GEOLOGIC FEATURES WITHIN THE GUAM SEASHORE STUDY AREA

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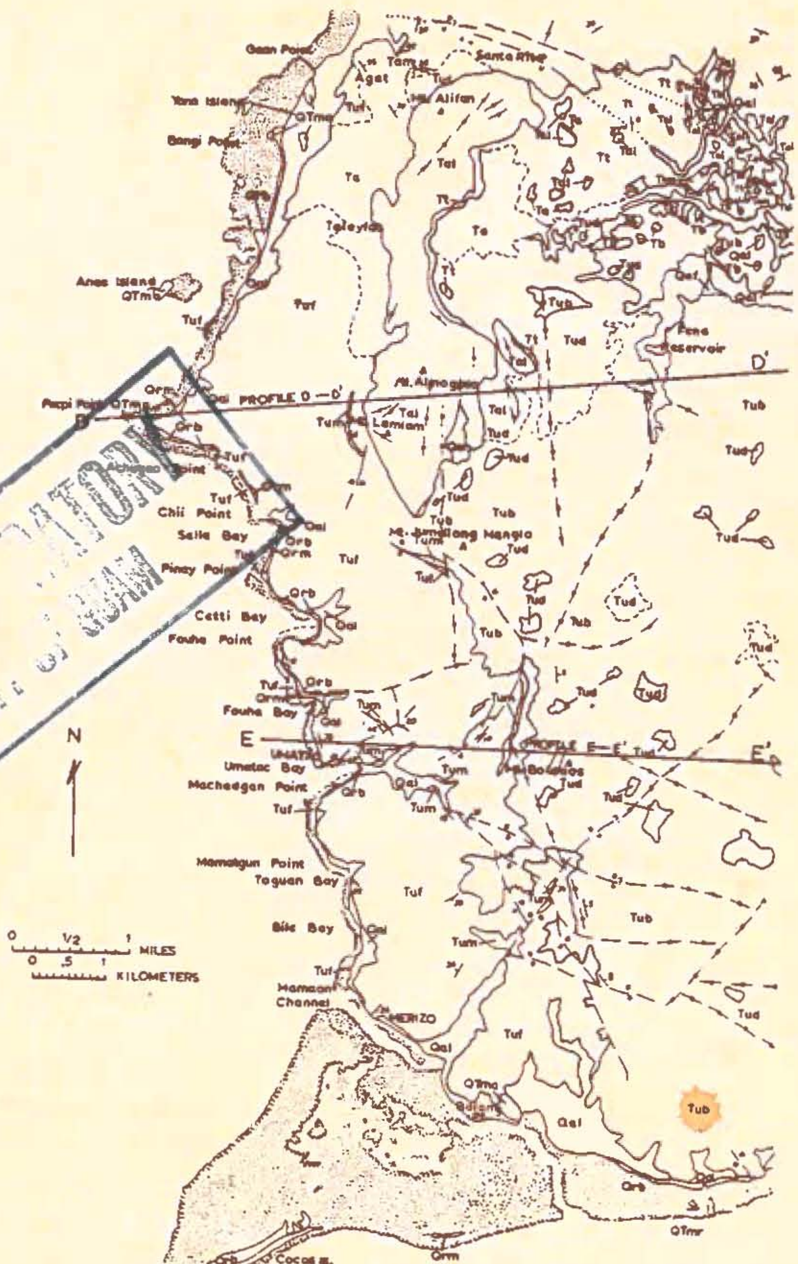

UNIVERSITY OF GUAM MARINE LABORATORY

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By

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INTRODUCTION

Scope of Work

This report provides an overview of the general geologic features within the proposed Guam Seashore Study Area (GSSA), located in the western half of southern Guam (Fig. 1). Specifically the general geologic features include the physical geography, geologic succession, structural geology, marine geology, economic geology, geologic history, soils, and a bibliography of pertinent literature. Objectives to be determined from the overview are: 1) identify and evaluate significant geologic features, 2) indicate any known problems relating to the preservation or protection of significant geologic features, and 3) identify any unique geologic features and relate their significance to known similar features elsewhere in the Pacific Basin region.

For the most part this overview was summarized or taken, in part, from a series of publications resulting from investigations conducted jointly by the Corps of Engineers, U. S. Army, and the U. S. Geological Survey of the geology, soils, and water resources of Guam as follows:

1) physical geography -- Tracey et al., 1959 and Tracey et al., 1964;

2) geologic succession -- Tracey et al., 1959; Tracey et al., 1964; Stark, 1963; Tracey and Stark, 1963; and Schlanger, 1964;

3) structural geology -- Tracey et al., 1959 and Tracey et al., 1964;

4) marine geology -- Emery, 1959 and Emery, 1962;

5) economic geology -- Tracey et al., 1964 and Randall, 1975;

6) geologic history -- Tracey et al., 1959 and Tracey et al., 1964;

7) soils -- Stensland, 1959ab and Carroll and Hathaway, 1963.

Other citations are given in the content of the report, and the references of all the publications reviewed are listed in the bibliography.

GENERAL GEOGRAPHIC FEATURES OF GUAM

Guam is the largest and southermost of the fifteen small islands that make up the Mariana Arc. Agana, the capital of Guam, is located at latitude 13°28'N. and longitude 144°45'E. The island is 30 miles long, 4 to 11½ miles wide, and excluding reefs is 212 square miles in area. The northern half of Guam is a gently undulating limestone plateau bordered along the coast by cliffs and steep slopes. The plateau has an altitude of more than 600 feet at the north end and less than 100 feet near the middle of the island. The limestone plateauland is so permeable that no permanent surface drainage system of rivers or streams is developed on its surface.

The southern half of Guam is a broad dissected upland developed mostly on volcanic rocks. The surface is weathered into peaks, knobs, ridges, and basin-like areas and is deeply eroded by rivers and streams. A low chain of mountains, ranging in height from 1000 to 1334 feet, parallel the west coast about 1 to 2 miles inland. Slopes west of the mountain chain are steep and at places grade into a coastal plain about 300 feet high. Slopes east of the mountain chain dip gently eastward and merge into a narrow limestone plateau along the coast. Except for a few river gaps that cut through the limestone plateau from the interior volcanic uplands there are no permanent streams developed upon its surface.

GEOLOGIC SUCCESSION

Islandwide Geologic Succession

The column of rocks exposed on Guam ranges in age from Late Eocene (Teritary b of the Indonesian letter classification of Vlerk and Dickerson, 1927) to Recent. The earliest rock unit is the Alutom Formation of Eocene (Tertiary b) and Oligocene (Tertiary c) age, which forms the central part of the island. It consists of a sequence of water-laid tuffaceous shale, sandstone, and conglomerate; lava flows and blocky breccias; and reworked tuff-breccia and conglomerate containing fragments of reef-associated limestone. The limestone-bearing breccia and the Mahlac Member of the Alutom Formation, composed mostly of a marine calcareous shale, are of Oligocene (Tertiary c) age.

The southern part of the island is formed mostly of a volcanic sequence of Miocene (Tertiary e) age, named the Umatac Formation. This formation comprises the basal Facpi Volcanic Member, consisting of pillow lavas, flow breccia, and tuffaceous shale; the Maemong Limestone Member, consisting of lenses bedded into the upper part of the Facpi; the Bolanos Pyroclastic member that overlies the Facpi, consisting of thick-bedded reworked tuff breccia and volcanic conglomerate containing fragments of limestone of the Maemong Member; and the

Dandan Flow Member, consisting of an upper cap of scattered thin lava flow remnants.

The Bonya Limestone of Miocene (Tertiary f) age overlies older volcanic rocks unconformably and in turn is overlain by the Alifan Limestone which now caps the highest mountains of Guam. The lower part of the Alifan contains a basal clayey conglomerate, the Talisay Member of Miocene (Tertiary g) age. In northern Guam reef-associated limestone equivalent to the Alifan is present. The central part of the north plateau is formed of a bank-type deposit called the Barrigada Limestone, of Miocene (Tertiary g) age. Along the east coast of the north plateau a well-bedded globigerinid limestone of Miocene (Tertiary g) age is called the Janum Formation. Deposition of both the Alifan and Barrigada Limestones possibly lasted well into Pliocene time.

The Mariana Limestone of Pliocene and Pleistocene (Tertiary h) age is the youngest major formation on the island. It forms most of the north plateau, the fringing limestone plateauland along the east coast of southern Guam, and the cliffed plateau of Orote Peninsula. It comprises a peripheral reef facies mostly along the present-day cliffs; a detrital facies that was deposited primarily in a lagoon in back of the reefs; a molluscan facies of fine-grained lagoonal-type limestone rich in mollusc shells; and a peripheral forereef facies of sandy to rubbly limestone. Much of the Mariana Limestone near its contact with underlying volcanic rocks contains clayey contaminates. The clayey limestone has been designated the Agana Arigillaceous Member of the Mariana and includes the various facies recognized in the pure Mariana Limestone.

Merizo Limestone of Recent age is a low-lying limestone, mostly 2 to 5 feet thick, that forms scattered deposits on the present-day reef-flat platforms and along the shoreline.

Succession, Distribution, and Description of the Rock Units Within the GSSA

A generalized stratigraphic column of the rocks within the GSSA is given in Figure 2. Relative stratigraphic positions of the various rock units are shown in Profiles D and E (Fig. 3) for the northern and southern parts of the GSSA respectively. Surface distribution of the exposed rock units are mapped in Figure 4.

Volcanic Rocks

The volcanic rocks of Guam consist of lava flows, dikes, and pyroclastic beds formed of olivine basalt, basalt, hypersthene-bearing basalt, sodic to calcic andesite, and hypersthene-bearing andesite. They are predominantly continental and belong to the circumpacific province. Similar volcanic rocks are found on the nearby Island of

Saipan. A classification of the volcanics, according to the color index of the groundmass, shows the Guam lavas to be about 45 percent mafic andesite, 10 percent medium andesite, and 45 percent basalt and olivine basalt. Both andesite and basalt have hypersthene-bearing varieties.

Olivine basalts are found in both the Alutom and Umatac Formations, and are especially common in the Facpi Member of the latter. Textures of the olivine basalts are intergranular to intersertial, generally porphyritic, with traces of ophitic and subophitic textures commonly preserved. Color ranges from black when fresh to various shades of gray, brown, and red when weathered. Many of the lava flows are weathered to a soft clay-like material with a mauve tint.

The basalts of Guam differ from the olivine basalts chiefly in having less than 5 percent olivine. These basalts are found in flows and relict boulders of the Alutom and Umatac Formations. The textures of the basalts range from porphyritic to nonporphyritic and commonly show traces of ophitic and subophitic patterns. Very small vesicules characterize many of the fine-grained basalts and extend throughout some of the dikes and flows.

Hypersthene-bearing basalts are formed in flows and relict boulders of the Alutom and Umatac Formations. Except for the greater amount of hypersthene, these rocks are generally similar in texture and composition to the other basalts of Guam.

The calcic and sodic andesites of Guam are found in relict boulders of the Alutom and Umatac Formations. Calcic andesites predominate and grade into basalts. In general, the andesites are less porphyritic than the basalts, although a few flows contain phenocrysts to 8 mm in length that form 40 percent of the rock.

Hypersthene-bearing andesite is found in flows and boulders of the Dandan Flow Member of the Umatac Formation. Except for an increase in orthorhombic pyroxene, hypersthene-bearing andesites are similar in texture and composition to the other andesites.

Pyroclastic sedimentary rocks of the Alutom and Umatac Formations are composed of fragments of rock and minerals and their weathered products that are similar in texture and composition to the flows and dikes. Sedimentary structures and marine fossils in most outcrops signify to their submarine origin. Outcrops are composed of water-laid tuffs and tuffaceous shales, tuffaceous sandstones, and pyroclastic conglomerates and breccias.

The water-laid tuffs are fine-grained friable to well-indurated pyroclastics of dust-sized particles, presumably derived from submarine explosions. They grade horizontally and vertically into tuffaceous shales and sandstones. Tuffs and shales are light in color in most outcrops and range from dead white through grays to dark gray. A light-green color characterizes the tuffs where silica, chalcedony, and quartz have been deposited by circulating waters. None of the outcrops are completely fresh, and most show white chalky clouding due to secondary development of clay minerals.

Tuffaceous sandstones differ chiefly from the tuffs and tuffaceous shales in being coarser grained and darker in color. They grade laterally and vertically into one another. With an increasing amount of black crystal and rock fragments, the beds become black and cindery. The degree of induration ranges from beds which are easily crumbled in the hand to well cemented sandstones. As with the tuffs, the more thoroughly silicified sandy beds are green and range from lighter shades where silicification is slight to dark green flint-like beds.

Pyroclastic conglomerates and breccias are composed of lapilli, cobbles, blocks, and boulders which range in size from a fraction of an inch to several feet in diameter. The fine material of the matrix consists of tuffaceous shale and sandstone. The coarse fragments are similar in texture and composition to the volcanic rock types previously described.

Mineralogy

The essential minerals of the volcanic rocks of Guam are plagioclase, pyroxene, olivine, and quartz. Primary accessory minerals are magnetite, hematite (?), hornblende, biotite, and an alkali feldspar. Silica minerals such as quartz, chalcedony, tridymite, crystobalite, and opal are conspicuous in cavities and interstitial in the fine-grained groundmass as late crystalizations and replacements. Secondary and alteration minerals are chlorite, serpentine, calcite, pyroxene, zeolites, quartz, chalcedony, iron oxides, and clay minerals.

Alutom Formation

Eocene volcanic rocks of the Alutom Formation are found at the north end of the GSSA where a small exposure occurs on each side of the southern mountain ridge. The Alutom Formation is characterized by well-bedded, fine-grained, water-laid tuffs with lenses that grade into sandstone. The tuffs contain large amounts of glass and particles of plagioclase, pyroxene, and magnetite. Tuff particles are cemented by both calcite and silica. Fresh tuff from drill-holes is generally cemented by calcite and well indurated, although in outcrops most of the calcareous cement is leached out. The formation also consists of about 10 percent basic lava flows and 20 percent conglomerate beds ranging from coarse conglomerate with blocks up to 6 feet in diameter to a lapilli pyroclastic breccia. Limestone fragments ranging from small chips and grains to blocks 2 feet in diameter are prominent in some of the lapilli conglomerate beds.

Intense weathering, ranging in depth from a few inches to 40 feet, characterizes surface outcrops. The weathered rock is commonly red, yellow, brown, and mauve in color. The Mahlac Member of the Alutom is not exposed within the GSSA.

Umatac Formation

The Umatac Formation is made up of four members:

1) the Facpi Volcanic Member,
2) the Maemong Limestone Member,
3) the Bolanos Pyroclastic Member, and
4) the Dandan Flow Member.

The bulk of the formation is made up of the Facpi Volcanic and the Bolanos Pyroclastic Members. The relative stratigraphic positions of the four members of the Umatac Formation are shown in Figure 5.

Facpi Volcanic Member -- The Facpi Volcanic Member is named for Facpi Point, where a thick section of pillow basalts cut by dikes is exposed. This member consists of approximately 1400 feet of basic lava flows and pillow basalts which include, in the vicinities of Merizo and Umatac, beds of tuffaceous limestone and pure limestone 15 to 260 feet thick. The basal flows crop out along the west coast of Guam from a point at the extreme southern tip of the island, approximately two miles east of Merizo, and continue northward through Facpi Point to Taleyfac, where they overlap the tuffaceous shale of the Alutom Formation. The lava flows extend eastward from the west coast and form the major part of the deeply weathered foothills between Mount Lamlam and the sea.

The lava flows and dikes are basaltic and andestic in composition. Essential minerals are plagioclase feldspar, pyroxene, and magnetite. Olivine is abundant in some outcrops; in others it is absent or entirely altered to serpentine. Vesicular fillings and veins of zeolite and calcite are extremely abundant and give a spotted white appearance to flows and pillow structures. Quartz amygdules occur, but much less commonly than zeolite and calcite. Glass is abundant in the groundmass.

All but a few of the flows show ellipsoidal pillow structures. The ellipsoids range in shape from nearly spherical to elongated pillows eight feet long. In general they average from 1 to 3 feet in length and approximately one third of this in width. A few flows show columnar jointing. Many dikes 1 inch to 6 feet wide cut the flows in the vicinity of Facpi Point and southward along the coast to Umatac. They commonly show well developed banding parallel to the dike walls. The bands range from 1/8 inch to 1 inch in width and are due to incipient jointing which in weathered outcrops gives the rock a stratified appearance. The flows and interbedded pyroclastics appear to be nearly horizontal but tops and bottoms of flows are obscured by veining and alteration between the pillows, and by numerous joint and shear zones. Gentle east-northeasterly dips are found in the overlying pyroclastic beds. A prominent normal fault along the southwest coast is downthrown to the west.

Flat marine benches exposed at low tide border the cliffs of pillow lavas between Umatac and Cetti Bay. Glassy selvages around the ellipsoidal pillows are more resistant to erosion and form rims an inch or less thick around the pillows. At low tide the bench becomes a surface of shallow basins with glassy rims surrounding more deeply eroded centers of the ellipsoids.

The pillow lavas are fresher in cliff surfaces than on the deeply eroded uplands, but in no outcrops are they entirely unaltered. Most outcrops are weathered to red, brown, and yellow clay rock easily dug into with a pick. Even in the most deeply weathered outcrops the outlines of ellipsoidal structures are preserved by differences in color due to weathering between the periphery and centers of the pillows. In other deeply weathered exposures a stockwork of zeolite veins gives the rock the appearance of a clastic breccia or conglomerate. Such outcrops can commonly be traced through gradational stages into unmistakable lava flows. The dikes are the least altered igneous rock. Many are hard, crystalline, black basalt. Others show alteration along columnar joints and along closely spaced incipient joints parallel to the dike walls.

Maemong Limestone Member -- Within the GSSA the Maemong Limestone Member outcrops along the western slopes of the southern mountain chain where limestone and tuff are exposed in stream valleys. In these valleys the Maemong Limestone is interbedded with the Facpi Volcanic Member. The limestone and tuff of this area are called a deep-water facies. In the vicinity of the Geus River the Maemong Limestone is approximately 260 feet thick.

The deep-water facies of the Maemong Limestone Member ranges in lithology from gray, fine-grained, laminated, tuffaceous limestone containing only tests of globigerinid Foraminifera to thick-bedded, conglomeratic limestone containing algal, coral, and foraminiferal detritus in a matrix of recrystallized limestone. These thick-bedded deposits contain volcanic detritus ranging in size from sand to rounded boulders of basalt. The deep-water facies is everywhere interbedded with the Facpi Volcanic Member. These beds generally dip to the east 5 to 10 degrees, although some of the beds of this facies that were probably involved in faulting dip up to 45 degress to the southwest.

The deep-water facies was formed, in part, in water possibly as deep as 3,000 feet, as indicated by the globigerinid fauna. The thick-bedded conglomeratic beds of this facies probably were laid down at intermediate depths as an off-reef deposit. The deep-water facies contains no coral heads in growth position.

Bolanos Pyroclastic Member -- The Bolanos Pyroclastic Member is made up of water-laid conglomerate, breccia, and sandstone and shale beds. It is here named for the thick section forming the upper 750 feet of Mount Bolanos. The member is divided into a conglomerate facies and a sandstone-shale facies. These facies are gradational into each other in south-central Guam with the conglomerate facies generally underlying the sandstone-shale facies. Deposits of the Bolanos Pyroclastic Member cover the interior mountain range and flanking uplands of southern Guam. They extend from the south shore of the island to Mount Jumullong Manglo and have projections into the Fena basin.

The conglomerate facies of the Bolanos Member is composed of subrounded to angular rock fragments that range in size from coarse sand to boulders several feet in diameter. Gravel-size fragments predominate. The larger constituents are embedded in a tuffaceous sandy matrix. Near crests of the higher peaks the water-laid character of this facies is shown by well developed stratification, sorting, and rounding of fragments. On the south coast, opposite the western tip of Agrigan Island, large blocks of stratified tuffaceous shale from a few inches to several feet long characterize the outcrop of the conglomerate facies. The large bulk of this facies, however, is composed of gravel and lapilli deposited rapidly in water with only slight evidence of reworking. Most of the fragments are basaltic in composition, as are the vesicular and amygdaloidal pyroclastic lava flows of the underlying Facpi Volcanic Member. Nearly all outcrops of the conglomerate facies of the Bolanos Member are characterized by the presence of abundant limestone fragments derived from the Maemong Limestone Member. On top of Mount Jumullong Manglo the limestone fragments are widely dispersed and small. The high peaks of Mounts Bolanos, Schroeder, Sasalaguan, and the associated spurs, which form the dissected crest of the central mountain range, are carved out of the conglomerate facies of the Bolanos Member.

Well stratified beds of tuffaceous shales and sandstones near the crest of Bolanos and Sasalaguan Mountains strike in a general north-northwesterly direction and dip from 5° to 10° to the east-northeast.

Many surface exposures of the Bolanos Member are so deeply and so intensely weathered that the original character is obscured. On ridges both fine and coarse pyroclastics are altered to a red, yellow, and brown clay-like material in which no trace of primary structure is preserved. Ferruginous veins and ironstone beds are a common feature of this weathered rock. Such lateritic clay-like surfaces characterize hilltops throughout the volcanic areas regardless of whether the underlying bedrock is a pyroclastic sediment or a lava flow. Recently cut slopes and stream beds expose the best relict structures. The clay-like material is commonly pale mauve and has shadow relicts of phenocrysts. It probably is a weathered lava flow.

The base of the member is taken to be at the change from dominant flows of the Facpi to dominant pyroclastic conglomerate of the Bolanos.

Dandan Flow Member -- Basaltic lava flows cap small areas of Bolanos pyroclastics on top of Mount Bolanos and are exposed in isolated outcrops on ridges east of Mount Jumullong Manglo and on high points of the dissected upland east of the central mountain range. The extension of the flows over a considerable area between Mount Bolanos and the Dandan area is indicated by residual boulders scattered over the dissected area east of the mountain range. The relict boulders range from a few inches to 20 feet in diameter. In the dissected uplands they are concentrated in valleys and basins.

Many boulders of the Dandan Flow Member are fresh basaltic rock composed essentially of plagioclase, pyroxene, magnetite, and olivine. The olivine is commonly completely altered to secondary serpentine. The fresh rock ranges in texture from fine- to medium-grained. Phenocrysts are always present. Vesicles and mineral-filled pores are relatively scarce, in sharp contrast to their occurrence in the Umatac flows. The residual boulders are as fresh as any igneous rock on Guam. Commonly they have shells 1 to 2 feet thick of exfoliation and weathering around a fresh basalt center. Outcrops of the Dandan Flow Member are in general deeply weathered and show every gradation from fresh rock to soft, limonitic, clay-like masses.

The Dandan Flow Member is separated from beds of the underlying Bolanos Conglomerate Member by a bed of basal flow breccia up to 10 feet thick. No volcanic units younger than the Dandan Flow Member have been recognized. In the Fena basin area near Mount Almagosa the Dandan Flow Member is overlain by Bonya Limestone of Tertiary f age. The Dandan Flow Member is assigned to a late Tertiary e age on this basis.

Limestone Rocks

All the limestone on the island had, as primary constituents, various combinations of coral, coralline algae, Halimeda, Foraminifera, molluscs, echinoids, minor amounts of worm tubes and bryozoans, fine limemud, and volcanic material in the form of clay, single crystals of various minerals, and rock fragments. The limestones are classified into two main groups: incrustate and particulate. Incrustate limestones are those that have been built predominantly by incrusting or attached organisms such as colonial corals, coralline algae, and incrusting Foraminifera. Particulate limestones are those that have been formed by the accumulation of individual foraminiferal tests or fragmental skeletal debris. A minor group includes the metasomatic limestones in which replacement of a variable amount of the original carbonate has taken place by dolomite, silica, manganese, or phosphate.

The Maemong Limestone Member of the Umatac Formation was described as unit with the volcanic rocks.

Bonya Limestone

Northwest of the Fena Reservoir a few small outliers of Bonya Limestone are found in the vicinity of the Bonya River. The thickness of the Bonya Limestone generally does not exceed 120 feet. The Bonya Limestone is a buff-white, pink, brown, gray or gray-black, porous to dense, friable to indurated, generally medium- to coarse-grained, clayey or volcanically contaminated, fossiliferous, detrital limestone. It contains an abundance of Foraminifera tests throughout and in places it contains remains of corals, calcareous algae, and molluscs.

The Bonya Limestone is medium- to thick-bedded, jointed and fractured throughout, and is horizontal or dips as much as 20°, generally eastward. Caving and collapse have resulted in the scattering of many boulders and blocks in the sinks and along streams in the karst areas. Argillaceous contamination of the Bonya is sufficient to cause most of it to break unevenly and crumble easily.

The Bonya Limestone, by its field relations, thickness, lithology, and fauna represents a period of deposition in a relatively narrow but fairly deep bay or estuary. Benthonic foraminifers were abundant. Erosion seems to have been continuous during the time of deposition, judging from the contamination of the entire formation by fine- to coarse-grained volcanic detritus. Likewise, the abundance of Bolanos and Maemong pebbles and cobbles in the base of the Bonya in many places indicates a certain amount of contemporaneous erosion of earlier sediments.

Alifan Limestone

The Alifan Limestone caps the southern mountain crest from the vicinity of Mount Lamlam northward to the park boundary. At places along the eastern boundary of the limestone cap a marley conglomerate of the Talisay Member forms a narrow outcrop between the lower part of the Alifan Limestone and older underlying volcanic rocks.

Talisay Member -- The Talisay Member in the Fena basin consists of several recognizable strata of distinctive lithology. The lowest stratum is a highly weathered, plastic, clayey, red, yellow-brown, green, and mottled red-green pebble- to boulder-sized conglomerate containing subangular to rounded fragments of volcanic tuff and vesicular and porphyritic lavas embedded in a fine clay matrix. The conglomerate pebbles are almost completely weathered to clay. Overlying the conglomerates are marls and clayey coralline rubbles of variable size and composition, very fossiliferous in places, containing fragments of *Porites*, other corals, and whole pelecypods and gastropods. In general the marls are more calcareous toward the top of the beds. The matrix of the coralline rubble is a bentonitic clay. A highly plastic, green to white, marine-deposited clay bed 1 to 2 feet thick underlies the Alifan Limestone. The member is thickest in the west side of the Fena River basin. A 30-foot Talisay section below an outlier of Alifan Limestone consists of marl overlying volcanic conglomerate; the lower contact is concealed.

The Talisay Member is thin- to thick-bedded, fractured and jointed in some outcrops, and dips from 0° to about 15° generally toward the east or southeast, although at one locality it dips 50° to the northwest.

The Talisay Member appears to be mostly a near-shore deposit of clay, conglomerate, and marl derived in part from extensive subaerial weathering and erosion of volcanic rocks. The formation blankets and obscures pre-existing topography.

Alifan Limestone -- the Alifan Limestone overlies the Talisay Member. On Mount Lamlam the Alifan Limestone is a massive, moderately hard, light pink to red detrital limestone containing abundant branching *Porites* and *Acropora*, and mollusc molds. These fossils indicate generally undisturbed lagoonal deposition.

Maximum thickness of the Alifan Limestone is more than 200 feet on Mount Almagosa.

Mariana Limestone

Mariana Limestones are poorly represented in the GSSA by a single small patch and a few rocky islets along the coastal region. Asgodao, Fofos, and Agrigan Islets located on the fringing reef platform along the southern coast are composed of the reef facies of the Mariana Limestone. The Agana Argillaceous Member of the Mariana Limestone is represented by a small exposure along the north side of Achang Bay and at Facpi and Anae Islands.

On the small coastal islets along the southern shore the reef facies of the Mariana is a white coral-algal limestone with many of the corals in position of growth and cemented by algal crusts. The coral and algal remains are well consolidated, generally porous, and greatly recrystallized.

The remaining exposures of Mariana Limestone at Achang Bay and on islets along the western coast are of the Agana Argillaceous Member. These limestones contain some clay disseminated through the rock, giving it a cream to pale yellow color at places, but the general lithology is similar to that described for the reef facies found in the southern coastal islets.

Merizo Limestone

Merizo Limestone of Recent age is intermittently distributed along much of the GSSA shoreline as a narrow band, generally less than two meters in elevation above mean sea level. Merizo Limestone also forms a narrow low-lying band along the seaward side of Cocos Island, and it entirely forms Babe Island located on the southern Cocos barrier reef platform and many other small islets and mushroom-shaped rocks on the fringing reef-flat platforms.

Exposures of the Merizo Limestone show closely packed heads of coral, many of which are in position of growth. The corals are cemented in a hard calcareous matrix that weathers away leaving the colonies standing out in relief.

The thickness of the Merizo Limestone ranges from a thin veneer on some of the basaltic benches to 3 feet or more. Most of the preserved patches cover parts of the reef-flat platforms and present beach line.

Radiocarbon dates of the Merizo Limestone range from about 3000 to 6000 years (Tracey et al., 1964 and Easton et al., 1978).

PHYSICAL GEOGRAPHY

Description of the Physiographic Units Within the GSSA

The GSSA is bordered by the Philippine Sea and Pacific Ocean on the west and south sides respectively (including small islands on fringing, patch, and barrier reef platforms), and by a somewhat tentative landward boundary that extends eastward from Anae Island to the Fena Reservoir and then south to Ajayan Bay (Figs. 1 and 4).

Within the GSSA the land is divided into a number of physiographic units as shown in Figure 6. In order of largest area these physiographic units are:

1) the mountainous land unit which occupies the steep slopes west of the north-south trending mountain ridge,

2) dissected sloping and rolling land that occupies the more gentle slopes east of the mountain ridge,

3) rough summit land that caps the northern part of the mountain ridge,

4) coastal lowland and valley floor land that occurs discontinuously along the coast and penetrates inland at river valleys, and

5) interior basin and broken land located in a structurally depressed region at the northeast corner of the GSSA.

Mountainous Land

Mountainous land forms all the rugged southwest part of Guam, except where it is bordered intermittently by stretches of coastal lowland and valley floor units. The unit comprises most of the area within the GSSA and includes the steep slopes of Mounts Jumullong Manglo, Bolanos, Schroeder, and Finasantos. The eastern boundary is less distinct where the mountainous land merges with dissected rolling and sloping land.

The mountainous land includes both sharp and relatively flat mountain summits bounded by long, irregular, steep to precipitous slopes. Mounts Jumullong Manglo and Bolanos retain a relatively flat remnant of an upper summit surface. Farther south the summits of Mounts Schroeder and Sasalaguan are more peaked and Mount Finasantos is sharp and spine-like. Much of the mountain land surface is dissected into V-shaped valleys and sharp-crested ridges. Remnant fault scarps form a complex pattern, but are quite eroded at most places.

The mountainous land ranges in elevation from sea level to 1250 feet at Mount Jumullong Manglo. Relief of Mount Bolanos is 1220 feet, Mount Sasalaguan 1110 feet, Mount Schroeder 1050 feet, and Mount Finasantos 820 feet. Median elevation of the mountainous unit is about 625 feet. The sharpest and most complex relief is found in the vicinity of the Geus River valley and the west slopes of Mount Bolanos, where it ranges between 850 to 900 feet for the upper slopes and more than 1000 feet at places where streams are deeply incised. At the very southern part of the GSSA the relief is a more uniform 200 to 300 feet.

Most slopes in the mountainous land are steep to precipitous. The principal or overall slope is uneven toward the south as evidenced by the decreasing elevation of the mountain summits in that direction. Secondary slopes face mostly east and west of the north-south trending mountain ridge, with those on the west being the steepest in the unit. Tertiary slopes formed by streams and faults dissect the principal and secondary slopes.

The mountainous land is developed upon the volcanic rocks of the Umatac Formation. Soils are absent to 50 or more feet thick, and bare rock faces are common on steep to precipitous slopes. Savanna vegetation of grasses, scrub bush, and scattered trees is developed on ridge crests, humps, and upper valley slopes, but in ravines it is forest with tangled undergrowth. Microrelief is smooth on clayey surfaces, particularly on gentle slopes, but may be uneven and abrupt where slump scars and gullies are present. Rough rocky and boulder-strewn surfaces are also present here and there.

The mountainous land is drained by many streams. The steeper western slopes of the unit constitute a parallel drainage system, whereas the more gentle slopes to the east form a dendritic pattern. A number of small and large fresh-water springs flow from the base of the porous Alifan Limestone where it overlies volcanic rocks. Some of these larger springs are the headwaters of streams. Stream profiles are steep at places, and have average slopes ranging from 1 in 4 to 1 in 7.

The mountainous land was formed as a result of stream dissection of stratified lava flows and tuffs raised high above the sea level. Little remains of the original surface of this unit except for possibly part of the dissected, slightly tilted summit surfaces of Mounts Bolanos and Sasalaguan.

Dissected Sloping and Rolling Land

Dissected sloping and rolling land unit occurs in the middle part of southern Guam, and is represented by a small area on the eastern border of GSSA. The unit includes the relatively long, gradual eastern slopes of the mountainous land unit to the west. Other than the gently undulating or rolling topography, the major landforms are V-shaped stream valleys cut below the general surface. Maximum elevation of the unit within the GSSA ranges from about 660 feet at the eastern slope of Mount Bolanos to 350 feet at the eastern border of the park. Maximum relief in the unit is about 310 feet in stream valleys with an average relief ranging from 150 to 200 feet. The principal slope of the dissected sloping and rolling land is slightly downward to the east. Secondary slopes are mostly north and south from the crests of the east-west trending, rolling, and undulating surface features. Tertiary slopes resulting from stream dissection of the primary and secondary slopes are gentle to precipitious.

The dissected sloping and rolling land is developed upon volcanic rocks of the Umatac Formation (Bolanos Pyroclastic and Dandan Flow Members). Soils are thin to absent in bare rock areas, but may be 50 or more feet thick on flat or gentle-sloping land. Savanna vegetation of grasses, scrub brush, and scattered trees occupies the flat and gentle-sloping surfaces, and forest is developed in the stream valleys. The microrelief of the surface is generally smooth and clayey with scattered patches of large boulders and bare rock. Stream beds are bouldery in places as well.

Drainage of the dissected sloping and rolling land is by a network of streams that empty on the east coast of the island. Overall slopes of major rivers in the area are about 1 in 30 to 1 in 50, but within the GSSA the slopes are for the most part steeper and the river slopes are slightly greater. Headwaters of most of the streams in this unit originate in the mountainous land to the west.

The dissected sloping and rolling land was formed by stream erosion of broad primary slopes beveled by successive advances and retreats of the sea. Faults and tilting movements complicate the flow of streams. Much of the unit may once have been covered by relatively thin limestone now removed by erosion.

Rough Summit Land

This physiographic unit is located in the southwest part of Guam, including the summits of Mounts Alifan, Almagosa, and Lamlam and the area between and around these peaks. The unit is elongate in a north-south direction with the southern half within the GSSA.

Rough summit land includes high knobs, sharp ridges, irregular depressions with steep to vertical walls, scarps, and cone-shaped peaks. The unit has a median elevation of about 950 feet. The southern part has a maximum elevation of 1334 feet, which is the highest for the island. The unit slopes gradually downward toward the north and has a maximum relief of about 650 feet in the vicinity of Mount Lamlam. Relief in this region is accentuated by steep slopes and numerous separate knobs, peaks, sharp-edged ridges, and sinkholes.

The rough summit land is developed entirely upon the Alifan Limestone. Soils are a few centimeters thick to absent over much of the unit, but local accumulations up to 3 feet or more may be found in some low depressions or sinks. Vegetation is very heavy and consists of large and small trees, bushy undergrowth, and tangled vines. Some small patches of grassland are found in the southernmost part of the unit. The microrelief of the surface is rough to jagged, boulder-strewn, and generally rocky. Talus deposits at the base of some slopes and scarps may be up to 3 feet or more thick.

All drainage in the rough summit land is downward into the porous underlying limestone resulting in the absence of surface streams and rivers. During heavy rains sheetwash deposits alluvium in depressions and sinks.

The rough summit land has been formed by solution and recrystallization of a greatly jointed and faulted limestone formation originally 200 to 300 feet thick. Fault zones formed preferential subsurface groundwater channels, and extreme recrystallization followed by erosion of adjoining masses of rock resulted in the development of sharp elongate ridges characteristic of the unit. The rough summit land is a mature karst topography.

Coastal Lowland and Valley Floor

Within the GSSA most of the coastal lowland occurs discontinuously along the coast and at places penetrates inland as valley floor land at the Sella, Cetti, La Su Fua, Umatac, Toguan, Geus, Sumay, and Liyog Rivers. The unit includes low unconsolidated terraces or flat land, beaches, low coastal exposures of raised limestone, and valley floors. Most of the land is relatively flat with little relief. Included also within this unit are Cocos Island and Babe Island on the Cocos Barrier reef and Asgadao, Fofos, and other low limestone islets located on the fringing reef-flat platforms along the southern coast.

Elevations in the coastal lowland and valley floor unit range from sea level up to about 45 feet for the coastal lowlands and to 50 feet for some of the valley floors. The principal slope of the coastal lowland and valley floor unit is gently seaward. Beaches in the unit have average foreshore slopes of about 1 in 7.

The coastal lowland and valley floor unit is developed upon exposures of alluvium, beach sands, and Mariana and Merizo Limestones. Soils are thin over beach sands, generally thin to absent over limestone lowland, and generally thick and mucky or marshy in valley floors. Vegetation is cleared in some of the lowland and forested at other places. Scattered coconut palms and other strand vegetation is developed along most of the beaches and low coastal exposures of limestone. Mangrove swamp occurs at the mouth of the Geus River and along the coastal region bordering the Manell Channel. Swamps also occur along parts of some river valleys, and grassy marshes with scattered trees are found at places where wide stretches of coastal lowland are found at the northern end of the park and along the southern part bordering Cocos Lagoon. Surface microrelief is smooth and sandy at beaches; sandy to muddy in lowlands; and rough, rocky, boulder-strewn, and pinnacled where limestones are exposed. Valley floors are generally smooth and clayey.

Drainage at beaches and on limestones is by percolation downward into the rock. In rainy weather marshy and swampy coastal lowland land may accumulate standing water a few inches deep. Valley floors are partially drained by their rivers and streams, but swampy regions may have standing water up to 3 feet deep at places during the rainy season.

Valley floors have developed as a result of filling in of older deep valleys with alluvum transported by streams. Coastal lowlands have been formed of stream alluvium in places, but in many locations it has been mixed with sand from the shoreline. Beaches have developed largely by deposits thrown upon the shore by waves. Some lowland has been beveled by waves or resulted from reef deposits associated with previous higher stands of the sea.

Interior Basin and Broken Land

The interior basin and broken land occurs entirely in south central Guam. A small area of this unit occurs in the northeast corner of the GSSA. The unit includes karst topography, many small conical hills, an impounded water body (Fena Reservoir), some dissected sloping land and deeply eroded stream valleys, numerous scarps, some gently undulating land in the bottom of the basin, and many small valley floors.

Elevations within the GSSA range from about 100 to 420 feet. Relief of the dissected slopes west of Fena Reservoir is about 200 feet, and to the south where the unit adjoins the dissected sloping and rolling land the relief is generally less. Relief is least in the northwestern region where low hills are generally less than 40 feet high. The principal slope of the interior basin and broken land is slightly southeastward. Secondary slopes are gentle to steep and inclined to the east and northeast toward the center of the basin. Tertiary slopes are gentle to precipitous, with a high proportion of the latter because of the many scarps and small steep hills.

Interior basin and broken land is developed upon exposures of the volcanic rocks of the Alutom and Umatac Formations, Bonya Limestone, Alifan Limestone, Talisay Member of the Alifan, and alluvium. Soils are absent to many feet thick. Vegetation on the perimeter slopes of the unit is largely grassy with some patches of forest growth. Within the lower parts of the basin thick forest with heavily tangled undergrowth predominates. Marshes and swamps are also common in the lower basin. Microrelief is smooth on the clayey land of gentle slopes and valley floors; uneven and abrupt where slumps scars and gullies are present; rough to jagged, boulder-strewn, and rocky where limestones are exposed; and muddy where marshes and swamps are present. Talus slopes of clay and limestone boulders are common.

The interior basin and broken land is ultimately drained by surface streams, but the unit also includes some limestone exposures where runoff does not occur. Streams within the GSSA are part of an overall larger centripetal drainage network that join a dendritic network east of the Fena Reservoir. Flooding of low areas in basins occurs frequently in the rainy season.

The interior basin and broken land is a structural depression that has been flooded by the ocean several times during the geologic history of south Guam. Estuaries reaching far inland have permitted the deposition of the various limestone formations. Upon emergence these limestones were eroded into the hilly, knobby, and karst topography that is now so characteristic of the area.

STRUCTURAL GEOLOGY

Structural Provinces and Major Faults

The limestone plateau of northern Guam, the folded Eocene volcanic rocks of central Guam, and Miocene volcanic rocks of southern Guam form the three major structural provinces of Guam. Each of these structural provinces consists of several blocks separated by major fault zones (Fig. 7).

The bulk of the land area within the GSSA lies in the Bolanos block which is bounded by the Talofofo fault zone on the north and by the Cocos fault on the south. The Cocos block forms the triangular-shaped barrier reef and enclosed lagoon at the southwest corner of the park. The Cocos reef and lagoon are thought to have grown on a basement of the Umatac Formation. The shape of the reef supports the idea that a block of the Umatac Formation dropped along a fault which strikes almost parallel to the Talofofo fault zone and the Adelup fault. The Talofofo fault zone at the northern boundary of the Bolamos block lies just outside of the GSSA.

Minor Faults and Other Structural Features

Within the GSSA, normal faults and minor folds are found in Miocene volcanic rocks and normal faults are found in limestones of Miocene age. Prominent joint zones and structural breaks are well developed in both limestones and volcanic rocks. The joint zones in limestones are characterized by parallel, narrow, deep fissures, between which have developed elongated spines and ridges. Such spines and ridges are especially well developed in the Alifan Limestone which caps the southern mountain chain. The volcanic rocks are cut by structural breaks which show either as a series of knobs and ridges cutting across topographic trends or as long, straight alignments in otherwise normal terrain. Drainage patterns are determined, in places, by these lines, as are valley-wall alignments. Minor movement along these joint zones and breaks may have occurred, but significant stratigraphic displacement is not evident.

Fault zones, joints, breaks, and other structural features within the GSSA are shown in the geologic map (Fig. 4) and the engineering geology map (Fig. 8).

MARINE GEOLOGY

Submarine Topography

Overall submarine slopes off the southwestern and southern coasts are steep and complex compared to the gentle slopes off the east coast. Those on the east coast have average slopes of about 4° to the 6000-foot depth contour, whereas off the south and southwest coasts the slopes average $14\frac{1}{2}^\circ$ to the same depth contour.

Upper submarine slopes are known in more detail from a series of 40 profiles made around the island by Emery (1962). Eight of these profiles (profiles 31-38) were made offshore from the coastal region of the GSSA. Profile 31 extends offshore a short distance east of Manell Channel, profile 32 extends offshore from the eastern tip of Cocos Island, Profile 33 extends offshore of the western tip of Cocos barrier reef, profile 34 extends offshore midway along the northern Cocos barrier reef, profile 35 extends offshore from Mamaon Channel, profile 36 extends offshore from Umatac Bay, profile 37 extends offshore from Sella Bay, and profile 38 extends offshore from Facpi Point.

Four submarine terraces at mean depths of 55, 105, 195, and 315 feet were recognized from the eight profiles. The shallowest terrace at 55 feet was found in profiles 31, 32, 35, 36, and 37; the second deepest at 105 feet was found in profiles 33, 34, 37, and 38; the third deepest at 195 feet was found in profiles 31, 32, 34, 35, and 36; and the deepest terrace at 315 feet was found in profiles 31 and 33. Emery's profiles do not show terraces shallower than 55 feet because of the limitations of the sounding vessel to operate in shallower inshore waters. The 55- and 315-foot submarine terraces are fairly common in other parts of the world, but the 105- and 195-foot terraces are less known at other locations.

Sediments

Generalized charts of the Pacific Ocean floor in the vicinity of Guam show that sediments consist of either coral mud and sand or volcanic mud and sand, both of which grade downward and outward into *Globigerina* ooze, which in turn grades into radiolarean ooze and red clay at very great depth (Murray and Renard, 1891; Hanzawa, 1928; Revelle, 1944). More specifically, bottom samples around the island slopes show that reef debris is restricted to depths less than 3000 feet. At greater depth and distance from shore the sediment is *Globigerina* ooze.

In composition, most bottom samples ranging in depth from 27 to 1170 feet contain *Halimeda* segments, encrusting red algae, and coral fragments. Since these organisms live only in the photosynthetic zone their presence in the deeper samples indicate a reworking or movement of these sediments downslope into deeper water. Foraminifera, fragments of mollusc shells, echinoid spines, sponge spicules, pteropods, and fine to coarse sand and silt also occur in most samples, but these are less definitely restricted to shallow reef areas. The insoluble residues of the samples consist chiefly of silts and clays from weathered volcanic rocks and a few grains of feldspar and olivine.

Reefs

The shoreline along the western and southern coasts of the GSSA is bordered by fringing reefs of various widths and reef-like volcanic platforms. A triangular barrier reef encloses a shallow lagoon at the southwest corner of the park and a patch reef with a limestone islet on its surface lies a short distance offshore at the northern end (Fig. 4). Regardless of the type of reef or platform present, most subtidal parts are covered with a variety of corals, benthic algae, and other reef-associated organisms. At some locations reef development is exceeding erosion and the platforms are growing seaward, while at other places erosion is predominant. Reef development is intermittent and inconsistent along this region. Many of the reef-flat platforms are exposed during low tides and lack coral growth. The subtidal reef front and shallow submarine terrace zones show considerable evidence of reef growth and development, but at other places, these same zones are represented by older erosion surfaces with a veneering coral community type of development. Reef growth and development is also somewhat influenced by the numerous rivers that transport silt, mud, sand, gravel, and organic debris to the fringing reef platforms and inshore water mass along this part of Guam's coast. The fringing reef platforms are cut partially to completely through by channels at many of the river mouths.

Fringing Reefs Along the West Coast -- Along the western coast of the GSSA the shallow fringing platforms are for the most part truncated volcanic rocks with an outer fringe of reef limestone. Here and there reef growth completely veneers the volcanic platform, and at a few places the entire platform consists of truncated volcanic rock. Basaltic inliers protrude through the limestone at places, and near the contact rounded volcanic boulders and gravel-sized sediments are incorporated into the limestone matrix. Basaltic sea stacks occur on the platforms at Sella and Fouha Bays. Numerous dikes cut the basaltic platforms along this part of the coast. At places, the dikes are truncated to the same general level as the platform, but at other sites they stand up in relief from a few inches to 5 or 6 feet. At the outer edge of the shallow fringing platform the wave-washed reef margin zone usually lacks algal ridge development, but at places is regularly cut by short surge channels. Where the outer edge of the platform consists entirely of volcanic rock, the margin is generally cut by irregular cracks and fissures, and at places large reentry channels are eroded into the platform.

Along much of the western coast the submarine topography of the deeper forereef zones reflect the overall general slope and topography of the bordering coastal mountain valleys and ridges. The presence of buttress and channel development, pinnacles, knobs, and mounds in the shallow reef front zone and on the adjacent submarine terraces is evidence of active coral growth and reef development. Shallow submarine terraces extend outward from the fringing platforms along much of this coastal region. The depth of the inner part of these terraces is variable and ranges from less than 10 feet to 30 feet. At many places the outer edge of the terraces break sharply at the upper part of the steep seaward slope zone 20 to 55 feet deep, and at other places they gradually slope downward to depths of 150 feet or more.

Fringing Reefs Along the South Coast -- A wide fringing reef-flat platform borders the entire southern coast of the GSSA from Manell Channel to Asgadao Bay (Fig. 4). At most places the middle part of the reef flat is somewhat depressed in respect to the outer and inner parts and during low spring tides retains a moat of water that supports corals and other reef organisms that cannot tolerate long periods of exposure. The inner part of the reef-flat platform is covered with a thin veneer of sediments that support the most extensive seagrass beds found on the island. The outer part of the reef-flat platform is a relatively flat reef-rock pavement that exposes during low spring tides and, except for scattered patches of boulder rubble, is mostly swept clean of smaller-sized sediments. Channels partially bisect the reef-flat platform at two locations opposite the mouth of rivers. The reef margin at the outer edge of the reef-flat platform has a slight algal ridge developed at places, but is much less pronounced as those found along the more exposed northern and eastern coastsof the island. Short surge channels cut the reef margin at places, while at other locations they are absent or represented by shallow irregular troughs less than three feet deep.

The forereef slope has a moderately well-developed channel and buttress system present in the reef front zone. In general the reef front channel and buttress system is most pronounced where algal ridge development is present along the reef margin, and irregularly developed where such ridges are absent. At most locations the upper forereef slope is interrupted by a shallow, gentle downward-dipping submarine terrace 15 to 20 feet deep near the outer edge of the reef front and 30 to 55 feet deep where the gentle slope abruptly breaks, forming a steep slope that is interrupted again at places by the 195- and 315-foot terraces.

Cocos Barrier Reef and Enclosed Lagoon -- This region is a complex system consisting of both a lagoon fringing reef along the shore and an offshore barrier reef, a lagoon with a deeper centrally located hollow surrounded by a broad shallow terrace, numerous patch reefs, two deep passes, a wooded mile-long barrier reef island, mangrove swamps, small river estuaries, and seagrass beds (Fig. 4). Emery (1962) divided Cocos Lagoon and associated barrier and fringing reefs into five physiographic units: reef, lagoon hollow, reef bar, deep channel (Mamaon Channel), and nearshore shelf. In a later study Randall et al. (1975) included the deep Manell Channel as part of the Cocos lagoon-barrier reef complex, increasing the number of physiographic units to six.

Closest to land is the nearshore shelf or lagoon fringing reef, which is apparently a seaward continuation of the coastal lowland that borders the lagoon between the head of Mamaon channel and Achang Bay. Its slope is gentle from the shore to depths of about five feet at its outer edge where it grades into the lagoon hollow.

The outermost physiographic unit is the barrier reef, which averages abut 300 yards in width. The upper surface is shallow reef-flat platform that partially exposes during low spring tides. The platform can be divided into an outer seaward facing part which is slightly elevated in respect to the lagoonward facing part which slopes gently downward into the lagoon hollow. The seaward reef margin zone lacks well-developed surge channels and an algal ridge except for stretches along Cocos and Babe Islands where the algal ridge is moderately developed and cut by conspicuous surge channels. The reef front zone channel and buttress system on the upper forereef slope is poorly developed along most of the barrier reef except where algal ridge and surge channel development is present at the reef margin. Below the reef front zone the forereef slope is interrupted by a submarine terrace similar to that described for the southern fringing reefs.

Between the nearshore shelf and the north end of the barrier reef is the deep Mamaon Channel. The channel is fairly straight, about a mile long, 100 to 200 yards wide, and about a 100 feet deep where it passes through the reef.

The reef bar unit is located in the northern part of the lagoon where it separates the nearshore shelf and Mamaon Channel from the main part of the lagoon. Most of the upper surface of the reef bar is less than 10 feet deep, but it is very irregular because of scattered coral heads.

The lagoon hollow unit is enclosed by the barrier reef, reef bar, and nearshore shelf. It consists of a peripheral sandy-floored shelf generally less than 10 feet deep and a deeper hollow floored with finer sand and mud. The floor of the central deeper hollow is somewhat undulating with a maximum depth of 43 feet.

The sixth physiographic unit is the deep Manell Channel which separates the southeast part of Cocos Lagoon from the southern fringing reefs. The channel is somewhat crooked, about a mile long, 100 to 200 yards wide, and over 100 feet deep where it passes through the reef.

Three islands are located on the barrier reef-flat platform. Cocos Island, slightly longer than a mile, lies along the west end of the south barrier reef. Its elevation is generally less than 10 feet and is composed mostly of unconsolidated reef debris except for a narrow band of Merizo Limestone that borders the seaward side. A second small sand islet with no vegetation has developed on the lagoon side of the barrier reef about 1000 feet east of Cocos Island. Babe Island is the third, which consists of a scrub covered elongated strip of raised limestone less than three feet in elevation. It is situated on the southern barrier reef about midway between the eastern end of Cocos Island and the mouth of Manell Channel. The island is thought to constitute a continuation of the narrow band of Merizo Limestone along the seaward side of Cocos Island.

ECONOMIC GEOLOGY

This section of the report identifies the geological aspects within the GSSA which have economic potential with existing technology.

At present there are no metallic mineral deposits being mined or extracted. Precious metals are not found at all, except as trace elements, and of the nonferrous metals, only aluminum bearing minerals in weathered volcanic soils are abundant. From the various ferrous and ferroalloy metals, only manganese minerals were found as replacement deposits in the Bonya Limestone and in deeply weathered volcanic rocks. At the present time none of the metalic mineral deposits are of economic importance.

Geological evidence of petroleum has not been found on Guam or in the nearby submarine slopes and associated basins.

Ceramic mineral materials are of low quality and are important only in the development of products related to home industry or small-scale operations. Metallurgical and refractory minerals are for the most part absent or are not of economic significance. Industrial, chemical, and manufacturing minerals, except for some filter sands and clay minerals for local use, are not found or are not of economic importance at this time.

Construction materials related to building activities appear to have the most economic significance and possibilities of any mineral group found within the GSSA, and at the present are the only mineral substances mined or extracted at all. This group of minerals includes building and structural stone, crushed and broken stone, sand and gravel, and topsoil. The mining and extraction of these abundant rock minerals are for local demand and use. The rock minerals and unconsolidated sediments can be divided into three major groups, comprising nine subunits, each with characteristic properties and distribution (May and Schlanger, 1959). The distribution of these groups and subunits are mapped in Figure 8, and descriptions of their geologic and engineering properties are given in an accompanying map legend.

No economic deposits of chemical, fertilizer, or abrasive minerals are found within the GSSA. Limestone is available for the manufacture of various lime and cement materials for agriculture use and the building industry, but the only significant deposits are the alifan limestone capping the southern mountain chain. Limestone rock materials are much more abundant and accessible elsewhere on the island.

Except for small local deposits of chalcedony and various zeolite minerals in the volcanic rocks of southern Guam, there is little in the way of semiprecious stones or mineral material within the GSSA. Chalcedony and zeolite minerals could possibly be fashioned into a line of local jewelry oriented toward the tourist trade.

In conclusion, the short range possibility of developing any economic mineral deposits within the GSSA seems rather improbable. Because of Guam's relatively small area and population, lack of developed natural energy resources, remoteness from large manufacturing and industrial centers, and small agricultural and industrial development, there is little demand locally or elsewhere for most minerals, other than the present rock materials being extracted. The potential value of rocks may be not only in their ability to be mined or extracted, but also in their value in aesthetic or natural beauty, educational uses, and tourist appeal as well.

SOILS AND BEACHES

Soils and Micellaneous Land Types

Guam is well within the belt of tropical soils with soil forming processes that are predominantly lateritic. Regosols, lithosols, latosols, and lithosolic latosols are the soil groups most extensively represented on Guam.

Within the GSSA, regosols and latosols are predominant on the volcanic rocks. They are generally acid, reddish, yellowish, and brownish clays over deeply weathered volcanic material on hilly to mountainous upland. Minor areas of reddish-brown and yellowish-brown lithosols and latosols are found on the limestone outliers in the volcanic rocks. Other soils include: a regosol formed on discontinuous, narrow, coastal terraces of calcareous sand slightly higher than the present beach and with soil similar to the Shioya soil mapped in the Palau, Okinawa, and Saipan Islands; and alluvial soils consisting of sediments from volcanic uplands, accumulated in sink basins, valley flats, alluvial fans, and low coastal terraces, most of which are periodically flooded in the rainy season and some which are marshy. Miscellaneous land types which cannot be classed as soils are limestone rock land and made land, the latter consisting chiefly of artificial fill.

Stensland (1959a) describes twelve soil types, of which five are from upland soils on volcanic rocks, three are from soils on limestone rocks, and four are from soils of coastal terraces and valley floors. Three additional micellaneous land types are also described. Distribution of these soils and micellaneous land types are shown in Figure 9, and brief descriptions of each are given in an accompanying legend.

Beach Deposits

The beaches within the GSSA are of two main types. White or buff sands which consist of calcareous organic remains of reef origin comprise part of the beaches, and sands that are light brown to black because of the presence of appreciable quantitites of detrital volcanic minerals make up the remaining beaches. Areas lacking a surface drainage system of rivers and streams to carry terrestrial sediments to the coastal regions will have beaches composed nearly 100 percent of white to buff colored bioclastic sands of reef origin.

Within the GSSA a more complex province exists where surface rocks are dominantly of volcanic types. A network of large and small streams drain this area and transport nonbioclastic sediments to heads of coastal embayments, where the sands contain large percentages of insoluble or volcanic grains. The regions between these embayments have beaches composed of bioclastic sands generally containing less than few percent volcanic grains to none at all. Apparently, the bioclastic sand of these intervening areas is washed ashore, and little of it enters the coastal embayments where streams empty. In turn, the volcanic sands carried by the streams are more or less contained in the general region of the embayments. Between Toguan Bay and Umatac, where volcanic rocks reach the coast and are subject to wave erosion, the beaches are supplied with sediments from both land and the adjacent fringing reefs, resulting in a mixture of bioclastic and volcanic deposits. Beaches along the lagoonward side of Cocos Island are composed entirely of bioclastic deposits of reef origin.

Major beach deposits along the coastal region of the GSSA are mapped in Figures 4, 8, and 9.

ENGINEERING GEOLOGY

The engineering aspects of geology provide information for the suitability of rocks and unconsolidated deposits for foundations and underground installations and on the characteristics, mode of occurrence, availability, and uses for construction material. These geological aspects have been mapped and described in nine different units by May and Schlanger (1959). Figure 8 shows the distribution of the nine map units and gives a brief description of each in an accompanying legend.

GEOLOGIC HISTORY

The earliest geologic event within the GSSA was the formation of an Eocene volcano and the subsequent deposition of volcanic rocks of the Alutom Formation in the northern part of the park area. The presence of limestone fragments in these rocks indicates that beds of limestone must have been present not far away. Cole (1963) assigned Foraminifera found in the limestone fragments to Oligicene (Tertiary c) age. Possibly these Eocene volcanic deposits were uplifted and eroded during Teritary d time.

Following the collapse of the caldera of the Eocene volcano, the formation of a Miocene volcano, located somewhat southwest of the present island, produced the flows and pyroclastic breccias and conglomerates of the Umatac Formation. Deposition of the flows of the Facpi Volcanic Member of the Umatac Formation was complicated by minor faulting and interrupted by one or more periods quiet enough to allow the deposition of lenticular beds of the Maemong Limestone Member. Following the deposition of the Maemong Limestone Member several hundred feet of flows, tuffaceous limy shale, and breccia of the Facpi Volcanic Member were laid down. Explosive volcanism started before deposition of the Maemong Limestone Member and increased during deposition of the upper part of the Facpi Member. This explosive phase culminated in the deposition of the Bolanos Pyroclastic Member of the Umatac Formation.

This nearly continuous sequence of tuff-breccia and volcanic conglomerate includes some intermittent flows. The final episode in the development of the Umatac Formation was the eruption of a series of sheetlike flows called the Dandan Flow Member, now exposed only as weathered remnants. Deposition of the flows of the Dandan Member ended the known major volcanism on Guam. Collapse of the caldera of the large Miocene volcano was for the most part concurrent with the flows of the Dandan Member, following the explosive volcanism that resulted in the deposition of the Bolanos Pyroclastic Member. Lowermost fossils found in the Umatac Formation are larger Foraminifera of Tertiary e age according to Cole (1963). Fossils of similar age are also found in the lenses of the Maemong Limestone Member.

The flows of the Dandan Member are overlain by the Bonya Limestone of Tertiary f age. After effects of the collapse of the Miocene volcano caldera may have continued through the period of the deposition of the Bonya Limestone, since the deposits are restricted to the eastern side of the Bolanos structural block. Foraminifera in the lower Bonya Limestone indicate a deepwater environment, but the fauna toward the upper part increasingly indicates a shoal-water environment. The above sequence indicates that parts of the island were probably emerging during deposition of the Bonya Limestone. Toward the top of the Bonya Limestone there is an increased presence of volcanic detritus in the deposits. This evidence, along with the absence of Bonya Limestone deposits on the west side of the Bolanos structural block, indicates that subaerial weathering and erosion of volcanic rocks to the west was probably taking place. At the end of the Bonya deposition, erosion and deposition of the weathered volcanic material increased sharply to form the basal, clayey conglomeritic deposits of the Talisay Member of the Alifan Limestone.

Deposition of the Alifan Limestone started when the island was mostly emergent at the close of the deposition of the Bonya Limestone. Alifan Limestone deposits are present on the west side of the Bolanos structural block which indicate that the collapse of the Miocene volcanic caldera was mostly accomplished by this time. The gross shape of the southern half of the island was therefore largely determined by the end of the Bonya Limestone deposition. After the early deposits of the Alifan Limestone were deposited the island gradually submerged. Basal Alifan Limestone deposits capping the present mountain ridge are arigillaceous, but as submergence continued less and less of the volcanic uplands were exposed to subaerial weathering and the deposits become less argillaceous and more coraliferous. Extensive reefs formed and the limestone that caps the high Mount Lamlam-Mount Alifan ridge was thought by Tayama (1952) to represent a raised atoll. It is doubtful that all of southern Guam was submerged at the time the Alifan atoll was deposited, for evidence indicates that the upper 300 feet or so of the Eocene volcanic rocks stood as an island to the north, and the upper several hundred feet of the Bolanos ridge from Mount Jumullong Manglo to Mount Sasalaguan was also emergent as an island to the south.

Both of these island areas are now lower than the present limestone-capped summit of Mount Lamlam, indicating that warping or faulting of several hundred feet has taken place since deposition of the Alifan Limestone. Fossils in the lowermost Alifan Limestone are of Tertiary f age and most of the remainder is probably of Tertiary g (upper Miocene) age. Possibly the uppermost beds are Pliocene age.

The broad transition from deposition of the Alifan Limestone to deposition of the Mariana Limestone was interrupted by a period of emergence caused by, or accompanied by, structural deformation and faulting. The southern part of the island emerged, probably to at least its present level, for a period long enough to allow erosion and dissection of the lower lying Alifan Limestone. After this it was resubmerged to about the 300-foot level. Dissection of the weathered uplands continued. The small islets of Mariana Limestone presently situated along the west and southern coasts were possibly deposited at this time, or possibly later, as reefs at other locations around the island continued to grow well into the Pleistocene. Mariana deposits along the western coast may have been more extensive than the few remnant islets left on the present fringing and patch reef platforms at Anae, Facpi, Asgadao, Fofos, and Agrigan Islands. Widespread deposition of the Mariana Limestone on Guam ended at some time in the Pleistocene with emergence of the island followed by cutting of terraces at several levels and by continued deposition of reef associated limestones on the terraces at lower and lower levels. Accurate interpretation of later Mariana history is difficult because the events are affected by several geologic circumstances. Movements, both up and down, during the Pleistocene happened most likely in episodes. During these movements, tilling of probably the whole island to the southwest took place. Structural readjustment during these up and down movements led to displacements of large parts of the island relative to other parts, and numerous minor faults have been almost continuously recurrent during Pleistocene time.

The latest geologic event was the deposition of the Merizo Limestone on a former terrace that was only a few inches higher than the present reef-flat platform. Radiocarbon dates for the Merizo Limestone range between 2880 and 5115 years with an average of about 3600 years (Tracy et al., 1964 and Easton et al., 1978). These deposits were subsequently raised and now stand about 6 feet above the present reef-flat platforms.

Other recent events include the continued filling and accumulation of alluvium in sinks, depressions, coastal lowlands, and valley floors. Beach deposits are accumulating from bioclastic sediments derived from reefs and volcanic detrital material carried to the coastal region by rivers and streams. Reef growth is taking place along the present fringing and barrier reefs and other shoal-water environments at most locations, but at some places benches are being cut into rocky headlands.

SIGNIFICANT AND UNIQUE GEOLOGIC FEATURES

Guam is a rather small volcanic island with raised deposits of older limestone, and in respect to many other islands in the western Pacific Basin has undergone a rather typical geologic history. This is especially true of two of Guam's nearest neighbors, Rota and Saipan. Even so, Guam has many significant geologic features, and some of these are found in GSSA.

Rock Formations

In regard to the various volcanic rock formations there are none that are entirely unique to the GSSA, but the Facpi Volcanic Member of the Umatac Formation is for the most part contained within the GSSA. Although Eocene rocks are poorly represented by two small exposures in the northern part of the GSSA, the entire sequence of Miocene volcanism on Guam is well represented along the ridge crest and steep western slopes of the southern mountain chain. The Facpi Volcanic Member has pillow basalts cut by columnar jointed flows in the lower part and upper flows with interbedded lenses of Maemong Limestone and pyroclastic tuffaceous shales and sandstones which are exposed only between the crest of the southern mountain ridge and the southwest coast within the GSSA. Exposures of dikes cutting through pillow lavas and relatively unweathered basalts are especially common along the shoreline between Facpi Point and the village of Merizo. Capping the predominant lava flows of Facpi Volcanic Member are the pyroclastic conglomerate, breccia, sandstone, and shale beds of the Bolanos Pyroclastic Member which are widely exposed along the crest and gentle eastern slopes of the southern mountain chain within the GSSA. The eastern slopes of the crest also contain remnant patches of the Dandan Flow Member which is the uppermost and last major deposit resulting from the Miocene volcanism.

The Facpi Volcanic Member of this Miocene sequence of volcanism is particularly well exposed in a section along a prominent spur that extends from Facpi Point to the limestone-capped crest of the Mount Lamlam-Almagosa ridge. With the exception of abundant tuffaceous shales this sequence includes most of the significant geologic features found in the Eocene volcanic rocks of central Guam which lie outside of the GSSA. Starting at the base of this section is Facpi Island which has already been identified as a National Natural Landmark. A wide, intertidal, basaltic bench showing good examples of pillow basalts and dikes extends from Facpi Island to the shoreline. Of particular note on the truncated bench platform is a prominent dike that is offset by a series of echelon faults and stands about 8 feet in relief above the surrounding surface. At the shoreline a headland about 100 feet high shows good exposures of dark colored, partially weathered volcanic rocks and a number of dikes in the exposed cliff face. Some of the dikes exposed in the cliff face are traceable out onto the intertidal bench. A prominent plateau between 100 and 400 feet in elevation occupies the lower slope between the shoreline at Facpi Point and the mountain summit. This plateau is an open area that supports a savanna grassland with scattered trees. The plateau surface is cut by stream valleys and is sculptured on the intervening slopes and ridges into an irregular slump-scar topography that provides one of the best exposures of weathered volcanic rocks on the island. The rocks here are weathered into a great variety dark red, brown, yellow, and green colored clays which in places preserve the original structural characteristics of the rock; including pillow lava outlines, dikes, and jointing planes. Veins and cavities filled with zeolite and chalcedony minerals are also common to abundant in the weathered rock exposures. Between the plateau and the mountain summit the slopes are steeper with ravine forests occupying the lower valley slopes and savanna grassland with scattered trees dominating the upper valley slopes and ridge tops. Slump scars and deeply weathered exposures of rock similar to that described for the lower plateau surface are common, but scattered exposures of darker colored less weathered volcanic rocks are also found in some places. A distinguishing feature of the steep upper slopes along this section is the presence of limestone outcrops formed by lenses of the Maemong Limestone Member that are interbedded within the upper flows of the Facpi Volcanic Member. These limestone lenses outcrop at various places along the western slopes of the entire Mount Lamlam-Sasalaguan ridge and are unique to the GSSA.

The Bolanos Pyroclastic and Dandan Flow Members of the Miocene sequence of volcanism are best exposed on the island along the crest and eastern slopes of the southern mountain chain between Mounts Jumullong Manglo and Sasalaguan. The pyroclastic rocks of the Bolanos Member represent a period of explosive volcanism whereas the lower lava flows of the Facpi Member represent predominantly quiet lava eruptions. The Bolanos pyroclastics are particularly well exposed along the mountain crest where large slumps occur. At most places the Dandan Flow Member occurs as relict dark-colored boulders scattered over the upper weathered surface of the Bolanos pyroclastics, but the most extensive deposits found on the island occur on the slopes between the Mount Lamlam-Alifan ridge and Fena Reservoir. Some of the freshest basaltic rocks on the island can be found in these relict monoliths scattered about on the gentle east slopes of the southern mountain ridge.

Of the limestone formations on the island the GSSA has very good exposures of Miocene age represented by the Alifan Limestone which caps the northern part of the southern mountain chain and by lenses of Maemong Limestone interbedded in the upper flows of the Facpi Volcanic Member. The Bonya Limestone of somewhat older Miocene age is poorly represented by a few patches in the northeast corner of the GSSA, but if the present northeast boundary was extended somewhat to the Mahlac River valley the representation of these limestones would then be excellent. This suggested boundary extention would also include nearly all of the Maemong Limestone exposed in southern Guam, most of the Talisay Member of the Alifan Limestone on the east side of the Mount Lamlam-Alifan ridge, and a more representative exposure of the Eocene volcanic rocks that would also include a major part of the Mahlac Member of that formation. Mariana Limestone of Pliocene and Pleistocene age are poorly represented in the GSSA by a few coastal islets, but the Merizo Limestone of Recent age is represented very well by low coastal exposures along the south and southwest coasts and at Cocos and Babe Islands.

Physiography and Landforms

As with the geologic rock formations, there are no major or entire physiographic land units that are unique to the GSSA, but of the seven units the island is divided into, five are found within the park area. The only units lacking are limestone plateauland and hilly land developed upon argillaceous limestones. Distinguishing or essential features of the five land units within the GSSA are all well represented.

Although there are no unique major land units in the GSSA, there are many significant landforms and features of lesser stature. The largest landform present is the southern mountain chain which forms a cuestal ridge with gentle slopes toward the east and steep slopes toward the west. The cuestal ridge extends the entire length of the GSSA, and includes Mount Lamlam which is already designated as a National Natural Landmark. In terms of prominence, Mounts Schroeder and Finasantos at the southern end of the chain are more conspicuous, sharper peaked, and more easily recognized than Mount Lamlam whose principal feature of note is its greater height. Nowhere along the entire southern mountain chain do you find a ridge crest which gives such unencumbered views of the island as that found along the mountain crest trail between Mounts Jumullong Manglo and Sasalaguan. From the crest vantage point the mountains of central Guam and extensive plateauland of the northern half of Guam can be seen to the north, the dissected sloping and rolling land and limestone plateauland of southeast Guam can be seen to the east, and the Cocos lagoon-barrier reef system and steep slopes of the southern cuestal mountain ridge can be seen to the south and west.

The rough summit land developed upon the Alifan Limestone in the southern mountain chain is a unique physiographic unit on the island. The southern and most diverse part of this land unit occupies the summits of Mounts Lamlam and Almagosa in the GSSA. The unit is classified as a mature karst topography and has very rugged relief features. Although the unit now occupies the highest elevation on the island, the rocks comprising it represent the weathered limestone remains that were deposited in an atoll reef environment. At many locations, including the area around Mount Lamlam, the weathered exposures are very fossiliferous. Stick-like branching corals of Porites and Acropora species are especially common. Except for a small grassy patch south of Mount Lamlam, the unit supports a dense limestone forest that contains some floral elements that are unique or rare on other parts of the island.

Another limestone karst unit with somewhat different topography is represented by a small area of the interior basin and broken land unit in the northeast corner of the GSSA. As mentioned earlier, if the northeast boundary of the GSSA was extended to the Mahlac River valley, it would then include most of the older Bonya Limestone and interior depression that has been the site of a shallow marine bay a number of times in Guam's geologic history. These estuaries have permitted the deposition of many limestone formations, which upon emergence, have been eroded to yield the hilly, bumpy karst topography which so characterizes the unit. Excellent representation of this karst topography is found in the Bonya Limestone in the center of the unit. The Maemong, Bonya, and Talisay Rivers drain into the greatly channeled, caved, and cavernous Bonya Limestone, where they form the Talaeyuus River. This river flows through the Bonya Limestone and twice disappears under it before reappearing to empty into the Maagas River. The deep sinkholes in the Bonya Limestone were formed by roof-caving over parts of solution channels developed throughout the rock mass. Separate sinkholes later coalesced to form elongate depressions which formed the present disappearing Tolaeyuus River.

Physiographic landforms of significance are also found along the coastal and marine regions of the GSSA. From an aesthetic view point the natural beauty and isolation of the coastal embayments at Sella, Cetti, and Fouha Bays are unsurpassed by any elsewhere around the island. An excellent view of Cetti Bay, as well as other parts of the southwest coast can be seen from a roadside platform on the highway between Agat and Umatac. Other coastal features unique to the GSSA are the presence of two volcanic sea stacks and a number of slightly elevated and intertidal volcanic bench platforms cut into rocky headlands. The sea stacks are located on the inner part of volcanic benches at Sella and Fouha Bays. The stack at the latter bay has also been named as a National Natural Landmark. The stacks are conical in shape, between 50 and 80 feet high, and composed of relatively unweathered pillow basalts. Slightly elevated bench platforms cut into basaltic rocks are found at Achugao Point, Fouha Point, the south side of Fouha Bay, and Machadgan Point along the western coast. Although a few sea level volcanic benches are found elsewhere around the island, the bulk of such features are found along the western coast between Anae Island and Merizo. The structural variation of these sea level benches is also greater along the western coast, where they range from those that extend all the way from the shoreline to the upper forereef slope to those that are fringed by a variable width of limestone reef deposits on the outer seaward part.

In the marine environment the most significant marine geologic feature is the triangular Cocos barrier reef and enclosed shallow lagoon system. The barrier reef and lagoon system at Apra Harbor is commercially developed and the reefs greatly altered, whereas the Cocos system is developed along the shoreline at Merizo Village and at Cocos Island, but the barrier reefs and lagoon patch reefs are for the most part in their natural state. The Cocos barrier reefs, lagoon, and island at the western tip are presently used quite heavily as a tourist and recreation center.

With regard to structural geology, the major feature found within the GSSA is the Cocos fault which separates the Cocos and Bolanos blocks. The larger part of the GSSA occupies the wester half of the Bolanos block whose northern boundary is the Talofofo fault which lies outside the park area. At a much smaller scale, but very conspicuous, are the numerous slumps and slump scars along the slopes of the steep mountain land. The reticular drainage pattern on both the western and eastern slopes of the southern mountains is also most likely related to structural features developed in the underlying rocks.

Although no unique soil type is found within the GSSA, all but two of the twelve soil types designated for Guam are found within its boundary. Because of erosion and slumping various colorful soil profiles and weathered exposures that preserve the original outlines of old pillow basalts, conglomerates, sandstones, shales, and other structural features are conspicuous at many places within the GSSA. Of significance also, is a deposit of alluvium high in the mountainous land on the east slope of Mount Lamlam where a V-shaped pocket forms a localized marsh and peripheral swamp land. This wetland region is over 1100 feet in elevation, difficult to gain access, and may be the last habitat refuge for the endangered nightingale reed-warbler, Acrocephalus luscinia (Quoy and Gaimard).

Although beaches are generally small and intermittently developed along the coastal region of the GSSA, they possess some interesting features. Most significant of these are the occurrence of light cream to buff colored beaches intersperced with stretches that are predominantly dark colored. Black to dark colored sands are not restricted to the coastal region within the GSSA, but the most widespread occurrence of such beaches occur at Cetti and Sella Bays and at other bays and stretches of coastline where volcanic rocks reach the shoreline within the park area.

About the only significant economic geologic feature within the GSSA is the presence of relatively unweathered exposures of basaltic and dike rock that could be used for construction purposes. Beach sand is also of economic importance, and in high demand for construction purposes. These resources are of limited extent and should be protected. Sand and rock for construction purposes can be obtained from other sources. Hard crystalline limestone for construction purposes is abundant on the northern plateau. Sand for similar purposes can be obtained by crushing crystalline limestone rocks or weakly cemented lagoonal deposits from the northern plateau.

In summary, the proposed GSSA would include more significant geologic formations, physiographic land units, smaller-scaled landforms, soil types, and diverse marine and coastal features than any other part of the island. By extending the northeast boundary to include the Mahlac River valley the significance and diversity of geologic features would be considerably enhanced. The proposed area is also relatively undeveloped and sparcely populated, and consequently has a greater area of pristine environment than any other similar sized part of the island.

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REFERENCES

Caroll, D., and J. C. Hathaway. 1963. Mineralogy of selected soils from Guam, with a section on description of soil profiles, by C. H. Stensland. U. S. Geol. Surv. Prof. Pap. 403F:F1-F53.

Cloud, P. E., Jr., and W. S. Cole. 1953. Eocene Foraminifera from Guam and their implications. Science. 117(3039):323-324.

Cole, W. S. 1939. Large Foraminifera from Guam. Jour. Plaeontology. 13(2):183-189.

__________. 1963. Tertiary larger Foraminifera from Guam. U. S. Geol. Surv. Prof. Pap. 403-E:1E-28E.

Cox, L. M. 1904. The island of Guam. Am. Geog. Soc. Bull. 36(7): 385-395.

Doan, D. B., and H. G. May. 1956. Younger limestones and late geomorphic features of Guam [abs.]. 8th. Pacific Sci. Cong., Manila 1953, Proc. 2:262.

Easton, W. H., T. L. Lu, and R. H. Randall. 1978. Recent reefs and shorelines of Guam. Micronesica 14(1):1-11.

Emery, K. O. 1959. Marine geology. pp. 107-111. In Military geology of Guam, Mariana Islands. Part I, Description of terrain and environment. U. S. Army, Chief of Engineers, Intelligence Division, Headquarters, U. S. Army Forces Pacific. 282 p.

__________. 1962. Marine geology of Guam. U. S. Geol. Surv. Prof. Pap. 403-B:1B-76B.

Hanzawa, S. 1928. Preliminary report on marine deposits from the southwestern North Pacific Ocean. Japan Oceanog. Works Recs. 1(2):59-77.

Hathaway, J. C., and Dorothy Carroll. 1964. Petrography of the insoluble residues. pp. D37-D50. In Petrology of the limestones of Guam. U. S. Geol. Surv. Prof. Pap. 403-D:D1-D52.

Johnson, H. J. 1964. Fossil and recent calcareous algae from Guam. U. S. Geol. Surv. Prof. Pap. 403G:G1-G40.

Jones, R. S., R. H. Randall, and R. D. Strong. 1974. An investigation of the biological and oceanographic suitability of Toguan Bay, Guam as a potential site for an ocean outfall. Univ. of Guam, Marine Lab., Tech. Rept. 11:1-97.

May, H. G., and S. O. Schlanger. 1959. Engineering geology. pp. 219-258. In Military geology of Guam, Mariana Islands. Part II, Engineering aspects of geology and soils. U. S. Army, Chief of Engineers, Intelligence Division, Headquarters, U. S. Army Forces Pacific. 282 p.

Murray, J., and A. F. Renard. 1891. Report on the deep-sea deposits based on the specimens collected during the voyage of H. M. S. "Challenger" in the years 1872 to 1876. London, Longmans. 525 p.

Pacific Islands Engineers. 1948. Historical reviews of the meteorology, seismology, oceanography, and geology of Guam, with references (4 vols.). Prepared for U. S. Dept. of the Navy, Bureau of Yards and Docks, contract Noy-13626 (unpublished).

Randall, R. H. 1975. An economic geology survey of Guam. pp. 98-115. In The social-economic impact of modern technology upon a developing insular region: Guam. Vol. II, Parts III and IV. Univ. of Guam. 152 p.

Randall, R. H., and Jeanne Holloman. 1974. Coastal survey of Guam. Univ. of Guam, Marine Lab., Tech. Rept. 14:1-404.

Randall, R. H., R. T. Tsuda, R. S. Jones, M. J. Gawel, J. A. Chase, and R. Rechebei. 1975. Marine biological survey of the Cocos barrier reefs and enclosed lagoon. Univ. of Guam, Marine Lab., Tech. Rept. 17:1-160.

Randall, R. H., and C. Birkeland. 1978. Guam's reefs and beaches. Part II, Sedimentation studies at Fouha Bay and Ylig Bay. Univ. of Guam, Marine Lab., Tech. Rept. 47:1-77.

Revelle, R. R. 1944. Marine bottom samples collected in the Pacific Ocean by the "Carnegie" on its seventh cruise--Scientific results of Cruise VII of the "Carnegie." Carnegie Inst. Washington Pub. 556:1-196.

Schlanger, S. O. 1964. Petrology of the limestones of Guam, with a section on petrography of the insoluble residues, by J. C. Hathaway and Dorothy Carroll. U. S. Geol. Surv. Prof. Pap. 403-D: D1-D52.

Stark, J. T. 1963. Petrology of the volcanic rocks of Guam, with a section on trace elements in the volcanic rocks of Guam, by J. I. Tracey, Jr., and J. T. Stark. U. S. Geol. Surv. Prof. Pap. 403-C: C1-C32.

Stark, J. T., and S. O. Schlanger. 1956. Stratigraphie succession on Guam [abs.]. 8th Pac. Sci. Cong., Manila 1953, Proc. 2:262.

Stearns, H. T. 1940. Geologic history of Guam [abs.]. Geol. Soc. American Bull. 52(12):1948.

__________. 1941. Shore benches on north Pacific islands. Geol. Soc. Am. Bull. 52(6):773-780.

__________. 1945. Eustatic shorelines of the Pacific. Geol. Soc. Am. Bull. 56(11):1071-1078.

Stearns, N. D. 1937a. Significance of limestone in Guam. Guam Recorder. 14(3):28-43.

__________. 1937b. Explosive rocks of Guam. Guam Recorder. 14(4): 36-37.

__________. 1938. Pillow larvas of Guam. Guam Recorder. 14(11): 7-8.

__________. 1939. Dike rocks of Guam. Guam Recorder. 15(10):8.

Stensland, C. S. 1956. The soils of Guam [abs.]. 8th Pacific Sci. Cong., Manila 1953, Proc. 2:271.

__________. 1959a. Soils. pp. 117-165. In Military geology of Guam, Mariana Islands. Part I, Description of terrian and environment. U. S. Army, Chief of Engineers, Intelligence Division, Headquarters, U. S. Army Forces Pacific. 282 p.

__________. 1959b. Engineering soils. pp. 258-264. In Military geology of Guam, Mariana Islands. Part II, Engineering aspects of geology and soils. U. S. Army, Chief of Engineering, Headquarters, U. S. Army Forces Pacific. 282 p.

__________. 1963. Description of soil profiles. pp. F43-F49. In Mineralogy of selected soils. U. S. Geol. Sur. Prof. Pap. 403F:F1-F53.

Tayama, R. 1952. Coral reefs of the South Seas. Japan Hydrographic Office Bull. 11:1-292.

Todd, R. 1966. Smaller Foraminifera from Guam. U. S. Geol. Surv. Prof. Pap. 403I:I1-I41.

Tracey, J. I., Jr. 1956. Geological investigations on Guam [abs.]. 8th Pacific Sci. Cong., Manila 1953, Proc. 2:271.

Tracey, J. I., Jr., C. H. Stensland, D. B. Doan, H. G. May, S. O. Schlanger, and J. T. Stark. 1959. Military geology of Guam, Mariana Islands. Part I, Description of terrain and environment. Part II, Engineering aspects of geology and soils. U. S. Army, Chief of Engineers, Intelligence Division, Headquarters, U. S. Army Forces Pacific. 282 p.

Tracey, J. I., Jr., and J. T. Stark. 1963. Trace elements in the volcanic rocks of Guam. pp. C27-C32. In Petrology of the volcanic rocks of Guam. U. S. Geol. Surv. Prof. Pap. 403C:C1-C32.

Tracey, J. I., Jr., S. O. Schlanger, J. T. Stark, D. B. Doan, and H. G. May. 1964. General geology of Guam. U. S. Geol. Surv. Prof. Pap. 403-A:A1-A104.

Vlerck, I. M. van der, and R. E. Dickinson. 1927. Distinctions among certain genera of Foraminifera, for the field geologists of the East Indies. Jour. Paleontology. 1(3):185-192.

Ward, P. E., and J. W. Brookhart. 1962. Military geology of Guam, Mariana Islands, Water resources supplement. U. S. Army, Chief of Engineers, Intelligence Division, Headquarters, U. S. Army Forces Pacific. 182 p.

Ward, P. E., S. H. Hoffard, and D. A. Davis. 1965. Hydrology of Guam. U. S. Geol. Surv. Prof. Pap. 403-H:H1-H28.

Wiseman, J. D. H., and N. I. Hendey. 1953. The significance and diatom content of a deep-sea floor sample from the neighbourhood of the greatest oceanic depth. Deep-Sea Research. 1:47-59.

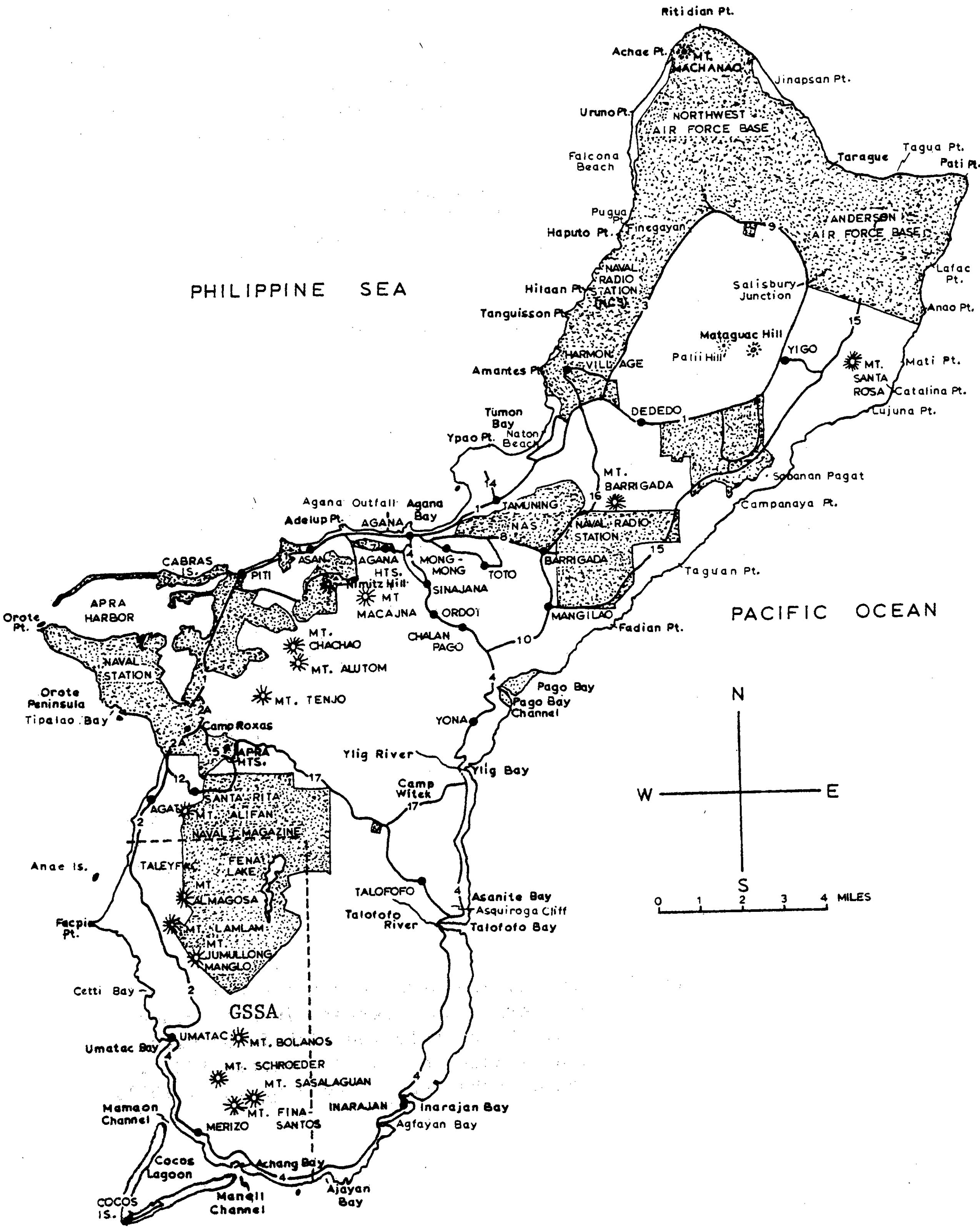


Figure 1. Map of Guam showing the location of the GSSA.

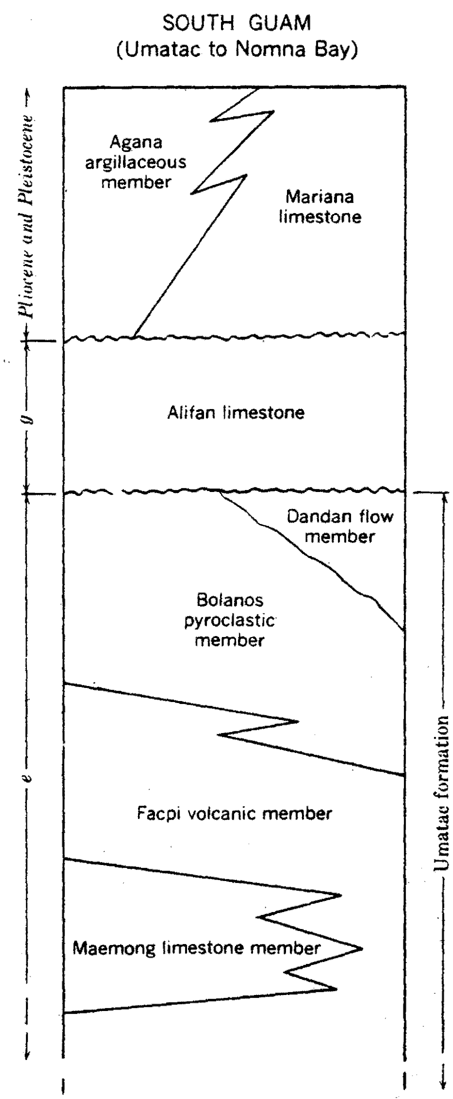
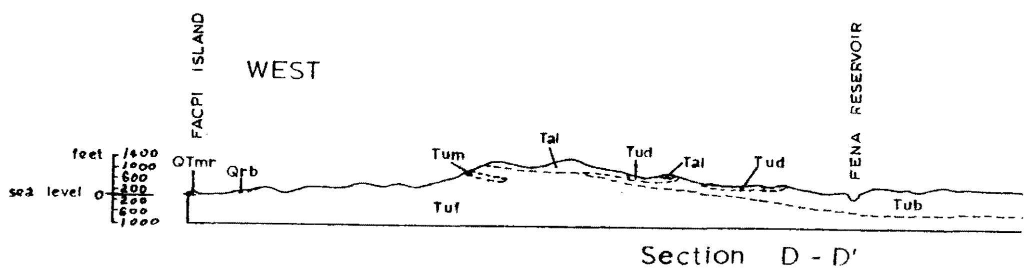


Figure 2. Generalized stratigraphic section for southern Guam. Letters in age column indicate correlation with Indonesian faunal zones of Van der Vlerk (1927). Column taken from Tracey et al. (1964).



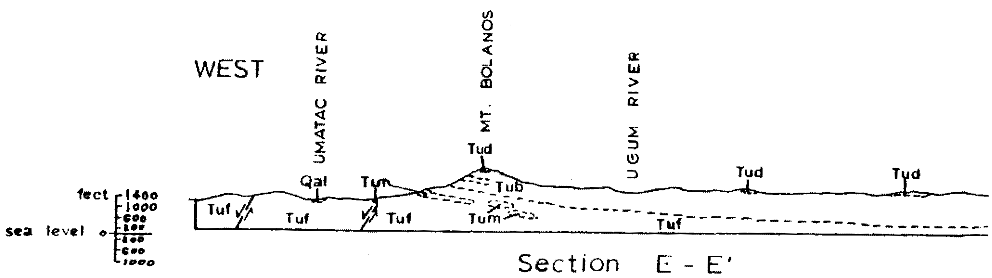


Figure 3. Profile sections for the northern (Section D-D') and southern (Section E-E') parts of the GSSA. See Figure 4 for profile locations and rock formation, member, and facies names. Profiles modified from Tracey <u>et al</u>. (1964).

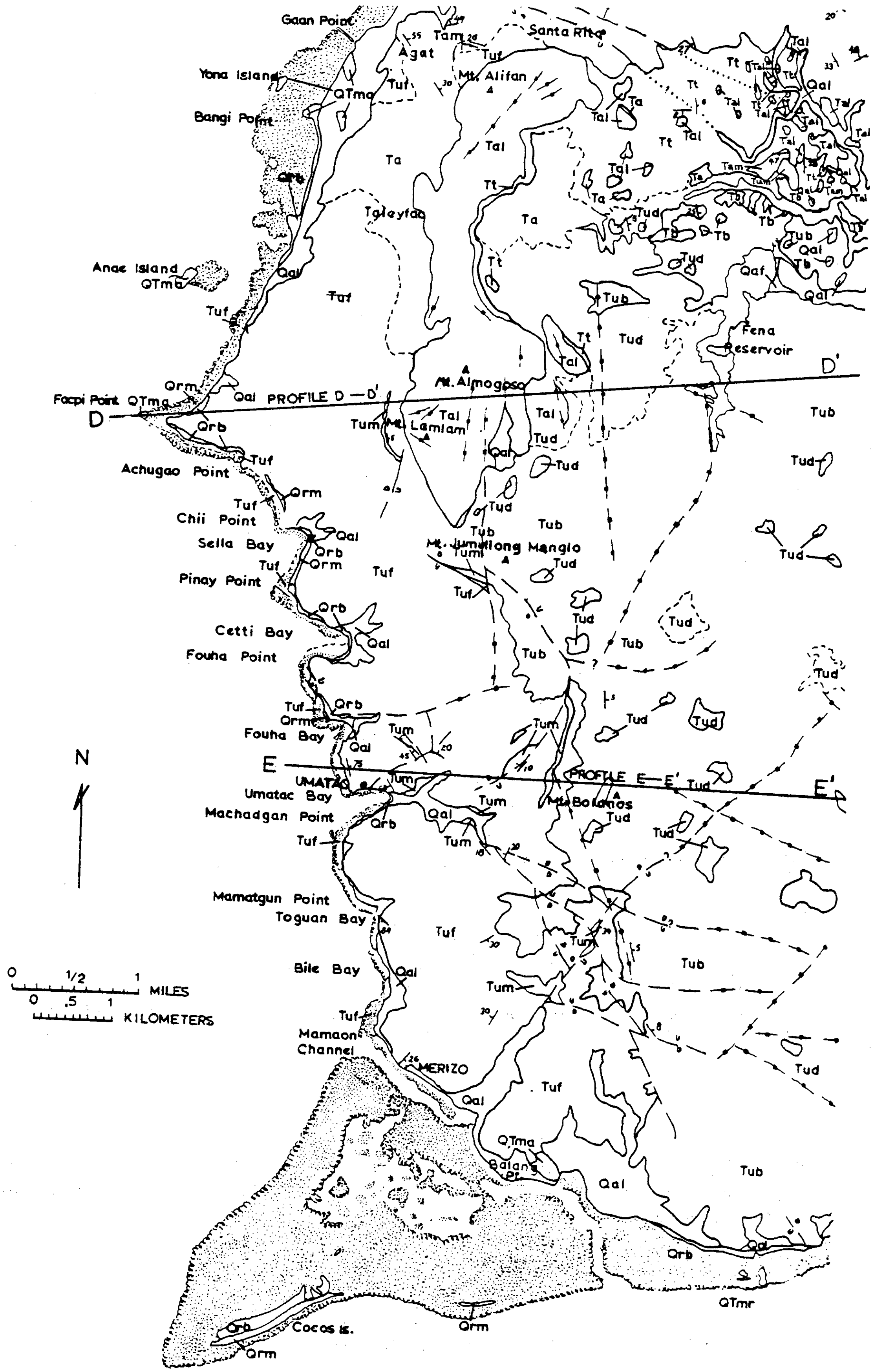


Figure 4. Geologic map of the GSSA. Legend for the map is on pages 42 and 43. See Figure 3 for profile sections D-D' and E-E'. Map modified from Tracey et al. (1964).

LEGEND FOR GEOLOGIC MAPS

Qaf - Artificial fill

Qrb - Beach deposits

Qrm - Merizo limestone

Qal - Alluvium

Mariana limestone:
Qtmr - Reef facies
Qtmd - Detrital facies
Qtmm - Molluscan facies
Qtmf - Fore-reef facies
Qtma - Agana argillaceous member

Tal - Alifan limestone
Tt - Talisay member

Tj - Janum formation

Tbl - Barrigada limestone

Tb - Bonya limestone

Umatic formation:
Tuf - Facpi volcanic member
Tum - Maemong limestone member
Tub - Bolanos pyroclastic member
Tud - Dandan flow member

Alutom formation:
Ta - Alutom formation
Tam - Mahlac member

\- Reef margins and reef flats

Contact

Dashed where approximately located, gradational or inferred.

? U D

Fault, showing dip

Solid where definitely located; dashed where approximately located; dotted where concealed. Queries indicate uncertainty as to existence of fault. Arrows show relative movement. U, upthrown side; D, downthrown side.

Brecciated zone

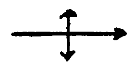
Crushed and brecciated zone in limestone. Zone may grade into joint and fault zones along its strike, and into massive, structureless rock perpendicular to its strike.

Thrust fault

Dashed where inferred. T, indicates upper plate.

Legend continued on next page:

Legend For Geologic Maps (Continued)



Anticline
Showing crestline and bearing and plunge of axis.

Syncline
Showing position of trough and bearing and plunge of axis.

Strike and dip of beds.

Strike and dip of joints.

Strike of vertical joints
A line of joint symbols indicates a prominent joint or structural lineament, along which unbrecciated limestone is cut by a dominant set of joints in which solution has produced deep fissures bounding elongate, pinnacled ridges or along which volcanic rocks are cut by recognizable structural lines that show as a series of knobs and ridges crossing topographic trends or as fine fissures. In places, drainage patterns and valley-wall alinements are determined by these lines. Minor movement at the zone may have occurred, but significant stratigraphic displacement is not shown.

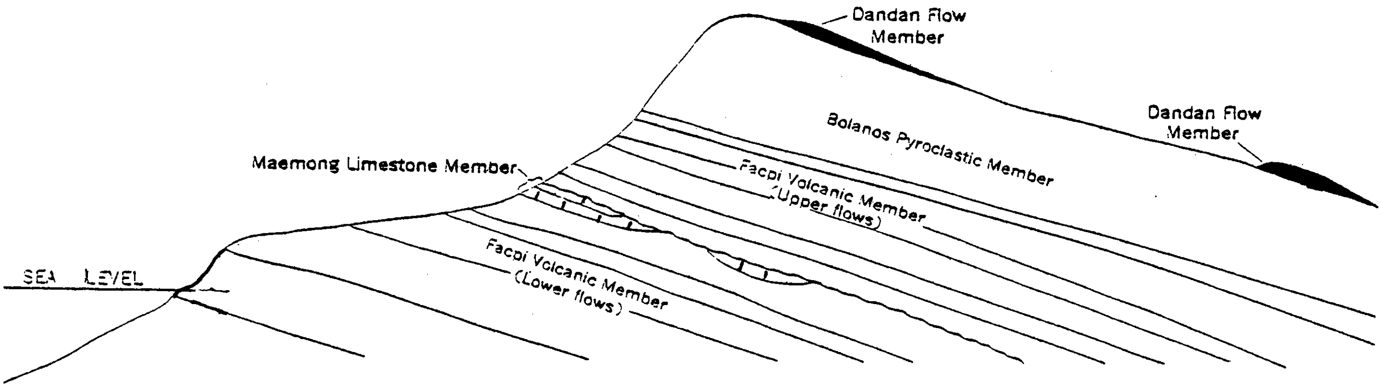


Figure 5. Relative stratigraphic positions of the various members of the Umatac Formation within the GSSA. Modified from Tracey and Stark (1963).

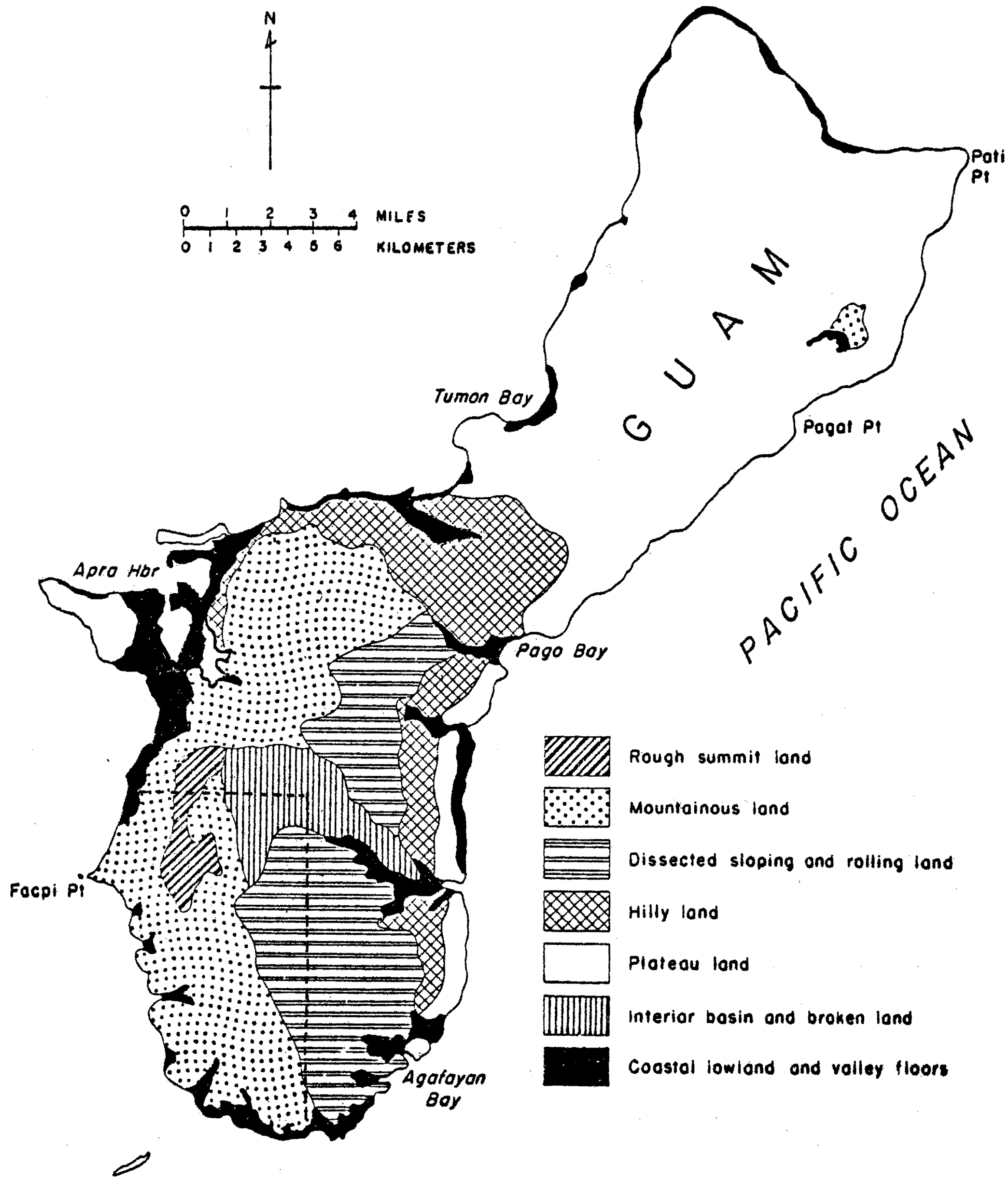
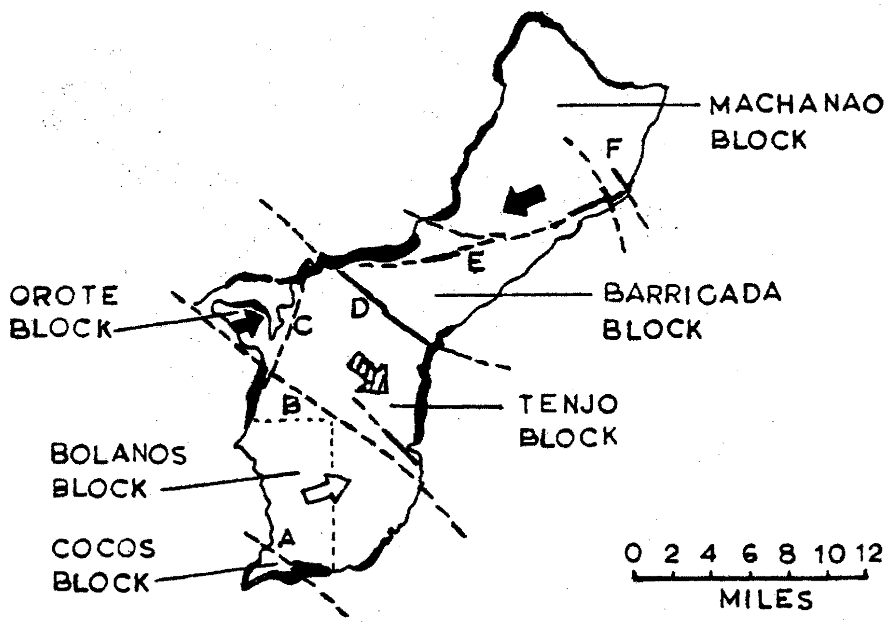


Figure 6. Physiographic divisions of Guam. Figure taken from Tracey et al. (1959).



EXPLANATION

Fault mapped on Guam

Inferred fault mapped on Guam and offshore extensions of both mapped and inferred faults

Topographic dip of structural blocks

Black arrows indicate tectonically tilted block; white arrow indicates slope due to primary depositional dip; slashed arrow indicates slope due to combination of circumstances

A - Cocos fault
B - Talofofo fault zone
C - Cabras fault
D - Adelup fault
E - Tamuning-Yigo fault zone
F - Faults bounding the Santa Rosa horst

Figure 7. Structural subdivisions of Guam. Figure modified from Tracey et al. (1964).

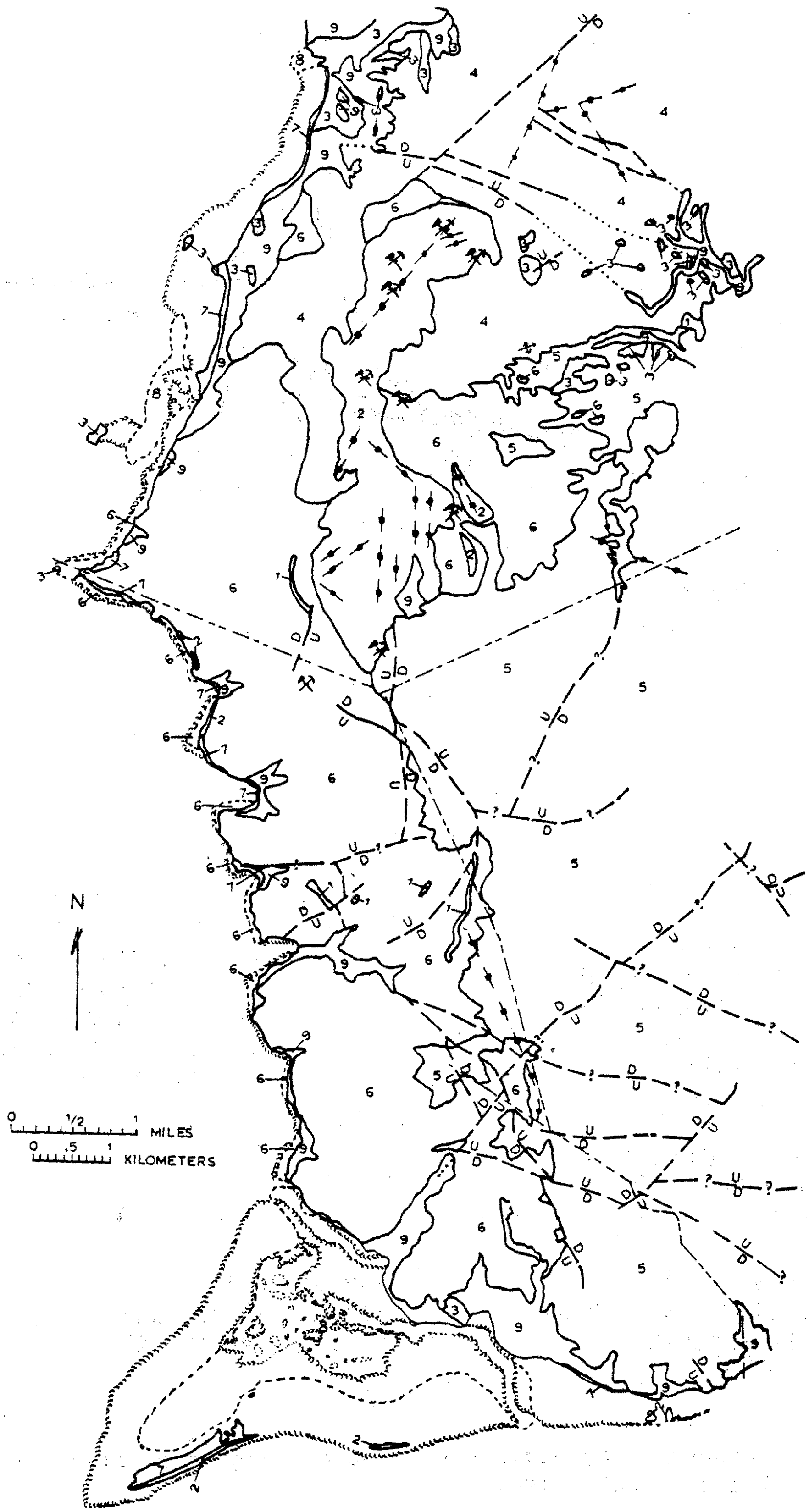
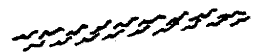


Figure 8. Engineering geology map of the GSSA. See pages 48-50 for map legend and short description of the various units. Map modified from May and Schlanger (1959).

LEGEND FOR ENGINEERING GEOLOGY MAP

FAULT, SHOWING DIP

Dashed where approximately located; dotted where concealed. Question mark indicates inferred fault. U, upthrown side; D, downthrown side.



BRECCIATED ZONE

Zone of many intersecting, closely spaced fractures. The rock in places comprises angular fragments in a friable matrix. Zone may grade along its trace to joint and fault zones, and at depth, to massive, structureless rocks.

THRUST FAULT

Dashed where inferred. T indicates upper side of fault.

ANTICLINE

Showing location of structural ridge. Single arrow at end indicates direction of downward inclination of the structure.

SYNCLINE

Showing location of structural trough. Single arrow at end indicates direction of downward inclination of the structure.

STRIKE AND DIP OF INCLINED JOINTS

STRIKE OF VERTICAL JOINTS

QUARRY OR PIT

ENGINEERING GEOLOGY

EXPLANATION

Limestone Materials

1 - Compact Coralline Limestone. Massive, compact, recrystalized, white to light-brown limestone containing numerous coral heads in a hard, fine-grained algal matrix; includes some porous limestone and some limy rubble. Thick, irregular sheathings of Unit 1 occur on rugged coastal slopes, upon the seaward margins of porous limestones of Units 2 and 3. Excavation requires extensive drilling and blasting. This unit supplies very good cyclopean riprap, and crushed aggregate for base course, wearing course, and concrete. Large quarries are at Cabras Island and Fadian Point.

2 - Coralline Limestone And Rubble. Predominantly white to reddish-brown coralline rubble in a loose to porous lithified limesand matrix. There are also scattered massive ledges and lenses of vuggy and compact coralline limestone, and large, irregular exposures of chalky limestone; vuggy limestone commonly is along the margins of Unit 1, and chalky limestone generally is in the central part of Unit 2 on the northern plateau. Most rocks of Unit 2 can be excavated by power equipment; drilling and blasting will expedite removal of the vuggy limestone. Unit 2 supplies very good base course and, if processed, aggregate for roads; extensively developed and utilized.

3 - Clayey Coralline Limestone And Rubble. Predominantly reddish-brown, clayey, rubbly coralline limestone. There also are scattered lenses and beds of porous, clayey limestone; 5 to 20% of the unit is disseminated clay in the rock, and clay filling cavities in the rock. Locally the rock is buried by soils as much as 50 feet thick. Volcanic rocks of Unit 4 and 5 dip under the rocks of Unit 3. Most of Unit 3 can be excavated with power equipment; drilling and blasting will expedite excavation in compact limestone and in well bonded rubble. Unit 3 supplies good to fair aggregate for fill and sub-base, and clay-coated aggregate; Limited development for material for local roads and fill, and many small quarries (mostly abandoned). Concealed caverns are common.

Volcanic Rock Materials

4 - Volcanic Tuff. Predominantly thick, bedded, fine-grained volcanic tuffs. There also are interbedded volcanic conglomerates and breccias, and interbedded lava flows. Fractures and joints are common; locally there is complex folding and faulting. Most hard rock on rolling uplands is buried under 50 or more feet of clay and soft clayey rotten rock; much hard rock is exposed on steep and rough broken land. Weathered rock can be easily excavated with hand tools and power equipment; drilling and blasting will expedite removal of hard rock. Rarely used for construction materials; provides poor fill and embankment; selected hard boulders and compact limestone may be suitable for sub-base and base courses. Roadbeds and foundations for heavy installations on weathered rock must have adequate drainage.

5 - Volcanic Conglomerate. Predominantly dark-gray, massive volcanic conglomerate with included limestone fragments. There also are massive and bedded, gray tuffaceous shales and sandstones. Rocks of Unit 5 are similar in character to those of Unit 4, but are less fractured and faulted. Much of Unit 5 is deeply weathered.

6 - Lava Flows. Upper part of the unit consists of basalt flows with interbedded massive and bedded tuffaceous shales, sandstones, and conglomerates; the lower part, of thick, moderately hard pillow basalts and dikes. There is some interbedded grayish limestone. Weathered rock can be easily excavated by hand and power tools; hard rock must be drilled and blasted. Much of the rock is deeply weathered to clay. Not used for construction materials, although hard dike rock is very good for crushed aggregate. Roadbeds and foundations, expecially on weathered rock must have adequate drainage.

Unconsolidated Materials

7 - Beach Sands And Gravels. Predominantly discontinuous veneering beach and embayment deposits of unconsolidated limey granular materials. Materials include fragments of shells, corals, algae, and other reef materials. Volcanic detritus and clay are common constituents along volcanic rock coasts, and are major constituents of the mouths of rivers draining volcanic rock hinterlands. Beach materials above the water table can be easily excavated with hand tools and power equipment. Unit 7 supplies limesand for filler in coarse aggregate and blanket cover on clays. Active sand pits are at Tumon and Tarague embayments.

8 - Lagoonal Deposits. Limy, granular marine deposits 10 to 50 feet thick in the shallow basins of larger lagoons; generally contaminated by clay and organic material. Granular material ranges in size from silt to pebble and gravel to large coral boulders as much as 10 feet in diameter; average size is sand and gravel, or cobbly gravel. Can be easily excavated with dredging equipment and dragline. Significant reserves are at Apra Harbor and Cocos Lagoon and probably in embayments along the southeast coast; used extensively around Apra Harbor for fill.

9 - Alluvium. Predominantly clayey sediments 5 to 150 feet thick in nearly all valley bottoms and on gently sloping alluvial fans and earthy floors in large basins in limestone terrain. Subsoils are varicolored clays and silts, generally firm to plastic when moist, soft, and plastic and sticky when wet, hard and cracked when dry; topsoils are dark colored and contain much organic matter. Water table ranges in depth from a few feet near the coast to a few tens of feet inland. Clays are viscous and soupy in saturated zones. Dry earth material can be easily excavated by hand tools and power equipment; heavy equipment bogs down in wet seasons when flooding is common. Clayey materials are generally unsuitable for construction uses.

F - Artificial Fill And Made Land.

Figure 9. Soil map of the GSSA. See pages 52 and 53 for a short description of the various soil units. Map modified from Stensland (1959).

Upland Soils (On Limestone)

1 - Guam Clay. Reddish, granular, permeable Latosol; generally very shallow (less than 12 inches), but has some pockets or narrow troughs of deep soil; prevailing surface gradient 1 to 8 percent.

4 - Saipan-Yona-Chacha Clays. Chacha-Saipan clays with a shallow brownish Lithosol (Yona clay) on many of the narrow convex ridge-tops and steep slopes; soil depth similar to Unit 3, except Yona clay which generally grades into clayey limestone at about 12 to 24 inches below surface; reaction of Yona clay is thus alkaline or calcareous; prevailing surface gradient 8 to 25 percent. (see page 235 for description of Unit 3).

5 - Yona-Chacha Clays. Yona clay is on most narrow convex ridge-tops and steep side slopes, with Chacha on intervening slopes; also small areas of shallow stony phase Saipan clay; depth of soil with convex surface is generally less than 2 or 3 feet, with concave surface it is generally more than 3 feet; slopes range from 25 to more than 100 percent but prevailing surface gradient is commonly 30 to 65 percent.

Upland Soils (On Volcanic Rocks)

6 - Atate-Agat Clay, Rolling. Remnant benches or small mesas of an old red, granular, porous, acid Latosol (Atate clay) with deep, reddish, mottled, plastic to hard clay C horizon, pale yellow, olive, or gray in lower part; and its truncated counterpart (Agat clay) with similar C horizon of saprolitic clay, ranging in depth from a few feet to about 100 feet, and averaging about 50 feet; prevailing surface gradient of Atate clay is 1 to 8 percent, and of Agat clay 8 to 15 percent.

7 - Agat-Asan-Atate Clays, Hilly. Atate-Agat clays and a dark grayish-brown Regosol (Asan clay) developed in more severely truncated saprolite (similar to lower part of C horizon described in Unit 6); soil depths similar to those of Unit 6, except Asan clay which ranges from a few feet in depth to generally less than 50 feet; prevailing surface gradient 15 to 50 percent.

8 - Agat-Asan Clays And Rock Outcrop, Very Hilly To Steep. Chiefly of the truncated Latosol (Agat clay) and the Regosol (Asan clay) with some un-named dark grayish-brown Lithosols and scattered small areas of volcanic rock outcrop (basalt and bedded tuffs); depth to rock ranges from 0 to 50 or more feet and averages perhaps 20 to 35 feet; prevailing surface gradient 35 to more than 100 percent.

Soils of Coastal and Valley Flats

9 - Pago Clay. Brownish, granular to firm and plastic Alluvial clay, with gray mottling to within 24 to 30 inches of the surface; generally alkaline to neutral; soil depth is generally more than 10 and less than 150 feet; moderately well drained; subject to occasional flooding; prevailing surface gradient 1 to 3 percent.

10 - Inarajan Clay. Similar to Pago Clay but lower, wetter, and shallower (thins out on coastal sands and bedrock); water table at or near the surface (within 30 inches) most of the time; poor drainage, mottlings (gray) within 6 to 12 inches of the surface; depth to sand or bedrock ranges from 3 to 25 or more feet; reaction is alkaline in water saturated zone; poorly drained; frequently flooded; prevailing surface gradient 0 to 1 percent.

11 - Muck. Black to brown, soft muck and peat, with some clay and silt; depth to underlying material (chiefly limesand or shelly clay) ranges from 3 to 20 feet, averages 5 to 10 feet; alkaline reaction below the water table, which is generally at or near the surface; prevailing surface gradient is level or very nearly level.

12 - Shioya Soils. Pale brown to white, fine-, medium-, or coarse-grained limesand, commonly with grayish-brown loamy sand or sandy loam surface horizon 6 to 18 inches thick; depth to water table ranges from 5 to 25 feet, depth to bedrock ranges from 3 to 35 feet; prevailing surface gradient 1 to 5 percent.

Miscellaneous Land Types

13f - Limestone Rock Land, Steep. Similar to Unit 13b but consists largely of steep ridges, scarps, and cliffs; prevailing surface gradient 25 to more than 100 percent, with many scarps or cliffs nearly vertical. (see page 235 for description of Unit 13b).