification in the gabbros and diorites is now vertical or overturned and has an attitude similar to the bedding in the surrounding metasediments, and (3) rock magnetism measurements on the early dikes and batholithic rocks consistently indicate a minimum rotation of 80 to 90 degrees about an axis approximately parallel to the strike of the surrounding metasediments; in one case the axis of rotation corresponded to an axis in the bedding and perpendicular to the a-lineation formed by aligned hornblendes in the metasediments. Additional rock magnetism measurements should be made on the massive batholithic rocks in an attempt to determine the variation of rotation with position in the batholith and also variation between rock types.

Post Miocene regional uplift of the eastern portion of the area is indicated by a limestone on the north shore of Tortola. This uplift had a north-south axis and probably took place after the development of the Anegada trough but prior to the Pleistocene since no regional warping is indicated on the Virgin Island platform which probably was formed by erosion during the Pleistocene lowering of sea level. A topography similar to the present one had been developed prior to this regional warping.

Minor faulting is very common in the Virgin Islands, but very few faults with displacements over 10 feet were seen in the British Virgin Islands. Part of this is due to the problems of correlation without which displacement could not be proved. In addition faults could readily be missed in areas of poor exposure because of the general similarity of all the pyroclastic rocks which make the observation of a fault displacement very difficult. Thus, uncertainty is present in any discussion of either the abundance or the attitudes of faults of major displacement.

Near vertical dextral strike-slip faults having an orientation of N45W to N65W were the most commonly observed and apparently have the largest displacements. Many shoreline features have roughly this attitude which reflects the importance of this fault or fracture direction. The largest displacement observed was about 4,000 feet.

Sinstral strike-slip faults, also vertical, form a complementary set to the dextral strike-slip faults. They are divided into three groups, namely, those with strikes near N55E, N30E and N15E. The Anegada trough is related to the N55E set which is also expressed as graben-like structures along the southern shore of St. Thomas (Donnelly, p. 86). The most pronounced development of the N15E set is on Salt Island (See Plate 3).

Faults with a NS vertical attitude are present throughout the islands and have small strike-slip displacements of both dextral and sinstral character. In addition to these NS faults there is a NS to N15W set of fractures with little or no displacement. These fractures have controlled the orientation of the late dikes, however, and probably should be considered to be extensional fractures associated with the early development of the Anegada trough. The dikes parallel to the fracture trend are most abundant on the southern islands in the immediate vicinity of the trough.

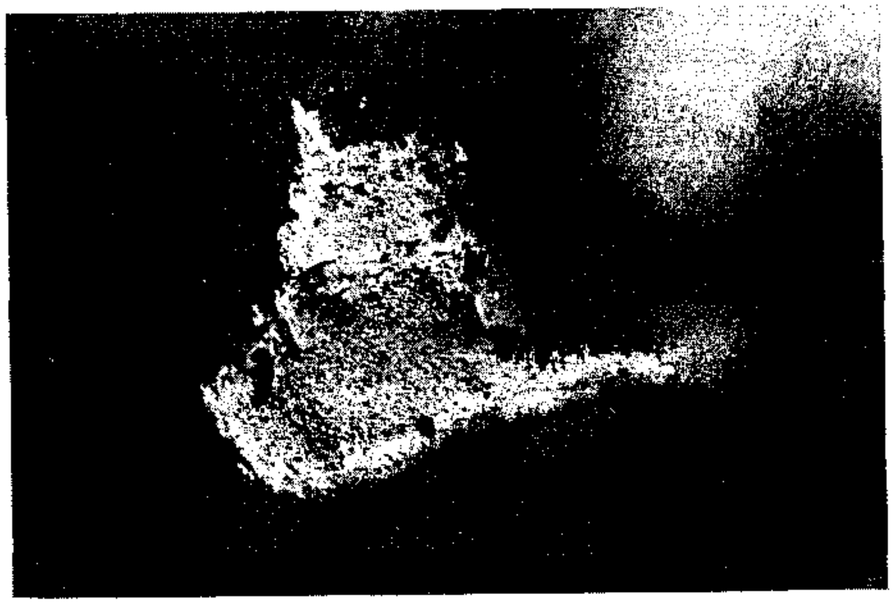


Figure 43. Aerial photograph of West Dog Island. The island is all massive granite. Note the very well developed north-south and east-west joints.

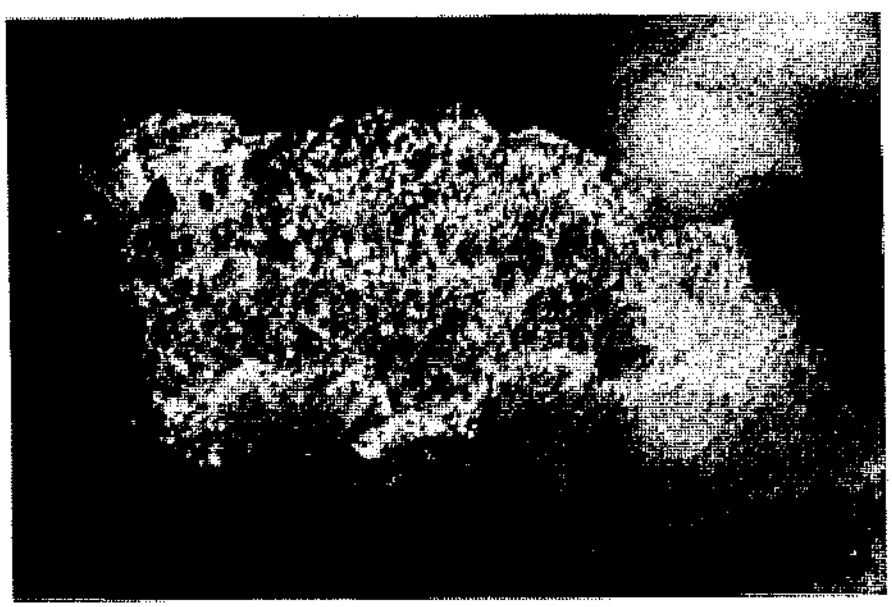


Figure 44. Aerial photograph of Fallen Jerusalem illustrating the joint control of the weathering of the granitic rocks of the batholith.

Crossfolding, seemingly related to the faulting, is present in St. Thomas (Donnelly, p. 88) but was not observed in the British Virgin Islands other than in the vicinity of West End, Tortola.

Jointing (See Figures 43 and 44) is well developed on the sea cliff exposures but is seldom observed inland. No statistical study of the jointing was attempted, however joint sets are present parallel to each of the major fault directions. Other shallow dipping joints are also present but it is not known to what feature these should be related.

Schistosity is well developed in the metamorphic rocks and is always parallel to the bedding. The foliation in the batholith is parallel to the margins of the intrusive and thus is also virtually parallel to the original bedding. On Salt and Cooper Islands a strong lineation is present, formed by elongation of pebbles and alignment of hornblende and plagioclase crystals. This is apparently an a-lineation of the major fold, however it plunges about 70 detrees to the south-southeast which is probably a reflection of the later uplift of the eastern portion of the area.

A summary of the tectonic events in the Virgin Islands is as follows:

1) Welt developed on the sea floor (pre-Cenomanian)
2) Vulcanism (pre-Cenomanian)
3) Folding about NS axis and uplift and erosion
4) Vulcanism (Cenomanian)

5) Submergence to 200± meters

6) Tilting to north or northwest (Cenomanian)

7) Erosion and deposition

8) Vulcanism (middle Eocene)

9) Emplacement of batholith

10) Regional strong folding about EW axis (post-middle Eocene)

11) Uplift and erosion

12) Tilting to west (post-Miocene)

13) Faulting associated with Anegada trough development

14) Continued uplift and erosion.

# ECONOMIC GEOLOGY

The only deposits of possible economic importance in the British Virgin Islands are copper, molybdenum, graphite, salt, and sand. These are usually present in subcommercial quantities but copper, molybdenum, salt and sand have been profitably exploited in the past.

## Copper and Molybdenum

Copper stains occur throughout the British Virgin Islands, but have only been prospected extensively on the island of Virgin Gorda. A mine was opened in the 1860's on southern Virgin Gorda (Copper Mine Point) and for several years chalcopyrite and chalcocite were mined from fractures in a quartz vein about six feet thick. The ore was hand cobbed at the mine and shipped as a hand concentrate to England for smelting. The tonnage produced is not known.

Molybdenite is associated with the copper mineralization at Copper Mine Point and was rejected along with the quartz during the early mining operation. However, during World War I, the mine tailings were reworked, again by hand, and a large quantity of the molybdenite was removed. The tailings still have a considerable amount of molybdenite in them. This mine is currently under lease to A. D. Fraser of Jamaica who has recently completed a drilling program to determine the extent of the ore body.

Other areas in which considerable copper stain was observed include: the north shore of Great Thatch Island, the western point of Ginger Island, on eastern Tortola north of Buck Island, on the eastern portion of Beef Island, and on the north shore of Sandy Cay.

Graphite

Graphite bearing schists crop out in the vicinity of West End, Tortola and on Salt, Cooper, and Ginger Islands. Some of these schists contain up to 50 percent flake graphite. As far as is known, these graphite bearing rocks have never been prospected. The abundance of graphite in the specimens collected by the author indicates that these deposits should be sampled further in an attempt to evaluate their economic significance.

Salt

Shallow, virtually landlocked salt ponds occur on two of the islands, namely Anegada and Salt. The evaporation losses from these ponds exceeds the fresh water additions during about six months of the year and as a result salt is precipitated from them. This salt is virtually pure sodium chloride and its recovery provides the residents of Salt Island with a small income throughout part of the year. The production of salt from the salt ponds could be substantially increased by the control of surface runoff in such a way that it would not dilute the brine in the ponds.

Sand and Gravel

The sand and gravel deposits of some of the beaches are mined by a few of the local inhabitants with most of their production being sold to the construction industry in the American Virgin Islands.

## GEOLOGICAL HISTORY

The present Virgin Islands are the erosional remnants of a thick accumulation of deformed pyroclastic rocks that were deposited on the northern slope of a geanticlinal rise.

The development of the Virgin Islands began with the extrusion of the Water Island spilites and keratophyres during or prior to the Cenomanian. These volcanics may be abyssal deposits as interpreted by Donnelly, but probably represent volcanics laid down in shallow to moderate depths of water. Following the deposition of 10,000 to 15,000 feet of these volcanics, moderate folding about north-south axes took place. This was in turn followed by uplift and erosion with the development of a surface of moderate relief prior to the beginning of deposition of the Virgin Island group.

The basal member of the Virgin Island group consists of augite-andesite pyroclastics of the Louisenhoj formation (thickness 500 to 14,000 feet) which were deposited on the Water Island erosional surface during the Cenomanian. The cone which provided these pyroclastics was in the vicinity of Pillsbury Sound and deposited most of its pyroclastics to the west. This volcanic activity came to a close with the submergence of the area to moderate but by no means abyssal depths where the siliceous Outer Brass limestone was deposited. Following the deposition of about 600 feet of this limestone the area was gently tilted to the north and west and the Tutu formation of Cenomanian or Turonian age, consisting of volcanic wackes, was deposited. These wackes were derived from an upland area to the south in which rocks of Louisenhoj and Outer Brass lithologies were exposed. During the early part of Tutu time the area continued to subside, however this subsidence had ceased prior to the deposition of the carbonaceous units below the Congo Cay limestone which probably represents subaerial or lagoonal depositional conditions. Following the deposition of this unit the area was again submerged a few tens or hundreds of feet while the Congo Cay limestone and surrounding sediments were deposited.

Renewed volcanic activity marked the close of Tutu time and the beginning of Tortola time. The first volcanic source to develop was in the vicinity of Hans Lollik Island and contributed the augite-andesite pyroclastics present in the western portion of the Tortola formation. Shortly thereafter additional volcanic sources developed, one in the vicinity of Virgin Gorda and another to the south. These three sources provided most of the 20,000 feet of pyroclastics which comprise the Tortola formation. The cones from which these pyroclastics were derived were probably subaerial since the slumped breccias derived from them contain fragments of shallow water limestone of middle Eocene age.

The deposition of the Tortola formation was followed by the intrusion of the Virgin Gorda batholith as a series of slightly crosscutting sills. Several other large granitic masses, notably the Jost van Dyke pluton, were also intruded at this time. During the intrusion of later portions of the batholith a series of welded tuffs and andesite breccias were deposited which were subsequently deformed and mildly metamorphosed by the last members of the batholith. These deformed breccias and welded tuffs, together with the slightly later pyroclastics, have been termed the Necker formation. This formation is at least 6,000 feet thick and was deposited both during and after the intrusion of the batholith.

Strong regional deformation about an east-west axis began shortly after the intrusion of the batholith; some of it may have begun prior to the deposition of the upper portion of the Necker formation. The area continued to be deformed about this east-west axis until portions of it had been rotated through more than 130 degrees. Strike-slip faulting took place after the major folding.

The block that was uplifted during the folding was apparently eroded about as rapidly as the uplift took place. The Rogue's Bay calcarenite was deposited upon this erosional surface after the major folding had ceased, sometime between the late Miocene and the Recent. This calcarenite has been tilted to the west about 20 degrees which shows uplift of the eastern portion of the area after the major deformation.

A series of subparallel hornblende andesine porphyries were intruded along north-northwest fractures sometime after the major deformation and erosion had taken place. These dikes are probably associated with the development of the Anegada trough and indicate that it was formed considerably later than the Eocene.

During the Pleistocene lowering of sea level a flat-topped platform developed. The present islands are mountainous areas above this platform that survived the Pleistocene erosion.

# APPENDICES

Appendices A through G are additional detailed descriptions of rocks from the British Virgin Islands.

## APPENDIX A

Hans Lollik Member, Tortola Formation

LJVD-1 is a green coarse lithic tuff with several rounded fragments up to 30 mm long. The smaller fragments are generally less than 3 mm and consist of several textural types of andesite as well as dark green glass fragments. The smaller fragments are angular and probably have not been reworked, however a weak banding produced by alignment of tabular fragments is present and may indicate some water transport.

Augite: individual crystals; $2V = 53° \pm 1°$; $N_y = 1.696 \pm 0.001$; $Ca_{44}Mg_{36}Fe_{20}$.

Chlorite: in fragments and in matrix (both brown and green in plane light); some probably is serpentine.

Plagioclase: individual crystals and phenocrysts in fragments, also as laths in matrix and in groundmass of fragments.

Magnetite: euhedral, 0.1-0.5 mm.

Epidote: as replacement within some fragments.

Glass: red brown, isotropic, shows flow banding in plane light.

Calcite

Prehnite or zeolite: replacing glassy matrix of fragments.

This sample generally resembles JVD-13 below except that it is finer grained and better sorted. Other than for a few large fragments, the particle size is between 0.1 and 4.0 mm; the finer sizes being single crystals of plagioclase and pyroxene. The groundmass consists of small fragments and silt sized material of probably tuffaceous origin (possibly glass now largely recrystallized to chlorite and clay minerals), and makes up some 10-15 percent of the sample. The textures within the individual fragments have considerable variation, again much like JVD-13 except that amygdule bearing fragments are much less common and glass more abundant.

The rock has not undergone strong metamorphism, however the presence of prehnite and epidote suggest some hydrothermal alteration or mild metamorphism, neither of which would be unexpected.

The calcite which appears to have been introduced as a cementing material is restricted to local areas. Several of the larger fragments show some alteration to calcite and epidote. The calcite is not present in smaller fragments of similar lithology and may have been formed, along with some of the epidote, prior to their arrival in the depositional environment.

JVD-9 is a mildly metamorphosed dark grey coarse lithic tuff. In outcrop it is seen to be massively bedded with indistinct bedding planes and with virtually no sorting. Numerous crystals of plagioclase and pyroxene are present throughout the sample.

Pyroxene: $2V = 49^{o} \pm 1^{o}$; $N_y = 1.694 \pm 0.002$; $Ca_{40}Mg_{40}Fe_{20}$.

Plagioclase: some zoned with hornblende replacing chlorite along zone boundaries.

Epidote: in amygdules in fragments and as scattered replacement patches throughout rock.

Prehnite: replacing plagioclase and in amygdules in some fragments.

Chlorite: variety pennine; in amygdules and in groundmass.

Hornblende: marginal replacing (also in cores of some) of pyroxene and as minute needles in the groundmass (these needles are probably actinolite).

Magnetite: corroded anhedral grains up to 0.5 mm.

The rock is a crystal lithic tuff (crystals to 2 mm, fragments to 5 mm) that has undergone virtually no reworking since zoned plagioclase phenocrysts show no abrasion or rounding. The plagioclase phenocrysts are strongly fractured and broken suggesting breakage during ejection. The groundmass consists of small broken crystals of plagioclase and pyroxene, fine-grained rock fragments and chlorite that may be an alteration product of original glass shards. Little sorting either as to composition or grain size is present.

The rock has been mildly metamorphosed with the development of some hornblende along the borders of pyroxene crystals and actinolite as a replacement of the chlorite in the groundmass.

JVD-13 is a green to dark grey green lithic lapilli tuff with many fragments in excess of 25 mm. Although it has apparently undergone mild metamorphism, the individual fragments have not lost their texture or angularity. The fragments have considerable variation in texture from aphanitic andesite to porphyritic andesite and a few felsites. No glassy fragments were seen in the hand specimen.

Chlorite: in amygdules, in fragments and in groundmass.

Plagioclase: as phenocrysts in fragments, as small laths in fragments and groundmass, also in a few large individual crystals.

Pyroxene: as phenocrysts in fragments and as individual crystals in groundmass; $2V = 47^{\circ} \pm 1^{\circ}$, $N_y = 1.695 \pm 0.001$; $Ca_{38}Mg_{41}Fe_{21}$.

Epidote: deuteric(?) alteration of groundmass.

Magnetite: small euhedral crystals in fragments.

Glass(?): brown, isotropic.

Calcite: as alteration of groudmass or as a primary precipitation in pore spaces.

Pumpellyite(?): parallel extinction, strong green (parallel to fibre) to colorless (perpendicular to fibre) pleochroism, moderate birefringence (low second order).

The lithic fragments encompass a wide variety of textural types--generally fine grained porphyritic andesites showing marked flow alignment of plagioclase phenocrysts and laths. In addition there are many fine grained amygdular andesites with no phenocrysts and a few fragments are present that may have been predominatly glass. These are now crystalline on a submicroscopic scale as a result of the devitrification of the original glass.

The sample shows no sorting and only a slight amount of rounding. The matrix is fine grained tuffaceous material which has been cemented by calcite. No alteration was seen other than that evidenced by the epidote which is probably of deuteric origin, possibly formed from the same fluids that filled the amygdules.

JVD-15 is a brown to grey brown thin bedded tuffaceous volcanic sandstone, maximum grain size about 1 mm, interbedded with volcanic wacke. Sorting is moderately good and considerable reworking has taken place. A slight grading is present in the coarser units. The unit is about 25 feet thick.

Plagioclase: crystals showing slight rounding from reworking.

Chlorite: in groundmass, probably from glass shards.

Magnetite and Hematite

Calcite: restricted to a few layers.

Pyroxene: small euhedral somewhat broken grains.

Prehnite: replacing plagioclase crystals.

Quartz: in reworked amygdule.

Clay minerals: dark brown nearly opaque very fine grained material in groundmass in portions of the rock.

The rock is thin bedded and has been reworked by water. It is composed of about equal parts of crystals, average size 0.1 mm to maximum near 1.0 mm, lithic fragments (about same size as crystals) and a fine grained groundmass. Sorting is fair in that no exceptionally coarse fragments are present, however little sorting is present among the finer materials. Some beds appear to consist entirely of tuffaceous material with little addition of reworked material. The groundmass of these layers is characterized by the presence of chlorite between the clasts instead of the dark clay-like material of the layers showing signs of reworking. Some of the chlorite is present in shard-like masses and appears to represent the alteration of glass shards which suggests a tuffaceous origin for these layers.

This sample is interpreted to represent alternating deposition of reworked and non-reworked material along the margins of an active cone. The calcite possibly indicates deposition in an aqueous and possibly marine environment in that it is restricted to the less tuffaceous beds. The prehnite was probably formed during the period of contact metamorphism associated with the late intrusives. Prehnite replacement occurs only in the more coarse grained and better sorted tuffaceous layers. Its development probably was enhanced by the higher porosity of these layers relative to the interbedded silty or clayey layers.

In addition to the above samples which have undergone little, if any, metamorphism, several mildly metamorphosed samples are described here since they represent types that were not observed in the unmetamorphosed section.

JVD-8 is a light grey green coarse crystal-lithic tuff that has apparently been mildly metamorphosed and altered to form epidote and clay minerals respectively. The sample consists of about 40 percent plagioclase crystals up to 4 mm in length in a matrix of lithic fragments. About 5 percent of the rock is small, up to 1.5 mm, pyroxene crystals. In the hand specimen no bedding or banding is present, however in outcrop it is seen to be indistinctly massively bedded.

Plagioclase: $An_{78\pm5}$.

Pyroxene: altering to hornblende.

Hornblende: after pyroxene(?); actinolite(?) in groundmass after chlorite(?).

Epidote

Prehnite

Chlorite: in amygdules.

The rock has undergone metamorphism about equivalent to the epidote amphibolite facies; chlorite is present but only as amygdule fillings in original fragments. No metamorphic fabric other than the felted amphiboles has been developed and much of the original texture still remains in the form of dark rims of original fragments. The original mineralogy has, for the most part, been replaced by its metamorphic equivalent but this has not destroyed the outline of the fragments. Textures internal to the fragments or in the groundmass show considerable alteration but suggest that considerable variation was present--probably much like JVD-13 or LJVD-1 only finer grained. The rock appears to have been composed of about equal parts of crystals and lithic fragments (of about the same size) set in a groundmass comprising about 25 percent of the rock. The original grain size of the crystals and fragments was about 0.5-1.5 mm. The above suggests that the rock may have been a crystal lithic tuff.

JVD-36 is a highly metamorphosed lithic lapilli tuff with fragments up to 12 mm in diameter. Many hornblende crystals probably after pyroxene crystals are present throughout the matrix. Little sorting or reworking appears to have taken place, however, these characters have been somewhat masked by the metamorphism. Most of the fragments were apparently porphyritic andesite.

Hornblende: after pyroxene phenocrysts and chlorite of groundmass.

Plagioclase: $An_{60\pm5}$; recrystallized after phenocrysts and groundmass laths.

Magnetite: being incorporated in hornblende.

Sphene(?): after ilmenite.

The rock is a metamorphosed lithic lapilli tuff in which a textural variation between fragments remains but probably no longer represents original textures. No metamorphic foliation was developed as only a felted mat of amphiboles is seen. The fragments are poorly sorted with their maximum size over 10 mm. The groundmass of fine tuffaceous material (now thoroughly recrystallized) appears to have made up about 30 percent of the rock, the rest being fragments upward of 0.2 mm. Some free crystals of plagioclase and pyroxene (now entirely replaced by hornblende) are present.

JVD-41 is a grey green to dark grey coarse lithic tuff or volcanic sandstone. The maximum particle size is about 3 mm, with the average being near 0.5 mm. Sorting is very poor but is present and variations in it have formed slight bedding with individual layers ranging between 1 mm and 20 mm. The sample has been moderately metamorphosed which has obscured many of the original textural features.

Plagioclase: $An_{65\pm5}$; the grains are anhedral and have been broken yet show no abrasion, i.e., they are very angular. The average grain size is about 0.5 mm. Some grains show alteration along their borders to a more albitic plagioclase, probably produced during metamorphism.

Hornblende: after pyroxene and chlorite.

Epidote: after plagioclase and as selective replacement of portions of fine grained fragments.

The sample has been subjected to metamorphism (epidote amphibolie grade) and a weak foliation has been developed approximately parallel to bedding, however this has not destroyed many of the original textures.

The rock is a fine tuff (0.5 mm maximum grain size) composed of crystals and some lithic fragments. Many of the chlorites appear to have a shard-like form, however this has been largely masked by the partial recrystallization of the chlorite to actinolite during the metamorphism. Pyroxene fragments were present in the original rock and are now represented by hornblende phenocrysts up to 0.2 mm in diameter. The rock originally consisted of about equal amounts of fragments and chloritic matrix; the fragments being about equally divided between crystals and lithic material.

T-170 is a moderately metamorphosed light grey green crystal-lithic coarse tuff with a maximum grain size near 5 mm and an average of about 3 mm. The crystals of plagioclase and pyroxene (or hornblende after pyroxene) are set in a matrix of lithic fragments and fine grained chloritic(?) material. Patchy alteration to epidote is present throughout the samples and may represent alteration along original fragment boundaries which have otherwise been entirely obscured by the metamorphism. No sorting, banding or bedding is present either in hand specimen or in the field.

Plagioclase: $An_{25 \pm 5}$; highly altered euhedral grains, many of which have been broken. Many crystals are larger than 3 mm. There are also minute laths in the matrix.

Epidote: as amygdule fillings and as replacement of groundmass and plagioclase phenocrysts.

Hornblende: after pyroxene.

Actinolite: very small needles in the groundmass, grown during metamorphism.

Magnetite(?): very small specks.

The rock is a crystal tuff with very little sorting, i.e., large crystals in a groundmass of fine grained material. Most of the original textures have been eliminated during metamorphism and only the presence of phenocrysts of plagioclase and pyroxene is now certian. The sample shows no foliation or shearing and was apparently not subjected to metamorphism greater than that of the epidote amphibolite facies. No pyroxene is present in the slide, however hornblende having the crystal outline of pyroxene is present and is assumed to represent the original pyroxene crystals.

## APPENDIX B

Sage Mountain Member, Tortola Formation

T-184 is a lapilli tuff which is typical of the lapilli tuffs of the upper part of the Sage Mountain member. It consists of lithic fragments of extremely varied texture but of andesitic composition, some of which are up to 50 mm in diameter; numerous pyrite crystals and a few plagioclase crystals are present throughout the sample. Hand specimen mineralogy: pyrite, plagioclase, and chlorite. The sample is very similar to T-185 below.

T-185 is a lapilli tuff similar to T-184 but has undergone considerably more metamorphism probably due to proximity to a nearby dike. The fragments have been stretched and molded together. There is considerable epidote replacement throughout the sample, particularly between fragments.

Calcite, Epidote and Chlorite: as amygdule fillings in fragments and also as replacement of plagioclase phenocrysts. Chlorite is also present as a replacement of glass in the fragments.

Plagioclase: as phenocrysts and as fine crystals in the groundmass of fragments; also as free crystals. The phenocrysts are altered to clays, calcite, epidote, and chlorite.

Magnetite: small anhedral grains throughout fragments and groundmass.

The rock is a lithic lapilli tuff that has undergone low grade metamorphism. It consists entirely of fragments from 1 mm to 20 mm in diameter. No matrix is recognizable between many fragments which appear to be molded together. The textures within the fragments are quite variable but all are fine grained and probably originally had glass in the groundmass. The epidote, calcite, and chlorite were formed post deposition by selective replacement of crystals, groundmass, fragments, and as amygdule fillings. Some fragments contain partially devitrified glass in the groundmass.

T-200 is a thin bedded tuffaceous volcanic sandstone. The finer units have an average grain size of 0.1 mm; the coarser beds about 0.5 mm, with some lithic fragments up to 2 mm. Mineralogy: Pyroxene, plagioclase, chlorite, pyrite.

The sample is poorly bedded and has lenses of fine grained material interbedded with the coarse. Some grains are rounded which suggests some reworking during water transport. However, many of the grains are very angular and are probably of airborne origin. The material comprising the rock has been transported a short distance by water, possibly by streams. No evidence of metamorphism is present.

For further descriptions see T-213 and T-226 under metamorphism of the Tortola formation.

## APPENDIX C

Shark Bay Member, Tortola Formation

T-220 is a lapilli tuff, some portions of which would be best called a breccia. Many fragments are tabular and show an alignment parallel to bedding. The color is light whitish green and numerous leucocratic fragments, up to 20 mm in diameter, are present. Dark green glassy fragments constitute about 10 percent of the rock. Patchy replacement epidote, or possibly fragments of granular epidote, are present throughout the sample. Sorting is very poor. (See Figure 11, p. 56b.)

Epidote: in patches and as discrete grains throughout the sample. It is present in both the groundmass and the fragments and apparently is not selective as to texture of the original fragments.

Chlorite (pennine?): most abundant in the groundmass portion of the rock, however it is also present in most of the fragments and occurs as amygdule fillings in several of the fragments.

Plagioclase: crystals up to 1 mm throughout the groundmass; some grains are bent, and most of them are broken; no zoning was observed and twinning is not common. The plagioclase is probably albite or sodic-oligoclase, all of which has been altered to some extent to clays and sericite.

Calcite, quartz, chlorite, and (?)zeolites occur in amygdules in some fragments.

The rock is a lithic lapilli tuff, showing no metamorphism but showing some deuteric alteration in the form of epidote and chlorite.

T-223 is a grey green lithic coarse tuff. The outcrop consists of indistinctly interbedded coarse tuffs and lapilli tuffs. Several fragments in excess of 20 mm are present in the hand specimen which is otherwise a coarse tuff. The fragments are quite variable in texture and composition, encompassing light purple aphanitic andesite, green aphanitic andesite, purple porphyritic andesite, felsite and dark green glassy material. Plagioclase crystals are also present throughout the sample. A slight banding, produced by orientation of tabular fragments, is present, but since the angular fragments show very little abrasion, this banding is thought either to be primary or to have been developed during slight slumping and not through water reworking. Many of the surrounding outcrops show conspicuous slumping although this one does not.

Glass: perlitic (onion skin) structure is present in a few fragments. The glass is now all devitrified to a fine grained colorless low birefringence material, possibly plagioclase or quartz.

Epidote: replacing plagioclase.

Chlorite: predominately in matrix but also in fragments;

as amygdule fillings; also after glass with relic perlitic structure.

Calcite: present between fragments and as amygdule fillings in fragments; it also replaces(?) plagioclase phenocrysts.

Plagioclase: phenocrysts in fragments; individual crystals in matrix and as minute grains in matrix and fragments.

Magnetite: small irregular crystals.

Quartz: as vein filling in fragment, rarely as crystals in matrix.

The rock fragments are very variable in texture from devitrified glass to porphyritic felsites with plagioclase crystals up to 2 mm. Many single plagioclase crystals up to 1 mm are present. No flow or metamorphic texture is seen except in fragments (primary flow textures). The rock appears to be a lithic tuff that has undergone little or no transportation or reworking. It has undergone alteration with development of epidote and calcite.

LJVD-2 consists of scattered fine grained volcanic fragments up to 40 mm in diameter in a matrix of coarse lithic tuff. The rock is whitish green in color and contains numerous dark green glassy fragments. A slight banding is present produced by orientation of tabular fragments. The fragments are quite varied in both texture and mineralogy. See Figure 5, page 46b.

Pennine: as amygdule fillings.

Quartz: amygdule fillings.

Epidote: as selective replacement of the groundmass along fragment borders, apparently formed post deposition, yet in some cases it has the relic orientation of the original groundmass.

Plagioclase: $An_{20\pm5}$, as euhedral to anhedral broken grains in the groundmass and as phenocrysts in fragments. Also as very fine laths in the groundmass and in felsite fragments.

Magnetite: anhedral crystals up to 0.2 mm normally altered to hematite.

Hematite and Limonite: as amygdule fillings.

Pumpellyite and Chlorite: amygdule fillings in amydgules rimmed with quartz.

Analcime: interstitial fillings.

This sample is similar to JVD-13 (p. 172) except that the average fragment size is over 5 mm and there are very few free crystals in the matrix. Most of the lithic fragments are very angular yet some are possibly molded about earlier fragments, suggesting hot, airborne origin. These clusters of fragments could be reworked material from a spatter cone. This is probably the case since a very large variation in texture is present between fragments which suggests a mixing of sources.

Little alteration or metamorphism has taken place--

the only evidences of which are the amygdule fillings and the devitrification or alteration of glass to chlorite and clay minerals. The groundmass consists of fine tuffaceous material, chlorite and clay minerals (after glass fragments?) and comprises about 20 percent of the rock.

The rock is apparently a mildly reworked lithic lapilli tuff.

No pyroxene is or was present.

JVD-43(1) In a polished surface the sample consists of several large slightly rounded fragments 3 to 4 cm in maximum dimension (maximum in outcrop is over 10 cm) set in a groundmass of lithic lapilli tuff (See Figures 9 and 10, page 56a). Several fragments appear to be bombs since they have a sharp cusp-like termination and a weak flow structure parallel to the margins of the fragment. A few dark green glassy fragments are present. Epidote is present throughout much of the groundmass and was formed post sedimentation. The rock has probably been metamorphosed slightly by some of the neighboring dikes.

APPENDIX D

Flows, Tortola Formation

T-101b is from the base of an amygdule rich andesite flow. The rock is medium grey and appears to consist of about 30 percent amygdules varying in size from 0.1 mm to 4 mm. No flow orientation of the amygdules is present.

Quartz: filling amygdules.

Plagioclase: phenocrysts with relic zoning showing brown color characteristic of metamorphic plagioclase.

Hornblende: acicular crystals in plagioclase phenocrysts; also as an acicular "matted" mass in the groundmass, also some in amygdules.

Magnetite: small subhedral grains in the groundmass.

Biotite(?): trace in amygdules.

The rock shows no shearing or foliation. Thirty percent of the rock is quartz filled amygdules. Another 30 percent is plagioclase phenocrysts, and the remainder is a groundmass of matted hornblende crystals, plagioclase laths and magnetite.

T-102 The hand specimen shows numerous amygdules up to one inch in diameter in very fine grained groundmass. Phenocrysts of plagioclase (to 2 mm) and probably also of pyroxene are also present. The sample was taken near the top of a flow.

Microscopically, T-102 is the same as T-101b except that the amygdules are smaller and contain plagioclase (after zeolite?); also several hornblende phenocrysts (after augite?) are present.

T-46a In hand specimen the rock consists of glomero-porphyroblasts and phenocrysts of feldspar or else amygdules filled with zeolites in a fine grained groundmass of chlorite. A few small lithic fragments may be present but could be local segregation in a flow.

In thin section the texture is that of a porphyritic flow. Plagioclase phenocrysts are large and well zoned but not broken. Some glomero-phenocrysts are also present of igneous(?) origin. The groundmass (about 40 percent of the rock) is amphibole (actinolite?) and fine grained plagioclase; some chlorite may also be present.

T-160 is from the top of a brecciated flow. No amygdules are present in the very fine grained fragments. Areas between fragments appear to consist entirely of epidote which may be replacing zeolites, chlorite and/or prehnite.

T-181 and T-182 are samples of the flows in the vicinity of Meyers which contain phenocrysts of plagioclase and pyroxene up to 3 mm long and amygdules up to 1.5 cm long. Many amygdules are pipe shaped or tabular and are more abundant near the interpreted top of the flow. Epidote, quartz and calcite are in the amygdules.

## APPENDIX E

Necker Formation, North of Virgin Gorda

The following descriptions in approximate stratigraphic order (bottom to top) are included to give the reader a more detailed picture of the sediments.

PP-11 is a light bluish green very fine grained tuff with a few fragments up to 5 mm arranged in bands parallel to bedding. The green color is probably due to chlorite and epidote. PP-12 is a tuff as in PP-11 but with large (1" by 6" by ?) epidote nodules in it as a replacement of the tuff.

Microscopically PP-11 and PP-12 are very similar to N-7, page 198.

PP-10 is light green lithic lapilli tuff resembling those of the Shark Bay member of the Tortola formation. A banding is present parallel to bedding produced by alignment of shard-like fragments in the finer grained portions of the sample. A large variation in fragment types is present with a range of variation from porphyritic andesite to aphanitic andesite to felsite. Pyrite crystals are present, some now replaced by limonite. Dark green glassy fragments are also present. Epidote is present throughout the groundmass and in a few fragments. The mineralogy includes epidote, plagioclase, chlorite, pyrite, and probably quartz. (See Figure 14, p. 64a.)

PP-1, PP-2 and PP-3 are lithic lapilli tuffs composed of fragments of a wide mixture of textural and compositional types set in a groundmass of finer fragments of about the same character. The fragments vary from pilotaxitic felsites to trachytic felsites and from porphyritic brown andesites to aphanitic green andesite, they also include numerous fragments of earlier fragmentals and a few fragments of dark green chlorite-rich material, probably altered glass. Several fragments of what was probably a fine grained tuff are also present. No granitic fragments were observed except PP-4 which is discussed below. Alteration with the formation of epidote is common throughout the samples but other signs of metamorphism are missing. Several fragments in PP-2 are over 5 cm in maximum dimension; all other fragments are within the range of lapilli tuff. Several breccia beds were seen in the field but were not sampled. For photographs of PP-1 and PP-2 see Figures 15a and 15b, page 64b.

In thin section sample PP-3 consists of

Plagioclase: in groundmass and as crystals and phenocrysts; some phenocrysts are replaced by epidote and albite.

Epidote: replacing plagioclase phenocrysts and as free crystals; also replacing the groundmass.

Chlorite: in amygdules and in irregular blebs after glass(?).

Quartz(?): very small grains.

No magnetite.

Several fragments are greater than 15 mm in diameter, some of which are fragments of earlier tuffs which look much like N-13.

This lithic lapilli tuff shows little evidence of reworking except possibly by slumping. The fragments are of many types, all of which are fine grained. All fragments are angular as are the plagioclase crystals in the matrix.

PP-4 is a fragment about 12 cm in diameter in one of the breccias like the lithic lapilli tuffs described above (PP-1, 2, 3). In hand specimen the fragment consists of large phenocrysts(?) of plagioclase with quartz in the interstitial areas along with a fine grained dark material, either a finely crystalline groundmass or a mineral such as hornblende or chlorite. Epidote is also present in many of the interstices. The border areas of the plagioclase phenocrysts are intergrown with the quartz.

Fragment #1

Quartz: showing graphic intergrowth with plagioclase and orthoclase.

Plagioclase: intergrown with quartz, as above; altered to clays and sericite.

Orthoclase(?): apparently all altered to sericite.

Sericite: alteration of orthoclase and possibly also of plagioclase.

Clays: alteration of plagioclase.

Chlorite: interstitial to quartz-plagioclase intergrowths.

Epidote: alteration of plagioclase.

Ilmenite(?): altered to leucoxene or similar mineral.

The fragment is a granophyre very similar to many of the late intrusives in the upper portion of the batholith. However, it differs from the intrusives in the batholith in that it contains more chlorite and epidote and less opaque minerals. It has also undergone considerably more alteration with the development of sericite and clays after the feldspars.

Fragment #2

Plagioclase: euhedral to subhedral crystals in a finer plagioclase and quartz(?) matrix.

Epidote and Chlorite: as alteration of hornblende(?).

Quartz: very fine grained, in interstitial areas.

The fragment is a fine grained diorite similar to those in the upper portion of the Virgin Gorda batholith. Epidote and chlorite have replaced the ferromagnesian minerals which were probably originally hornblendes.

The matrix which contains the fragments consists of chlorite, epidote, plagioclase and quartz. A fine grained opaque mineral is also present, probably limonite. Numerous broken crystals of plagioclase are present throughout the matrix along with fragments of felsite and a few chlorite rich areas representing either original glass or amygdule fillings. Several fragments of pilotaxitic andesites are also present. The matrix has been sheared, however unsheared portions of it show that it had some flow banding, developed by slumping; the shearing has broken many of the plagioclase phenocrysts and felsite fragments.

The rock from which the fragment was taken is a lithic lapilli tuff with local breccia lenses.

PP-5 consists of thin bedded to laminated fine tuffaceous sandstone and shale, now partially altered to epidote which has developed throughout the sample. Considerable small scale distortion of bedding is present; it was probably developed during post depositional regional deformation. The unit is about 50 feet in thickness.

PP-8 is a green lithic coarse tuff with a few fragments of felsite up to 15 mm. The sample shows poor sorting and a weak graded nature, possibly due to air sorting. A very weak banding produced by orientation of tabular fragments is present and is parallel to bedding. Epidote is present in small grains throughout the rock.

In thin section the sample consists of:

Quartz: filling vugs, replacing plagioclase, and as detrital grains.

Plagioclase: subhedral phenocrysts and broken crystals, $An_{34\pm}$; also as fine laths in the groundmass.

Epidote: replacing plagioclase and growing into vugs; that replacing plagioclase seems to be growing into the plagioclase from the borders; replacement epidote is also common in the groundmass.

Chlorite: after plagioclase and in vugs and groundmass.
Apatite: inclusions in the plagioclase.

The rock is a crystal lithic tuff showing considerable alteration since deposition, much more altered than samples on Necker Island. This probably is due to the proximity to the Virgin Gorda batholith. Free quartz grains are present throughout the sample and are very angular. The sample shows no evidence of reworking although slumping or very short transport by water may have taken place.

PP-9 is a large fragment in lithic lapilli tuff. The sample has undergone considerably more metamorphism than other samples from Prickly Pear. Some hornblende is present and the fragment boundary is indistinct and is surrounded by an alteration rim of a much lighter color.

M-1 is a light green to grey lithic lapilli tuff that has undergone considerable alteration, possibly low grade metamorphism, with the result that fragment boundaries are very indistinct. Epidote occurs as alteration patches, up to 8 mm in diameter, throughout the sample. The largest fragment is over 30 mm in diameter. In the field the unit is massive with very indistinct contorted bedding, probably the result of deformation during slumping.

M-2 is a coarse grained light grey green lithic tuff or tuffaceous sandstone. No bedding or other macroscopic structures are present.

N-1 is a very light grey to very light tan tuff with very poorly developed bedding. It apparently has undergone alteration with the production of clays. Most likely it is a devitrified vitric tuff.

In thin section it is a very fine grained tuffaceous(?) sediment with maximum grain size 0.05 mm. It has an intergrown texture, probably the result of crystallization from glassy fragments. No bedding or sedimentary structures were observed. The minerals present are quartz and plagioclase.

N-2 is an interbedded lithic coarse tuff and lithic lapilli tuff. A strong banding parallel to bedding is present produced by plate-like fragments of dark green chlorite (after glass shards?); other lithic fragments are felsites and fine fragmental andesites. The maximum fragment size is about 10 mm with most lithic fragments being below 5 mm in finer units.

Plagioclase: phenocrysts up to 1.0 mm long and also as fine laths in the groundmass.

Chlorite: in large (3 mm) patches enclosing plagioclase.

Quartz: after glass(?) and as interstitial fillings.

Epidote: scattered throughout the slide as a patchy alteration.

Magnetite(?)

Prehnite or Sericite: as a very fine alteration of the groundmass and also of plagioclase.

In thin section lithic fragments (to 2 mm) are set in a matrix of plagioclase phenocrysts (to 1 mm) and fine grained to microcrystalline groundmass that locally shows a marked flow texture. This may have been produced by slumping of the tuff shortly after deposition or it may be evidence of an ignimbritic origin. No evidences of reworking were seen and, other than the flow-like banding, no internal structures were observed. The rock is probably a lithic tuff with some vitric and crystal components.

N-3 is a light tan to olive fine tuff with no banding. Bedding in the field is from 2 inches to 2 feet. The sample is moderately well sorted with no fragments over 1 mm.

In thin section it is a fine grained tuffaceous(?) sediment with recognizable plagioclase fragments up to 0.1 mm in diameter. These plagioclase crystals have been added to in place and now are intergrown with the surrounding crystals suggesting that the rock may have been a crystal-vitric tuff which has now recrystallized to plagioclase, quartz and chlorite. No bedding or other sedimentary textures were seen in thin section.

N-4 is a highly altered lithic lapilli tuff in which the fragment boundaries have been obscured by the patchy development of epidote. Most of the fragments are of andesitic origin with no felsites observed. Many fragments have dimensions up to 30 mm, and many of these are dark green chloritic fragments, which are possibly altered glassy(?) fragments.

N-5 is a light tan lithic fine tuff with moderately developed, yet diffuse, bedding, possibly developed during reworking by water, but most likely by original size variation in the airborne material. A definite shard-like texture parallel to the bedding is observed on the cut surface. This texture seems to support an airborne origin as it is doubtful if these shards could survive any reworking.

N-6 is a light brown to grey brown lithic tuff with a maximum grain size of 1.5 mm. Very little sorting is evidenced and a slight banding parallel to bedding is present, caused by orientation of chlorite aggregates which may be an alteration of original glass shards. The rock is apparently a subaerial tuff but may have been deposited in shallow water; if so, very little reworking took place as it is not evidenced in the hand specimen or in the field.

In thin section N-6 is a fine grained tuffaceous sediment much like N-3 and N-5. The grain size is normally less than 0.2 mm. The minerals present are plagioclase, chlorite, opaque oxide (limonite? or magnetite?), epidote crystals, and quartz. The sample has weak flow orientation in an otherwise felted groundmass. Sorting is very poor, and the plagioclase grains are angular with little, if any, evidence of abrasion. Most lithic fragments are less than 0.5 mm. No bedding is present, however a banding is present in the fine grained groundmass parallel to the long axes of the plagioclase phenocrysts, suggesting a shard origin for the groundmass. The rock is most likely a vitric-lithic fine tuff with some (about 8 percent) crystals scattered throughout it.

N-7 is a light blue green, very fine grained vitric(?) tuff with very slight banding parallel to bedding. In the field it is thin bedded to massive (1 inch to about 5 feet), however, the bedding planes are very indistinct.

Mineralogy: plagioclase, chlorite, magnetite, prehnite(?) rare, and quartz(?).

The above minerals developed by devitrification of a very fine grained vitric tuff. Plagioclase fragments larger than 0.01 mm are very rare and the largest crystal seen was 0.1 mm. Rock fragments up to 1 mm may have been present but their texture is so similar to the matrix that their presence is hardly more than a suggestion. No bedding or other sedimentary features were observed.

N-11 is a lithic coarse tuff which has undergone considerable alteration to form epidote, chlorite and clays, after original plagioclase, glass and ferromagnesian minerals, yet the fragment borders are moderately sharp and angular. Slight banding is present which is parallel to bedding and formed by orientation of tabular lithic fragments and dark green chlorite aggregates which may be an alteration after original glassy shard-like fragments. The maximum fragment size is 10 mm, with most fragments being less than 5 mm. The sample is probably a subaerial tuff that has undergone very little reworking.

N-13 is a lithic lapilli to lithic coarse tuff composed of fragments up to 30 mm in diameter. Very fine grained, light purple reaction rims are present around the larger fragments, however smaller fragments, under 8 mm, have no reaction rims. A slight banding is present parallel to bedding caused by oriented chlorite aggregates which may be altered glass shards. The whole rock has a general grey to grey brown color and weathers to a rough surface consisting of spheroidal masses, the cores of which consist of altered felsite material.

Plagioclase: $An_{5\pm5}$, as phenocrysts and as minute grains in the groundmass.

Epidote: in single crystals and as aggregates throughout the rock. This alteration is very selective having replaced the groundmass but rarely having replaced any of the fragments. Some areas of the rock are apparently fragments but no textural differences are present other than no epidote is present within the fragment-like area while considerable diseminated epidote is present outside.

Magnetite: small subhedra in fragments.

Quartz: in groundmass and in fragments.

In addition to the epidote the groundmass consists of plagioclase and quartz crystals that are interlocking along their margins. The fragments, which are virtually free of epidote, are 5 to 10 mm in diameter. The texture, other than for the epidote, is the same inside and outside of many of the smaller fragments suggesting that they may have been formed by selective alteration of an otherwise homogeneous groundmass. However, the larger fragments are felsites with pilotaxitic to trachytic textures with the flow textures in the fragments having no relation to each other. The present texture in the groundmass is predominately one of recrystallization, as indicated by the interlocking of the plagioclase and quartz crystals which suggests that the rock was a vitric fine tuff. However, the large felsite fragments and some of the chlorite aggregates seen in hand specimen suggests that the sample is actually a lithic or lithic-vitric coarse to lapilli tuff.

# APPENDIX F

## Necker Formation, 'Guana Island Section

The descriptions below are included to give both the petrographic character of the rock as well as a more detailed description of the typical rock types exposed in the 'Guana Island portion of the Necker formation.

G-1 is a brown, very thin-bedded tuff, the bedding being very indistinct; even on cut surfaces. The rock has been highly weathered, probably by subaerial weathering at the time of deposition. No coarse particles are seen, however some aglomeration of fine particles is present which may represent incipient tuff ball formation as is present in G-5.

Mineralogy: plagioclase, quartz, magnetite and hematite, calcite.

The rock is a very fine grained sediment, probably a devitrified tuff. It has been thoroughly replaced by calcite.

G-2 is a light tan lithic coarse tuff with a maximum particle size of about 2 mm and an average less than 1 mm. The sorting is poor, yet bedding is marked but not distinct. Bedding is represented by alignment of coarser-grained material interbedded with finer lamella. A slight compositional change is also present between the various lamellae. The sample was weathered at the time of deposition by subaerial weathering suggesting that it was deposited as an ash and was not subjected to water reworking. Very indistinct cross bedding is present possibly representing poorly developed aeolian ripples. The rock may have undergone mild deformation in the form of shearing.

Pyroxene: very small grains.

Quartz: a few detrital grains, most not primary.

Plagioclase: albite.

Chlorite: secondary.

Epidote: secondary.

Magnetite or Hematite: in very small grains.

The rock is a fine crystal or vitric crystal tuff that has undergone mild metamorphism with the production of epidote throughout the groundmass. The rock is finely bedded and shows slight crystalographic orientation parallel to bedding. Chlorite is present throughout the groundmass, and is probably derived from original glass.

G-3 is a light green tuff which has been highly altered with the formation of calcite and epidote as a replacement of much of the groundmass and some of the original lithic fragments. The rock can be described as a lithic coarse or lapilli tuff depending on where in the outcrop one looks. Some fragments are greater than 100 mm across, however the predominant fragment size is 10 to 20 mm, and in many areas it is entirely less than 4 mm. The mineralogy present is chlorite, plagioclase, epidote and probably considerable amounts of clay. Calcite is present as a replacement of some of the fragments, which possibly were calcareous in the beginning. No banding or obvious bedding is present and the outcrop as a whole may well represent a slumped mixture of coarse tuff and lapilli tuff.

One fragment is a fine grained dark green porphyritic andesite that looks much like some of the keratophyres of the Water Island section. Pyrite is present throughout the fragment and some mild zoning parallel to the borders in which the pyrite has been removed indicates an alteration of the fragment near the time of deposition. Other fragments are quite similar to this, but most of them are coarser grained and have numerous plagioclase phenocrysts up to 5 mm long.

G-4 is a dark green breccia with considerable color variation being present between individual fragments. It consists of numerous rock types, based upon texture, the series varying from fine grained aphanitic andesite to porphyritic andesite which is the most predominate (See Figure 20, p. 78a). However, several fragments of a trachytic nature are also present possessing a texture much like some of the welded tuff units described below. Several fine grained felsite fragments are also present in the groundmass which consists of fine grained chlorite and plagioclase. Many dark green chlorite rich areas are present, probably representing original glassy fragments. The maximum size particle as exposed in the hand specimen is greater than 120 mm, however, fragments of this size are uncommon, most of them being less than 20 mm in maximum dimension. One fragment is present which appears to be concretionary and is possibly an enlarged version of some of the mudball structures as seen in G-5. Epidote has replaced much of the groundmass and has also selectively replaced fragments and portions of fragments.

G-5 consists of three samples taken over a stratigraphic interval of about three feet. They consist of coarse lithic tuffs with a weak bedding some of which is graded. They are light green to grey green in color and contain distinctive concertionary structures, resembling pisolites, that were probably formed by raindrops falling in a fine subaerial ash which balled up to form mudball-like structures up to 8 mm in diameter (see Figure 21, p. 78b). Some of the units do not contain these structures and are normal lithic fine and coarse tuffs; some of which have flat tabular fragments 3 by 30 mm which are plates from a fine grained mudcracked surface. These are incorporated with lithic fragments of tuffaceous origin up to 3 mm in diameter. Some units are very fine grained and silty in appearance and possibly represent deposition on a playa-like surface. The section shows little metamorphism and probably can be considered to be virtually unaltered since deposition, except for some weathering at or shortly after the time of deposition.

Plagioclase: largely replaced by epidote.

Chlorite

Epidote

Calcite

Quartz: amygdule(?) fillings.

Concentric spherulitic structures (mud balls).

Very fine grained groundmass, plagioclase, epidote and clays.

The rock is a mildly metamorphosed (or altered) vitric-lithic tuff with about 10 percent plagioclase crystals now largely replaced by epidote. The origin of the mud balls is uncertain. They always have a core of coarser material enclosed within a rim of fine grained particles. Alteration to epidote has masked any other original features.

G-8 is a fine porcelaneous tuff, thinly bedded to laminated, and consists entirely of particles visible only under the microscope. Several quartz filled fractures cut through the sample; however, they show no displacement other than a slight dialation. The color is light tan to almost white on a fresh surface.

Mineralogy: Quartz, Calcite, and Epidote(?).

The sample is too fine grained to show anything in the thin section other than a very weak bedding.

G-11 is a dull purple lithic lapilli tuff with fragments having an average size near 10 mm. The sorting is moderately good, yet the fragments show no signs of reworking. All fragments are highly altered and original textures are quite indistinct.

G-34 is a light green lithic lapilli to coarse tuff with about 20 percent of the rock being large fragments, up to 15 mm in diameter. The fragments consist of many textural and compositional types from dark green chloritic fragments, apparently originally glass, to felsite, with porphyritic andesites and aphanitic andesites also being present. Considerable color variation also exists between fragments varying from dark green to red to white. Two fragments have cuspate ends, suggesting that they may have been cooled in the air, i.e., they were bombs rather than blocks. The sorting is poor and no evidence of reworking is present. The sample was apparently deposited as a subaerial ash and may have undergone slight slumping since deposition.

G-12 is a light purple to brown welded tuff with a very fine banding. Considerable fracturing is present which may be due to later deformation. Amygdules are present, however they have been considerably elongated and squashed parallel to bedding.

Chalcedony: filling cavities, both spherulitic ones and flattened ones. Large grains of quartz are also present, normally associated with the fine grained radial cavity filling chalcedonly.

Limonite: (oxide at least) always present forming rims around spherulitic quartz filled cavities.

Calcite: in the groundmass in large optically orientated patches elongate parallel to bedding(?) or maybe the elongate patches give a pseudo bedding.

Quartz: probably an amygdule filling since a similar habit occurs in large rimmed ameboid masses surrounding and intergrown with calcite.

Magnetite: minute euhedra in unaltered portions of the sample.

Plagioclase: albite; as large laths in unreplaced areas of the sample.

The sample is very highly altered to calcite which replaces about 50+ percent of the plagioclase phenocrysts and groundmass. Several altered albite phenocrysts are present. A strong planar structure is present in the groundmass as evidenced by the orientation of the small tabular plagioclase(?) crystals in the groundmass, and by the calcite alteration which has in part been controlled by this structure so that it is now parallel to it. Quartz and chalcedony filled spherules are present throughout the sample and probably represent filled vessicles; the chalcedony may, however, represent variolitic structures.

The sample was probably a felsic flow or possibly a welded tuff in which banding is present on a large but somewhat variable scale. No ferromagnesians were seen except for the limonite present throughout the slide, which occurred mainly as haloes around the quartz and chalcedony filled vesicles.

G-23 is a highly altered welded tuff showing columnar jointing in the field; the hand specimen is very vesicular, however this is a selective alteration of the original phenocrysts and amygdules. The less altered groundmass is light green to whitish green in color and consists of glass or it's devitrified products. Thin flow banding is present and is formed by the less weathered streaks of the above mentioned glass and the more weathered vesicular appearing areas.

G-24 is also a welded tuff very similarly banded, and may actually be a less weathered equivalent of G-23. Some glassy areas may be present, however most are apparently devitrified to chlorite and feldspar with a few plagioclase phenocrysts scattered throughout the rock; calcite alteration is present throughout the sample.

Quartz: as replacement of groundmass and in some amygdules.

Chalcedony: as radiating rims on amygdules, often about a sericite core.

Plagioclase: phenocrysts--highly altered to sericite, calcite and clay; some are near $An_{50}$ in composition, others near $An_{30}$ and some have been entirely replaced by albite.

Calcite: as amygdule fillings.

Sericite: as replacement of original plagioclase phenocrysts and as replacement of the groundmass.

Magnetite: associated with the amygdules.

Limonite: after magnetite and as stain around amygdules.

Pumpellyite(?) and Hematite or Limonite: as alteration products, possibly associated in time with present day weathering; occur in weathered portion of the rock.

Chlorite: throughout rock as possible amygdule filling; also present in groundmass.

Clays: after plagioclase phenocrysts.

Zeolite(?) associated with chlorite in amygdule--weakly brief, colorless, occurs as either fibres or blades.

Two types of amygdules are present--one is a radiating mass of chalcedony fibres with sericite at the core. These are always very near to being round and contain a rim rich in iron hydroxide. The second type, more truly amygdule-like in character, has an irregular shape and is filled with quartz, calcite, chlorite and (?)zeolite.

The rock is a flow, probably a welded tuff. The plagioclase phenocrysts show alignment and the large irregular amygdules are also elongate in this direction suggesting flattening. The calcite and sericite replacements have obscured most textures and have no apparent orientation except when they have replaced a previously oriented grain.

G-27 is a thinly banded welded tuff; the banding is contorted and shows evidence of flowage. The sample is probably a fresh equivalent of G-26. The glassy bands are light grey in color, the intervening areas are white to brown, depending upon the degree of alteration. Calcite, as an alteration, is present throughout the sample.

Limonite

Plagioclase: phenocrysts, $An_{10\pm5}$; also as very fine crystals in the groundmass.

Sericite: alteration of plagioclase phenocrysts.

Calcite: as alteration of plagioclase phenocrysts and of the groundmass.

The sample is probably a flow or a welded tuff in which the glassy groundmass has crystallized to plagioclase, quartz and hematite and which has undergone replacement by calcite. This has been followed by weathering. G-23 may be much the same.

G-33 is a flow breccia with many fragment types, however felsite is most abundant, in a purple grey groundmass which also includes minute felsite fragments (See Figure 19, page 78a). The thin section shows that the rock has been highly altered with the formation of calcite throughout the rock. No obvious flow banding or other characteristics of flow are present in the thin section, nor does the sample appear to be a tuff.

# APPENDIX G

## Early Intrusives

JVD-6 In hand specimen plagioclase and pyroxene phenocrysts are present surrounded by a fine grained groundmass in which a few amygdules may be present. The sample has been highly metamorphosed but no foliation has developed.

Plagioclase: mildly zoned, with considerable twinning in the phenocrysts; fine crystals in the groundmass.

Amphibole: after pyroxene phenocrysts and as minute crystals in the groundmass. These small crystals in the groundmass are probably actinolite.

Magnetite: partially resorbed euhedra throughout the rock.

The rock is a porphyritic intrusive augite-andesite that has undergone metamorphism with little change of texture but with recrystallization of the mafic components. The intrusive may have been a feeder, or offshoot of one, for the later augite-bearing tuffs.

JVD-4 The hand specimen is comprised of plagioclase and pyroxene phenocrysts in a fine grained groundmass of plagioclase and amphibole(?).

In thin section it is the same as JVD-6 but with a higher percentage of plagioclase phenocrysts and a few patches of quartz in what may be amygdules. Plagioclase is $An_{60 \pm 5}$

and possibly as high as $An_{80}$ in the cores of the more strongly zoned crystals.

JVD-56 The hand specimen is very fine grained with no phenocrysts present. This sample and the associated pyroclastics are strongly metamorphosed and their original textures or compositions are not obvious. The rock may be a meta-tuff or an intrusive.

Mineralogy: Plagioclase, epidote, quartz, hornblende, prehnite(?) in amygdules, magnetite, chlorite in amygdules and biotite(?).

The rock is a metamorphosed and partially replaced fine grained pyroxene-free andesite intrusive, probably a dike. The amygdules suggest that the dike was intruded at a shallow depth, probably contemporaneously with some of the overlying tuffs and breccias which contain fragments very similar in texture to that of this intrusive.

The metamorphism has resulted in the development of amphibole, probably at the expense of chlorite but does not seem to have destroyed much of the original texture or to have developed any metamorphic fabric other than felted amphiboles.

T-96 The hand specimen is a medium grey porphyritic basalt which has been mildly metamorphosed. Phenocrysts (up to 2 mm) of plagioclase and hornblende after pyroxene(?) are abundant throughout the sample.

In thin section the sample consists of:

Plagioclase: as large phenocrysts and as minute crystals in the groundmass; the phenocrysts tend to be euhedral but have been broken and highly altered along fractures and cleavage by biotite, hornblende, sericite and magnetite.

Amphibole: strongly pleochroic--colorless to green to blue green; occurs in two habits: hornblende(?) as replacement of pyroxene(?), and as acicular needles in the groundmass. These acicular amphiboles may be actinolite.

Biotite(?): small crystal aggregates along borders of plagioclase crystals and in relic amygdules(?); possibly stilpnomelane.

Magnetite: small euhedral grains.

Quartz: in relic amygdules; possibly also in the groundmass as minute grains.

Sericite: alteration of plagioclase.

Epidote: patchy alteration of the groundmass.

The rock is a metamorphosed porphyritic basalt very similar, except for the metamorphism, to those seen on 'Guana Island. No foliation was developed during metamorphism, however decussate amphibole needles have been formed in the groundmass.

T-131 The hand specimen is a dark grey finely crystalline amphibolite with relic phenocrysts of plagioclase and (?)pyroxene.

The rock has the field relations of an intrusive, probably a thick dike.

In thin section it consists of:

Plagioclase: $An_{65 \pm 5}$; subhedral to anhedral; many grains have been broken and partially replaced by sericite and acicular hornblende; some crystals are mildly zoned.

Hornblende: pleochroism--colorless, green, blue green; some possibly replacing pyroxene.

Biotite: probably a relic deuteric alteration of original interstitial areas; associated with skeletal magnetite crystals.

Magnetite: as skeletal crystals associated with hornblende and biotite masses.

Quartz(?): in small ovoid areas; very finely crystalline; possibly relic amygdules.

Limonite(?): minute red grains in weathered portion of sample.

Sericite: as an alteration of the plagioclase phenocrysts, particularly along cleavage and fractures.

The sample is holocrystalline and apparently is a metamorphosed diabase. No pyroxene is present, however many large hornblende crystals are present that could be replacement of pyroxene. Acicular amphibole, found throughout the slide, formed during metamorphism, predominately in the plagioclase crystals. It has no preferred orientation. The rock has a slight tendency to be porphyritic.

JVD-20 is a dike cutting the lithic lapilli tuffs and consists of pyroxene and plagioclase phenocrysts, the plagioclase being somewhat altered, in a fine grained chlorite and (?)plagioclase groundmass.

Augite: $2V = 49^{\circ} \pm 1^{\circ}$; $N_y = 1.694 \pm 0.001$; $Ca_{40}Mg_{40}Fe_{20}$.

Plagioclase: phenocrysts of calcic bytownite, $An_{85\pm5}$; largely replaced by albite.

Magnetite

Prehnite: a replacement along with epidote and chlorite of plagioclase phenocrysts; also in patches in the groundmass.

Calcite

Quartz(?)

Epidote

Chlorite

The sample consists of fine grained interlocking plagioclase laths including phenocrysts of plagioclase, pyroxene and magnetite. Calcite, prehnite, quartz, albite, chlorite and epidote occur as an alteration of the plagioclase in both phenocrysts and groundmass. The groundmass between the laths of plagioclase is predominately chloritic.

The rock is a porphyritic basalt dike. Cooling was apparently moderately slow thus providing time for complete crystallization as well as providing an opportunity to develop late stage alteration products such as the prehnite.

T-177 In hand specimen the rock is a very finely crystalline light grey green andesite with rare plagioclase phenocrysts. The sample has been mildly metamorphosed.

Plagioclase: small laths throughout rock; virtually no phenocrysts, those present altered to epidote.

Amphibole: idioblastic, fine grained, and weakly pleochroic, probably actinolite.

Epidote: replaces plagioclase and fills veins.

Magnetite: subhedral.

The rock is a fine grained pleotaxitic felsic intrusive. The amphibole developed during the metamorphism, as did some of the epidote. Post-metamorphic fractures have been filled with epidote and plagioclase, The texture of this sample in thin section is quite similar to that seen in the felsite fragments in the upper Tortola formation.

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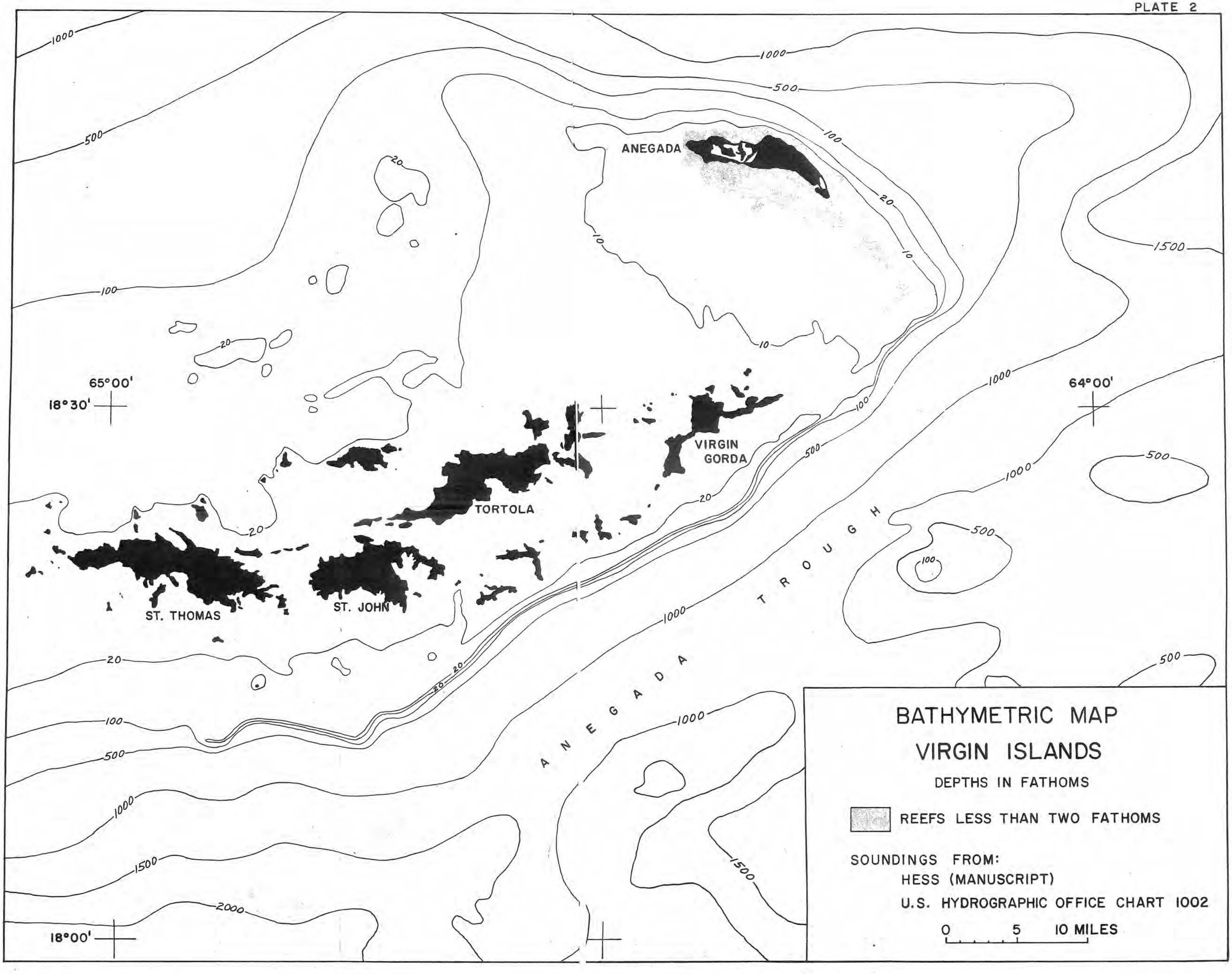
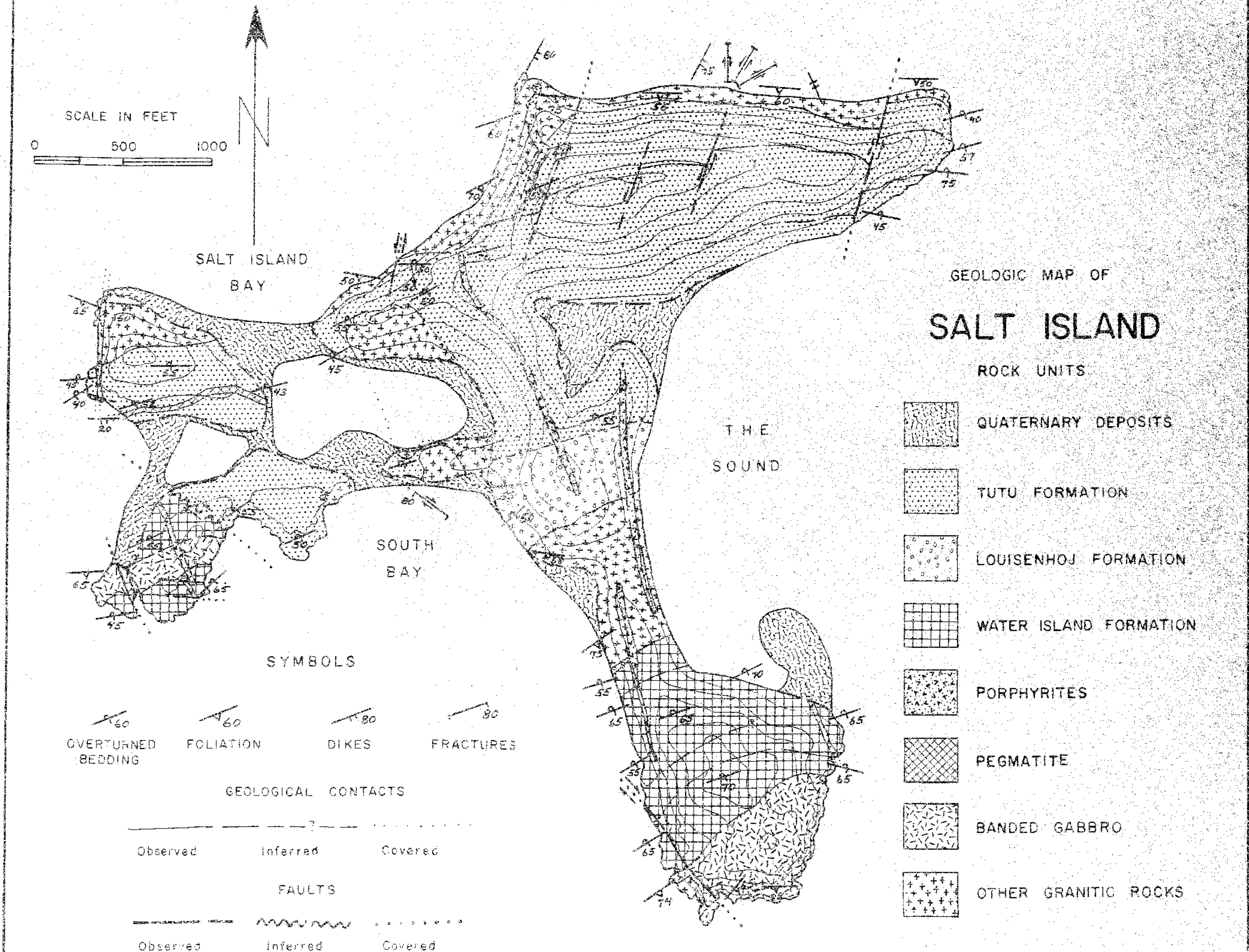
PLATE I


N
S
A
A'
ANEGADA TROUGH
VERTICAL AND HORIZONTAL SCALE
0 1 2 3 4 5 MILES
NECKER ISLAND
MOSQUITO ISLAND
PRICKLY PEAR ISLAND
EUSTATIA ISLAND
SEAL DOGS
NORTH SOUND
'GUANA ISLAND
GREAT CAMANOE
GEORGE DOG
WEST DOG
GREAT DOG
SCRUB ISLAND
LITTLE CAMANOE
MARINA CAY
PLUM TREE BAY
SOUTH SOUND
COLLISON POINT
VIRGIN GORDA
COPPER MINE POINT
LITTLE JOST VAN DYKE
GREEN CAY
GREAT TOBAGO
LITTLE TOBAGO
JOST VAN DYKE
SANDY CAY
ROGUE'S POINT
ROGUE'S BAY
SHARK BAY
JOSIA'S BAY
BREWERS BAY
MT HEALTHY
EAST END
BEEF ISLAND
BUCK ISLAND
ROADTOWN
ROAD HARBOR
PARAQUITA BAY
TORTOLA
FALLEN JERUSALEM
ROUND ROCK
GREAT BRITAIN
UNITED STATES
GREAT THATCH ISLAND
WEST END
FRENCHMANS CAY
HAVERS
THE NARROWS
CONGO CAY
SALT ISLAND
THE SOUND
GINGER ISLAND
DEAD CHEST
COOPER ISLAND
PETER ISLAND
ST. THOMAS
ST. JOHN
NORMAN ISLAND
64°30'
18°30'
64°20'
64°50'
18°20'
GEOLOGIC MAP
BRITISH VIRGIN ISLANDS
GEOLOGY BY C. E. HELSLEY
— LEGEND —
SEDIMENTARY ROCKS
RECENT
Qal
ALLUVIUM: Valley fill, Beach rock, and Mangrove deposits
UNCONFORMITY
MIOCENE to PLEISTOCENE
Trb
ROGUE'S BAY CALCARENITE
UNCONFORMITY
EOCENE
Middle Eocene
Tn
NECKER FM: Quartz-Andesite Tuffs and Breccias with minor Welded Tuffs
TORTOLA FM: Andesitic Pyroclastics, Volcanic Sandstone, and Limestone
Ttmh-MOUNT HEALTHY LIMESTONE
Ttsb-SHARK BAY MEMBER: Glass Bearing Andesitic Breccias and Tuffs
Ttsm-SAGE MOUNTAIN MEMBER: Andesitic Breccias, Tuffs, and Volcanic Sandstone
Tthl-HANS LOLLIK MEMBER: Augite-Andesite Breccias and Tuffs
(?) UNCONFORMITY
UPPER CRETACEOUS
Cenomanian
Ktcc
Kt
TUTU FM: Volcanic Wacke and Megabreccia
Ktcc-CONGO CAY LIMESTONE MEMBER
UNCONFORMITY
Kob
OUTER BRASS LIMESTONE: Thin Bedded Silicified Limestone
Kl
LOUISENHOJ FM: Augite-Andesite Breccia and Tuff with minor Conglomerate
UNCONFORMITY
Wi
WATER ISLAND FM: Keratophyre Flows, Flow Breccias, and Tuffs; Radiolarites; and Spilites
IGNEOUS ROCKS
MIDDLE EOCENE(?)
Tgr
GRANITIC ROCKS: Predominately Diorite, Tonalite, and Granodiorite
Tpb
PORPHYRITIC BASALT
Tld
LAMPROPHYRE DIKES
Tpd
PORPHYRITE DIKES
SYMBOLS
STRIKE AND DIP OF BEDDING
Normal
Overturned
Vertical
Horizontal
FOLIATION IN GRANITIC ROCKS
FRACTURE AND FAULT ATTITUDES
GEOLOGIC CONTACTS AND FAULTS
Observed
Inferred
Covered
STATUTE MILES
1 0 1 2
GEOLOGY OF THE U.S. VIRGIN ISLANDS FROM DONNELLY (1959)
TOPOGRAPHIC BASE FROM D.O.S. 346 (Series E837)
CONTOUR INTERVAL 250 FEET

PLATE 2



BATHYMETRIC MAP
VIRGIN ISLANDS
DEPTHS IN FATHOMS
REEFS LESS THAN TWO FATHOMS
SOUNDINGS FROM:
HESS (MANUSCRIPT)
U.S. HYDROGRAPHIC OFFICE CHART 1002
0 5 10 MILES
ANEGADA
VIRGIN GORDA
TORTOLA
ST. THOMAS
ST. JOHN
ANEGADA TROUGH
65°00'
64°00'
18°30'
18°00'
1000
500
100
20
10
1500
2000



SCALE IN FEET
0
500
1000
SALT ISLAND BAY
SOUTH BAY
THE SOUND
GEOLOGIC MAP OF
SALT ISLAND
ROCK UNITS
QUATERNARY DEPOSITS
TUTU FORMATION
LOUISENHOJ FORMATION
WATER ISLAND FORMATION
PORPHYRITES
PEGMATITE
BANDED GABBRO
OTHER GRANITIC ROCKS
SYMBOLS
OVERTURNED BEDDING
FOLIATION
DIKES
FRACTURES
GEOLOGICAL CONTACTS
Observed
Inferred
Covered
FAULTS
Observed
Inferred
Covered


65°00'
64°40'
18°30'
18°30'
18°20'
18°20'
ST. THOMAS
ST. JOHN
TORTOLA
VIRGIN GORDA
100 FATHOMS
DISTRIBUTION OF
IGNEOUS AND METAMORPHIC ROCKS
IN THE VIRGIN ISLANDS
IGNEOUS ROCKS AND UNDERWATER EXTENSIONS
AMPHIBOLE ASSEMBLAGE METAMORPHICS
CHLORITE–ACTINOLITE ASSEMBLAGE
CHLORITE ASSEMBLAGE AND LOWER GRADES
FAULT- SHOWING RELATIVE MOTION
IGNEOUS CONTACT
100 FATHOMS— NORTHERN MARGIN OF THE ANEGADA TROUGH
0 1 2 3 4 5 MILES