MILITARY GEOLOGY OF GUAM, MARIANA ISLANDS

PART I

DESCRIPTION OF TERRAIN AND ENVIRONMENT

PART II

ENGINEERING ASPECTS OF GEOLOGY AND SOILS

by

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Terrain model of Guam, Mariana Islands.

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Foreword

Engineer Intelligence Study - Guam, Mariana Islands

This report on the Military Geology of Guam, Mariana Islands, has been prepared in cooperation with the U. S. Geological Survey, Department of the Interior, as part of the Pacific Geological Mapping Program of the Corps of Engineers, U. S. Army.

The program is designed to collect and compile information on the military geology of areas of the Pacific, by field mapping and analyses of selected islands, and to publish the information in a form usable to the Armed Forces and the island civil administrations.

The Description of Terrain and Environment of Guam (Part I) includes basic data on geology, geography, soils, vegetation, and climate. Laboratory tests of rock and soil, and specific observations in the field furnish additional basic information, from which are evaluated the suitabilities for construction materials, road and airfield construction, and underground installations (Part II). Suitabilities of the terrain for amphibious and airborne operations and for cross-country movement are evaluated in a separate, classified volume (Part III). Water Resources will be published as a Supplement.

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MILITARY GEOLOGY OF GUAM, MARIANA ISLANDS

INTRODUCTION

Present Work

The present studies were made for the Engineer, Army Forces Far East, by personnel provided by the Military Geology Branch of the U. S. Geological Survey; surface- and ground-water studies were made by the Water Resources Division of the U. S. Geological Survey. Rocks and soils were mapped from the fall of 1951 to the fall of 1954 by a field party consisting of J. I. Tracey, Jr., party chief; D. B. Doan, H. G. May, S. O. Schlanger, and J. T. Stark, geologists; C. H. Stensland and J. B. Paseur, soils scientists; J. W. Brookhart, ground-water geologist; R. K. Chun, surface-water engineer. Marine geology studies were made by K. O. Emery in the summer of 1952, assisted by S. Keesling. Vegetation studies were made by F. R. Fosberg in December 1953 and January 1954. Studies of engineering geology materials were supervised by A. H. Nicol; soils studies were supervised by E. H. Templin.

Photos are by members of the field party. unless otherwise credited; most photos in the vegetation section are by F. R. Fosberg.

Previous Work

Early studies undertaken by the Spaniards are of little significance for military studies, but after the American occupation in 1899, early reports of the U. S. Navy are excellent and thorough. Lt. Governor William Safford's classic, "Useful Plants of Guam", (1905), and the report of L. M. Cox, C. E., USN, on the island of Guam (1904), contain much useful information.

In 1937, Harold T. Stearns of the U. S. Geological Survey made a 2-month study of the island and published the geologic history of the island as an abstract (1940). His work was undertaken for the U. S. Navy, and resulted in an unpublished study, "Water Resources of Guam", which is one of our principal sources of information. His field notes were referred to during this study and are hereby acknowledged. Later reconnaissance studies by Bridge (1946), and Cloud and Schmidt (1951), aided the mapping. Water investigations were made by Piper (1946) and Sundstrom (unpublished). All these workers were members of the U. S. Geological Survey. In 1948-49 the Pacific Islands Engineers, Architect-Engineer for Guam, undertook a geological study of middle Guam as USN contract no. Noy 13626. Their work included the preparation of the most extensive bibliographies yet made for Guam; but far more important was the drilling of large numbers of core-drill holes in areas where major construction was to be undertaken. Soils borings to considerable depths were also made in many areas, especially in Apra Harbor and the Talofofo Valley. Representative complete cores from each major area have been sent to Washington for further study by the U. S. Geological Survey. The data and reports of the Pacific Islands Engineers are not published but are available at the Bureau of Yards and Docks, Washington, D. C., in mimeographed form. A list of the reports referred to is included in the references.

Acknowledgements

Logistical support for the field party was provided chiefly by the 19th Bombardment Wing (M) (later the 6319th Air Base Wing), USAF. Office space and other support, especially for water resources studies, was provided by the Government of Guam. Some quarters and considerable technical support were furnished by Commander Naval Forces Marianas (COMNAVMAR). Special acknowledgment is due the Base Development Officer, Commander Naval Forces Marianas, for engineering tests and chemical analyses provided by the Base Development Testing Laboratory under the direction of Charles Shirley. The commanding officers and engineering staffs of the Base Development Office, the officer in charge of construction, and the Public Works Center have all given generous assistance. The Commanding Officer and staff of the Air Installations Office, 6319th Air Base Wing, and the 809th Aviation Engineer Battalion, have been especially helpful regarding water and construction problems on the north end of the island.

Organization of the Report

The Guam Military Geology Report is in four parts: Description of Terrain and Environment, including sections on geography, oceanography and reefs, climate, geology, soils, and vegetation; Engineering Aspects of Geology and Soils, including sections on construction materials and construction sites; Tactical Aspects of Coast and Terrain, including sections on amphibious operations, terrain appreciation, cross-country movement, and airborne operations; and Water Resources. Generally, basic data are given in the general Description part; following parts are interpretive. The Tactical Aspects part is published as a separate, classified volume; Water Resources will be published as a Supplement.

Maps are on a topographic base prepared by the 64th Engineer Battalion (Base Topographic), under the direction of the Engineer, HQ. AFFE.

Elevations, distances, and areas for significant features of topography and geography discussed in the text are given in both metric and English systems of measurement.

PART I. DESCRIPTION OF TERRAIN AND ENVIRONMENT

Geography

Location and Extent

Guam, the largest and southernmost of the Mariana Islands, is at 13°28' 29" north latitude, 144°44' 55" east longitude (Agana monument) (fig. 1). It is about 49 kilometers (30 miles) long and tapers in width from 14 kilometers (8 1/2 miles) in the north to 6 1/2 kilometers (4 miles) at the central waist, widening again to the south to a maximum width of 18 1/2 kilometers (11 1/2 miles) from Orote Point to Ylig Bay on the east coast (see pl. 4, in pocket). The land area, exclusive of the reefs, is 550 square kilometers (212 square miles). North of the narrow waist line, which extends from Agana to Pago Bay, the axis of the island trends northeast, and south of the waist the trend is north-south. There are twelve small limestone islands along the reef. The largest is Cocos Island, off the southwest coast; it is a "low island" similar to the atoll islands of the Pacific.

Figure 1. Index map of the western Pacific Ocean.

Relief

The north half of Guam is a broad, gently undulating limestone plateau bordered by steep cliffs. The plateau slopes generally southwestward from an elevation of approximately 183 meters (600 feet) in the north to less than 30 meters (100 feet) at the narrow mid-section of the island. Three prominent peaks rising above the level of the north plateau are Mt. Santa Rosa (262 meters or 860 feet) and Mataguac Hill.(180 meters or 592 feet), both made up of volcanic rock, and the limestone peak of Barrigada Hill (200 meters or 660 feet).

The limestone is so permeable that no permanent streams exist on the plateau, but well developed sinkholes are numerous. Along the shore the plateau is bordered in places by a coastal plain, irregular in width and fringed by a coral reef. The steep seaward cliffs that encircle the plateau are marked by wave-cut escarpments and terraces irregularly spaced above one another.

The southern half of Guam is a broad, ruggedly dissected upland developed chiefly on volcanic rocks. The surface is weathered into peaks, knobs, ridges, and basin-like areas and is deeply channeled by streams. A nearly continuous mountain ridge, the crest of which lies from 1 to 2 miles inland, parallels the west coast from the highland west of Piti to the southern tip of the island. The principal peaks from north to south on this backbone ridge are Mount Alutom (328 meters), Mount Tenjo (309 meters), Mount Alifan (266 meters), Mount Lamlam (405 meters), Mount Jumullong Manglo (365 meters), Mount Bolanos (372 meters), Mount Schroeder (321 meters), and Mount Sasalaguan (338 meters). The west coast is bordered by a plain that rises from sea level to approximately 90 meters (300 feet). Two prominent limestone masses, Cabras Island and Orote Peninsula, project westward from the plain at Apra Harbor.

The dissected upland slopes gently eastward from the mountain ridge and merges into a narrow limestone plateau, from 30 to 107 meters (100 to 350 feet) above sea level, which fringes the east side of the island from Pago Bay to Inarajan.

Roads

A network of paved and secondary roads covers the northern and central parts of the island. A well paved road crosses the waist from Agana to Pago Bay and follows the coast except for 3 miles between Umatac village and Mt. Lamlam to the north around the southern half of the island.

Population

The constantly changing military population is centered principally around Andersen Air Force Base in the northeast part of the island, the Naval Air Station near Agana, and the Naval Station at Apra Harbor. The Naval Air Station is used by several commercial airlines, and a part of Apra Harbor is used by commercial shipping.

The non-military population is concentrated in villages in the central section, and along the coastal road around the southern half, and in two villages in the north part of the island.

The 1953 population of the principal villages, including both U. S. citizens and non-citizens but exclusive of military personnel, is given below:

Agana	1,037	Sinajana	4,002
Agat	2,078	Talofofo	1,504
Asan	1,502	Tamuning-Tumon	2,615
Barrigada	4,066	Umatac	609
Dededo	1,601	Yigo	908
Inarajan	1,484	Yona	1,630
Merizo	1,162	Agana Heights	2,400
Mongmong-Toto	1,516	Chalan Pago-Ordot	1,365
Piti	1,233	Mangilao	1,028
Santa Rita	1,532		
		Total population	33,272

Oceanography and Reefs

The ocean dominates the island of Guam and is largely responsible for its climate. The ocean temperature is about 81° F. the year around.

Currents and Tides

The northern Equatorial Current caused by the northeast trades generally sets in a westerly direction near the island of Guam with a velocity of 1/2 to 1 knot. Currents in the western Pacific are not as well known as are those in the Atlantic.

Tides at Guam are semi-diurnal with a mean range of 1.6 feet and a diurnal range of 2.3 feet. Datum for the island is mean lower low water, and other applicable data are tabulated below with relation to this datum:

	feet
Mean higher high water	2.3
Mean high water	2.2
Mean tide level	1.4
Mean low water	0.6
Mean lower low water	0.0

Extreme predicted tide range at Guam is about 3.5 feet (from 2.6 to minus 0.9 feet), during June and December.

Waves and Swells

Wind waves are dominantly from the northeast to southeast, driven by the trade winds. Normal trade wind waves are low (less than 2 feet) to medium (less than 9 feet) in height and are mostly less than 5 feet. Occasional calms are common from April to September, but periods of more than 2 or 3 days of calm are rare. Wind waves higher than 6 feet are usually associated with storms.

Considerable damage may be done by waves generated periodically by storm centers as much as 1,000 miles from Guam. Most commonly, the waves are caused by typhoons moving westward after they have passed north or south of Guam. Severe waves are sometimes associated with large typhoons that strike Guam (special meteorological report on typhoon of September 1946, by the Pacific Islands Engineers; also the ComNavMar report on typhoon Allyn, November 1949). During typhoon Allyn large stretches of beach from Ylig Bay to Merizo were destroyed, and water passed over large parts of Cocos Island. Much damage can also be caused by storms at some distance from Guam. On December 17, 1953, large waves damaged Marine Drive (Route 1) and a number of buildings near Asan, Piti, and Agana. The waves that washed over the road near Agana passed across a reef flat more than 2,000 feet wide. The storm generating the waves was a typhoon 350 miles north of Guam. On March 27 and 28, 1952, the Glass Breakwater was damaged by waves generated by a storm off the coast of Japan 1,200 miles northwest of Guam (Schlanger, 1952).

The frequency of damage by storm waves is in part a function of the number of typhoons that pass near Guam. For the relatively few years that accurate typhoon tracks have been plotted, it has been estimated by a researcher of the U. S. Navy Fleet Weather Central on Guam that an average of 1.25 typhoons a year, with a wind intensity of 58 mph (50 knots), passes within 200 miles of Guam. In 1953, three typhoons of that intensity passed within 200 miles of Guam, yet damage to the Glass Breakwater was caused by waves generated by typhoons at least 6 times during 1953.

For planning operations the military services on Guam assume that the island will be affected by winds of from 40 to 58 mph (35 to 50 knots) three to four times a year, and that the island will be hit by a full destructive typhoon once in four years. These figures may be called "probable maxima". Inasmuch as wind and wave damage, flooding, landsliding, and other damage from intense rainfall are all related to the incidence of typhoons, accurate records are necessary. Statistical analyses of such records for purposes of engineering design and planning are valid only if the records are continuous over a long period of time.

Reefs

Guam is completely encircled by fringing reefs except along parts of the limestone cliffs. In two places barrier reefs have developed that enclose or partly enclose small lagoons -- at Apra Harbor on the west coast and Cocos Island at the south end of Guam.

The fringing reefs range from narrow cut benches around limestone headlands, thinly veneered by encrusting algae below sea level, to broad reef flats more than 3,000 feet wide containing a variety of corals and algae. Although the reefs vary greatly in character from place to place, the development of certain features seems to depend to some extent on their location. The reefs are briefly described here in 9 segments clockwise around the island, including the 2 lagoon and barrier reef areas already mentioned (fig. 2).

<u>Broad reefs from Tepungan to Tumon Bay</u>: The coast from Tepungan Channel by Cabras Island to the headlands north of Naton Beach on Tumon Bay, a distance of 8 1/2 miles, is fringed by reefs that range in width from 750 to 3,000 feet and average about 2,000 feet.

A submerged terrace or cut bench is present over much of the area, sloping gently seaward at a depth of 20 to 30 feet near the reef edge; in many places cracks across the bench are visible from a boat.

The seaward reef margin is moderately well developed. A broad but low algal ridge is cut by scattered surge channels on north-facing segments of the reef, but is smooth and ungrooved on west-facing or lee segments. The reef flats are partly exposed during extreme low tide on calm days, but large areas of the Piti and Agana reefs are covered by 1 or 2 feet of water, and the Tumon Reef is covered by 2 or 3 feet of water. These low areas have sandy bottoms with scattered large clusters or patches of coral that grow to low tide level. Exposed areas of the reef or those parts covered by only a few inches of water are generally rocky and contain scattered small coral colonies that become more abundant to the reef margin. Over both Agana Reef and Tumon Reef an irregular band 100 to 300 feet wide of boulders or unconsolidated rubble separates the marginal zone from the reef flat.

The Piti reef margin is very irregular with a large embayment 1,000 feet in length. The reef flat contains several large and many small open pools 10 to 20 feet deep. The largest pool is more than 500 feet in longest dimension.

A limestone cliff forms the coast line from Saupon Point to Ypao Point. Here no true fringing reef exists; rather, a cut bench 6 to 20 feet wide borders the cliff at sea level (pl. 1A). The bench ranges in elevation from about mean tide level to 4 or 5 feet above. The inner edge of the bench forms a notch in the cliff which in places completely roofs over the bench. The floor is flat with scattered shallow pools, and is covered by soft algae. The outer edge is steep, irregular, and coated with pink calcareous algae and a few corals.

Reef fringing cliffs from Goggna Beach to Ritidian Point: The coastline from the north end of Tumon Bay to the north end of the island, 10 miles in length, is an undulating cliff line 200 to 600 feet high fringed by irregular, relatively narrow but in places very well developed coral-algal reefs ranging in width from 20 or 30 feet to about 750 feet. The terrace that forms the upper part of the offshore slope is broad and gently sloping. The reef front shows a variety of forms ranging from smoothly lobate or irregularly eroded in westerly sectors, to poorly grooved but well developed algal fronts on more northerly sectors. Examples of the smooth or eroded reef fronts are south of Amantes Point, near Tanguissan Point, and along the Haputo-Pugua Coast (pl. 1B). Good examples of grooved reefs are just north of Amantes Point, Hilaan, and from Uruno Point to Ritidian Point.

The algal reef margin is mostly exposed at low tide, but is low and flat. Corals are abundant. The reef flat where narrow is covered in places with pink calcareous algae, as north of Pugua, and it constitutes an extension of the margin. More commonly the reef flat is wider, submerged at low tide, and coral growth is so abundant that the reef floor is extremely rough.

Several stretches of this coast, especially north of Haputo and south of Falcona beach, have a poorly developed reef or none at all. Where there is no reef, a cut bench at high to mean water level similar to that described around Saupon Point and Ypao Point is present.

Northeast reefs, Ritidian Point to Pati Point: A well developed windward reef 200 to 700 feet wide extends about 6 miles from Ritidian Point to Tagua Point, and a narrow reef or terraced shelf is present from Tagua Point to Pati Point, a distance of 1 1/2 miles.

Along this coast a 60-foot-wide submarine terrace is rather well defined. It slopes gently seaward from the reef front where it is 15 to 20 feet below sea level. The reef front shows an excellent development of long algal spurs growing on the terrace, and separated by narrow grooves. The reef margin has a strongly marked algal ridge with a crest in places more than 2 feet above the reef flat. Many large channels cut through the crest. Some are more than 200 feet long onto the reef flat, and open into small pools 5 to 10 feet deep and 10 to 20 feet in diameter (pl. 2A). The reef flat has an outer richly coral-

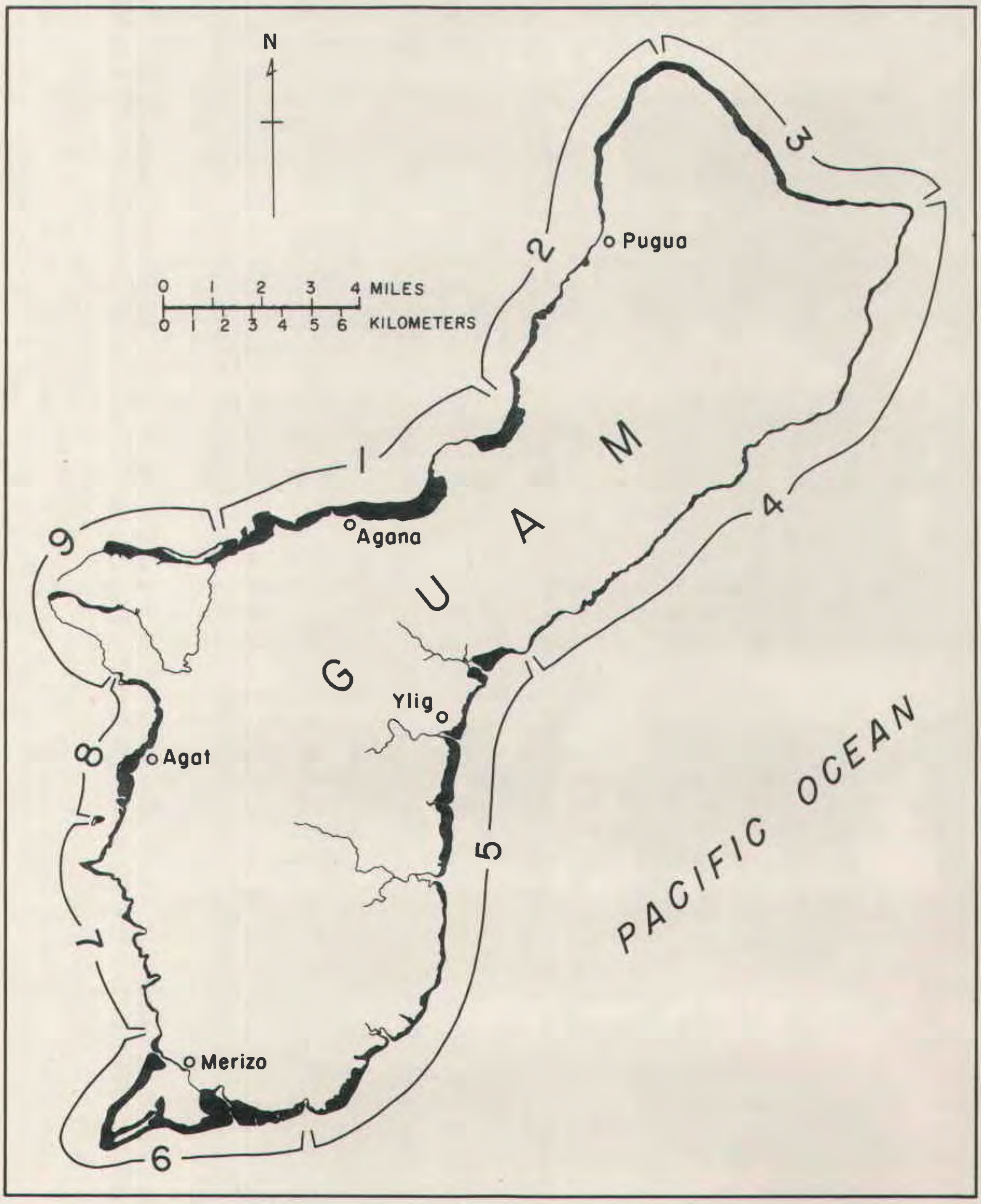


Figure 2. Reef segments around Guam.

liferous zone covered by less than 6 inches of water at low tide, and an inner zone of scattered, irregular coral patches on a rough rock floor covered with a veneer of coarse sand and gravel. This zone is mostly about 2 feet deep at low tide. In the eastern part of the coast numerous limestone remnants 3 to 6 feet in height above the reef flat are eroded relics of a former higher reef level.

From Tagua Point to Pati Point the coast is rugged, and the reef is very narrow if present. Mostly the coastal cliffs are fringed by rimmed algal terraces and the reef flats are truncated benches.

Eastern cliffed coast, Pati Point to Pago Bay: This 16-mile-long coastline is generally rocky, backed by a prominent cut terrace or bench 10 to 50 feet above sea level. The shoreline is mostly cliffed, with a few scattered small reentrant beaches of gravel and boulders.

Reefs along the coast are narrow and discontinuous. Headlands are rimmed by narrow cut benches bordered by rimmed worm-algal terraces (pl. 2B). In some places, as along the coast at Janum Point, a well developed algal margin is present (pl. 3A). Reef flats are generally 25 to 50 feet wide and in a few places are as much as 200 feet wide. The flats are mostly cut benches, and coral growth is sporadic.

East coast, Pago Bay to Ajayan Bay: The southeastern coast of the island, 14 miles in length, is bordered by a well developed wide windward reef marked in places by exceptional algal growth on the seaward margin. The coastline includes a number of bays at the mouths of the principal streams of the island, as well as smaller channels and breaks in the reef where smaller streams emerge.

A broad rocky bench 15 to 25 feet below sea level at the reef edge slopes gently seaward. The reef front along most of the coastline consists of conspicuous closely spaced grooves that cut the reef in many places as surge channels. The reef margin is a broad, low algal ridge, and the reef flat is a sand-veneered rock flat, mostly exposed at low tide, 400 to more than 2,000 feet in width. Coral growth is scattered and colonies are small.

Unusual development of the reef margin is seen near Aga Point where algal knobs or bosses 5 to 20 feet apart at the seaward edge merge landward to form a "room-and-pillar" type of reef (pl. 3B). Open pools on the reef flat, 10 to 20 feet in diameter and 5 to 12 feet deep, are connected by covered channels under the reef floor. Short stretches of this coastline are bounded around headlands by cut benches rather than by reefs (see pl. 6). Pago Point is bounded by benches 3 to 12 feet above sea level; other headlands are fringed by broad benches with step-like rimmed terraces.

Cocos Island reef - Ajayan Bay to Bile Bay: From Ajayan Bay to the east end of Cocos Island, a distance of 4 miles, the reef margin is rough and irregular. It grows on a gently sloping, unusually shoal submarine terrace which can be seen in aerial photographs, and which is probably the main reason for the roughness of the margin. From the east end of Cocos Island to the southwest point or bend of the reef the reef margin is strongly developed with marked grooves and some surge channels.

The reef flat broadens from 750 feet in width at Ajayan Bay to more than 3,000 feet near Mannell Channel. Near Mannell Channel most of the reef is exposed at low tide, but closer to Cocos Island the inner reef flat is covered by 1 to 5 feet of water, and is profusely covered with coral patches. The outer reef flat, within 100 to 500 feet of the reef margin, is covered by tracts or bands of rubble that are exposed at low tide.

The western reef front has a smooth lobate margin containing many submerged reentrants or "holes" parallel to the reef edge. These are probably torn in the reef front by storm waves. The reef flat is rough and rocky, with small irregular patches of coral and rubble, and is covered by 1 to 2 feet of water at low tide.

Basalt reefs from Bile Bay to Anae Island: The reefs that fringe this 6-mile-long section of coastline are cut in basalt at low tide level, and are veneered on the reef front by smooth encrusting algae, and on the surface near the margin by abundant coral and algal growth.

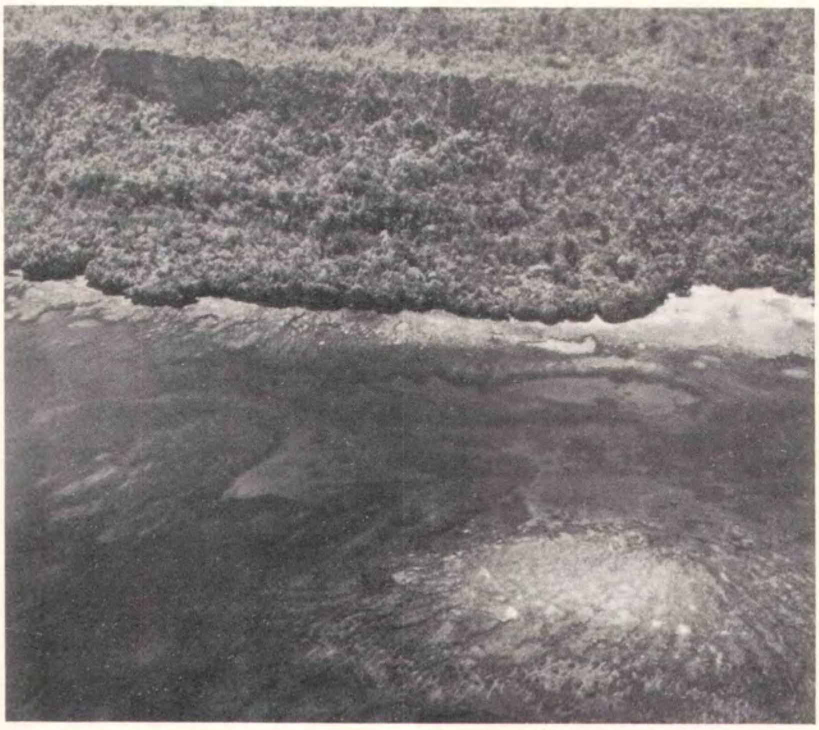
The inner reef flats of smoothly truncated basalt are exposed at low tide (see pl. 5A). A broad submarine terrace slopes away from the reef. It is from 10 to 20 feet below water level at the reef front, and 50 to 60 feet or more at a distance of 100 to 200 yards from the reef edge.

Irregular broad reefs from Anae Island to Orote Peninsula: The reefs along this 4-mile-long coast have broad, barren muddy flats fringed by a smooth, cuspate algal margin. Large irregularities in the margin and holes in the reef are due in part to the small streams that empty on the west coast. The reef ranges from 500 to 2,500 feet in width. The margin, reef front, and offshore slope are similar to those of the reefs from Bile Bay to Anae Island.

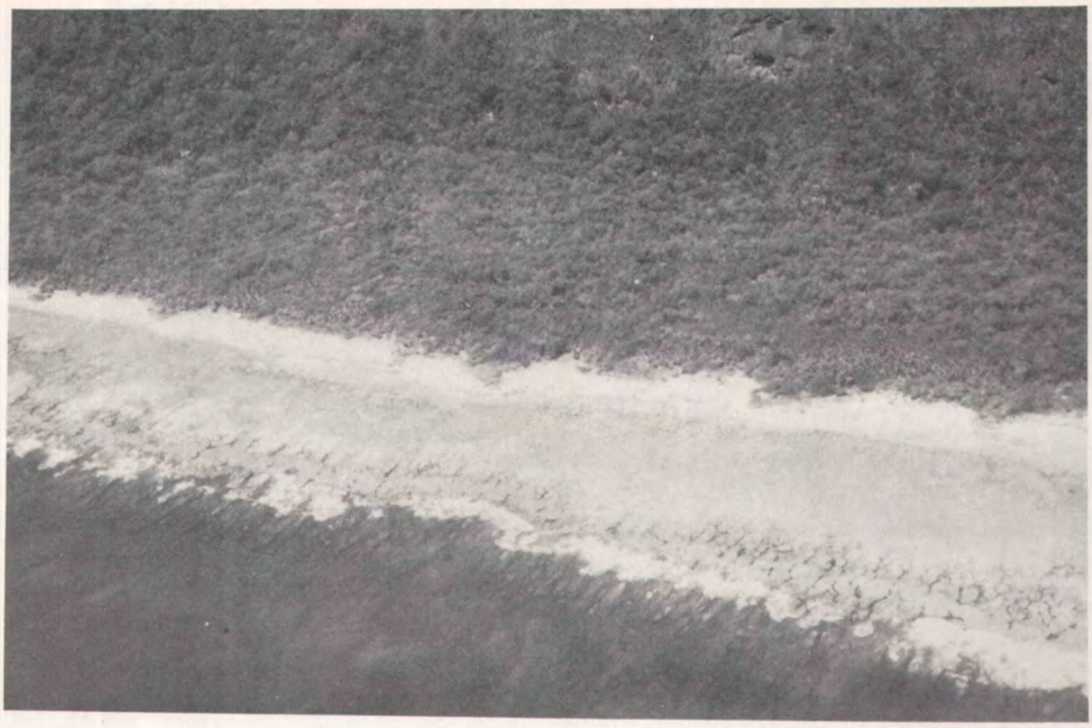
Reefs of Apra Harbor and Orote Peninsula: Apra Harbor is an open lagoon or bay formed by the limestone cliffs of Orote Peninsula on the south and by the long barrier of Cabras Island and Luminao reef on the north. Luminao reef is mostly submerged to depths of 1 to 6 fathoms and forms the foundation for the Glass Breakwater.

Three kinds of reef are present around the harbor, but they are so altered by dredging and other activities that no detailed description will be given. In reentrants on both sides of Orote Peninsula are relatively small patches of reef with well developed coralliferous reef flats and with grooved or partly-grooved margins. Luminao reef, the barrier reef west of Cabras Island, is a submerged, wide coralliferous flat with a grooved algal margin on the seaward side. The large flat patch reefs and coral knolls in the harbor form the third type of reef. These formerly were actively growing, but now are mostly killed by harbor activities, and are covered by a scum of green and brown algae.

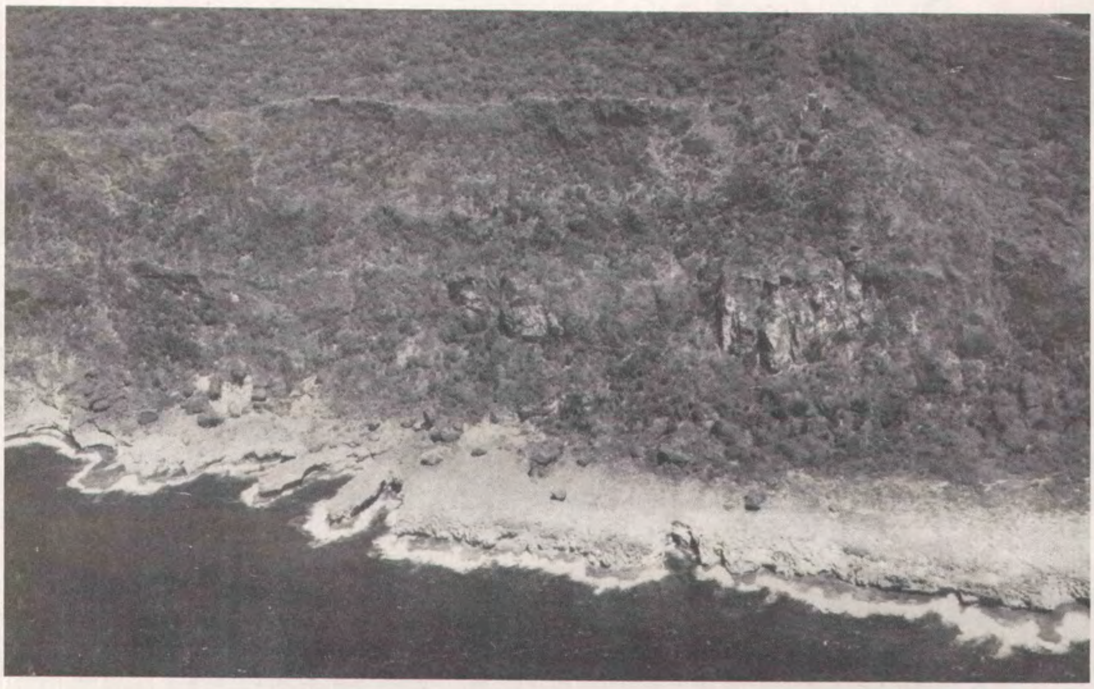
A. Benches at Saupon Point. Such benches commonly replace reefs along cliffed headlands. The narrow bench here is cut into headlands formed of the detrital facies of the Mariana limestone. (Reef segment no. 1).



B. Narrow irregular reef near Pugua. Reefs below cliffs such as the ones shown in the photo generally are irregular and range from broad, well developed reefs to narrow cut benches. Cliff in the background is about 113 meters (370 feet) high. (Reef segment no. 2). Photo by U.S. Navy.



A. Surge channels at Jinapsan Beach. Some of the channels in this beach are more than 60 meters (200 feet) long: (Reef segment no. 3). Photo by U.S. Navy.



B. Cliffs and sea level cut bench at Pati Point. Cliffs and distinct terraces are cut in the detrital facies of the Mariana limestone. Strongly marked joints and small faults are prominent on both cliff and coast. Photo by U.S. Navy.

A. Algal buttresses near Janum Point. The reef margin is well developed although the reef flat is only a few feet wide. Buttresses and surge channels are generally best developed on windward coasts such as this. (Reef segment no. 4.)

B. Broad reef at Aga Point. The unusual reef margin is formed of round algal knobs or bosses that grow horizontally at sea level from a shallow submerged shelf or bench, and that merge to form an irregular surface underlain by cavernous room-and-pillar structures. (Reef segment no. 5). Photo by U.S. Navy.

Climate

by

David I. Blumenstock [1]

Summary

The climate of Guam is warm and humid. Mean temperature variations are slight from month to month. In the Apra Harbor area, for example, the coolest month averages 79.2° F. and the warmest averages 82.5°. At all locations except on the highest peaks, daytime temperatures are usually in the middle to high eighties, and nighttime temperatures in the middle to high seventies. The humidity commonly varies between 65 to 80 percent in the late afternoon and 85 to 100 percent at night. Annual rainfall ranges from 85 to 115 inches, with the least average rainfall in the Apra Harbor area and the most in the higher mountain areas. On the northern plateau, rainfall averages are intermediate.

Despite the uniformity of temperature and humidity conditions, there are two distinct seasons on Guam: a five-month dry season, from January through May; and a five-month rainy season, from July through November. December and June are transitional rainfall months.

During the dry season the rainfall averages 12 to 20 inches; during the wet season, 60 to 75 inches. Other major differences between the seasons are related to wind and storm. The dry season is the tradewind season. Winds are nearly always from easterly directions and windspeeds are commonly in excess of 15 mph; calms are rare. During the wet season, winds often blow from any direction, windspeeds seldom exceed 15 mph, and calms are frequent. Major storms, such as typhoons, may occur in either season or in either transitional month, but they are about 5 times more likely to occur during the wet season than during the dry season.

Typhoons are moderately common in the vicinity of Guam. The chances are approximately two in three that one or more typhoons will pass within 120 nautical miles of Guam in any particular year. The chances are about 1 in 3 that in any year one or more typhoons will cause considerable damage; coastal inundation, destructive winds, and flood-producing rains are the dangers posed by a typhoon. In extreme instances, typhoons have produced inundations of over 12 feet, winds of over 150 mph, and rainfall of well over 20 inches in a day. The highest rainfall of record was 26 inches in one day at Umatac during the typhoon of October 1953. The 2-day rainfall at Umatac during the same typhoon was 48 inches.

The other aspects of the climate of paramount practical concern at Guam are the high humidity and warmth as related to deterioration of goods and equipment, and drought as related to water supply. Deterioration through the action of fungi or through corrosion is most rapid during the wet season, when humidities are somewhat higher than at other times and when wind movement is low. Moderate drought is normal during the dry season. Extreme drought, with less than 0.1 inch of rain on any one day, commonly persists for at least two weeks at some time during the dry season and the chances are approximately 1 in 5 that such an extreme drought will persist for 4 weeks or more.

1/ Climatologist, Weather Bureau, U. S. Department of Commerce.

General Climatic Setting

Broad climatic characteristics: To a casual observer accustomed to the colder climes of higher latitudes, the climate of Guam would appear at first to be singularly monotonous. Regardless of the time of year, the weather is warm. Even at higher elevations on the island the nights bring but a slight lowering of temperature as compared with the marked temperature drops that are commonly felt in such regions as the central United States. Both night and day the humidity would be high, often uncomfortably so.

Yet despite the very real uniformity of temperature and humidity conditions, an observer would in time come to recognize that there are pronounced weather seasons on Guam, that there are very marked weather events such as tropical storms, and that there are significant variations in weather and climate from one place to another on the island. These seasonal variations, weather episodes, and areal differences in weather and climate are for most practical purposes of even more importance than the relative temporal and areal uniformity of temperature and humidity conditions. Indeed, it is these variable aspects of the weather and climate that give Guam its distinctive climatic regime.

Seasons: There are two distinct seasons on Guam: a dry season of five months extending from January through May; and a wet season of five months extending from July through November. The two intermediate months of June and December are transitional in nature.

The mean annual rainfall on Guam ranges from about 86 inches in the coastal area around Apra Harbor to about 112 to 115 inches in the highest mountain locations (fig. 3) of the southern half of the island (see fig. 4). Of these annual amounts, 15 to 20 percent falls during the dry season and 68 to 73 percent in the wet season, the exact percentage differing somewhat from location to location. The remaining 10 to 12 percent is divided virtually equally between the two transition months.

Though the chief distinction between the dry and wet seasons is in terms of amounts of rainfall, this is by no means the only important distinction. The dry season is the tradewind season. Winds blow from easterly directions more than 90 percent of the time. Windspeeds often exceed 15 mph. Calms are rare. Virtually all the rain is in the form of showers, which are chiefly light to moderate and typically widely scattered; steady rain is unusual. And tropical storms and typhoons occur so infrequently that during a 30-year period (1924-53) only three passed within a distance of 60 nautical miles from Guam.

In contradistinction to these characteristics of the dry season, during the wet season the wind often blows from other than trade (easterly) directions. Windspeeds are seldom in excess of 15 mph. Calms are frequent. Showers are typically moderate to heavy and often are closely spaced during those frequent, episodic periods when unsettled weather and light variable wind conditions prevail. Steady rain is also common. And the wet season includes the period of highest frequency of tropical storms and typhoons. During the 30-year periods, 1924-53, 24 passed within a distance of 60 nautical miles from Guam.

There are still other, less pronounced, differences between the dry and wet season. During the dry season both the humidity and the cloudiness are slightly less than during the wet season. Correspondingly, visibility is somewhat greater. At the Naval Air Station Agana, for example, in March, at the heart of the dry season, visibility exceeds 10 miles about 70 percent of the time whereas in September it exceeds 10 miles 50 percent of the time (judging by records covering 6 1/2 years of observations). The dry season also brings slightly cooler nights than does the wet season.

In general, the two seasons on Guam are distinctly different in character. They do not display many of the extreme contrasts that mark the changing seasons in such continental areas as Manitoba, Illinois, or even Florida; but they do present contrasts of considerable quantitative magnitude and of very real practical importance.

Areal variations: In a climatic sense, Guam is neither a truly mountainous island such as Hawaii or New Guinea, nor is it an island of low relief, such as an atoll or even Yap. Although there are areal variations in climate upon the island, these variations are wholly moderate, for the island affords only a modest obstruction to the warm, moist air that moves across it from the surrounding tropical ocean.

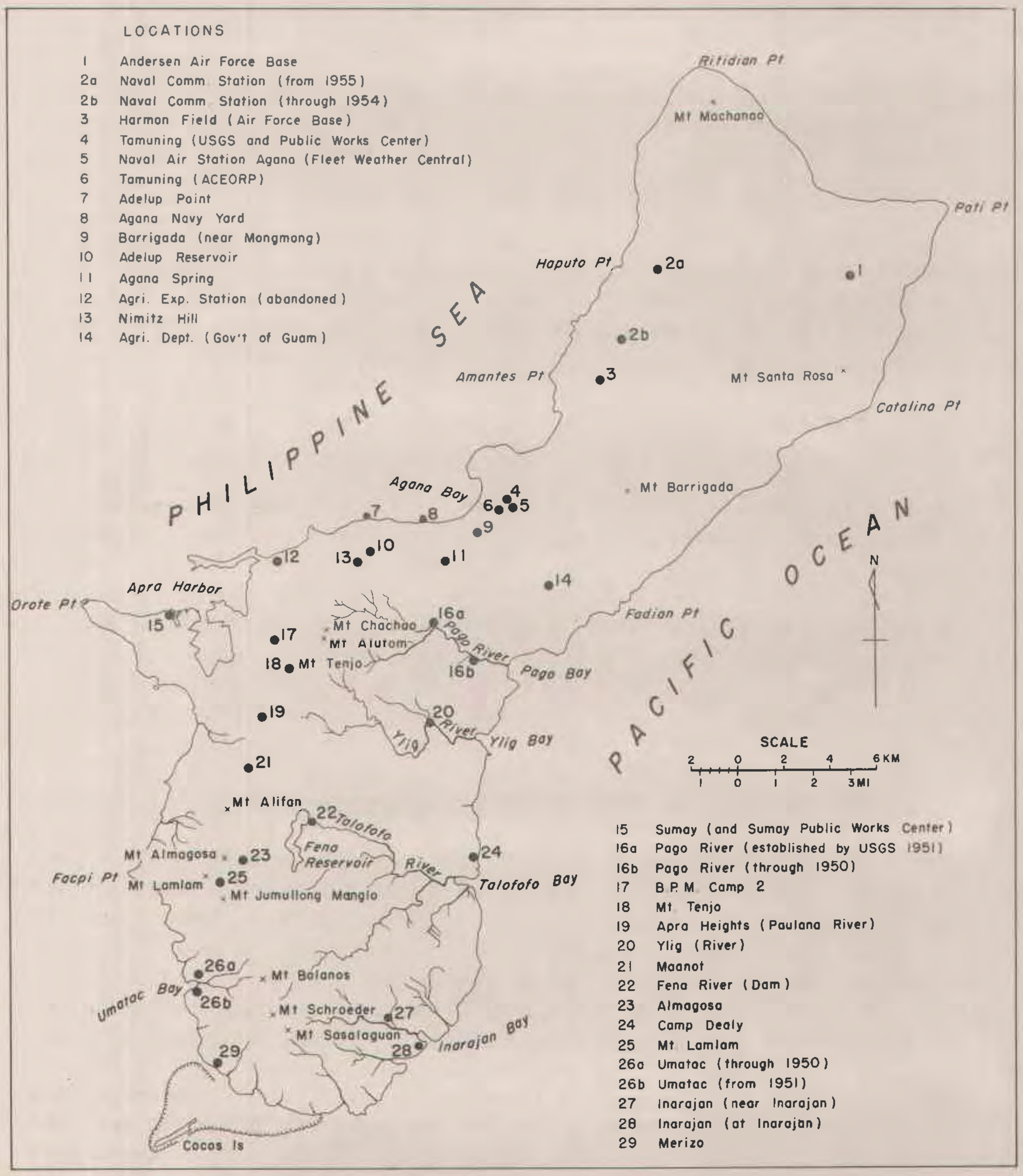


Figure 3. Locations of weather stations, Guam.

The areal differentiation of climatic conditions upon Guam is chiefly related to two topographic factors: elevation and exposure. Localities at higher elevations receive more rainfall on the average than those at lower elevations, as do also localities that are open to the east so that they receive the tradewind flow "face on". These factors are reflected in the map of mean annual rainfall (fig. 4), which shows that the wettest areas, at the highest elevations that are exposed to the trades, receive about one-third more rainfall in the average year than does the driest area, near sea level and leeward of the mountains with reference to the trades.

Temperature and wind conditions are also influenced by elevation and exposure. Average temperatures are 3 to 4° F. cooler on such mountains as Lamlam and Bolanos than they are near sea level on either coast. Furthermore, localities well exposed to the tradewinds, such as Inarajan on the east coast, are slightly cooler than localities at similar locations along the west coast because they are more often and more immediately submerged beneath fresh, slightly cooler air from off the ocean. Wind conditions vary greatly from place to place depending on the local topography. The greatest contrast is between exposed headlands along the east coast and sheltered valleys embedded in the mountains of the southern half of the island. Windspeeds may be 15 mph and more at headland locations along the southeast coast while at the same time there is no appreciable wind in the upper Fena (Maagos) Valley.

Climatic Factors of Principal Interest

To the military engineer concerned with problems of logistic support and of ground force operations on Guam, the climatic factors of chief interest are temperature and humidity, wind conditions, rainfall, and the nature and frequency of major storms, especially typhoons. Temperature and humidity are of practical concern because of their influence upon the deterioration of structures, equipment, and other materiel and upon the comfort and efficiency of troops. Wind conditions are of concern from many viewpoints, as, for example, in paratroop operations, in small boat operations, and, where very high winds are involved, in the damage they may produce and the hazards that they pose. Rainfall is a highly critical factor from the viewpoints of both water supply and flood hazard. Because of the violence of their winds, the torrential rains that they produce, and the "tidal waves" that they sometimes generate, typhoons are clearly of major practical concern.

These various factors -- temperature conditions, wind, humidity, rainfall, and storms -- are especially stressed in the remainder of this section. Also considered, though much more briefly, are air pressure, and illumination, insolation, cloudiness, ceilings, and visibility. In addition, such topics as deterioration of materiel and of troop efficiency are considered from a climatological point of view at appropriate places in the text, and the topic of microclimatic variations is treated separately at the end of the section.

Temperature Conditions

The major features of the temperature regime on Guam are illustrated by the data of Table 1, which presents mean and extreme temperatures by months and for the year at Sumay, Agana Navy Yard, and the Agricultural Experiment Station. From these data and from data for

Fena Reservoir (1954-56), Harmon Field (1945-49), Naval Air Station Agana (1945-52), and Andersen AFB (Dec.1949-Nov.1954), it is possible to summarize the general characteristics of the temperature regime for the island as a whole and to indicate the nature and magnitude of geographic variations.

Throughout the island, the coolest period is January-February and the warmest is May-June. The temperature range between these periods is, however, less than 3° F. in terms of the average monthly temperature. This is far less than the mean diurnal temperature range, which averages at least 8° F. in all months at all stations for which data are available.

In areas on the coast or at elevations below about 80 feet near the coast, daytime temperatures are commonly between 83 and 88° during the warmest part of the afternoon and in the middle seventies during the coolest part of the night (just before dawn). In extreme instances, however, maximum daily temperatures are in the middle to high nineties and nighttime temperatures fall to 65 to 70°. For localities on or near the coast, the greatest extremes of record are 100°, at the Agricultural Experiment Station during February, and 64°, at Sumay, also in February.

On the northern plateau, both maximum and minimum temperatures are about 2° lower than at low elevations near the coast. During a 4 1/2-year period, 93° was the extreme high temperature observed at Harmon Field, while at Andersen AFB there were only two readings of 90° or over during a 5-year period. At the other extreme, a minimum temperature of 62 to 63° has been observed at Harmon Field; while at Andersen AFB there have been 8 instances of minima of 69° or below. (The values cannot be defined more precisely because of the manner in which they were tabulated.)

The lowest temperatures of all on Guam occur near and at the summits of the highest mountain peaks. In these locations there are occasional minimum temperatures of 55 to 59°, and minima of 60 to 64° are common. Obversely, maximum temperatures would not be expected to exceed 87 to 88° and usually lie between 80 and 85°.

During the dry season with moderate to strong tradewinds blowing, east coast localities tend to be 2 or 3° cooler than west coast ones, especially during the afternoon. At all times of the year there are minor temperature variations from place to place associated with local variations in cloudiness. Similarly, the precise variations in temperature throughout the day at any one locality is certain to reflect diurnal variations in cloud cover.

(The temperature values shown in Table 1 and the values used in the preceding discussion all refer to temperature in the shade at a height of about 5 feet above the ground).

Humidity

The very high humidity of the air that passes across Guam is well illustrated by the relative humidity values for the Naval Air Station, shown in Table 2. As is evident from that table, the relative humidity commonly exceeds 84 percent during the nighttime in all months of the year. Even during the warmest part of the day the average humidity is at least 66 percent in every month. Further, with humidity as with temperature, there is only a slight variation from one season to another. The dry season is only a little less humid than the wet season.

Even in the most extreme instances the relative humidity at the Naval Air Station has rarely dropped below 60 percent. Of the 54,000 hourly observations taken over a period of 5 3/4 years, only 1.4 percent were below 60 percent; and only 11 observations showed a relative humidity of less than 50 percent. No observations showed less than 40 percent. At the other extreme, 14.4 percent of the observations showed a relative humidity of 90 to 100 percent.

In terms of the mixing ratio, the moisture content of the air at Guam ranges from about 12 to 27 grams of water vapor per kilogram of dry air (from 85 to 200 grains per pound). About half the time the mixing ratio exceeds 19 grams/kg (133 grains/lb). These figures are based on Naval Air Station data.

High humidity in an area such as Guam, where temperatures are always moderately high, creates special military problems because of the difficulty of preventing the deterioration of goods and equipments and because of the effect of the climate on the efficiency and morale of the troops.

The list of the kinds of goods and equipments that are apt to deteriorate markedly on Guam includes "optical instruments, electrical equipment, tents, tarpaulins, and textile equipment, leather, natural and synthetic rubber, wool, silk, and synthetic fibers of the protein type, synthetic resins, paints, varnishes, asphalt, waxes, lubricants, and hydraulic fluids, and wood and wood products" (Wessel and Thom, 1954). Fungus, wood-boring pests such as termites, and corrosion are the chief agents of deterioration on Guam. Of these, the most widespread in their effect are the various fungi.

Warmth, high humidity, darkness, and poor ventilation all promote the growth of fungi. The rainy season is the season of maximum hazard not only because of the slightly higher humidity and the high rainfall totals, but also because of the low windspeeds. The climatic situation during the wet season is especially pernicious because nearly every night brings at least a few hours of very high relative humidity accompanied by calm or near-calm wind conditions. Under such circumstances, the usual nighttime lowering of temperature is ample to cause the condensation of moisture on the surface of goods and equipment that are not either ventilated artifically or protected by artificial heating, as in a hot locker.

Where metal goods are concerned, the chief hazard is corrosion, which is accelerated by warmth, high humidity, and the presence of salt particles in the air. Though the effects of direct salt-water spray are limited to coastal locations, the air at all localities is heavily laden with salt particles. To some extent these particles are deposited on exposed surfaces through the direct impact of the wind. It seems likely, however, that the chief deposition occurs under one of two circumstances. Light to moderate showers that are sufficiently intense to bring down great quantities of the salt particles that are nuclei for many of the raindrops, yet not so intense as to wash away nearly all of the deposited particles, probably cause considerable salt deposition; and even more deposition is probably caused through the condensation of water droplets directly upon exposed surfaces. Because both of these mechanisms are most frequent during the rainy season and because that season is also the time of slightly higher humidities and less continuous wind, the corrosion hazard is generally greater during the wet season than during the dry season.

The conditions of continuous warmth, high humidity, and low windspeeds that result in deterioration of goods and equipment also combine to produce climatic conditions that are often enervating for persons accustomed to cooler climates. So many variables have an influence upon the exact climatic limits of "zones of comfort", and the physiological and psychological relationships involved are so complex, that it is impossible to define precisely and quantitatively at just what point high temperatures, high humidity, and low windspeeds give rise to climatic conditions that seriously impair the morale or efficiency of troops. A few generalizations are, however, possible. chiefly on the basis of studies made by engineers concerned with air conditioning and by organizations (such as the Quartermaster Climatic Research Laboratory) which are concerned with the effects of different climates upon supplies, equipment, and men.

Standard comfort charts, such as those presented by Winslow and Harrington (1949, p. 107), make it clear that for still air conditions men working indoors in unventilated quarters on Guam would find it oppressively hot and uncomfortable the great majority of the time throughout the year. More specifically, all men not yet acclimatized would be acutely uncomfortable whenever the temperature was above 80°, the relative humidity was above 60 percent, and there was little or no air movement. Throughout the usual working day the air temperature is virtually always above 80° and the relative humidity is virtually always above 60 percent. Therefore, the chief variable is air movement. The distinctly higher windspeeds of the dry season make it the preferred season for comfort on Guam. Indeed, on most days during that season the majority of unacclimatized men would find the conditions indoors (with windows open to the breeze) tolerably comfortable. In contrast, the majority of unacclimatized men would find most days during the wet season to be distinctly uncomfortable, to such an extent that their efficiency would be markedly lowered.

With acclimatization, virtually all men would find conditions tolerably comfortable during the dry season and the majority would find conditions no more than marginally uncomfortable on those days of the wet season when there was little or no wind. Acclimatization involves metabolic and cardio-vascular changes that are nearly always completed within a few weeks and sometimes within only a few days, depending on the individual. There is no doubt, however, that a significant percentage of men -- perhaps around 10 percent -- will have their efficiency significantly lowered by the climate, especially during the wet season. A few individuals never adapt to a climate such as that of Guam, though whether such failure is wholly physiological is not definitely known.

Wind Conditions

The outstanding characteristic of the wind regime on Guam is the dominance of the tradewinds. Tradewind flow is dominant even during the period July through October, when winds from every direction are not uncommon. Tradewind flow is especially pronounced and persistent during the dry season, from January through May. Then the winds blow from between the NE and ESE well over 90 percent of the time. The dominance of the trades is evident from Tables 3 and 4, which show wind direction frequencies by months at Sumay, Naval Air Station, and Harmon Field. The tables also show the greater variability in wind directions during the period July through October.

Except for very occasional tropical storms and typhoons that bring exceedingly highspeed winds, the greatest windspeeds usually occur under tradewind conditions. At the Naval Air Station, during a 5-year period, the windspeed was 21 knots (23.7 mph) or more 1.8 percent of the time during February, and of the 74 occurrences observed all were from between NE and SE. In August, when the winds are most variable, winds of 21 knots or more were observed 1 percent of the time, and of the 47 occurrences making up this percent 27 were from between NE and SE, while 9 more were from the SSE.

The foregoing example, with the windspeed data of Table 5, shows that except when there are tropical storms or typhoons, surface windspeeds are not excessive on Guam, but that winds of moderate speed are distinctly more common during the dry season than during the rainy season. The seasonal variations in windspeed are brought out even more strikingly when the frequency of calms is considered. Calms have been observed almost 20 percent of the time on the average during the rainy season, whereas during the dry season they have been observed only 5 or 6 percent of the time. The percentages by months appear in Table 5.

The diurnal wind regime is fully as pronounced as the seasonal regime. This is evident from the following tabulation for the Naval Air Station, which shows the percent of observations by windspeed groups for the periods of highest and lowest speeds:

Month	Hours	Mph: 1/ Knots:	0-2.9 0-2	2.9-8.6 3-7	8.7-14.4 8-12	14.5-29 13-20	>29 >21
February	1100-1600		1	6	37	51	5
	2000-0500		6	41	43	10	1
August	1100-1600		4	22	50	23	2
	2000-0600		22	55	18	3	1

The hourly time intervals shown above differ slightly from February to August because in August the low-wind period continues until 0600 whereas in February the windspeeds have begun to increase appreciably by 0600. This difference may be associated with the greater cloudiness in August, which may delay slightly the warming of the lowest air and so similarly delay an increase in windspeed. Certainly both in February and August, as in all months, the occurrence of highest windspeeds in the very late morning and the afternoon is the result of such heating, just as the occurrence of lowest speeds at night is the result of cooling of the air in the layers near the ground.

The extremely high winds produced by typhoons may occur at any time of the day or night. When a typhoon passes directly over the island or when its center is within a few miles of the island, winds of 100 mph are not unusual and steady winds of over 125 miles per hour have been observed. During such a situation the highest instantaneous windspeed ever observed was 156 mph, during the typhoon of March 25, 1923. There is no question, however, but that still higher instantaneous speeds were produced in one or more localities on Guam during this typhoon and in others as well. The subject of wind conditions during typhoons is discussed at greater length in the section on Storms.

1/ See footnote 3/, Table 5.

Rainfall

No aspect of the climate of Guam is of greater practical concern than rainfall. At one extreme, tremendous rains, especially those accompanying tropical storms or typhoons, may yield devastating floods over many sections of the island. At the other, the lack of appreciable rainfall for many consecutive weeks may induce such severe drought that acute water shortages develop. Even under conditions far less extreme than these, the variations in rainfall from day to day are of major concern in a water supply sense because despite its high average yearly rainfall, which everywhere exceeds 85 inches, Guam's water resources are heavily taxed even with its present peacetime population. And if this population were ever materially increased, as during an emergency, the problem of water supply would become decisively critical.

For the purposes of this study, the rainfall climate of Guam may be usefully discussed under four sub-topics: the general rainfall regime; rainfall variability; extreme rainfall intensities; and drought. Rainfall conditions during tropical storms and typhoons will be discussed under Storms.

General rainfall regime: The distribution of mean annual rainfall on Guam is shown in Figure 4. As is evident from that figure, the average rainfall varies from less than 90 inches in the vicinity of Apra Harbor to over 110 inches in the most mountainous section of the island. This geographic variation cannot be defined more precisely because although at least some rainfall data are available for more than 40 different locations on Guam, the records at nearly all of these locations are for periods of only a few years and furthermore are seldom concurrent and seldom uninterrupted. The only stations for which there are more than 10 years of reliable rainfall records are Sumay, with 41 years of record (1906-39; 1947-53); Agana Navy Yard, with 19 years (1915-1933); and the Agricultural Experiment Station with 14 years (1918-1931). The average annual rainfall values for these stations in these years are 86.5 inches at Sumay, 89.3 at Agana Navy Yard, and 93.8 at the Agricultural Experiment Station (see fig. 3 for locations).

The mean annual rainfall map of Figure 4 is approximate only, for it is based on data from 19 stations with only 4 to 8 years of concurrent records. It was necessary, therefore, to use interpolated values for one to four years at all but three of the stations and then to adjust all values to the long-term Sumay mean to compensate for the shortness of the eight-year period. More detailed information concerning construction of the map is carried in Figure 4.

The seasonal variations in rainfall are evident from Figures 5 and 6 and from Table 7. From Figure 6, which shows the median monthly rainfall at Sumay (as well as the extreme and quartile values), it is clear that the rainfall curve swings sharply upward between June and July, and sharply downward during November. November is rightfully included along with July-October in the rainy season only because ample rainfall is still received in November despite the distinct drop in total from October to November. In contrast, rainfall is not usually ample in the marginal month of December.

The maps of Figure 5 show the monthly distribution of rainfall in terms of the median, which is the middle rainfall value during the 8 years of record that were used. The maps represent the best estimates that could be made and the values shown by the isohyets (or obtained by interpolation between the isohyets) are certainly not in error by more than 20 percent and probably not in error by more than 10 to 15 percent. The important features of the maps are the geographic variations that they bring out and the marked quantitative contrast between the maps of the rainy season and those of the dry season. Also, as is clear from a comparison of the maps for February and August, in percentage terms there is usually far more variation in rainfall from one locality to another during the dry season than during the wet season. During the wet season there is almost always ample rainfall everywhere on Guam. During the dry season the rainfall is frequently barely ample in favored mountainous localities while at the same time it is decidedly inadequate in other areas. This assumes a definition of "ample" that calls for 4 to 6 inches of rainfall, or more, for such local requirements as sufficient catchment in open reservoirs to meet minimum household needs for potable water.

Table 6 shows the estimated median rainfall values by months for 22 locations. These are the data on which Figure 5 is based, but with certain values combined, as for the two Inarajan stations and the two Tamuning stations. The median values are most reliable for those stations having 6 or more years of actual (non-interpolated) records during the 8-year period. It is these values that were given the greatest weight in constructing the maps of Figure 5.

Seasonal variations in rainfall on Guam involve not only variations in monthly totals but also in the character of the rainfall and in its diurnal distribution. During the dry season, on virtually all days with rain the rainfall is received in the form of showers, which usually are very light (table 7). During the wet season, on about one-third of the days with rain the rainfall is of longer duration and is properly described as "steady rain". Also, as shown in Table 7, appreciable amounts of rain are much more frequent. Throughout the year, drizzle, the third kind of rainfall, is so rare as to be recorded on less than 1 percent of all rainfall days. These values are based on data from the Naval Air Station, but they apply in a general sense to all locations on Guam.

At all times of the year on Guam there is relatively little diurnal variation in the frequency of rainfall, judging from 5 2/3 years of hourly rainfall records at Andersen AFB. During the dry season the diurnal variations are not statistically significant. However, during the wet season, especially during August, there is somewhat more chance that rain will occur between 1500 and 1900 local standard time (150° E.) than at other times of the 24-hour day. For August, the mean rainfall frequency at hourly observation times between 1500 and 1900 averaged 16 percent, whereas for the remaining hours of the day the average was 12 percent and for no other period of 5 consecutive hours was it more than 13 percent. In this particular respect Guam differs markedly from most other islands in the tropical Pacific area, where there are pronounced diurnal variations in rainfall frequency at all seasons of the year.

Rainfall variability: There are wide variations from year to year in the rainfall of any particular month on Guam. Absolute and inter-quartile ranges of these variations at Sumay are shown in Figure 6. Variations of the same order of magnitude occur at all locations on the island.

By individual months, the widest swings in rainfall from one year to another occur during the wet season, especially from July through October. In part these extreme variations are associated with the relatively high frequency of typhoons during these months. A single typhoon may contribute 10 or more inches of rain within a 2 or 3 days period even though the center of the typhoon may not actually cross the island.

Though rainfall variability is not quantitatively very great during most of the dry season months, the variations that do occur are often extremely critical. Any month with less than 4 inches of rain must for practical purposes be deemed a dry month, as Mohr (1954) has shown with reference to the East Indies. It is significant, therefore, that in all five months of the dry season the rainfall has been less than 4 inches in more than half the years of record at Sumay. In the transition months of June and December, the rainfall has been below 4 inches in more than one-quarter of the years. In contrast, during its 41

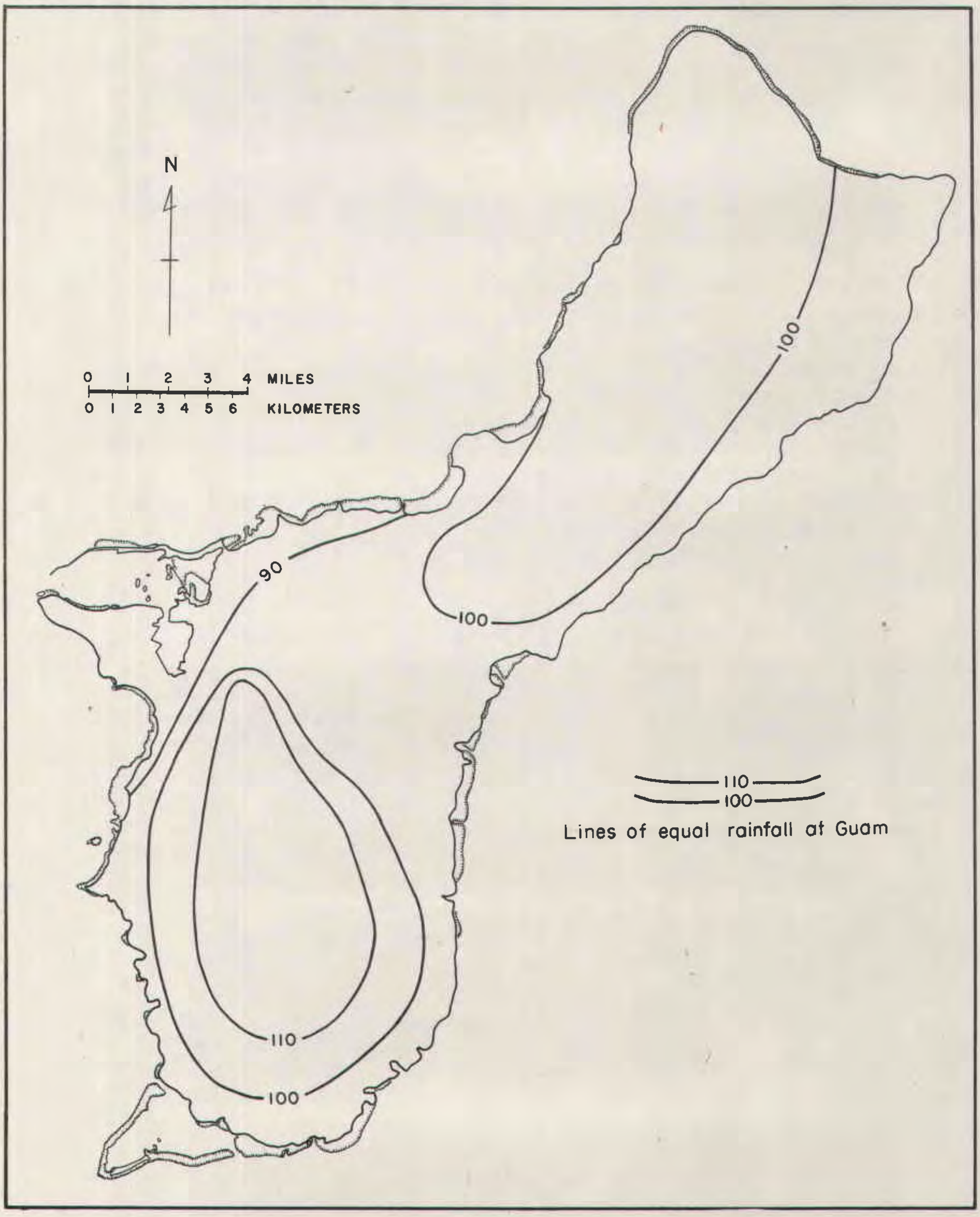


Figure 4. Mean annual rainfall at Guam.

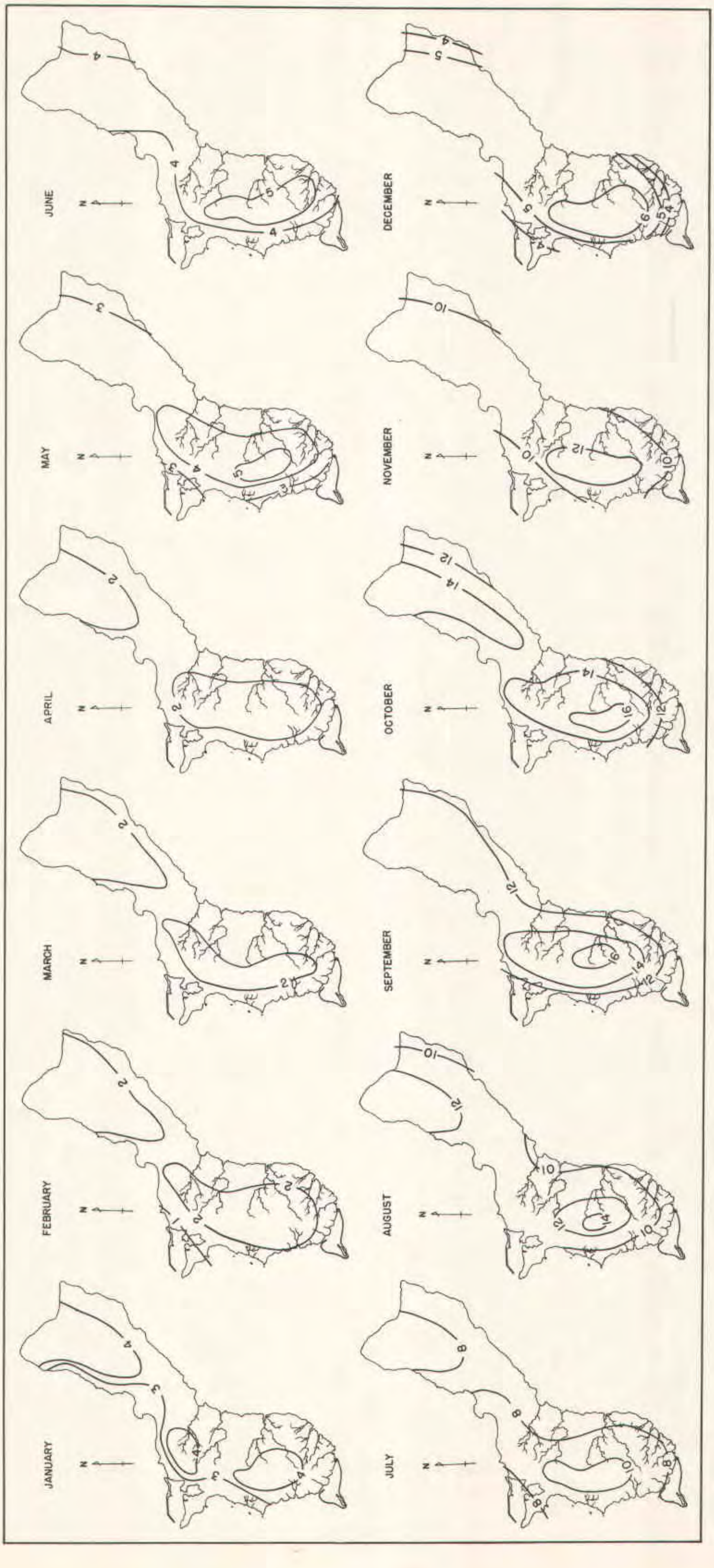


Figure 5. Median monthly rainfall at Guam (in inches).

years of record Sumay has received less than 4 inches of precipitation only once during July, September, October, and November; while in August the minimum value of record has been 5.8 inches (see fig. 6).

Rainfall variations from year to year are not perfectly synchronous throughout the island. Especially during the dry season, when the rainfall is chiefly in the form of local showers, one location may receive above-average rainfall in a particular month and some other location a few miles distant may receive distinctly less than average rainfall. The heavy and prolonged rains associated with typhoons, tropical storms, or with disturbances aloft do, however, affect all parts of the island even though the totals received are certain to differ greatly at times from place to place. Organized disturbances of this kind are, however, far more characteristic of the wet season than of the dry season (Jordan, 1955).

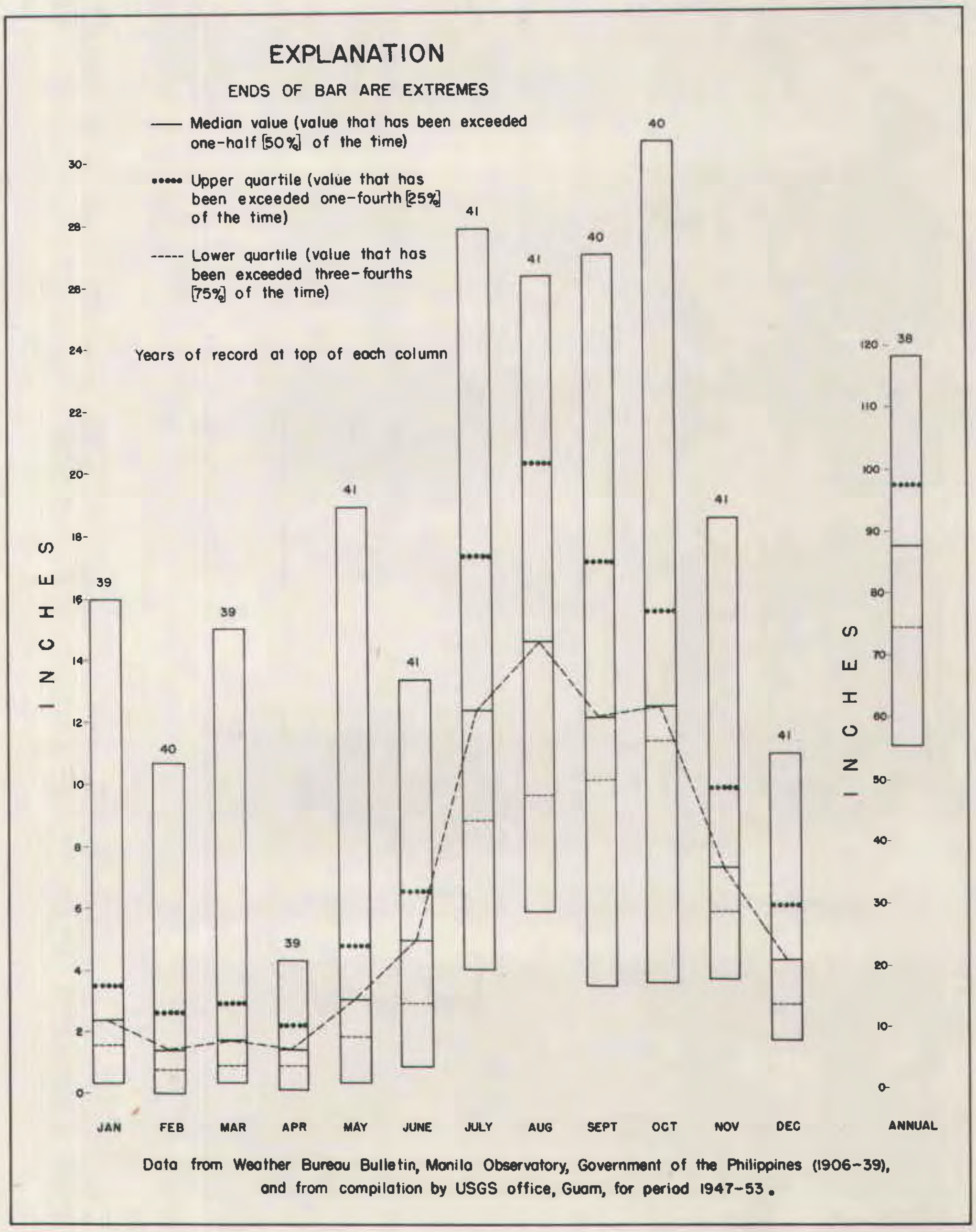


Figure 6. Monthly and annual rainfall variability for Sumay, Guam, 1906-1939 and 1947-1953.

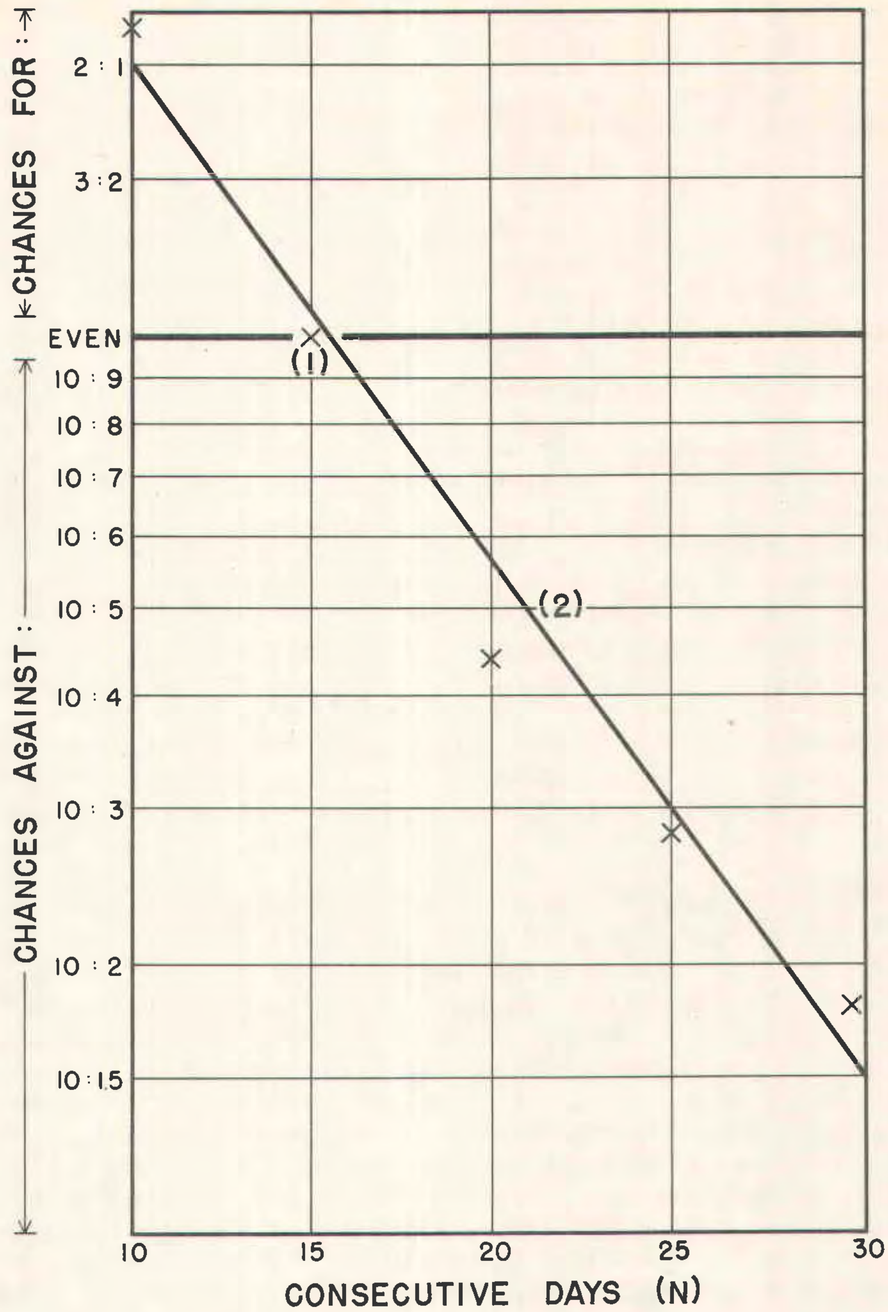


Figure 7. Chances during any given dry season of experiencing N or more consecutive days with no more than 0.09 inches of rain on any one day.

For this curve the dry season is defined as December through May and all droughts starting in the dry season are included.

EXAMPLE: (1) In any one year the chances are even that there will be a dry period (as defined) of 15 or more days, beginning sometime between December 1st and May 31st.

(2) The chances are 10:5 or 2:1 against a dry period of 21 or more days.

Based on data in Table 11, using mean frequency figures for Sumay, Naval Communications Station, and Fena River (Dam). Mean frequency values were cumulated and then reduced by one-third to give estimates of mean return periods and, hence, of chances.

Extreme rainfall intensities: Because Guam is subject to repeated invasions of very moist, unstable air during the rainy season and especially because it occasionally is within the zone of influence of a passing typhoon or tropical storm, extreme rainfall intensities are very high. In the entire continental United States, including Florida and the Gulf Coast with their occasional hurricanes, the highest 24-hour rainfall of record over a period of more than 100 years has been 26.12 inches, at Hoegess Camp, California, 22-23 January 1943 (Seamon and Bartlett, 1956). At New Orleans, which has experienced several hurricanes, the maximum 24-hour rainfall from 1889-1950 has been 14.01 inches (WB Tech. Paper 15, 1955). Yet at Umatac on Guam, during only a 9-year period, a rainfall of 26.0 inches was received in a single day during the typhoon of October 14-15, 1953. And the 2-day total at Umatac during this same typhoon was 48 inches.

The high intensity of extreme rains on Guam is further underscored by comparing the intensity-frequency values for Sumay with those for Miami, New Orleans, and Galveston, all of which lie in the zone of highest rainfall intensity in the continental United States. As is shown in Table 8, every 10 years on the average a daily rainfall of 9.1 inches or more may be expected at Sumay. Yet even though Sumay is in the zone of lowest rainfall intensity on Guam, this value is about the same as the 10-year values for Miami, New Orleans. and Galveston, which are 9.8, 9.6, and 8.6 inches, respectively. (WB Tech. Paper 25) It is reasonable to suppose that on the northern plateau and especially at exposed locations on the upper slopes of the mountains of southern Guam extreme rainfall intensities are at least 10 percent higher than at Sumay.

It is evident from the data of Tables 7 and 9 that rainfall intensities are distinctly higher at all locations from August through October than at any other time of the year and that intensities are lowest from February through April. Thus at the Naval Air Station Agana on 12 percent of the days during the period August-October the rainfall has exceeded 1 inch (on the average for the period of record); while during February-March it has exceeded 1 inches on not quite 2 percent of the days. Similarly, with the exception of one heavy rainfall day in March at the Agricultural Experiment Station, for 19 of the 22 stations of Table 9 the two highest daily values listed have occurred between August and October (inclusive); while for each of the remaining 3 stations of Table 9 the length of record is only 1 year, so that the values shown are not significant.

There are virtually no records available showing rainfall intensity values for periods shorter than a day. Those data that are available are summarized in Table 10. However, the records for the stations listed in Table 10 are only 6 to 12 months long, so that the only significance of the values is that they tend to support the reasonable view that short-time intensities, like those for daily periods, are at least as high as in the Gulf region of the United States. For New Orleans, the hourly rainfall intensity values are 2.1 inches for a return period of 2 years, 2.6 inches for 5 years, and 3.1 inches for 10 years. Guam values are probably about the same or very slightly higher.

Tables 8, 9, and 10 summarize all the data that was available on extreme rainfall intensities on Guam. In using the data of these tables, however, allowance must be made in most instances for the shortness of the period of record.

Drought: Drought is a normal feature of the climate of Guam. Severe drought is not unusual. The period of greatest drought hazard is February through April. However, it is possible any time between the first of December and the end of May to have an intense dry period of several weeks duration.

Table 11 shows the number of occurrences at three stations on Guam of successive periods of different length without as much as 0.1 inch rain on any one day during the dry period. Though the data of this table are based on only 8 to 10 years of record at each of the 3 stations, they show that dry periods of this degree of severity are somewhat more frequent in the Apra Harbor area, as represented by Sumay, than on the plateau or southern mountain areas, as represented by the Naval Communications Station and Fena River. The difference between the Sumay values and those for the other 2 stations is, however, partially due to the slightly different definitions used, as indicated in the footnotes to the table.

Figure 7 presents a curve showing the chances of experiencing N or more consecutive days with less than 0.1 inch of rain. This curve, which is for values of N of from 10 through 30, applies generally to all parts of Guam, since it is based on the combined data from Sumay, Naval Communications Station, and Fena River. Further, since less than 0.1 inch of rain cannot possibly contribute significantly to surface or underground water supplies anywhere on Guam, the curve in effect gives the chances of experiencing extreme drought.

So far as surface water supplies and crops are concerned, any month with less than 4 inches of rain may be termed a drought month. In these terms January, February, March, and April may be expected to be drought months 3 years out of 4 at Sumay (fig. 6); and February, March, and April may be expected to be drought months 3 years out of 4 at all locations on the island, even allowing for the higher rainfall in the plateau and mountain areas as compared to Sumay. Combining these rough probabilities, the chances are about 6 in 10 that at least two consecutive months during the period February through April will have less than 4 inches of rain each month and the chances are about 4 in 10 that all three months will have less than 4 inches each. Thus for many practical purposes, severe water shortages will often occur.

Storms

The storms that contribute markedly to the climatic character of Guam are of two principal kinds. On the one hand, there are small-scale storms, notably squalls and thunderstorms. On the other hand, there are large storm systems, notably tropical storms and typhoons. The small-scale storms are evanescent and at any one moment dominate the weather over areas of the order of 10 to 20 square miles. The large storm systems persist for many days or even 2 or 3 weeks and at any moment dominate the weather over areas of 100,000 square miles. The large systems are usually well defined moving systems, so that they dictate the weather conditions on Guam for a period of only a few days at most, after which they move to other regions.

Small-scale storms: Squalls may occur in the Guam area at any time of the year. Their frequency and character vary, however, from the dry to the wet season.

During the dry season it is usual on any day to have a few scattered squalls in the immediate vicinity of Guam (within 8 or 10 miles). These are small storms, perhaps 1 to 3 miles in diameter. They are embedded in the tradewinds and they move with the trades from east to west. Over the water they produce showers that may be quite intensive for a few minutes and they often yield gusty winds with momentary windspeeds in excess of 25 mph. When they move onto the land their gustiness usually decreases somewhat, especially inland from the immediate shore area.

During the wet season, especially on those frequent days when winds are light and variable, there are often scores of squalls over the waters immediately surrounding Guam. Sometimes these are distinguishable as individual squalls. Usually, however, the squalls are so numerous and closely spaced that they simply produce "squally weather" with frequent showers over wide areas of the sea. Winds are typically intermittent. The wind will suddenly spring up, will achieve a high gust velocity of 15 to 20 mph or so, and then will die out again. This process will be repeated again and again, often with marked variations in wind direction over distances of a few hundred yards. At the same time beneath the different squall clouds the rainfall will vary greatly in intensity. In one small area there may be extremely intense rain for 5 or 10 minutes while at the same time there may be only a light shower half a mile away in one direction and no rain at all half a mile away in another direction. Wet season squalls of this kind often drift onto Guam. When they do, the arrangement of clouds and rainfall becomes a little more regular because of the tendency for the squall clouds to mass along the mountain crests, where the most intense and prolonged rainfall is apt to occur.

During conditions of squally weather in the wet season, there are occasional well developed thunderstorms. In the vicinity of the Naval Air Station, thunderstorms have been reported on 1.4 percent of the days in July and on approximately 0.5 percent of the days in the other months of the wet season. For May and June they have been reported only 0.1 percent of the time and in all the remaining months of the year, from December through April, they have been reported only 4 times in 6 years. These percentages are approximately duplicated by data for Harmon Field, on the northern plateau.

Tropical storms and typhoons: Major tropical weather disturbances are commonly classified on the basis of their intensity in terms of the windspeeds that are produced and the surface air pressure associated with them. In these terms the most mild disturbance is a pressure wave that is not sufficiently pronounced to produce a closed storm system or to yield winds that are more than a few miles an hour greater than is average. Sometimes, however, pressure waves produce moderate to heavy rainfall over wide areas -- areas much larger than Guam. More pronounced than the pressure wave is the tropical depression, which can be recognized on the weather map as a closed pressure system but which still does not yield notably high winds even though, once again, excessive rainfall may result. Tropical storms are closed pressure systems about which the air moves counterclockwise in the northern hemisphere with windspeeds of from 33 to 65 knots (38 to 74.9 mph). Typhoons are similar to tropical storms, but are accompanied by winds of 65 knots or more. Both the tropical storm and the typhoon commonly yield very large amounts of rainfall.

Major tropical weather disturbances of these various kinds all occur at Guam. They are far more frequent during the rainy season than during the dry season, but have been known to occur in all months of the year. Because of their great intensity and the extreme winds, floods, and "tidal waves" that they often produce, typhoons are primarily stressed in this section. Some stress is placed also, however, on tropical storms and mention is made of major disturbances of lesser intensity.

Table 12 shows the frequency of typhoons, tropical storms, and "possible typhoons" passing within 120 nautical miles of Guam during the period 1924-53. During this 30-year period 43 storms that were definitely typhoons passed within this distance of Guam. If tropical storms and storms that were "possibly" typhoons are included, the total becomes 82. Taking the lower figure of a total of 43 typhoons in 30 years, the average figure for number of typhoons per year (within 120 miles) is 1.4. By actual count, however, during the 30 years in question there was one typhoon or more in only 18 of the 30 years, so the chances of there being one or more typhoons within 120 miles of Guam in any particular year are roughly 18 in 30 or 3 in 5. This rough probability, compared with the actual frequency, reflects the fact that during some years of the 30-year period there were 2 or more typhoons; and, indeed, in each of three years (1940, 1943, 1945) there were as many as 5. Such an extreme clustering of typhoon passages within a relatively small area (within 120 miles of Guam) in the same year is only moderately unusual, since sometimes one typhoon forms and moves virtually in the wake of another, and in general the kind of weather situation that favors typhoon formation in a certain wide region of the ocean and favors the movement of that typhoon through a particular broad zone across the ocean may persist for a period of several weeks.

The seven typhoons whose centers moved directly across Guam (table 12) occurred in six different years. (There were two square hits on Guam during 1941 -- in July and in September.) The chances are therefore roughly 6 in 30 or 1 in 5 that Guam will suffer a direct hit by a typhoon in any particular year. A typhoon can, however, be just as damaging to the island if its center passes within a few miles as if the center actually passes across the island. The center of the extremely destructive typhoon of November 3, 1940, only came very close to the island as did the more recent destructive typhoon of October 1953. Each of these was far more destructive than the typhoon of August 1953, whose center crossed Guam.

During the 44-year period 1898-1941, there were 17 seriously destructive typhoons at Guam during 13 years (Pacific Islands Engineers). Thus for purposes of rough estimation, the chances are a little less than 1 in 3 that there will be one or more seriously destructive typhoons in any particular year. Less destructive typhoons, producing such consequences as heavy rains, minor flooding, and minor wind damage can, however, be expected to be at least as frequent. This would give a chance of about 2 in 3 of experiencing in any particular year one or more typhoons that were either seriously or mildly destructive -- a chance figure that is in keeping with the roughly 2 in 3 chance estimated above of having a typhoon center pass within 120 miles of Guam.

The likelihood of typhoons is greatest during the three months of July through September, least during the four months of January through April, and intermediate in May-June and November-December. Although Table 12 shows no typhoons passing within 120 miles of Guam in April during the years 1924-53, there is at least a slight chance of experiencing a typhoon in April as well as in every other month of the year.

There are seasonal variations in the character of typhoons in the

Guam area as well as in their frequency. The typhoons of January through May are usually small and intense, with highspeed winds, in excess of 75 mph, extending outward only 25 to 50 miles from their centers. The typhoons of December, and of May, June, and July are somewhat larger, often with highspeed winds at distances of 50 to 75 miles from their centers. Those of August, September, October, and November are usually the largest and most intense of all. Their highspeed winds may reach outward 100 miles and windspeeds near their centers tend to be higher than those of the typhoons of other months. Typhoons of this period not uncommonly carry sustained windspeeds of 150 mph in their inner core, within 25 miles of the center of the storm. For all typhoons in the northern hemisphere, windspeeds are greatest on the right-hand side of the storm, the right-hand side being defined with reference to an observer facing the direction toward which the typhoon is moving.

One of the major hazards of a typhoon is that it may sweep water onshore and so produce a "tidal wave". In any particular instance, the pattern of inundation on Guam is closely related to the direction in which the storm was moving and its direction from Guam at point of nearest approach or, if its center crossed Guam, its exact track across the island. As is shown in Figure 8, nearly all typhoons in the Guam area move either from east to west or from southeast to northwest. For storms with such movement, inundation will occur almost exclusively on the east and south coast for storms passing to the south or southwest and on the north and west coasts for storms passing to the north or northeast. When the center of a typhoon crosses Guam, inundations will occur on the right-hand side of the storm center along the coast of arrival and on the left-hand side of the storm center along the coast of departure. Thus a typhoon passing squarely across Guam from east to west will inundate the northeast and southwest coasts. Figure 8 presents a tabulation of the direction of movement of typhoons in the vicinity of Guam during the period 1924-53 and the direction of the typhoons from Guam at point of closest approach.

Even if there is no appreciable inundation of the coast in the sense that there is an actual rise in sea level, damage in beach areas is apt to be especially great because of unusually high surf. For example, during the typhoon of September 1946, Agat village suffered very heavy wave damage even though the rise in mean sea level was very slight, according to the report of Pacific Islands Engineers (June, 1948). The wave damage was especially severe at Agat because during the period of strongest winds the wind was directly onshore (from the west). In contrast, exposed beaches on the east coast experienced offshore winds and little wave damage was suffered.

The distribution of wind damage during the typhoon of September 1946, illustrates the importance of topography in determining where the windspeeds will be highest and damage accordingly the greatest. To quote from Pacific Islands Engineers (June, 1948):

> "The Asan Camp was considerably damaged. The camp faces a deep cut in the ridge through which Marine Drive passes. The increased velocity produced by funneling of the wind through this cut was sufficient to lift most of the buildings from their foundations."

> "Most of the native communities are located against hillsides which provide protection from the wind, or in other areas where they are sheltered by trees and vegetation. Such com-

munities received very little damage. On the other hand, Agat Village, located on the beach, was heavily damaged both by the wind and the sea."

In general the most vulnerable locations are exposed beaches and small bays, localities lying in saddles that are approximately parallel to the direction of very strong winds, hill tops, and relatively flat open areas unprotected by dense vegetation, such as are found 2 or 3 miles NNW of Inarajan and in many parts of the northern plateau.

Often the only extensive damage from a typhoon is that which results from heavy rains. This is especially true of typhoons whose centers do not approach within 30 or 40 miles of Guam. From the two reports of Pacific Islands Engineers (May and June 1948) and from rainfall data whose sources are shown in the footnote to Table 9, it is possible to cite a few examples of extreme typhoon rainfalls that have produced severe flood damage:

October 1924	19 inches in 15 hours; 28 inches in 30 hours; and 33 inches in 48 hours.
September 1946	16 inches in 2 days.

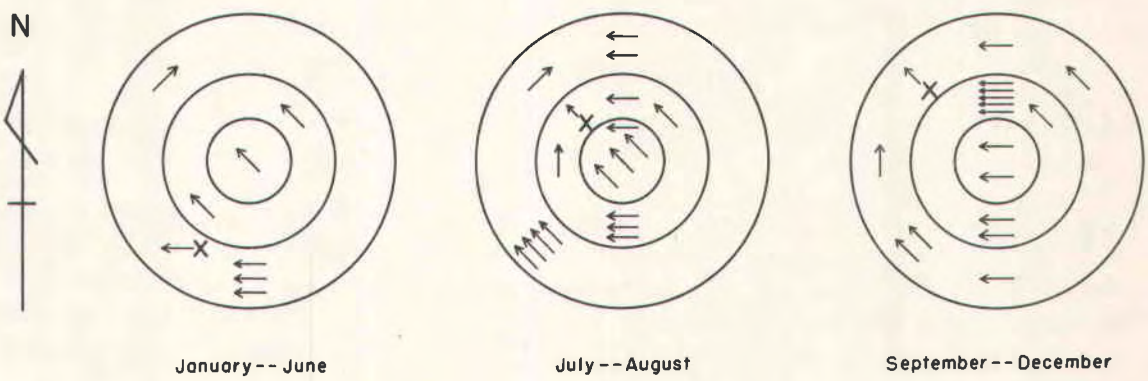


Figure 8. Typhoons in the vicinity of Guam, 1924-1953 1/

(Showing direction from Guam of each, and the direction of movement of each at time of closest approach to Guam.)

Each arrow represents a typhoon and shows direction of typhoon movement to nearest 1/8th point of the compass.

x indicates point of typhoon origin.

Inner circle contains arrows for typhoons crossing Guam; middle ring, for typhoons passing 1 to 60 nautical miles from Guam; and other ring, for typhoons passing 61 to 120 nautical miles from Guam. Within the two outer rings, the distance of the arrow from the center of the inner circle is not significant; the direction of the arrow from the center of the inner circle shows the direction from Guam, to the nearest 1/8th point of the compass.

1/ Compiled from Royal Met. Obs., Hong Kong, Charts of Typhoon Tracks.

August 1941	12 inches in 2 days.
August 1953	At least 7 inches in 2 days at each of 13 stations. Maximum for 2 days: 12 inches at Mt. Tenjo.
October 1953	18-48 inches in 2 days at 11 of 12 stations. At the twelfth (Inarajan) the total was only 5 inches. The maximum of 48 was at Umatac. Andersen AFB received 24; Fena River, 22.

The typhoon of October 1953 passed just to the north of Guam (center 13 miles to the north according to the Fleet Weather Central Typhoon Report, 1953). Thus the winds were northwesterly to westerly, which helps explain the maximum rainfall at Umatac on the windward side and the minimum at Inarajan, leeward of the mountains. The moist air that streamed upslope over Umatac thoroughly drenched that locality but produced comparatively little rain at Inarajan, on the downslope side of the mountain.

The rainfall amounts listed above were all for true typhoons (storms within which the windspeed was 65 knots or more). Tropical storms with maximum winds between 33 and 65 knots may also produce very heavy rains. Certainly rains of 3 to 5 inches in a day might readily result from the passage of a tropical storm, and rains of this intensity are sufficiently great to produce heavy local flooding. The impression given by Table 12 that tropical storms are far more unusual than typhoons is certainly not correct. Quite likely all or virtually all of the storms tallied under "possible typhoons" were tropical storms. This would make tropical storms about as frequent as typhoons, which is probably the case.

Moderately extreme rains of 2 to 4 inches in a day are often produced by a passing pressure wave or a tropical depression. However, neither of these kinds of storms produces anything like the torrential rains that are sometimes produced by typhoons or well developed tropical storms; and neither carries with it the danger of extremely high winds or waves.

Surface Air Pressure

The mean seasonal variation in air pressure at Sumay (elevation 61.4 feet) (see fig. 3 for station locations) ranges from a minimum of 1009.3 mb. (29.805 inches) in August to a maximum of 1012.1 mb. (29.887 inches) in February (after Clayton). For general purposes, mean surface air pressure on Guam may be reduced to sea level or to other elevations by applying a correction factor of 3.5 mb. (0.103 inch) per 100 feet of elevation. When these factors are applied to the Sumay values, the approximate seasonal pressure variations at sea level and at the Naval Air Station (elevation 245 feet) are as follows:

Sea level -- 1011.4 to 1014.2 mb. (29.868 to 29.950 inches)
Naval Air Station -- 1002.8 to 1005.6 mb. (29.616 to 29.698 inches)

In making precise barometric corrections to sea level or to other elevations at any particular observational time it is not possible to use the general corrections just cited. Instead, correction must be made for a variety of factors, especially temperature (List, 1951, pp. 203 ff.).

Diurnal variations in air pressure at Guam are of the same order of magnitude as seasonal variations. During the dry season the mean diurnal range is about 4 mb. (0.12 inch); during the wet season, about 2.5 mb. (0.07 inch). The highest daily air pressure usually occurs about 10 a.m.; the lowest, about 4 p.m. There is a secondary daily maximum about 10 p.m. and a secondary minimum about 4 a.m.

Some notion of the actual frequencies of different surface air pressures is provided by data from Andersen AFB for a 5-year period. When these data are reduced to sea level following the approximate procedure noted above, 98.6 percent of the values lie between 995.8 and 1013.7 mb. (29.41 and 29.93 inches); 1.4 percent lie between 1013.8 and 1031.8 mb. (29.94 and 30.47 inches); and only 13 of over 23,000 observations give air pressures equivalent to sea level values of below 995.8 mb. The lowest value of all was below 978.1 mb.

Sea level pressures of below 1,000 mb. occur only with a tropical storm or typhoon somewhere in the vicinity of Guam. The lowest surface air pressure of record is 954.0 mb. (28.17 inches), on July 6, 1918, during a typhoon. It is not known if this pressure, which was observed either at Sumay or the Agana Navy Yard, represents the direct station reading or the station reading after reduction to sea level.

Illumination Regime and Insolation

The period between sunrise and sunset on Guam ranges from 12 hours and 56 minutes, at the summer solstice on June 21, to 11 hours and 19 minutes at the winter solstice, December 22-23. Throughout the year, the duration of civil twilight is almost constant, varying from 22 to 24 minutes. This increases the length of the daylight period by 44 to 48 minutes, which provides a period of over 12 hours in late December and over 13 1/2 hours in late June with sufficient illumination to pursue nearly all outdoor work without the need for artificial illumination.

The mean figures just given do not take into account the shadowing effect of the mountains on Guam. Therefore the period of "broad daylight" may be shortened by an hour or so in localities where rising or setting sun is totally obscured by mountains or hills.

Because of the great cloudiness, it is very unusual on Guam to experience bright sunlight, with the sun unobscured, for more than 30 or 40 minutes consecutively. On many days, especially during the wet season, the sun is not visible at all; and cloudless skies are exceedingly rare at all times of the year (table 13).

At the latitude of Guam, the solar radiation at the outer limits of the atmosphere varies from a maximum of about 900 gram-calories/day around the first of May to a minimum of about 700 at the winter solstice. Not quite 900 gram-calories are also received around August first. This secondary maximum results from the fact that both length of day and solar declination influence the amount of incoming solar radiation and the declination is 13 1/2° N. (the latitude of Guam) both in late April and in mid-August.

The great cloudiness at Guam and the high amounts of water vapor present in the atmosphere, even on relatively cloudless days, result in considerably more reflection and absorption of the incoming solar radiation than is usual at most places in the world. It is doubtful that more than 675 gram-calories/sq.cm./day ever reach the ground surface on Guam and certainly on many days the total is less than 450 around the time of the winter solstice and less than 550 during the period April-August.

Cloudiness, Ceiling, and Visibility

The average cloud cover in tenths of the total sky-dome varies from a minimum of 6.8 tenths during the period January-March to a maximum of 8.0 during July-September. These values, which are derived from observations at Sumay, are in keeping with the more detailed monthly values of Table 13, which presents sky-cover values for Harmon Field and the Naval Air Station.

In contrast, January is the month of most favorable ceiling conditions; ceilings below 1,050 feet occur less than 2 percent of the time and ceilings above 9,750 feet more than 75 percent of the time. These somewhat more favorable ceiling conditions are generally characteristic of the period December through May.

Just as ceiling conditions are generally excellent on Guam, so also are visibility conditions. Even during August, when conditions are least favorable, the visibility at both Harmon Field and Naval Air Station exceeds 6 miles 92 percent of the time. In January, which is the most favorable month, it exceeds 6 miles 96 percent of the time. In all months either the ceiling is over 2,000 feet or the visibility is over 3 miles at least 98 percent of the time. It is therefore almost certain at all times of the year that aircraft aided by ground control devices can land safely.

The excellent ceiling and visibility conditions at all locations on Guam except, perhaps, at the highest mountain peaks is in keeping with the high cloud cover only because of the frequent occurrence of middle- and high-level clouds at altitudes of 8,000 feet and more. At all times of the year the sky is often partially or wholly covered with high-level cirrus clouds and middle-level stratus or cumulus with only scattered to broken cloud layers at lower altitudes.

Microclimatic Contrasts

The influence of elevation and exposure upon air temperature, cloudiness, and rainfall from place to place on Guam have already been discussed. It may be useful, however, to mention two additional aspects of microclimatic variations, particularly with reference to still finer-scale contrasts.

With moderate to fresh trades (12 to 24 mph), temperature differences from place to place are minimized. Then even on a day with considerable sunshine, such normally effective heating surfaces as a runway or barren soil produce little or no effective local heating. Temperatures above such surfaces are within 1 or at most 2 degrees of being the same as above vegetated surfaces. This conclusion is based on detailed measurements made on Tinian on two days during April 1957; but the results doubtless apply to Guam as well. (On Tinian, a much smaller island, no measureable heating effect was evident.) However, on days when winds are light or absent, local temperature contrasts of 5° or more often develop even where the contrast is between localities at the same elevation. Under these circumstances, the contrasts are greatest at night, with lowest temperatures in open fields and areas of barren ground or pavement. There are, however, appreciable differences in the daytime as well, especially along the coast where the temperatures usually increase 3 or 4° within a mile of the ocean.

Contrasts in humidity are also related to wind conditions. Within dense stands of vegetation the humidity is nearly always at least 10 percent higher than in more open areas, as at the Naval Air Station or Andersen AFB. The difference becomes the greatest, however, with moderate to fresh winds, for then the air in open locations is continually swept away and replaced by drier air while the air trapped among dense vegetation is replenished relatively slowly if at all. These differences in natural ventilation are important from the viewpoint of storage of materiel that is subject to mildew or corrosion.

Table 1. Mean and extreme monthly temperatures: Sumay, Agana Navy Yard, and Agricultural Experiment Station 1/

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	ANNUAL	Years of record
SUMAY														
Mean	79.2	79.2	80.2	81.5	82.3	82.5	81.4	81.0	80.8	80.8	81.1	80.4	80.9	26
Mean maximum	83.5	84.2	85.3	86.9	87.8	88.2	86.4	86.2	86.0	85.6	85.6	84.6	85.8	26
Mean minimum	74.8	74.1	75.0	76.1	76.8	76.8	76.3	75.9	75.7	75.9	76.6	76.1	75.8	26
Extreme max.	89.0	93.0	90.0	92.0	94.0	94.0	92.0	91.0	91.0	91.0	90.0	92.0	94.0	26
Extreme min.	68.0	64.0	68.0	70.0	71.0	72.0	70.0	71.0	70.0	69.0	69.0	70.0	64.0	26
AGANA NAVY YARD														
Mean	85.9	86.4	86.3	88.2	88.6	88.1	87.1	87.3	87.5	87.0	88.1	87.0	87.4	14
Mean maximum	94.4	95.3	96.0	95.1	98.0	96.1	96.5	96.8	97.1	98.1	97.4	96.4	96.4	14
Mean minimum	68.7	66.7	68.0	69.6	71.5	71.3	72.7	73.1	72.9	72.9	72.0	70.3	70.8	14
Extreme max.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Extreme min.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AGR. EXP. ST.														
Mean	81.0	81.0	81.0	82.0	82.0	82.0	81.0	81.0	81.0	81.0	82.0	81.0	81.0	15
Mean maximum	86.0	87.0	87.0	88.0	88.0	88.0	87.0	86.0	87.0	87.0	88.0	87.0	87.0	15
Mean minimum	75.0	74.0	75.0	76.0	77.0	77.0	76.0	76.0	76.0	76.0	76.0	76.0	76.0	15
Extreme max.	92.0	100.0	96.0	96.0	99.0	93.0	98.0	93.0	93.0	97.0	95.0	98.0	100.0	15
Extreme min.	65.0	68.0	69.0	70.0	71.0	72.0	68.0	69.0	69.0	64.0	69.0	68.0	64.0	15

1/ Data from U.S. Joint Army-Navy Study of Mariana Islands (JANIS No. 102) and U.S. Navy, Weather Summary for H. O. Publ. 273, both as quoted in Historical Review of the Meteorology of Guam, Pacific Islands Engineers, 1948.

Table 2. Diurnal variations in humidity at Naval Air Station as whown by mean maximum and mean minimum relative humidities and their times of occurrence 1/

Month	Mean Maximum and Time of Occurrence 2/	Mean Minimum and Time of Occurrence 2/
January	85% -- 0100-0600	71% -- 1200-1500
February	85% -- 0300-0500	66% -- 1300
March	85% -- 0300-0600	66% -- 1200-1500
April	84% -- 0200-0600	66% -- 1300-1400
May	86% -- 0200-0600	69% -- 1200-1400
June	86% -- 0300-0600	69% -- 1300-1400
July	88% -- 0400-0600	71% -- 1200
August	89% -- 0400-0600	74% -- 1400-1500
September	89% -- 0500-0600	75% -- 1200-1300
October	89% -- 0500	75% -- 1100
November	87% -- 0200-0600	73% -- 1400
December	86% -- 0100	71% -- 1400

1/ Chief of Naval Operations, Aerology Branch, Summary of Monthly Aerological Records, Guam, NAS, covering the periods 9/45-2/46 and 5/47-12/52.

2/ Standard time, 150° E. longitude.

Table 3. Wind direction frequencies (in percent) at Sumay 1/

Month	N	NE	E	SE	S	SW	W	NW	Calm
January	4	79	15	1	1	0	0	0	0
February	5	72	17	3	1	0	0	1	1
March	5	65	27	2	1	0	0	0	0
April	2	52	36	5	2	0	0	1	2
May	3	44	33	8	3	2	1	1	5
June	4	30	39	9	3	4	2	1	8
July	3	19	21	20	15	9	4	3	6
August	5	19	11	14	17	19	6	4	5
September	6	19	12	8	13	19	9	6	8
October	6	30	16	13	12	8	5	3	7
November	4	53	28	8	2	1	1	1	2
December	1	72	20	4	2	1	0	0	0
ANNUAL	4	46	23	8	6	5	2	2	4

1/ After U.S. Navy; Weather Summary for H.O. 273, Naval Air Pilot, 1943, as quoted in Historical Review of the Meteorology of Guam, Pacific Islands Engineers, 1948.

Table 4. Wind direction frequencies (in percent) at Naval Air Station and Harmon Field 1/

Month	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
								NAVAL AIR STATION									
January	*	*	9	27	31	20	7	1	1	*	*	*	0	0	0	*	2
February	*	1	11	26	36	16	3	*	1	*	*	*	*	*	*	*	3
March	1	1	8	21	35	22	7	1	*	*	*	0	*	*	*	*	4
April	*	*	3	14	40	24	10	2	2	*	*	0	*	*	1	*	2
May	*	*	2	8	31	32	16	4	1	*	*	0	*	*	*	*	4
June	*	*	1	7	28	37	17	2	1	*	0	*	*	*	*	*	6
July	1	1	3	5	17	20	19	6	5	1	1	*	1	*	1	*	13
August	1	1	3	5	14	16	17	7	8	2	3	2	3	1	1	1	15
September	3	2	5	5	11	12	14	7	8	3	2	1	2	1	2	1	21
October	3	2	5	6	16	12	13	6	8	3	3	1	1	1	3	1	16
November	2	3	10	13	28	17	10	5	3	*	*	*	*	*	*	*	6
December	*	1	10	24	36	17	7	2	1	*	0	*	*	*	*	*	3
ANNUAL	1	1	6	13	26	20	12	4	3	1	1	*	1	*	1	*	9
								HARMON FIELD									
January	*	*	1	23	41	19	5	1	1	*	0	0	0	0	0	0	9
February	*	1	6	26	47	10	2	*	*	*	*	*	*	0	*	0	8
March	0	*	1	14	65	12	2	*	*	0	0	0	*	0	*	0	5
April	*	*	1	8	54	28	3	1	*	0	*	0	*	*	1	*	4
May	0	0	*	5	49	32	8	1	1	*	0	0	0	0	0	0	3
June	*	*	*	6	41	33	10	2	1	*	*	0	*	0	0	0	6
July	*	*	3	5	26	16	11	4	7	3	4	2	4	1	2	*	13
August	1	1	2	4	19	13	14	3	4	5	6	3	4	1	4	1	17
September	2	2	4	3	11	10	13	5	6	6	5	3	3	1	4	2	22
October	1	1	4	6	16	11	8	3	6	5	5	3	3	2	3	2	22
November	*	1	4	13	35	15	6	3	3	1	1	*	*	1	1	1	15
December	*	*	2	25	50	11	3	*	*	*	0	0	0	0	0	0	8
ANNUAL	1	1	3	11	35	16	8	2	3	2	2	1	2	1	1	1	12

* Less than 0.5%, but more than 0%.

1/ Sources: Chief of Naval Operations, Aerology Branch, Summary of Monthly Aerological Records, Guam, NAS, 9/45 thru 2/46 and 5/47 thru 12/52; Dept. of the Air Force, Air Weather Service, Uniform Summary of Surface Weather Observations, Guam, Harmon Field, 7/45 thru 9/49 less 1/46-6/46, 5/58. Hourly obs. at both stations.

Table 5. Percentage frequency of occurrence of surface winds, by windspeed groups

HARMON FIELD 1/

Windspeed Mph:	Calm	1-3	4-12	13-24	25-31	32-46	>46
Month							
January	9	4	59	27	1	**	**
February	8	9	58	25	1	**	**
March	5	8	63	24	*	**	**
April	4	5	69	22	**	**	**
May	3	8	70	18	*	**	**
June	6	9	68	18	*	**	**
July	13	18	62	7	*	**	**
August	17	17	57	8	*	**	**
September	22	16	56	6	*	*	*
October	22	13	60	5	*	**	**
November	15	10	58	17	*	*	**
December	8	6	58	26	1	*	**
ANNUAL	12	11	61	16	*	**	**

NAVAL AIR STATION 2/

Windspeed							
Mph: 3/	<3.5	3.5-8.6	8.7-14.4	14.5-23.6	23.7-35.1	35.2-46.6	>46.6
Knots:	<3	3-7	8-12	13-20	21-30	31-40	>40
Month							
January	2	23	47	26	3	0	***
February	4	26	43	26	2	0	0
March	4	28	45	21	1	0	0
April	3	25	47	25	1	0	0
May	4	26	42	25	3	*	0
June	7	32	43	17	1	***	0
July	18	41	30	10	1	***	0
August	15	43	31	10	1	***	***
September	21	45	28	6	*	0	***
October	16	46	30	8	*	0	***
November	6	36	37	17	4	*	***
December	3	25	45	24	3	*	0
ANNUAL	9	33	39	18	2	*	***

* Between 0.1 and 0.4% (inclusive).
** Less than 0.1%, including 0%.
*** Less than 0.1% but more than 0%.

1/ Dept. of Air Force, Air Weather Service, Uniform Summary of Surface Weather Observations, Guam, Harmon Field, covering period of 7/45-9/49 (incl.); less 1/46-6/46, 5/48 (hourly observations).

2/ Chief of Naval Operations, Aerology Branch, Summary of Monthly Aerological Records, Guam, NAS, covering period 9/45-2/46 and 5/47-12/52 (hourly observations).

3/ Ranges of mph windspeed groups include midpoints between adjacent knot windspeed groups. For example, 8.7-14.4 mph includes 7.5-12.5 knots.

Table 6. Estimated monthly median rainfall for 22 stations on Guam 1/
(for the periods July 1947 thru December 1950, and January 1952 thru June 1956)
(Upper figure gives median in inches; lower figure shows number of years of actual record.)

Station	Elevation (in ft)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
ADELUP POINT (7) 2/	30	-	-	-	-	-	-	6.6 4	12.0 4	12.9 4	14.6 4	8.4 4	4.4 4
ADELUP RESERVOIR (10)	250	2.4 5	1.4 5	1.9 5	1.6 5	3.7 5	3.0 5	8.5 4	10.5 4	15.2 4	14.2 4	9.1 4	4.4 4
AGANA SPRINGS (11)	10	3.3 5	2.1 5	2.2 5	1.6 5	5.3 5	3.6 5	8.5 4	11.1 4	11.8 4	12.6 4	13.0 4	5.6 4
AGRICULTURE DEPT. (14)	200 3/	3.5 8	2.0 8	1.9 8	1.8 8	3.4 8	4.1 8	6.7 8	12.7 8	11.8 8	16.2 8	11.3 8	5.4 8
ALMAGOSA (23)	700 3/	4.3 8	2.9 8	2.6 8	2.4 8	5.5 8	5.9 8	10.2 8	14.0 8	14.5 8	17.5 7	10.1 7	6.6 7
ANDERSEN AFB (1)	520	3.6 7	3.2 7	2.4 7	1.7 7	2.8 8	3.3 8	7.5 8	10.3 8	13.9 8	12.0 8	9.5 7	4.9 7
APRA HEIGHTS (19)	280 3/	3.5 5	2.0 5	2.5 5	2.3 5	4.8 5	5.6 5	12.1 6	11.7 6	12.7 6	14.0 6	13.5 5	7.0 5
B.P.M. CAMP 2 (17)	280 3/	4.4 5	1.9 5	2.3 5	3.5 5	3.9 5	4.8 5	8.1 5	11.9 5	15.5 5	16.8 5	-	-
CAMP DEALY (24)	30 3/	-	-	-	-	-	-	7.9 4	11.2 4	12.5 4	14.4 4	10.7 4	5.2 4
NIMITZ HILL (13)	560 3/	5.1 7	1.4 7	1.9 7	1.9 7	4.0 7	3.6 7	6.6 7	11.9 7	15.4 7	16.1 7	11.7 7	5.4 7
FENA RIVER (DAM) (22)	50 3/	3.5 8	2.8 8	1.9 8	2.2 8	4.8 8	4.8 8	9.8 8	13.0 8	16.0 8	14.9 8	11.4 8	6.6 8
INARAJAN (22) (at Inarajan)	20 3/	-	-	-	-	-	-	7.7 4	7.1 4	8.9 4	9.6 4	9.7 4	3.6 4
INARAJAN (27) (3/4 mi. NW Inarajan)	100 3/	-	1.7 5	1.8 5	1.9 5	4.8 5	5.0 5	-	-	-	-	-	-

Table 6. (Concluded).

MAANOT (21)	395	2.8	2.2	1.5	2.2	4.1	5.2	6.0	11.1	-	-	12.6	5.6
		5	5	5	5	5	5	4	4			4	4
MT. TENJO (18)	880 3/	3.4	1.9	2.6	2.5	4.0	4.0	8.5	9.2	11.4	12.7	9.3	4.9
		7	7	7	7	7	7	8	8	8	8	8	8
NAVAL AIR STATION (5)	245	2.4	1.9	1.9	1.6	3.4	3.8	9.0	12.1	13.9	14.0	12.1	5.1
		6	6	6	6	7	7	6	6	6	6	6	6
NAVAL COMMUNICATIONS	340 3/	4.0	2.5	2.5	2.2	3.5	4.6	7.9	12.6	13.3	13.7	10.2	5.4
STATION (2a, 2b)		8	8	8	8	8	8	8	8	8	8	8	8
PAGO RIVER (16a, 16b)	90 3/	4.4	2.3	2.2	2.0	4.1	4.7	8.0	9.6	13.6	7.3	11.4	6.0
		5	5	5	5	5	5	4	4	4	4	4	4
SUMAY (15)	61	2.4	0.9	1.3	1.6	2.7	5.3	8.0	11.3	11.4	12.6	8.4	3.5
		5	5	5	5	5	5	6	6	6	6	6	6
TAMUNING	35 3/	-	-	-	-	-	-	9.1	10.2	13.2	12.3	10.4	6.2
(ACEORP) (6)								5	5	4	4	5	5
TAMUNING	30 3/	2.8	1.5	1.6	1.4	3.0	3.5	9.4	10.9	-	-	10.4	7.0
(USGS)		5	4	4	4	4	4	4	4			4	4
UMATAC 4/ (26a, 26b)	20 3/	3.5	2.2	1.4	2.0	2.7	2.2	9.5	9.4	11.4	13.5	10.6	6.1
		8	8	8	8	8	8	8	8	8	8	8	8

1/ Where the full 8 years of records were not available, medians were computed by using interpolated monthly values for the missing years provided there were at least 4 years of actual records. Each missing monthly value was computed on a proportionate basis following the equation: $T_X/T_C = S_X/S_C$ where T_X was the missing monthly total, T_C was the mean total for the same month for five "control" stations, S_X was the sum of the actual recorded values for the month in question at the station in question, and S_C was the mean sum for the same years for the control stations. The 5 control stations were Almagosa, Fena River, Naval Communications Station, Nimitz Hill, and Umatac.

2/ Location numbers on Figure 3.

3/ Estimated elevation.

4/ Based on combined record at two nearby locations at about the same elevation.

\- Less than 4 years of record, hence median not computed.

Table 7. Percent of days with specified amounts of rainfall at Naval Air Station 1/
September 1945-February 1946; May 1947-June 1952;
and September 1952-December 1952.

Daily Amount (in inches)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	ANNUAL
0	31	46	43	45	41	34	23	12	24	21	28	21	30
T*- 0.05	23	26	28	26	23	22	20	15	15	15	18	24	21
0.06-0.10	11	12	7	8	9	10	10	8	9	6	9	14	9
0.11-0.50	28	14	19	17	20	27	34	38	28	31	28	35	27
0.51-1.00	4	*		3	4	4	8	16	11	15	8	3	7
1.01-2.00	*	2	2	0	2	2	4	10	10	6	7	1	4
2.00-5.00	1	0	0	1	1	1	1	1	3	5	2	1	2
>5.00	0	0	0	0	0	0	0	0	*	*	0	0	*

* Trace amount.

1/ From Chief of Naval Operations, Aerology Branch, NAS.

Table 8. Daily rainfall amounts equaled or exceeded for mean return periods, at Sumay 1/

Mean Return Period (years)	Daily Rainfall (inches)
10	9.1 or more
6	6.4 or more
5	5.9 or more
3	4.9 or more
2	4.5 or more
1 1/2	4.2 or more
1	3.5 or more

1/ Based on analysis of daily records. Estimates made by taking the n year (return period) value as that exceeded in (2n + 1) years (see Brooks and Carruthers, p. 135).

Table 9. Maximum daily rainfall (by months) at 22 stations on Guam 1/

(Upper figure shows number of years of record; lower shows maximum rainfall in inches.)

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	ANNUAL
					ADELUP RESERVOIR							
5	5	5	5	5	5	5	5	5	6	6	6	
1.5	4.0	*	*	1.7	2.1	2.2	6.6	9.4	10.0	2.7	2.0	10.0
					AGANA SPRINGS							
5	5	5	5	5	5	5	5	5	5	6	6	
1.6	4.7	*	*	1.7	1.9	2.1	8.0	2.3	10.0	3.2	2.0	10.0
					AGRICULTURAL EXPERIMENT STATION							
9	9	9	9	9	9	9	9	9	9	9	9	
2.3	4.3	7.6	1.0	2.1	2.1	5.1	5.5	3.2	8.9	4.1	2.5	7.6
					AGRICULTURE DEPARTMENT (GOVERNMENT OF GUAM)							
5	5	6	5	6	5	6	5	6	5	5	5	
4.0	5.5	*	*	3.6	2.1	3.5	7.9	4.2	8.5	2.2	1.7	8.5
					AIMAGOSA							
1	1	1	1	1	1	1	1	1	1	1	1	
1.1	*	*	*	4.5	3.1	1.9	1.6	3.7	3.8	2.4	1.2	4.5
					ANDERSEN AIR FORCE BASE							
5	5	5	5	5	5	5	5	5	5	5	5	
**	2.6	**	**	3.7	**	**	7.1	4.2	18.3	4.9	2.7	18.3

Table 9
Continued

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	ANNUAL
APRA HEIGHTS													
	3 1.0	2 2.0	2 *	2 *	2 2.0	2 1.1	2 2.0	2 8.0	2 4.2	3 13.0	2 10.0	2 2.0	13.0
BARRIGADA													
	3 2.0	3 2.0	3 *	3 *	3 1.4	3 *	3 1.6	3 7.2	2 2.9	2 10.9	3 3.5	3 1.8	10.9
B. P. M. CAMP 2													
	2 *	2 *	2 *	3 2.3	4 4.2	4 2.9	5 2.3	5 4.4	4 3.5	5 7.0	4 5.5	2 1.5	7.0
FENA RIVER AND DAM													
	6 1.4	6 3.1	6 *	6 1.2	10 4.4	10 2.0	10 4.4	9 9.0	10 5.4	10 12.2	10 7.8	10 4.2	12.2
FLEET WEATHER CENTRAL													
	6 1.4	8 5.9	6 *	6 *	9 3.4	9 2.2	10 2.8	10 5.5	10 9.3	10 15.5	10 5.0	10 2.3	15.5
INARAJAN													
	6 2.0	5 *	4 *	4 *	7 2.0	7 2.3	8 2.0	8 8.6	8 2.3	8 4.0	8 4.6	8 2.7	8.6
LAMLAM													
	1 1.1	1 *	1 *	1 *	1 5.4	1 1.9	1 3.2	1 2.3	1 3.2	1 3.5	1 2.4	1 1.2	5.4

Table 9
Continued

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	ANNUAL
MAANOT													
	3	3	3	3	3	4	4	4	3	3	3	3	
	2.8	2.0	*	*	2.4	*	2.6	9.0	1.8	13.0	2.5	1.3	13.0
MERIZO													
	1	1	1	1	1	2	2	2				1	
	*	*	*	*	*	*	1.3	8.0				*	8.0
NAVAL COMMUNICATIONS STATION													
	8	8	6	6	10	9	10	10	10	10	10	10	
	3.3	2.3	1.1	1.2	5.5	2.5	3.2	8.7	2.8	13.3	4.9	2.1	13.3
PAULANA RIVER													
	3	1	1	1	4	4	4	4	4	4	4	4	
	2.3	*	1.0	*	3.0	2.5	2.5	2.3	4.4	9.3	6.5	2.7	9.3
PUBLIC WORKS CENTER													
	2	2	2	2	3	3	3	3	3	3	3	3	
	*	1.9	*	*	1.5	*	2.0	5.4	2.6	13.0	3.0	1.5	13.0
SUMAY													
	32	33	31	31	33	33	35	38	37	37	38	37	
	4.4	3.2	6.5	***	4.5	4.4	10.5	9.6	5.5	16.0	11.7	4.0	16.0
TAMUNING													
	2	1	2	2	2	1	3	2	2	2	2	2	
	*	*	*	*	*	1.7	2.0	2.5	3.8	7.8	2.3	2.6	7.8
UMATAC													
	5	6	5	6	9	9	10	10	10	9	10	10	
	*	1.1	1.8	*	2.1	2.1	3.0	4.1	4.2	26.0	6.0	4.0	26.0
YLIG													
	2	3	3	3	2	1	1	2	2	2	3	3	
	1.3	1.3	*	*	2.0	*	1.6	2.0	1.5	2.0	3.1	1.4	3.1

* = less than 1.0 inch   ** = less than 2.6 inches   *** = less than 3.0 inches

1/ Sources: For <u>Sumay</u>, 1905-39 (but not for 1947-49), Monthly Bulletin, Weather Bureau, Manila Observatory, Gov't of the Philippines. For <u>Andersen AFB</u>, November 1948 thru October 1953, a manuscript sheet headed, "ANDERSEN AFB PRECIPITATION DATA", with sub-head "A. Twenty highest 24-hour precipitation amounts". For <u>Agr. Exp. Station</u>, 1923-31, Historical Review of the Meteorology of Guam, by Pacific Island Engineers. For all other stations (and for Sumay for the period 1947-49), the data shown above were compiled from one or both of the following sources: H. E. Romine, Report on Recent Rainfall Observations at Guam, Mariana Islands, which gives daily rainfall values for the period 1947-49, and the monthly manuscript sheets tilted, "Rainfall Report for Guam", that have been compiled by the USGS, Guam, and that were available for the period 1950-1956. The years of record actually used in the compilation at the various stations were as follows: Adelup Reservoir, 1951-56; Agana Springs, 1951-56; Agriculture Department, 1950, 1952-56; Alamagosa, 1950; Apra Heights, 1950-53, Barrigada, 1951-54; BPM Camp 2, 1948-52; Fena River and Dam, 1947-56; Fleet Weather Central, 1947-50, 1952-56; Inarajan, 1947-55, Lamlam, 1950; Maanot, 1951-54; Merizo, 1952-53; Naval Communications Station, 1947-56; Paulana River, 1947-50; Public Works Center, 1951-53; Sumay, 1905-39, 1947-49; Tamuning, 1951-56; Umatac, 1947-56; and Ylig, 1952-56. For nearly all of these stations the records are broken within the periods listed.

Table 10. Maximum 2-hour, 4-hour, and 6-hour rainfall at selected stations 1/

Station	Period of Record 2/	2-hour Max. and Date (inches)	4-hour Max. and Date (inches)	6-hour Max. and Date (inches)
Almagosa	Aug-Dec 1950	2.3 10/2	3.2 10/2	4.1 9/6-7
Dobo Springs	Jan-July 1950	1.5 6/26	2.2 5/9	2.6 5/4-5
Fena River	Jan-Dec 1950	2.4 10/2	4.3 10/2	5.6 10/2
Mt. Lamlam	Jan-Dec 1950	2.0 10/2	3.0 10/2	3.2 5/9

1/ Values extracted from Computation Sheets (duplicated), Base Development Department, COMNAVMARIANAS.

2/ Months as given are inclusive.

Table 11. Total number of occurrences of N consecutive days with less than 0.1 inch of rain on any one day, at Sumay, Fena River (Dam), and Naval Communications Station

N Days	Month During Which Dry Period Began						Total December through May
	Dec	Jan	Feb	Mar	Apr	May	
SUMAY (1923 thru 1932) 1/							
10-14	3	2	2	3	4	3	17
15-19	1	2	4	3	2	2	14
20-24	0	1	2	4	1	0	8
25-29	0	1	1	1	0	0	3
30-34	0	0	0	0	1	0	1
35-39	0	0	0	0	0	0	0
40-44	1	0	0	0	0	0	1
FENA RIVER (DAM) (1949-56) 2/							
10-14	0	1	1	3	3	5	13
15-19	1	2	1	1	0	0	5
20-24	0	0	0	1	0	0	1
25-29	0	0	0	0	0	0	0
30-34	0	0	0	0	0	0	0
35-39	0	1	0	0	0	0	1
NAVAL COMMUNICATIONS STATION (1948-56) 2/							
10-14	3	3	3	4	2	3	18
15-19	0	0	0	0	0	2	2
20-24	0	0	1	1	0	0	2
25-29	0	1	0	0	0	0	1

1/ For Sumay, 3 mm (0.12 inch) of rain was taken as breaking a dry period, as the data were in mm units. The frequency totals given were taken from an analysis of daily records in the Monthly Bulletin, Manila Central Observatory, Weather Bureau, Government of the Philippines.

2/ For Fena River and Naval Communications Station, 0.10 inch was taken as breaking a dry period. For Fena River the exact period of records analyzed was 1947-1946 (inclusive) for December, and 1949-50, 1952-56 (inclusive) for January through April. For NCS the period was the same as for Fena River, except that January-April 1948 was included. For both stations data were from USGS manuscript sheets titled, "Rainfall Report for Guam".

Table 12. Frequency of typhoons, tropical storms, and "possible typhoons" in the vicinity of Guam, 1924-53 1/

Month	Storm Center Crossed Guam			Storm Center within 60 Miles of Guam 2/			Storm Center 60 to 120 Miles from Guam 2/			Monthly Total			
	Typhoon	Tropical storm	Probable typhoon	Typhoon	Tropical storm	Probable typhoon	Typhoon	Tropical storm	Probable typhoon	Typhoon	Tropical storm	Possible typhoon	All storms
January	0	0	0	0	0	0	1	0	0	1	0	0	1
February	0	0	0	1	0	0	0	0	0	1	0	0	1
March	1	0	0	0	0	0	1	0	0	2	0	0	2
April	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	1	0	0	2	0	0	3	0	0	3
June	0	0	0	0	0	0	1	0	0	1	0	0	1
July	3	0	0	2	0	1	4	0	4	9	0	5	14
August	1	1	1	5	0	3	3	0	4	9	1	8	18
September	2	0	0	2	1	4	4	0	3	8	1	7	16
October	0	0	1	2	0	3	1	0	6	3	0	10	13
November	0	0	1	3	2	1	1	0	2	4	2	4	10
December	0	0	0	1	0	0	1	0	1	2	0	1	3
Totals:	7	1	3	17	3	12	19	0	20	43	4	35	82
Grand Totals:		11			32			39					

2/ Nautical miles

1/ Compiled from Royal Met. Obs., Hong Kong, Charts of Typhoon Tracks

Table 13. Mean monthly frequency of different amounts of sky cover at Harmon Field and Naval Air Station (by months) 1/
(tenths of sky dome)

	0	1-2	3	4-5	6-7	8-9	10
HARMON FIELD							
January	*	7	7	17	16	17	36
February	1	9	9	24	21	20	17
March	*	6	6	20	25	20	23
April	*	7	10	23	22	19	19
May	1	7	9	20	21	18	25
June	2	8	10	19	23	19	20
July	*	3	5	12	15	23	41
August	*	3	3	12	16	21	45
September	*	1	2	9	15	27	45
October	*	3	4	14	18	17	43
November	*	4	8	24	18	19	27
December	1	9	10	20	17	17	26
NAVAL AIR STATION							
January	*	2	6	15	15	22	39
February	*	3	5	14	15	21	43
March	*	3	4	14	18	21	39
April	*	7	7	16	15	17	37
May	*	5	5	14	14	25	38
June	*	2	4	16	18	19	41
July	*	2	3	12	14	25	44
August	*	1	2	8	9	20	60
September	*	3	2	9	11	18	57
October	*	2	3	13	16	24	42
November	*	7	6	17	16	21	33
December	*	5	6	14	16	18	41

* Less than 0.5%.

1/ Harmon Field data are from Department of the Air Force, Air Weather Service, Uniform Summary of Surface Weather Observations, Guam, Harmon Field, and are based on hourly observations for 7/46-4/48 and 6/48-9/49 (incl.). NAS data are from Chief of Naval Operations, Aerology Branch, Summary of Monthly Aerological Records, Guam, NAS, and are based on hourly observations for 9/45-2/46 and 5/47-12-52.

Notes

Geology

Introduction

The geology map (pl. 4, in pocket) shows the formations defined and named by this field party. The names proposed here are tentative only and have not been approved (1956) by the Stratigraphic Names Committee of the U. S. Geological Survey. Descriptions and analyses of the geology in this report are generalized. Correlations and ages assigned are believed to be accurate although detailed paleontologic investigations are incomplete (1956). Few paleontologic details are presented. W. S. Cole of Cornell University identified some of the larger Foraminifera and supplied most of the age determinations on which the stratigraphic sequence is based. M. R. Todd of the U. S. Geological Survey and W. R. Riedel of the Scripps Institute of Oceanography have determined smaller Foraminifera and Radiolaria, respectively, and have furnished ecological data upon which was based some of the geologic history of the island.

Regional Geologic Setting

A prominent geologic feature of the western Pacific Ocean is a series of arcuate submarine ridges paralleled by deep trenches (fig. 9). One belt of trenches extends from Japan to the Palau Islands and includes the Japan Trench, the Mariana Trench, the Yap Trench, and the Palau Trench.

This belt of trenches forms a structural and petrographic boundary between the Philippine Sea, an area almost completely bounded by island arcs and characterized by the dominance of andesitic rocks, and the Pacific Basin proper, which is characterized by basaltic rocks.

These trenches are thought to be the result of a downbuckling of the earth's crust. Such downbuckled structures are known as tectogenes. The axes of the tectogenes lie along the trenches. Uplift along the concave side of tectogenes is responsible for the arcuate submarine ridges known as geanticlines.

The Mariana Islands arc may be considered in two parts: the southern Marianas, including Farallon de Medinilla, Saipan, Tinian, Aguiguan, Rota, and Guam; and the northern Marianas, including Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros. The southern Marianas display limestone caps, now emergent, that developed on volcanic foundations. The youngest volcanic rocks in the southern group are Miocene in age. The northern Marianas are, in general, relatively simple volcanic mountains; some volcanoes in this group are still active. A sulphur boil took place 25 miles west of Saipan in 1944 (Hess, 1948) indicating a southern extension of recent volcanic activity characteristic of the northern Marianas. The distribution of volcanic sediments around the northernmost of two submarine peaks west of Guam (fig. 14) suggests that the cone may be a submerged volcano active in fairly recent time.

General Statement

The present physiography of Guam is due largely to the stratigraphic and structural relations of the formations present. The island is broadly divisible into three physiographic provinces: the northern plateau; the central mountains; and the southern mountains. The northern plateau is the product of uplift, tilting and normal faulting, and weathering of reef and bank limestones. The scarps that separate the northern plateau from the central mountains are due to a fault, downthrown to the north, that crosses the island from Adelup Point to Pago Bay (pl. 4, in pocket).

The dissected terrain developed on the central mountains is largely fault-controlled. Mounts Tenjo, Chachao, and Alutom are all bounded by high-angle normal faults. Lithologic differences in beds in the Alutom formation are responsible for many ridges and knobs in this central region (pl. 5A).

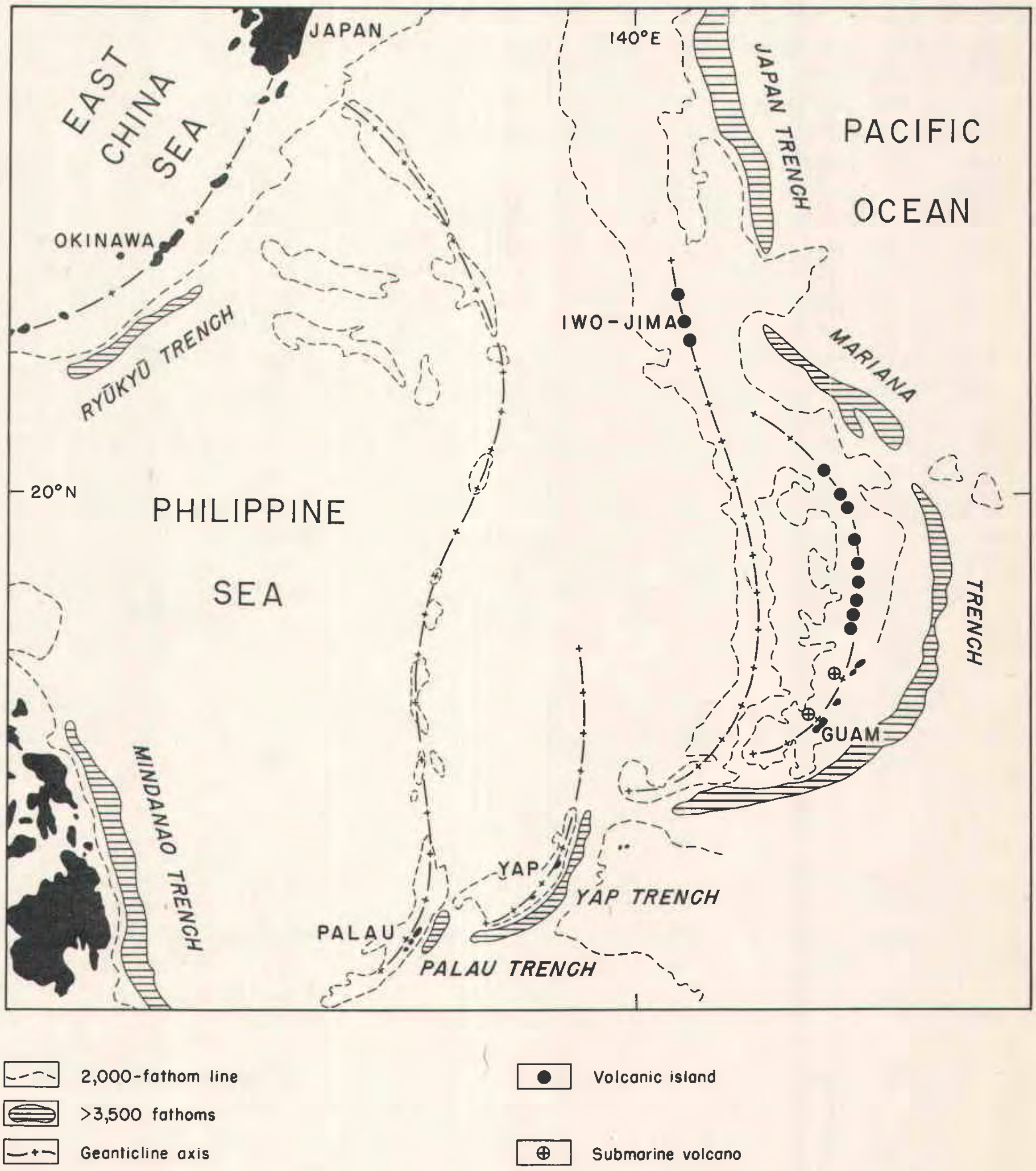


Figure 9. Trenches and island arcs of the western Pacific Ocean. (after Hess, 1945).

The southern third of the island is dominated by a high cuesta that approximately parallels the west coast, and by a gentle dip slope that reaches from the cuesta ridge to the capping limestones along the east coast (pls. 5B, 6; see pl. 3B). It is thought that some tilting to the east accompanied by normal faulting along the west coast (and in the interior of the southern part of the island) is responsible for the over-all configuration of this part of the island.

Guam is made up of Eocene limestones and volcanic rocks, shales of Oligocene age, Miocene volcanic rocks, and Miocene to Recent limestones (pl. 4 and fig. 10). The mountainous central core of the island is a succession of over 600 meters (2,000 feet) of folded and faulted marine tuffs, limestones, conglomerates, and lava flows of Eocene and Oligocene age - the Alutom formation -- which includes more than 60 meters (200 feet) of shales and sandstones rich in Foraminifera of Oligocene age -- the Mahlac member. The northern plateau is a limestone cap resting unconformably on the Alutom formation and made up of the relatively flat-lying Bonya limestone, the Janum formation, and the Barrigada limestone, all of Miocene age, and the Mariana limestone of Plio-Pleistocene age. The southern third of the island is made up of a succession of Miocene volcanic rocks and limestones approximately 670 meters (2,200 feet) thick, dipping gently to the east -- the Umatac formation -- made up of 4 members: 1) the Facpi basalt member; 2) the Bolanos conglomerate member; 3) the Maemong limestone member; and 4) the Dandan basalt flow member. This southern succession is thought to be in fault and overlap contact with the central Eocene and Oligocene mass. Figure 10 shows the stratigraphic relationships of the various formations.

Several distinct periods of structural deformation affected the formations mentioned above. The Alutom formation of Eocene age is, in general, intensely folded and faulted. Numerous high-angle faults with closely associated joints characterize many outcrops of this formation. At Mount Santa Rosa there is evidence of overthrust faults and tight folding. The Alutom formation is structurally the most complex formation on the island. The Miocene volcanic and limestone rocks have been normally faulted throughout, and display minor folding. The Miocene to Pliocene and Pleistocene limestone cap that forms the northern plateau is cut only by high-angle normal faults associated with wide breccia zones.

Prominent normal faults cut across the island in both the northwest-southeast and northeast-southwest directions.

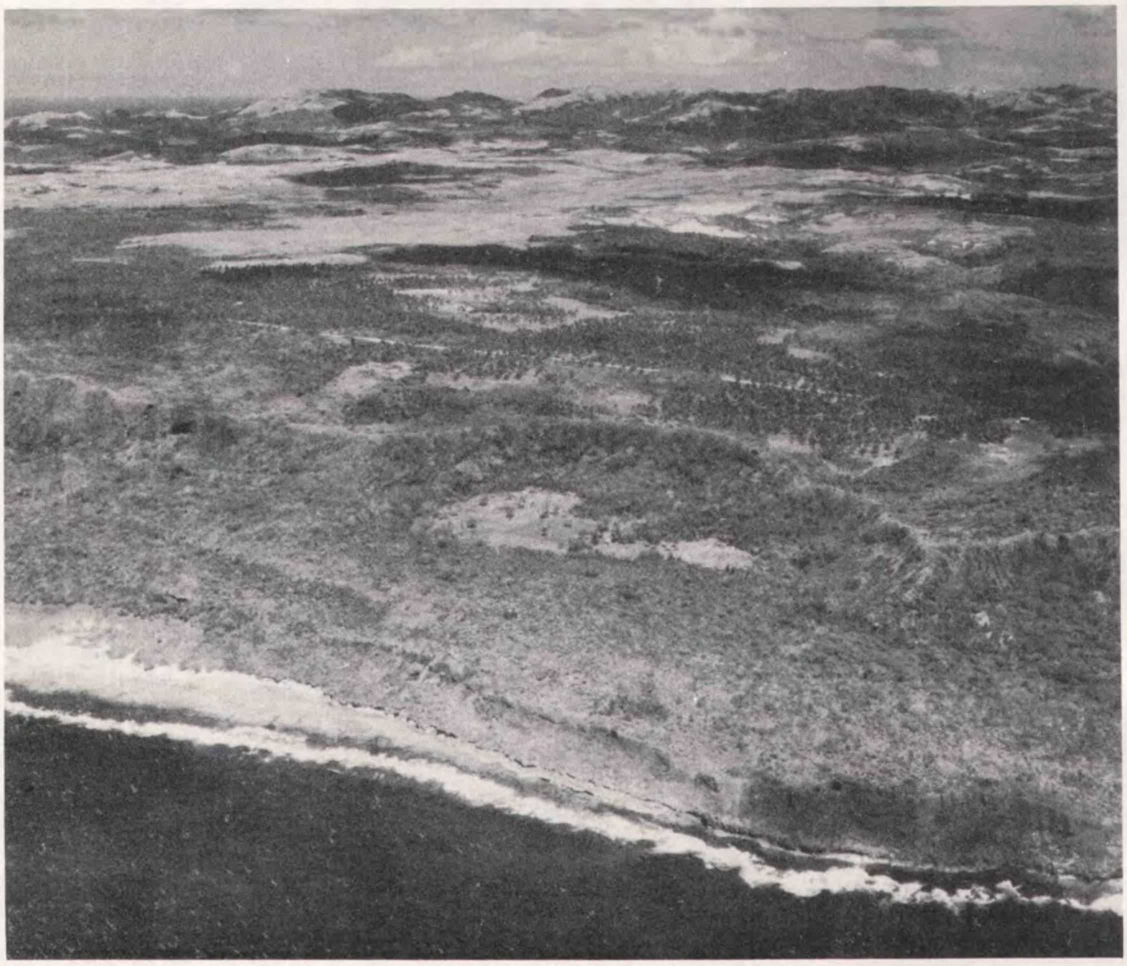
Physiography

General statement: Guam, with a total area of about 580 square kilometers (225 square miles), is one of the larger and more complex islands of the Pacific Ocean. It is composed of volcanic flows and tuffs partly covered by coralline limestones. Different parts of the island have been eroded to different degrees, resulting in a complex pattern of topography and physiography (see pl. 4).

The total surface is divided into seven physiographic units (fig. 11), including rough summit land, mountainous land, dissected sloping and rolling land, hilly land, plateau land, interior basin and broken land, and coastal lowland and valley floors. The units have been divided, and are discussed, according to the simplest grouping of the primary physiographic characteristics of relief, slope, surface, and drainage. These characteristics in turn depend upon elevation, the lithology of underlying rock, geologic structure, soils, and vegetation.

A. Weathered surface on Mount Tenjo. The top of the mountain is a truncated surface on which many knobs and ledges of indurated rock stand out.

B. Southwest coast of Guam. Rugged topography is characteristic of the western edge of the cuesta in the Umatac formation. Mount Lamlam on the right, Mount Jumullong Manglo in the center, and Mount Bolanos on the left, form the steep side of the cuesta. Reefs and sea cliffs around Cetti Bay, in the foreground (reef segment no. 7), are in the Facpi basalt member of the Umatac formation; basalt dikes cut both reef and sea cliff. Photo by U.S. Navy.



Southeast coast of Guam. Gentle backslope of the cuesta rises to the crest of the ridge in the background, and is mostly a dip clope on the Bolanos conglomerate member of the Umatac formation. (Contrast with topography in Plate 5B). Volcanic rocks near the coast are covered with an apron of Mariana limestone that forms the coastal cliffs. Narrow beach merges into a cut bench at Asiga Beach south of Talofofo Bay. (Reef segment no. 5). Photo by U.S. Navy.

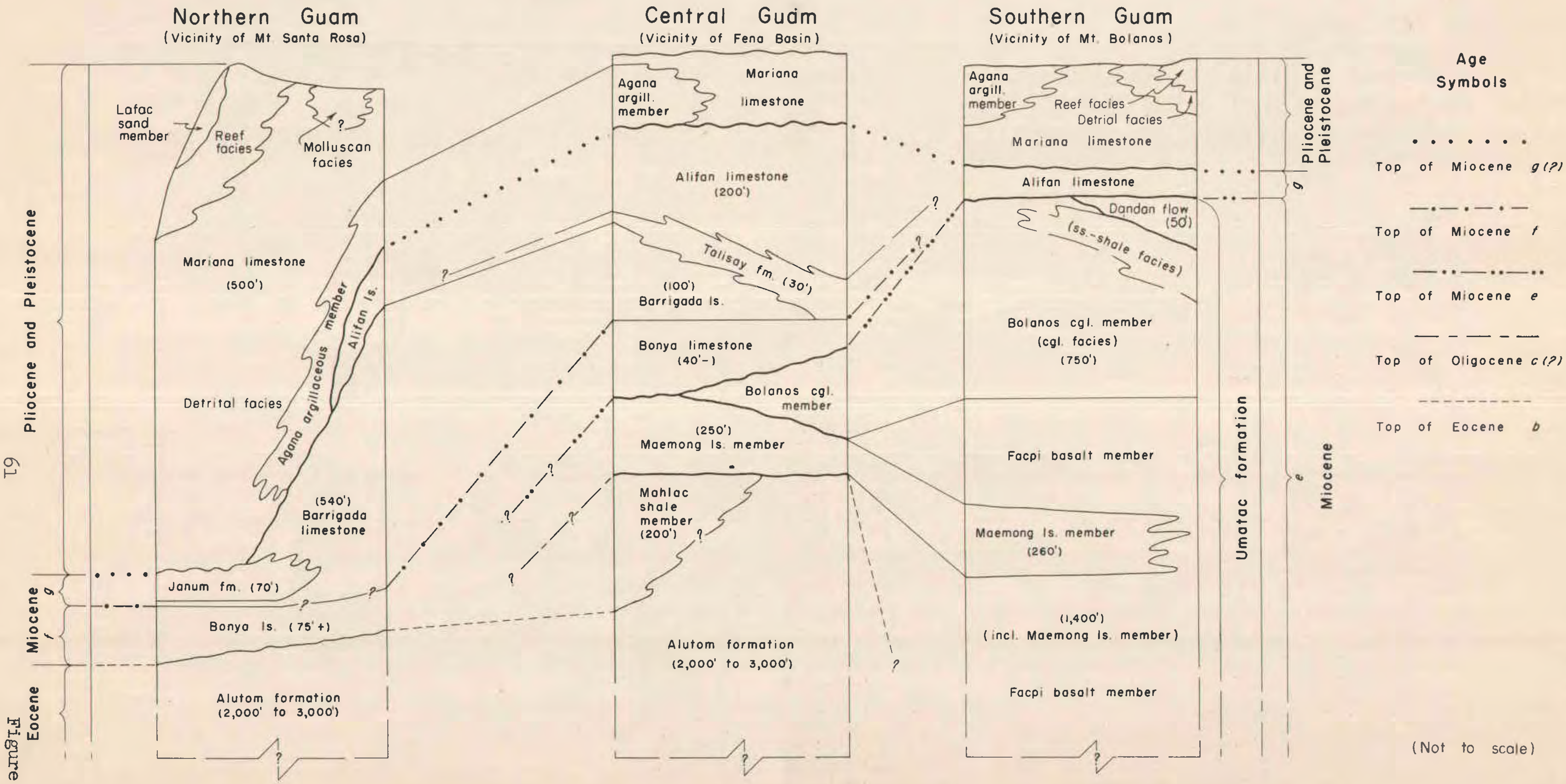


Figure 10. Stratigraphic columns, Guam

Rough summit land: The rough summit land unit occurs entirely in southwest Guam, and includes the summits of Mounts Alifan, Almagosa, and Lamlam, plus the area included between these peaks. The unit is elongate in a north-south direction. It comprises roughly 5 to 8 square kilometers (2 or 3 square miles) but has a maximum north-south dimension of 7 kilometers (4 miles).

Rough summit land includes high knobs, sharp elongate hills, irregular depressions with vertical walls, scarps, and cone-shaped peaks. Land intervening between these features is rough, and forms a small proportion of the total area of the unit. This rough summit land is

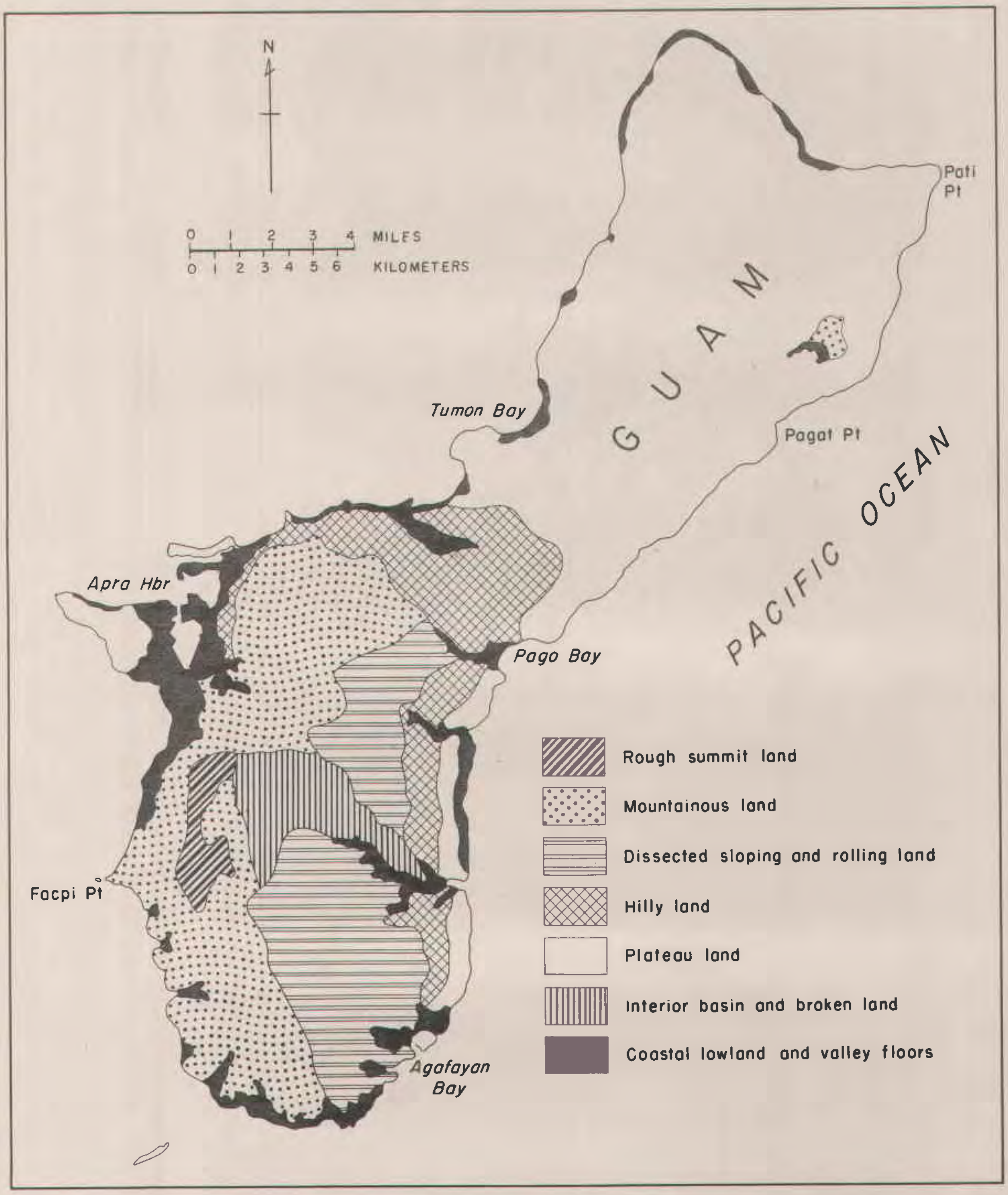


Figure 11. Physiographic divisions of Guam.

Figure 11

noteworthy for its cliff ramparts, or elongate sharp ridges parallel to and surmounting the scarps within the unit. As distinguished from other cliff ramparts, such as the ones bordering the north Guam plateau, the ramparts in the rough summit land unit have greater relief if viewed perpendicular to the cliff line. Some large individual crenulations resemble great dorsal fins, as exemplified by Mount Almagosa and, to a lesser extent, Mount Lamlam.

The unit has a median elevation of about 290 meters (950 feet). The south part of the unit is highest with a maximum elevation of 405 meters (1,329 feet), the highest for the island. The unit slopes gradually downward toward the north, with the lowest elevation, about 200 meters (650 feet), at the northeastern boundary. There is a pronounced relief, the maximum being about 650 feet (in the Mount Lamlam area). Relief decreases toward the north along with the median elevation of the unit, and in the vicinity of Mount Alifan it is only about 60 meters (200 feet). In the vicinity of Mount Almagosa several sharp, elongate hills separated by steep-sided depressions have a relief of 90 meters (300 feet). Relief in this unit is accentuated by steep slopes and by a great number of separate knobs, spires, knife-edge ridges, and sinkholes.

The principal or over-all slope of the entire unit is very gentle downward to the north. This principal slope does not represent the specific slopes, however, which commonly are steep. Many vertical and near-vertical scarps transect the unit. In the middle of the south part of the unit some relatively horizontal land separates the two systems of steep to precipitous hills forming the east and west boundaries of the unit.

The rough summit land is developed entirely upon the Alifan limestone and accompanying alluvium. Soils are a few inches thick to absent over much of the unit but thicken to 2 or 3 feet in low depressions where alluvium may occur. Vegetation is very heavy and consists of large and small trees, bushy undergrowth, and tangled vines. The microrelief, or surface detail, is rough to jagged, boulder-strewn, and generally rocky, with many rock slopes. Talus deposits at the base of some slopes may be several feet thick.

No surface streams occur in the unit; all drainage is downward into the porous underlying limestone. During excessive rains sheetwash probably helps deposit alluvium in depressions.

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 the sharp, elongate ridges characteristic of the unit. The rough summit land is a mature karst topography.

Mountainous land: The mountainous land unit occurs mainly as the western half of south Guam, and includes Mounts Alutom, Tenjo, Chachao, and Macajna in the north and Mounts Jumullong Manglo, Bolanos, Schroeder, Finasantos, Sasalaguan, and Magpogugae in the south part of the unit. Mount Santa Rosa, in north Guam, forms a relatively small additional patch. Mountainous land forms all of the rugged southwest coast of the island, except where it is bordered by relatively small ramps of coastal lowland and valley floor units. North of Facpi Point the coastal unit widens significantly, forming a wide apron of lowland between the mountainous land unit and the shoreline. The Pago Bay-Adelup Point fault system forms the abrupt north boundary of the mountainous land. The east boundary is sinuous where the mountainous land merges gradually with dissected rolling and sloping land, except where the interior basin and broken land makes a pronounced westward indentation into the unit. This indentation continues as a south-trending arm of rough summit land. The greatest north-south dimension of the mountainous land is about 25 kilometers (16 miles), and the width east-west varies between 6 and 13 kilometers (4 and 8 miles). The northern patch is not more than 2 kilometers (1 mile) in any dimension. Total area of the entire unit is about 116 square kilometers (45 square miles).

The mountainous land unit includes both sharp and relatively flat mountain summits bounded by long, irregular, steep to precipitous slopes. The most prominent feature in the north part of the unit is the flat to rolling summit land of Mount Tenjo flanked by long, sheer slopes, particularly on the long west side and shorter south side. Mounts Chachao and Alutom are rounded knobs rising somewhat higher than the Tenjo summit surface. Mount Macajna is an extension of the Tenjo surface at a lower elevation.

In the south part of the unit the mountains are generally sharper and more peaked. Mounts Jumullong Manglo and Bolanos preserve a small, relatively flat remnant of an upper or summit surface, but this is obliterated farther south at Mounts Schroeder, Sasalaguan, and, particularly, Finasantos. The last-named is an abrupt conical peak, almost a spine, protruding between Mount Sasalaguan and Mount Schroeder. Viewed from the southwest, the profiles of Schroeder and Sasalaguan show flat upper limits at differing elevations, which may represent remnants of the Bolanos summit surface displaced by faults.

The mountainous land unit includes comparatively large, V-shaped stream valleys, the most spectacular being the Geus River valley extending northeast from Merizo and separating Mount Sasalaguan and Finasantos to the southeast from Mounts Schroeder and Bolanos to the northwest. Another major valley is the Lonfit River valley system in the north part of the unit between Mounts Chachao and Macajna. Unlike the Geus, the Lonfit River has large tributaries with separate valleys. Many smaller stream valleys, of course, cut the mountain slopes in both the north and south parts of the unit.

Fault scarps and fault line scarps form a complex pattern in the mountainous land north of the northwest boundary of the interior valley and broken land unit. Some of these scarps are not as greatly eroded as the remnants of scarps in the southern area, particularly along the west face of Mount Bolanos, where streams have cut deeply into the slopes.

The mountainous land ranges in elevation from sea level to about 380 meters (1,250 feet) at Mount Jumullong Manglo. The maximum elevations in the Mount Tenjo block are somewhat less, with a maximum of 328 meters (about 1,080 feet) at Mount Alutom, 305 meters (1,000 feet) at Mount Chachao, and about 300 meters (950 to 1,050 feet) for the summit surface of Tenjo itself. The median elevation in the north part of the mountainous land unit is about 150 meters (500 feet). In the southern part of the unit, in addition to the elevation of Jumullong Manglo noted above, Mount Bolanos reaches 370 meters (1,220 feet), Sasalaguan 338 meters (1,110 feet), Schroeder 321 meters (1,050 feet), and Mount Finasantos about 250 meters (820 feet). The median elevation of the south part of the unit is about 190 meters (625 feet). Mount Santa Rosa, in north Guam, has an elevation of 262 meters (860 feet) -- considerably less than that of the peaks in south Guam.

The mountainous land, as might be expected, has the greatest relief in the island. The sharpest and most complex relief occurs in the vicinity of the Geus River valley and the west slopes of Mount Bolanos, where it ranges between 260 and 275 meters (850 and 900 feet) for the upper slopes and more than 305 meters (1,000 feet) in some places where streams are deeply incised. The relief is uniformly at least 60 to 90 meters (200 to 300 feet) in the south part of the unit.

In the north part of the mountainous land unit the greatest relief occurs where the south and southwest slopes of Mount Tenjo rise smoothly up high above the foothills and coastal area. Maximum relief is about 245 meters (800 feet) in this area. West of Mounts Tenjo and Alutom the deep stream valleys have a relief of 60 to 150 meters (200 to 500 feet). Mount Santa Rosa has a total relief of about 75 to 90 meters (250 to 300 feet).

Most slopes in the mountainous land unit are steep to precipitous. There is no principal or over-all slope for the entire unit. Summits in the north part form a very slight northward slope, which is denoted by the general upper surface of the Tenjo block. Summits of the southern mountains decrease in elevation in a southerly direction but display a very uneven profile.

Secondary slopes of the general surface occur in both the north and south parts of the unit. In the north part the secondary slopes face west-northwest and east-southeast, the former being much steeper. In the south part of the unit the secondary slopes face approximately east and west, the west being not only steeper in this area but also the steepest of any secondary slopes in the entire unit. The specific, or what might be called "tertiary", slopes are the ones formed by streams and faults cutting across the rock mass. These precipitous slopes place the land in the mountainous category; the over-all and secondary slopes alone would produce only a rolling to steep upland.

The mountainous land is developed upon the Alutom and Umatac formations. Soils are absent to 50 feet or more thick, and many bare rock faces are exposed in steep slopes. Vegetation is largely bushy and grassy on humps and open slopes, but in ravines or along other water courses it is forest with tangled undergrowth. The surface or microrelief is smoother in the north part of the unit where a clayey surface is more common. Even here there are many abrupt, steep-sided gullies and ravines that cannot be crossed easily on foot. Although rough rocky surface occurs in many places in the north it is most common in the south part of the unit, where fractured and boulder-strewn rock faces form long, steep, sloping sides of mountains. Some smoother, clayey surface also occurs in the south part.

The mountainous land is drained by many streams. The steeper western slopes of the unit are drained by a system including about 35 larger streams at the shoreline where they empty into the ocean. Most of these streams have several large tributaries and many small ones. In general they constitute a parallel drainage system. The eastern, less steep slopes are drained by approximately the same number of streams but they form a roughly dendritic drainage pattern where they flow eastward across the unit boundary into the dissected sloping and rolling land. Many small and several large fresh-water springs emanate from the base of the relatively porous Alifan limestone where it overlies volcanic rocks, marking the boundary between this unit and the enclosed rough summit land unit. Chepek and Dobo Springs in the Almagosa area have a high volume of flow. In the west slopes, the Sella, Asmafines, and Taleyfac Rivers are examples of streams whose ultimate sources are springs. All of these spring-fed streams are also fed by tributaries whose sources are surface run off. Stream profile slopes may be steep. Some average slopes of upper reaches of streams are 1 vertical in 4 horizontal for the Big Gautali River, 1 in 7 for the Imong River.

The mountainous land was formed as the result of stream dissection of stratified lava flows and tuffs raised relatively high above sea level. The north part of the unit may have been originally a marine terrace, and the present topography is the result of uplift, faulting, and stream dissection. The south part of the unit was a built-up series of flows and tuffs. It does not today preserve remnants of as extensive an upper surface as does the north or Tenjo block. The south part at Mount Bolanos, Mount Sasalaguan, and to a lesser extent at Mount Schroeder, display dissected, slightly tilted summit surfaces which appear to have been originally a single surface or marine terrace. The southernmost part of the mountainous land unit is the most sharply dissected and seems to be undergoing the most active erosion at present.

<u>Dissected sloping and rolling land</u>: The dissected sloping and rolling land unit occurs entirely in the eastern part of south Guam. It occupies two areas east of and adjacent to the mountainous land unit; it is separated into north and south divisions by the NW-SE-trending interior basin and broken land unit. Generally, it is bounded on the north and east side by the hilly land unit except for bordering patches of the coastal lowland and valley floor unit.

The two dissected sloping and rolling land areas trend north-south and comprise a total area of about 78 square kilometers (30 square miles). The longest dimensions of the two units are roughly in line in a north-south direction and are about 8 and 12 kilometers (5 1/2 and 7 1/2 miles) for the northern and southern area respectively. The northern area includes the Asquidachay, Manengon, Pulantat, Sigua, and Jangga districts; the southern area includes the Finogchaan Toro, Bubulao, Dandan, Atate, and Umafit districts.

The unit includes the relatively long, gradual eastern slopes of the mountains forming the mountainous land unit in the western part of south Guam. In the Manengon-Pulantat district these slopes are generally straight in their descent from the Mount Tenjo - Mount Alutom heights to the hilly land bordering them to the east. Farther south, in the Bubulao-Atate district, the slopes are gently concave from the summits of Mount Jumullong Manglo and Mount Bolanos eastward to the hilly land and lowland along the southeast coast (see pl. 6). Most of the dissected sloping and rolling land proper in this area, however, is straight-sloping, the major break in slope marking the boundary of the unit.

Other than the long slopes and, in the south part, gently undulating or rolling topography, the major landforms are the stream valleys cut below the general surface. These valleys are steep-sided and V-shaped for the most part. Very narrow floodplains have formed in some larger valleys such as the upper Ugum, the Lonfit, and the Ylig. The Lonfit, Sigua, Manengon, and Ugum Rivers in the unit under discussion all show incised meander patterns in their middle and upper reaches.

The dissected sloping and rolling land ranges in elevation from sea level to about 200 meters (660 feet) at the eastern foot slope of Mount Bolanos and the east slope of the Mount Tenjo - Mount Alutom block. The highest points of the unit are along the west boundaries. The unit extends down to sea level only near Agfayan Bay and Ajayan Bay. The least elevation of the northern unit is about 49 meters (160 feet) near the upper Ylig River valley. The median elevation of the north area is about 122 meters (400 feet), and the south area about 100 meters (330 feet).

Except for the gentle slope of the principal surface of the dissected sloping and rolling land unit, the major relief is expressed by steep-sided stream valleys. These are valleys of the Ylig, Manengon, Ugum, Pauliluc, Inarajan, and Agfayan Rivers. The maximum relief of these valleys is 110 meters (360 feet), as displayed in places along the Manengon and Inarajan Rivers. The average relief is much less, probably about 45 to 60 meters (150 to 200 feet), as shown by all larger stream valleys.

The principal slope of the dissected sloping and rolling land is very slightly downward to the east. Secondary slopes are roughly north- and south-trending modifications of the principal eastward slope caused by undulations in the topography. Specific slopes vary from slight to precipitous, with two very definite classes of slope within this range: one class comprises the slight to moderate slopes of the general upper surface of the unit; the other class comprises the steep to precipitous slopes of the sides of stream valleys cut into the general upper surface. The steep slopes of the latter class are well defined and generally are separated from the gentle slopes of the former class by distinct breaks.

The dissected sloping and rolling land is developed upon exposures of the Alutom formation, Mahlac shale, Bolanos conglomerate member, and Dandan flow member. Soils are thin to absent in some bare rock faces but may be 50 feet thick or more in relatively flat areas. Vegetation is bushy and grassy in much of the flat to gently sloping topography. In stream valleys, vegetation is mostly thick forest with tangled undergrowth. Some forest occurs also in the flat to gently sloping topography. The surface or microrelief is generally smooth and clayey with scattered patches of large boulders. Stream beds contain boulders in many places. Some boulder talus has formed at the bases of valley sides, where it may make very loose stream banks.

Drainage of the dissected sloping and rolling land is accomplished by a network of streams emptying along the east coast of south Guam. Stream valleys are generally cut deeply enough that they can accommodate considerably more than the flow observed during heavy rains, although the alluvial flats or floodplains may be flooded. The major streams draining this unit are the Pago, Lonfit, Ylig, and Manengon Rivers in the northern area and the Asalonso, Ugum, Sarasa, Sagge, Pauliluc, Inarajan, Agfayan, and Ajayan Rivers in the southern area. Typical stream slopes in the northern area are about 1 in 30 (upper Ylig River) and in the southern area about 1 in 50 (Ugum River).

Both areas of this unit display patterns of streams trending northeast and southeast (fig. 12). The headwaters of many of the larger streams lie in the mountainous land unit. The over-all stream pattern is dendritic to rectilinear.

The dissected sloping and rolling land was formed by stream erosion of broad, sloping land bevelled by successive advances and retreats of the sea. Faults and probably regional tilting movements complicated the flow of streams and caused many right-angle changes of course. Much of the unit may once have been covered by relatively thin limestone now removed by erosion. Some of the streams possibly developed as subsurface drainage channels under limestone.

Hilly land: The hilly land unit occurs in central and south Guam. It separates the dissected sloping and rolling land from the plateau land forming the coast. This strip of hilly land is divided by

Figure 12. Drainage patterns on Guam

Figure 12

the interior basin and broken land unit as well as by the coastal lowland and valley floors unit. The central Guam area of the hilly land is bordered on the north and east by the plateau land, on the west by coastal lowland and valley floor land, and on the south by mountainous land. The maximum dimension of the hilly land in any direction is about 12 kilometers (7 1/2 miles) east and west in the central Guam area. The entire unit comprises about 52 square kilometers (20 square miles) and includes the Sinajana, Barrigada, and Chalan Pago districts as well as parts of the Yona, Talofofo, Assupian, and Pauliluc River districts. A small additional strip along the west coast includes part of the Asan-Piti district.

The hilly land includes much hilly, rolling, and undulating topography showing a relatively fine dendritic pattern of dissection of what was originally a flat surface. It is noteworthy that many or most of the small valleys in this unit contain no streams or bodies of standing water. Rounded hills and knobs are characteristic, and are much smaller than those of the mountainous land. In places the valleys form nearly a filigree pattern in contrast to the more open dendritic pattern of the dissected sloping and rolling land. The relief of the hilly land is the least for any dissected topography in Guam.

The hilly land ranges in elevation from sea level in the Agana and Pago districts up to about 70 meters (230 feet) at Barrigada, 183 meters (600 feet) at Nimitz Hill, 100 meters (330 feet) near Piti, 80 meters (260 feet) near Yona, 100 meters (330 feet) near Talofofo village, and about 90 meters (300 feet) at Assupian. The upper surface is thus generally 80 to 100 meters (260 to 330 feet) above sea level, disregarding the Nimitz Hill occurrence which is a modified hilly land topography having a different upper surface than the remainder of the unit. The median elevation of most of the unit is about 50 meters (165 feet).

Most of the hilly land has a relief of 30 to 60 meters (100 to 200 feet) throughout the labyrinthine network of little valleys and rounded hill crests. In the Piti-Asan district including Nimitz Hill, however, the relief is over 120 meters (nearly 400 feet). The unit's most typical development, in the vicinity of Ordot and Barrigada, shows the unit relief decreasing gradually from the southwest border toward the northeast. Beyond Barrigada the relief disappears into the comparatively smooth surface of the plateau land. The finest texture, as it were, of relief throughout the island is displayed by the hilly land.

The principal slope of the hilly land is very slightly downward toward the south. An exception to this is the area between Yona and Talofofo, where the slope is slightly downward to the north. The specific slopes of the unit are the valley walls, which are almost uniformly steep and in some places precipitous. Slopes decrease somewhat toward the north part of the central Guam area along with the decrease in relief noted above. Near Barrigada the topography has an undulatory or rolling quality that results from the abundant moderate and gentle slopes. Typical slopes of the valley bottoms in the hilly land range from 1 in 20 to 1 in 100.

Hilly land is developed upon exposures of the Agana argillaceous member of the Mariana limestone as well as on some pure Mariana limestone and some Alifan limestone. Soils are extremely variable in thickness, ranging from a foot or less on some ridge crests to more than 20 feet on some valley sides. Vegetation in the unit is mostly forest with tangled undergrowth, but in some places it is grass, particularly swordgrass. The surface or microrelief is gently rolling to rocky and rough for most of the areas of the unit. Talus is not common. Limestone pinnacles 3 or 4 feet high occur sporadically.

The hilly land shows only a minor development of surface drainage, particularly in central Guam where the intermittent Fonte and Agana (or Chaot) Rivers drain the area. Most drainage is downward into the rock mass. The Assupian River is the only other major stream developed upon the hilly land topography. Rivers in the Asan-Piti district flow mostly upon relatively impervious volcanic rock underlying the clayey limestone of the hilly land. The Agana River flows for at least part of its course upon clayey alluvium which, presumably, is washed from the argillaceous limestone exposed in that area.

The hilly land evidently formed as the result of erosion of clayey limestones by small streams having small tributaries. At present only torrential rains flood the valley bottoms and cause active erosion; otherwise, the small relative volume of runoff either percolates gradually down into the rock or seeps laterally through alluvium or soil in the valley floors. The alinement of some of the major valleys in the dissected network suggests that joints and faults exerted an early control upon erosion.

Plateau land: The plateau land unit includes all but a small part of north Guam, a belt along the southeast coast of the island, much of Orote Peninsula, and Cabras Island.

In north Guam the plateau land is bordered by patches of coastal lowland and valley floor land except along the southwest border near Barrigada village, where it adjoins the hilly land of central Guam. The mountainous land and valley floor units of Mount Santa Rosa are completely enclosed by the plateau land unit.

Along the southeast coast the hilly land borders the plateau land on the west. Discontinuous patches of coastal lowland and valley floor divide the plateau land into separate areas and border it on the east side between Ylig Bay and Sagua Anite Bay.

Both Orote Peninsula and Cabras Island are outlying areas of plateau land separated from the main body of Guam by coastal lowland and valley floor.

The longest dimension of any separate part of the plateau land is roughly 26 kilometers (16 miles) in a north-south direction in the large area of the north Guam plateau. The remaining areas of this unit are relatively small. Total area of the unit is about 233 square kilometers (90 square miles).

The plateau land unit in north Guam consists essentially of a single broad plateau surface bordered by steep coastal cliffs. The surface of the plateau includes scarps, mounds, sink-holes, cliff summit ramparts, elongate swales, and coastal terraces. Barrigada Hill, a broad-domed hill, protrudes above the general plateau surface. The most prominent scarp upon the plateau extends from Tamuning village northeastward to Finegayan and then eastward toward Sabanon Pagat. The southeast coast area of plateau land has many relatively small scarps, most of them transecting the upper surface at an angle to the coastal cliffs. Orote Peninsula has one very prominent scarp parallel to the trend of the peninsula. The Orote Peninsula sea cliffs are vertical and sheer, and have no coastal lowland on the south side. In some places steplike terraces are prominent in the plateau cliffs. The best display is between Achae Point and Ritidian Point, on northernmost Guam, where 6 terraces occur between the upper plateau surface and sea level.

Elevations in the plateau land unit range from sea level to about 210 meters (690 feet) in north Guam near Mount Santa Rosa. Mount Machanao, near the north tip of the island, is 192 meters (630 feet) above sea level, Pati Point is 170 meters (560 feet), Fadian Point is 100 meters (330 feet), Uruno Point is 170 meters (560 feet), Haputo Point is 125 meters (410 feet), Amantes Point is 125 meters (410 feet), and Ypao Point is about 60 meters (200 feet). These elevations are indicative of the general elevation of the included plateau surface. Barrigada Hill, rising above the plateau, reaches about 200 meters (655 feet). The median elevation for the north plateau is about 107 meters (350 feet).

In the southeast coast area the maximum elevation is about 126 meters (415 feet) at Asquiroga, overlooking Talofofo Bay. The area east of Assupian reaches 110 meters (360 feet) and the Camp Witek area, or Maleyuc Hill, reaches 116 meters (380 feet) above sea level. The median elevation in this area is about 64 meters (210 feet).

Orote Peninsula ranges up to about 60 meters (200 feet) above sea level and Cabras Island to about 30 meters (100 feet), which is approximately the median elevation for Orote Peninsula.

Most of the relief in the surface of the plateau land is subtle compared with the broad expanse of the plateaus. The near-vertical cliffs, some 183 meters (600 feet) high in north Guam, bordering the plateau land constitute the major relief of the unit. Barrigada Hill is the major eminence above the north Guam plateau and has a total relief of about 85 meters (280 feet). The Tamuning-Finegayan-Sabanon Pagat scarp has a maximum relief of about 80 meters (260 feet) immediately north of Mount Barrigada. Most other scarps have a relief of less than 28 meters (90 feet). Some of the sinkholes near Haputo are 30 meters (100 feet) deep. Generally the plateau land in north Guam is flat to slightly undulatory and has a relief of only 4 1/2 to 6 meters (15 to 20 feet). Relief diminishes with total elevation in the long slope southward to sea level near Tamuning.

Orote Peninsula, with a total relief of 61 meters (200 feet), has in its upper surface a scarp with a relief of about 11 meters (35 feet). Most of the plateau land unit in southeast Guam has less relief in its plateau surface than does Orote. Sea cliffs along the southeast coast, however, have a total relief of as much as 126 meters (415 feet).

The principal slope of the main area of plateau land is very slightly downward to the south-southwest, from 210 meters (690 feet) near Mount Santa Rosa down to sea level near Tamuning, 17.5 kilometers (11 miles) distant. Orote Peninsula slopes gradually downward to the east. The sea cliffs are in general either precipitous from base to summit or else steeply sloping in the lower, and precipitous in the upper parts. Scarps and sinkholes have moderate to steep slopes. Other slopes in the plateau land, particularly the mounds and swales, are gentle.

The plateau land is developed mainly upon exposures of the Mariana limestone, Barrigada limestone, and Alifan limestone. Soils are very thin, generally not more than a few inches thick. Vegetation is large forest with tangled undergrowth in most of the plateau land, although much clearing has been accomplished for purposes of farming and construction. Second growth in some of these areas is low and bushy. The surface or microrelief is variable between extremes of smooth ground and rough, rocky, boulder-strewn, or jagged, limestone-pinnacled ground. The latter occurs particularly near cliff summit ramparts in north Guam.

There are no streams in the plateau land (fig. 12); drainage is by downward percolation into the porous limestone. During torrential rains, sheetwash flows in many areas, particularly into swales. Standing water bodies may accumulate and require two or three days to drain.

The plateau land was formed during a time when this part of the island mass was beneath the sea. Coralline limestones accumulated in shallower areas both as growing reefs and as fragmental deposits. Probable regional uplift resulted in the emergence of the great expanse of land that is now plateau land. Intermittent faulting and wave erosion produced the bordering sea cliffs. Fault scarps and ground-water solution features such as sinkholes and swales probably developed after emergence.

Interior basin and broken land: The interior basin and broken land unit occurs entirely in south central Guam in the Bona, Mepo, Fena, Mapao, and Talofofo districts. It is bordered chiefly by the mountainous land and dissected sloping and rolling land units, plus some areas of rough summit land, hilly land, and coastal lowland and valley floor. The shape of the unit is elongate northwest-southeast, with the longest dimension about 10 kilometers (6 miles). The total area is about 31 square kilometers (12 square miles).

The interior basin and broken land is heterogeneous in topographic expression. It includes karst topography, many small conical hills, an artifically constructed freshwater body, some dissected sloping land, some deeply eroded stream valleys, many scarps, some gently undulating land in the bottom of the basin, and many small valley floors.

Elevations in the interior valley and broken land range from roughly sea level to about 128 meters (420 feet) in the area northeast of Mepo and south of the cross-island road. The summits of the steep hills in the Mapao district are about 119 meters (390 feet). The eastern extremity and the south and southwest boundaries do not exceed about 100 meters (330 feet). The western boundary area diminishes northward from 100 to about 49 meters (330 to about 160 feet). A few surfaces within the low central part of the basin exceed 45 meters (150 feet) but the elevation of most of the area is less. The median elevation for the entire unit is roughly 64 meters (210 feet).

The greatest relief in the interior valley and broken land unit is in the eastern part along the north bank of the Talofofo River where individual scarps are as much as 80 meters (260 feet) high. At Mapao the hill summits are 150 meters (490 feet) above the Mahlac River, and north of Mepo the total relief is about 100 meters (330 feet) between the hills and the floor of the basin. Neither of these latter two places, however, has scarps as steep as in the Talofofo River District. The dissected slopes west of the Fena Reservoir show a relief of about 60 meters (200 feet). Along the south boundary where the unit adjoins the dissected sloping and rolling land the relief is generally less than 60 meters (200 feet).

Near the center of the basin vertical scarps 36 meters (120 feet) high border the stream valleys and sinkholes. Directly eastward, the prominent hill between the Mahlac and Maagas Rivers has a relief of 60 meters (200 feet). Relief is least in the northwestern end of the basin where low hills commonly are not more than 12 meters (40 feet) high.

The principal slope of the interior basin and broken land, as reflected by the slope of the floor of the basin, is slightly southeastward, but secondary slopes, generally gentle to steep, are inward toward the center of the basin. Specific slopes are gentle to precipitous, with a very high proportion of the latter because of the many scarps and small steep hills constituting the broken land within the basin. The relief of some parts of the unit is nearly as fine-textured as that of the hilly land unit.

The unit is developed upon exposures of the Alutom formation, Umatac formation, Bonya limestone, Talisay formation, Alifan limestone, Mariana limestone, and much present alluvium. Soils are absent to many feet thick. Vegetation on the flanks or perimeter slopes of the basin is largely grassy with some patches of forest growth. Within the lower part of the basin this changes to thick forest with heavily tangled undergrowth. Many marshes and swamps occur throughout the unit, the largest along the Mahlac and Maagas Rivers. The surface or microrelief includes everything noted under the other physiographic unit descriptions plus much clayey ooze and wet muck in the lowlands. Surface may be smooth, rough, rocky, boulder-strewn, limestone-pinnacled and jagged, gullied, or combinations of these characteristics. Talus deposits are common, some of soft clay and others of hard limestone boulders.

The interior basin and broken land is drained ultimately by surface streams but the unit includes some limestone exposures upon which runoff does not occur. Instead, water percolates downward into the rock and reappears as springs at the basal contact of the permeable limestone masses where they overlie relatively impermeable volcanics. A good example of karst topography and drainage is displayed by the Bonya limestone in its largest exposure in the center of the basin. The Maemong, Bonya, and Talisay Rivers drain into the heavily channelled, cavernous, and caved Bonya limestone, where they form the Tolaeyuus River. The latter flows through the Bonya limestone and twice disappears under it before reappearing to empty into the Maagas River. The above-mentioned rivers plus the Fena, Chepek, and Maulap Rivers all empty into the Maagas River. The Maagas combines with the Mahlac, Sagge, Sarasa, and finally the Ugum to form the Talofofo River, which has the greatest drainage area of any river in Guam.

The streams in the west part of the unit form a centripetal drainage network which joins a dendritic network downstream from the Maagas-Tolaeyuus confluence.

Stream profile slopes in the interior basin and broken land unit are generally very slight. The average slope of the Maagas-Talofofo River is 1 in 420, which partly accounts for its sluggish rate of flow.

Torrential rains swell the streams so that, in places, they are barely contained by their valley walls. The Maemong and Tolaeyuus Rivers, for example, are normally about 2 feet deep; in the rainy season they may at times increase to 3 or 4 feet. After an extraordinary torrential rain in October 1953 the water rose roughly 40 feet where the Tolaeyuus first flows under the Bonya limestone. Flooding of low areas in the basin occurs frequently in the rainy season.

Originally a structural depression, the interior basin and broken land has been flooded by the ocean several times during the geologic history of south Guam. Estuaries reaching far inland have permitted the deposition of many limestone formations. All of these, upon emergence, have been eroded to yield the hilly, bumpy, or karst topography now characteristic of the area. The deep sinkholes or dolines in the Bonya limestone were formed by roof-caving over parts of solution channels developed throughout the rock mass. Separate dolines later coalesced to form uvalas, or elongate depressions, such as the present valley of the Tolaeyuus River.

Faults produced great scarps which have been modified by erosion until at present many of them merely blend with and add to the broken topography. Other fault or fault-line scarps, such as those in the block forming the north side of the Talofofo River valley, are not yet so greatly eroded and can be distinguished without difficulty.

<u>Coastal lowland and valley floor</u>: The coastal lowland and valley floor unit occurs discontinuously along the coast of the island except for the long stretch around the northeast side between Pago Bay and Tarague. In addition it penetrates inland as valley floor at Agana, Pago, Ylig, Talofofo, Inarajan, Merizo, Umatac, and near Apra Heights. Penetrations of 3 1/2 to 5 kilometers (2 to 3 miles) occur at Agana and Talofofo. The longest straight line dimension of the unit is about 13 kilometers (8 miles), from Piti to south of Agat. Total area of the unit is about 39 square kilometers (15 square miles).

Coastal terrace or flat land, beaches, and the floors of wide valleys make up this unit. Most of the land is flat and shows little relief. Low coastal scarps, beach berms, and natural levees formed by streams are the main landforms of the unit.

Elevations in the coastal lowland and valley floor unit range from sea level up to about 12 meters (40 feet) for the valley floor and slightly higher, about 15 meters (50 feet), for some of the inner margins of coastal lowland. The median elevation is about 6 to 7 1/2 meters (20 to 25 feet). The sharpest relief displayed by this unit is between 3 and 4 1/2 meters (10 and 15 feet), at the storm berms along some beaches. In the Agana River marsh, however, several limestone hummocks protrude as much as 9 meters (30 feet) above the surface. West of Apra Heights, near Camp Roxas, more limestone hummocks occur. One or two broad hills about 15 meters (50 feet) high are situated where Orote Peninsula joins the island.

The principal slope of this unit is gently seaward, except for the eastern part of Orote Peninsula where the slope is very slightly eastward toward the main island mass. Some typical valley floors, such as those of the Ylig and Talofofo Rivers, have slopes of 1 in 525 and 1 in 240 respectively. The marsh area along the Agana River has an average slope of about 1 in 390 although it is somewhat rougher than the aforementioned two valley floors.

Beaches in the unit have average foreshore slopes ranging from 1 in 4 near Inarajan to 1 in 30 near Agat. The majority of slopes in this class, however, approximate 1 in 7.

The coastal lowland and valley floor unit is developed upon exposures of present alluvium, beach sands, and Mariana limestone. Soils are thin over the beach sands, generally thin over limestone lowland terrain, and generally thick, mucky, or marshy in valley floors. Vegetation is cleared in much of the lowland but may be present as coconut palms on beaches, as at Tumon, Haputo, and Tarague. Swamp in valley floors may include thick forest, as in the valleys of the Talofofo and Ylig Rivers. Swamps such as the one along the Agana River are very grassy and have thinner forest cover. Surface or microrelief is smooth and sandy at beaches, sandy to muddy in lowlands such as the Agat area, and rough, rocky, boulder-strewn, and pinnacled near some beaches where limestones have been actively eroded. Valley floors are generally smooth and clayey but may have tangled roots of large trees 2 feet above the ground surface.

Drainage at beaches and on adjacent limestones is by percolation downward into the rock. Some coastal lowland, for example that in the Inarajan, Agat, and Asan-Piti districts, is not well drained. Wide bodies of standing water accumulate to depths of several inches in very rainy weather.

The valley floors are partially drained by their major streams but may also have accumulations of standing water 3 feet or more deep in the rainy season. In places, minor accessory streams drain the back-swamp pools lying outside the natural levees built by the main streams.

Valley floors have developed as the result of filling of older deep valleys with alluvium transported by streams. Coastal lowlands have been formed of stream alluvium in places; in many places it has been mixed with sand from the shoreline zones. Beaches are largely sand thrown up upon the shore. In places such as Tumon, Hilaan, Achae Point, and Tarague great quantities of sand have accumulated. Some lowland has been planed or beveled by waves associated with previous higher stands of sea level.

Rock units

Alutom formation (Ta): The Alutom formation of Eocene and Oligocene age, named for Mount Alutom, is the oldest rock sequence exposed on Guam. The formation crops out over a large area in central Guam from the vicinity of Asan and Piti villages to Mount Almagosa and the northern environs of the Fena Reservoir. Mount Santa Rosa, Mataguac Hill, and nearby Palia Hill are inliers of the formation which underlies much of the north plateau (see pl. 4). Tuffaceous shales form prominent ridges and peaks along the road from Nimitz Hill to Mount Alutom and Mount Tenjo.

The Alutom formation is characterized by well bedded, fine-grained, water-laid tuffs with lensing gradations into fine sandstone. They range in color from gray to chalky white and form steep cliffs, projecting ledges, and rounded peaks. The more thoroughly cemented parts resist erosion and stand up as ledges and knobs above the general rolling upland (see pl. 5A). The tuffs contain much glass and particles of plagioclase, pyroxene, and magnetite-- the chief minerals of the lava flows. The tuffs are cemented by both calcite and silica. The indurated green tuff and breccia exposed near Mount Tenjo and Mount Alutom are siliceous. Fresh tuff encountered in drill holes is generally calcareous and well indurated, although in outcrop most of the calcareous cement is leached out.

The formation consists of about 10 percent of basic lava flows, and about 20 percent of conglomerate beds composed of blocks of basaltic rock ranging from coarse conglomerate with blocks up to 8 feet in diameter to a lapilli pyroclastic breccia. There are many gradations into tuffaceous sandstone and gravelly beds but the dominant rock is the white to grayish-green, fine-grained tuffaceous shale (pl. 7A).

Limestone fragments ranging from small chips and grains to blocks 2 feet in diameter are prominent in some of the lapilli conglomerate beds. The fragments contain foraminifers of Eocene age which can be readily picked out from small talus accumulations of sand and gravel. Tests of pelagic Foraminifera and Radiolaria occur in many of the sandy tuff beds.

The structure of the Alutom formation is markedly more complex than that of younger formations. It has a regional strike to the northeast and displays many small anticlines and synclines and local areas of extremely complex folding (pl. 7B). Several of these highly distorted areas are exposed along the cross-island road from Apra Heights to Talofofo. The beds are broken into many slightly tilted to vertical segments, intimately folded and faulted, with lava flows so completely intermingled that outcrops now present a confused jumble of blocks of pyroclastic and flow rocks. The Mount Tenjo and Mount Chachao areas have been faulted up above Miocene rocks to the south.

The base of the formation is not exposed but the thickness exposed above sea level is estimated to be 2,000 to 3,000 feet.

Intense weathering, ranging in depth from a few inches to at least 40 feet, characterizes surface outcrops. Ellipsoidal pillow lavas on Mount Santa Rosa and in Sasa Valley weather to soft punky rock that crumbles readily and forms a gritty plastic clay when wet. The weathered rock is commonly red, yellow, brown, and mauve in color. The fine-grained tuffs weather in situ to soft, plastic, red, yellow, green, buff, and white clays, which grade both vertically and laterally into unaltered tuffaceous beds. Silicified beds stand up in thousands of knobs, cliffs, and ledges of unaltered pyroclastics surrounded by deep surficial weathering.

The Alutom formation contains larger Foraminifera of Tertiary b (Eocene) and Tertiary c (Oligocene) age. Eocene planktonic Foraminifera and Radiolaria have also been identified.

All volcanic explosions and extrusions responsible for the building up of Guam from the ocean floor are believed to have been submarine. The volcanic ejectamenta were reworked and spread out on the sea floor between periods of explosive activity. Blocky submarine flows were extruded and broken up. Contemporaneous deformation occurred and subsequent folding and faulting took place before, during, and after the uplift of the island above sea level.

<u>Mahlac member (Tam)</u>: The Mahlac member of the Alutom formation is named for the Mahlac River in the Mapao area of south Guam. It crops out in the Fena Valley and along the northeast flank of the basin. A small outcrop near Santa Rita village on the west slope of Mount Alifan is the westernmost exposure. The most accessible exposure of the Mahlac member is about 3,000 feet north of the Fena Reservoir. Here the folded Mahlac member is exposed in a patch about 2,000 feet in greatest dimension. Another small patch is exposed 2,500 feet east of this larger exposure. In the Mapao area about 2 miles east-southeast of the two exposures mentioned above is a large exposure of the Mahlac member. Here the entire north flank of the Mahlac River valley

A. Alutom formation at Mount Santa Rosa. Thin-bedded, weathered tuffaceous shale and sandstone here are similar to that in the Mount Tenjo area.

B. Contorted and weathered Alutom formation near Manengon. Beds of clayey tuffaceous shale are crumbled and folded. The top of the outcrop is a small mesa capped with red soil of a former erosion surface.

is formed by this member, which continues into the prominent scarp extending for about 2 miles southeast.

The Mahlac member is a buff to tan or yellowish-tan, partly weathered, friable, fossiliferous shale composed of volcanic detritus deposited in water. In some exposures the matrix is calcareous. Weathering has produced vaguely defined sinuous bands of limonite stain through the rock. Many fracture surfaces also display a very thin and splotchy coating of limonite. Small to microscopic clusters of manganese oxide crystals occur throughout the rock.

The Mahlac is thin-bedded to laminated. In the Fena basin north of the reservoir it is fractured and crushed. The Mahlac River outcrops, although faulted, show less fracturing and the bedding planes are more discernible.

Tests of large and small foraminifers occur in the Mahlac shale; some beds contain many, others contain few or none. In general, large foraminifers are scarce compared to the abundance of small pelagic foraminifers.

The known thickness in the Mahlac River exposure is 200 feet, but judging by the general structure and presumed area of exposure, the formation probably is at least 500 to 1,000 feet thick there.

In the Fena River basin the Mahlac shale is unconformably overlain by the Maemong limestone member of the Umatac formation. Near Santa Rita it is overlain by the Facpi basalt member of the Umatac formation. The Mahlac dips gently eastward or southeastward into the slope of Mount Alifan. Only a few strata are exposed and the older, lower beds are disturbed or concealed.

The Mahlac shale is tentatively assigned to the Tertiary c (Oligocene), on the basis of smaller Foraminifera.

<u>Umatac formation</u>: The Umatac formation, of early Miocene age, named for the village of Umatac, is made up of four members: 1) the Facpi basalt member (Tuf); 2) the Maemong limestone member (Tum); 3) the Bolanos conglomerate member (Tub); and 4) the Dandan basalt member (Tud).

The Bolanos conglomerate member occurs in a conglomerate facies, and in a shale and sandstone facies. The Maemong limestone member also occurs in two facies: a shallow-water facies and a deep-water facies. These facies of the Bolanos conglomerate member and the Maemong limestone member are not differentiated on the geologic map (pl. 4) but are described below.

The bulk of the formation is made up of the Facpi basalt member and the Bolanos conglomerate member (see fig. 10). In the vicinity of Umatac and Merizo, in southwestern Guam, a composite section of the formation is as follows:

Umatac formation (from top downward)

Unit	Thickness (in feet)
Dandan flow member, including basal flow breccia	50
Bolanos conglomerate member	750
Facpi basalt member containing several beds of the Maemong limestone member (deep-water facies) which range from 15 to 260 feet in thickness	1,400
Total	2,200

The Facpi basalt member, the lowermost of the four members, underlies the Bolanos conglomerate member in the Umatac-Merizo area. The Bolanos conglomerate member in this area is not known to contain thick flows, although thin beds thought to be flow rock are present.

The conglomerate facies of the Bolanos conglomerate member is best developed on the upper slopes and crests of Mount Jumullong Manglo, Mount Bolanos, and Mount Schroeder. Toward the east this conglomerate grades stratigraphically upward into a shale and sandstone facies.

The Maemong limestone member contains two facies having a definite areal distribution. The shallow-water facies comprises residual masses of limestone in the Fena Valley lying on Eocene and Oligocene rocks and in many places overlain by the Bolanos conglomerate member. The deep-water facies forms tongues in the Facpi basalt member which crop out in stream beds on the western slopes of south Guam between Mount Lamlam and Merizo.

The Dandan flow member overlies the Bolanos conglomerate member in south Guam and is separated from this conglomerate by a bed of flow breccia which is as much as 10 feet thick.

Facpi basalt member (Tuf): The basal member of the Umatac formation, the Facpi basalt member, is here named for Facpi Point where a thick section of pillow basalts cut by dikes is exposed. This member consists of approximately 1,400 feet of basic lava flows and pillow basalts which include, in the vicinities of Merizo and Umatac, beds of tuffaceous limestone and pure limestone from 15 to 260 feet thick. The limestone is well exposed in stream bottoms of the Geus and Umatac Rivers. Beds of tuffaceous limestone and limestone ranging from a few feet to over 100 feet in thickness are exposed in stream channels and cliff faces from Merizo to the western slopes of Mount Lamlam. These beds of tuff and limestone are interpreted as a deep-water facies of the Maemong limestone member.

The basal flows crop out along the west coast of Guam (see pl. 5B) 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 flows form large outliers at Agat and Santa Rita (pl. 4). 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 many flows. Pink calcareous material commonly fills spaces between the ellipsoidal 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 (pls. 8A, 8B). 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 (see pl. 5B). 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 (pl. 8B). 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.

The beds of the deep-water facies of the Maemong limestone member contain large foraminifers identified as middle or late Tertiary e in age, corresponding generally to the early Miocene and thus establishing the age of the Facpi member as Tertiary e (Miocene).

Maemong limestone member (Tum): The Maemong limestone member of the Umatac formation is here named for the Maemong River which flows through the Fena-Mapao area in central Guam.

The Maemong limestone member is exposed in two principal areas in south Guam. The first area is in the Fena-mapao area of central Guam. There a shallow-water facies of the Maemong limestone member occurs as outliers upon volcanic rocks, interbedded with tuffs and conglomerates, and as small, scattered boulders and patches too small to show on the geologic map. The Maemong outliers are very noticeable in some places, where they form conical, steep-sided hills on more gently sloping volcanic rocks. These limestone hills have a vegetation cover significantly different from that developed on the acid volcanic soils surrounding the base of the hills. The outliers, thus, are prominent both by topography and vegetation. The interbedded Maemong limestone, in contrast, does not have recognizable physiographic features in the Fena area.

A. Sea stack of pillow basalt at Sella Bay. Stack and reef are pillow basalt of the Facpi basalt member of the Umatac formation.

B. Weathered pillow basalt near Agat. The pillows, of the Facpi basalt member of the Umatac formation, are completely weathered to clay.

Probably the most striking feature of the distribution of the shallow-water facies of the Maemong limestone member is the dispersal and small extent of individual outcrops. This probably results both from the lenticular character of the deposits and from faulting and subsequent erosion which has occurred since the deposition of the limestone.

The second area of outcrop of the Maemong limestone member is along the western slopes of south Guam, where limestone and tuff are exposed in stream valleys. In these valleys the Maemong limestone member is interbedded with the Facpi basalt member. The limestone and tuff of this area are called a deep-water facies.

The shallow-water facies of the Maemong limestone member is typically a white or pink-white, hard, compact, fine- to coarse-grained, partly recrystallized, fossiliferous, detrital limestone. It contains an abundance of large and small Foraminifera, a few molluscs, much calcareous algae, and many coral heads in position of growth. This facies is made up of almost pure limestone with small coatings of iron and manganese oxides in some places.

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 Maemong limestone member is approximately 260 feet thick where measured along the Geus River. Both the top and bottom of the member are exposed, whereas most of the outcrops in the Fena-Mapao area show the top eroded or the bottom concealed. One of the outliers along the north bank of the Mahlac River in the Mapao area is approximately 200 feet thick, but an undetermined thickness has been eroded. Drill cores east of the Mahlac River outliers show that the Maemong limestone member diminishes in thickness to as little as 20 feet.

The shallow-water facies in the Fena Valley area generally overlies the Mahlac shale member of the Alutom formation, although one small outlier lies on a white calcareous tuff containing numerous globigerinid Foraminifera. This tuff is thought to correlate with the deep-water facies of the Maemong limestone member at Merizo and Umatac. Most outliers of the shallow-water facies are on the sides of the Talofofo River valley well above the younger formations in the Fena Valley. One outcrop of the shallow-water facies in the Fena basin is covered by the Bolanos conglomerate, another by the Bonya limestone of Miocene f age.

The deep-water facies, except for the calcareous tuff in the Fena basin mentioned above, is everywhere interbedded with the Facpi basalt member. These beds generally dip to the east from 5 to 10° although some of the beds of this facies, probably involved in faulting, have dips up to 45° to the southwest.

The shallow-water facies of the Maemong limestone, which contains many coral heads in growth position, was formed as a reef and flanking detrital deposit on submerged volcanic slopes.

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, such as characterize the shallow-water facies.

The Maemong limestone member is assigned a Tertiary e (early Miocene) age on the basis of the following larger Foraminifera: Spiroclypeus higginsi; Miogypsina dehaartii; Heterostegina borneensis; and Spiroclypeus tidoenganensis.

Bolanos conglomerate member (Tub): The Bolanos conglomerate 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 conglomerate member cover the interior mountain range and flanking uplands of southern Guam (see pl. 6). They extend from the south shore of the island to Mount Jumullong Manglo and the valley of the Talofofo River with projections into the Fena basin and the Togcha River gorge.

The conglomerate facies of the Bolanos conglomerate member is composed of sub-rounded 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 basalt 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. South and east there is a pronounced increase in their size and number; many exposures contain angular limestone blocks up to a foot in diameter. Some outcrops in the Fena River area and near Dandan show small lenses or tongues of well rounded gravel containing limestone pebbles.

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. This facies is also exposed in the hills and stream bottoms in the vicinity of the Inarajan water system.

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.

The dissected upland between the central mountain range and the limestones fringing the east coast, extending from the Fena basin and Talofofo River southward to Inarajan River, is underlain by the sandstone-shale facies of the Bolanos member (pl. 9). The sediments consist predominantly of tuffaceous sandstone, sandy gravels and tuffaceous shales, with coarse conglomeratic beds and lenses forming less than 10 percent. The sandstone-shale facies is gradational with and in general above the coarse conglomerate facies. Outcrops of coarse conglomerate of the Bolanos member are exposed in eroded crests of small anticlinal folds near Dandan; approximately 100 feet of tuffaceous shales and weathered conglomerates of the sandstone-shale facies overlie compact typical conglomerate facies.

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 Bolanos conglomerate member is above the Facpi basalt member and the Maemong limestone member of Tertiary e age. The Bolanos member includes limestone fragments that contain large foraminifers of Tertiary e age. At the top of the Bolanos member, well preserved foraminifers are present in the matrix. These do not appear to be abraided or derived from pre-existing rocks, and are identified as late Tertiary e.

Dandan basalt member (Tud): 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. They are especially prominent in the Dandan area, from which area the unit is named.

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 (pl. 9). 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 basalt 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 relatively simple structure of the Dandan flows can be seen from vantage points on Mounts Alutom and Tenjo. The northeasterly slopes of Bolanos, Jumullong Manglo, and other peaks in the southern mountains are clearly seen as dip slopes extending to the dissected eastern tableland. These dip slopes parallel the contact between the Dandan basalt member and the underlying Bolanos conglomerate member (see structure section E-E', pl. 4). Angles of dip average between 5 and 10°.

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 basalt member are in general deeply weathered and show every gradation from fresh rock to soft, limonitic, clay-like masses.

The Dandan basalt 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, lavas mapped as Facpi flows but possibly equivalent to the Dandan basalt member are overlain by Bonya limestone of Tertiary f age. The Dandan basalt member is assigned to a late Tertiary e age on this basis.

Bonya limestone (Tb): The Bonya limestone is here named for the Bonya River which flows through the outcrop area of this limestone in the Fena basin in central south Guam.

The Bonya limestone crops out over much of the lowest areas of the Fena basin, the Mapao-Maagas River area, along scarps of the Talofofo, Ugum, and Togcha Rivers. It is exposed principally as a series of outliers and karst features, but also occurs interstratified with other deposits. Good sections are exposed in many places, particularly in the karst area adjacent to the northeast side of the Fena Reservoir. Many of the larger outliers, between the Bonya, Maemong, Maagas, and Mahlac Rivers, are surrounded by alluvium.

Limestone outcrops similar in lithology or foraminiferal content are tentatively assigned to the Bonya limestone: the exposures northeast of Yona, and the limestone near Mount Santa Rosa, both on the plateau and along the coast.

PLATE 9

Weathered surface near Dandan. Boulders and blocks weathered from the Dandan basalt member lie upon the tuffaceous sandstone-shale facies of the Bolanos conglomerate member of the Umatac formation. The large erosional scars, typical of this part of the Bolanos member, give an arid aspect to a landscape which receives an average of 90 inches of rain per year.

The principal Bonya exposures are concentrated in a relatively small area in the Fena-Talofofo Rivers valley. Other small exposures occur on the southeast side of the Ugum River scarp and on the steep-sided Togcha River valley.

Most of the outliers of Bonya limestone are topographically prominent because of their steep or vertical sides and the numbers of sink-holes formed in the larger masses. Several streams have cut underground channels through the Bonya. Some very flat areas in volcanic terrain on both sides of the valley of the Fena-Talofofo Rivers have Bonya boulder debris scattered about the surface where at a previous time there evidently were thicker deposits of the formation. The Bonya limestone crops out also on the flanks of Mount Santa Rosa and along the east coast of north Guam.

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.

Some outcrops, particularly the ones in the exposures between the Talofofo and Ugum Rivers, show the Bonya as a buff-white, compact limestone having much gray to black manganese oxide which evidently replaces the calcium carbonate. These manganiferous rocks are mottled in appearance and are more dense than the normal porous Bonya limestone. Fairly large pieces of rock seem to be almost completely replaced and are dark gray to black on a fresh surface.

Corals are not common and occur mainly in a few outcrops which possibly may represent an old reef surface. Algal remains are more common than corals but are confined largely to outcrops which apparently represent shallower deposition than does the bulk of the formation.

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 shows a zone of weathering in which iron and manganese in the rock oxidize and, in places, change the color from gray to pink or buff.

The limestone northeast of Yona is a dense, white, pure, extremely hard foraminiferal limestone formed of the packed tests of the foraminifer *Rotalia*. In appearance it is much like some present-day beach rock. The outcrops near Mount Santa Rosa are more similar in lithology to the facies in the Fena River basin.

The thickness of the Bonya limestone generally does not exceed 120 feet. Many outliers are much thinner because of the removal of the rock material by solution. A section in the Fena basin dips about 3° and has accessible, well exposed contacts with the overlying and underlying rocks; a section in the Togcha River is also well exposed. Fairly good sections are exposed in some of the vertical walls of sinks in the karst area, but these commonly have concealed lower contacts and eroded upper contacts.

The Bonya thins to 40 feet or less over most of its mile-long western margin.

The Bonya limestone rests upon rocks of Tertiary e (early Miocene) age in south Guam. Generally the limestone is underlain by the Bolanos conglomerate member of the Umatac formation, but in one place in the Fena Valley it lies directly over the Maemong limestone member. The Bonya in turn is overlain by the Barrigada limestone in some areas and by the Talisay formation in others (see fig. 10).

The lower contact of the Bonya limestone is generally unconformable over most of the area of outcrop. Locally the contact grades in 5 to 15 feet from the underlying Bolanos conglomerate member, but the basal Bonya carries large cobbles and fragments of the older formation, indicating generally unconformable relations.

The upper contact of the Bonya limestone, where present, is conformable with the overlying rock unit, which near the east coast is the Barrigada limestone. The north side of the Talofofo River valley, 3/4 mile west of the bayhead, is a steep scarp showing a conformable upper contact dipping 15° S. 80° E. between the Bonya limestone and the Barrigada limestone. The lowest Barrigada limestone here contains abundant corals.

Along its northern boundary in the Fena basin the Bonya is conformably overlain by the greatly weathered volcanic conglomerates forming the base of the Talisay formation.

In north Guam the Bonya limestone crops out on the northeast flank of Mount Santa Rosa where it unconformably overlies the Alutom formation and is unconformably overlain by Mariana limestone. The Bonya limestone also crops out along the east coast of north Guam where it unconformably overlies the Alutom formation and grades upward into a thin section of Barrigada limestone, or where this is lacking, sharply underlies the Janum formation.

The foraminifers *Rotalia atjehensis*, *Cycloclypeus* (*Katacycloclypeus*), *Lepidocyclina parva*, *L. sumatrensis*, and *Miogypsinoides cupulaeformis*, occur in the Bonya limestone, which is tentatively assigned a Tertiary f (Miocene) age.

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.

Barrigada limestone (Tbl): The Barrigada limestone is named for Barrigada Hill, along the lower slopes of which is exposed the type section. The rock is white, even-grained, and has a chalky fracture. It contains genera of large foraminifers which are criteria for recognizing: *Operculinoides* sp., *Gypsina* sp., and *Cycloclypeus* sp. The base of the formation is not exposed on north Guam; the top is overlain by the Mariana limestone (see fig. 10). In south Guam the formation is on the Bonya limestone and is overlain by the Agana argillaceous member of the Mariana limestone.

The Barrigada limestone crops out from Harmon Field and Barrigada Hill north to Haputo and east to Mount Santa Rosa. It forms a ring-shaped area 6 miles in diameter, and the width of outcrop averages about a mile. A small inlier is mapped at the base of the Tarague cliffs. Other small scattered patches may be present although not mapped.

In south Guam only two exposures are known. These are shown on the geologic map of the valley slope north and south of the Talofofo River near its confluence with the Ugum River.

Barrigada limestone is moderately homogeneous over most of its area of outcrop. It is thick-bedded to massive, intensely white, pure detrital limestone. It is compact in appearance but is finely porous and permeable. Much of the limestone is tough and difficult to break with a hammer; a fresh fracture has a dusty or chalky appearance.

Sand-size calcareous detritus is the dominant component of the Barrigada. Relict structures of many fossils and detrital grains are poorly preserved and most fossils are obliterated by distintegration or recrystallization. The foraminifers and algae generally appear well preserved, but as seen under a hand lens they are chalky and friable.

The unconsolidated calcareous sand of the sand pit 1 mile north-west of Barrigada hill is mapped as Barrigada limestone in the lower part of the pit. The lower fine sand is barren of fossils except for a few *Pecten* and *Ostrea*, but rare, poorly preserved *Gypsina* in the sand make a correlation with Barrigada appear plausible.

The maximum thickness of the Barrigada is unknown. It is no more than 100 feet thick in any outcrop or well in south Guam. Rock from the bottom of a well near Haputo, in north Guam, that was drilled in limestone to a depth of 543 feet is similar in lithology and foraminiferal content to Barrigada limestone exposed at the surface. The maximum thickness is therefore presumed to be greater than 543 feet.

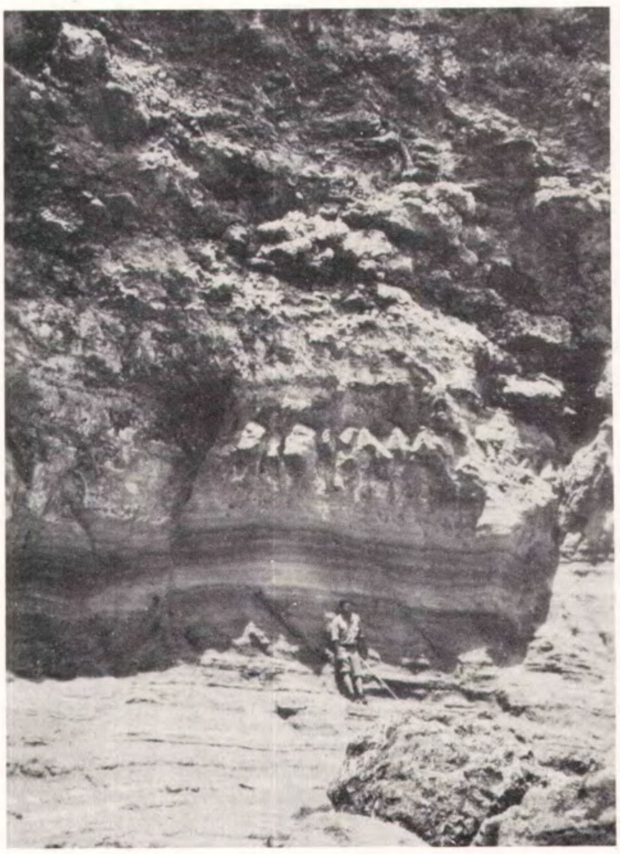
Corals and shells of molluscs are rarely well enough preserved to identify, although branching *Acropora*, *Seriatopora*, and *Porites* are known to be present in the upper part of the formation. It is possible that some molluscan-rich or coralliferous parts of the Barrigada have been mapped as Mariana limestone where diagnostic foraminifers are not present.

The detrital foraminiferal sands of the Barrigada limestone are interpreted as being submarine bank limestones formed at depths of about 600 feet. The peripheral slopes of the formation and the abundance of coral and molluscan remains in the upper Barrigada indicate that the banks shoaled in late Barrigada time sufficiently to permit reef growth near the surface.

The age of the Barrigada limestone is not definitely known. In north Guam it is believed to be Tertiary g, (late Miocene), as one species of *Operculina* resembles a species obtained from the Tertiary g of a Bikini core at a depth of 900 feet.

In south Guam as well as at Catalina Point, the Barrigada overlies the Bonya limestone which contains *Katacycloclypeus*, *Miogypsinoides*, and *Lepidocyclina* of Tertiary f age. The most reasonable age for the Barrigada limestone is therefore Tertiary g (late Miocene).

A. Janum formation at Catalina Point. Slightly faulted, well bedded foraminiferal tuffaceous limestone lies under a conglomerate of the detrital facies of the Mariana limestone.



B. Janum formation at Catalina Point. This close-up photo of the exposure shown in Plate 10A shows small faults in the Janum formation that do not extend into the overlying Mariana limestone.

Janum formation (Tj): The Janum formation is named from Janum Point on the northeast coast of Guam. The type section is at Catalina Point where approximately 70 feet of the formation is exposed in a coastal reentrant (pl. 10A).

The Janum formation crops out in 7 places along the northeast coast between Lujuna Point and Anao Point. Lenses exposed north and south of Catalina Point thin away from the type locality. At Anao Point 6 feet of the formation is exposed and at Lujuna Point, 4 feet.

The rock is compact to friable, red, pink, brown, yellow, or white, slightly to highly tuffaceous or argillaceous, fine- to medium-grained, well bedded, foraminiferal limestone. The beds are closely faulted and jointed (pl. 10B).

Contacts with the overlying Mariana limestone are sharp and well defined unconformities except at Anao Point where a conglomerate of mixed cobbles is present, bearing both pink fragments of the Janum formation and white cobbles of the Mariana limestone.

At Lujuna Point the lower contact is sharp and well defined with the Janum formation resting conformably on compact, white, jointed Bonya limestone. At Catalina Point the Janum formation grades downward into a few feet of the Barrigada limestone which in turn grades down into the Bonya limestone (see fig. 10).

A profuse variety of pelagic Foraminifera and some benthonic Foraminifera are abundant in the Janum formation. These fossils are thought to indicate deposition at depths of from 100 to 1,500 fathoms, more likely closer to 100 fathoms. The Foraminifera are Miocene in age. The Janum formation possibly represents an offshore equivalent of the Barrigada or Alifan limestones, and therefore may be Tertiary g in age.

Talisay formation (Tt): The Talisay formation is named for the Talisay River that flows through the area of outcrop in the western part of the Fena River basin and the east slopes of Mount Alifan. The Talisay formation is made up of volcanic conglomerate, bedded marine clay, marl, and clayey limestone.

The formation is present in the area west of the Fena Reservoir, in the floor of the Fena River basin, and on the east slope of Mount Alifan. It crops out near Santa Rita on the west slope of Mount Alifan, and covers part of the lowland east of Apra Harbor. The Talisay is represented chiefly by clays in southwestern outcrops and is difficult to differentiate from weathered volcanic rocks. In the Fena basin, however, thin clay beds in the Talisay are distinctive.

The Talisay formation consists in the Fena basin 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 prophyritic 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. It is notably constant in composition and appearance over a distance of several miles.

A buff-white, porous to compact, fine- to coarse-grained, partly recrystallized detrital limestone containing abundant molluscs and foraminifers occurs in some outcrops, overlying the other beds of the Talisay formation; the limestone may be equivalent to basal Alifan limestone. Contacts between these various units are in general clearly defined, but good sections of the formation are few.

The Talisay formation is thin- to thick-bedded, is 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 formation 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 conglomerate is more than 7 feet and probably less than 15 feet thick. In another outcrop half a mile to the southeast, the Talisay consists only of volcanic conglomerate about 30 feet thick.

A good section of the Talisay formation occurs near the northeast side of the exposure area, 1 1/2 miles southeast of the first outcrop mentioned above, and 1 mile east of the second. It consists of a 10-foot-thick weathered volcanic conglomerate overlain by 5 feet of bentonitic coralline rubble, in turn overlain by approximately 12 feet of molluscan limestone assigned to the Talisay formation. This 27-foot section is conformable upon the Bonya limestone. The top of the Talisay here is an erosional unconformity or disconformity between the molluscan limestone and the overlying Alifan. The beds are nearly horizontal.

In general the Talisay formation appears to be conformable with the underlying Bonya limestone, and unconformable with the underlying Alutom formation. It is generally overlain conformably by the Alifan limestone and was probably formed in part as a basal conglomerate or downslope facies of the Alifan limestone.

The formation contains Rotalia atjehensis, and molluscs which have not been identified. Marly beds contain such corals as stick-like Acropora and Porites, as well as molluscs that appear identical to those in the overlying Alifan. The Talisay conformably overlies the Bonya limestone, whose top contains the foraminifer Cycloclypeus (Katacycloclypeus), probably of Tertiary f age. The top of the Bonya also marks the disappearance of Lepidocyclina and Miogypsina, which is the original definition of the Tertiary f-Tertiary g contact. For these reasons the Talisay formation is tentatively assigned to the Tertiary g, or late Miocene. The Talisay is probably equivalent in age to at least a part of the Barrigada limestone.

The Talisay formation 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 (Tal): The Alifan limestone is named for Mount Alifan, where the best section of the formation is exposed in the Alifan (Naval Ammunition Depot) Quarry. Relations to overlying and underlying formations are not shown in the type locality, but are inferred from the mapped relations (see fig. 10): the Alifan overlies the Talisay formation, and is overlain by the Mariana limestone.

The limestone exposed in the Mount Alifan Quarry is a crudely bedded, white to buff detrital limestone containing molds of molluscs and branching corals, and some recrystallized massive corals. The bottom of the quarry is in pink to red, compact, fine limestone with abundant large tubes, probably of boring molluscs. The tubes are about an inch in diameter, 1 to 3 feet long, crooked, and nearly vertical.

On Mount Lamlam the Alifan limestone is a massive, moderately hard, light pink to red detrital limestone containing abundant branching *Porites* and *Acropora*, and molluscan molds.

On Nimitz Hill about 70 feet of the formation is well exposed in a quarry. It is a white to light buff, poorly consolidated, thick-bedded, porous detrital limestone, and is formed of hard, rubbly fragments of limestone in a moderately soft matrix. Molds of molluscs and branching corals are common but not abundant. Large *Tridacna* and *Ostrea* are reported from this pit.

Light-red flaggy limestone similar to the lowermost rocks in the Alifan Quarry is exposed near the quarry. Roadcuts along Nimitz Hill show massive compact recrystallized limestone, highly jointed and faulted, that can be traced into the porous, rubbly-bedded quarry limestone.

In Agana scarp, in Sinajana, and in the other localities mapped on the north plateau, the Alifan is a white to buff, massive and compact recrystallized limestone. It is strongly jointed and fractured, and is overlain with a marked unconformity by less recrystallized and less disturbed fossiliferous Mariana limestone.

The maximum thickness of the Alifan limestone probably is more than 200 feet, on Mount Almagosa. It is difficult to infer a maximum thickness on the Mount Alifan - Mount Lamlam ridge because of the irregularity of the surface of the underlying volcanic rocks.

Near Dandan on the southeast side of Guam, thin patches of sandy fucoidal limestone are correlated with the Alifan limestone. These are overlain by *Turritella*-bearing argillaceous limestone of the Agana member of the Mariana limestone. In most places along the east coast the Alifan limestone is missing, but its equivalent may be represented by thin *Globigerina*-bearing calcareous clay between the Bonya limestone and the Mariana limestone.

Delicate branching *Porites* and *Acropora* corals are abundant in places. Bivalves and burrowing worms or gastropods are abundant in other places. These fossils indicate generally undisturbed lagoonal deposition.

Foraminifera from the lowermost limestone on Mount Alifan, which probably is equivalent in age to the Talisay formation, also occur in the Miocene strata of Guam. Molluscs from the top of the formation on Mount Alifan might be as old as Miocene, although similar or identical species live in present seas. At Agana, limestone interpreted to be the Alifan is unconformably overlain by the Agana argillaceous member of the Mariana limestone, which probably is of Pliocene age. The Alifan formation therefore probably is Tertiary g (late Miocene) or Tertiary h (early Pliocene) in age.

<u>Mariana limestone</u>: The Mariana limestone forms about 80 percent of the exposed limestone of Guam. It is correlated with

the Mariana limestone, of probable older Pleistocene and possible Pliocene age (Cloud, et al., 1956), previously described on Saipan and Tinian. The Mariana limestone is a complex of reef and lagoonal limestone mapped as five units (fig. 13). The reef facies (QTmr) forms a discontinuous peripheral belt of rock at or near the present cliff line; this facies encloses the detrital facies (QTmd) and the molluscan facies (QTmm), both of lagoonal origin. The Agana argillaceous member (QTma) is restricted to a fringe around the older volcanic rocks that were the source of the clay in this member. The Lafac sand member (QTml) is a foraminiferal sand and gravel of fore-reef type on low coastal terraces and scarps.

As can be seen from the geologic map (pl. 4), the Mariana limestone is the most widely exposed formation on Guam. It covers most of the north plateau including almost all the cliffs and terraces (see pls. 1B, 2A, 2B), thinly fringes the west coast from Adelup Point to Facpi Point, forms the massive cliffs of Orote Peninsula, and makes the broad marginal limestone apron from Pago Bay nearly to Merizo (see pl. 6).

The Mariana limestone formed as interlensing lagoonal sediments and peripheral reef deposits on a floor of irregular volcanic rock and older limestone. The thickness of the formation is therefore highly variable. As the base of the formation is rarely exposed, the thickness is difficult to judge, but it ranges from a thin edge, where the formation lenses out on older deposits, to more than 500 feet on some coastal cliffs.

A small high-spired gastropod, *Turritella filiola*, is one of the few distinctive fossils found in this formation; it has been useful as a field criterion or index fossil. It is reported to be common in the lower Pliocene of Okinawa. It is restricted to the Mariana limestone on Guam, where it is found in fine-grained sediments. *Turritella filiola* is abundant throughout the Agana argillaceous member of the Mariana limestone from Barrigada village south to Inarajan. In pure limestone of the north plateau *Turritella filiola* has been found in several localities in both the molluscan and detrital facies in fine-grained sublithographic limestone. The mollusc apparently was restricted to muddy bottoms.

The Mariana limestone unconformably overlies Alifan limestone and Barrigada limestone, and in places the older volcanic rocks near the coasts (see fig. 10). It is not overlain by any deposits except on its margins where late terraces were cut into it and Recent coral and sandy veneers were deposited.

Reef facies (QTmr): This facies is best exposed near Mount Machanao on northwest Guam where extensive areal deposits of coral and algal reef rock overlie and grade laterally into the detrital facies. Three rock types were mapped separately and later combined into this facies: 1) a reef rock containing abundant corals, a large proportion of which are in position of growth; 2) a coral-algal reef rock containing abundant corals, many in place and cemented by algal crusts; and 3) an algal reef rock made up mainly of calcareous algae similar to the *Porolithon* on present-day reef margins.

The lithology of the reef facies is distinctive. The coral and algal remains form a well consolidated rock that is generally porous, but near cliffs is completely recrystallized with pores filled by calcite to form a sheath of compact limestone. Joints and faults are zones of recrystallization near cliffs.

Inshore from the cliffs, the abundant corals become more scattered, and the proportion of detrital material between corals increases until the reef facies merges with the detrital facies described below (fig. 13). The detrital facies is interpreted as lagoonal in origin. Patches of highly coralliferous reef rock, many of them large enough to be mapped, are common among the lagoonal sediments; the patches are interpreted as reef knolls formed in the lagoon, within the encircling reef. Reef corals of types such as _Favia_, blunt _Acropora_, _Pocillopora_, and meandrine or "brain" corals are common. Reef molluscs such as _Trochus_, _Turbo_, and elongate coral borers are abundant in places. The distribution of the reef facies is shown on the geologic map (pl. 4). This facies is neither continuous nor uniform, but generally forms the peripheral cliffs of the island (pl. 11A). Some discontinuities and breaks, for instance near Campanaya Point, can be interpreted as more deeply submerged intervals or channels in the original reef, where detrital material was dominant. Other gaps between mapped areas of the reef facies, such as between Tanguisson Point and Amantes Point, are probably caused by subsequent removal of parts of the cliff line by erosion or faulting.

Detrital facies (QTmr) and molluscan facies (QTmm): The detrital facies is well exposed in the north-facing cliff behind Tarague beach and in quarries on Andersen Air Force Base (pl. 11B). The molluscan facies is well shown at Salisbury Junction. The detrital and molluscan facies include several lithologic and biologic varieties: 1) A detrital coral rock in which corals are the dominant fossil. A significant proportion of the corals are broken or worn, but in places some may be found in position of growth; in other places the worn corals form a conglomerate. Corals in general make up less than 10 percent of the rock. 2) Detrital-molluscan limestone containing pelecypod and gastropod molds in a fine- to medium-grained detrital matrix. 3) A coral-molluscan limestone containing abundant corals and molluscs. 4) Rock in which scattered fossils are abundant but in which no single fossil group is predominant. 5) Fine-grained, almost sublithographic limestone containing molds of mud-burrowing clams and gastropods. 6) A _Halimeda_-rich limestone.

Agana argillaceous member (QTma): The pale-yellow to yellowish-brown clayey limestone that fringes most of the volcanic mass of southern Guam has been mapped as a member of the Mariana limestone and is here named the Agana argillaceous member, after the city of Agana. The type locality of the member is the cliff behind Agana where the argillaceous limestone overlies with marked unconformity a massive, fractured, pure limestone mapped as Alifan limestone.

The Agana argillaceous member generally overlies volcanic rocks, and is distributed around the southern part of the island from Agat north to Adelup Point, and from Pago Bay south nearly to Merizo. North of the Adelup Point-Pago Bay fault, on the north plateau of Guam, the Agana member forms a triangular area of exposure that ends near Barrigada Hill, about 5 miles from the volcanic hills.

The Agana argillaceous member contains lenses of rock equivalent to members mapped in the pure Mariana limestone. These members have not been differentiated within the bounds of the Agana argillaceous member. The lithology is mostly similar to that of the detrital and detrital-molluscan facies of the Mariana limestone except for a contaminating clay, which is mostly disseminated sparsely through the limestone but here and there is concentrated in pores and cavities within the limestone by percolation of water. The Agana argillaceous

A. Reef facies of the Mariana limestone at Lafac Point. Outcrop is an excellent cross-section of one of the "ramparts" that typically rim the limestone cliffs.

B. Detrital facies of the Mariana limestone at Andersen Air Force Base. Serrate profile below the flat surface of the northern Guam plateau results from red soil filling small solution pits and pipes.

member contains roughly 2 to 6 percent of clay disseminated through the rock. Many cuts, for example the roadcuts and quarries between Talofofo Bay and Inarajan and roadcuts from Asan to Orote, show much clay in cavities, fissures, and small pockets. The total clay content in many cuts exceeds 20 percent and in a few may exceed 50 percent of the rock mass, but throughout most of the mapped area the limestone in a fresh fracture does not appear to contain much clay.

Lafac sand member (QTml): The Lafac sand member is exposed in two areas on the east coast of Guam. At Lafac Point, the type locality, this member forms apron-like, wedge-shaped deposits thickening seaward, and directly overlying the rest of the Mariana limestone. At the type locality at least 150 feet of the member is exposed, and the beds extend below sea level. The deposit here is a thin-bedded, white, well sorted, friable, medium- to coarse-grained limestone made up almost entirely of tests of foraminifers weakly cemented by calcite. The beds dip gently to the southeast, and cover massive Mariana limestone. The second exposure of this member, flanking the mouth of the Togcha River, is made up of conglomeratic limestone containing pebbles and boulders of Bonya limestone in a matrix of weakly-cemented tests of foraminifers. This matrix greatly resembles the lithology of the type locality.

The Lafac sand member of the Mariana limestone contains *Calcarina spengleri*, *Amphistegina*, *Marginopora*, and *Gypsina* -- a foraminiferal assemblage distinctive of the Pleistocene epoch. The Lafac occurs generally as a mantling deposit on older parts of the Mariana limestone; it is believed to have been laid down as a fore-reef sand and, possibly, talus conglomerate during late Mariana limestone time.

Some detrital limestone on terraces seaward and below the reef facies must have formed as off-reef slope deposits seaward of the reef. Few if any of the supposed off-reef deposits can be differentiated lithologically from the lagoonal detrital deposits. Notable exceptions are the bedded, gently dipping, foraminiferal Lafac sand just described, and the well bedded, steeply-dipping conglomerate beds along the northeast coast from Janum Point to Catalina Point. These conglomerate beds dip about 25 to 30 degrees to the southeast, and like the Lafac sand, are interpreted as off-reef deposits.

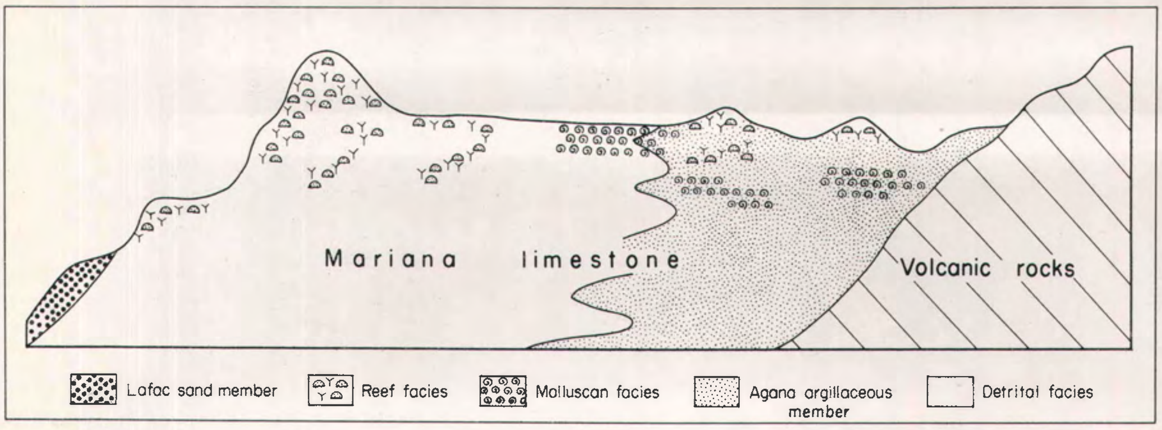


Figure 13. Relationships of facies and members of the Mariana limestone.

Weathering and Erosion

The volcanic rocks and the limestones of Guam show great basic differences in their reaction to weathering and erosion. The physiography of the limestone on the north plateau has been discussed in a preceding section. Weathering and erosion is by solution of calcium carbonate in percolating rainwater. The purity of much of the limestone results in the essential absence of any residual product of weathering.

Much of the thin, friable, red soil found on pure limestones (see pl. 11B) contains considerable alumina in the form of the mineral gibbsite, and much iron oxide as limonite and hematite. The soil is thought to be derived from material transported onto the limestone surface, rather than from impurities contained within the limestone. Reddish-brown to yellowish-brown clayey soils, on the other hand, are found on the Agana argillaceous member of the Mariana limestone, and on the contaminated facies of other older limestones. These contaminated limestones all furnish clays that remain as residual products of weathering; the clays are thought to be mostly kaolinite and illite.

In contrast to the limestones, the volcanic rocks are deeply weathered to clay over most of their area of outcrop. A series of 9 soils borings were made with a power auger to test variations in thickness of the weathered mantle in areas where it was especially well preserved. The average depth of severe weathering was found to be about 50 feet, but one hole 79 feet deep did not encounter fresh rock.

Excellent sections of the weathered mantle are exposed in many places. One section is on the cross-island road between Apra Heights and Camp Witek, where 5 to 7 feet of red, friable clay overlie contorted varicolored tuff beds that are completely weathered to clay. At least 30 feet of weathered rock is exposed above the general land surface (see pl. 7B). In the erosional cut next to the Agat dump, on the road to Mount Lamlam, 4 to 8 feet of red, friable clay overlie more than 50 feet of exposed weathered pillow basalt and conglomerate. The pillow basalt structures are perfectly preserved although entirely weathered to kaolinite and illite (see pl. 8B). Some of the conglomerate is a primary conglomerate or agglomerate associated with the basalt and weathered to clay; the rest, which can hardly be differentiated from the primary conglomerate, is a rubble or breccia of slumped weathered pillow basalt. Masses of such clayey breccia were seen forming in slides that took place after saturation by the rains of October 15, 1953. Much of the weathered clayey conglomerate and breccias of south Guam may have formed in this manner.

Clay minerals that have been identified from the weathered rocks of Guam are kaolinite, halloysite, and montmorillonite. Gibbsite has been identified from some of the overlying red friable clay. Small nodules and concretions collected on Nimitz Hill in 1946 by Josiah Bridge were found to consist dominantly of gibbsite. The weathered profile of a red, earthy, alumina- and iron-rich layer overlying completely weathered clayey rocks is typical of lateritic weathering described from other humid tropic regions. Agricultural and engineering problems on these materials will be similar to those encountered in other tropical islands that have experienced a similar geologic history, including a period of intensive lateritic weathering followed by intensive erosion.

The capping red lateritic material is preserved mostly as scattered small, mesa-like remnants on the rolling uplands of south Guam, which generally are between elevations of 150 and 600 feet and concentrated between 400 and 500 feet. They range in size from 50 feet in largest diameter to 5 or 10 acres in area, and represent the actual residuals of a former rolling land surface now highly dissected and largely eroded away. The general configuration of the former surface is still apparent over much of the areas between the mesas, and the surface forms present-day gently sloping and rolling tablelands. The tablelands form the tops of divides between major streams and the plateau-like crests of both the Tenjo-Alutom Mountains block and the Jumullong Manglo-Bolanos-Sasalaguan Mountains ridge or cuesta. Remnants of the former surface are found on lower slopes from Apra Heights to Umatac.

The dissection of the old, intensely weathered surface of south Guam is severe. Erosion of the weathered mantle on remnants of the surface is also severe and it increases toward the crest of the mountains. Much of the area of the residually weathered surface was formerly covered by the Alifan limestone, and probably by the underlying conglomerate and clayey beds of the Talisay formation, as well preserved molluscs and corals, especially stick-like Acropora and Porites, are found associated with the red lateritic surface. Most of the remnants of the lateritic surface are higher than present outcrops, or inferred former outcrops, of Mariana limestone. Therefore, the intense weathering is thought to have occurred principally during a single cycle, after uplift and considerable erosion of the Talisay and Alifan formations, but before the younger clayey Mariana sediments were uplifted and eroded. The intensive weathering probably is late Pliocene or early Pleistocene in age.

Especially widespread erosion and dissection of the deeply weathered surface started after uplift of the island to its present altitude, and has continued to the present time. It is estimated that only 1 to 5 percent of the original weathered surface persists in the form of small mesas. In south Guam about 30 to 40 percent of the old surface is recognizable as poorly drained, flat to rolling upland areas with much slump topography. These areas, which slope generally from 5 to 20 percent, are covered in most places by 50 feet or more of weathered rock, although outcrops of hard rock protrude here and there, and although slumping and dissection of the mantle has produced extreme variability in its thickness.

Details of the extent and distribution of the mantle are shown on the soils map of Guam. The knowledge of this mantle is especially important for its effect on engineering planning on the island, and because it is the aquifer which feeds the major perennial streams of south Guam.

Structural Geology

The island of Guam displays structures such as folds, normal faults, and thrust faults in the Eocene volcanic rocks; normal faults and minor folds in the Miocene volcanic rocks; and normal faults in the limestones of Miocene and post-Miocene age. Prominent joint zones and structural breaks are well developed in both the limestones and the volcanic rocks. The joint zones in the limestones are characterized by parallel, narrow, deep fissures between which have developed elongate spines and ridges (see pl. 2B); the rock itself is generally not brecciated. The volcanic rocks are cut by structural breaks, easily traced on aerial photographs, which show as a series of knobs and ridges cutting across topographic trends or as long, straight alinements in otherwise normal terrain. Drainage patterns are, in places, determined by these lines, as are valley wall alinements. Minor movement along these joint zones and breaks may have occurred but significant stratigraphic displacement has not been found. These zones and breaks are shown on the geologic map (pl. 4) by alined joint symbols. Joints are present in all of the formations on the island.

Major faults and fault zones: Several large faults of considerable displacement cut the island. Some of these, listed below, form boundaries between physiographic, lithologic, and structural units.

Pago Bay-Adelup Point fault: This fault, which extends across the narrow "waist" of Guam from Pago Bay to Adelup Point, offsets the Alutom formation and the Alifan limestone and forms the structural boundary between the northern and southern parts of Guam. The Alifan limestone, where it is cut by this fault on the north side of Nimitz Hill and on the sides of the Fonte River valley, is slickensided and contains wide zones of recemented limestone breccias. The fault planes in the limestone strike northwest and dip approximately 40° to the northeast. The limestone on Nimitz Hill is correlated with a similar limestone near the base of the scarp south of the town of Agana, under The Naval Hospital; the total vertical displacement is estimated at from 200 to 600 feet. Movement along this fault has not disturbed the Agana argillaceous member of the Mariana limestone that unconformably overlies the Alutom formation at the foot of the fault scarp between the Fonte and Pago River valleys. Major movement along this fault occurred after the deposition of the Alifan limestone but before the deposition of the Agana argillaceous member of the Mariana limestone. The prominent joint zones that cut the Mariana limestone just south of Pago Bay probably are surface expressions of minor post-Mariana limestone movement along this fault.

Santa Rita-Talofofo River valley fault zone: Several nearly parallel, high-angle normal faults (of which two are mapped) cut the Alutom formation for about 2 miles southeast from Santa Rita settlement. From Fena basin to Talofofo Bay these faults are thought to continue southeastward to Talofofo Bay, but are concealed beneath post-Eocene deposits. Major movement along these faults probably took place after the deposition of the Alutom formation. Some movement occurred during the deposition of the Miocene volcanic rocks and limestones, which show many small local faults that do not carry into younger overlying rocks. Later movement, after deposition of the upper Mariana limestone, along the fault zone extension through Talofofo Bay is indicated by the vertical offsetting seen in cliffs of the upper Mariana limestone around the bay. This fault zone lies along the physiographic boundary between high, broken uplands developed on the Alutom formation and the plateaus developed on the Miocene volcanic rocks of southern Guam.

Tamuning-Barrigada fault: This is a high-angle normal fault marked by a long fault scarp that begins on the west coast at Tamuning and trends northeast to die out on the plateau northeast of Barrigada Hill. The south side is uplifted an estimated 50 to 200 feet. The fault trace, with its associated fracture and brecciated zones in the scarp, transects exposures of both Barrigada and Mariana limestones. Discontinuous fracture planes occur in quarries along the slope of the scarp; elsewhere the fractured rock and breccias are the main evidence of faulting.

Some of the faulting was probably contemporaneous with the Pago-Adelup faulting and the emergence of the Alifan limestone mound at the summit of Barrigada Hill. Later movement brecciated the overlying Mariana limestone.

Pugua fault: This high-angle normal fault strikes west of north, and extends from Uruno Point, where its trace lies offshore, through the cliff at Pugua. It dies out in the Barrigada limestone near Taguac. Major movement along the fault took place before the deposition of the Mariana limestone; minor movement took place possibly as late as post-Mariana limestone time.

Mount Santa Rosa horst block: The Alutom formation rocks that make up Mount Santa Rosa have been uplifted as a horst block bounded by three high-angle normal faults. The most prominent of these faults forms part of the southwest boundary of the volcanic rock exposures. The second fault forms the northeastern boundary of the horst block and cuts the Bonya and Mariana limestones. The third fault forms the southeast boundary of the block. The last major movement along these faults took place after the deposition of the reef facies of the Mariana limestone. The intense shearing in the Bonya limestone in the vicinity of Mount Santa Rosa indicates that an earlier period of faulting, prior to the post-Mariana movement described above, may have occurred in the interval between the deposition of the Bonya limestone and the Mariana limestone. The prominence of the bounding fault on the southwest side of the horst block and its alinement with the general trend of faulting in the Alutom formation indicates that, in addition to post-Bonya and post-Mariana movement, pre-Miocene movement along this fault may have taken place after the deposition of the Alutom formation.

Structures in the Alutom formation: The main area of outcrop of the Alutom formation in central Guam is structurally separated from the rest of the island by the Pago Bay-Adelup Point fault and by the Santa Rita-Talofofo River valley fault zone and is considered to be a horst block raised relative to the adjacent younger rocks.

Within the Alutom formation the dominant structures are high-angle normal faults, anticlines, and synclines. Section C-C' of Plate 4 shows structures typical of the Alutom formation from Sasa Valley across Mount Chachao and Mount Alutom to the fringing limestones along the east coast. As shown on the geologic map, many fold axes and fault traces in the Alutom rocks fall into a definite alinement trending from N. 45° E to N. 70° E. A second major direction of alignment is occupied by high-angle normal faults that trend approximately S. 45° E. No major fold axes are known to follow this second trend.

The structures in the Alutom formation within the Mount Santa Rosa horst block generally follow the above-mentioned trends. The dominant structures at Mount Santa Rosa are thrust faults, high-angle normal faults, and strike-slip faults. The thrust faults trend northeast-southwest and are offset by normal and strike-slip faults that trend northwest-southeast.

Minor structures: Throughout the Alutom formation are numerous small faults, folds, and shear zones that have not been plotted on the geologic map. These structures seem to be randomly oriented. Minor fault planes are characterized by shiny black coatings of manganese minerals on which slickensides are pronounced. Shear zones are marked by contortion of the beds and, in some places, by the obliteration of bedding characteristics. Within these shear zones small blocks of rock are commonly slickensided on all of their surfaces, indicating complex movement. The minor folds die out in short distances and are commonly offset by the minor faults.

Joints are well developed in this formation. Intersecting joints effectively break the rock mass into angular fragments, the size and shape of which depend on the spacing and orientation of the joint planes. As many as four distinct directions of jointing are present in some outcrops. The spacing of these joint planes ranges from approximately 1/2 inch to several feet.

Fault breccias and gouge: Large faults and fault zones in the Alutom formation are associated with breccia and gouge zones; in many places the width of these zones exceeds 50 feet. The breccias are made up of angular to round fragments of various volcanic rocks in a coarse- to fine-grained, sandy matrix. Zones of completely crushed rock reduced to clay are commonly associated with faults in this formation.

Silicification in fault zones: Thin veins of translucent, milky, dense chalcedony are commonly present in fault zones. Silicification which has resulted in the induration of beds has taken place in many fault zones. These silicified beds generally weather less than the unsilicified beds around them and thus stand out in relief. Most of the silicified beds are light green in color and, in extreme cases of silicification, have fracture surfaces that are conchoidal with a glassy luster. Many of the breccias in the Alutom formation are thus silicified.

Landslide and slump structures: Several areas of outcrop of the Alutom formation in central Guam expose well bedded tuffaceous sandstones and shales, as well as pillow basalts, in a structurally chaotic condition (see pl. 7B). In these outcrops large blocks, many of which are 50 to 100 feet in length, have widely divergent strikes and dips. Many of these blocks are warped and deformed and numerous small faults cut across the areas in random fashion. The chaotic deformation of these beds of tumbled, warped, and faulted rock may have been produced by submarine slumping that occurred in association with the deformation that produced the well defined structures in the Alutom formation.

In many places a similar-appearing clayey conglomerate or rubble overlies weathered rock in eroded outcrops. Such clayey rubble has been formed by relatively recent slumping and sliding of saturated weathered rock. The recent weathered rubble is always a surficial feature, does not contain the massive blocks, and does not show the large-scale intense deformation of the early slumping.

Effects of structures on physiography: Strike ridges, asymmetrical in profile and offset laterally and vertically, are one of the dominant features of the topography of this formation. Normal faults at the foot of the steep slopes of these asymmetrical ridges parallel the ridges and are, for the most part, responsible for the saw-tooth profile characteristic of sets of ridges. The Mount Chachao-Mount Alutom area is bounded by normal faults that dip away from these peaks, the topography around the peaks reflects offsetting along normal faults.

The drainage pattern, much of which probably follows the general trend of the structure, has accentuated the relief (see fig. 12). Many streams follow valleys developed parallel to the strikes of resistant beds.

Effects of structures on weathering: The traces of faults in the

Alutom formation are among the most deeply weathered areas of outcrop. The intensity of weathering commonly lessens with distance from the fault trace. Thus a saddle is formed by deep weathering of a fault that cuts a strike ridge; the well indurated beds that make up the crest of the ridge are not as deeply weathered as the beds that abut the fault trace in the saddle.

Structures in Miocene volcanic rocks: The dominant structural features of the Umatac formation are, first, the gentle regional dip to the east, and, second, the reticulate pattern of high-angle normal faults that cut the southern plateau of Guam.

Between Fouha and Cetti Bays a high-angle normal fault cuts the headland. Differential movements along the fault were complex but small slickensides and mullion structures indicate that the seaward side moved downward relative to the present bluffs and that the displacement was nearly vertical. The attitude of the Miocene volcanic rocks strongly suggests that the southern plateau of Guam, which terminates in the high cliffs inland of Umatac, is a remnant of a more extensive rock mass that existed, possibly until late Miocene time, above sea level west of the present shoreline. It is possible that the entire coastline from Facpi Point to Cocos Island has been normally faulted along one or more major sets of faults.

Many of the numerous dikes that cut the pillow basalts in this area are involved in the faulting and brecciation. Other dikes appear to have been intruded more or less contemporaneously with or slightly later than the faulting. One unsheared dike cuts directly across a brecciated dike in the fault zone. In the vicinity of Facpi Point these dikes form an extremely complex pattern that may be related to the main directions of faulting along this coast.

Folding: The beds of the Bolanos conglomerate member are gently folded in many places. It is possible that these folds were formed in connection with the large-scale normal faulting and tilting that affected the entire Miocene volcanic series.

Joints: Joints in the Miocene volcanic rocks are in general restricted to: 1) the centers of the dikes in the Facpi basalt, which display well developed columnar jointing; 2) the massive basalts of the Facpi basalt member which are cut, in a random fashion, by several sets of joints spaced from a few inches to a few feet apart; and 3) the fine- to medium-grained tuffaceous beds in the Bolanos conglomerate member which are closely jointed in several directions.

Effects of structure on physiography and weathering: The structural features described above greatly influence the physiography of southern Guam. Uplift and eastward tilting have combined to produce the arcuate ridgeline from Mount Jumullong Manglo to Mount Sasalaguan, and the eastward-dipping plateau of south Guam. The drainage of this plateau follows the structural pattern. Erosion has accentuated the relief.

On the upland surface immediately east of Facpi Point there are several ridges trending N. 60-80° W, that probably are formed by dikes. Relict structures typical of basalt flows do not extend into these ridges.

Fault breccia and gouges in the fault zones in the Miocene volcanic rocks are more intensely weathered than is the country rock.

Structures in Miocene limestones: The Miocene limestones are all cut by high-angle normal faults, some of which do not extend upward into the Mariana limestone. The Bonya limestone and the Janum formation are well jointed and show evidence of warping and tilting prior to the deposition of the Mariana limestone.

Bonya limestone: Northeast and southwest of Mr. Santa Rosa the Bonya limestone is cut by high-angle normal faults that also cut the Mariana and Barrigada limestones. However, in outcrops at several localities along the east coast between Lujuna Point and Anao Point, the Bonya limestone is cut by southeasterly-dipping normal faults that extend upward into the Janum formation but do not cut the Mariana limestone.

Janum formation: As exposed along the east coast this formation is warped, faulted, and jointed. The dominant structures are a series of nearly parallel normal faults that strike N. 35-50° E., and dip at angles of from 75 to 80 degrees to the northwest. These faults do not extend upward into the overlying Mariana limestone.

Barrigada and Alifan limestones: Structures in the Barrigada and Alifan limestones are confined to high-angle normal faults and several sets of joints. Faults and joints in the Barrigada limestone in the vicinity of Finegayen do not cut the overlying Mariana limestone. These faults probably developed at the same time as the structures in the Bonya limestone and the Janum formation. The pattern of faulting in the Barrigada and Alifan limestones follows the over-all structural pattern of the island.

Breccia zones made up of angular fragments of limestone closely fitted together and, in some places, recemented into a solid mass are numerous. Crushed, chalky zones are common, particularly in the Barrigada limestone.

The physiographic expression of the faults and joint zones in the Barrigada limestone make them easily observable in the field. In many places the faulted and jointed Barrigada limestone forms narrow, sharp, elongate ridges that stand out in relief above the flat terrain around the fault or joint zone. Recrystallization in many of these zones has indurated these ridges to a greater extent than the surrounding rock.

Structures in the post-Miocene limestones: The only large structures directly affecting the Mariana limestone are high-angle normal faults. The pattern of faulting generally follows the trends established in the older rocks; faults trending northwest and northeast are dominant.

The relationships of many of these faults to the Mariana limestone permit the dating of two periods of faulting that have occurred subsequent to the deposition of the Agana argillaceous member. The Agana fault has displaced the Alifan limestone and extends upward into the Agana argillaceous member but does not completely cut it. This fault, therefore, probably formed during the deposition of the argillaceous member. The Fadian Point faults cut the reef facies of the Mariana limestone overlying the Agana argillaceous member. This fault was formed after the deposition of the uppermost Mariana limestone.

Fault breccia and gouge: Faults in the Mariana limestone are generally characterized by wide zones of brecciation and fault gouge. The breccias are made up of angular blocks of well lithified limestone in a sandy matrix. The fault gouges are mainly comminuted limestone containing rounded gravel and boulders of coral and other limestone types. These breccias and gouges on the plateau are commonly friable or loosely cemented, although secondary cementation has indurated them to a compact hard, conglomeratic limestone on cliffs and ledges. The line of demarcation between the breccias and gouges and the adjoining sides of the faults are poorly defined because most faulting has affected broad zones of limestone.

Joints: Joints trending in the same direction as the fault sets described above are common in this formation. Jointed zones several hundreds of feet wide are found around the northern coasts of the island as well as on the north plateau. In these zones the joint planes are spaced from several inches to several feet apart. Solution has widened the partings in the rock to the extent that numerous joint openings are now 3 to 4 feet wide. The surface of the rock in these jointed areas has a deeply furrowed appearance.

Many of the high cliffs bordering the north plateau of Guam trend parallel to sets of joint planes. Erosion and collapse of these cliff faces is, in part, directed along joint planes.

Physiography as related to faulting: The physiography developed on the post-Miocene limestones has been influenced to a great extent by the widespread normal faulting described above.

Many sections of the coastline around north Guam and Orote Peninsula have alinements that are more or less parallel to one of the dominant or subsidiary fault or joint sets in the post-Miocene limestone. One of the more prominent of these alinements is that displayed by the coastline from just north of Haputo Point to Uruno Point. It is possible that this coastline is controlled by the Finegayen fault.

On the north plateau, scarps are prominent along many fault traces. Among these is the Barrigada-Tamuning bluff and the less well defined Agafo-Gumas scarp.

Swales and sinks are commonly alined along the bases of these scarps. It is probable that the funneling of drainage into the breccias and gouges associated with these faults has produced some cavernous conditions at depth.

The entire plateau of Guam north of the Pago Bay-Adelup Point fault has been tilted towards the southwest. The tilting occurred after deposition of the reef facies of the Mariana limestone and may be contemporaneous with the latest recognized period of faulting.

Structural history: The sequence of structural development on Guam is as follows:

Middle to late Oligocene deformation and uplift. Within this time interval the Alutom formation was folded and faulted. The presence of an early Oligocene fauna in this formation indicates that the major deformation did not take place probably until middle or late Oligocene time; uplift of these volcanic rocks probably accompanied the deformation. The structural trends established during this period of deformation have determined, to a large degree, later structural trends.

Late Miocene or early Pliocene faulting and uplift. After deposition of the Umatac formation, uplift accompanied by faulting affected the Miocene rocks of Guam. Tilting of the Miocene volcanic rocks to the east may have taken place at this time. It is possible that there was more than one period of faulting during this time interval. Uplift and faulting of the Miocene limestone now underlying the Mariana limestone that caps the north plateau took place at this time.

Plio-Pleistocene faulting and uplift. High-angle normal faulting at the beginning of Mariana limestone time resulted in uplift of the limestone now capping Nimitz Hill and Mount Almagosa. More normal faulting occurred during the deposition of the Agana argillaceous member. A later well-defined period of faulting and uplift took place after deposition of the reef and lagoonal facies of the Mariana limestone that now forms the cap of the north plateau, makes up Orote Peninsula, and caps the fringing limestone around the southeast coast of Guam.

From the above summary it can be seen that the type and degree of development of structures produced from the Oligocene to the Plio-Pleistocene epochs differ; in general, the structures become less complex in each succeedingly younger formation. This lessening complexity is probably due to a shift from compressive forces, dominant in the Eocene and Oligocene epochs, to uplift, dominant in post-Oligocene time.

Seismology

The downbuckling and uplift responsible for the tectogenes and geanticlines discussed above (see Regional geologic setting) are crustal dislocations and as such are associated with seismic activity. Hess (1948, fig. 6a), figured the depth distribution of moderate- and deep-focus earthquakes from Guam to the island of Honshu (in Japan) along a composite profile. The moderate- and deep-focus quakes are in a zone that dips away from the axis of the tectogene toward the geanticline. Hess further states that the shallow earthquake epicenters are concentrated, in general, over the tectogene.

Guam, which lies about 70 miles northwest of the deep Mariana Trench, is in an active seismic zone. Repetti (1939) published a "Catalogue of Earthquakes felt on Guam from 1825 to 1938", compiled from many sources, including records and observations of the Guam Seismograph Station that were destroyed during World War II.

The Pacific Islands Engineers (1948, unpublished) made a very complete review of the literature and records dealing with the seismology of Guam.

Destructive earthquakes: The most detructive earthquakes listed in Repetti's catalogue are tabulated below with estimated intensities on the Rossi-Forel scale and on the modified Mercalli scale.

Date	Estimated Intensity Rossi-Forel scale	Equivalent Intensity Modified Mercalli scale
April, 1825	VIII	VII-VIII
May, 1834	VIII	VII-VIII
Jan. 25, 1849	IX	VIII-IX
July 1, 1862	VII	VI
Dec. 7, 1863	VI	V-VI
June 24, 1866	VI	V-VI
May 13, 1870	VI	V-VI
May 16, 1892	VIII	VII-VIII
Sept. 22, 1902	IX	VIII-IX
Dec. 24, 1902	VI	V-VI
Feb. 10, 1903	VII	VI
Dec. 10, 1909	VIII	VII-VIII
Oct. 26, 1912	VI	V-VI
May 10, 1917	VI	V-VI
Nov. 24, 1917	VI	V-VI
June 12, 1932	VI	V-VI
Oct. 30, 1936	VIII	VII-VIII
Nov. 12, 1936	VI	V-VI
Dec. 14, 1936	VII	VI

Since 1825 there have been 19 recorded shocks of estimated intensity of VI or more (Rossi-Forel), and two of an estimated intensity of IX.

Great damage by the severe earthquake of September 1902 was described in some detail by Cox (1904) who mentioned, among other observations, that many landslides in the mountains were caused by the shocks.

Since the war, no consistent seismic records have been kept. The U.S. Navy Microseismic Laboratory on Nimitz Hill kept records of seismic shocks for a time, in 1951 and 1952, using an adapted microseismograph. Records from the station during this period show an average of about two shocks a day strong enough to be recorded. Of these, about two per month were strong enough to be felt.

Seismic sea waves (tsunamis): Except for a sea wave associated with the earthquake of January 1849, no damaging tsunami is recorded for Guam. The wave caused by the 1849 earthquake is reported by Repetti to have rolled into Talofofo Bay and carried out to sea a woman who was walking on the coastal road. The same earthquake caused a series of waves that washed over Satawal Island, 450 miles southeast of Guam.

A tsunami was recorded on Guam on November 5, 1952. It originated from an earthquake, the epicenter of which was at 51° N. 158° E. according to the warning sent out by the Magnetic Observatory at Honolulu. This tsunami was recorded at Guam as a seiche of 40 to 50 minute period in Apra Harbor with an initial amplitude of a foot or less.

In Ylig Bay a series of waves with periods of about 8 minutes were observed, the largest with an amplitude of more than 5 feet. According to John Knauss, an oceanographer from the Office of Naval Research, who made the observations, the computed period of the seiche (natural period of resonance) for Ylig Bay is about 8 minutes. Approximate seiche periods for other bays are as follows:

Talofofo	7 3/4 minutes
Umatac	5 3/4 minutes
Inarajan	7 3/4 minutes

The seiche period of all these bays is between 5 and 10 minutes. Tsunamis are reported to have periods of 10 minutes to one hour. It is therefore possible that large and destructive oscillations might be set up in any of the open bays of Guam by tsunamis larger than that of November 5, 1952. The probability of a large tsunami causing considerable damage appears remote, however, as most of the low land on the island is protected by a band of coral reefs which acts as a filter or baffle for long-period waves. Open bays unprotected by reefs, such as Pago, Talofofo, and Inarajan, are most likely to be flooded if a tsunami should strike Guam.

Marine Geology

by

K. O. Emery

Submarine topography: The submarine topography around Guam is characterized by gentle slopes, conical peaks, and flat-topped banks (fig. 14). The bottom configuration to the west is considerably more complex than to the east. The more northerly of two prominent peaks west of the island rises to within 3,000 feet of the surface from a bank at 7,800 feet; the more southerly rises to within 600 feet of the surface from a bank at 4,000 feet depth and is asymmetric, with an elongate ridge projecting toward Guam. Southwest of Guam, Santa Rosa Reef and Galvez Bank reach to within 21 and 84 feet of the surface, respectively.

The slopes east of Guam that lead down into the Mariana Trench are smooth and gentle. The average declivity from the shoreline of the east side of the island to a depth of 6,000 feet is about 4°. The gradient steepens between the shoreline and the 1,200-foot depth such that this section has an average gradient of about 11°. The slopes off the west side, in contrast, are complex, and off the south half of Guam they are steep, averaging about 14 1/2° between the shoreline and 6,000-foot contour.

Detailed profiles of the upper parts of the submarine slopes were measured to determine the steepness, and the presence of terraces (pl. 12). The positions of these profiles are indicated on the inset map of Plate 12. Profiles 6 and 7 were made by hand soundings from a skiff; all others are from sonic soundings obtained aboard two fleet tugs, USS Abnaki (ATF 96) and USS Metaco (ATF 86), that were made available by the U.S. Navy. Profiles 1 through 5, 8 through 13, and 33 through 40 were made from USS Metaco, and 14 through 32 from USS Abnaki.

Inspection of the profiles shows the common presence of a flattening, or terrace, at the shallow end of most profiles, as for example Profiles 2, 29, and 31. This terrace was not crossed in Profiles 28, 32, and others, yet it is evident that there must be some flattening at some depth shallower than the shallowest depth reached on these profiles. In many profiles one or two additional deeper flattenings may be observed, for example in Profiles 12, 21, 27, and 39. These flattenings have slopes of 0° to 4°, in contrast to the steeper slopes of 5° to 44° on the steps between the flattenings. If these flattenings

Note: Samples listed on Table 14 taken above 500-foot depth are not plotted. Samples plotted but not numbered on the figure are from various sources.

Sea-floor contours based on survey made by U.S.S. Bowditch, 1944 – 1945

Figure 14. Submarine topography and bottom sediments around Guam.

Figure 14

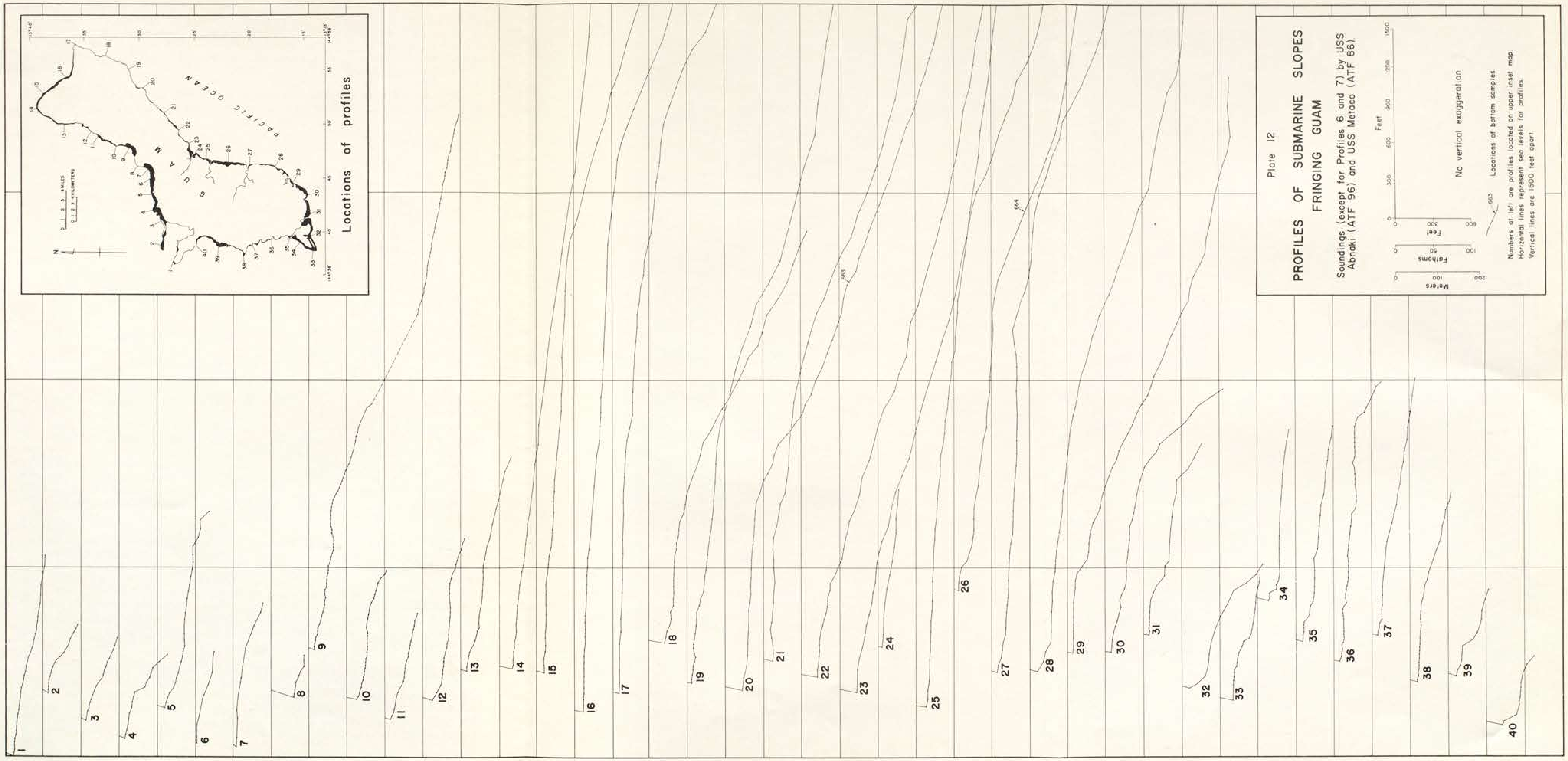


Plate 12
PROFILES OF SUBMARINE SLOPES FRINGING GUAM
Soundings (except for Profiles 6 and 7) by USS Abnaki (ATF 96) and USS Metaco (ATF 86).
Feet
Fathoms
Meters
No vertical exaggeration
Locations of bottom samples.
Numbers at left are profiles located on upper inset map.
Horizontal lines represent sea levels for profiles.
Vertical lines are 1500 feet apart.
Locations of profiles
PACIFIC OCEAN
GUAM

are wave-cut terraces or organic reefs, one might well expect that the original topographic expression has been more or less obscured by sediments that were deposited on them at a later time. Such sediments could have been provided by the cutting of a higher terrace, by reworking of earlier sediments as the island was submerged to its present level, and by debris from the present reef and land areas. The presence of masking sediments is shown by samples 663 and 664 on Profiles 20 and 26, respectively.

Because of this masking effect, there is some uncertainty about the existence of particular terraces as revealed by flattenings of the profile. Nevertheless, from one interpretation it appears that there are four terraces. The shallowest one, recognized in 20 profiles on all sides of the island, has an average depth of 55 feet at its outer edge. The next deeper one, with an outer edge at an average depth of 105 feet, was detected in only 11 profiles, all of which are on the west or north slopes of Guam. The most common terrace of all, occurring in 25 profiles, has an average depth of 195 feet and is best developed on the east side of Guam, although it also occurs on other sides. The deepest terrace, noted in 16 profiles, is at an average depth of 315 feet. A possible, but very uncertain, terrace at a depth of 1,200 feet may be due to local conditions, for it was recognized only in two adjacent profiles.

It should be noted that none of the 40 profiles contain all four of the main terraces, and only 6 of them have three terraces. Some profiles failed to reach into deep enough water to cross all four terraces, but it appears that in many areas certain terraces either were not sufficiently cut to be recognized by the sounding methods or, if cut, were later removed by erosion or buried under sediments. Similar gaps also occur on north Guam in terraces now above sea level.

Detailed soundings of Santa Rosa reef and Galvez Bank were made by the Hydrographic Office survey ships in 1944. The shallowest depths were found to be 21 feet and 84 feet. Although the soundings are too widely spaced for measurement as detailed as those made from the profiles of Plate 12, terraces can be recognized in both areas. The 55-feet-deep terrace of Guam is represented only on Santa Rosa Reef, for Galvez Bank is at a greater depth. The best-developed terrace of both reef and bank is at about 110 feet depth, and is evidently the equivalent of the 105-foot terrace at Guam. Guam's 315-feet-deep terrace is recognizable on both Santa Rosa Reef and Galvez Bank, although in neither area is it very flat.

There is no relationship between the number or depth of terraces and the presence or absence of reefs. Similarly, there appears to be no dependence of the steepness of the step between the terraces upon the reef width. The steps range between 6° and 44° slopes at depths less than 315 feet, with a mean of 15°. Below the 315-feet-deep terrace the slopes have a mean of 17° down to 750 feet, and gradually become gentler at greater depths. Though it was not practical to measure it, the steepness between 0 and 55 feet may be controlled by whether the bottom surface is reef or bedrock.

Sediments: Generalized charts of the Pacific Ocean floor indicate that the sediments near the Mariana Islands 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 downward into radiolarian ooze and red clay at great depth. A more detailed picture of the distribution of sediments near Guam is presented in

Figure 14. The USS Nero took 29 samples in this area in 1899. Five other samples from near the entrance to Apra Harbor are shown on Japanese Hydrographic Bureau Chart no. 2105 (1935), and are presumed to have been taken by Japanese ships. Six additional samples from the deeper slopes were taken from the USS Abnaki during the course of this study, making a total of 40 deep sea samples upon which Figure 14 was based.

These samples show that reef debris is fairly well restricted to depths of less than 3,000 feet except off Apra Harbor where, perhaps because of the tidal currents, it appears to reach 6,000 feet. The tops and upper slopes of Santa Rosa Reef and Galvez Bank probably are covered with similar debris although no samples from these areas are available. At greater depth and distance from shore the bottom sediment is *Globigerina* ooze, except for 4 samples of volcanic mud which may possibly have been derived from the small, conical seamount about 15 miles northwest of Guam.

More detailed information on the composition of the upper part of the slopes is available from samples taken at depths as great as 315 feet off Mamaon Channel by hand line from a launch, and by winch line from the USS Abnaki from depths between 570 and 1,170 feet. Positions of the latter samples are shown on Figure 14 and brief descriptions of all are given on Table 14. *Halimeda* fragments are abundant in most samples even to the greatest depths. As *Halimeda* lives only in the photic zone (principally shallower than 200 feet) the abundance of its debris at greater depths is a good indication of reworking or shifting of sediments on the slope. Similarly, coralline-encrusting algae, the lithothamnoids, also require sunlight, but nonetheless their remains occur at great depth. Fragments of gastropod, pelecypod, and pteropod shells, echinoid spines, and sponge spicules, were found in most of the samples but the living organisms are less generally restricted to shallow water during their lifetimes. Broken corals of the massive reef types were found at great depth, probably also indicating reworking. Foraminifera generally increase in abundance with depth, with a higher percentage of pelagic tests at greater than at shallower depths. An encrusting form, probably *Homotrema* or *Miniacina*, coats many of the coral fragments and other debris and is a major factor in making the material into well cemented, subspherical, flat, and irregular masses, several dozen of which were recovered in dredge hauls.

Geologic History

The geologic history of Guam can be described in terms of the major geologic processes that produced the island as it stands today: deposition of rock by volcanic activity and by animals secreting calcium carbonate; deformation of these rocks by tectonic forces; and weathering and erosion, both subaerial and submarine.

The presence of shallow-water limestones within the Alutom formation indicates that by Tertiary b time the area around Guam was shallow enough to allow the formation of such limestones, and possibly coral and algal reefs. Volcanic detritus in these limestones shows that volcanic activity took place prior to or contemporaneously with the deposition and fragmentation of the Tertiary b limestone. Most of this limestone was engulfed by later (Tertiary b or c) volcanism which produced the bulk of the Alutom formation. Most of the formation was deposited as deep-water tuffaceous shales and sandstones with subordinate amounts of lava flow rock.

Table 14. Samples from slopes fringing Guam (arranged in order of increasing depth)

Sample number	Depth (feet)	Latitude (North)	Longitude (East)	Sample quantity	Composition (in percent) Foram-inifera	Shells	Fine sand and silt	Halimeda debris	Litho thamnion	Coral	Median diam.	Sorting coeff.	Insoluble residue
613	27	13°17.36'	144°39.24'	5 gm	11	5	1	38	40	5			
606	28	16.14'	39.33'	3 gm	3	5	75	2	2	13			
614	34	17.35'	39.22'	15 gm	5	7	5	70	8	5			
615	37	17.33'	39.22'	60 gm	2	20	3	5	40	15	2.20 mm	1.60	0.7%
617	40	17.27'	39.18'	10 gm	15	20	50	1	10	4			
616	41	17.29'	39.18'	10 gm	40	5	10	27	13	5			
618	46	17.24'	39.16'	6 gm	3	5	1	1	10	80			
619	108	17.26'	39.07'	1 gm	1	12	2	30	10	40			
607	115	16.17'	39.28'	150 gm	15	10	10	18	22	25	0.64	1.40	0.9
608	120	16.17'	39.26'	10 gm	0	0	0	0	0	100			
609	135	16.18'	39.18'	25 gm	0	0	0	0	0	100			
610A	165	16.23'	39.10'	300 gm	15	10	25	10	5	35	0.44	1.53	2.4
610B	235	16.29'	39.03'	5 gm	0	0	0	0	60	40			
611	315	16.31'	38.97'	250 gm	40	15	22	10	2	10	0.22	1.55	9.9
664	570	22.00'	47.2'	10 kg	40	5	25	10	5	15	1.08	4.53	3.4
661	690	39.00'	50.4'	10 kg	65	0	0	34	0	1	0.48	1.71	0.0
660	810	40.00'	50.0'	10 kg	40	5	20	10	0	25	0.58	3.02	0.3
663	972	29.80'	54.1'	10 kg	15	5	40	30	0	10	0.48	3.52	0.1
665	1000	15.60'	38.3'	10 kg	45	5	35	10	2	3	0.75	1.80	4.3
662	1170	41.50'	50.3'	10 kg	40	5	20	32	2	1	0.80	1.88	0.7

The Mahlac shale member of the Alutom formation was probably deposited during the early Oligocene.

Following the deposition of the Alutom formation, or in part contemporaneously with its deposition, these rocks were folded and faulted by tectonic activity associated with the further development of the Mariana geanticline. The Adelup Point-Pago Bay ("waistline") fault and the Talofofo-Santa Rita fault zone probably developed either in late Tertiary b or c (Eocene) time, and resulted in the dropping of the Alutom formation in areas of what is now north and south Guam. Mount Santa Rosa probably stood as a horst block above the rest of the Alutom formation in the northern plateau area. The Fena embayment which now is a structual depression probably also underwent its initial development at this time.

During Tertiary e (early Miocene) time the Umatac formation was deposited, mainly over the area that is now south Guam. The thick section of pillow basalts mapped as the Facpi basalt member of the Umatac formation was the basal unit laid down, probably from submarine vents. Intrusion of dikes took place during and probably shortly after the deposition of the pillow lavas. The dikes were deformed and cut by other dikes, probably contemporaneously. Beds of the deep-water facies of the Maemong limestone member within the Facpi basalt member indicate that this volcanic activity was intermittent. Contemporaneous with the deposition of the deep-water facies along what is now the southwest coast, reef limestones were being deposited in the Fena Valley area. Further eruptions after the deposition of the Maemong limestone produced the materials of the Bolanos conglomerate member. This member contains abundant fragments of limestone eroded from the Maemong member during the Bolanos volcanism. A final flow phase deposited the Dandan flow member, the youngest volcanic rock on Guam.

Normal faults and gentle folds in the Umatac formation probably formed late in the deposition of the formation. The northeast-trending faults that cut south Guam may possibly have developed as faults subsidiary to the collapse of a volcanic cone west of the present southwest coast of Guam.

Tertiary f time was marked by the deposition of the Bonya limestone in the Fena Valley area. (The present site of Fena Valley was then a bay.) Volcanic detritus in the Bonya limestone indicates the presence of volcanic rock above sea level. It is possible that uplift followed the deposition of the Umatac formation, and preceded the deposition of the Bonya limestone. In north Guam the Bonya limestone was deposited around the flanks of a volcanic mass which is now Mount Santa Rosa.

The Barrigada limestone was deposited as a submarine bank limestone in the north Guam and Ugum River area in water 100 or less fathoms deep, probably during Tertiary g time.

The Janum formation of north Guam was deposited at about the same time as the Barrigada limestone. The depth of deposition of the Janum formation has been interpreted at from 100 to 1,500 fathoms. The Barrigada limestone of the north plateau lacks volcanic detritus, which suggests that there was submergence of any nearby volcanic mass that might have contributed detritus.

In south Guam during late Miocene time, possibly during the Tertiary g stage, the Talisay formation was laid down as a near-shore deposit unconformable on pre-existing formations.

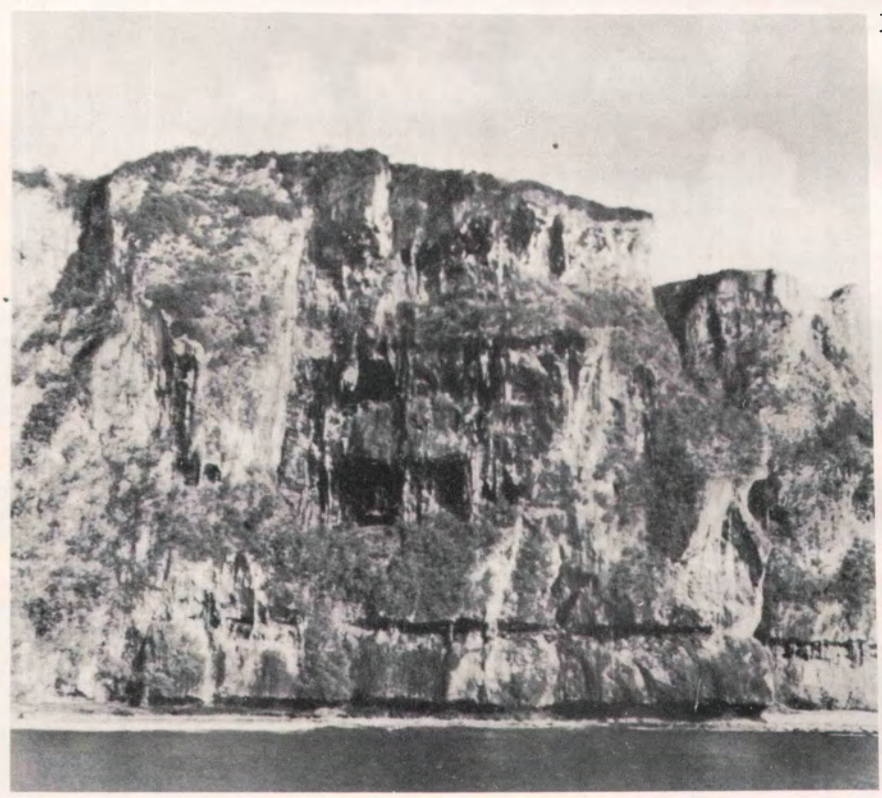
Following the deposition of the Talisay formation, the central part of the island was submerged, allowing deposition of the Alifan limestone which is interpreted as a lagoonal deposit. Although the Alifan limestone now occupies the highest point on the island, abundant volcanic detritus in many of its beds, including those on the uppermost peak of Mt. Lamlam, indicates that a nearby volcanic mass probably was at least as high as Mt. Lamlam during deposition of the limestone.

Late Miocene uplift and faulting raised the larger part of south Guam above water and raised the submarine bank limestones of the Barrigada limestone close enough to the surface to allow formation of the Mariana limestone as a shallow-water reef associated with lagoonal deposits. The Agana argillaceous member received large amounts of volcanic detritus from the southern volcanic mass, thus becoming lithologically distinct from the rest of the Mariana limestone.

Post-Mariana limestone faulting and uplift then raised the north plateau, along with Orote Peninsula, from the sea. The southeastern coastal limestones also emerged at this time. Movement along the "waistline" fault probably accounted for the southwestward tilt of the north plateau.

Pleistocene marine abrasion and reef growth at various stands of the sea produced the many terraces that mark the raised limestone masses of the north plateau (pls. 13, 2B) and the fringing limestone along the western coast of south Guam. The most recent stands of the sea at 10 feet and 6 feet produced the sea nips around much of the present coastline of the island.

PLATE 13



Notches at Amantes Point. The cliff face is about 100 meters (340 feet) high and shows well the series of notches left by former stands of the sea. The cliff is the detrital facies of the Mariana limestone capped by the reef facies.

Notes

Notes

Soils

by

Carl H. Stensland

Introduction

A detailed-reconnaissance soil survey was made on Guam from 9 October 1952 to 9 October 1954, as a part of the combined rock, soil, water, and vegetation study described in other sections of this report. The preliminary reconnaissance soil survey was completed on 1 September 1953 by C. H. Stansland, soil scientist. The reconnaissance soil map contained eight major units of soils and an explanation describing the characteristic vegetation, terrain, and physical properties of the soils, with a preliminary engineering classification and interpretation of the soils, the latter based on tests and advice from Messrs. Shirley, McCloskey, and Crawford of the ComNavMar Soil Testing Laboratory. Although not published, this map was used as a basis for further, more detailed work, and it was also used by the geologists.

Another soil scientist, J. E. Paseur, joined the field party in September 1953. Investigations with a mobile power-auger (pl. 15), collection of numerous soil samples for examination and testing, and running of a limited number of differential thermal analyses on selected clays were performed during the ensuing winter and spring.

A field soil inspection and review was conducted during June 1954 by E. H. Templin, a senior soil scientist on loan as technical consultant from the U. S. Department of Agriculture. The reconnaissance mapping was reviewed and parts of it were incorporated in the detailed-reconnaissance mapping legend which was set up for completion of the survey. Liaison was also completed with the Director of the Navy soil testing laboratory (Base Development) in regard to the number of soils to be tested and the kind of engineering tests to be made. The soil mapping was completed on Guam by Stensland and Paseur on 9 October 1954.

In the following pages the soils and miscellaneous land types of Guam are described as they were mapped in the detailed-reconnaissance soil survey. The soils are described in the order of their genetic and geographic relationships rather than alphabetically, because many of the units are interrelated associations of individual taxonomic units. This system is used to facilitate the necessary cross reference required in a study of the different associations or units of related soils.

The soils are described from the surface of the ground down to bedrock. Color, texture, structure, consistence, pH reaction, and other apparent physical characteristics are noted in each horizon of the complete profile. The topography, relief, and prevailing surface gradient is described for each soil unit, as is the vegetation observed on it, the internal and external drainage, the frequency and severity of flooding and erosion, and the kind of underlying bedrock. Standard Munsell color notations are used in the profile descriptions.

The location and distribution of each soil unit is shown in color on maps of Guam, Mariana Islands, 1:25,000 scale, Edition 1 - AMS (AFFE), Plate 14, 11 sheets (in pocket). Locations of soil profiles and other soil investigation or sampling sites described in the text are referred to by the identifying site number and by appropriate numbers or digits of the military grid, following the standard method for 1,000 meters and tenth decimals thereof. "Correlation samples" mentioned in the text are samples which were selected for rather thorough analyses and for possible correlation with similar soils in other areas.

Lettered soil horizon designations are tentative, pending evaluation of mineralogical and chemical studies and tests made of samples from several of the described soils.

Photographs are by the author, except those credited otherwise.

General Statement

Guam is well within the belt of tropical soils, and although the soil-forming processes are predominantly lateritic, the island has no significant areas of true laterite soil (ground-water laterite). Regosols, Lithosols, Latosols, and Lithosolic Latosols are the great soil groups most extensively represented on Guam.

In the northern half of Guam, which is chiefly an undulating limestone plateau, is an extensive Lithosolic Latosol (Kellogg, 1949). This soil, although generally slightly alkaline, is rich in hydrated oxides of iron and aluminum. It is red, soft, friable, and porous throughout. Although generally shallow, it ranges in thickness from a few inches on gently rounded ridgetops to a few feet in small depressions or solution cavities.

In southern Guam, Regosols and Latosols are predominant on the volcanic rocks. They generally are 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 on the hills and scarps of fringing limestone terrace remnants along the coast and on limestone outliers in the volcanic rocks.

In central Guam, separating the two major soil provinces of the north and south, is a large, fan-shaped area of moderately deep, yellowish-brown and red plastic clays (with dark brown surface horizons) on argillaceous limestone. These soils may be considered (McCracken, 1957) to be intergrades between Latosols and some group such as the Red-Yellow Podzolic soils.

Other soils on Guam include: 1) 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 Palaus, Okinawa, and Saipan; and 2) Alluvial soils consisting of sediments from limestone and volcanic uplands, accumulated in sink basins, reentrants, valley flats, alluvial fans, and low coastal terraces, most of which are periodically flooded in the rainy season and some of 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.

Stream drainage patterns are developed in the southern province of volcanic soils and in the central area of limestone karst, but no continuous surface drainageways are developed in the more porous limestones of the northern plateau.

The vegetation on the volcanic upland soils of the southern province is markedly different from that in central and northern Guam; it consists largely of coarse swordgrass (Miscanthus floridulus) and a Dimeria species. Many of the ravines in the central and southern areas contain thickets or mixed secondary forest, and the secondary forest is common on parts of the northern plateau which are not cleared for small fields or for military use.

Table 15. Acreage and proportion of each soil unit on Guam

Unit	Unit Name	Sq. miles	Percent of Island	Acres
1	Guam clay	75.05	35.40	48,030
2	Toto clay	0.24	0.11	155
3	Chacha-Saipan clays	5.17	2.44	3,310
4	Saipan-Yona-Chacha clays	11.47	5.41	7,340
5	Yona-Chacha clays	13.06	6.16	8,360
6	Atate-Agat clays, rolling	13.12	6.20	8,400
7	Agat-Asan-Atate clays, hilly	37.13	17.50	23,760
8	Agat-Asan clays, and rock outcrop	23.47	11.09	15,020
9	Pago clay	3.72	1.75	2,380
10	Inarajan clay	3.63	1.72	2,320
11	Muck	0.81	0.38	520
12	Shioya soils	3.79	1.78	2,425
13b	Limestone rock land, gently sloping	5.30	2.50	3,390
13f	Limestone rock land, steep	14.29	6.74	9,150
14	Made land	1.51	0.71	965
	Total land	211.76	99.89	135,525
	Total inland water	0.24	0.11	155
	Total island area	212.00	100.00	135,680

Compiled and computed by planimeter adjusted to map scale; total of individual units compiled on a map sheet was checked against a separate compilation of the map sheet area, with maximum error less than 1 percent.

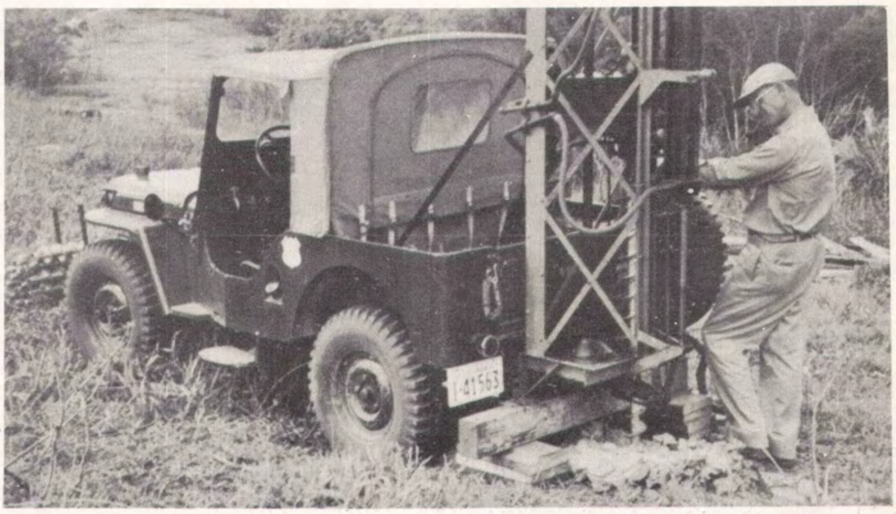


PLATE 15

Mobile drill for ascertaining depths to water table, bedrock, and various soil horizons. Hydraulic pressure unit of the drill was also used to force tubes into soil horizons to obtain undisturbed samples for engineering tests. 9 March 1954.

Upland Soils (on limestone)

Unit 1: Guam clay

General features: Guam clay, a Lithosolic Latosol consisting of reddish, granular, friable clay, thinly mantles the large, purer portion of the Mariana limestone. In total area it is the most extensive soil unit on Guam (see table 15), but because of its shallowness and low moisture-holding capacity it is not very important agriculturally or in engineering.

Topography, distribution, and extent: This soil occupies undulating slopes on much of the north plateau of Guam, the Orote Peninsula, and a part of the southeast coastal upland. The prevailing surface gradient ranges from 1 to 8 percent. Total area of the unit is about 48,000 acres.

Underlying regolith or bedrock: The shallow clay in which this soil is developed is highly lateritic or concentrated in its content of iron and alumina; percent of alumina was about 50 and that of iron about 20, in samples tested. This is hard to explain in view of the shallowness of the total soil material (generally less than 12 inches) and the relative purity of the underlying limestones (geologists estimated the insoluble residue content as probably less than 1 percent by volume). Detailed descriptions of these limestones are in the General Description part of the report, under Geology. In brief, they are deep (thick), heterogeneous, fossiliferous, massive, porous, and relatively free of impurities.

Profile description: The following profile is in a small depression on characteristic undulating topography, about 1 mile south of abandoned Northwest Guam AFB (Soil investigation site 150, military grid BR678030, Soils map sheet 3):

A_1 0 to 2 inches. Dark reddish-brown (2-5YR 2/3, moist) clay; strong fine-granular structure; friable before disturbance, firm when kneaded or remoulded; porous and permeable; pH 6.5; grades shortly to

B(?) 2 to 10 inches. Dark-red (2.5YR 3/6, moist) clay; strong fine-granular structure; friable in place; firm after kneading; porous and permeable; pH about the same as in horizon above, but reaction grades to slightly alkaline within an inch or two of the underlying limestone.

D At 10 inches below surface, rests abruptly on hard, porous, white limestone, with some coastings or films of red clay in the crevices.

The soil-bedrock contact is generally abrupt but very irregular, with clay extending down pockets or cavities in the limestone, and with bedrock cropping out on the surface in perhaps 10 percent of the surrounding area. Effective over-all soil depth is about 4 or 5 inches here (probably slightly below average for the unit as a whole), but it cannot be estimated accurately. Soil-on-limestone characterizes 60 to 80 percent of the unit on Guam (pls. 16A, 16B, and 16C; see also pl. 11B).

Range in characteristics: Color of the soil ranges from dusky red to yellowish red (Munsell hues 10R to 5YR), with dark reddish brown (2.5YR 3/4, moist) in the surface and dusky

A. Guam clay in solution channels or "pipes" in Mariana limestone. West of Andersen AFB (Site 151); 3 February 1953.

B. Shallow, abrupt, undulating contact of Guam clay with underlying white, porous, relatively pure detrital Mariana limestone. Near Naval Communications Station, northwest Guam (Site 152); 17 February 1953.

C. Guam clay in sharp, serrate contact with Mariana limestone. Near Naval Communications Station, northwest Guam; 17 February 1953.

red, red, or dark red (hues 10R to 2.5YR) most common in the bulk profile. The distinct granular structure ranges from strong, medium (2-5 mm) granular at the surface to moderate, very fine (less than 1 mm) granular lower in the profile, with strong, fine (1-2 mm) granular in the surface portion and very fine granular in the remainder of the profile as perhaps the predominant condition. Faint horizonation in the surface is characterized chiefly by a slightly darker value and chroma in the color, and by slightly larger and perhaps stronger aggregation of the particles.

Drainage, erosion, and soil moisture: The soil is well drained and the underlying limestone seems to take water freely, except in times of unusually heavy rains. There are no streams and there is very little evidence of erosion from surface runoff. During heavy rains there is some convergence of surface water into the numerous swales or troughs in the limestone, but most of these depressions are haphazard or disconnected and the water soon settles into the limestone below.

Moisture-holding capacity of this shallow soil is low. Crops grown during the dry season (two or three months of scanty rainfall, usually between January and May) may require irrigation.

Special features: Limestone fragments making up 5 to 10 percent of the total unit volume are in and on the soil in many places; in several places they are scarce or absent. It is often difficult to tell if slightly protruding rock is bedrock or a partly buried fragment.

Associated or included soils: Subunits of limestone rock land (13b and 13f) too small or difficult to map are found in many small knolls or ledges within this unit. Some areas of a brownish, somewhat deeper and more plastic clay are also included, especially in the area within a triangle formed of lines connecting Mataguac Hill, Mount Santa Rosa, and Barrigada Hill. Small areas of Chacha-Saipan clays complex (Unit 3) may also be included along the contact boundaries with that unit.

Use and vegetation: (See Vegetation, in the general description part of the report, for detailed discussion of vegetation). At the beginning of the survey, probably 60 to 70 percent of this total unit area was idle land covered mostly with young secondary mixed forest, with scattered older trees throughout. Breadfruit (*Artocarpus*) and *Pandanus* are dominant varieties, with banyan (*Ficus*) and Guamanian ifil (*Intsia*) represented individually, among many more varieties. Smaller *Pandanus*, *Cycas*, shrubs, vines, and luxuriant ferns constitute a dense undergrowth in many places.

A paved 'loop' road with paved or coral-surfaced offshoots connects the several large military reservations on a large part of this soil unit in northern Guam, and a network of unsurfaced jeep-trails cleared through the jungle growth served the scattered farmsteads and native garden plots throughout the area. These small farms or gardens were mostly in the small basins or low flats in the undulating terrain.

Clearing of this forest growth from large, previously un-used portions of the military reservations and the partial clearing and establishment of numerous new farmsteads took place during the two years of the soil mapping program on Guam. Perhaps 50 percent of the total unit area has now been cleared or partly cleared of the young forest growth.

All of the airports of Guam are located on Unit 1.

Suitability for use: Soil of this unit is so shallow that consideration of the engineering aspects is limited to sites where there are clay-filled large fissures or pockets in the limestone, or in places where the soil material may be used for small fills or embankments. These or similar engineering problems are discussed in the Engineering Aspects part of the report.

Agricultural problems consist of finding enough soil on the small upland flats and in the potholes or depressions to furnish sites for cropland. If crops are planted during the relatively dry season that usually occurs in the late winter or spring, supplemental moisture or irrigation may have to be provided. In the latter case, a system of overhead sprinkling would seem most feasible, as the soil and bedrock are too permeable to support a ditch-type irrigation.

Potassium and nitrogen are among the fertilizers most needed. Phosphate-rich areas are reported in one or two small areas of the limestone plateau, but the availability of this element in the soil has not yet been determined. There is also a possible lack of certain trace elements, a deficiency common in tropical areas, which should be determined if intensive farming is proposed.

Unit 2: Toto clay

General features: Toto clay consists of deep, pale-olive to pale-yellow, reddish-mottled, firm and plastic clay Grumusol on limestone. It is mapped only on a few flat, microundulating ridgetops southeast of Agana, among areas of Saipan-Yona-Chacha clays. The soil is subject to unusual shrinkage and expansion; it has large cracks in dry weather and is water-logged in wet weather. The pH reaction is acid near the surface and generally alkaline at depths of more than 3 or 4 feet below the surface.

Topography, distribution, and extent: This soil is mapped in only two areas, about 2 miles southeast of Agana on gently sloping to flat ridgetops which in some places merge into the more rolling Saipan-Yona-Chacha clays, and which are generally surrounded by the steeper Yona-Chacha clays. The prevailing surface gradient ranges between 1 and 8 percent. Total extent of the mapped area is only 155 acres.

Underlying regolith or bedrock: The soil is developed in volcanic bentonitic clays which contaminated the limestone during its formation, or which were laid on the limestone and into its joints and crevices during inundation subsequent to a period of emergent weathering and erosion of the limestone. The volume of clay incorporated in the limestone pores, joints, and crevices is estimated to be generally less than 5 or 6 percent by volume, although locally this percentage may be much greater. Depth of the clay of this unit over limestone bedrock appears to range from about 5 to 30 feet and to average 10 to 20 feet.

Profile description: The following profile was examined on a microundulating, convex ridgetop, in pasture land. Prevailing over-all surface gradient is about 4 percent; relative microrelief of the numerous small humps and depressions (each about 4 or 5 feet in diameter) is 6 to 12 inches (pl. 17A). The soil had cracks 3 to 6 inches wide at the surface and more than 3 feet deep. (Site 20, grid BQ587889, sheet 5):

A_1 0 to 6 inches. Dark-brown (7.5YR 3/2, moist) clay; strong granular structure; sticky and moderately plastic (wet), very hard (dry); contains 20 to 30 percent ferruginous concretions (2 to 15 mm diameter) and some small roots; numerous vertical cracks in the soil; pH 5.5 to 6.0.

A-B 6 to 11 inches. (Zone of gradual transition to next horizon below, see pl. 17B). Mixed dark-brown, brown, and strong-brown clay, with numerous reddish, soft concretions, and red staining or coating on many of the soil aggregate surfaces; firm, plastic; slightly sticky; pH 5.0.

B_1 11 to 30 inches. Pale-olive (5Y 6/3, moist) clay; faintly to prominently mottled with strong brown, yellowish red, and red; strong subangular blocky structure; firm; plastic; contains a few pinholes, roots, and root hairs. Mottling mentioned above constitutes about 10 to 20 percent of the over-all color. pH 5.0.

B_2 30 to 42 inches plus. Light gray (5Y 7/2, moist) clay, with coarse, prominent mottlings of strong brown (7.5YR 5/8, moist), yellowish red (5YR 5/8, moist), and red (2.5YR 4/8, moist); firm; plastic; pH 5.0.

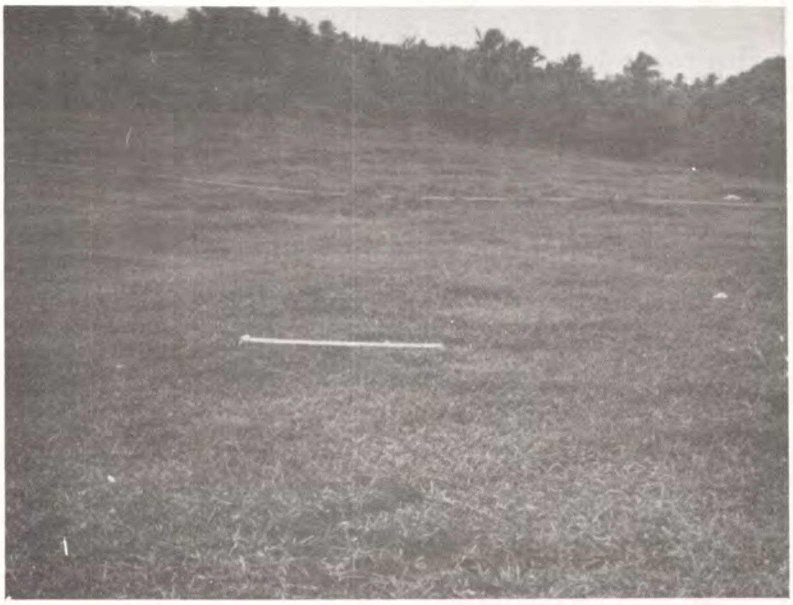
The above profile was cut through a micro-hump. In a nearby micro-basin the dark-brown surface horizon was only 3 inches thick, and the subsoil was firm, moderately plastic, and pale yellow with mottling about as described above. Limestone bedrock was not encountered, but in a nearby road-cut appeared to be at least 10 feet below the surface.

Depth to limestone was 27.5 feet in a power-auger boring (Site 45, grid BQ601877, sheet 5) about one mile southeast of the profile described above. The subsoil was firm, moderately plastic and pale yellow with prominent varicolored mottlings in the upper part, and with reddish-yellow stains or contamination in the lower part, possibly from limonitic concretions crushed by the auger.

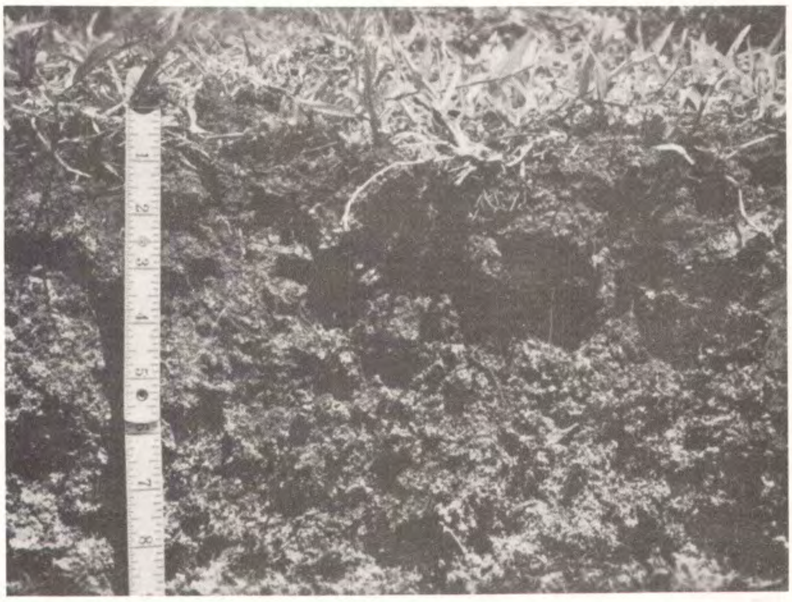
Range in characteristics: Thickness of the dark-brown surface horizon ranges from 2 to 3 inches to 6 or 8 inches within short horizontal distances. Color of the subsoil is varied and mixed, with reddish mottles or stains in a matrix of pale-yellow, pale-olive, or light-gray clay as the most common condition. The soil developes large cracks extending several feet down from the surface in dry weather, and the soil reaction is generally acid in this part of the profile; in the lower, permanently moist part of the profile the soil reaction was alkaline wherever tested.

Drainage and erosion: The soil is imperfectly drained because of surface water catchment in the micro-basins and swelling or expansion in the soil mass when wet. The soil will erode rapidly after gullies are started because of the vertical jointing and cracking in the dry soil. Vertical sides and overfalls in the gullies are thus enlarged, with much spalling or talus accumulation which washes away easily during heavy rains.

Special features: Although gently sloping over-all, the soil surface is uneven, containing alternate small humps and



A. Microrelief of the gilgai type on Toto clay. Central Guam; June 1954. Photo by E. H. Templin.



B. Surface horizon of Toto clay; contains up to 30 percent of ferruginous concretions. Central Guam; July 1954. Photo by E. H. Templin.

depressions every few feet. This "pit-and-mound" gilgai effect is a surface characteristic of Grumusols (Templin, E. H., et al., 1956). Relative microrelief between the bottom of a basin and the top of a nearby hump is generally about 6 to 12 inches (pl. 17A). Whether or not this condition is related to unusual shrinkage and expansion observed in the soil during alternate wet and dry periods has not been determined, but preliminary tests indicate that the clay is largely montmorillonite. The soil develops large cracks during dry weather; these cracks are 5 or 6 inches wide at the surface and extend more than 3 feet into the soil. Some of the dark-brown clay surface soil spalls off and falls into the cracks, as was observed along the wall of a test trench. During wet weather the soil expands or runs together again, closing the cracks, and assumes a water-logged and sticky consistence which makes excavation or vehicular traffic difficult. When air-dried again, a small piece of the soil dropped into water will disintegrate very rapidly into a soft, fluffy or granular mass; the granules do not again cohere, unless compressed while moist.

Associated or included soils: Only a gently sloping phase of this unit was mapped, on rather broad undulating ridgetops where it was associated with the Saipan-Yona-Chacha complex (Unit 4) and with Yona-Chacha clays (Unit 5) on adjacent steeper slopes.

Vegetation and use: Most of Unit 2 was in pasture. The vegetation was mainly Hilo grass (*Paspalum conjugatum*) and a shorter grass with prickly, bluish-colored seeds; there were also scattered woody shrubs 3 to 15 feet tall, and a few trees.

Suitability for use: Until more is known about this soil, its present use as pasture would seem to be most feasible.

Unit 3: Chacha-Saipan clays

Unit 3 contains two kinds of soil so intimately associated that time was not available to map them separately. In many places the gradation of individual characteristics between the two soils was such that their separation on the map would have to be purely arbitrary.

General features: This unit consists of yellowish-brown to strong-brown, firm, plastic Chacha clay and the red, firm, plastic Saipan clay, both moderately deep to very deep on the argillaceous Agana member of the Mariana limestone. The unit is on undulating or youthful karst topography. Convex surfaces are well drained; concave surfaces are moderately well drained and are subject to temporary flooding. The dark surface horizons are about neutral in reaction and the subsoils are acid except near limestone.

Topography, distribution, and extent: The main portion of this unit lies in an area of about 4 square miles, southeast of NAS Agana, from the vicinity of Barrigada Hill toward the head of Pago Bay. Smaller areas are mapped along the east coastal upland, between the coastal limestone ramparts and the inland volcanic rocks. Prevailing surface gradient is between 1 and 8 percent. Total extent of the unit is 3,310 acres.

Underlying regolith or bedrock: The soils of Unit 3 are developed in clays washed from the deeply weathered adjacent volcanic upland, and deposited in and on the limestone -- possibly during two periods of inundation (see description of Unit 4).

The amount of clay in the fissures and joints of the limestone bedrock was described for Unit 2 and the occurrence is typical of the Agana argillaceous limestone which underlies Units 2, 3, 4, and 5. Depth of clay on the limestone differs considerably, however, among the above-mentioned units. In the Chacha-Saipan clays the thickness of clay over limestone ranges from shallow to deep (1 to 10 feet; average 3-5 feet) on convex surfaces (with bedrock to the surface in a few places), and generally deep or very deep (10 to 60 or more feet) in areas of concave or depressional surfaces. Low ridges or convex surfaces lying within a larger, widespread depressional area may be underlain by very deep clay; site 62, grid BQ626895, sheet 5, possibly represents an old, partly-filled sink which is now being dissected and base-leveled at a lower elevation because of emergence and progressive solution in the underlying limestone. A 49-feet-deep boring at this site did not encounter bedrock.

Profile description: The following profile (Correlation sample S54 Guam 1), at Site 1, grid BQ626896, sheet 5, is representative of Chacha clay which occupies gently sloping terrain just within the rim of a large limestone sink more than half a mile wide, near the center of which is Site 62, mentioned above:

A_1 0 to 6 inches. Very dark grayish-brown (10YR 3/2, dry) clay; very hard (dry); firm, plastic (moist); subangular blocky structure, with some coarse granular aggregates at the surface; contains a few small (2 to 3 mm diameter), black, moderately hard pellets or concretions, probably of ferro-manganese composition; numerous roots; pH 6.5. Grades through

B_1 6 to 18 inches. (Correlation sample S54 Guam-1-2) Transition zone of brown (7.5YR 4/4, slightly moist) to strong-brown (7.5YR 5/6) clay; angular blocky structure; very firm, plastic (moist); very hard (dry); many small root hairs and pin-holes; several coarse roots in upper part; the peds, partings, and root channels have coatings or films of dark brown and reddish brown (5YR 4/4, moist); numerous small black and reddish-brown concretions (less than 1 mm diameter); soil appears fairly porous in rather dry state, with several cracks (less than 1/4 inch diameter) to depths of 36 inches in the profile; pH 5.5.

B_2 18 to 32 inches. (Correlation sample S54 Guam-1-3) Strong-brown (7.5YR 5/6, moist) clay; sharp, angular blocky structure; firm, plastic; a few root hairs; some root channels (up to 1 inch in diameter) filled with hard reddish-brown clay; in places there are soft, black, or blue-black concretions in the upper part; many small roots and root hairs; a few roots up to 1/4 inch in diameter; pH 6.5. Grades very gradually to

B_3 32 to 46 inches. (Correlation sample S54 Guam-1-4) Strong-brown (7.5YR 5/4, moist) clay; angular blocky structure; firm; plastic (moist); similar to horizon above but with less discoloration on peds or fracture faces; also fewer roots and concretions.

D 46 to 52 inches, plus. Rubbly, white, argillaceous limestone, with numerous cavities partly filled with strong-brown and brown clay, and some partly filled or lined with limonitic material; the limestone is sharp, angular, and pitted, but surfaces are soft, white, powdery.

Saipan clay (described under Unit 4) is similar to Chacha clay in reaction and degree of firmness and plasticity, but it is predominantly red or yellowish red throughout. The Saipan clay may be related to the Alifan limestone which underlies the argillaceous limestone and protrudes through the surface in some places.

Some mapped inliers of the Alifan limestone and perhaps many unmapped small inliers or the residuum thereof, may be within the areas of these soils.

Range in characteristics: Ferro-manganese concretions in the surface soil of the Chacha clay range in size from less than 1 mm to 15 or more mm in diameter; in volume of the containing soil mass, they range from less than 1 percent to an estimated 30 percent. Thickness of the dark-brown surface soil horizon averages about 6 inches, except on slopes which have been disturbed and eroded. Color of the subsoil ranges from yellowish brown to strong brown. Over-all thickness or depth of the Chacha-Saipan clays over limestone bedrock was discussed with the regolith and underlying bedrock. In Unit 3, some of the Saipan clay is only shallow to moderately deep and is more friable than firm in the upper part of the profile. Some Chacha-Saipan clay is included in Unit 1, Guam clay, mostly along the contact of Unit 1 with Unit 3.

Drainage, erosion, and soil moisture: Parts of this unit with convex surfaces are well drained; those with concave or depressional surfaces are moderately well drained and are subject to temporary flooding. Erosion is not severe in undisturbed areas, but disturbed or plowed areas have suffered considerable sheet erosion and moderate to severe gullying. Moisture is retained in the soil well into the dry season for deep-rooted or perennial crops, but the surface portion becomes very hard and cloddy upon drying if disturbed or plowed while wet.

Associated or included soils: Delineations of this unit may contain small areas of Guam clay (Unit 1), Saipan-Yona-Chacha clays (Unit 4), and possibly some of Toto clay (Unit 2). The Saipan-Yona-Chacha clays (Unit 4) mapped on rolling terrain are closely associated with this unit southward from Barrigada village. Adjacent to volcanic bedrock in central and southern Guam, Chacha clay and Saipan clay overlap and thin out on the saprolite (pl. 18A).

Vegetation and use: Practically all of this unit has been in cultivation for many years. The undulating to rolling terrain contains a fairly complete network of highways and roads. The largest urban area is Barrigada village. The adjacent area is rapidly becoming suburban, with houses, gardens, and small fields rather closely spaced along the roads. Field layouts and property lines seem to be fairly well maintained elsewhere also, but cultivation of this unit area is neither complete nor intensive. Many property owners seem to have other employment, allowing their farms to remain largely in pasture consisting of grass (*Panicum purpurascens* and *Paspalum conjugatum*), weeds, old coconut groves, scattered trees, and clumps of shrubs, vines and trees (*Leucaena glauca*), and breadfruit (*Artocarpus*). Garden crops, a few papaya, bananas, and ornamental plants are grown near the dwellings.

Suitability for use: When first cleared for agriculture, these soils were probably fairly productive. A certain amount of sheet erosion, severe in some places, and deterioration of the plow-layer structure has developed, reducing yields and workability of the soil. Some of this deterioration is permanent, but the soil most certainly will respond to good management. Crop rotation, with legumes, green manure crops, barnyard and commercial fertilizers, with some of the newer forms of weed and pest control should be among the more obvious initial steps toward restoring productivity of this unit.

Unit 4: Saipan-Yona-Chacha clays

Unit 4 is an association of three kinds of soil on rolling to moderately hilly slopes. Except for stronger prevailing surface gradients, two of the soils (Saipan clay and Chacha clay) are essentially as described in Unit 3. The other soil of this association, Yona clay (Lithosol), is found on many of the convex surfaces, and some of its identifying characteristics are mentioned here. A detailed description of Yona clay is given under Unit 5, Yona-Chacha clays, where it is the predominant soil of the unit.

General features: This unit consists of reddish Saipan clay and the yellowish or strong-brown Chacha clay (profile described under Unit 3) mapped on rolling or more strongly sloping topography than in Unit 3. These soils are interspersed with shallow, brownish Yona clay on many of the narrow, convex ridgetops. Relative relief of the soils may be regarded as intermediate between the undulating topography of Unit 3 and the deeply dissected or hilly to steep terrain of Unit 5.

Topography, distribution, and extent: Soils of this unit are distributed on rolling to hilly topography of the Agana argillaceous limestone, chiefly between Barrigada and Inarajan villages on the east side of the island, and between Barrigada and Agat on the west side. Prevailing surface gradient ranges from 8 to 25 percent. A total of 7,340 acres were mapped in this unit.

Underlying regolith or bedrock: The soils of Unit 4 are developed in clays washed from the adjacent deeply weathered volcanic upland and deposited on the Agana argillaceous member of the Mariana limestone -- possibly during two periods of inundation (see indication of a buried soil in the Saipan clay profile description, next paragraph). Depth to limestone bedrock ranges about as described for Unit 3, except that it is consistently very shallow on ridgetops occupied by Yona clay. The shallow, brown Yona clay is generally less than 12 inches thick over limestone, but in most places the upper part of the bedrock is fragmented or severely jointed and pitted, with clay in the interstices constituting up to 30 percent of the total volume.

Profile description: A profile of the reddish, firm, plastic Saipan clay in this unit is described below. It is deeper than average for this soil in such a position. It occupies a narrow ridgetop in an area somewhat more deeply dissected (local relief is 35 to 50 feet) than normal for the unit. It is recorded here because the soil is described to considerable depth, and also because the lower half of the profile (at 20 to 45 feet below the surface) is apparently a buried soil. (Site 46, grid BQ595878, sheet 5):

A_1 0 to 12 inches. Very dark grayish-brown (10YR 3/2, moist) clay; very fine to medium subangular blocky structure; plastic;

porous; contains some small (less than 1 mm diameter) non-calcareous, light-colored particles, and numerous small, soft, dark reddish-brown to black concretions; small roots and root hairs; pH 6.0.

B_2 12 to 24 inches. Yellowish-red (5YR 5/6) clay; firm; plastic; very hard (dry); angular blocky structure; some splotches or mottles of very pale brown (10YR 7/3); pH 5.5.

B_3 2 to 11 feet. Mixed about equal parts of red, yellowish-red, and very pale-brown clay; firm, plastic; very hard (dry); medium acid, pH 5.4.

C_1 11 to 13 feet. 60 percent very pale-brown, 30 percent yellowish-red, and 10 percent red clay; firm, plastic; very hard (dry); massive structure; pH 5.0.

C 13 to 15 feet. Predominantly red (10R 4/8) clay, with some light-red and very pale-brown mottles or stains; contains some silt and sand; plastic to slightly friable (moist); very hard (dry); pH 5.0.

C 15 to 20 feet. 60 percent yellowish-red (7.5YR 7/6) and 40 percent very pale brown (10YR 7/3) clay; firm, plastic; very hard (dry); pH 5.0.

A_{1b} 20 to 22 feet. (Buried, old A horizon.) Dark-brown (10YR 4/3) clay; friable to firm (moist); slightly hard (dry); medium granular structure; contains a small (3 mm diameter) piece of limestone, and a slender, preserved plant fiber or leaflet; pH 5.0 (reaction probably influenced by acid solutions from overlying soil).

B_{1b} 22 to 25 feet. Brown (7.5YR 4/4) clay; firm, plastic; hard (dry); pH 5.0.

B_{2b} 25 to 30 feet. Brown to strong-brown (7.5YR 5/6) clay; contains rounded, dark reddish-brown and black grains (concretions?, some of which are magnetite); also some red staining on particle surfaces; firm, plastic; hard (dry); pH 5.5 to 6.0.

C_{1b} 30 to 35 feet. Brown to light yellowish-brown (10YR 6/4) clay; very firm; very plastic; very hard (dry); contains some black and very pale-brown spots and streaks; pH 8.0.

C_b 35 to 40 feet. Same as immediately above, but with 10 or 15 percent of red mottling; pH 8.0.

C_b 40 to 42.5 feet. Brown (7.5YR 4/4) clay; contains some small bright red and black concretions (some of which are magnetite), and some subrounded limestone fragments (1/2 inch by 1 inch in size); pH 8.0.

C_b 42.5 to 44.5 feet. Brown to reddish-yellow clay; contains silt to gravel-size pieces of angular and subangular limestone; pH 8.0.

D At 45 feet, stopped drilling, in what appeared to be limestone bedrock. A similar profile of reddish Saipan clay, with more typical dark reddish-brown surface horizon, was drilled at

Site 47, grid BQ722972, sheet 3, in which there was no subprofile of buried soil, and limestone bedrock was encountered at 19 feet. The profile contained increasing amounts of magnetite crystals downward.

Range in characteristics: The Saipan clay described above is deeper than average for Guam. This soil was only 3 to 10 feet deep to limestone bedrock in many places in the vicinity of Ordot village, where it was mapped as a part of Unit 3. And all of the ridgetops in Unit 4 are not occupied by Saipan clay; many of them contain only a few inches of brownish, granular clay (Yona clay) on limestone, and where more than 12 inches deep, have strong-brown, plastic clay in the subsoil similar to Chacha clay. Reddish mottling, such as found along the road-cut at Site 124, grid BQ582833, sheet 8, is found in some of the Chacha clay. A shallow, stony phase of the Saipan clay is also found in small patches in this unit, especially on strong or convex slopes.

Drainage, erosion, and soil moisture: Convex surfaces are well drained; upland valley flats and sink-flats are moderately well drained and may be temporarily flooded during heavy rains. Except the shallow Yona clay, most of the soil retains moisture fairly well, and although some cracking of the soil does occur in dry weather, it is not nearly as severe as that observed in Toto clay (Unit 2). Sheet erosion and rilling were observed on some disturbed slopes, but ridgetop drainage areas are generally so small that gullying has not developed on the hillsides under heavy, continuous vegetative cover, but roads or paths running directly down-slope will wash or develop gullies.

Special features: The sub-profile of an older, buried soil shown in the profile description may be of interest to pedologists. Shallow stony soil on many of the ridgetops is also worthy of note.

Associated or included soils: Delineations of Unit 4 may contain small areas of Units 2, 3, or 5. Also, the Chacha clay which has developed on old half-filled limestone sinks and valleys may contain some Pago clay (Unit 9) developed in more recent sediments, in small areas which were not seen during the mapping.

Vegetation and use: Nearly all of this unit has in times past been cleared for some kind of argicultural use, and small ranches or farmsteads are found throughout most of the area. But farming is not very intensive at the present time. Only small field or plots are cleared. Mixed young forest, thin to dense, occupies much of the area not actually cultivated. Old coconut plantations, usually 1 to 6 acres in size, occupy many of the wider ridgetops or benches in the area. Grass, weeds, vines, and shrubs are now growing in these and in other places which have been cleared but not recently tilled. Access to primary roads by means of narrow, poorly surfaced or unimproved private roads is available in much of the unit, but several areas are isolated and accessible only by foot-trails.

Suitability for use: The suitability conditions mentioned for Unit 3 apply to much of this unit. But allowance or consideration must be given for the stronger slopes and areas of shallow, stony soils (chiefly Yona clay, but some of the Saipan clay and Chacha clay on convex surfaces also come into this category).

Unit 5. Yona-Chacha clays

General features: The unit consists of shallow, browish, granular Yona clay and yellowish (strong-brown), firm, plastic Chacha clay in deeply dissected topography of the argillaceous limestone. Chacha clay, described in detail under Unit 3, is found on some of the ridgetops, on lowermost ridge slopes, and in those ravine and sink bottoms which have only small, intermittent surface drainage and relatively little accumulation of recent sediments. Yona clay, described here, is found on most of the narrow ridgetops and adjacent steep slopes. It is tentatively classed as a Lithosol.

Topography, distribution, and extent: The two major soils of Unit 5 are associated in the areas of strongest slopes and greatest local relief found in the argillaceous limestone on Guam. This unit occupies hills and escarpments with slopes ranging from 25 to more than 100 percent, but prevailing surface gradients are most commonly between 30 and 65 percent. Some areas of this unit are on the western side of Guam, between Agana and Apra Harbor, but it is chiefly distributed in the central and southeast part of Guam, between Agana, Barrigada, and Agfayan Bay. Total extent of the unit is 8,360 acres.

Underlying regolith or bedrock: Soil on the steep slopes and ridgetops, mostly Yona clay, is about 6 to 12 inches deep on limestone which contains considerable clay in small pockets, joints, and crevices in its upper part. Some limestone fragments are in and on the soil and bedrock crops out as ledges or pinnacles, especially along steep escarpments. Yona clay grades into a shallow phase of Chacha clay, 2 or 3 feet deep, in many places on the ridgetops. Chacha clay in the ravine and sink bottoms and adjacent foot slopes is more than 3 feet deep. Character of the underlying limestone is mentioned in the soil descriptions and more detailed descriptions are given in the section of the report on Geology.

Profile description: The following profile is typical of Yona clay, the Lithosol on narrow ridgetops and steep slopes, examined in an area of very hilly terrain with local relief of 50 feet and prevailing hillside gradients of 35 to 40 percent. (Site 132, grid BQ593899, sheet 5):

A_1 0 to 5 inches. Very dark-brown (10YR 2/2, moist) clay; strong medium to coarse granular structure; firm; moderately plastic; permeable; considerable swelling and shrinkage with moisture change; roots permeate the mass; moderately calcareous (where it contains fragments of limestone).

C 5 to 10 inches. Mixture of strong-brown clay and fractured, pitted limestone.

D 10 inches to 5 feet. Massive, non-bedded, light-buff colored, cellular, porous limestone with strong-brown (7.5YR 5/6, moist) clay in the cavities ranging up to an estimated 30 percent of total volume at this place.

Range in characteristics: Bedrock or limestone fragments in soil range from few or none on some hilltops to numerous fragments and ledges of limestone exposed on some steep slopes. Color in the surface soil ranges toward dark reddish brown in some places. Gradation toward a shallow, stony phase of Chacha clay is

A. Chacha clay thinly overlapping saprolite of volcanic soil Unit 6; relationship common near boundaries of Chacha clay with soils of Units 6, 7, and 8. Southeast-central Guam, near C.A.A. Site; 24 March 1954.

B. Volcanic soil terrain in south-central Guam. Rolling foreground is Unit 6; dissected middle ground is Unit 7; mountainous background is Unit 8. January 1954.

evident in some places, with development of 12 to 24 inches of strong brown, firm, plastic clay subsoil.

Drainage, erosion, and soil moisture: Convex surfaces are well drained; flat-bottomed valleys or sinks are moderately well drained and are subject to temporary flooding. Undisturbed soil with vegetative cover does not show much active erosion, but steep slopes with vegetation removed will suffer sheet erosion, and gullying will develop if the soil is disturbed.

Associated or included soils: Smaller areas of a shallow stony phase of Saipan clay are included in this unit, associated with Yona clay. Some steep hills or scarps in the unit contain enough limestone at the surface to be classed as "Limestone rock land", but they are rather narrow and discontinuous for delineation on the map. Pago clay on well drained valley bottoms and Inarajan clay on poorly drained flats are adjacent to this unit in many places.

Vegetation and use: Thin to dense, mixed young forest occupies much of this unit. Some small cleared patches on ridgetops and in sink bottoms are cultivated, and numerous others in grass, weeds, and scattered brush are sometimes grazed. Swordgrass (*Miscanthus floridulus*) is found on some ridgetops adjacent to the volcanics. Roads are not numerous in this unit. There are farmsteads here and there, mostly accessible only by jeep-trail or foot-paths.

Suitability for use: Forest and limited grazing is about the only practical use for much of this unit. Subsistence farming can be practiced in small areas.

Upland Soils (on volcanic rocks)

Three major soils and one land type are mapped on the weathered volcanic rocks of Guam. These four taxonomic units are grouped in various ways into three mapping units, based somewhat upon the geographic association and topographic relationship of the soil (pl. 18B). Names of the soils in each map unit are listed in the order of dominance or extent of individual soils within the unit.

Unit 6: Atate-Agat clays, rolling

General features: Unit 6 consists of two soils -- a Latosol, and a truncated-Latosol -- with similar C horizons. Atate clay, the Latosol, is red, granular, acid clay associated with small bench-like mesas in the more gently sloping terrain (pl. 19A) on all kinds of volcanic rock. Thickness of the reddish, granular clay over the deep, mottled C horizon ranges from 2 to 8 feet. Adjacent rolling to hilly slopes mostly truncated by erosion are generally of Agat clay. Exposed C horizons of the two soils are similar, consisting of friable to plastic, varicolored, red-stained or mottled volcanic rock weathered to clay to depths ranging from a few feet to about 100 feet and averaging about 50 feet.

Topography, distribution, and extent: Total local relief is only in tens of feet, generally less than 50 feet, with a most common range of perhaps 10 to 30 feet. Maximum relief in an area of this soil is furnished by small mesas or flat-topped erosional remnants (generally less than one acre in extent) which commonly lie 10 or 20 feet above the gently sloping, irregular ridge or upland drainage basin terrain (pl. 19B). Surface gradients range from almost zero to slightly over 20 percent; most of the Atate clay is on slopes between 1 and 8 percent, while the associated Agat clay in this unit slopes with prevailing surface gradients of 8 to 15 percent, although some small areas of steeper slopes are included. This unit is distributed here and there over most of the southern volcanic half of Guam, except in the western mountains. Total extent of the unit is 8,400 acres.

Underlying regolith or bedrock: The formations of volcanic rocks and detrital volcanic materials on Guam are about equally represented in the bedrock of this unit. The older Alutom formation (of Eocene and Oligocene age) is largely bedded, waterlaid, fine-grained to sandy tuffs. The tuffs contain much glass and particles of plagioclase, pyroxene, and magnetite---the chief minerals of the lava flows. The tuffs are cemented by both calcite and silica---silica has replaced the leached-out calcite in many of the numerous small places where hard rock crops out. About 30 percent of the formation is composed of basic lava flows, basaltic conglomerate, and lapilli-sized volcanic breccia. The younger Umatac formation (of early Miocene age) consists largely of submarine basaltic and andesitic lava flows, pillow basalt, basaltic conglomerate, and lapilli-sized breccia.

Depth of weathering in the rock ranges from a few feet to perhaps 100 feet and averages about 50 feet. The weathered rock is decomposed to clay in which much of the texture and structure of the original rock is still apparent (known as "saprolite") (pl. 20A). Exposed or aerated saprolite is friable to hard; samples excavated from moist depths are firm and plastic; wet samples are soft, plastic, and sticky. Red color predominates in the upper part, and along bedding planes and joints to considerable depths in a matrix of pale yellow, olive, or gray. Thin discontinuous layers of soft to hard limonitic, hematitic, manganitic or bauxitic material in narrow bands of white, yellowish-brown, or dusky red clay are common just below the granular surface soils, the clayey material probably representing varied concentrates of compounds in the system Al_2O_3 - SiO_2-H_2O.

Profile description: The following profile of Atate clay is on a small high upland flat which slopes about 3 percent across the sampling site. There are steep erosional scarps nearly all around the small mesa which stands 10 to 30 feet above the surrounding terrain. The locality is in the vicinity of Bataa Sabana, about 2 miles northwest of Yona village (Site 4, grid BQ560850, sheet 8; correlation sample S54 Guam-5):

A 0 to 6 inches. (Lower 3 inches is irregularly transitional to horizon below). Dark reddish-brown (5Yr 3/3, dry) clay; very fine subangular blocky structure; very hard; noncalcareous; some "bauxitic" concretions (rounded to angular, pitted, pinkish-white pieces, 2 to 10 mm in diameter) and some fine, egg-shaped, black pellets of hydrous iron or manganese oxides, or both, less than 1 mm in diameter; and a few very fine threads or fibers of some mineral with shiny or glassy lustre; porous; full of small roots; pH 5.5 to 6.0.

B_1 6 to 18 inches. Red (10R 5/6 to 2.5YR 3/5, dry) clay; moderately fine blocky; firm; slightly sticky; contains some irregularly pitted concretions of a whitish mineral (gibbsite), 1 to 10 mm diameter, more numerous in lower part; contains a few small pinholes and root hairs. pH 5.0.

B_2 18 to 53 inches. Same as above, but with whitish (gibbsite) concretions up to 5 percent of total volume.

B_3 53 to 60 inches plus, red (10R 3/6, dry) moderately fine clay; finely mottled with light gray and bright yellow; a few or no concretions; no worm casts of "tonhäuchen"; fine tubes numerous; pH 5.0.

C_1 10 to 10.5 feet. (A lower segment of the small mesa scarp.) Red (7.5R 4/6, dry) clay; strong, fine subangular blocky to coarse granular or nutty; hard; plastic; sticky; porous; numerous joints or fractures; contains a few distinct fine, white mottles; pH 4.5 to 5.0.

C 28.5 to 29 feet. (Farther down, near base of small mesa scarp.) Soft, highly-weathered tuff (probably mostly clay); white (in 2 mm layer bordering joints or fractures) and reddish-yellow (7.5YR 7/6, dry) clay; each fracture zone coated with weak red (10R 4/4, dry); the weathered tuff breaks readily into angular blocks; very hard (dry); pH 4.5 to 5.0.

The nodular, pitted, whitish, gibbsite concretions, generally plentiful in the upper subsoil, are most numerous in this vicinity, and form a gravel pavement on eroded places at base of the small mesa scarp.

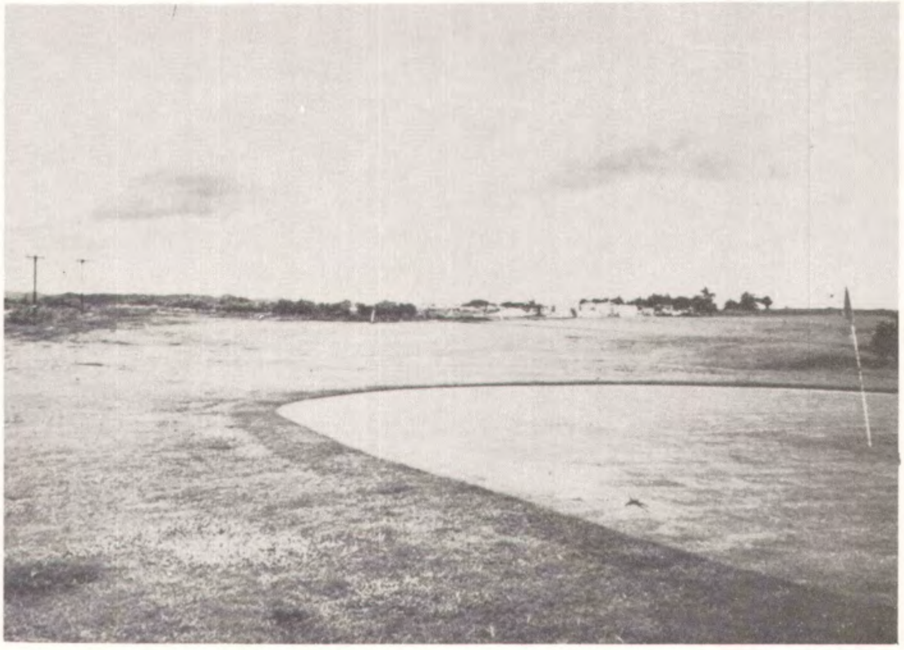
Range in characteristics: The dark reddish-brown surface horizon ranges from 2 to 30 inches in thickness and averages 6 to 8 inches. Total thickness of the reddish, granular, porous, acid A and B horizons ranges from about 1 foot to 10 or more feet; the average thickness ranges from 2 to 5 feet, and is deepest on the mesa tops or in swales between the ridges.

The pitted whitish, gibbsite concretions are most abundant west of Yona village; concretions of hematite, limonite, and manganese are common at or near the surface of flat areas nearly everywhere, but are abundant west of camp Witek and west of Yona where large ironstones are on the surface; small magnetite crystals, common everywhere in these soils, are most abundant at some places south of the Talofofo River, where they form dark bands at the base of the red granular A and B horizons, i.e., at 28 to 32 inches and at 55 to 59 inches (Site 115, grid BQ560723, sheet 10).

Drainage, erosion, and soil moisture: Small, flat-topped mesas with scarps on nearly all sides are somewhat excessively drained. The scarps are kept barren by cracking, spalling, and scouring action of the wind in dry weather, and by rilling and sheet erosion in rainy weather.

Lower, flat or slightly convex areas are well drained. Drainage is slow in the clay saprolite or C horizon, however, and small depressions in this material, especially along flat, natural drainageways, are almost permanently wet.

Special features: As seen in cross-section, the red, porous, strongly aggregated, acid Atate clay lies on a succession of almost completely dissected benches, beginning high on the shoulders of the southern mountains and extending seaward here and there on both flanks in a series of ragged, disjointed ridges and adjacent lower flats of relatively low relief (compared to the major bedrock dissection of the volcanic rocks).



A. Soils on Unit 6 on part of Windward Hills golf course, southeast Guam. Fairway grass is darker in color adjacent to the fertilized green. 19 August 1957.

B. Small mesa-like remnant of Atate clay in moderately dissected Unit 6. About 3/4 mile south of Nimitz Hill (Site 139); 22 March 1954.

A. Spheroidal weathering in saprolitic basalt. Such weathering is common in basaltic substrata of soil Units 6, 7, and 8. Roadcut about 1/4 mile east of Apra Heights; 19 August 1957. Photo by J. E. Paseur.

B. Granular mulch on exposed basaltic saprolite, formed by exfoliation of flakes and granules from the saprolite during alternate wetting and drying. Heavy rains carry off the mulch and spread it as flat alluvial fans at lower levels nearby (a very common process in soil units 6, 7, and 8). Near Libugon, west of Nimitz Hill; July 1954. Photo by E. H. Templin.

A tendency of the granular soils (pl. 20B) to accumulate in flat benches, as seen in the old flat-topped mesas and in the more recent lower flats adjacent to the mesas, is of interest. The fact that such flats are being formed today in newly eroded material points toward characteristics of the deeply weathered material which may partly account for this feature of local "base-leveling". The following observations are offered: 1) a cubic inch of clay from an air-dry exposed column or block in the C horizon of these soils dropped into a glass of water exfoliates and disintegrates into a mass or porous granules, with almost violent rapidity. These granules do not again cohere or assume a solid mass unless compressed while moist. If the water is drained off and the material in the glass is dried, the granules remain as weak to strong aggregates, which if allowed to oxidize for a long period of time, would seem to be more or less permanent if not too much disturbed or abraded. 2) V-shaped gully starts to cut back into a 25 percent hillside slope (pl. 21A). Cracking, jointing, and spalling off of the clay walls or sides of the gully in alternate periods of sun and rain causes the gully to widen out or to become a crescent-shaped gouge in the side of the hill (pl. 21B). The floor of this hillside cut or gouge is a relatively flat (pl. 21C), fluffy, porous mass of newly formed granules or clay aggregates (see pl. 20B), similar in texture to those formed from the disintegrated cube mentioned above. Some of these deposits appear to be stratified (pls. 22A and 22B). Superficial local "base-leveling" of this nature appears to be taking place on Guam today (pl. 21C), and if projected through geologic time it would produce considerable bench-like terrain.

Associated and included soils: Small areas of Unit 7, and possibly some of Unit 9, are included in this unit. There are also included some small areas of a reddish-mottled, pale-olive to pale-yellow clay in terrace positions on volcanic rocks, at headwaters of the Pago and Fena Rivers (Sites 136 and 137, grids BQ558868 and BQ558869, sheet 8, and 138, grid BQ497793, sheet 7). This soil is similar to Toto clay (Unit 2), except that it lies on volcanic rocks instead of on argillaceous limestone. As only small areas were identified, late in the mapping program, it is not being proposed as a unit of soil at this time.

Vegetation and use: Most areas of this unit are accessible by vehicle and by foot trails. The well aggregated or granular, porous, well drained solum of the Atate clay takes water so rapidly that jeeps or trucks can be driven over it in most places within a few hours after a heavy rain. There is evidence of considerable military use of these areas during and after World War II. Much of the unit is now in pasture or in idle land, with a few truck gardens or small farms here and there. Uncultivated land contains scattered clumps of swordgrass (Miscanthus floridulus) and Dimeria, with Gleichenia linearis and Chrysopogon aciculatus encroaching upon disturbed or erosion-scarred places. Scattered small shrubs such as Myrtella, Wikstroemia, Scaevola, Geniostoma, and Blechnum orientale are common. Scattered Casuarina equisetifolia are found, mostly around the rims of the small, flat-topped mesas. Thickets of Pandanus and limon de china are in a few small sheltered coves. A large reed, Phragmites karka, grows in the small, poorly drained depressions, but these are more common in the drainageways of Units 7 and 8.

Suitability for use: The numerous small, flat-topped, steep-sided mesas or erosional remnants of old soil surfaces are mostly too small, and because of their isolated, elevated positions, are too well drained for cropland, although some of the larger ones might be farmed. Slopes lying between the mesas and the depressions or wet spots would seem to be most suitable for cultivation. A system of contour planting along terraces supplied by small surface-water catchment basins or reservoirs could be established. Pineapple should grow well in much of this unit, under such conditions. Tomatoes, cucumbers, and lettuce under good management were doing well in the granular, porous soil of this unit. Sweet potatoes should also grow well.

Fertilizer test plots should be established on some of the more gently sloping parts of Unit 6 which may be considered for farming. Response of grass on a golf fairway to fertilizer applied during treatment of adjacent newly established green is shown in plate 19A.

Unit 7: Agat-Asan-Atate clays, hilly

General statement:. The three taxonomic soils listed in the name of this map unit are developed equally on the major volcanic rock formations which make up much of the southern half of Guam. Because of the great depth and advanced degree of weathering in these rocks, the kind of original rock formation has little influence upon the kind of soil developed on it. There is evidence that the red granular material of the Atate clay A and B horizons may have been formed as long ago as Plio-Pleistocene time (see rock descriptions under Geology). Subsequent truncation, erosion, and dissection of a large part of this ancient soil mass have played a large part in the creation of the present soil landscape. The ways in which the taxonomic soil units are associated in the different soil map units (Units 6, 7, and 8) more or less reflect the influence of relief and topography upon the processes of soil formation (see pl. 18B).

General features: Unit 7 is an association of soils in hilly terrain. Relief is intermediate between that of Unit 6 (rolling) and of Unit 8 (very hilly). The reddish-stained and mottled clay subsoils of Atate clay and of Agat clay average 50 feet or more in depth. The grayish, pale-yellow to pale-olive substrata of Asan clay are not as deep and have only minor amounts and intensities of red staining, mostly in the upper part. External drainage is rapid; internal drainage is slow; depressions in the C horizon are permanently wet. pH reaction of dry or only occasionally wet soil is generally acid; in the lower zones of continuous saturation it is alkaline.

Topography, distribution, and extent: Total local relief ranges from about 50 feet to more than 400 feet, with a range of 50 to 200 feet most common. Slope or surface gradients range from 15 to about 50 percent, with prevailing gradients generally between 20 and 35 percent. Areas of this unit are distributed throughout the southern half of Guam, with the largest areas lying northeast and southeast of the Fena basin. Total extent of the unit is 23,760 acres.

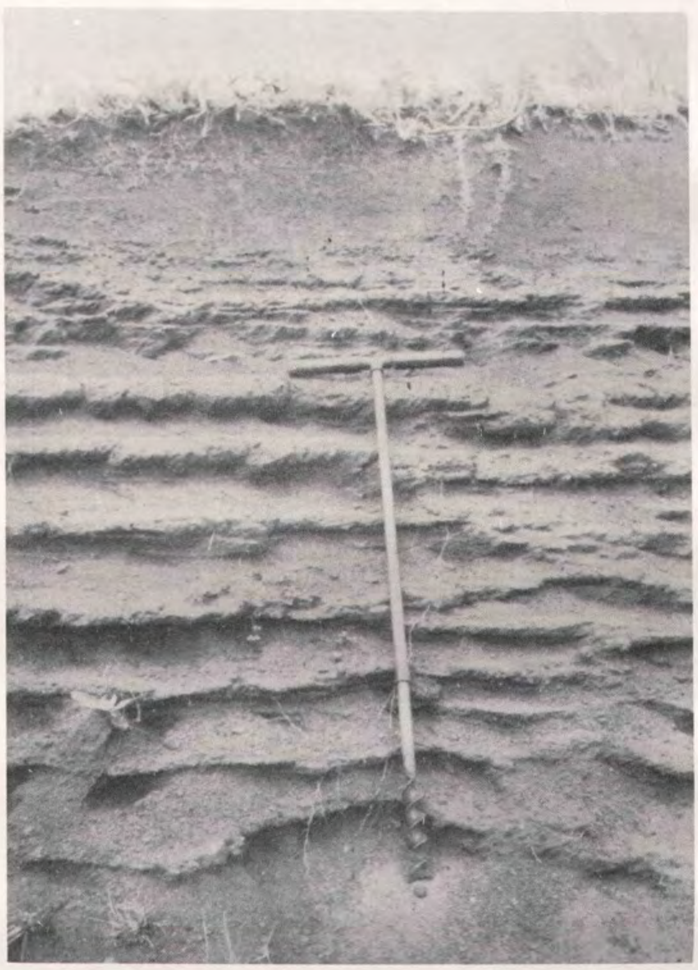
Underlying regolith or bedrock: Formerly indurated, marine-deposited, pyroclastic sediments and flows are weathered and decomposed to clay to depths averaging about 50 feet. Spheroidal weathering is common in the basaltic substrata. Relict shapes, which look like rock, can be cut with a knife and are mineralogically clay (see pl. 20A). Depth to hard bedrock in some places ranges from near zero to about 100 feet within rather short horizontal distances, and in other places the depth is fairly uniform over areas of considerable extent. Atate clay and Agat clay C horizons are

A. Fresh gully development in Atate clay, south-central Guam. Caused partly by sapping or eroding of porous Latosol by a small stream flowing 6 feet underground on relatively impermeable saprolitic substrata. 19 March 1954.

B. Wide erosion scar in Atate clay (Unit 6) at head of flat-bottomed gully about 1/2 mile west of Inarajan village; 18 August 1957. Photo by J. E. Paseur.

C. Erosion of a Pleistocene soil bench (right center); material is being deposited at a lower level. Laterization of the newly-laid material may preserve it in place, forming a bench which may in turn be destroyed as weathering and erosion attain greater depth in the volcanic saprolite. About 1/2 mile west of Inarajan village; 18 August 1957. Photo by J. E. Paseur.

A. "Stratified" latosolic sediments on massive saprolite, west-central Guam. Roadside cut along Spruance Drive (Route 6); 7 April 1953. (Origin is discussed under Special Features, Unit 6.)



B. "Stratified" latosolic or partly laterized sediments, southwestern Guam. The "strata" may represent different depositional layers, or former ground-water levels at which thin layers of alluvial fan material were faintly indurated by lateritic action. In volcanic upland about 1,200 yards south of Mt. Jumullong Manglo; 12 November 1953.

A. Small mesa remnant of Atate clay in severely dissected Unit 7. Pillow basalt saprolite is slumping on vertical shear plane along irregular dark line in photo center. This red-stained saprolite is characteristic also of the truncated Agat clay. About 2 miles south of Agat village, along Route 2 (Site 9); 10 May 1954.

B. Reddish-stained pillow basalt saprolite. (Closer view of extreme right foreground of Plate 23A).

predominantly red in the upper part, and are red in mottling and in coatings or fillings along joints and bedding planes to considerably greater depths -- to more than 30 or 40 feet in places (pl. 23A). Asan clay C horizon is predominantly pale yellow, pale olive or light gray in color, with minor amounts of red near the surface, mostly as coating or staining in joints, fractures, and along bedding planes.

Although Agat clay and Asan clay are referred to in these descriptions as truncated-Latosols, there is some question whether or not Asan clay has ever undergone the degree of latosolic development evidenced in subsoil of the Agat clay. Asan clay in many places has a few inches of dark gray A horizon development, which if widespread or general enough, would tend to put the soil in the category of the Regosols. This development, thought to be superficial or at least subsequent to the great Plio-Pleistocene period of latosolic development, is further exemplified by a similar A horizon development in only a few inches of clay overlying hard bedrock. Such a soil is classified as a Lithosol, but the numerous small, scattered patches were not mapped in this survey.

Profile description: A profile of Atate clay was described under Unit 6; Asan clay is described under Unit 8. A profile of Agat clay, principal soil of Unit 7, 1 mile west of Inarajan (Site 39, grid BQ539690, sheet 10) is as follows:

A 0 to 8 inches. Dark reddish-brown (5YR 3/3 to 3/4) silty clay; subangular blocky to nutty structure; plastic (moist) friable to hard (dry); pH 6.5.

B_3 8 to 30 inches. Red (2.5YR 4/6) clay, mixed or interbedded with grayish-white clay; plastic (moist); hard (dry); subangular blocky to massive; pH 6.0.

C_1 2.5 to 21 feet. Reddish-brown (5YR 4/4) to yellowish-red (5YR 4/6) clay; plastic (moist); hard (dry); subangular blocky to massive; pH 5.5 to 6.0.

C_1 21 to 30 feet. Reddish-brown (5YR 4/4) clay; plastic; subangular blocky to massive; contains numerous pellets of what appear to be rounded fragments of zeolite (common filling in joints); pH 5.5.

C 30 to 36 feet. Dark-brown (7.5YR 4/4) clay; subangular blocky to massive; plastic; contains fragments of weathered tuff; pH 5.5.

C 36 to 60 feet. Brown (7.5YR 5/4) to yellowish-brown (10YR 5/4) clay; very plastic; massive structure; contains a few fine pieces of what appear to be weathered tuff; pH 5.5.

C 60 to 79 feet. Brown (10YR 5/3) clay; massive structure; very plastic (moist); hard (dry); contains pale-brown (10YR 6/3) weathered rock fragments up to 1/2 inch in diameter; pH 6.0. Stopped drilling because of heavy load on jeep-mounted power auger; bedrock estimated to be within a few feet of bottom of test-hole.

Range in characteristics: As this is a somewhat severely truncated-Latosol, the quantity of reddish, granular surface soil is generally sparse. Intensity and depth of the red staining or coloration in the upper C horizon ranges from a few feet to more than 40 feet below the surface. Red, white, yellow, brown, and black thin bands, veins, streaks, splotches, crusts, and concretions of hard to soft clayey material are common in the upper part. Various concentrations of iron, alumina, and manganese compounds probably account for the varied colors and degrees of hardness. A bluish-black, moderately hard substance, somewhat waxy in appearance, is a common filling in joints. Nodular, pitted, whitish concretions of gibbsite or bauxitic material are at the surface of C horizon exposures in many places, chiefly west and southwest of Yona village.

Apparent texture and structure of the decomposed rocks ranges through that of bedded to non-bedded, fine- to coarse-grained tuff, and fine- to coarse-grained pillow basalt (pl. 23B) and conglomerate, most of which, when disturbed, prove to be clay and which can be crushed and kneaded by hand when moist. (The peculiar slaking or granulation of this material when disturbed, air-dried, and then immersed in water, has already been described.)

Drainage, erosion, and soil moisture: Erosion of these soils was discussed under Special features, Unit 6. Erosion of the soils in Unit 7 is more severe because of greater relief and steeper prevailing surface gradients. Normal geologic erosion has undoubtedly been considerably accelerated, directly and indirectly, by activities of man. Periodic burning of large areas of the vegetation as practiced today by the natives of mixed Spanish blood may have been going on for the past two or three hundred years. Reduction of the cover and soil fertility by burning may have accelerated the rate of sheet erosion, solifluction, gullying, and formation of landslides, all of which are common on the present-day hillsides in the volcanic areas of southern Guam. Many of the present active gullies, landslides, and barren, raw erosion scars are also directly traceable to effects of vehicle movement, shell or bomb bursts, or to activities of bulldozers.

Surface runoff is the predominant means of natural drainage in this unit. Convex surfaces and the numerous strong slopes are well drained. Internal drainage in the clay C horizon is slow, and small depressions in this material along wide, natural drainageways or on upland flats are almost permanently wet. These places are identifiable by lush, dense growths of the large reed *Phragmites karka*. Many large upland basins and wide, nearly level drainageways contain colluvial accumulations of the granular surface soils or exfoliated, flakey clay from eroded subsoil exposure; these alluvial accumulations are porous and retain water for several days or weeks after heavy rains and furnish water by seepage to the many small, intermittent streams.

Special features: Reaction of permanently saturated soil, whether in very shallow or in very deep borings, was almost invariably alkaline; dry or moist soil above the water table was mostly acid.

Another special feature of this unit is the occurrence of several small outcrops of hard, relatively unweathered conglomerates, tuff, tuffaceous sandstone, and pillow basalt. A large field of scattered basalt boulders is in the Dandan area, midway between Inarajan village and the Ugum River, and there are scattered boulders and small areas of boulders in other places.

Associated or included soils: Areas of Pago clay (Unit 9) or of Inarajan clay (Unit 10) too small to map are in some drainageways. An overlap of Chacha-like clay, 20 to 30 inches thick, was observed on the volcanic saprolite of Unit 6, near the boundary between Unit 6 and Unit 4 (Site 126, grid BQ548795, sheet 8) (see pl. 17A).

Vegetation and use: A large variety of vegetation grows on the soil of this unit, but the predominant or most widespread cover consists of swordgrass (Miscanthus floridulus) and another associated grass called Dimeria, with some scattered shrubs and Australian pine (Casuarina equisetifolia) (pl. 24A). Patches of weeds (Stachytarpheta indica, Hyptis capitata, Hyptis scareolens, and Elephantopus mollis) are common in recently disturbed areas, and the pioneer Gleichenia linearis and Chrysopogon aciculatus are among the first to encroach upon erosion-scarred areas. Thickets of vines, shrubs, and trees are in some ravines or on some steep slopes which have not been recently burned (pl. 24A). Varieties of trees in these places include the mango, the betel nut palm, and species of Pandanus, Triphasia (limon de china), Casuarina, Hibiscus, and Pisonia. The previously mentioned large reed, Phragmites karka, grows in depressions that are permanently wet. A few small plantations of coconut trees are still growing on narrow colluvial terraces and low upland flats in this unit.

Chief use of the soils of this unit is for grazing. A few subsistence gardens of small size are on colluvial slopes or terraces at the base of steep slopes, near the villages. Roads which give access to areas of this unit are mostly built on more favorable terrain of associated units, such as on Units 6 or 9. Roads built on this unit during or right after World War II are now mostly impassable because of washouts or gullying. A cross-island road recently constructed on soils of Units 6 and 7 has already been damaged by concentration of surface runoff in several places and shows the need for careful planning and proper installation of gutters, bridges, and culverts with weirs large enough to handle 100 percent surface runoff after the soil is saturated.

Suitability for use: There are many areas of soil on gentle slopes, too small to separate on the map, which are similar in use-capability to the soils of Unit 6. Such areas make up 10 or 15 percent of the total unit area. But most of the unit seems unfit for cultivation, unless a very intensive system of terracing is used, such as is practiced on Okinawa and other thickly populated areas. Introduced cover crops, protection from fire, and controlled grazing are some of the logical first steps. The thin, scattered, but fairly uniform distribution of young growing Casuarina trees indicates the possibility of establishing vegetation other than grass, if the periodic burning can be controlled or stopped.

Unit 8: Agat-Asan clays and rock outcrop, steep

General features: Unit 8 is an association of soils in very hilly to mountainous terrain. It consists predominantly of the truncated-Latosol, Agat clay, and Asan clay (a Regosol), with some dark grayish-brown Lithosols and scattered small areas of rock outcrop. In some places the reddish-stained and mottled Agat clay is predominant, while in other places the grayish, pale-yellow to pale-olive Asan clay is more prevalent. External drainage is very rapid; internal drainage is slow; depressions in the C horizons are permanently wet. pH reaction is generally acid above the water table and alkaline in the water

A. Hilly to steep volcanic soils (Agat and Asan clays of Units 7 and 8), southern Guam. Coarse grasses and scattered evergreen "ironwood" trees are most common on the upland; mixed secondary forest with thickets of pandanus, hibiscus, and scattered betel palm are in the valleys. 1954.

B. A-C profile of Asan clay (a Regosol) on truncated saprolite. Near Mt. Tenjo road (Site 18); 4 March 1954.

table, except in areas of Lithosols or bedrock outcrop where the reaction may be largely alkaline, with acid reaction only at some places near the surface.

Topography, distribution, and extent: Local relief ranges well into the hundreds of feet in the mountainous areas. Surface gradients range from about 35 to more than 100 percent, and prevailing surface gradients average 50 percent or more (pl. 24A). Distribution of the unit is chiefly on both flanks of the north-south mountain range, in the western half of southern Guam. Total extent of the unit is 15,020 acres.

Underlying regolith or bedrock: The type of bedrock and degree of weathering has been described under Units 6 and 7. Depth of weathering in Units 6, 7, and 8 may have been about equal, but much greater relief in this unit may have caused more loss of the weathered material. Small areas of Lithosols and outcrops of hard rock are more common in this unit. The predominance of reddish soils is less marked. The grayish, pale-yellow Asan clay (Regosol) predominates in some areas. Where not too severely eroded, it has a dark grayish-brown A horizon 2 to 8 inches thick developed on a C horizon of pale-yellow clay 3 to 50 or more feet thick (averaging perhaps 20 to 35 feet thick).

Profile description: The following profile of Asan clay (pl. 24B) is on a narrow convex ridgetop along the pipeline road southeast of Nimitz-Mt. Tenjo housing area (Site 18, grid BQ527879, sheet 4; correlation sample S54 Guam 23).

A_1 0 to 8 inches. Dark grayish-brown (10YR 4/2.2, dry) clay; coarse granular to coarse subangular blocky; hard (dry); contains pale-yellow spots less than 1 mm in diameter, and has numerous soft, reddish-yellow to yellowish-brown (7.5YR 6/8 to 10YR 5/8, dry) stained lapilli or concretions (4-15 mm in diameter) pH 5.5 to 6.0. Grades abruptly to horizon below.

C_1 8 to 72 inches. Pale-yellow (5Y 7/4, dry) to pale-olive (5Y 6/4) and greenish clay, with dark-red (2.5YR 3/6, dry) and dark reddish-brown, thin coatings or staining on some fracture faces. The different shades of yellow clay seem to be alteration patches in the greenish or olive matrix; coarse subangular blocky to massive; there are some small lapilli or pellets of pink or weak-red clay in the olive matrix, and also some which are very dark gray (lapilli 1/4 inch diameter) with small, pale-yellow inclusions; there are coatings or films of dark red on some of the fracture faces and some of the red has penetrated into the soft interior of angular pieces broken during excavation; hard (dry); pH 5.5 to 6.0.

In spite of the red staining mentioned in the above description, the over-all color is a pale yellow to pale olive. Total depth of clay C horizon is estimated to be about 30 feet at this place. Another similar profile, one-fourth mile north of Merizo village (Site 36, grid BQ474680, sheet 11), is 19 feet to relatively unweathered bedrock.

Range in characteristics: The A horizon, absent in many places, is commonly only 2 to 4 inches thick on steep slopes. In many places ragged, linear strips of A horizon have slipped downhill a few feet, exposing bare subsoil. These "slips" may be related in some way to dip and shear in the underlying saprolite, and are caused by a "zone of flow" developed along the contact of A and C horizons when the soil is saturated. The process is called solifluction.

Ferro-manganese incrustations (pl. 25A), magnetite, quartz, calcite, and glauconite crystals and pieces of limestone have been found here and there, in and on the C horizon. The whitish, bauxitic nodules or concretions are scarce.

Drainage, erosion, and soil moisture: Erosion and solifluction are active in this unit. External drainage is very rapid; internal drainage is slow. There are numerous small seeps along the lower edge of inclined beds or joints in the saprolite and bedrock. Blocking of this natural seepage by heavy earth fills or road embankments will cause landslides unless drainage is provided along the line of seepage. Depressions or low, flat, granular deposits are perennially wet, as in Unit 7.

Special features: In the vicinity of Mounts Tenjo, Alutom, and Chachao, and also north and east of Umatac village, many of the outcrops of slightly to moderately weathered tuffs are calcareous. *Leucaena glauca*, which seems to favor soil of alkaline reaction, was growing in clumps or thickets in some of these places.

Vegetation and use: Vegetation on the soils of this unit is of about the same kind as on Unit 7. Stands of grass are thinner and less vigorous in many places, especially where Lithosols or exposures of bedrock prevail. Trees, shrubs, and vines which have not been burned are predominant in some valleys and steep slopes. Natives forage back into these relatively inaccessible places for betel nuts, mangos, breadfruit, peppers, and other tropical foods and condiments. Taro is also grown in some of the small wet places which are fed by seeps or small springs.

Roads are scarce in this unit because of the steep terrain. Access is mainly by foot trails along ridgetops or ravine bottoms. Uncontrolled grazing and burning are practiced throughout most of the unit.

Suitability for use: Soils of this unit are unfit for cultivation, except in scattered small areas which may be hand-tilled. Grazing should be controlled. Burning should be prohibited. Such management would permit re-establishment of larger stands of native trees, shrubs, and vines which furnished so much of the food, clothing, and building materials formerly produced and used by the island inhabitants. A thin but persistent scattering of the evergreen "ironwood" (*Casuarina equisetifolia*) would soon furnish a good pioneer forest cover on soil Units 6, 7, and 8 if burning could be effectively prohibited or controlled (see pl. 24A). Experience in tropical regions indicates that reforestation of eroded, grassy slopes is very difficult or impossible with most varieties of desirable trees until forest-growth conditions in and on the soil have been re-established by propagation of some locally adaptable species, such as the "ironwood" seems to be on Guam.

Soils of Coastal and Valley Flats

Unit 9: Pago clay

General features: Unit 9 is a deep, moderately well drained, noncalcareous Alluvial clay developed in sediments derived chiefly from volcanic rocks, but which are laid down and permeated by waters containing solutions from limestone. The subsoil is varicolored, firm, plastic clay, predominantly reddish or yellowish brown, with gray mottling in the lower part. The soil is subject to occasional flooding, but the water table is 1 to 7 meters below the surface during much of the year.

Topography, distribution, and extent: This soil occupies valley bottoms of the larger streams (pl. 25B) and alluvial fans of smaller streams in the south half of Guam. Prevailing surface gradients are nearly level (0 to 3 percent). Total extent of the unit is 2,380 acres.

Underlying regolith or bedrock: Unit 9 is underlain by limesand, limestone, or rock of volcanic origin. Thickness of the clay over such material is generally more than 10 feet and less than 150 feet.

Profile description: A profile of this soil, located in the Talofofo River bottom (Site 8, grid BQ555759, sheet 10) is as follows:

A_1 0 to 9 inches. Very dark grayish-brown (10YR 3/2, dry) clay; granular to nuciform; extremely hard (dry); very firm (moist); slightly sticky (wet); porous, with pin-holes and root-holes; roots and rootlets numerous; white and yellowish-brown particles visible under 10-power lens; some yellowish-brown stains on the ped or particle faces; numerous small cracks or joints; pH 7.5.

A_3 9 to 16 inches. Same as soil above, but subangular blocky and nongranular; firm; plastic; more yellowish-brown staining, with two distinct bands 1/2-inch to 1 inch wide at 10" and 14" below surface; roots and root hairs numerous; pH 7.5.

C_1 16 to 27 inches. Very dark grayish-brown clay; moderate subangular blocky; firm; plastic; yellowish-brown and reddish-brown stains and coatings on peds; some fine roots and a few up to 1/2-inch diameter; some white and pale-yellow soft granules visible under 10-power lens; many pores and pin-holes (less than 1/2 to 1.0 mm diameter); pH 7.5.

C_2 27 to 41 inches. Very dark grayish-brown clay; has 15-20 percent yellowish-brown and reddish-brown stains and coatings on peds; numerous soft, black and dark reddish-brown concretions (1.0 mm up to 0.5 inch in diameter); fine to medium subangular blocky; root fibers numerous; pH 7.5.

D(?) 41 to 60 inches. Grayish-brown (10YR 5/2, moist) clay; plastic; soft to moderately firm; sticky; strongly mottled with strong brown and yellowish brown; some soft black concretions and stains; numerous pin-holes (less than 0.5 mm diameter); pH 6.5.

D 5 to 10 feet. Soil-auger boring to a depth of 10 feet showed yellowish-brown, plastic, sticky clay to water table at 10 feet, with strong gray mottling below 8 feet.

A. Ferro-manganese incrustations in and on basaltic saprolite substrata of eroded Asan clay. About 1 3/4 miles west of Yona village; 19 March 1954.

B. Pago clay in the Pauliluc River valley. This Alluvial soil is seasonally flooded. Along Route 4, southeastern Guam; April 1954.

Range in characteristics: The above profile is more dark grayish brown in the subsoil and more nearly alkaline in reaction than is typical in this soil. The subsoil is more commonly brownish or reddish brown, grading into yellowish brown or mottled gray substrata at depths between 30 inches and 10 feet. Reaction is generally neutral to slightly acid above the water table, and alkaline below. The gray mottling commences at depths not less than 24 to 30 inches.

Drainage, erosion, and soil moisture: The soil is moderately well drained. It is subject to occasional moderate to severe flooding; but the water table ranges 3 to 50 feet below the surface and is 5 to 25 feet below the surface in most of the unit during a considerable part of the year. The surface soil becomes hard and develops cracks 2 or 3 feet deep after several weeks of little or no rain. It becomes plastic, sticky, and has water standing in surface depressions for a few hours or days after heavy rains, depending upon the intensity and duration of the rain. Severe erosion by converging flood waters in some places and local deposits of clayey and silty mud are among the natural occurrences which affect this unit.

Special features: Numerous small areas in this unit are almost perennially wet because of seepage from adjacent higher beds or from granular soils (Atate clay of Unit 6) overlying such beds and serving as aquifers for a considerable time after each heavy rain. Most of these places are shown by wet spot symbols and are identified in the field by *Cyperus*, *Paspalum*, *Phragmites karka*, or other moisture-loving plants.

Associated or included soils: Pago clay is higher and better drained than Inarajan clay, with which it is associated. It may contain small inclusions of Inarajan clay, however, and possibly some of muck also. Pago clay, as mapped along the southern coast of Guam between Umatac and Merizo, includes an overlapping of Shioya-like, sandy soil along the seaward margin.

Vegetation and use: Areas of this unit served by roads or jeep-trails have numerous cleared areas which, when not cultivated, are quickly overgrown with grass and weeds such as *Paspalum conjugatum*, *Panicum* sp., and *Stachytarpheta indica*. Scattered old coconut plantations are also common. Cultivated crops growing during the early spring months (usually the time of least rainfall) were corn, bean, pea, onion, cucumber, cabbage, tomato, sweet potato, melon, and squash.

Narrow colluvial terraces along the margins of the stream floodplains were generally included with the soil of this unit in mapping. These commonly contain a few breadfruit or mango trees, and some plantings of banana or papaya near farmhouses.

Areas of this unit not penetrated by roads or jeep-trails are generally farther inland, toward the stream headwaters. Heavy jungle growth of trees, shrubs, vines, and fern are in many of these places. *Hibiscus tiliaceus* and *Pandanus tectorius* are predominant trees in such places, but many other varieties also occur. Such areas seem to be used only for pasture. Traverse is difficult; depressions between the trees, scoured by tumbling flood waters and dammed by heavy root growth, seem to hold enough water to keep the soil saturated for several days after heavy rains. The small places that are permanently wet contain moisture-tolerant plants such as *Phragmites karka*, *Cyperus* sp., *Barringtonia racemosa*, or *Hibiscus tiliaceus* and *Pandanus tectorius*.

Suitability for use: The soil of Unit 9 is generally suitable for the crops mentioned above. Only a small part of the unit is utilized for tilled crops at the present time. Weeds, snails, and insects were problems not overcome by many of the small farmers or itinerant "gardeners". But a few farms were operated intensively on a rather large scale, indicating that the difficulties are not insurmountable.

Unit 10: Inarajan clay

General features: Unit 10 is a wet, poorly drained equivalent of Pago clay (Unit 9), with the water table on the surface for brief periods but most of the time at shallow to moderate depth below the surface. Poor-drainage mottling is at depths shallower than 30 inches, generally at 10 to 24 inches. The clay is moderately plastic and moderately firm, except in local, depressed areas where organic content is high in the surface layer and the clay is only moderately firm to friable. The pH reaction is neutral to alkaline.

Topography, distribution, and extent: This soil occupies coastal and valley flats a few feet above sea level south of Agana on the west coast, and in the Pago River valley and southward along the east coast. Prevailing surface gradient is less than one percent. Alternate small rounded hummocks and depressions 12 to 24 inches in diameter furnish a micro-relief of about 18 inches in many places. Total extent of this unit is 2,320 acres.

Underlying regolith or bedrock: Unit 10 is underlain by limesand, limestone, or beds of weathered volcanic rock at depths ranging from as little as 3 feet, along the coast, to 10 or more feet inland.

Profile description: A profile of this soil, at the mouth of the Inarajan River floodplain (Site 26, grid BQ557690, sheet 10) is as follows:

A_1 0 to 6 inches. Very dark gray (10YR 3/1, dry) silty clay; hard (dry), plastic (wet); medium granular to medium angular blocky; contains grass roots, small pieces of limestone (1/2 mm to 3 mm diameter) and some limonitic concretions (up to 5 mm diameter); pH 8.0; grades to

C_1 6 to 18 inches. Very dark grayish brown (2.5Y 3/2, moist) clay with many distinct medium and coarse mottlings of yellowish brown (10YR 5/6, moist); contains numerous small pieces of limestone (1-2 mm to 1 inch in diameter); soft, plastic, sticky (moist); pH 8.0.

C_2 18 to 40 inches. Mixed dark yellowish-brown and yellowish-brown clay, with faint to distinct medium mottling of gray (10YR 5/1 and 6/1, moist) which becomes coarser and more distinct downward; soft, very plastic, sticky (moist to wet); pH 8.0; water table at 40 inches (31 Mar 54).

D 40 to 48 inches. Gray silty, sandy, and gravelly clay (the angular to subrounded gravel fragments are of limestone, coral, and some beach rock, up to 4 inches in diameter); the soil mass is wet, plastic, gritty and calcareous.

Range in characteristics: At a considerable distance inland from the coast, this soil is not calcareous in the upper part. Volcanic sediments are apparent in many such places, reaction is commonly 6.5 or less above the mottling and pH 7.5 to 8.0 plus (alkaline) within the zone of mottling. Light gray, yellowish brown, pale brown, and olive are common colors in the mottled subsoil. Depth of the mottling below the surface ranges between 6 and 30 inches and is most commonly between 10 and 24 inches. The clay substrata may overlie limesand, limestone, clayey organic matter, or weathered volcanic bedrock at depths between 3 and 10 feet near the coast. Lobes or "islands" of limestone are at shallower depths between Piti and Agat villages along the west coast.

As indicated by the mottling, depth to the water table is mostly from 0 to 3 feet, but for a time during the dry spring months it may be considerably lower.

Drainage, erosion, and soil moisture: The soil is subject to occasional severe flooding and depressions are frequently ponded (numerous small ones are almost permanently ponded). Siltation and erosion occur as small streams overflow, damaging buildings and especially highways, culverts, and bridges. After two or three months of relatively dry weather, usually in the early spring, the surface soil becomes dry and hard, with a network of cracks 1/2 to 1 inch in diameter and 2 or 3 feet deep (pl. 26A).

Special features: Numerous depressional areas with the water table at or near the surface most of the time are in this unit, constituting nearly all of some delineated areas. Thick cover of the large reed *Phragmites karka* or tangled jungle of *Hibiscus* and *Pandanus* trees are characteristic vegetation in these places.

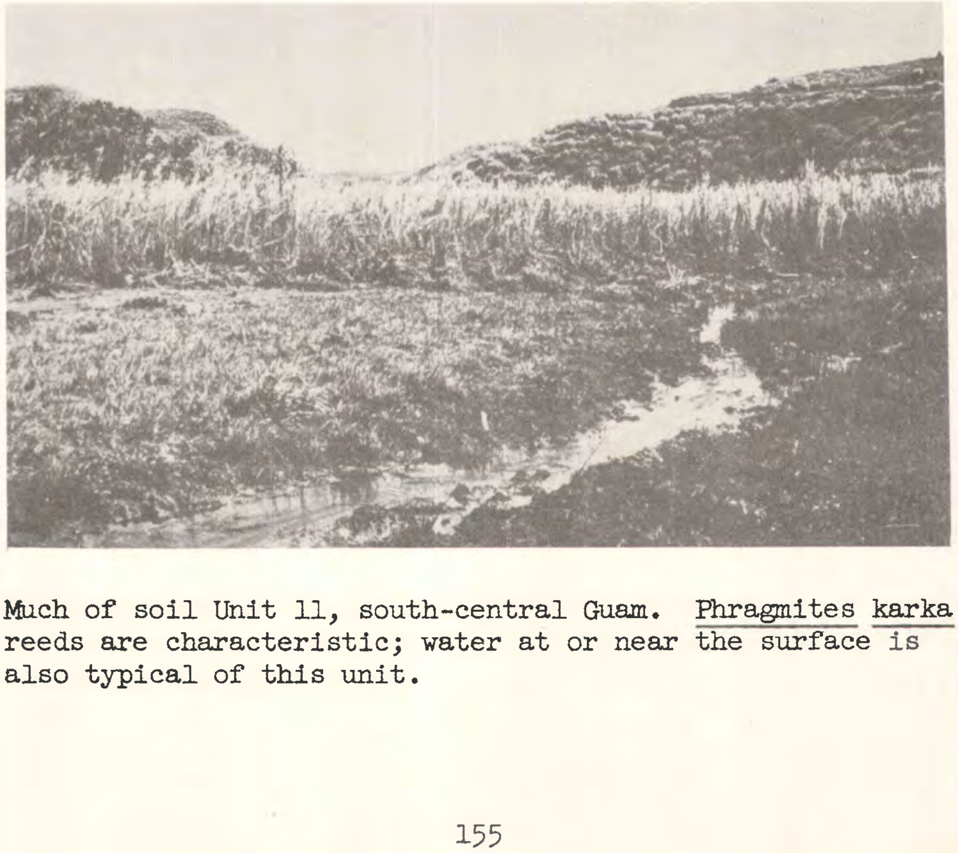
Associated or included soils: Areas of slightly higher, well drained Pago clay (Unit 9) too small to separate on the map are in this unit. There are also some similarly small areas of muck (Unit 11).

Vegetation and use: Much of this unit was cleared and planted to rice during occupation by the Japanese in World War II, especially along the west coast south of Agana. Present vegetation in these places consists of grass, weeds, random clumps or thickets of *Leucaena glauca* and *Triphasia* (limon de china) trees, a few mango trees and remnants of old coconut plantations. Areas subject to only shallow overflow or to infrequent severe flooding have some garden or small field plots of bananas, egg plant, long beans, sweet peppers, tomatoes, cucumbers, melons, and squash.

The perennially ponded areas within this unit (shown on the map by marsh or wet spot symbols) contain marsh or swamp vegetation. The large reed *Phragmites karka*, the *Cyperus* sedge, or thickly matted *Panicum* grass are in the marshy areas. Trees characteristic of the swampy areas are *Hibiscus tiliaceus* and *Pandanus tectorius*, either mixed or separately, and some areas of *Barringtonia* sp., the latter chiefly in the Talofofo River valley.

There are several roads and buildings on the soil of this unit, particularly along the west coast south of Agana, but considerable bridging, diking, and open drainage work is involved. Such construction is at a minimum in the larger stream floodplains, where flooding is more severe. Chief agricultural use of this unit is for grazing, in a casual sort of way. Garden plots, near houses, and some small farms are cultivated, chiefly during the least rainy, spring months.

A. Characteristic cracks in dry Inarajan clay (Unit 10), in Gautali River valley flat. Near Inner Apra Harbor; 14 May 1953.



B. Much of soil Unit 11, south-central Guam. Phragmites karka reeds are characteristic; water at or near the surface is also typical of this unit.

Suitability for use: Local drainage conditions, underground strata or bedrock conditions, and probability of severe flooding need to be examined carefully before construction is planned on this unit. Agriculture could be practiced more intensively, as was demonstrated by the Japanese. Tastes and incentives of the present population are probably governing factors in this regard. Water-tolerant plants, in addition to the Panicum grass, could probably be introduced for grazing.

Unit 11: muck

General features: Unit 11 (a Bog soil), consists of poorly drained, thin to thick deposits of decomposed organic matter and is referred to as muck. The muck is a mixture of black or very dark-colored, soft, decomposed plant remains with considerable pale-brown to light yellowish-brown plant fibers and generally enough clay, silt, and limesand or shell fragments to make the mass soft, sticky, and slightly gritty (wet), spongy and plastic (moist), and hard (dry). The muck is in some places interstratified with layers of silty clay a few inches to several inches thick. Light gray mottling is common in these clayey layers. Depth of the muck and interstratified clay ranges from 3 feet to more than 18 feet and averages 7 feet, in a series of random samples. Average thickness of the muck, minus the clay layers, is 6 feet. Grains of limesand and whole or broken shells are noticeable at depths of 3 to 5 feet and, in the coastal or adjacent alluvial flats, are the predominant material immediately underlying the muck. The water table is at or near the surface most of the time (pl. 26B). Reaction of the permanently saturated soil is alkaline; reaction of the soil above the level of permanent saturation is neutral to moderately acid.

Topography, distribution, and extent: The largest area of this unit is in the so-called Agana Swamp, just south of Agana town. Most of the other areas are in slight depressions at the base of Orote Peninsula and in the coastal flat northward from Orote to Piti village. A few other areas, too small to map at this scale, are in the volcanic rocks of the south half of Guam. Total extent of the unit is 520 acres.

Underlying regolith or bedrock: This unit is underlain by limesand, limestone, or soft weathered volcanic rock or clay at depths ranging from 3 to more than 25 feet below the surface, but which are commonly between 5 and 20 feet below. Limesand is the material most generally underlying this unit.

Profile description: A profile of Unit 11, in Agana Swamp (Site 88, grid BQ570897, sheet 5), is as follows:

1 0 to 6 inches. Black (10YR 2/1, moist) to very dark-brown (10YR 2/2, moist) silty muck and peat; extremely high in organic matter content; contains some silt; water table surface is at bottom of this layer; pH 7.0.

2 6 to 24 inches. Very dark-brown (10YR 2/2, wet) muck; somewhat sticky; contains many fibrous old roots, and some silty clay; pH 7.5.

3 24 to 72 inches. Very dark grayish-brown (10YT 3/2, wet) muck, containing partly decomposed plant material; slightly sticky; pH 8.0.

D 72 to 84 inches. Gray (2.5Y 5/0, wet) silty coarse limesand; sticky; consists largely of subangular to angular shells and fragments of marine animal skeletons; some vegetal organic matter; pH 8.0.

Range in characteristics: Color of the muck is black, very dark brown or very dark gray. The fibrous plant remains are pale brown to yellowish brown. The clayey horizons are commonly mottled with light gray. Density of the natural, saturated soil mass is very low; the soil would not sustain the weight of a person standing on it without the mat of vegetation and root fibers at the surface.

Drainage, erosion, and soil moisture: There is some surface runoff after flooding, and some siltation during flooding. Internal drainage is restricted to a few inches in the upper part during dry weather because of the generally high water table.

Special features: Brackish or slightly saline groundwater is in the part of this unit adjacent to the sea. But most of the unit supports normal water-tolerant vegetation.

Associated or included soils: This unit is associated with Inarajan clay (Unit 10), and some very small areas of that unit may be inadvertently included in this unit.

Vegetation and use: The large reed *Phragmites karka* (pl. 26B) and *Hibiscus tiliaceus* trees are the predominant vegetation in this unit. Some smaller reeds, *Scirpus erectus*, and *Panicum* grass are also on this unit, near the base of Orote Peninsula and northward along the coast.

The unit is all idle land, except where roads have been constructed through it. The Japanese started to construct a drainage-irrigation system in the upper (inland) portion of Agana Swamp, probably intending to grow rice and taro, but the project was barely begun when World War II ended.

Suitability for use: Rice and taro could be grown in part of this unit, as previously proposed by the Japanese. Excavated, dried muck is suitable for use by the one or two small potted-plant nurseries on Guam. It is recommended for use as the main soil ingredient rather than as a fertilizer, however, because the fertility and nitrate concentration in muck is generally not high enough for fertilizer.

Unit 12: Shioya soils

General features: Unit 12 (a Regosol), consists of light-colored limesand 3 to 35 or more feet deep, generally with some loaminess (up to 11 percent fines) and slightly dark organic coloring developed in the surficial A horizon. The soil is rapidly drained to the water table. Where present, in test holes to bedrock, the water table ranged from 5 to 25 feet below the surface. Underlying bedrock is chiefly limestone, but in southern Guam the unit grades downward into volcanic sediments or is on weathered volcanic bedrock in some places. Narrow strips of beach (white limesand) are not separated out of this unit.

Topography, distribution, and extent: This soil occupies discontinuous, low coastal terraces 1 to 10 meters above the sea, chiefly between Facpi and Ritidian Points on the west coast, and between Pago Bay and Merizo village along the east coast of Guam. The prevailing surface gradient is between 1 and 5 percent. Total extent of the unit is 2,425 acres.

Underlying regolith or bedrock: The unit is underlain chiefly by limestone, but in southern Guam it grades downward into weathered volcanic bedrock or pyroclastic sediments in some places. Thickness of the sand over these materials ranged from 5 to 35 feet in a number of test borings.

Profile description: A profile of soil in this unit, located at Tumon Beach (Site 69, grid BQ623945, sheet 5), is as follows:

A_1 0 to 8 inches. Brown to pale-brown (10YR 5/3 to 6/3, dry) loamy sand; friable; single-grain structure; calcareous; contains numerous roots and root hairs; brownish powdery material (which coats 50 percent or more of the sand grains) remains on the hands after handling.

A_3 8 to 24 inches. Pale-brown (10YR 6/3, dry) sand; fine-textured (grains chiefly less than 0.25 mm in diameter); loose; grains consist of subangular to rounded shell and coral fragments; calcareous.

C 2 to 5 feet. White to very pale-brown (10YR 8/2 to 8/3, dry) sand; loose, single-grained structure (sides of hole stand fairly well while drilling); fine limesand; composition and shape of grains similar to horizon above.

C 5 to 10 feet. White to very pale-brown, fine to very fine, loose, single-grained limesand; grains are subangular to rounded calcareous; contains some cemented grains, in chunks 1 to 5 mm in diameter. The sand of this sample was screened and 98 percent of it is smaller than 0.42 mm and larger than 0.061 mm.

C 10 to 12 feet. White (10YR 8/2, dry) very fine to fine limesand; loose; predominantly single-grained, but there are a few small aggregates or chunks of cemented sand; the grains are more angular or less rounded than in horizon above.

C 12 to 14 feet. White, wet sand; mostly single-grained; very fine to fine texture; calcareous; water table surface is in this horizon.

C 14 to 15 feet. White, fine limesand; contains marine shells and coral fragments up to 24 mm in diameter.

C 15 to 20 feet. Light-gray to white, fine limesand; contains numerous pieces of limestone up to 50 mm in diameter.

(?) 20 to 35 feet. Water in hole prevented recovery of the sand from this section of the boring. End of hole at 35 feet was on limestone.

Range in characteristics: Prevailing thickness of the brownish or grayish-brown A horizon ranges from 2 to 18 inches and averages about 8 inches. Percentage of fines (material passing U. S. Standard Screen No. 200) ranged no greater than 10.86 in the A horizons of 21 profiles tested; percentage of fines at depth of 28 to 48 inches ranged less than 3.57 and was generally less than 1.50 in the same profiles. The average texture of tested samples was medium to coarse sand, with enough finer and coarser sediments to make the material poorly sorted or well graded. Generally, the sand was fine- to medium-textured on the west side of the island and medium to coarse-textured on the east (windward) side. It was also progressively finer, darker, and shallower from the coast inland. Grains of serpentine, hornblende, augite, olivine, and magnetite were in the sand in the southern half of Guam, but such contamination was not considerable except adjacent to the mouths of streams, and at such places the contamination was chiefly by magnetite and by colloidal material from volcanic rocks.

Drainage, erosion, and soil moisture: Unit 12 is rapidly drained above the water table. Where present, in test holes to bedrock, the water table ranged from 5 to 25 feet below the surface.

As mapped in this survey, narrow strips of beach (white limesand) too narrow to separate out are included in almost every delineated area of this unit. These seaward portions of the unit are subject to erosion and deposition by wave action, especially during typhoons. During typhoons, occasional waves roll inland over the entire unit in many of the areas and nearly all of every delineated area is subject to flying salt spray and fine sand particles. Erosion and deposition were severe on many areas of this unit south of Inarajan village during typhoon Hester, 1 January 1954.

Special features: Gravels, pebbles, cobbles, and small boulders (of 62 samples taken from 21 profiles) averaged less than 3 percent by weight but ranged up to 28 percent in two samples. Limestone bedrock crops out at or near the surface in some small places in this unit. A few large residual boulders or slump blocks of limestone are in some areas of this unit, but they are not numerous.

Associated or included soils: This unit is named "Shioya soils" instead of "Shioya loamy sand" or "Shioya sand" because the two types are intermingled and are not separated on the map. Such separation might prove to be feasible or practical on a more detailed survey of a local area at a larger scale.

A narrow strip of beach sand is included in almost every delineated area of this unit. This consists of white to very pale-brown limesand, adjacent to the sea, which has no A horizon development and contains little or no vegetation because of the effects of constant or frequent wave action.

Vegetation and use: Coconut trees -- remnants of old plantations -- are the most widespread single type of vegetation on this unit. These have a thick to very thin or spotty understory of trees, shrubs, vines, weeds, and grass. The following kinds of understory plants were observed:

<u>Cocos nucifera</u>	<u>Ipomoea pes-caprae</u>
<u>Leucaena glauca</u>	<u>Ipomoea telefolia</u>
<u>Casuarina equisetifolia</u>	<u>Passiflora foetida</u>
<u>Pandanus tectorius</u>	<u>Flagellaria indica</u>
<u>Hibiscus tiliaceus</u>	<u>Chloris inflata</u>
<u>Cestrum diurnum</u>	<u>Eleusine indica</u>
<u>Scaevola frutescens</u>	<u>Dactyloctenium aegyptium</u>
<u>Thespesia populnea</u>	<u>Blechnum brownei</u>
<u>Hernandia sonora</u>	<u>Lepturus repens</u>
<u>Messerschmidia argentea</u>	<u>Sporobolus virginicus</u>
<u>Morinda citrifolia</u>	<u>Paspalum vaginatum</u>
<u>Kalanchoe pinnata</u>	<u>Stachytarpheta indica</u>
<u>Cassia fistula</u>	<u>Guettarda speciosa</u>
<u>Pipturus argenteus</u>	

Banana and papaya trees were planted around some farm houses on parts of the unit farthest from the sea. Considerable housing, much of it temporary, is built on this unit behind Tumon and Nimitz beaches. Parts of Tumon and Agana towns are built on this unit, and highways or roads are common, generally along the inland side. Parts of Marine Drive and other coastal roads built on this unit were damaged by typhoon-caused waves during the time of this survey. Several houses and some small stores were destroyed or damaged at Agana town and along the coast between Talofofo Bay and Merizo village.

Sand from pits behind Tumon Beach and Tarague Beach is used by the military and civilian construction outfits for concrete and as cushioning material for pipelines.

<u>Suitability for use</u>: Fruits, vegetables, melons, and peanuts can be grown on Unit 12. Yields will be restricted generally by lack of moisture and low fertility in the soil, and will be reduced locally by damage from wind, salt spray, and encroaching sea during storms.

Roads and buildings on this unit should be at least 100 yards from the shore and on ground which is at least 5 meters above sea level. Mortar or concrete made from sand of this unit is suitable for light walls, floors, or foundations, but tests should be made to determine strength of the concrete for heavy structures. The sand should be washed in fresh water before using in concrete.

Miscellaneous Land Types

The following units and subunits (13b, 13f, and 14) are miscellaneous land types instead of soil units. Miscellaneous land types are used in soil classification and mapping for areas of land that have little or no natural soil or that are too nearly inaccessible for orderly examination (or for other reasons).

Unit 13: limestone rock land

General features: This unit is shown on the map as subunits 13b and 13f, on the basis of important differences in prevailing surface gradients. Except for this marked difference in slope, the subunits may be described as one. Patches of reddish or brownish granular clay, generally very shallow, are interspersed among exposures of limestone bedrock, pinnacles, boulders, and fragments which occupy more than 25 percent of the entire area and more than 75 percent of local areas of this unit.

Topography, distribution, and extent: Most of this unit occupies parts of the upland rim and nearly all of the adjacent seaward-descending cliffs, scarps, and slopes of the northern limestone plateau. It is also on Cabras Island and around the rim of Orote Peninsula, and it occupies the high upland ridge from Mount Alifan to Mount Lamlam. Continuity of the unit along the east coastal ramparts is interrupted at Pago Bay and southward, where it is broken into a series of irregular strips which terminate south of Inarajan village.

Maximum relief in the unit approaches 200 meters at Mount Machanao (192 m), near the northwest tip of Guam. Relief in this unit around the northern plateau rim is chiefly between 100 and 175 meters; in the south half of the island it is generally less than 100 meters and is less than 25 meters in several places. Maximum elevation on Guam (405 meters above sea level) is in this unit, at Mount Lamlam.

Prevailing surface gradient in most of the unit is steep to precipitous, with slopes ranging from 25 percent to vertical. Subunit areas with this class of topography make up most of the unit and are mapped as 13f (see pl. 2B). A minor part of the unit has prevailing surface gradients ranging between 2 and 15 percent, and is mapped as subunit 13b (pl. 27A).

Unit 13 is described as a single unit of Limestone rock land, but it is mapped in two categories or classes of slope; these subunits, indicating different ranges of prevailing surface gradient, are shown on the map as follows:

Symbol	Name	Prevailing gradient of surface	Total extent (in acres)
13b	Limestone rock land, gently sloping	2-15%	3,390
13f	Limestone rock land, steep	25-100% plus	9,150
		Total acres in Unit 13:	12,540

Underlying regolith or bedrock: This unit is composed chiefly of limestone bedrock. Most of the unit occupying the northern plateau rim and coastal scarps or slopes is composed of the Mariana limestone -- both the reef and detrital facies. These are massive, dense to porous, indurated to friable, generally permeable, white limestones. In the south half of Guam, nearly all of the limestone formations of the island are represented in this unit. Chief among these is the large, high upland ridge of Alifan limestone, extending from northeast of Mount Alifan and southward to Mount Lamlam, the highest point on Guam. The Alifan limestone is white, buff, or pinkish, massive to coarsely bedded, porous to dense, chalky to hard detrital limestone, with fossils generally common, but scarce to abundant locally.

Character of the limestone at any specific place can best be determined from the map and text in the Geology part of this report.

Profile description: There is no continuous soil profile developed on this unit. Soil is generally sparse, averaging only 2 or 3 inches in thickness between the numerous exposures of limestone bedrock; but there is some deep soil in pockets, joints, and caverns in the rock and on narrow benches at the base of steep slopes.

Character of the soil in this unit differs from place to place on the island. The following soil-rock descriptions at selected sites may be of interest to soil geneticists, if not to engineers or gardeners who may have to utilize some of the soil in fissures or on isolated narrow benches in this unit:

Site 154, grid BR686095, sheet 1, just south of Ritidian Point; elevation between 165 and 170 meters above sea level; gently sloping topography. The rock is Mariana limestone, reef facies; the soil is similar to Guam clay, Unit 1. Surface soil-rock conditions are as follows: 2 or 3 inches of reddish granular clay interspersed among predominent bedrock exposures, limestone float, and boulders. The rock constitutes 30 to 90 percent of the surface area, but there is enough soil in small depressions, fissures, and cavities to support 50 to 70 percent tree canopy, plus a patchy understory of vines, shrubs, weeds, and grass. Plate 27A was taken at this site.

Site 156, grid BQ489897, sheet 4, on Cabras Island; elevation about 25 meters above sea level. Hilly topography; a narrow limestone ridge; the rock is mapped as Mariana limestone, reef facies; the soil is similar to that of Unit 5, Yona-Chacha clays. The general soil and rock relationships at this site are: a few inches of dark yellowish-brown clay; friable to slightly plastic and firm; calcareous; interspersed among outcrops of limestone bedrock and residual boulders, the latter 2 to 4 feet in diameter. Vegetation consists of a few small trees, shrubs, and weeds. The surface area has been disturbed by foot traffic, pick and shovel, bulldozers, jeeps, and drilling machinery.

Site 158, grid BQ475793, sheet 7, about 0.5 mile south of Mount Alifan; elevation about 250 meters above sea level; gently sloping ridgetop; limestone rock land (Alifan limestone) consisting of 25 to 50 percent bedrock with sharp ledges and pinnacles 6 inches to 2 feet high sticking out of the ground; patches of soil less than 6 inches deep consisting of dusky-red (10R

3/4, moist) to dark reddish-brown (2.5YR 3/4, moist) clay; very fine granular; soft; friable; pH about 6.5. This clay is similar to Guam clay, Unit 1.

Site 159, grid BQ469756, sheet 9, near top of Mount Lamlam; elevation about 385 meters above sea level; on a narrow bench in rough terrain above end of jeep road; the rock is Alifan limestone; the soil is similar to Yona-Chacha clays, Unit 5. The limestone ledges, pinnacles, and boulders are interspersed on a narrow, gently sloping bench with soil such as the following:

0 to 6 inches. Dark-brown clay; very firm (dry); contains pieces of limestone 2 to 3 inches in diameter; pH of the clay is 6.5.

6 to 10 inches. Yellowish-brown clay; firm; plastic; contains pieces of limestone 2 to 3 inches in diameter; rests upon uneven surface of fucoidal (?) limestone, pinkish gray in color; the clay has a pH of 6.0.

Range in characteristics: Separation of this unit into subunits 13b and 13f according to the class of prevailing surface gradient is designed to reduce the wide range in kinds of topography within the unit. But many small flat areas are in the steep subunit 13f, just as there are many small areas of steep land within the delineations of gently sloping subunit 13b.

There is also considerable range in the character of the limestone rock in this unit. Specific information about the distribution and kinds of the limestone can best be obtained from the geologic map (pl. 4) and text.

Drainage and erosion: Most of the drainage is by internal percolation through cracks, joints, and pores in the limestone, but there is some surface water runoff during infrequent torrential rains. At such times, during the period of this survey, surface water did accumulate in shallow troughs or depressions just behind the rim of the NAS-Agana plateau above Tumon town. On four or five occasions during the two years of this survey, such accumulated water spilled over the rim of the plateau, sluicing quantities of soil and rock down onto Marine Drive, a four-lane highway immediately below. But such occurrences may have been aggravated by disturbance of the natural soil and rock conditions above or back of the plateau rim. Considerable alteration of the surface contour and natural drainage may have been effected by heavy blading with bulldozers and by construction of roads and numerous buildings on the plateau top adjacent to the site of this damage by surface water runoff.

Special features: There are several caves and numerous wide, columnar cracks or joints opening on the cliff-face exposures of this unit.

Isolated ravines or deep solution troughs in this unit may afford sanctuary for some of the original vegetative types or species on Guam because of relative inaccessibility of this unit (especially subunit 13f).

Associated or included soils: The most common inclusions of other units are small, narrow flats or troughs of Guam clay, Unit 1. Some larger areas of Yona-Chacha clays, Unit 5, are quite probably included in this unit. Time available precluded detailed examination of many of the large, rougher areas of this unit; more time was spent on units of deeper soils.

Vegetation and use: The kind of jungle growth on Unit 13 is shown in Plate 27B. The following kinds of vegetation seemed to be most common:

Pandanus tectorius	*Ipomoea*
Cycas sp.	*Alyxia*
Intsia (Ifil)	*Morinda*
Pisonia grandis	*Ochrosia*
Artocarpus sp.	*Hernandia*
Ochrocarpos odoratus	*Merrilliodendron*
Ficus prolixa	*Triphasia*

Leucaena glauca was growing in dense thickets along some roads and in idle, formerly disturbed areas.

Some old quarries were located in this unit, probably because of greater ease in establishing a working course and perhaps also because the rock appeared to be harder or more dense (later found to be more or less a superficial phenomenon referred to as "case-hardening" by geologists).

Suitability for use of this unit appears to be rather limited. It is suitable for forest, wild life refuge, quarry sites, and as foundation for roads and buildings, where suitable sites exist. A certain amount of security from typhoons is provided by cliffs, ravines, and some caves. Some native farmer-fishermen long ago found and utilized some of these places for building houses, sheltering livestock or poultry, and raising food crops in small gardens.

Unit 14: made land

This land has been altered by man, usually for construction purposes. It consists of artificial fills made for housing or building sites, or for dock and storage areas. The fill material consists of earth, trash, rubble, or material dredged from the harbor.

The larger areas of made land are additions to or extensions of the low coastal flats around Apra Harbor. Prevailing surface gradient is nearly level (0-3 percent). Total extent of the unit is 965 acres.

A. Limestone rock land (subunit 13b, gently sloping), northernmost Guam. Near Ritidian Point; 22 June 1954.

B. Jungle or secondary growth common on Limestone rock land (subunit 13b) and on large areas of Guam clay (Unit 1). East of Mt. Lamlam; 29 October 1953.

Notes

Vegetation

by

F. R. Fosberg

Introduction

The vegetation survey of Guam was a reconnaissance survey done by one person in less than two months, with the benefit of background and data from several previous short visits and experience on the other main islands of the Marianas, in other parts of Micronesia, and in the Pacific area.

The term vegetation, as used in this discussion, applies to the total plant cover of the island or of parts of the island. It applies not only to lists of the plants present, but more to the general character, appearance (physiognomy), and arrangement of the plant assemblages or communities concerned. Included, specifically, are considerations of such factors as height, density, spacing, degree of cover of the ground, layering, average leaf size, spininess, color, seasonal changes, and especially long- or short-term changes in any of these features and in the component species and their relative abundance. Attention was also directed to any correlations between vegetative cover and soils, rocks, ground water, and physiographic features, as well as with history, both geological and human. This was intended to make possible the use of such correlations to indicate features and characteristics of the ground that are not easy to observe, especially in ground covered by a thick cover of vegetation.

In two months of field work it was possible to treat these subjects in only a very superficial fashion. However, even with rather incomplete data it is possible to arrive at certain generalizations. Considerations that might be of military importance were investigated in the field and are discussed in the report. It is unwise, however, to neglect the basic data and interpretations on which such military factors are dependent. Technical language has been avoided as much as possible, but scientific names have been used for all but the most common plants as, generally, there are no English names for the trees and other plants on Guam. Guamanian names are given for some plants, but they are no more familiar than are the botanical names and are much more difficult to look up. No modern book on the flora of Guam is available. Safford's "Useful Plants of Guam" (1905), and Merrill's "Enumeration of the Plants of Guam" (1914), as well as various German and Japanese papers, have been of considerable value in identifying the plants, but the most dependable method of identification is by comparison with previously named specimens in institutions such as the U. S. National Herbarium, Washington, D.C., the Bernice P. Bishop Museum, Honolulu, Hawaii, and several Japanese herbaria. Many of the most common trees and other plants are shown in the photographs accompanying this report.

The vegetation map was based on an overlay compiled from aerial photographs, as to outlines of the areas of different vegetation types. The areas were identified by actual field studies and then generalized to an extent that the map would be readily understood. In the time available it was not possible to visit all of the areas outlined on the overlay, but sufficient numbers on each soil, rock type, and physiographic situation were visited to make the interpretation of the others reasonably reliable. Reliability was greatly enhanced by a flight of several hours duration at low altitudes over all parts of the island through the courtesy of the Naval Air Station, Agana; it was possible to verify many decisions and, especially, to gain a better concept of topographic correlations with vegetation.

All the photo plates in this section of the report are at the end of the section. Each plate (comprising two photos) illustrates a type of vegetation -- mangrove, or swordgrass savanna, for example -- or the vegetation characteristic of a specific environment of growth -- forests on limestone, or on volcanic soils, for example. The plates are arranged approximately in the same order as that in which the map units are presented, and are referred to in the text individually and by groups under the discussion of the map units.

General Statement

The greater part of Guam is forested, but substantial areas, especially in the southern half of the island, are covered by coarse grass, and smaller parts are in pasture or under various kinds of cultivation. There are few large stretches of uniform vegetation; most of the island is covered by a mosaic of small patches of extremely varied appearance. The forests are mostly second growth, many of them thickets, generally dense, tangled, and often with spiny undergrowth.

Limestone areas are usually wooded except for some vertical cliffs and some clearings. The original forest on limestone was of large trees with a thick canopy. A long history of disturbance by the Guamanians, by frequent typhoons, and by the destructive effects of World War II and subsequent military activities, has left little undisturbed primary forest on the island. Weed patches, partially revegetated clearings, thickets of fast-growing soft-wooded weedy trees, and scattered bare skeletons of dead forest giants are more characteristic than is undisturbed forest. Scattered patches of the latter remain here and there on the northern plateau, especially on cliffs and relatively inaccessible terraces around the steep coasts of the northern half of the island.

Much of the plateau has been cleared for military establishments, either active or abandoned. Some clearings are relatively bare of vegetation, others are grown up to tall grasses, thickets, and larger areas of _Leucaena_ (a tall, feathery-leafed shrub or small tree which has increased enormously in number since the war). Coconut groves are in many parts of the island, both on the plateau and along the coast. The lower central part of the island has been subjected to disturbance much longer than have other parts. Much of it is under cultivation (mostly in small patches) or is in larger areas of pasture, with diverse thickets, _Leucaena_, bamboo clumps, and small coconut groves. A large reed marsh, Agana Swamp, is just east and north of Agana. Other marshes are along the west coast from Piti to south of Agat, with small mangrove swamps interspersed.

The southern, volcanic half of the island is a complex mosaic of grassland and patches of forest. Lowlands in the valleys of the Talofofo River drainage and of some of the other rivers are occupied by extensive swamp forests and occasional cultivated clearings. In these valleys, as well as on uplands along the east coast, are large coconut plantations. Patches of mangrove occur at the mouths of the rivers.

If left unburned for a few years the grasslands may be abundantly invaded by *Casuarina* trees, which may eventually form open forests. These trees are, however, very susceptible to fire and stands of them of any extent in the savanna have grown up only since the Japanese invasion in 1941. They are again being destroyed by fire.

The forest patches in the volcanic region occupy a substantial total area but they are much broken up by ridges and flats covered by grass. The forest on volcanic soil in many respects resembles that on limestone, but tends to be thicker, lower, more brushy, and characterized by betel-nut palms. It is more commonly found in ravines, valley bottoms, and on steep slopes. These forests were undoubtedly much more extensive before the Chamorro people arrived on Guam, and the destruction of the forests has been especially rapid since the coming of the Europeans.

Summary of Military Aspects

Generally speaking, the forests on the limestone areas of Guam are rather freely penetrable to men on foot, with relatively little use of machetes except locally. Thickets of young second-growth, however, may need a fair amount of cutting and in many places are viciously spiny. On the volcanic soils in the southern half of the island both the forest and the grassland present difficulties; forests are mostly extremely thick, low in stature, filled with spiny undergrowth, and swampy in low places. The grassland, where mostly either swordgrass or reeds, is almost impenetrable off the trails and ridgetops because of the dense tangle of small tough canes and the sharp cutting edges of the leaves. Grassland can be burned off in dry seasons, though.

Visibility is usually poor in Guam forests because of the large amount of undergrowth and the usually thick canopy. Concealment is correspondingly good, both from air and ground observation. The evergreen nature of the forests, the mosaic of many shades of green, and the rapidity of growth of certain weedy vines and creepers are important considerations in planning camouflage. Cover is not especially good in most of the forests because of the scarcity of large trees. The swordgrass affords some concealment and poor visibility to ground observation, but complete visibility from the air; there is no cover here.

Guam forests formerly yielded much excellent construction timber. A comparatively small amount of this remains, mostly of rather small size and uneven quality, only enough for certain emergency uses. The destruction of the primary forest removed the best timber. The complete lack of any subsequent forest management or silviculture has resulted in its replacement in most areas by fast-growing, soft-wood trees which have little or no value.

As indicators of other matters of military importance, the Guam vegetation types have considerable value if used with judgment. Certain correlations, such as reeds with water at or close to the surface of the ground, swordgrass with volcanic (clay) soil and consequent slippery ground in wet weather, and *Pemphis* scrub with an abundance of salt spray, seem to be reasonably well established (with local exceptions). Other correlations are of a more general nature and more allowance must be made for variation with season, locality, and especially the effects of disturbance of the vegetation itself.

The Guam grassland or savanna is highly inflammable in the dry season and may present a serious fire hazard. Most of the other vegetation will burn only under extreme drought conditions and then not readily. There are few noxious insects in Guam except mosquitoes and wasps. One of the more annoying kinds of mosquito breeds in the leaf axils of Pandanus trees and is more abundant in areas where these trees are common. Wasps with painful stings make their nests in undergrowth and thickets and locally may be too common for comfort. Ticks, leeches, and chiggers, frequently associated with vegetation in the tropics, are either absent or inconspicuous in Guam. Poisonous plants are few on the island and of little consequence, but several spiny ones often cause discomfort in thickets. Emergency sources of food are more than commonly abundant in the Guam forests and a separate section of the report discusses them.

General Description of Map Units

The accompanying map (pl. 28, in pocket) includes nine units which represent either predominating vegetation types or complexes of types which occur in such small patches as to preclude satisfactory mapping at the scale of the map (1/50,000). No single unit should be taken to represent accurate detailed mapping of any one plant association or community, or even of a single major formation. The arrangement of plant communities in Guam, largely in very small areas with numerous transitions, necessitates for accurate mapping a much larger scale map and an enormous amount of detailed field study. And as much of the vegetation is in a state of relatively rapid change or vegetational succession, a map of such accuracy for the island as a whole would not have enough permanent value to justify a detailed study.

Unit 1: mixed forest on limestone plateau and cliffs (pls. 29 through 31): Unit 1 is basically a broad-leafed evergreen tropical moist forest (pl. 29), dominated in most relatively undisturbed areas by large trees of wild breadfruit (Artocarpus) and banyan (Ficus). In some parts of Guam, particularly the central part of the northern plateau, are stands almost exclusively of screw-pine (Pandanus), a tree which is a partial component in most other areas. Locally, other trees assume dominance, usually in variable mixtures rather than in pure stands. On the edges and faces of cliffs and near the sea on rocky coasts the forest varies to a dense scrub (pls. 30 through 32). On the rare sandy beaches, where these are not planted to coconuts, are groves of Casuarina. Areas that were formerly cleared and abandoned, or that were badly damaged by war activities are now principally a dense scrub forest of hibiscus and other secondary trees with scattered large dead or half-dead trunks towering above the general low level. The canopy in good examples of uncut forest is irregular, up to 75 feet high, and the larger trees (6 inches or more in diameter) may be fairly closely to widely spaced. The undergrowth is sparse and often fairly tall where the forest is little disturbed, but may be very dense where recent disturbance has been great. It is likely to contain a high proportion of palm-like cycads and spiny limon de china (Triphasia).

Concealment in this unit is generally good and cover fair to poor. Visibility is not good, either from the ground or the air. Some temporary construction timber is available but the logs are short and generally of poor quality. Coconut trees are common locally, providing some long slender logs for certain purposes, but not for sawing.

Unit 2: mixed forest on volcanic soil in ravines and on limestone outcrops in valleys (pl. 33): Unit 2 is also a broad-leafed evergreen tropical moist forest, dominated locally by hibiscus or screw-pine (*Pandanus*), rarely by wild breadfruit (*Artocarpus*) or other trees, usually very mixed. It is commonly characterized by betel palm (*Areca*) and varies frequently to a dense prickly scrub of limon de china (*Triphasia*) or to patches of reed marsh, swamp, and hibiscus scrub. Coconut palms are occasional to locally common. This unit includes many small areas of savanna (pl. 33).

The stature of this forest is generally low, seldom over 40 feet, and the canopy is dense to irregular. Larger trees are locally common, especially in ravines, and are closely spaced. The undergrowth is dense and often spiny and difficult to walk through. Concealment is generally good, visibility poor, and cover fair to usually poor. A little temporary construction timber of poor quality is available locally.

Unit 3: swamp forest: Mangrove and *Nipa* swamps (pls. 34A, 35A) occur locally near the sea, especially in river valley mouths, changing upstream to a mosaic of types of fresh-water swamp and reed marsh. The fresh-water swamp types include stands of *Barringtonia racemosa*, hibiscus, hibiscus and screw-pine, and tangled mixtures of trees and reeds. The stature is variable but usually low. Where *Barringtonia* dominates, the canopy is about 50 feet high and continuous; elsewhere it is usually much lower and irregular, or it may be absent. The undergrowth, except in the *Barringtonia* swamp, is very dense. The substratum may be mucky and unstable or it may be firm enough to walk on but not to support vehicles. Concealment is good, visibility very poor, and cover fair to absent. There is little or no construction timber here.

Unit 4: reed marsh: In the marshes of Unit 4 (pl. 35B) are pure stands of reeds or cane (*Phragmites karka*) growing on wet ground or in standing water. The canes are up to one-half inch in diameter, hollow but tough. They grow 6 to 18 feet tall and are spaced very closely, often only several inches apart. Concealment in dense stands of reeds is fair, horizontal visibility very poor, and cover lacking.

Unit 5: savanna: The savannas are made up of a mosaic of three very distinct kinds of grassland, other herbaceous vegetation, and erosion scars being revegetated by shrubs and tangled ferns (pl. 38A). Swordgrass (*Miscanthus*) (pls. 36, 43B) is dominant over large areas. Small ironwood trees (*Casuarina*) (pls. 35B, 37A, 41A) are scattered in many parts, locally forming a sparse woodland. The swordgrass (pl. 43B) is extremely dense, and well developed stands are hard to traverse on foot; the leaves are sharp and likely to lacerate the skin. Reed marsh (pl. 35B) is as described in map Unit 4. The other types are *Dimeria* grassland (pl. 37A), weedy herbaceous vegetation, and erosion scars. Concealment is poor or lacking, except in tall swordgrass, horizontal visibility is good to poor, cover is lacking. Timber is generally lacking. This unit may include small areas of ravine forest (pl. 33B), with the ravines tending to be filled by forest or thickets.

Unit 6: secondary thicket and cultivated ground: Unit 6 includes an extremely varied vegetation resulting from long-continued disturbance by man, and is usually on argillaceous limestone (pl. 40B). It is a fine mosaic of patches of forest, usually dominated by breadfruit (Artocarpus), coconut groves, bamboo clumps, patches of scrub or scrub forest, home sites, small cultivated fields and patches, pastures, and large areas of tangantangan (Leucaena) thickets. The undergrowth is locally very dense and spiny, and marshy places are common. Trees over 6 inches in diameter are very common and closely spaced in patches of breadfruit forest and coconut groves, while trees less than 6 inches are very abundant in other types of vegetation, except cultivated fields and pastures. Concealment is locally good, locally lacking, visibility varies similarly; cover is locally fair, locally lacking. There is some poor quality construction timber available.

Unit 7: coconut plantation (pl. 41): Unit 7 areas are dominated by coconut trees, often planted in rows (pl. 41). The trees are from 10 to 30 feet apart, or closer where self-seeded. The canopy is from 50 to 75 feet high, usually incomplete. Undergrowth is usually dense, often very dense, and sometimes spiny. Concealment is good, visibility poor, and cover fair. Coconut log timber is available, but of poor quality for most purposes.

Unit 8: predominantly open ground and pasture: Unit 8 is mainly open ground, a mosaic of pasture land, cultivated fields, dwellings, and thickets (pl. 40A). Concealment is usually lacking, visibility good, and cover usually lacking. There is no timber.

Unit 9: bare ground and herbaceous to shrubby vegetation at military installations and cities (pls. 39, 42): Unit 9 is a complex of bare ground, tall grass, weed patches, and shrubby growth, changing constantly. The vegetation is usually not a very significant feature, and affords little or no obstruction, little concealment, no cover, and no timber. However, within a very few years such weedy and bare areas on limestone soil may be expected to grow up to thick scrub (pl. 39A), followed by scrub forest which resembles the vegetation of Unit 6.

Detailed Description of Vegetation Types

The significant vegetation types on Guam and some of their variants are described below, grouped ecologically. It is probable that few or none of these exactly represent any of the original vegetation of the island, but represent, rather, the results of modification by man. In many of the types this modification has been profound or complete, and in some it has been so recent that no subsequent equilibrium has been attained and the vegetation is still changing rapidly. The types described first are the most stable and perhaps are nearest the original, while those resulting from recent disturbance and still changing are treated last.

The types described below do not correspond exactly with the units indicated on the map. The mosaic of vegetation on Guam is altogether too fine to be indicated without much generalization on a map of 1/50,000 scale. Each of the types here described may be included in several of the map units, and each map unit may include a number of the types described; therefore, with each description is included a statement of the principal map units in which the type is found. Also indicated are localities where the type occurs on Guam.

Forests on elevated hard limestones (in map unit 1): The mixed mesophytic, broad-leafed evergreen forest on the elevated limestone terraces, plateaus, and slopes must originally have been the most widespread vegetation type on Guam. The entire northern half of the island, except for Mt. Santa Rosa, a couple of smaller volcanic outcrops, and the beaches, is of hard limestone. Around parts of the southern half, on both east and west coasts, there are "ramparts" or other areas of hard limestone, and the high Mt. Lamlam-Mt. Alifan ridge and the hill west of the Fonte River are also of limestone. These areas were, and partly still are, covered by a tall dense mixed forest (pls. 29 through 34), mainly of evergreen dicotyledonous trees. In the central part of the island the argillaceous limestone may have borne the same sort of forest, but because that area was the most suitable agricultural land on the island, the original vegetation has been completely altered. (Its secondary vegetation will be treated in a separate section.)

It is difficult to be certain of the character of the original vegetation, even that of the hard limestone areas. Guam has been inhabited by man for possibly several thousand years, but practically nothing is known of his history there except during the last 430 years. For most of the 430 years (until 1941), the total population was not large, but at the time of Magellan's visit in 1521 there were at least many tens of thousands of aborigines. Their influence on the vegetation is hard to estimate, but it was more than negligible. Since Magellan's time, although the population has been smaller, the people have been much better equipped to destroy the forest; also, since that time they have been ably assisted by the cattle, goats, deer, and other four-footed animals brought by European conquerors. The actual changes brought about through 1941 by these influences cannot be well traced, but undoubtedly the local diversity of forest types growing on an essentially uniform substratum in the absence of much local climatic variation is one consequence.

Beginning with the Japanese invasion in 1941 the rate of change in most of Guam's vegetation types was enormously accelerated. Battles were fought in the forests, with highly destructive modern weapons. Enormous areas were cleared and scraped by bulldozers and changed permanently. (These areas will be discussed later in a section on weedy vegetation.) In the following paragraphs the main present-day aspects of this forest will be discussed.

Because of the presence practically everywhere of species that generally occur in secondary vegetation, and even of introduced plants (*Triphasia*, *Cestrum*, and *Carica*, for example), and because of the uneven, brushy nature of almost all of the remaining forests, it seems best to regard the present-day forests on the plateaus and terraces as secondary, or perhaps in places, as degraded primary forest. In a few places disturbance may not have been great enough to change the structure and composition entirely, but as a whole, what is presently growing on these areas is considered to be secondary forest.

Generally, the degraded and secondary forest on limestone has a thinner, more irregular canopy than primary tropical forest usually has, and consequently more abundant undergrowth. Several introduced species have become common in the undergrowth, notably *Triphasia trifolia* and *Morinda citrifolia*. The two species of *Pandanus*, *P. tectorius* and *P. dubius*, have probably increased greatly in abundance. *Intsia*, formerly much more common, has been logged out until it is quite scarce in many parts of the island. Logging of this species (the "ifil" of the

Guamanians) was carried on rather continually in the early part of this century, and large trees are now uncommon; but if found, they seem to be characteristically almost leafless. This is not true of the same species on other islands, and the reason is not obvious but may be exposure as the surrounding forest is cleared or destroyed.

In many areas on the northern part of Guam most of the large trees of various species are dead or half-dead. Several reasons are advanced for this: insect damage, typhoon damage, damage from military activities when fighting was intense in these areas, and exposure from partial clearing. Probably no one of these explanations accounts entirely for the large areas dominated by white skeletons towering above the lower growth in the forest. Possibly all of the above-mentioned factors and still others may be responsible for this condition. Examples can be seen west of Andersen Air Force Base and west of Northwest Guam AFB.

Present-day forest on limestone, although it varies continuously, includes several more conspicuous or frequent aspects. These aspects are described below and, if possible, are localized and correlated with topography and other features. It must be remembered, however, that in a continuously varying vegetation by no means all examples will fit any of the described categories.

Artocarpus forest: The most widespread aspect of the limestone forest is dominated by large trees of wild breadfruit or "dugdug". This is *Artocarpus mariannensis*, which is closely related to the cultivated breadfruit, *Artocarpus altilis*, but differs in having entire or few-lobed leaves, pubescent and brownish beneath, and a consistently seedy fruit, as well as a softer, yellower, finer-grained wood. A secondary dominant plant that is locally quite as abundant as *Artocarpus* is *Ficus prolixa*, a large banyan (called "nunu" by the Guamanians). The trunk of the banyan, which may be enormous, is not a clear column as in *Artocarpus*, but is an entwined and fused mass of large, tough aerial roots, some of which also hang from the branches and form smaller secondary trunks like pillars supporting the branches.

Besides the above-mentioned dominants this forest type is likely to have *Aglaia*, *Ochrosia*, *Premna*, *Tristiropsis*, *Elaeocarpus* (pl. 29B), *Intsia*, *Pisonia*, *Claoxylon*, and *Pandanus* as fairly large trees, and smaller plants of all of these, as well as *Guamia*, *Cycas*, *Morinda*, and *Triphasia* as understory. Locally any of the above trees may become common or even dominant.

Generally most of the trees in the forests on limestone form a dense second story 10 to 15 meters tall, with *Pandanus* and *Aglaia* commonly most abundant. Overshadowing this is a discontinuous layer of *Artocarpus* and *Ficus* which may be 25 or more meters tall. Locally these may be up to a meter in diameter, the *Ficus* even more, but most of the *Artocarpus* are much less. The understory and shrub layers are not sharply separate. They vary in density inversely with the age of the forest and the density of the upper layers. In a forest that has not been logged or cleared for many years it is possible to walk around rather freely with little trail-cutting; in younger or sparser stands the ground is likely to be choked with shrubs, vines, and luxuriant ferns.

This type of forest is found over large parts of the northern plateau, on the hard limestone on the east coast as far south as Talofofo Bay, and on the Mt. Lamlam-Mt. Alifan ridge (pl. 29A). It is no longer continuous over extensive areas because of the widespread military activities of the past ten years. Good examples may be seen in north-central Guam, on the road from Yigo to Agafo Gumas about 1 km northwest of Yigo. When this type of forest is cleared, any remaining large trees usually become unhealthy and die in a few years. Artocarpus seems to stand the exposure resulting from clearing longer than do most other trees.

Mixed moist forest: East of Mt. Santa Rosa and for an undetermined distance north and south just back from the edge of the cliff, there is a type of forest similar to that dominated by Artocarpus, but almost completely lacking in that genus. Here no one tree is especially outstanding in the landscape, though various ones may be so locally, especially Tristiropsis and Claoxylon; Ochrocarpos may be common here. Old stumps and logs of Intsia are frequent, and are said to date from logging operations in 1912. This logging may account for the presence in this area of large trees of secondary species such as Macaranga growing with the other trees enumerated under the Artocarpus type.

Forest similar to this is also found on the terrace back of Tarague Beach. Here Ochrosia and Cycas are the most abundant trees. Cycas makes up the understory.

Ochrocarpos type: On the eastern escarpment of the plateau, as at Anao, except where the escarpment is vertical, the dominant tree is Ochrocarpos odoratus (the "chopag" of the Guamanians). This is seldom a large tree, but locally may make up the greater part of the forest on steep slopes, ledges, and terraces (pl. 30A). The forest varies from rather uneven to dense, with a smooth canopy, and is usually of medium height with a well developed undergrowth. Aglaia, Guettarda, Cynometra, Bleekeria, Guamia, Ochrosia, and Ficus are generally common, and on the gentler slopes and terraces below the cliffs Pisonia grandis is common in places; on the gentler slopes Hibiscus tiliaceus is an important component, and, locally, Barringtonia asiatica.

Cordia type: On the steep slopes and cliffs back of Tarague Beach on north Guam the forest is locally dominated by Cordia subcordata, with Aglaia, Macaranga, Premna, Cycas, Morinda, Cynometra, Guamia, and Pipturus common. This forest is not tall and not particularly dense, but is rather difficult to walk through because the limbs of Cordia tend to be low, very widely spread and tangled just above the ground.

Merrilliodendron forest: On terraces at Haputo is an example of what may have been a more widespread forest type -- a tall forest, perhaps 30 to 45 m high, dominated by trees of Merrilliodendron megacarpum and Ficus prolixa, the latter less abundant but taller. The second story, only about 4 m tall, is of saplings of Merrilliodendron, and the lowest layer, from 0.5 to 1 m tall, is of seedlings of the same species. This tree seems completely tolerant of shade. Ficus seedlings are not found in these layers because they start as epiphytes in the crotches of trees, sending roots down the trunks of their hosts, eventually surrounding the hosts with a network of roots which strangles them.

Pandanus forest: Common on interior areas on the plateau are forests made up of an almost pure stand of Pandanus tectorius, the screw-pine ("kafu" of the Guamanians). The stand appears to be of one age, 10 to 15 m tall, the trunks 10 to 20 cm in diameter, and with a thick undergrowth. The prominent stilt-roots of the Pandanus add to the Flagellaria, Cestrum, Triphasia, Nephrolepis, and other components of the undergrowth to make walking difficult.

Pandanus forest is probably a secondary type, but whether it is or not, is extremely hard to determine. Study of successional relations in these forests would be time-consuming and uncomfortable, but possibly very enlightening.

There is every conceivable transition between Pandanus and the Artocarpus and mixed forest types, but the pure Pandanus is very conspicuous and covers considerable areas. Good examples of Pandanus forest may be seen along the highway northeast of Dededo (north-central Guam).

Halophytic and xerophytic scrub: On terraces and cliff edges not too far above the sea on the east and north coasts and on vertical limestone cliffs and their tops is a scrub of varying heights and densities that may be a response either to extreme salt spray, to dryness resulting from excessive drainage, or to excessive transpiration due to the exposure to winds, or to any combination of these factors. The scrub is low, tangled, often stiff, and conceals pits, pinnacle fields, and other dangerous irregularities in the limestone. Good stands of such scrub, showing considerable variation, occur at Campanaya Point on the lowest terraces a few meters above sea level.

Near the sea, Pemphis acidula is by far the most abundant plant, and where exposed to strong spray-laden winds may form almost a mat (pl. 30A). Back a short distance from the sea, Scaevola, Guettarda, Ochrocarpos, Messerschmidia, Clerodendum inerme, Pandanus dubius, P. tectorius, Hibiscus tiliaceus, and Ochrosia may all be present in dwarfed forms. On the steep cliffs, Bikkia, Hedyotis foetida, Cycas, Triphasia, Scaevola, Ochrocarpos, and Phyllanthus mariannensis all may be important components. At the tops of higher cliffs any of these may be present but Triphasia, Ficus prolixa, Colubrina, Jasminum and Cynometra are likely to be prominent. Scrub is not universally present, and may in places give way to forest. On steep cliffs the density is likely to vary with the steepness of the cliff (pl. 31A) and with the number of crevices, ledges, and other irregularities.

Ravine forest of southern Guam (in map unit 2): In valleys and ravines and on certain slopes in the volcanic soils part of Guam is an important type of forest that differs somewhat from that on the plateau limestones. As its floristic composition is rather variable it may conveniently be termed ravine forest (pl. 33). Good examples may be conveniently seen in the heads of ravines both north and south of the road between Apra Heights and Camp Witek. In addition to occupying ravines and slopes in the volcanic soil, this type or its variants occur on outcrops of Bonya and Maemong limestones in the Talofofo River drainage. The south side of the Talofofo River valley is largely forested with this type which also alternates with swamp forest in the valley bottom. Flat valley bottoms generally are swampy, and low hills and ridges have a forest similar to the ravine type.

Ravine forest is usually an uneven mixture of many kinds of trees of rather low stature, brushy and tangled. The canopy, if any, is only a few meters above the ground and its upper surface is typically irregular. Because it occurs in ravines there is seldom a great, continuous extent of woods. The small patches naturally vary in character with the depth of the ravines and the steepness of their sides; typically a belt of very thick scrub around the edges gradually changes inward to forest. In the ravine bottoms the forest may be tall enough and dense enough to permit free passage, or it may be low and tangled, or sparse and choked with brush and saplings. A tree layer and a shrub and herb layer may usually be distinguished in the deeper parts of the ravine, but toward the edges these merge and become indistinguishable.

In composition this forest type is variable from place to place but generally includes fewer kinds of plants than do forests on the limestone plateaus. The inclusion of the lowland limestone hills of the Talofofo Basin adds considerable variety to the total list of species growing in the ravine forest, although the aspect and principal species on this limestone are not much different from what is generally found in the ravines. A more intensive study would most assuredly result in the separation of one or more distinct types on this limestone; but for purposes of the present study, and with the information at hand, it seems better to consider them as a single type.

The most abundant trees in the ravine forest are Hibiscus tiliaceus, Pandanus tectorius, P. dubius, Ficus prolixa, Glochidion mariannensis, Areca cathecu, Premna obtusifolia, Cocos nucifera, and more locally, Artocarpus mariannensis, Cananga odorata, Ochrosia oppositifolia, Bleekeria mariannensis, Calophyllum inophyllum, and others. Shrubs are commonly Triphasia trifolia, Cycas circinalis, Timonius glabrata, Morinda citrifolia, Piper guahamense, Geniostoma sp., and rarely, around the edges, Cyathea lunulata and Melochia hirsutissima. Medinilla rosea, Freycinetia torresiana, Flagellaria indica, and Lygodium scandens are common climbers. Epiphytes occur but not abundantly. Herbs on the forest floor are Oplismenus compositus, Centotheca lappacea, a large species of Scleria, and several ferns.

The most nearly characteristic species, and the one which most generally sets this forest off from the plateau forest, is the betel palm, Areca cathecu. This species is almost always present in the ravine forest type and apparently is lacking in the plateau forest, except that it is found rarely on Mt. Lamlam. Calophyllum is also lacking from the plateau forest and is often found in the ravine forest. Glochidion is much commoner in the ravine type. There are, however, no tree species restricted to this forest type. The difference is one more of aspect and of average or percentage composition than of mutually exclusive species.

There seems no doubt, because of the widespread presence of Hibiscus tiliaceus, Areca cathecu, coconuts, Triphasia, and even bamboo, that the ravine forest is secondary. The abundance of artifacts, broken pottery, etc., as well as the scanty historical evidence, shows that parts of Guam were densely populated in pre-Spanish times, and undoubtedly the ravines were largely used for agriculture -- taro and rice-growing, and coconut culture. Betel chewing was a widespread habit and the betel palms (Areca) now found here are probably descendants of planted ones.

Outstanding variants of this forest type are stands of Calophyllum in the Talofofo region, groves of Areca or of Areca with Hibiscus in various places, and pure stands of Cananga in the Fena River area. All these species may possibly be of aboriginal introduction. In the Umatac and Merizo areas, and on the slopes of Mr. Schroeder, Artocarpus mariannensis is a dominant component; it is scarce or lacking in most ravine forest areas.

There seems to be no way of deciding, from information at hand, what the original forest of southern Guam was like.

Swamps and marshes (in map units 3 and 4): Wet land is not very extensive in Guam, but it is widely distributed on the southern half of the island. It occupies sufficiently different topographic situations that a number of distinctive vegetation types have developed on it.

Ground where the water table is either permanently at the surface or sufficiently near it to make the soil permanently wet may, in Guam, be conveniently divided into marsh and swamp, depending on the vegetation present: marshes are wet areas dominated by herbaceous, non-woody plants, frequently grasses and sedges; swamps are dominated by woody plants -- shrubs and trees. Several types of each division are on Guam. Bogs are absent on the island and are rare in the lowland tropics.

Marshes may be found in low places along the coast, along streams, in depressions and sink-holes in the argillaceous limestone region, and in small poorly drained spots, depressions, and ravine bottoms in volcanic soil. Most are fresh water though some close to the beaches may be brackish. Swamps are mostly along river beds at about sea level and in certain coastal areas. There is also a swampy depression, transitional in character between reed marsh and swamp, east of the high ridges of Mt. Lamlam. There is little or no wet ground on the northern part of the island, with the exception of a few marshy spots around Mt. Santa Rosa and Yigo. The drainage in the limestone is rapid and nearly complete.

The wet areas of Guam are mostly occupied by single species or mosaics of patches of single species, rarely by mixtures of a few species. Invasion and successional change undoubtedly occur very commonly, but in the time devoted to studying these types of vegetation little definite evidence of this was recorded.

The ground in all of the marsh and swamp types of vegetation is usually soft and in none of them can it be depended upon to support vehicles. Crossing such areas on foot may or may not be feasible, depending on the season and on local conditions. The vegetation itself, in the woody and reed types, usually makes progress extremely laborious. The Barringtonia swamp is an exception in that walking is fairly easy except for fallen trees and knee-deep water. The firmness of the ground is deceptive, however, and heavy vehicles such as caterpillar tractors bog down.

The principal types of vegetation represented in the marsh and swamp categories are as follows:

Marshes	Swamps
Reed marsh	Mangrove swamp
Scirpus marsh	Nipa swamp
Shallow water with Cyperus	Barringtonia swamp
Paspalum flats	Hibiscus tiliaceus swamp
Panicum purpurascens marsh	Hibiscus-Pandanus swamp
Rice and taro patches	
Miscellaneous marshy vegetation	

Marshes: It is almost certain that on Guam, as in most wet tropical areas, marshes are merely stages in successions leading to weedy vegetation, usually of a swamp character. In some of the marshes succession seems to be active; in others it is more or less retarded. The factors that retard the process of vegetational change are not known, but it is clear enough that in some cases man's activities may create and tend to maintain open conditions, even in areas of water-logged soil. It is possible that many areas are now open and marshy only because they were cleared out and used for rice cultivation by the Japanese during the war.

Reed marsh (in map unit 4) (pl. 35B) is by far the most frequent type of marsh vegetation. It is dominated by the tall tropical reed, Phragmites karka, often in pure stand. This reed forms hollow canes the thickness of a man's thumb and 6 to 15 feet tall. Ordinarily a stand of these canes is so dense as to make penetration by a man on foot difficult; stands are seen in which the canes may be an average of 3 inches apart. The individual canes, though tough, are easily bent or crushed. The color of a stand of Phragmites is a medium green except when in flower, when the whole stand assumes a bronze color and a soft fine texture because of the loose fine tassels of flowers (later fruits). This occurs in winter but the exact periodicity has not been recorded; it extends at least from December into February.

Although some areas of this vegetation are large, especially that in the swamp adjacent to Agana, smaller patches and narrow belts more commonly make mosaics with swamp forests and with the savanna. Reed marshes are found on soils derived either from volcanic or calcareous materials but are confined to areas which are wet with seeping, standing, or running water for the greater part of the year, and which never really dry out. Therefore their presence is a reliable indication of surface water or of ground water very near the surface. This water may, however, be either fresh or somewhat brackish. Because of its habitat requirements, this vegetation type is found only on the south half of the island. The total area occupied by this type is fairly large, though little of it shows on the vegetation map as most individual patches are small.

This vegetation masks minor topographic irregularities because of its tendency to grow in low wet spots; an unwary observer might very likely describe as smooth or undulating an area of coarse grass which was actually cut by shallow ravines. The general surface of the swordgrass on the dry slopes and that of the reeds in the ravines may be rather continuous and somewhat similar in appearance though the ground beneath might vary by several feet in relief and be as different as rough rock and soft mud.

Scirpus marsh, actually submerged ground covered by bullrushes (Scirpus erectus), exists in limited areas around the base of Orote Peninsula. The bullrushes are naked green stems the diameter of a finger and 3 to 8 ft tall, rising from a mat of prostrate rootstocks buried in the mud of the bottom. The stems are tough but soft and easily crushed, and are spongy inside; the tops taper and are pointed or end in a loose tassel of brown flower heads.

Pure dense stands of this plant grow in shallow standing water, usually covering parts of small ponds which may be partly open water and partly covered by other types of marsh vegetation. The water may be slightly brackish.

Shallow water with Cyperus is uncommon and the vegetation is not at all uniform. Shallow ponds occur with scattered tufts of Cyperus, usually Cyperus polystachyos but sometimes C. odoratus or C. javanicus. Rhynchospora corymbosa is occasionally found with them. Cyperus odoratus and, less commonly, C. javanicus, also occur in local stands in low wet ground. In all of these types, the dominant plant is a tufted grass-like plant with a whorl of long leaves at the top of the stem surrounding a cluster of greenish scaly flowers. These types of marsh are of small area and unimportant except that cyperus is often a good indicator of a muddy substratum. Examples may be seen at the base of Orote Peninsula.

Paspalum flats (pl. 34B) are lawn-like areas, usually wet and brackish, covered by a dense stand of *Paspalum vaginatum*. This plant is a wiry, creeping, mat-forming grass growing no more than a foot high, usually only a few inches. Though this grass may grow on mud as well as sand, and often in shallow standing water, it usually provides a safe footing for walking; the tough mat of roots will support a man even on soft mud.

Such flats are common around southern Guam near the coast wherever there are ponds or wet ground, as for example just south of Camp Bright. They are never large, and often mark places where ground water seeps out near high tide level. They may also occupy the edges of shallow ponds and the bottoms of depressions back of beach ridges, as at Umatac.

Panicum purpurascens marshes are similar in superficial appearance to *Paspalum* flats but are dominated by *Panicum purpurascens*. The mass of vegetation is much thicker, often 3 or 4 feet thick, and makes a much less firm mat. The stems are much longer and thicker and the leaves and sheaths are quite hairy. Walking is not easy through this type, both because of the deep, tangled nature of the growth and because the water or mud may be deep and the vegetation mat not firm. *Panicum* occurs in low wet places, but more commonly in water fresher than that in places occupied by *Paspalum*. Low places used as pastures are particularly dominated by this *Panicum*, which is a good forage grass. It was brought in for this purpose by the Guam Experiment Station several decades ago and has naturalized itself thoroughly, both on dry and wet ground. On wet ground, *Panicum* flats, possibly better called wet meadows, have resulted; one is at Camp Bright.

Rice and taro patches are at present uncommon on Guam, though during the war they were much more important. Rice is now grown only on one or two farms near Talofofo, but aerial examination shows traces of paddyfield pattern in the low coastal areas for some distance south of Orote Peninsula. Marsh taro culture still exists in some of the valleys of southern Guam, such as Talofofo, but is being supplanted by the easier dry land type of culture. The taro plant is also being supplanted by the yautia, a dry land plant grown for its starchy tuberous corms or underground stems.

Miscellaneous marshy vegetation that does not fit any of the common vegetation types may also be found occasionally. In places where roads or other disturbances of the ground have dammed ravines in the volcanic rock area there may be marshy patches of *Rhynchospora corymbosa* and *Acrostichum aureum*, ordinarily found in lowland swamp areas. In other wet spots may be found varying mixtures of sedges, grasses, *Jussiea*, *Dryopteris goggilodus*, and other herbs of wet soil. Rarely, especially along the west coast between Agana Swamp and Nimitz Beach, there are patches of nearly pure stands of *Ipomoea aquatica* and of *Eleocharis fistulosa* (both plants growing on muddy ground) or these may be mixed with other herbs.

The only one of these types sufficiently extensive to merit mapping as a separate unit is the reed marsh; the other types as well as the smaller patches of reed marsh are included in any units where they occur.

Swamps (in map unit 3): Almost any marsh tends to develop into swamp as shrubs and trees invade it. The brackish marshes are invaded by mangrove swamp plants, especially Avicennia (pl. 34B). Little or nothing is known of the courses of successions leading to the several swamp types other than mangrove swamps.

Swamp or swamp forest of any appreciable extent occurs only at or slightly above sea level along coasts and in the bottoms of the larger river valleys. (One exception to this is a patch of mixed marsh and swamp just east of the high ridge of Mt. Lamlam.)

Five types of swamp are recognized, but the actual stands cannot all be sharply separated into these types; they tend to grade into each other and to form mosaics with patches of two or more of them, usually also with patches of reeds. The Talofofo basin contains the largest area of swamp land; almost all of the alluvium filling the valley floor is swampy.

Mangrove swamps are very poorly represented in Guam, in comparison to those of islands and coasts to the south and west. There are a few small areas around the base of Orote Peninsula, now largely destroyed or degraded by dredging or by oil on the water. There are also still smaller areas east of Merizo and at the mouths of the rivers on the east coast. Only a very few of the typical species of western Pacific mangrove swamp plants are represented here, namely Rhizophora mucronata (pl. 34A), Bruguiera gymnorihiza, Avicennia sp., Xylocarpus moluccensis, Lumnitzera coccinea, Heritiera littoralis, Hibiscus tiliaceus, Acrostichum aureum, and Nipa fruticans.

Nipa swamps are even more feebly represented. There are a few patches of Nipa at the valley mouths of the Pago, Ylig, and Inarajan Rivers at the sides of the estuaries of the streams. These are of no importance except to represent a swamp type very well developed and yielding useful products in the Philippines, Indonesia, and southeast Asia.

Barringtonia swamp is a striking swamp forest type in Guam, known only from the Talofofo River. Where best developed it is a pure stand of Barringtonia racemosa 10 to 15 m tall, close-set, and with a dense, complete canopy. The trees are seldom more than 20 cm thick. There is no undergrowth whatever, and the trees grow on conspicuous hummocks separated by muddy channels. Water may be standing in these channels or they may be almost dry. The bottoms, though muddy, are firm enough to support a man on foot. Heavy equipment such as a bulldozer mires down immediately and tends to sink in very deeply. This type of vegetation does not form large areas and in places it tends to intergrade with the Hibiscus swamp types.

Hibiscus tiliaceus swamp (pl. 35A) fills most of the low wet ground in the Talofofo basin, either as a reasonably pure stand of Hibiscus or mixed with Pandanus.

Hibiscus-Pandanus swamp. This and the swamp types above may occur in fairly large areas or may form mosaics with Barringtonia swamp and reed marsh. Smaller areas occur in the river valleys and just east of Mt. Lamlam. This type of swamp is extremely difficult to traverse. The trees are sprawling, twisted forms, seldom or never proper trees with trunks. They are tangled together into an intricate mass of stems of all sizes, often laced with lianas of several sorts. The foliage is dense on the outside of this mass, but beneath, there is little but stems. The ground varies from fairly firm to soupy mud. These are as nearly impassable, because of both vegetation and substratum, as any vegetation type on Guam except the scrub on limestone cliffs.

All five of the above swamp types are mapped as swamp forest, as the individual types often occur together in small patches, forming a mosaic, and all have certain important characteristics in common.

Strand vegetation: There are three basic kinds of shoreline on Guam. The most extensive is probably on pitted, emerged coral limestone; the least developed is on low, swampy coast (pl. 34); the remainder is sandy beach. The vegetation of the coral limestone shores is scrub of Pemphis acidula (pl. 30A) which has been described earlier. It is of gnarled, twisted hardwood bushes, with small fleshy leaves with a slightly astringent taste. The mangrove vegetation of low swampy coasts also has been described above.

On the beach proper, there is no vegetation; the strand vegetation is well developed, principally on the beach ridge and on sandy flats just behind it. This vegetation may conveniently be divided into woody and herbaceous types.

The forest on sand ridges and flats just behind beaches is in some places a pure stand of Casuarina equisetifolia. These stands are of mature but not extremely old trees, generally not more than 30 to 40 cm thick and 20 m tall which do not form dense stands. Few other plants grow with them, possibly because few plants are able to establish themselves in the layer of dried branchlets or "needles" that accumulates beneath Casuarina trees, except under very wet conditions. As Casuarina becomes established under absolute pioneer conditions and grows rapidly, it is to be expected that pure stands or almost pure stands will be found.

On other sandy places the forest is of a mixed type, similar to that generally in strand habitats in the tropical Pacific, which may be a mixture of Thespesia populnea, Pandanus tectorius, Guettarda speciosa, Messerschmidia argentea, Scaevola sericea, Hernandia sonora, and Cocos nucifera (pl. 41). These trees may be present in varying proportions and with admixtures of others, but commonly Thespesia and Scaevola are most abundant; Hibiscus tiliaceus may be important locally.

Some beach ridges are covered by a pure stand of Leucaena glauca. This plant was dominant on almost the entire beach in front of Agana, but high waves accompanying the typhoon in December 1953 killed most of this stand. The plant apparently does not endure sea water at all well.

Herbaceous vegetation is not prominent on Guam beaches. There are similar strips, seaward of the woody vegetation, of Sporobolus virginicus, a low stiff grass with wiry rhizomes. Lepturus repens, another halophytic grass, spreads by above-ground runners and forms patches in some habitats. The normal tropical beach vegetation of Ipomoea pes-caprae, Triumfetta procumbens, Canavalia sericea, Vigna marina, and other creeping plants (pl. 41B) is found on Guam but is relatively restricted and poorly developed. The frequency and destructiveness of typhoons may have something to do with its restriction.

Another curious circumstance that is frequently noted is that a number of species commonly regarded as strand plants are, on Guam, in various inland habitats. Among these are Scaevola sericea, Ipomoea pes-caprae, Thuarea involuta, Clerodendrum inerme, Lepturus repens, and Fimbristylis spathacea. These all have been found inland in some part of the world, but the number of them so distributed in Guam, as well as the frequency of such occurrence, is most unusual. No adequate explanation of this circumstance is apparent.

Strand vegetation occurring as a narrow belt at the top of the beach is scarcely mappable at our scale, so it is included with other units that touch the coast where there are sandy beaches.

Grassland or savanna vegetation on volcanic soils (in map unit 5): Volcanic soil in the Marianas is generally thought of as covered by a dense stand of swordgrass, Miscanthus floridulus (pl. 36). This is only partly true, for although Miscanthus is dominant in many areas, there are forests in valleys and ravines (pl. 33), and on many steep slopes.

In the grassland vegetation there are at least five plant communities to be considered, which occupy more or less distinct habitats. These are: the Miscanthus community (pl. 36); the Dimeria community (pl. 37A); the erosion scar community (pl. 38A); the Phragmites or reed community (pl. 35B); and the weed community which follows disturbance. The first four form, at the present time, a natural mosaic over much of the volcanic rock part of Guam, with the fifth added where clearing and scraping of the soil has taken place after cultivation, after overgrazing, and after serious fires. The fifth community is only temporary, especially when it follows fire which does not commonly destroy the root crowns of the dominants of the other communities. These soon put forth sufficient new shoots to again dominate and slowly shade out the new pioneers.

Miscanthus community: In its best development this is almost a pure stand of Miscanthus floridulus, a coarse, sharp-edged, cane-like grass (pl. 36). It grows to a height of 2 or 3 m, the clumps so close together that it is very difficult to push through them. The color varies, with the season and local moisture conditions, from a bright light green to gray-green, straw color, drab, or a dull light brown, and these colors dominate the community and to a great extent the hills of southern Guam. In areas that have been protected from fires for some years there are usually small Casuarina trees (pl. 41A) scattered unevenly through this grassland.

Characteristically there are a number of secondary species growing with the Miscanthus, the number of species and of individuals varying inversely with the density and height of the Miscanthus; seldom are they completely absent, however. Almost any of a large number of accessory species may be found in this community, but any great abundance of them suggests recent burning, recent erosion, or a transition toward the Dimeria community.

The characteristic habitats of Miscanthus are fairly steep slopes, rocky and steep ridges, and low moist but not really wet places. It is in low moist places that Miscanthus reaches its greatest luxuriance, with fewest competing species. Good examples may be seen on the slopes of Mt. Alutom and Mt. Tenjo.

This community, in dry periods, is extraordinarily susceptible to fire. Fires, usually set or allowed to get out of control by the inhabitants, burn very rapidly up slopes and even down, if driven by a wind. The grass clumps usually burn down to the base, which generally resists burning and which can send up new shoots. These fires are a serious hazard for people caught in their paths, as the fires travel rapidly and people cannot easily move fast through swordgrass. A rocky or thin place (pl. 37) in the grass is the safest spot in which to weather a fire if a bare erosion scar or road cannot be reached.

Foot travel in a dense stand of swordgrass, except on trails or ridgetops, is always slow and at times almost impossible. The clumps of finger-thick canes are springy and tangled, and the microscopically saw-toothed edges of the hard-textured leaf blades cut the skin like knives (pl. 43B).

Miscanthus seems rather unsatisfactory for forage, though the young leaves and some of the accessory species are eaten by stock (pl. 38B).

Dimeria community: This is a low soft grassland dominated by *Dimeria chloridiformis*, a tufted, soft, hairy grass of a bluish-green color, with flowering stems up to one-half meter or more in height. Even when very well developed the tufts are far enough apart for many accessory species to be present in practically all stands, but in a well developed, undisturbed area of this community these accessories seldom make up 10 percent of the cover. In small numbers these are normally a part of the *Dimeria* type, but large numbers of clumps of *Miscanthus* indicate a transition to the *Miscanthus* community. Large numbers of young *Miscanthus* plants suggest invasion and eventual dominance by that species. Large numbers of other native species indicate an erosion scar recently healed over, and large weed populations indicate disturbance or overgrazing.

The *Dimeria* community is usually found on more or less level or gently rolling ground, seldom on marked slopes. It is not commonly found at such low altitudes as may be reached by swordgrass, even where conditions seem favorable. The soil is generally a fine clay, red or brown, resulting from weathering of pyroclastic rocks.

This vegetation presents no obstacle to walking, or to jeeps or other motorized transport, providing the ground is not eroded in a rough fashion. It is, however, likely to alternate with *Miscanthus* patches and to be discontinuous over large areas. Good stands can be seen in the saddle north of Mt. Alutom and north of the road east of Apra Heights (pl. 37A).

It is often used as pasture but will not support many animals, as the dominant species is not a first choice as forage. The stock tend to pass it by and to search out several minor species in the community.

Erosion scar community: Many of the characteristic savanna plants are pioneer species, coming up in bare soil and gradually being crowded out by the dominant species of the more stable communities. This accounts for their presence in small numbers in the grassland, as small bare spots are a common occurrence there. The deeply weathered volcanic materials on Guam are, however, subject to severe erosion, usually a "lateral erosion", in which broad patches of material are removed by both water and wind.

On the scars left by this erosion, after they have been exposed for a time, may be found a characteristic assemblage of species (pl. 38A) which may include, at times, most of the flora of the volcanic grasslands. The first plant to come in abundantly is usually Gleichenia linearis, which spreads over the bare soil by means of its horizontal rhizomes. Shrubs such as Myrtella, Wikstroemia, Scaevola, Geniostoma, and Melastoma are usually found, as well as the fern Blechnum orientale and the grass Chrysopogon aciculatus. Chrysopogon, next to Gleichenia, plays the most active part in preventing further erosion as its prostrate stems cling closely to the soil and form a dense sod.

This community is usually quite sparse, with much bare ground between the plants; the bare ground gradually fills in as more plants become established. Miscanthus and Dimeria soon invade and eventually one or the other will dominate and produce one or the other of the communities described above. For a long time, however, the erosion scar will be identifiable by the unusual abundance of the species characteristic of such areas.

Phragmites community (in map unit 4): Reed brakes -- pure stands of Phragmites karka (pl. 35B) -- are so often found in wet ravine bottoms in the savanna that they may be regarded as reliable indicators of ponded or marshy condition or of running or standing water, except in the driest season.

These canes are usually from 2 to 5 m tall and as thick as a man's thumb, hollow, tough, easily bent but difficult to break off. They grow from 5 to 20 cm apart in thick stands completely covering the ground. As they usually grow up level with the top of the surrounding vegetation they give a false appearance of smoothness to country that may be cut by ravines.

Walking through such a brake is a slow, fatiguing task. The canes may be pushed aside readily enough, but the soft mucky ground underfoot, with tangled canes which snare one's feet, make it desirable to avoid this sort of ground if at all possible.

Weed communities: A varied assortment of pioneers or weeds, practically all introduced plants, appear after any serious disturbance or elimination of the vegetation of an area. The disturbances commonly seen in the savanna area are fire, grazing, cultivation, and clearing and removal of vegetation. After such treatment, the principal weeds appearing are Stachytarpheta indica, Elephantopus mollis, Hyptis capitata, Hyptis suaveolens, Mitracarpum hirtum, and Chrysopogon aciculatus. These may occur in mixture, or, more commonly, any one of them may be dominant locally.

Such weed communities may last several years, but are eventually replaced by the communities dominated by Miscanthus or Dimeria. Meanwhile, they serve the function of weeds the world over in retarding erosion of the surface soil. As long as land is in active cultivation, weeds may be a nuisance, but when an area is abandoned they are the first step toward revegetation.

Weed vegetation offers no serious obstacle to traverse on foot or in vehicles except where it may conceal ditches or holes in the ground. Elephantopus may be rather irritating to bare skin, but this is seldom more than a minor annoyance.

Swordgrass on limestone soil: For some years the idea has been current that swordgrass, Miscanthus floridulus, is a reliable indicator of volcanic soils. Some doubts about this idea were raised during the Economic Survey of Micronesia in 1946 but no definite exceptions were found.

In 1950 on Saipan, Miscanthus was found in two places growing directly on bare hard limestone. One of these spots was on the east side of the summit of Mt. Tagpochau, the other was to the north. Two peculiarities were noticed: both stands were in quite exposed places; and both were pure stands of Miscanthus with none of the commonly associated savanna species.

In 1953 on Guam there were reports from soil scientists and geologists of the occurrence of swordgrass on limestone. A search was made for such localities and a dozen such stands were located; questionably, others exist. Four of these stands, two on the upper ridge of Mt. Lamlam and two on the north and northeast slopes of Mt. Almagosa, (pl. 43A) were on Alifan limestone, two on thin soil coverings, two in crevices in bare rock. The other eight are on the Agana argillaceous member of the Mariana limestone or on soil derived therefrom, at the following places: Piti, just above Marine Drive; 2.5 km north-northeast of Sinajana; the Agriculture Farm Dairy; the Agriculture Farm at Manguilao; the small hill just south of Pago River bridge; the top of hill south of Talofofo River bridge; and on small hills in Martinez Pasture at Dandan.

These stands differ greatly in location, ranging from a few feet above sea level to near the top of Guam's highest peak, from sheltered to quite exposed positions, from slopes and cliffs to level surfaces. The number of associated savanna species ranges from none to 15; most of the stands, however, had very few or none. The actual figures are: five stands had none; two had one each; five stands had 2, 3, 5, 13, and 15 species each, respectively. The last stand is a very small spot surrounded by savanna, but the others are well separated from any savanna.

Most of the occurrences are on limestone with a fair argillaceous content, and possibly all have some clay. It has been suggested that availability of silica is the controlling factor in the distribution of swordgrass, but this is manifestly not the case, as there are many argillaceous localities where swordgrass is lacking.

Of the Guam localities listed above, half were being actively invaded by Leucaena, and the swordgrass showed the effects of shading in long spindly growth habit, sparseness, and some dead clumps. In areas where swordgrass is found on the volcanic soils, it is missing wherever a patch of forest has become so thick as to shade the ground completely.

None of the obvious factors seems adequate to account for the distribution of swordgrass. The best explanation that has been suggested so far is that swordgrass is likely to establish itself on any area that remains open for a considerable length of time. It is encouraged by repeated fires. If Leucaena, Triphasia, or other woody species invaded it in large numbers they will eventually shade it out.

The main conclusion is that although Miscanthus is generally an indication of a volcanic substratum it must not be regarded as completely reliable; at least 14 places are known where it grows on limestone.

Vegetation on argillaceous limestone (in map unit 6): The area underlain by the Agana argillaceous member of the Mariana limestone is highly dissected and very complex terrain, but of low relief -- never more than 50 m and usually 20 or 30 m. Though it is an old karst topography it has been greatly weathered, the ridges rounded, the sink holes plugged by clay soils, and the drainage patterns containing intermittent streams. A deep brown soil as much as 10 m or more in depth covers even some of the ridges, although the underlying limestone crops out here and there and loose limestone fragments litter the surface in places.

This area has been occupied and used agriculturally perhaps longer and more intensively than has any other part of Guam. It is cut up into many small farms which are reached by a network of roads, mostly in very poor condition. As a result, there is none of the original vegetation left and it is impossible to say what the original plant cover may have been.

At present the vegetation is an intricate mosaic of small areas of a number of different types and transitions between them, all either secondary or cultivated. Coconut trees are scattered in large or small numbers over almost the whole area. Patches of pure stands of *Leucaena* are very common as dense growths with fine feathery foliage, the individual plants as tall as 5 or 6 m, with smooth stems seldom more than 5 cm in diameter. They usually grow so closely together that a man often cannot walk between them with comfort. The ground may be covered with seedlings of the same plant which quickly grow up and fill any gaps in the continuous canopy of foliage above. In stands of this nature there are seldom any other plants, except that around the edges, thorny bushes of *Triphasia trifolia* sometimes seriously impede walking.

In areas of relatively low relief there may be large patches of mixed scrubby thicket 3 to 4 m tall, the trees usually continuous but with occasional small openings. The principal woody species are *Cestrum diurnum*, *Leucaena glauca*, *Triphasia trifolia*, *Pithecellobium dulce*, *Morinda citrifolia*, *Psidium guajava*, *Carica papaya*, *Annona* sp., in varying proportions, with local patches of *Moghania strobilifera*. Morning-glory vines of several kinds are tangled in these trees and bushes. Open spaces are grassy, or, in ravine bottoms, are filled with a low growth of one or more species of *Cassia*.

This scrubby growth is difficult to walk through, especially where *Triphasia* is an important constituent. The trunks may be 5 to 10 or more cm thick, with low branches which are likely to be quite tangled. It is possible to chop a way through them with a machete, but it is advisable to take every advantage of what openings there are.

Mixed, taller thicket or forest occupies much of the area, especially where the relief is sharper. This ordinarily has a very uneven upper story of coconut and breadfruit trees about 25 m high which do not form a complete canopy. The second story, 3 to 10 m high, contains most of the small trees and shrubs listed in the low thickets described above, with the addition of *Hibiscus tiliaceus*, *Canange odorata*, *Pandanus tectorius*, *P. dubius*, *Mangifera indica*, *Muntingia calabura*, and tangled masses of a large bamboo, probably *Bambusa arundinacea*. There may be an undergrowth of shrubs and tall herbs, often the large-leafed *Alocasia macrorrhiza*, and the aromatic *Piper guahamense*. The whole may be tangled with vines such as morning-glories. Penetration is generally less difficult than in the scrubby thickets, but where *Triphasia* or bamboo are abundant, walking may be almost impossible.

Interspersed with the foregoing vegetation types may be patches of open pasture dominated by such grasses as Panicum purpurascens, Paspalum conjugatum, and Paspalum orbiculare. These patches are either in marshy low-lying spots, in old limestone sinks, or on open rounded ridges. If in poor condition because of overgrazing, there may be great patches of Achyranthes, Stachytarpheta, and other weeds, not or scarcely eaten by the stock. A few such areas are occupied by swordgrass, Miscanthus floridulus, 1 to 2 m tall. This grass is much more characteristic of the volcanic rock areas of Guam (see section on savanna vegetation above).

Patches of bananas (pl. 40B), cassava, taros, and other edible plants, as well as coconut and citrus groves, are very common, usually associated with dwellings and small dooryard gardens always well planted to ornamentals.

The details of this mosaic are constantly changing, as clearings are made, cultivated ground is abandoned, and fallow fields grow up to scrub or to patches of Leucaena. It can be characterized only as a complex unit whose local characteristics are completely dependent upon the activities of its human inhabitants.

Coconut groves and plantations (in map unit 7): Large and small areas almost throughout the island are occupied by more or less pure stands of coconut palms (pl. 41) most of which have been planted by the Guamanians to provide food for themselves and their domestic animals and to produce copra for export. Large groves occur on sand flats back of beaches (as at Tarague Beach), on flat ground in some parts of the northern plateau, along the road down the east coast of the south half of the island, and in the valley bottoms in the volcanic rock areas. Extensive areas, for example, in the central Talofofo River drainage below Fena Dam are covered by these trees. Smaller groves form a conspicuous part of the vegetation in the argillaceous limestone area, as described above, and occur here and there in almost all other vegetation types except the savanna.

These plantations are mostly mature and consist of trees 15 to 25 feet tall, either in regular rows or spaced irregularly 5 or more meters apart. The trunks are slender and there is generally a more or less complete canopy of leaves high overhead. In most of the groves and plantations there is a thick undergrowth, often 4 or more meters high, composed of various shrubs and young trees as well as of abundant self-sown coconuts. Penetration of this undergrowth, especially where coconut seedlings are numerous, is difficult and laborious, even with a machete.

Copra production in these plantations is at present non-existent. Labor costs are so high that the copra produced would not pay the cost of production and shipping; furthermore, one or more poorly understood diseases have rendered many of the trees completely unproductive and some are actually dying. The only use made of the nuts at present is as feed for pigs, chickens, and other live-stock, plus minor use for human food.

Ruderal or weedy plant communities (in map units 6, 8, 9): Most of the vegetation on Guam has been disturbed rather profoundly and now contains weedy species which were not part of the original plant communities. Where the disturbance has been so great as to destroy completely the original vegetation, this is often replaced entirely by communities of the secondary, mostly exotic, pioneer species commonly called weeds.

The savanna communities, in most of their present habitats, seem to have had such an origin, but rather than introduced species, many of the plants are from the nearby natural savanna areas. The assemblages to be noted below however, are almost exclusively of exotic weedy plants. The vegetation described above on the argillaceous limestone could be included here, but as it forms a quite distinctive and recognizable mosaic it has been treated separately.

Disturbances of several kinds -- fire, clearing, bulldozing, filling, for example -- have produced bare ground in several different vegetation types. In fact, it would be possible to locate areas in almost any natural vegetation that have been occupied by weeds. Most weedy vegetation is on roadsides, clearings, abandoned cultivated fields, abandoned home sites and military installations, fills, and on fire scars.

The former vegetation, the type of soil, the amount of moisture, and the kind of disturbance all seem to have a bearing on the original composition and subsequent course of succession in these plant communities. Pure chance in what weed seeds happen to be present in sufficient numbers may be one of the most important factors.

These weed communities are mostly ephemeral, though at least one of them, the Leucaena glauca thicket, may persist indefinitely. These vegetation types may be only roughly classified. As with most vegetation situations, especially those where active succession is taking place, varying mixtures occur which defy classification and which may result largely from chance. On Guam these mixtures do not make up a disproportionate amount of the area, so that a rough arrangement and brief descriptions of the principal types seem feasible and useful. The following are weedy plant communities that are reasonably distinctive and that are recurrent enough to be more than merely accidental.

Mixed herb type: On cleared land, fills, roadsides, and burned areas the first colonists are normally a mixture of many non-woody species which can grow on bare soil. Between the time when the first few plants appear on a bare surface and the time when the herbaceous species are shaded out by the shrubs which eventually follow them in any reasonably moist climate there are an infinite series of variations which, together, may conveniently be referred to as a mixed herb type.

About 75 species commonly occur in such places. These form innumerable combinations. Generally the assemblages and proportions occurring on volcanic soil differ somewhat from those on limestone; also, those on bare rock differ from those on rich agricultural soil. Moisture strongly influences the abundance of species, as do the season and the degree of consolidation of the vegetation. These combinations are too numerous to be described conveniently. However, several striking aspects repeat themselves often enough to be pointed out, mostly where they are completely dominated by one species.

Most conspicuous and common of the aspects of the mixed herb community is that dominated by Stachytarpheta indica. This herb, growing to about 1 m in height, with purplish-blue flowers, completely dominates much ground on both volcanic and limestone soil that has been relatively recently cleared of vegetation. This is a vegetation of short duration, which is relatively soon succeeded by shrubs or savanna vegetation.

In some areas, mostly in volcanic soil, dominance is assumed by Elephantopus mollis, a tall, disagreeably bristly plant which is especially likely after savanna or weedy vegetation has been burned over. Where savanna dominated by swordgrass, Miscanthus floridulus, has been burned and replaced by Elephantopus, the resulting herb vegetation is likely to be short-lived, as the Miscanthus root crowns are not killed by fire; within a short time the Elephantopus will be crowded out. On burned-over weedy land this rapid succession will not take place, and the Elephantopus communities may last until another fire or until shrubs and trees or savanna vegetation have crowded them out by normal secondary succession.

Immediately after fire or other disturbance the resulting bare area may be dominated by a pure stand of Mitracarpum hirtum, a slender herb with small leaves and tiny white flowers. This is soon shaded out by taller herbs such as Stachytarpheta or Elephantopus.

On bare soil -- bare from whatever cause -- Chrysopogon aciculatus tends to form a dense turf that clings closely and firmly to the soil. Chrysopogon is a very low, creeping grass that may often form pure stands, especially on soil that is badly eroded. It is very important for retarding erosion.

A number of other weed communities do not seem to be particularly connected with the mixed herb type, although several of them occur on recently denuded ground.

Pennisetum polystachyum community: Along roadsides and around recently abandoned military installations, especially on the limestone areas of the island, are extensive pure stands of a recently introduced grass, Pennisetum polystachyum (pl. 39B). This is erect, about 1 m tall, and produces conspicuous cylindrical spikes of yellowish flowers in the fall. By the middle of January this plant is largely dry and drab, and its habitats are quite conspicuous; in fact they can be picked out from a considerable distance during both flowering and dry seasons by their straw-yellow or drab color.

Pennisetum purpureum type: Napier grass or elephant grass, an introduction from Africa, is gaining ground in open areas and of the edges of secondary thickets. It is common between Tamuning and Potts Junction, and seems to be spreading. When well developed it is a reed-like grass up to 4 m tall, and after the first year it forms dense tangles. The canes are up to 1 cm thick and branch freely. When young this species is considered excellent forage; when older it is tough and presents a tiring obstacle to movement on foot.

Tripsacum type: About half-way between Wettengel and Potts Junction is a small area of a grass introduced into Guam for forage. It seems to be spreading aggressively and will probably be much more common in the future than it is now. It looks much like a very dark-green maize plant and forms dense pure stands up to 3 m tall. It produces horizontal rhizomes, which, matted in the surface of the ground, enable it to exclude other plants.

Panicum purpurascens type: Along moist roadsides and in meadows, even where the ground is not marshy, Para grass forms pure stands which are identical with similar vegetation described above for marshes. Panicum purpurascens seems to grow perfectly well on either dry ground or mud.

Mixed grass community: In some areas, especially those kept open by grazing, there is meadow or pasture vegetation that is a mixture of several sorts of grasses, especially Paspalum conjugatum, Paspalum orbiculare, Panicum purpurascens, Chrysopogon aciculatus, Sorghum halepense, and others. Where grazed lightly, meadow of this sort may persist for some time before being replaced by other plants. If overgrazed, replacement will take place rapidly.

Nephrolepis hirsutula type: In clearings in the forest on the limestone plateau, an almost solid stand of Nephrolepis hirsutula, a luxuriant fern with erect fronds 1 to 1.5 m tall, is a common early stage in the development of vegetation. It is very dense, either as a pure stand or with other herbs, and will hide a man lying prone.

Carica papaya type: Along roadsides newly bulldozed in the forest on the northern plateau, especially in deep red soil, a dominant stand of wild papaya springs up within a few weeks. As a relatively pure stand it seems to last only one generation, growing up rather evenly to a height of several meters before being seriously invaded by other woody species. It is succeeded by a mixed shrub vegetation of the sort described below.

Carica papaya is a typical "rosette tree" having generally a single post-like trunk topped by a crown of great, palmately-divided leaves up to one-half a meter in diameter, on long petioles. The trunk is not very woody but rather pulpy and soft. If cut, leaves and stems exude an abundant white latex. This may be irritating to tender skins because of its protein-digestive properties.

Passiflora foetida-Ipomoea indica community: On bare limestone that has at sometime been scraped clear of vegetation and soil is frequently found a mat of Passiflora foetida and Ipomoea indica, both soft herbaceous vines. They cover the ground completely but usually to a depth of only a few inches.

Operculina type: Around Northwest Guam AFB, Operculina ventricosa forms huge dense mats of coarse vines. These may be a meter deep and are capable of smothering out other plants. The leaves are large and heart-shaped, the flowers white, and the fruits conspicuous in erect clusters.

Ipomoea pes-caprae type: In clearings on sand flats back of the beach, and to a lesser extent elsewhere, bare ground is rapidly covered by a mat of beach morning-glory. This under some conditions becomes so dense as to retard invasion by other plants. The leaves are leathery and bright green, characteristically two-lobed at the apex.

Mixed shrub community: On cleared limestone or limestone soil various secondary herbaceous vegetation types are frequently followed by shrubby vegetation of varying composition. It seems impractical to try to separate it, except to indicate that in some areas single species tend to assume dominance. Commonly this vegetation is a mixture of Hibiscus tiliaceus, Cestrum diurnum, Muntingia calabura, Triphasia trifolia, Leucaena glauca, and of many other species in lesser amounts. These last include certain undoubtedly indigenous species, such as Pipturus argenteus and Macaranga thompsonii, some of ancient introduction, as Morinda citrifolia, and some unquestionably of post-European introduction, as Psidium guajava, Carica papaya, and Lantana camara.

The density and stature of this scrub is as variable as its composition. In some stands the bushes are not or are barely in contact with one another and walking through is very easy. The opposite extreme is a thicket with gnarled and twisted branches completely entwined and impossible to penetrate without constant and vigorous use of the machete Abundance of Triphasia provides an additional obstacle -- very effective spines. If Caesalpinia major is present an even more formidable obstacle is encountered in the form of a clambering vine with large compound leaves that are beset with hooked prickles (pl. 43A). A vernacular name for this vine, "wait-a-bit", (sometimes used in other tropical countries) is very appropriate. Ordinarily the density of branching in such scrub is about as great near the ground as in the canopy.

In stature this scrub grades insensibly into secondary forest, both by the maturing of some of the ordinary component species and by a gradual shift in composition with increase in tree species. The available information is insufficient to indicate any real successional relations to forest types.

Any one of the five most abundant shrub species may occasionally assume dominance, sometimes exclusive dominance. Of the resulting vegetation types that with Leucaena dominant will be treated separately. The others can be regarded as variants, with certain notable characteristics enumerated below.

Stands of Cestrum diurnum are ordinarily dense but not difficult to traverse, light green in color, and 2 to 4 m tall. There are no spines and the stems are relatively slender and easily cut.

Stands of Muntingia tend to be less dense. The leaves are velvety and dull green Again, penetration is not difficult.

Triphasia, as indicated above, is viciously spiny. The wood is hard, but not too difficult to cut with a sharp machete. Cutting a branch, however, does not necessarily make penetration easier, as it may merely fall into a less favorable position. In this type of vegetation, the canopy tends to be above head height, with the lower part relatively open; but even when it seems feasible to walk through it, there are always enough low branches to make passage very disagreeable. In general, when the fine, shiny, dark green foliage of this plant seems to make up a large part of a thicket it is simpler to go around it than through.

Though Triphasia is unquestionably the most painful scrub to traverse, a stand of Hibiscus tiliaceus is more exhausting. The plant has no spines or other obvious disagreeable features; but it is an interminable tangle of twisted, winding, looping stems. A well developed thicket of Hibiscus is one of the favorite types used in moving pictures for a terrible tropical jungle: any individual stem is easily cut, but there are always many more, and when cut they may merely spring into more obstructive positions; feet are likely to be entangled, falls are frequent; and anything being carried is caught by branch after branch. This vegetation may be of any stature up to that of scrub forest.

In all of these aspects, as well as in the various mixed ones, lianas and herbaceous climbers are frequent and tend to complicate the tangles. Various morning-glories, Abrus, Entada, Mucuna, Canavalia, and Flagellaria, may be common. Caesalpinia, as noted above, adds a prickly complication here and there.

Leucaena glauca thicket: Perhaps the commonest of all types of vegetation in cleared areas at the present time is a dense pure stand of Leucaena glauca (the "tangantangan" of the Guamanians) (pl. 42). This plant is a slender, erect shrub or small tree with fine feathery foliage. It has no spines and individually is not an unattractive plant. Its pure stands are usually extremely dense, and may be of any height up to 10 m, depending on age and wetness of the situation. The stems are commonly less than 5 cm thick and grow so close together that they must be pushed aside to walk between them. Though the canopy is complete, there is usually a carpet of seedlings of the same species on the ground. In central Guam, however, an insect attacking the pods has very noticeably cut down the seed production. Also the giant African snail seems to kill the young branches in certain areas by rasping off the green bark.

Opinions on the desirability of this plant differ violently. Some regard it as a valuable forage (when kept cut close to the ground) and a protector and enricher of the soil; others, from persons who have tried to get rid of it or to check its invasion of an area, regret even its being brought to Guam. It is probably the most widely used tree for firewood on the island because of its abundance near populated areas. The wood is a good firewood--fast firing and relatively long burning. Unquestionably it has increased greatly in the last 8 years. The local Department of Agriculture, under Navy Administration, caused large quantities of Leucaena seed to be broadcast from planes, especially on the volcanic rocks of the southern half of the island. It is now very abundant on roadsides and over vast areas of former open field in the limestone part of the island. On the southern part it has scarcely become established on volcanic soil; it has, however, come up as hedges lining many roads which have been ballasted with crushed coral. The Leucaena grows well as far as the coral has been spread. Unfortunately, roads lined with Leucaena completely lack visibility to the sides and on curves.

Special Features of Military Significance

In addition to its importance as a general feature of the landscape, vegetation has certain properties that are of special concern in military planning. Of these the most important are its use as emergency supplies of construction timber, as emergency food sources, and as plants that are poisonous or noxious to man. These are treated in separate sections.

Construction timber: Many kinds of trees on Guam might be of value for construction purposes or other military uses, but few kinds are abundant enough to justify inclusion in this discussion. In pre-war Guam it would have been possible to obtain perhaps 20 kinds of timber in significant amounts. The extensive clearing and destruction of forests in the last 10 years has left few of these in any quantity, and only ten are worth any discussion. Information on the properties of these is also lacking. The existing situation may be briefly summarized by arranging the kinds of timber in order of abundance:

Coconut (Cocos nucifera): This is by far the most abundant single timber-sized species in Guam. It yields logs 8 to 12 inches in diameter and up to 50 feet in length, often not very straight, which are completely worthless for sawing or for permanent construction. They are, though, useful for emergency temporary construction, shoring, barricades, and the like. The wood is very hard on the outside of the log, spongy within, and rots easily. It is said to stop bullets effectively.

Coconut trees are found in abundance on most beaches, locally in most parts of the plateau, abundantly for almost the entire length of the east coast from Pago Bay south to Inarajan, in all valley bottoms and mouths around the south and southwest coasts, to some extent in most of the ravine forests, and in the upper part of Maagas Sabana below Fena Dam.

Wild breadfruit (*Artocarpus mariannensis* or "dugdug") and cultivated breadfruit (*Artocarpus altilis*): Wild breadfruit is dominant in much of the limestone plateau forest and in certain areas of ravine forest on the south and southwest slopes of Mt. Schroeder and other mountains above Umatac and Merizo. It is a close relative of the cultivated breadfruit, *Artocarpus altilis*, and in the past usually has not been distinguished from it. The wood of the dugdug differs significantly from that of the breadfruit: dugdug wood is soft, yellow, easily worked, and lumber from it has many of the properties of white pine or sugar pine; breadfruit wood is redder, coarser, and splits more easily.

As construction timber (opposed to saw timber), dugdug and breadfruit may be considered together from a military viewpoint. Both reach large sizes, up to several feet in diameter, with as much as 20 feet of reasonably clear length. Unfortunately, logs of such a size are not as abundant as formerly. They are said to resist termite attack, but do not resist moisture well; thus, they would not be good for more than temporary use in contact with the ground.

In utilizing this timber, other than in an emergency, careful distinction should be made between dugdug and breadfruit; the latter should not be cut because it is an important source of food, and trees are likely to be valued property. Any tree with more than two or three scallops on each side of the leaves should be regarded as breadfruit until its identity has been checked by asking a local inhabitant. This consideration may be important for maintaining good relations with the local people.

Banyan (*Ficus prolixa* or "nunu"): The trunks of this tree tend to be enormous, but are of no value whatever for sawed lumber; they are soft and very irregular -- really just a fused mass of aerial roots. The logs, however, reach several feet in diameter and many feet in length. They might be useful for temporary construction, barricades, earthworks, and other installations where a thickness of wood is needed to stop bullets and shrapnel. This tree is found in most of the forests on Guam.

"Ifil" (*Intsia bijuga*): This tree is generally considered to be the finest timber on Guam, and as such has been so relentlessly logged that relatively few large trees remain. Its wood is very hard, very heavy, and is not easily worked but takes a beautiful finish. It is unbelievably durable; there are foundations of it 150 years old in Guam. In the Philippines it is known to last at least 400 years in contact with the ground. It corrodes steel screws and nails, though.

There is not enough ifil left in Guam to justify logging, but it should be saved as timber when cut in clearing. Old logs of ifil lying in the woods are still sound, though perhaps cut many years ago. The wood of these is much darkened with age.

"Yoga" (Elaeocarpus joga): This tree is still fairly common, though never in concentrations. It grows in the plateau forests. The trees are large and will produce logs up to 2 feet in diameter and 20 feet long. Little is known of the properties of the wood, but according to the Guamanians it is excellent. Other species of the same genus elsewhere yield rather soft wood of very good quality.

"Daog" or palomaria (Calophyllum inophyllum): This is probably the strongest wood, for its weight, in Guam. Logs are of good diameter but not very long. It has been logged out of most parts of Guam but still grows in some of the ravine forests on the volcanic rocks part of the island. In some other islands logs of this wood are seasoned by soaking them for some months in brackish estuaries.

"Faya" (Tristiropsis obtusangula): This fairly common tree has a straight trunk which yields logs a foot or more in diameter and many feet long. It is useful for timber, at least for temporary purposes, but twists and warps very badly when sawed.

"Ahgao" (Premna obtusifolia): This tree is common in most forests on Guam, but large trees are not common. It is said to produce hard and durable logs up to 18 inches in diameter and 13 feet long.

"Fago" (Ochrosia oppositifolia): This tree is generally common in forests on limestone. The logs are likely to be a foot or less thick, not of large diameter, but may be 20 or 30 feet long; they are said to be good wood. Like most or all other timbers, fago is much better when grown in tall, dense forest; there is little such forest left on Guam.

"Chopag" (Ochrocarpos odoratus): Formerly abundant, this excellent timber is now common principally on and near the eastern escarpment of the north Guam plateau. The trees here are generally not large, but the wood is said to be excellent for construction.

"Umumu" (Pisonia grandis): This tree is found in various places, particularly on terraces near sea level. It has enormous trunks; but the wood is soft and pulpy and is useless for anything but the most temporary barricades and breastworks.

Conclusion: In general, at the present time, timber must be imported into Guam for all except emergency military use. The formerly excellent sources have been almost completely depleted in the last decade and the only way for Guam to become self-sufficient in lumber even for domestic use would be for forest reserves of considerable extent to be established and managed on a sustained yield basis. With lumber prices rising and world timber supplies shrinking a proper forest policy should pay good dividends in the not-too-distant future. Certainly any further clearing of forests on the island should be very critically studied before it is carried out.

Emergency food plants: Equipped with a certain amount of information about the more common plants he would encounter, a man need not starve anywhere on Guam; and if he were agile enough to climb a coconut palm, he need not suffer excessively from thirst. A considerable number of wild plants yield edible fruits or other parts, and in a real pinch a man need not be too much concerned whether or not the plants are wild. However, except in case of an actual emergency, a person would do well to bear in mind that large areas on Guam are private property and that the more obvious food plants, such as bananas, taros, coconuts, and fruit trees are most likely planted and that the owner may resent theft of his products and may be in a position to do something about it.

The more common plants with edible parts are listed here, with a few words of description, notes on occurrence, and information on the parts to be eaten, methods of cooking, and possible precautions to be observed. For fuller information on most of these as they occur generally in the Pacific, one may refer to one or another of the numerous "survival manuals" available, most of them published by branches of the Armed Services. Except for a few of the most important, these plants are grouped according to the type of food they produce.

Coconut (Cocos nucifera) (pls. 32A, 40A, 41): This is the most important food plant on Guam. It is a large palm, seen almost anywhere in Guam where trees are found, but most abundantly along low coastlines and around the more thickly settled parts of the island. The huge nuts are borne at all seasons and are edible as soon as they have reached full size, though they contain more nourishment after they have ripened and fallen from the tree. The white, oily flesh is delicious and may be eaten in any quantity with safety. The water that fills the cavity is also excellent to drink, but is much more palatable when the nut is still green but full grown. The best period is when the flesh is just beginning to become a firm layer rather than a soft "jelly". The unripened meat of the nut is also edible, even in the jelly stage; the water is then sweet and effervesces slightly. Nuts which have lain on the ground and sprouted are excellent eating until the sprouts are well over a foot high. The spongy mass that fills the cavity, as well as what remains of the white flesh, are edible. The flesh of fully ripe nuts may be grated and the resulting grated material wet with coconut water, then squeezed by twisting in a strong cloth, to produce a very passable milk; if allowed to stand a cream will even rise on the milk. Another part that is edible, though it is not at all recommended that trees be cut for this purpose, is the heart of the upper part of the stem where the young leaves are just forming -- in other words, the terminal bud. The very young, tender, white, rolled-up leaves make heart-of-palm or "millionaire" salad. The tree is killed however, when this is removed. If the tip of an unopened flower-cluster bud is cut off, a very sweet liquid drips out and commonly collected in a bottle hung on the bud. It is well to protect the mouth of the bottle with gauze to keep insects out, as some of them are very poisonous, and may pollute the collected sap. This liquid may be drunk fresh, boiled down to sugar, or fermented to form toddy (locally called "tuba") which resembles poor hard cider.

Breadfruit (Artocarpus altilis and A. mariannensis): Common trees on many or most parts of Guam, except the grasslands, are the breadfruits, both planted and wild. They are very large trees with large dark-green shiny leaves usually deeply lobed on the margins. The sap is milky and sticky. The fruits are large, green to yellowish green, cylindrical to spherical, from the size of a man's two fists to the size of his head. The wild forms have seeds, but cultivated ones are seedless. These fruits are starchy, edible either green or ripe, and may be baked, roasted, stewed, or cooked in many other ways. When ripe, they are soft and may be eaten raw, but are not very palatable. Baked when ripe, they are delicious. The seeds of the wild forms are edible either boiled or roasted, and are compared with chestnuts. They are about the size of a filbert and are borne in the outer layers of the fruit. The fruiting season in Guam is during the northern summer and early fall. One of the main problems in using these fruits is that the trees are very large and very high and harvesting them is difficult and may be dangerous. On some of the other Pacific Islands, they are harvested by two people, one to climb into the main branches of the trees and knock the fruits off the smaller branches with a long bamboo pole, the other to stand on the ground and catch them.

Bananas and plantains (*Musa sapientum*, *M. nana*, and *M. paradisiaca*): Bananas (pl. 40B) and plantains are commonly planted on Guam and in some places persist around old homesites. Everyone knows the fruit of the common banana. Many of the varieties in Guam are much smaller than those sold in the United States but some in Guam are very delicious and different in flavor. They must usually be picked green and hung up to ripen, as otherwise the rats will get them first; also the fruits are liable to dry-rot if left to ripen on the plant. They should be left on the plant until the fruits are no longer quite prismatic in shape and have a more or less circular cross-section. If left this long the ripened fruit will have much more sugar than if it is picked while still angular. Plantains are similar to bananas but usually the individual fruits are on longer stalks in the bunch. They are coarse and not especially sweet, and must be cooked to be really good to eat. This may be done by roasting or boiling in the skin, or by frying sliced or cut lengthwise after peeling. Both bananas and plantains grow on plants with great leaves several feet long, on an erect soft "trunk" which is really made up of tightly rolled leaf stalks. When the fruit is harvested this trunk may be cut down, as it will die and new plants will develop from the shoots at the base. Any fruit which looks like a banana, borne in large bunches, is safe to eat, though occasionally one will be found which is full of large seeds. The bananas and plantains are among the most important foods in the tropics.

Fruits: There are a number of edible wild fruits on Guam, as well as some planted ones around old homesites. By no means all wild fruits are edible, but the following may be eaten safely (several of these are small and not especially delicious, but in an emergency they are far better than nothing):

The mango (*Mangifera indica*) is a juicy fruit as large as a man's fist, slightly flattened and lopsided, hanging from a large, dense, very leafy tree with long pointed leaves. The fruit may be greenish or yellowish when ripe, usually flushed with red on one side. The skin is tough and usually has a slight flavor of turpentine. If the fruit is ripe, it is soft and the meat is bright yellow and usually very sweet. In poor varieties there may be a turpentine flavor and the flesh is filled with tough fibers. In spite of these features, the fruit is edible, but the better varieties with less fiber and no turpentine are, of course, preferred. The sap of the leaves, stems, and green fruit may affect some people in the same way as does poison ivy.

The lime and bergamot (*Citrus* spp.) are occasionally found, mostly around old homesites. These are familiar enough, though the bergamot may be mistaken for a small greenish orange. It is, however, exceedingly sour and would never be used except in drinks. Wild oranges are not common on Guam.

Papayas (*Carica papaya*) are found everywhere on Guam, especially in the limestone areas. Unfortunately, most are a very small variety not much bigger than one's fist. They are not very sweet and may even be bitter. They may be eaten safely, however, seeds and all. If picked green, they will ripen. If left on the tree to ripen, the rats, fruit-eating birds, and bats will usually get them first. The trees have soft columnar trunks and large roundish, deeply-cut leaves on long stalks. The milky sap may have an irritating effect on tender skins. The larger forms, usually found only in cultivation, are often very delicious. Small quantities of the green fruit may be cooked with meat to make it more tender.

The bullock's heart (Annona reticulata) and the sour-sop (Annona muricata), which are found occasionally in secondary thickets on Guam, have excellent fruits. Both are small trees bearing fruits from the size of two fists to much larger. The skin of the soursop is prickly and green when ripe. That of the bullock's heart is more or less smooth and dark reddish. The flesh is white, with large black seeds which are not edible. These fruits are eaten raw when ripe (they are ripe when they feel somewhat soft).

The star fruit (Averrhoa carambola) and the bilimbi (Averrhoa bilimbi) are found occasionally, especially around old homesite. The former is unmistakable, as it has prominent longitudinal ribs or keels and is several inches long and half as thick. It is sweet and juicy. The bilimbi is smaller, cucumber-shaped, and rather acid. Both grow on small trees. Very similar is the tree that produces the Otaheite gooseberry (Phyllanthus acidus), but the fruit is the size of a small cherry, slightly flattened, and rather sour.

Jujubes (Zizyphus jujuba) are occasional, small spiny trees, with leaves less than an inch long and white-woolly beneath. The fruits are the size of a marble, not juicy but sweet, with a large stone. Another spiny shrub, Ximenia americana, occasional in brushy places especially near the sea, yields bright-yellow, plum-like fruits that are acid but refreshing, also with a stone that is large for the size of the fruit. Ground-cherries (Physalis spp.), small tomato-like berries borne in small balloon-like envelopes on small non-woody plants growing in weedy places, are edible. The kinds on Guam are of much poorer flavor than some growing elsewhere. In the forests are shrubs or small trees (Ficus tinctoria) with lopsided leaves which bear small orange or reddish figs. These figs, distinguished from others by the fact that they are borne on short stalks, may be eaten either raw or cooked. They are not especially good, but are welcome to a hungry man. The Panama cherry (Muntingia calabura), a shrub with velvety pointed leaves, now becoming very common on Guam, yields a small pink berry which is insipidly sweet but edible.

Nuts or edible seeds: Besides the coconut, several other large seeds found in Guam may be eaten. The seeds of the dugdug or wild breadfruit have been mentioned above. They are eaten either roasted or boiled. Pandanus seeds are excellent, but only those of the broad-leaved species, Pandanus dubius, are commonly eaten, as the others are small and very hard to remove from the stone in which they are encased. P. dubius, with a very large and bluish-gray fruit head, has seeds about the size of a marble and with a delicious flavor. When ripe the fruits loosen from the head readily and may be cracked with a machete. The seeds are eaten raw. The seeds of the "tropical almond" (Terminalia catappa) and of the "fago" (Ochrosia oppositifolia) are also eaten raw. Both are fair-sized trees with bright green leaves (larger at the upper end), and with large fruits which are fleshy just under the skin and corky farther in. The fruits may be cracked crosswise with a machete. The fleshy part of fago fruits usually are eaten off by crabs, birds or other animals, leaving an egg-shaped corky mass covered by soft spines. Their seeds are thin but of good flavor. Ordinarily these, as well as the tropical almond, are not regarded as worth the trouble of cracking them to get out the seeds, but in an emergency they may be a valuable source of food.

"Federico" or "fadang" (Cycas circinalis): This is a very common plant, on most parts of Guam, which looks like a small palm with shiny green leaves. It bears large seeds about the size and shape of an egg, fleshy outside. These are poisonous if eaten without proper preparation, but many Guamanians subsisted on them for periods during the war. The large kernel must be removed, broken up and soaked for 10 days or more. Then it is dried and pounded into a powder and used as flour or starch for cakes. When thus soaked and made into bread or cakes which are baked well, the poison is removed. Use of these seeds as food is not advised, except in an emergency.

Starchy root vegetables: A number of these are found, varying greatly in edibility. In many Pacific Islands these are the mainstay of life. All except the yam-bean should be cooked. The yam-bean (*Pachyrrhizus erosus*) is a vine, with leaves of rather irregular shape, bearing a large turnip-like root which, peeled, is rather sweet and is eaten either raw or cooked. Wild yams (*Dioscorea spp.*) are common on Guam, especially on the east side of the south half of the island. Great patches of the vines begin to turn yellowish in January. After they are dry and brownish, the tubers on their roots are ready to harvest. The vines have large heart-shaped leaves and hooked prickles on the stems; they also have masses of the wickedest spines in the plant kingdom (borne just at the surface of the ground on short branched stems), which should be carefully avoided in digging the tubers, as they inflict painful wounds and will even penetrate tennis-shoe soles. The tubers, like other yams, may be cooked like potatoes and are very nourishing.

Island arrowroot (*Tacca leontopetaloides*) and tapioca (*Manihot esculenta*) are very different-looking tubers that must be prepared in the same way -- by grating the plants and washing out the starch, drying it, and using it for puddings, cakes, and the like. The washing is necessary to get rid of bitter and poisonous substances. *Tacca* tubers look like potatoes and are borne on stemless plants with much-divided leaves on tall stalks which come right out of the ground. The flowers and seeds are borne on taller stalks, 3 to 5 ft high. Tapioca plants are tall, with knobby stems and deeply-lobed palmate leaves. Both may be found in open or semi-open places, but tapioca does not persist long after cultivation, while *Tacca* seems to be a part of the normal flora of the island.

The taro and other taro-like plants are the most common of all, though it is probable that all are introduced. All have very large arrowhead-shaped leaves. All are acrid if eaten raw or insufficiently cooked, and some are exceedingly so. The several kinds may be distinguished as follows:

Leaves bright green, shiny, pointing upward
    Lower lobe of leaves sharp-pointed, stems and leaf stalks usually prickly: giant taro (*Cyrtosperma chamissonis*) (rare on Guam)
    Lower lobe of leaves blunt or rounded, stalks and stems smooth: false taro (*Alocasia macrorrhiza* and *A. indica*)

Leaves dull, bluish or grayish green, pointing downward, stalks attached inside the lower surface of the leaf: taro (*Colocasia esculenta*)

Stalks attached at the edge of the leaf at the bottom of a V-shaped notch: yautia or "Hawaiian" taro (Xanthosoma sagittifolia)

The tuberous stems of all except the false taros are commonly steamed or boiled, then eaten as they are or stewed or fried. They are very edible and nutritious. The Alocasias are not eaten on most islands except in times of famine; the thick stems are very starchy, but they are so acrid that they must be boiled vigorously many times, even when cut up into small pieces, with the water poured off each time. They are likely to burn the mouth even then, and are not advised as food except in time of extreme emergency or famine.

Greens or salad vegetables: The leaves of many plants may be eaten as greens, though most have peculiar flavors or bitterness and commonly are not eaten. Also, in tropical countries, little is known of the poisonous qualities of most plants, so it is not advisable to eat any of them except those that are well known or that are eaten by the natives. The several species of pigweed (Amaranthus spp.), familiar plants in weed patches even in the U. S., may all be cooked and eaten when young. Purslane (Portulaca oleracea), a common fleshy weed, also found in gardens and weedy places in the U. S., and seaside purslane (Sesuvium portulacastrum), a prostrate fleshy herb growing in saline places, may be cooked and eaten. One of the morning-glories which grows in muddy places (Ipomoea aquatica) has a soft fleshy stem, arrowhead-shaped leaves, and white flowers with purple centers, and may also be eaten cooked. The young leaves of the true taro (Colocasia esculenta) are very much like spinach when cooked, but must be cooked thoroughly to destroy an acrid component. They are often cooked with grated coconut. Both leaves and young fruits of the vegetable sponge (Luffa spp.) a cucumber-like plant with bright yellow flowers, are cooked and eaten but are rather bitter.

The unopened flowers of a rather common tree, Sesbania grandiflora, which are white, 1 to 2 inches long, and which hang down from the twigs on which they are borne, are eaten either cooked or as raw salad. The pods of this tree may be several feet long and hang vertically, and are not known to be edible.

Many other plants known to occur on Guam are edible, but are not common enough to be important. Still others may be edible, but not enough is known about them to advise experimenting. Of course, in a pinch, anything that does not have a bad taste may be tried in small amounts and if no bad effects are observed, larger amounts may be tried.

Poisonous plants of Guam: There are really very few poisonous plants of any note on Guam, and especially few of those known to be poisonous grow spontaneously. A number of the planted ornamentals have poisonous properties, but most of these are not commonly planted. It seems worthwhile to mention here only those with known dangerous characteristics which have actually caused discomfort or illness to man and which occur in sufficient numbers to be of importance. Plants that are simply spiny are not listed. No descriptions are provided, but two booklets by Professor E. D. Merrill, "Plant Life of the Pacific World," 1945, and "Emergency food plants and poisonous plants of the islands of the Pacific" (War Dept. TM10-420), include descriptions and illustrations of most plants listed below:

Contact poisons: Several plants found on Guam may cause dermatitis or irritation of the skin, especially in people with tender or sensitive skins. Two stinging-nettles are known from Guam: Fleurya interrupta, a small semi-woody species that is not at all common, and which produces a temporary burning and itching; and Laportea latifolia, a tree growing in the limestone forest, especially at or near the tops of cliffs and on benches and terraces, which is generally innocuous, but whose flower clusters cause burning welts that are painful for several days. There are no permanent effects from either nettle.

The pods and flower clusters of two large climbers, the cow-itch (Mucuna urens), and, to a lesser extent, the sea-bean (Mucuna gigantea), are covered by sharp brittle hairs which penetrate the skin and break off in it, causing a serious and persistent itching; these are especially bad if they get into the eyes.

The milky sap of one of the mangrove plants, Excoecaria agallocha, is very irritating to some people, and is said to cause blindness if it gets in the eyes. The plant also has a reputation for causing dermatitis when touched, even though the sap is not exuding. The plant is a shrub or small tree, whose old leaves turn red and whose flowers are in small green catkins. It is not common on Guam, but gorws in edges of mangrove swamps and on limestone rocks just above high tide level, rarely on sand.

Two of the giant taro-like plants, the "piga" and "papao" of the Guamanians (Alocasia macrorrhiza and A. indica) have an irritating sap which may produce blisters on tender skin. Washing with water seems to aggravate the irritation. All parts of these plants produce terrific, lasting burning sensations in the mouth. The rootstocks and stems are considered to be somewhat edible, as they contain much starch, but they must be boiled repeatedly to rid them of the acrid component.

Mango sap produces dermatitis in people who are very sensitive to poison ivy, but this is easily avoided if only fully ripe fruits are eaten.

Plant poisonous when eaten: A number of fairly common plants will cause serious illness or even death if eaten in any quantity; most of them are not especially likely to be eaten, but all have been known to cause trouble.

The seeds of the "federico" or "fadang" (Cycas circinalis), used as an emergency source of starch, are poisonous unless soaked in water for an extended period. Those of the physic nut (Jatropha curcas), common on Guam and very innocent-looking, will cause death if eaten in the quantities in which ordinary edible nuts are consumed. The large square fruit of the "puting" (Barringtonia asiatica), also common, is used as a fish poison when green. Because of the similar use of Derris, which is non-poisonous, it is sometimes said that the Barringtonia is harmless but this is not true and the seed, especially, is considered dangerously poisonous. Of course the quantities absorbed from the water by a fish do not render the fish inedible.

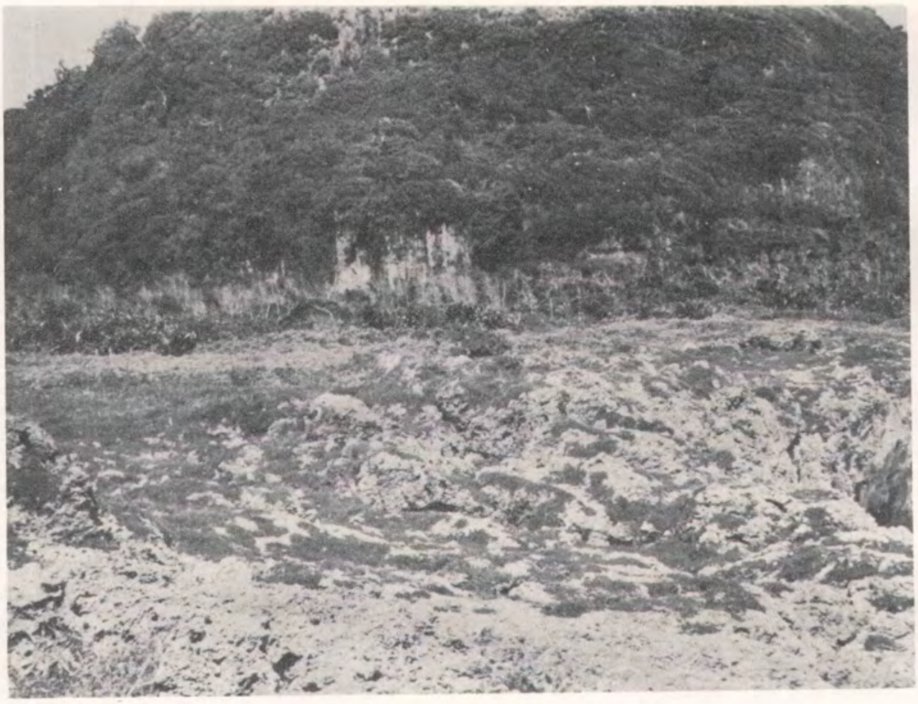
The seeds of the castor oil plant (Ricinus communis) and those of the "black-eyed Susan" (Abrus precatorius), called by the Guamanians "kolales halomtano" -- scarlet seeds with one end black, commonly strung for necklaces -- are poisonous when eaten, and much more so possibly fatal, if any of the material of the inside of the seed gets into the bloodstream.

A number of cultivated plants are poisonous. All of those belonging to the Araceae or calla family, such as the Alocasia (mentioned above), produce a strong and persistent burning sensation when put in the mouth. Those of the genus Dieffenbachia are called "dumb canes" because a bit of the juice paralyses the mouth completely. They are sparingly cultivated on Guam as house or garden plants. Two shrubs commonly planted as ornamentals, the common oleander (Nerium oleander) and the bestill tree or yellow oleander (Thevetis peruviana), deserve special mention, as small quantities of any part of the plant may cause violent illness or death if eaten. The seeds of the latter are the source of thevetin, a powerful heart stimulant.

In spite of the length of this list, anyone exercising reasonable caution need have no fear of being poisoned by plants on Guam.

A. Forest on hard limestone at top of Mt. Lamlam; Hibiscus tiliaceus in foreground.

B. Forest on hard limestone near Yigo, showing Elaeocarpus joga and Pandanus tectorius.



A. Wooded limestone cliff and open terrace at Campanaya Point; *Pemphis acidula* scrub in foreground is dwarfed by exposure to salt spray on windward coast of Guam.

B. Coastal scrub vegetation on sloping terrace north of Fadian Point sea cave. 1937. Photo by H. T. Stearns.

A. "Rampart" and cliff at Andersen Air Force Base, showing dwarfed scrub on cliff face and taller scrub on landward slope. (See caption of same photo, Plate 11A, for geologic mention of "ramparts").

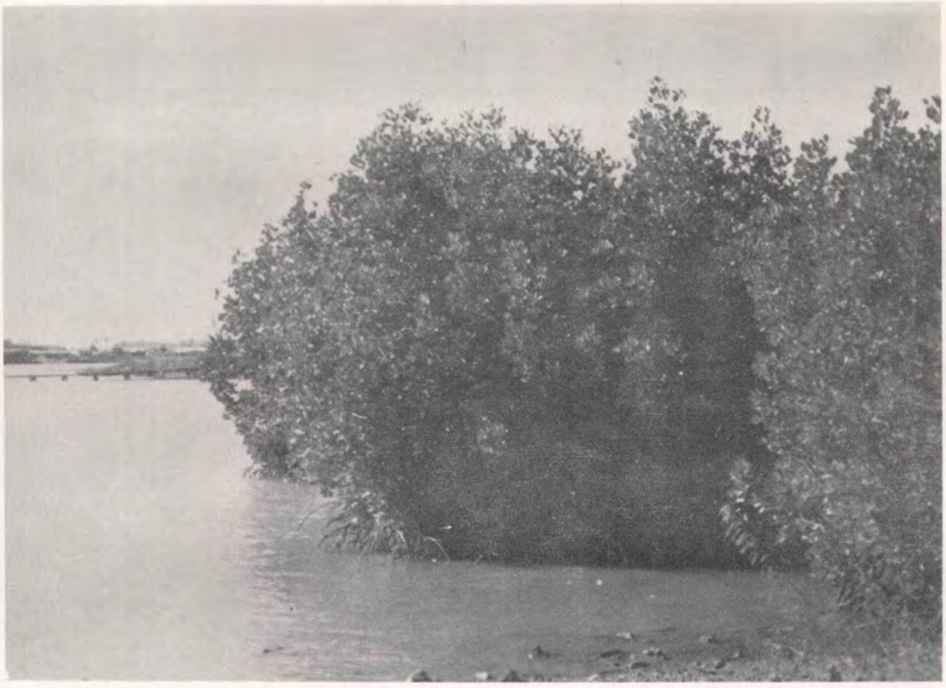
B. Secondary scrub and coconut palms on flat at base of Janum cliff.

A. Thickets at base of wooded sea cliff at Janum, showing scattered coconut palms (one notched for climbing).

B. Wooded cliff at Pugua.

A. Ravine forest with patches of savanna, at Mt. Bolanos.

B. Ravine forest with pandanus and coconut, north of Maemong Valley, Talofofo River drainage; swordgrass in foreground.



A. Mangrove swamp at base of Orote Peninsula.

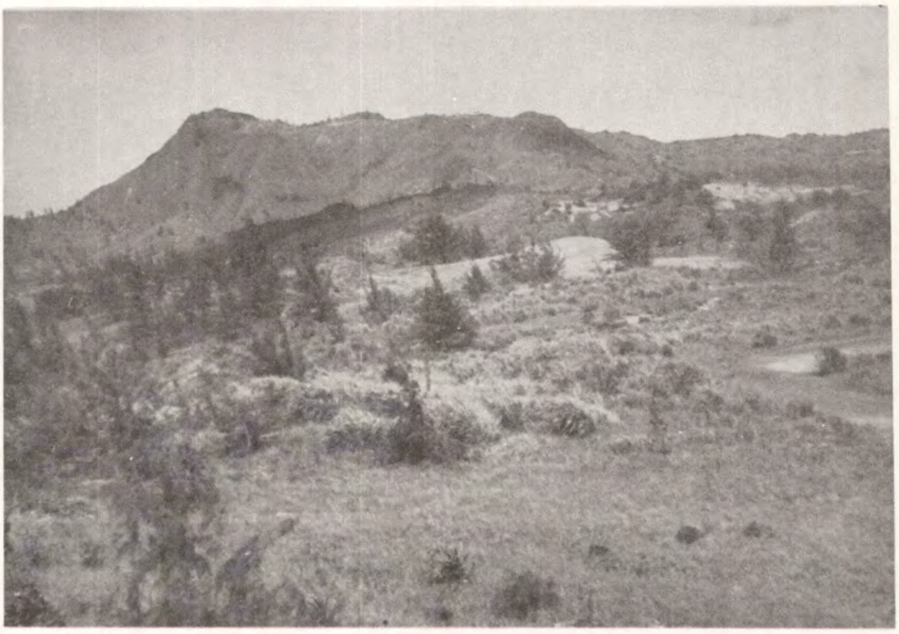
B. Paspalum vaginatum marsh with scattered Avicennia trees, near Camp Bright, just south of Orote Peninsula.

A. Dense, tangled swamp with Hibiscus tiliaceus and reeds (Phragmites karka), at Talofofo River (well above river mouth).

B. Ravine in savanna, filled with reeds and surrounded by swordgrass with Casuarina and pandanus; east of Apra Heights.

A. Swordgrass savanna. Photo looking from Mt. Alutom toward Mt. Tenjo.

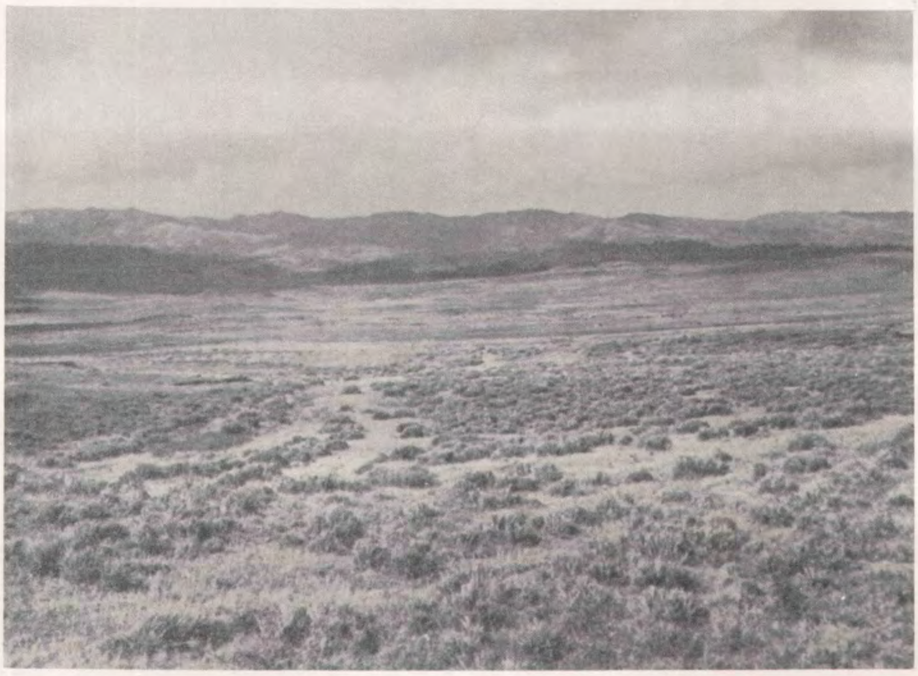
B. Swordgrass with admixture of *Hyptis* and other weeds, at base of Mt. Schroeder (above Merizo).



A. *Dimeria* savanna with patches of swordgrass and scattered young *Casuarina* trees; east of Apra Heights, looking toward Mt. Tenjo.

B. Thin savanna on tuff outcrop at Mt. Tenjo road. Photo by H. T. Stearns.

A. Erosion scar in savanna, being revegetated by Gleichenia ferns; at Dandan.



B. Savanna of Chrysopogon and swordgrass, showing effects of cattle-grazing on swordgrass; at Dandan.

A. Mixed scrubby second growth on limestone soil cleared a few years ago, near Sabanon Pagat.

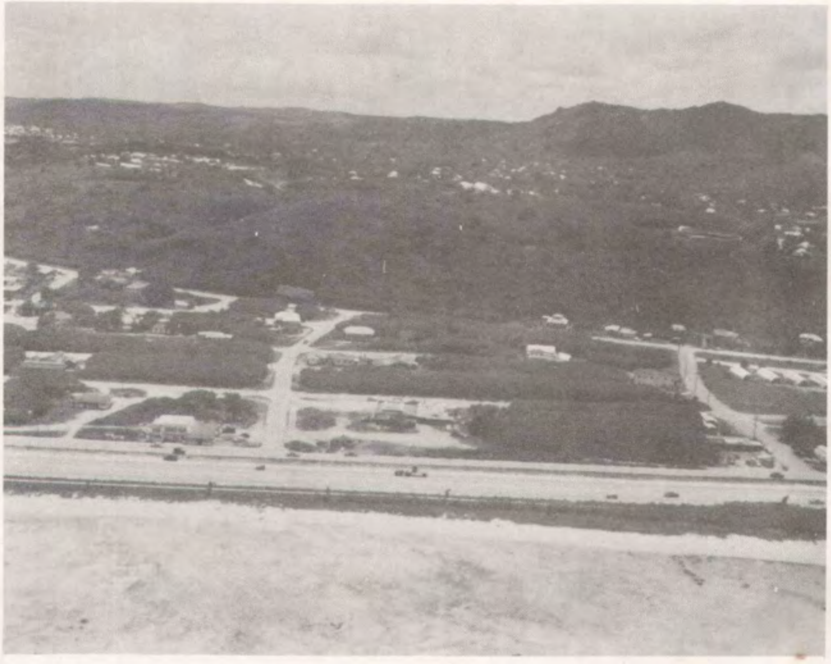
B. Revegetation in abandoned quarry; *Pennisetum polystachyum* in foreground, on limestone soil.

A. Maize field with coconut groves in background, at Merizo.

B. Banana plantation around prehistoric cultural remains in the Talofofo River valley. Photo by H. T. Stearns.

A. Coconut grove, and savanna with Casuarina trees in background, along coast near Cetti.

B. Coconut grove on Cocos Island, badly battered by a typhoon; with Scaevola scrub and beach vegetation.



A. Dense *Leucaena glauca* thickets covering vacant lots and low limestone hills at Agana.

B. Various stages in the development of secondary vegetation, mainly *Leucaena glauca*, on cleared land at Ypao Beach.

A. *Caesalpinia major* in small opening in forest on limestone near Agafo Gumas.

B. Exceptional occurrence of swordgrass on limestone at Mt. Almagosa.

Notes

PART II. ENGINEERING ASPECTS OF GEOLOGY AND SOILS

This section on Engineering Aspects of Geology and Soils presents information for engineers on the suitability of the rocks and soils of Guam for foundations and underground installations, and on the characteristics, modes of occurrence, availability, and uses (for both surface and underground construction) of construction materials. The first part of the section, Engineering Geology, deals with the rocks of Guam (although it includes many references to soils); the second part, Engineering Soils, is mostly contained in a map and in tables, rather than in the text.

Most of the information in this section of the report is from geologic and soils investigations by the field party. In addition, detailed well logs and core drills taken by the Pacific Island Engineers in 1948 provided data concerning the properties of rock at depth; the unpublished (1951) logs are in the files of the Bureau of Yards and Docks, U. S. Navy. Chemical and mineralogical analyses of rocks and soils were made by the Geochemistry and Petrology branch of the U. S. Geological Survey, and differential thermal analyses of clays were made in the field by members of the party. Laboratory studies of the engineering properties of rocks and soils in each engineering unit were made by the Base Development Testing Laboratory, Commander Naval Forces Marianas. The Director of the laboratory, Charles Shirley, and his staff furnished much information in addition to the test results. Engineering information and aid was also obtained from the staffs of the Base Development Officer, Officer-in-charge of Construction, and Public Works Center.

Rainfall, runoff, and flood estimates are derived from data collected for 2½ years from stream-gaging stations built and maintained by the Water Resources Division of the U. S. Geological Survey. The estimates may need modification as additional continuous, accurate records become available.

Engineering Geology

by

H. G. May and S. O. Schlanger

Conclusions

Geologic construction materials (rock materials) are abundant on Guam. Hard limestone for crushed coarse aggregate for concrete and for surface course, base course, and riprap is available and accessible, except on much of the southern half of the island. Coralline rubble suitable for base course is also abundant. Fine sand fairly suitable for concrete is locally available, and clay for binder is commonly available. Volcanic rock (similar to trap rock) is common, but this material in only a very few, relatively inaccessible dikes is suitable for concrete aggregate.

Excavation in well lithified limestone in the northern half of the island requires drilling and blasting; poorly lithified limestone at some places can be excavated with power tools. Excavation of fresh volcanic rock of the southern half of the island requires drilling and blasting; the weathered rock can be excavated with hand or power tools. Wet clay overburden sticks to excavation equipment.

Foundation conditions are good on most of the limestone, but the possible presence of caverns should be investigated. Foundation conditions are generally good on the sound volcanic rock of the southern part of the island, but are poor on the materials on deeply weathered slopes and in swamps, marshes, and the deep alluvium of stream valleys.

Road construction is easy over much of the limestone plateau of north Guam, moderately difficult over hilly limestone terrain and low rolling hills of volcanic rock, and difficult across limestone scarps and steep hills of volcanic rock, where much cut-and-fill and many steep grades and sharp curves are required. Well planned drainage and slope protection is necessary in all areas of volcanic rock; and special problems arise in marshy areas everywhere.

Suitable localities for underground excavations are available at the foot of precipitous slopes in both limestone and volcanic rock. Most suitable locations for airfields are already occupied.

Special engineering considerations are required in some areas because of caverns in limestone. In all areas, construction planning must consider the possibility of typhoons; structures should be able to withstand high-velocity winds, and drainage should be provided to prevent the vigorous erosion by sheetwash and gullying, and the soil saturation, following heavy rainfalls. Coastal areas are vulnerable to unusually high waves resulting from storms or from submarine earthquakes.

Engineering Geology Map Units

Introduction: The engineering geology map (pl. 44, in pocket) shows the rocks and unconsolidated sediments of Guam as three groups, comprising nine units; each group, and each unit within a group, has characteristic engineering properties.

The first group, Limestone materials, includes three map units: Unit 1 is compact coralline limestone (see pl. 45), most of which is well cemented, compact ledge rock; Unit 2 is coralline limestone and rubble (see pls. 46A, B), which is a mixture of vuggy ledge rock, rubble, and friable sandy limestone; Unit 3 is clayey coralline limestone and rubble (see pl. 46C) similar to that of Unit 2, but including 5 to 20 percent of clay.

The second group, Volcanic rock materials, also includes three map units: Unit 4 is volcanic tuff; Unit 5 is volcanic conglomerate; and Unit 6 is mostly bedded basalt flows, dikes, and pillow basalt, and some interbedded calcareous tuff. These three units have much the same ranges of engineering test characteristics, but the structural properties of the unweathered rock are thought to be distinctive, particularly for underground excavation. Widespread, irregular, much eroded, deep clayey weathered material covering the fresh rock hampered identification of the bedrock in the field.

The third group, Unconsolidated materials, includes: Unit 7, beach sands and gravels; Unit 8, lagoonal deposits; and Unit 9, deep clayey alluvium in river bottoms and marshes.

(Fill or made land is shown on the map but is not discussed in the text.)

Discussion of individual units within each group proceeds from description of the materials in a unit through interpretation of their properties for engineering. Special considerations pertaining to each group precede the discussion of the units in it; special considerations pertaining to a given unit are near the end of the discussion of that unit. Tables 16 through 19 (in pocket) summarize Geologic Conditions Affecting Construction, Suitability of Engineering Geology Units for Construction Materials, Engineering Geology Test Data, and Quarries and Pits Active in May 1954.

Limestone Materials

General statement: The three units of limestone materials outlined on the engineering geology map (pl. 44, in pocket) are delineated from the outlines of limestone formations shown on the geologic map (pl. 4, in pocket). The boundary between Units 1 and 2 generally is well within the boundary of the reef facies (QTmr) of the Mariana limestone; the boundary between Units 2 and 3 is, for the most part, identical with the boundary between the pure Mariana limestone and the Agana argillaceous member of the Mariana limestone. Interpretations of limestone units (see fig. 15) are generally valid to depths of several hundred feet or down to sea level, except where the limestone is near the mapped contact with underlying volcanic rock.

Limestone reserves are extensive and generally accessible. Large blocks of hard, compact limestone suitable for cyclopean and heavy riprap are available in clifftops at Orote Point, Amantes Point, Fadian Point, and at several other cliffed headlands in the areas of Unit 1. The best available materials for portland cement concrete are the proven reserves of clean coralline sand at the Harmon Quarry No. 8; when these reserves are depleted, the next most satisfactory material appears to be sand manufactured from the compact limestone of Unit 1. Calcareous beach sand is not suitable for making durable portland cement concrete.

Limestone everywhere on the island may contain concealed cavities and caverns; such open spaces below the surface are serious hazards to construction. (More information on caverns is given in the discussions of individual limestone units.)

Unit 1: compact coralline limestone:

Location and description: The compact coralline limestone of Unit 1 crops out around the perimeter and on the central part of the north plateau of Guam (pl. 44, in pocket). Part of the limestones that make up Orote Peninsula is included in this unit.

Steep cliffs up to 500 feet high, with 1:1 (horizontal:vertical) to vertical slopes (see glossary) on the seaward rim of the north plateau, are the most typical topographic features of Unit 1. Tops of cliffs generally form a steep, walled rampart 50 to 500 feet across the base and 30 to 75 feet high. Wide irregular zones of sharp fretted pinnacles and pits (karrenfeld) are on the inland sides of the cliff ramparts, and near the foot of the high coastal lines. Nips and cavernous zones occur at several levels in the hard cliff faces at different localities.

The dominant rock type in this unit is a massive, compact, recrystallized, white to light-brown limestone containing numerous coral heads in a hard, fine-grained algal matrix. Small lenses of sandy, well indurated limestone are present between the coral heads. Less common rock types are: a massive, dense to porous, well indurated to friable white limestone containing scattered coral heads in a matrix of indurated to friable, coarse- to fine-grained fragments of coral and algal material; and a massive, well indurated, porous white to buff limestone containing numerous casts and molds of molluscs. All the rock types are interbedded with and gradational into one another. The lithology within the unit changes over short distances. There is about 10 to 30 percent of irregular lenses and patches of porous and vuggy limestone included in Unit 1. Ninety percent of the unit is Mariana limestone, and the remainder is Maemong, Bonya, and Barrigada limestones.

Pure limestones of Unit 1 waste by solution, and form surficial pits, pinnacles, and fissures along joint planes. These surficial features range in size from several inches to several feet in diameter and generally are filled with red, granular clay. There are also concealed fissures and caverns. Overburden is either absent or consists of thin reddish-brown clay soils 0.5 to 1.5 feet thick (Engineering Soils Unit 1).

There are numerous high-angle faults, most of small displacement. Fault breccias with the characteristics of crushed rock -- containing much sand- and gravel-size material -- are common. The breccias are zones of possible caving, although the rocks in some fault zones are recrystallized and well indurated. Jointed, very blocky and seamy rock in and around many faults is common in cliffs (pl. 45). Joints and joint sets in Unit 1 may be closely or widely spaced; in general, joints are more numerous and more closely spaced in or near fault zones.

There are many open caverns in this unit along the high cliffs. Many caverns are located along fault zones; swales, basins, and sinks are developed along the surface traces of fault zones and behind the clifftops on the northern plateau. Areas of sink drainage on the plateau may indicate cavernous conditions at depth. Caverns range in size from a few feet across to 50 or more feet in depth, width, and length. Caverns formed along a fault plane may be rectangular or tabular in shape; those formed at the intersection of two or more fault planes may be tabular.

Unit 1 ranges in thickness from a few feet, near some of its contacts with the underlying volcanic rocks, to several hundred feet, on some cliff faces. The greatest height in a cliff face is about 500 feet, adjacent to Catalina Point. The limestone of this unit usually forms an irregular massive sheath upon the seaward margins of the rocks in Units 2 and 3; the sheath is more than 100 feet thick in places (fig. 15).

Excavation - method, facility, stability of slopes: Extensive drilling and blasting is required. Blasting in compact coral-algal limestone will cause high fragmentation; blasting also will loosen jointed rock and fault breccias to such an extent that caving may occur. Some of the breccia may be reduced to gravel and sand.

A. Faulted compact limestone at Fadian Point. Photo by U. S. Navy

B. Jointed compact coralline limestone at Fadian Point, Quarry No. 1. Photo by U. S. Navy, 1954.

C. Compact coralline limestone on Cabras Island. Photo by U. S. Navy, 1954.

The hardness of the limestone in this unit is not changed by excavation. Coatings of algal growth form dark splotches on the white walls of excavations after a year or so of exposure; the splotchy pattern apparently is restricted to the limestone of this unit.

The steepest natural slopes are vertical. Excavation slopes in shallow cuts are stable up to the vertical; in deep cuts the slopes generally are stable at $\frac{1}{2}$:1 in massive rock and at 1:1 in fractured and jointed rock. Observed stable slopes in fill are about 1:1. No erosion was seen in excavations in Unit 1.

Drainage: In parts of the northern plateau of Guam where the limestone-volcanic rock contact is below sea level, the water table is a few feet above sea level. In places where this contact is above sea level, rainwater will percolate down to volcanic rock and run off as subterranean streams; an excavation that cuts the contact may be flooded.

Seepage may be slow in massive unbroken limestone but is rapid in sheared and brecciated zones. Enough joints and fissures generally are present so that drainage construction is not necessary in surface excavations in Unit 1, except in rare large areas of unbroken rock. Subsurface excavations may have to be drained continually, as a tunnel in this unit may serve as a drain for ground water channeled by fault zones and joints, thus dewatering the surrounding rock. Ground water in this unit probably will deposit lime-scale, so drainage system pipes should be located so that they will be easy to inspect and replace.

Tunneling: Areas of steep slopes and cliffs suitable for adit entry locations are: 1) The north coast of Orote Peninsula. The high cliffs along this coast provide deep cover for short adits. Massive compact coral-algal limestone overlies less indurated limestone; a conglomerate of coral boulders separates the two rock types. 2) The bays along the coast of northern Guam. These bays afford easy access to steep cliffs, inland from low coastal terraces, in which a short adit would have deep cover. 3) The upper cliffs south of Tarague Beach, which are cut into Unit 1 and are underlain by rocks of Unit 2. The contact between the two units probably dips seaward; in places it is clearly gradational.

Tunnels will stand free in the massive unbroken rock, but liners and support may be required in joint and shear zones to prevent caving, spalling, and seepage. The breccias will have high and irregular overbreak (see glossary) and a short bridge-action period; dense coral-algal rock will have low, regular overbreak and a long bridge-action period. Rock pressures calculated (see glossary) for this unit, using an apparent specific gravity of 2.68 (167 lbs per cubic foot), are as follows:

Rock Condition	Estimated Volume Percent of Unit	Rock Pressure (lbs/sq ft)	Remarks
Intact	50	0	
Moderately blocky or seamy	25	min. = 0 max. = 835	Load may change erratically from point to point
Very blocky and seamy	10	min. = 2,330 max. = 7,350	Little or no side pressure
Crushed	5	up to 7,350	Considerable side pressure

Pilot tunnels or drill holes should be carried ahead of the main excavations in order to detect the limestone-volcanic rock contact, or caverns, fault zones, and "potential" caverns. (Potential caverns are lenses of fault breccias, clays, or gravels in the otherwise massive limestone that might wash out during excavation.)

Foundation conditions for structures: Bearing capacity is excellent, except on highly brecciated rock where footing support may fail. Footings for heavy permanent installations on sheared or jointed rock should be designed to provide for changes in footing support resulting from strong earthquakes. Heavy permanent installations should not be located near the edges of steep, jointed cliffs because of possible slumping of the joint blocks. Subsurface investigations are necessary at sites for heavy structures because of the possible presence of large concealed caverns or fissures anywhere in the limestones.

Road construction: Roads across steep, rugged terrain in this unit will have steep gradients, short-radius curves, and short alinements; tunneling may be necessary in high vertical cliffs. Road construction involves much cut-and-fill, and excavation requires extensive drilling and blasting. Excavated rock is suitable for all road building requirements except binder. Heavy jungle vegetation is common.

Airfield construction: The terrain of this unit is not suitable for the construction of major airbases.

Special engineering considerations: Small cavities and pockets are common in rough, pinnacled limestone near cliffs; the openings may be concealed by soil. Most large cavities and caves are near cliff lines, and are most common in well defined zones of fractures or joints (pl. 45). Examples of large caves in Unit 1 are the deep "shaft" at Amantes Point (20 feet in diameter and more than 150 feet deep), the caves at the top of the cliffs at Talofofo, and the caverns north of Fadian Point. Sides of such cavities are strongly recrystallized and the cavities can be bridged; steel girders were used to bridge a large cavity encountered during construction of Navy barracks at Tipalao on Orote Peninsula. Cavities in limestone are not a serious problem if their presence is recognized prior to excavation or construction.

Site investigation: Preliminary detailed study of sites should include mapping of all obvious fractures or broken zones, open cavities, and clay-filled pockets or depressions. Where there are known cavities, core drilling should be used to test for other, concealed cavities. Continuing examination of the site during clearing, trenching, and excavation may reveal significant cavities that must be filled or bridged.

Unit 2: coralline limestone and rubble:

Location and description: The largest outcrop area of Unit 2 is on the northern plateau of Guam (pl. 44, in pocket), where coralline limestone and rubble crop out from south of Barrigada Hill north to Ritidian Point and from the foot of Mt. Santa Rosa west to the coast. Another area of outcrop in the high cliffs south of Tarague Beach may be a northern extension of the plateau outcrop. Unit 2 is overlain by the compact coralline limestone of Unit 1 around the edges of the northern plateau, and in patches too small to map on the Mt. Alifan - Mt. Lamlam ridge and on Nimitz Hill.

Rolling plateaus make up most of the surface of this unit. Wide, shallow basins and broad, low rises are well distributed over the north plateau. Steep, terraced rocky slopes border the seaward margins of the north plateau; broadly indented coves and sharp headlands are prominent coastal features. Pit-and-pinnacle belts (karrenfeld) occur along rocky stretches of coast and in stony swales along the inland margins of the ramparts in Unit 1 at the top of the high coastal cliffs. On the north plateau there are widely scattered small, steep-sided depressions 150 to 300 feet across and 20 to 60 feet deep.

Most of the rocks of Unit 2 are white to reddish-brown coralline rubble in a loose to porous lithified limesand matrix (fig. 16). Scattered massive ledges and lenses of either vuggy or compact coralline limestone constitute 25 to 35 percent of the unit area. Large, irregular exposures of chalky limestone are common. Rubble particles range in size from small angular fragments about $\frac{1}{4}$ inch across through cobbles to coral boulders 10 feet in diameter; the average size is about 4 to 8 inches diameter. (The description of a small exposure of poorly consolidated limesand included in this unit is given for the Harmon Quarry (No. 8) in table 19.) Hard rocks of Unit 2 generally are finely crystalline and vuggy. Gently dipping bedding shows obscurely at some outcrops (pls. 46A, B). Mariana limestone (see pl. 4, in pocket) makes up about 75 percent of Unit 2; the remaining 25 percent includes most of the Barrigada limestone.

Limestone of Unit 2 wastes by solution, forming surficial features of ledge rock such as pit-and-pinnacle belts along coastal slopes, fissures along joints and fractures, and solution pipes in basins. There may be concealed caverns in the massive ledge rock of this unit. Overburden of reddish-brown clay soils (Engineering Soils Units 1, 13b, and 13f) is 0.5 to 1.5 feet thick -- thick in basins and thin or absent on adjacent slopes or flats; small pockets of soil as much as 7 feet thick were seen in quarries and elsewhere. The soil-rock interface is generally sharp and serrate in vertical cross-section. Bare rocky slopes are common along the coast.

Widely separated, well developed zones of joints and fractures are common, and are associated with the numerous high-angle faults, some of which are obscure. In some of the faults the rock is a dense recrystallized limestone that forms thin, sharp, steeply inclined ridges in the plane of the fault. Fault breccias are poorly fitted angular blocks of limestone. No large caverns were found in the coralline limestone and rubble of this unit; sinkholes and surface swales, however, indicate concealed caverns and potential caverns below the surface.

The maximum thickness of Unit 2 above sea level is about 550 feet (north Guam). Small lenses of Unit 1 are included in this unit. This unit locally lies upon volcanic rocks of Units 4, 5, and 6 (pl. 44, in pocket).

Excavation - method, facility, stability of slopes: Loose rubbly or chalky limestone (making up 65 to 75 percent of Unit 2) can be excavated by power equipment; the vuggy, massive limestone must be drilled and blasted. Friable rock may be reduced to gravel and sand by blasting; massive rock and brecciated rock in fault zones will be reduced to angular blocks. Throughout Unit 2 the drilling rates will be steady, although hard recrystallized rock in some fault zones will slow the rate of excavation. The unit has generally somewhat harder rock at the surface than at depth, and generally is harder on scarps and ledges than on flats and gentle slopes.

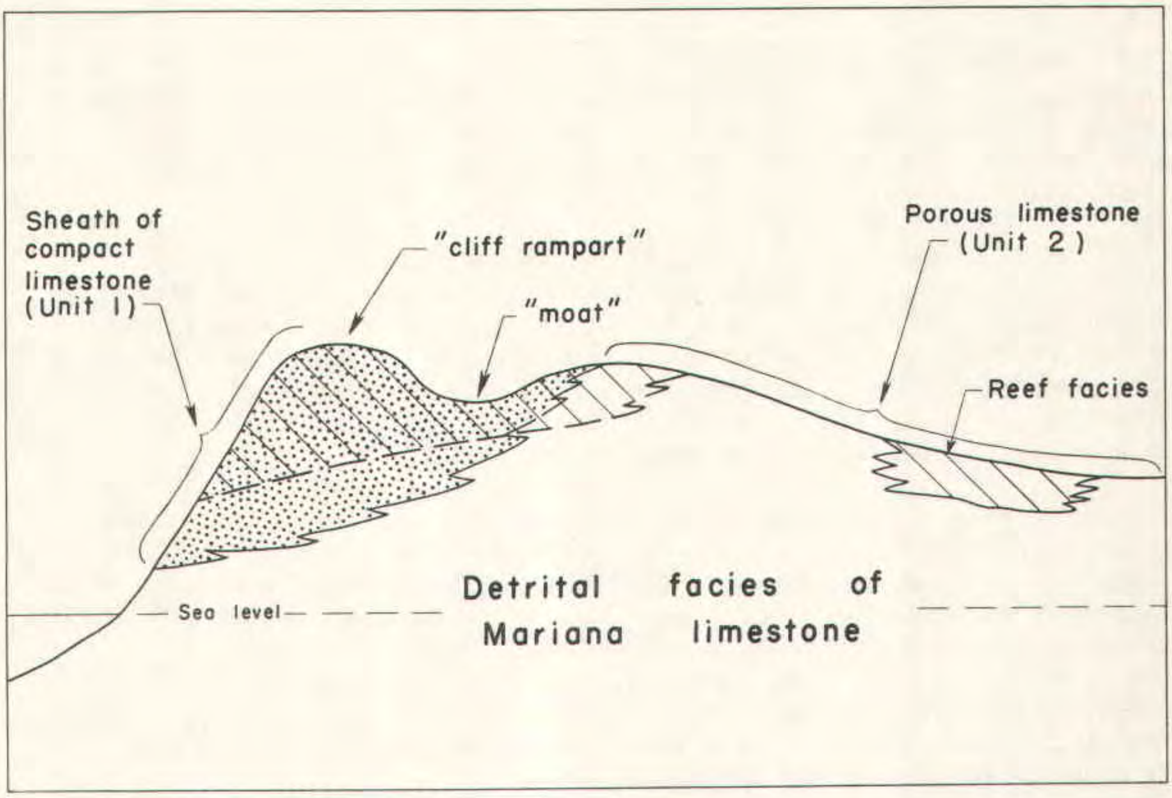


Figure 15. Diagrammatic cross-section showing relationships of Engineering Geology limestone units. Sheath of recrystallized, compact coralline limestone of Unit 1 on cliff face and outer plateau grades to porous rock of Unit 2 (coralline limestone and rubble). Unit 1 is mostly coralliferous reef facies of Mariana limestone, and Unit 2 is mostly detrital facies; but both facies are present in each unit.

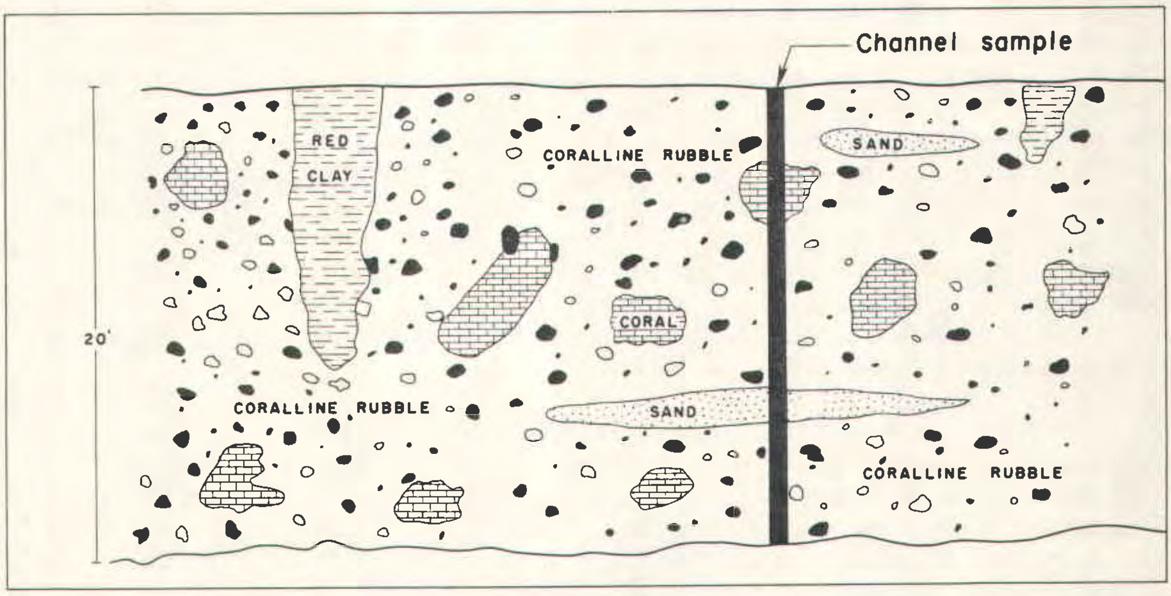


Figure 16. Coralline limestone and rubble of Engineering Geology Unit 2, containing coral heads, rubble, and sandy lenses. Channel sample site selected to give percentage volumes representative of the unit.

Fine sandy detritus exposed in quarries in this unit shows slight surficial crusting or self-cementing properties. Walls of old excavations generally are covered with a dark gray algal coating. Some construction men report that "chalky" limestone "sets up" or hardens if tamped and wetted.

Maximum stable excavation slopes are about 1:1 in loose rubbly limestone, and $\frac{1}{2}$:1 to nearly vertical in well-bonded rubble and vuggy hard rock. The steepest natural slopes are vertical; scarp slopes in loose rubble and chalky limestone are about 1:1. Excavation walls in loose rubble and highly fractured rock slump on oversteepened slopes. The only erosion seen in excavations was on slopes of highly brecciated limestone, where runoff water was channelized.

Drainage: The water table is at or near sea level except where the underlying volcanic rocks are above sea level, as along the Mt. Alifan - Mt. Lamlam ridge and on Nimitz Hill. In such areas the water table is above the limestone-volcanic rock contact. Seepage by downward percolation generally is so rapid in Unit 2 that no surface drainage construction is necessary. Runoff water may pond temporarily in depressions during exceptionally long and heavy rains. Locally the subsurface drainage may be channelized along faults, joints, and breccia zones that intersect basins.

In rock as permeable as that in Unit 2, a tunnel or room underground will become a drain; water will percolate into the excavation from all sides. Drainage into a tunnel dug along the limestone-volcanic rock contact will be heavy and may adversely affect the flow of springs in the area.

The ground water in Unit 2 is neutral to alkaline. The hard limy water may clog drainage pipes by depositing limescale, so pipes should be easily inspected and replaced.

Tunneling: Suitable locations for adit entries are: 1) The high cliffs south of Tarague Beach. Unit 2 crops out from 130 to 250 feet above sea level in these cliffs; a short adit would have 200 to 300 feet of cover. Several terrace flats nearby facilitate the development of tunnel approaches. 2) The lower slopes of Barrigada Hill. Deep cover is available, so short adits would be well protected. 3) Harmon Field quarries. The bluffs into which these quarries are cut are suitable for adit entries. The rock is friable and sandy. 4) The Alifan quarry (see pl. 46B). About 200 feet of Unit 2 limestone lies upon volcanic rocks at this quarry, but the contact of the two rock types is irregular. Adit entry would be easy. 5) The Nimitz Hill quarry (see pl. 46A). The situation is similar to that at the Alifan quarry, but there is less potential cover.

Tunnels probably will stand well without support, except in brecciated, rubbly, or friable rock zones. The massive, well indurated portions of Unit 2 probably will have low and regular overbreak; blocks in jointed and brecciated rock may be loosened by blasting, resulting in high and irregular overbreak. Rock pressures for Unit 2 (calculated from an apparent specific gravity of 2.53, or 159 lbs per cubic foot) are as follows:

Rock Condition	Estimated Volume Percent of Unit	Rock Pressure (lbs/sq ft)	Remarks
Massive to moderately jointed	75	min. = 0 max. = 795	Load may change erratically from point to point
Very blocky and seamy	10	min. = 2,200 max. = 7,000	Little or no side pressure
Crushed	15	7,000	Considerable side pressure. Seepage toward bottom of the tunnel may soften ground.

Pilot tunnels or drill holes should be driven in cavernous and faulted ground. Where the limestone-volcanic rock contact may be encountered, pilot drilling may detect large volumes of ground water concentrated at the contact.

Foundation conditions for structures: The bearing capacity of the materials of Unit 2 generally is excellent, but it is lower on brecciated zones and on deep soil pockets. The bearing capacity of massive ledge rock is nearly equal to that of continental crystalline limestones. Heavy permanent installations should be some distance from the edges of jointed cliffs and sheer rubbly slopes because slumping will weaken footing support. Footings for heavy structures on loose rubbly or brecciated rocks should provide for changes in support during strong earthquakes. Subsurface investigation is needed where heavy loadings are planned because concealed caverns may occur anywhere in limestone.

Road construction: New roads across the chalky rock and loose rubble in Unit 2 can be constructed with power equipment, but drilling and blasting are necessary in vuggy ledge rock and in well bonded rubbly limestone. Cut and fill are necessary in places on the north plateau, especially on steep slopes. Roads will have gentle gradients, long-radius curves, and moderate to long alinements on plateaus. Roads crossing steep coastal terrain will have steep gradients, short-radius curves, and alinements of variable lengths. The porous subgrade is excellent and generally self-draining, but drainage may be needed in basins with deep soil pockets. Roadside drains on slopes across brecciated rock need stabilizing to prevent downcutting during heavy rains. Unit 2 will supply very good aggregate for fill and base course; the massive, vuggy ledge rock can be used for concrete aggregate and light riprap. Jungle vegetation grows on steep slopes and over large areas of the north plateau.

Airfield construction: Four important airfields, two of them large, are at the best sites in Unit 2. Other suitable sites for major airbases require considerably more cut-and-fill than was made at existing airfields. The subgrade of this unit is generally excellent, except on deep clay pockets in the larger basins. Little drainage construction is necessary except in the clay pockets in basins, where drains may be necessary to prevent temporary ponding during extremely heavy rains. Infiltration of water can be accelerated by boring and blasting in the limestone subgrade. Unit 2 can supply base course and fill material for all requirements; vuggy ledge rock can be processed for concrete aggregate. Heavy jungle growth is extensive at possible airbase sites.

Special engineering considerations: Small cavities and solution pipes are rare on flat ground, but they are found especially along fractures or cracks in coralline limestone. Normally they are of no engineering significance. Most of the larger cavities and solution pipes common in the bottoms or sides of depressions and sinks are sealed by clay that fills the depressions, and the cavities may open up during heavy rains if the depressions pond. Cavities as much as 5 feet in diameter and 20 feet in depth were seen; these can be filled or bridged during construction.

There are no known large caverns and caves in Unit 2 on the north plateau, although there may be some unknown ones at the bases of ledges or scarps. Many large caves in this unit below the coastal cliffs, generally less than 100 feet above sea level, are in large bays or embayments such as Tarague, Tumon, and Campanaya. One such cave, the "Devil's Punchbowl", is 1,000 feet south of Ypao Point on a slope of 30° overlooking Tumon Bay. It has an opening on the hillside 25 by 30 feet in diameters, a depth of 57 feet from the lip of the opening to the floor, and a floor 85 by 150 feet. Water stands several feet deep on part of the floor. The cave was formed by solution and collapse of rubbly or conglomeratic limestone.

There are several caves in fractures zones in the Tarague embayment, on a limestone terrace 30 to 50 feet above sea level, and some extend 25 or more feet below water level. A large pumping station (Tarague No. 4 well) has been built in one of these caves. Another large cave near Campanaya Point was a Japanese water point during World War II. Several very large caverns are known north of Fadian Point.

Normally there is no surface runoff on Unit 2 because of the high permeability of the limestone and the thick cover of vegetation. Clay-filled depressions are local centers of drainage during severe rains, however, and ponding may open cavities under the depressions. Drainage should, therefore, be diverted from construction on such clay-filled depressions.

Site investigation: All obvious fractures, crushed zones, and clay-filled pockets should be mapped in a detailed investigation of sites. Preliminary core drilling is recommended to determine suitability for heavy construction. The pattern of drilling should be laid out to test the depth of soil in pockets or depressions, the soundness of rock along fracture lines or crushed zones, and the presence of cavities. Examination should be continued during clearing, trenching, and excavation.

Unit 3: clayey coralline limestone and rubble:

Location and description: Clayey coralline limestone and rubble of Unit 3 crops out across the central "waist" of Guam, along the west coast from Agana to Orote Peninsula, and along the east coast from Pago Bay to Inarajan. In the vicinity of Agana, Barrigada, Sinajana, and Ordot the rocks of this unit lie upon massive limestones of Unit 1; between Pago Bay and Talofofo they are on volcanic rocks of Unit 4; and south of Talofofo Bay they are on volcanic rocks of Unit 5.

Karst areas and dissected terrain with surficial drainage patterns are characteristic of Unit 3. Ridge-and-valley topography is widespread in the north-central part of Guam, and there are large basins with tributary gullies adjacent to the dissected areas. Narrow sinuous

A. Coralline limestone and rubble at Nimitz Hill. Photo by U. S. Navy, 1954.

B. Coralline limestone and rubble at Mt. Alifan. Photo by U. S. Navy, 1954.

C. Clayey coralline limestone and rubble at Asan Point. Photo by U. S. Navy, 1954.

valleys separated by sharp finger ridges are as much as 100 feet deep, and valley slopes range from moderate to very steep. The remainder of the terrain in the unit is similar to upland topography on Unit 2. Intermittent streams flow in well graded channels in the valleys during heavy rains. Perennial streams on alluvium have excavated wide, deep valleys across rock of Unit 3 along the southeast coast; steep rocky slopes border embayments at the mouths of these streams.

Buff to reddish-brown, clayey, rubbly coralline limestone makes up 65 to 75 percent of Unit 3; the remainder is scattered lenses and beds of porous, clayey limestone. Rock fragments in rubbly limestone range in size from $\frac{1}{4}$ inch in diameter to coral boulders 10 feet in diameter. In some places the rubble is loose, and in others the fragments are embedded in a porous, clayey limesand (pl. 46C). There are ledges of fine- to medium-grained limestone. The clay content of the rocks of the unit averages about 5 percent, but locally may be 20 percent. Pockets and fissures in rubbly limestone are filled with brown granular clays. There are many concealed caverns ranging in size from a few feet to about 50 feet in diameter and depth. Ninety percent of Unit 3 is clayey Mariana limestone, and the remainder is clayey Alifan and Bonya limestones (see pl. 4, in pocket).

Brown clay weathers out of the argillaceous limestone. Excavations commonly reveal small clay-filled cavities, pockets, and fissures as much as 5 feet across. The soils correspond to those of Engineering Soils Units 2, 3, 4, and 5 (see pl. 49), and generally range in thickness from 1 to 10 feet, averaging 3 feet. Thicker soils generally are in basins and thinner soils are on slopes. The clay mantle on limestone is 35 feet thick in one large basin, and 45 feet thick at the crest of a ridge; it may be more than 50 feet thick in some places. The soil-limestone contact is fairly distinct, and there are rock fragments in the lower part of the soil.

Joint systems and fracture zones, with 1- to 12-inch plane spacings, are widely separated, but are common in faulted rocks. High-angle normal faults associated with joint and fracture zones several hundred feet across are near the contact of the rocks of Unit 3 with volcanic rocks near Agana.

The estimated maximum thickness of this unit above sea level is 300 feet (near Yona).

Excavation - method, facility, stability of slopes: Loose rubble and chalky limestone (65 to 75 percent of the unit), and poorly indurated, very blocky and seamy rocks can be excavated with power tools. Dense, hard rock and well bonded rubble of the rest of the unit will need drilling and blasting. Blasting in tunnels may loosen breccias and cause high ultimate rock loads; close roof support and rapid backpacking may become necessary. Excavation rates will be affected by faults, caverns, and caving ground associated with breccia zones.

Clayey hard rock and well bonded rubble of Unit 3 slowly become softer after excavation, but loose coralline rubble and chalky limestone generally retain their initial hardness. The walls of old excavations show brownish mottling and are coated with dark gray algal films.

Slopes in loose rubble and fractured rock are stable at about 1:1. Dense massive lenses in the rubbly rock may help to stabilize that material. Slopes in hard rock and in well bonded rubble are stable from $\frac{1}{2}$:1 to vertical. The steepest natural slopes seen are vertical in limestone and about 1:1 in the clay mantle. Clay seams and pockets are numerous and may cause slumping and caving; slumping and slow ravelling were seen at old quarries in oversteepened slopes of loose rubble and finely brecciated or chalky rock. There is erosion on steep slopes in chalky limestones of Unit 3.

Drainage: The water table is at or near sea level except where underlying volcanic rocks are above sea level; at such places the water table is in the limestone above the underlying volcanic rocks. Drainage by downward percolation is fairly rapid in rubble and fractured rock, and the percolating rock will be channeled and concentrated in faulted and jointed rock. Percolation may be retarded by concealed clayey zones, and drains may be necessary.

Ground water will be a serious detriment to underground excavations in Unit 3. Perennial streams draining volcanic rock areas cross the unit, carrying large volumes of water. Tunnels in this unit probably will become drains for the surrounding rocks; water will percolate into the tunnels from all sides. Tunnels near stream beds may be flooded during heavy rains; those that cut the limestone-volcanic rock contact may be flooded continuously.

Water draining into excavations in Unit 3 may carry a heavy load of clay, and may precipitate limescale in pipes. Therefore, drain construction should include sediment traps to prevent clogging, and should permit easy inspection and replacement.

Tunneling: Many cliffs and slopes are suitable for adit entry. The Japanese, during World War II, dug extensive unlined small tunnels in Unit 3 along the base of the cliff back of Agana and along the Fonte River road (Route 7); most of these were still intact in 1953.

Small tunnels probably will stand without supports, but large tunnels must be supported. Cavern fillings must be stabilized or removed, because the concentrated drainage will open gravel, sand, and clay-filled pockets in a matter of hours by washing breccia and clay out of fault zones. Excavated rock free of clay can be used for backpacking.

In slickensided, sheared, jointed, or brecciated zones the overbreak will be high and will depend upon the spacing and orientation of clay seams. Fault breccias and cavern fillings will have short and irregular bridge-action periods; the massive zones will have a more regular period. Rock pressures for Unit 3 (calculated from an apparent specific gravity of 2.62, or 163 lbs per cubic foot) are as follows:

Rock Condition	Estimated Volume Percent of Unit	Rock Pressure (lbs/sq ft)	Remarks
Intact	25	0	
Very blocky and seamy	60	min. = 2,300 max. = 7,200	Little or no side pressure except where clay seams let the rock slump
Crushed	15	7,200	Considerable side pressure

Swelling ground may be encountered in ground with clay lenses. Rock pressures in the clay lenses may be as high as 30,000 lbs/sq ft.

Pilot tunnels or test borings should be carried ahead of main excavations to detect caverns, faults, swelling ground, and the limestone-volcanic rock contact.

Foundation conditions for structures: Bearing capacity is excellent on most of the rocks of Unit 3. It is lower, however, on jointed and fractured rock, on deep soil pockets, and over shallow concealed caverns and fissures. Concealed caverns probably are more common in this unit than in any of the units of limestone. Subsurface exploration is needed at places where heavy construction is planned. Temporary drainage during construction is needed at building sites to prevent water from ponding and opening new drainage fissures under footings (see description of cavity under the new Navy Hospital, in the section below on special engineering considerations). Footings for heavy installations should be designed to withstand strong earthquakes.

Road construction: Most excavation for new roads in rocks of this unit can be done with power equipment, but drilling and blasting will expedite removal of limited zones of hard rock. Moderately deep cut-and-fill is necessary. Roads will have moderate to steep gradients, long- to short-radius curves, and tangents of variable lengths. Subgrade conditions are excellent for most parts of the unit, but poor in small areas of deep clay pockets and deep clay overburden. The best road locations are along divides and flats, and around basins, swamps, and deep, narrow valleys.

Roads crossing streams and gullies must have bridges or culverts to carry drainage. Drainage construction usually is necessary in areas of deep clay overburden. Road-cut slopes in limestone are stable at 1:1 to $\frac{1}{2}$:1; small areas of deep clay overburden must have 2:1 slopes. Side ditches and drains in sloping terrain on fractured or chalky limestone must be stabilized, and must be protected from deep erosion or opening of fissures. The rocks of Unit 3 will supply good to fair base course and fill.

Airfield construction: The terrain of this unit is not suited for the construction of major airbases.

Special engineering considerations: Unit 3 is the only engineering unit on Guam in which concealed cavities and caves are likely to be a serious problem to construction. The cavities may be partly or completely filled with clay, and if the normal drainage is disturbed during construction, an increased volume of water may flow through the cavities and wash out the clay filling. Empty cavities in chalky or rubbly limestone of Unit 3 may slump or stope upward to the surface. Bridging generally is unsafe because cavity walls are likely to be weak. Descriptions of two large cavities that affected structures on Guam, and discussions of the measures taken to control the cavities, follow.

Cavity under footings of new Navy Hospital: The hospital, under construction 1951-1954, is on limestone of Unit 3 above the town of Agana, near Adelup Point. The terrain is gently rolling, with several gentle natural depressions 200 to 300 feet in diameter and 15 to 30 feet deep. Preliminary drilling at the site by the Pacific Islands Engineers showed that the depressions were underlain by 10 to 50 feet of clay. Several cavities near the edge of the clay filling were found by drilling, and one concealed cavity was drilled to a depth of 55 feet. The bottom of the latter cavity was partly filled with limestone rubble, and the top was covered by 15 feet of clay; the cavity was filled during construction. Numerous additional borings were made after the building sites were selected.

Most of the footings were on solid rock; a few were slab footings on clay. After heavy rains on 8 September 1952 (about 5 inches in 12 hours), a large cavity opened under one of the footings on solid rock (pl. 47 and fig. 17).

The rock roof above the cavity, upon which the footing stood, was limestone about two feet thick. The roof slumped, revealing a cavity 4 by 8 feet across at the surface which opened into an irregular shaft 43 feet deep dipping 75 degrees below the horizontal. The shaft was constricted at some places and widened into cavities at others. The bottom of the shaft opened into a room 11 feet in diameter and 15 feet high, floored with collapsed limestone rubble. One side of the room opened into a second chamber by a slot at floor level 8 feet wide and 1.5 feet high; this chamber was 25 feet in diameter and 4 feet high, floored with loose, coarse coral gravel and fine sand of unknown thickness. The walls of the shaft and rooms were soft, yellow rubbly limestone which was fractured and jointed in three dominant directions. Small cavities and pockets in the walls were filled with gummy brown clay.

The cavern probably was old before construction began, and may have been partly or entirely filled with sand, gravel, and clay. Excessive drainage below the hospital during the heavy rains washed out the clay and sand, and allowed slumping and stoping of the sidewalls and roof of the cavity. Further test drilling near the cavern showed no additional structural weaknesses. The cavern was filled with coral gravel and grouted at the top with cement.

Cavity in ditch on Route 7: After the heavy rains that opened the cavity below the hospital, another cavity opened in a ditch on the south side of Route 7 near the hospital. At this point, which is at an altitude of about 90 feet, the road and ditch cut through a bluff of clayey limestone of Unit 3.

The surface opening was 23 feet long, 10 feet wide, and 20 feet deep, connecting through a hole 2 feet wide with another cavity that extended at least 16 feet deeper. The upper cavity was elongate east-west, paralleling the most prominent fracture system in the area. The sidewall of the limestone bluff by the ditch was crushed chalky limestone which slumped readily for several days after collapse of the cavity.

The cavity was filled with riprap and rubble. A later heavy rain resulted in a flow of more than 3,000 gallons per minute along the ditch. All the flow disappeared into the filled cavity, so the ditch was sealed with asphalt to prevent further washing out or caving beneath the road.

Several cavities have recently opened in Unit 3, and some quarries and roadcuts reveal large pockets completely filled with clay. Evidently, open or clay-filled cavities are common in the unit, and may be present anywhere in it.

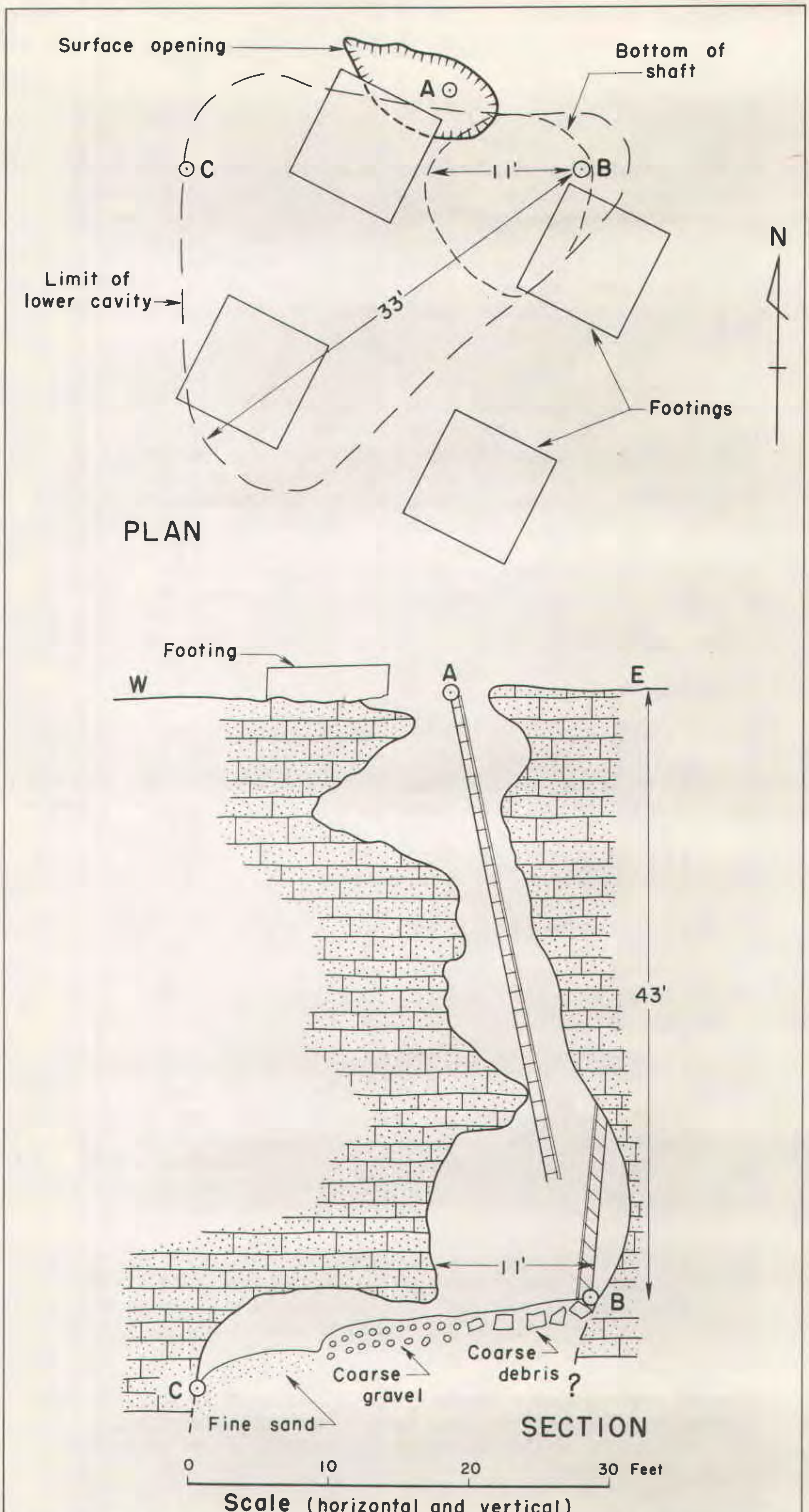


Figure 17. Plan and nearly vertical section (through A, B, and C) of cavern under footing of new Navy Hospital. A and B are at top and foot of ladders; C is at west side of lower cavity.

Figure 17

A. Cavity in limestone under new Navy Hospital, showing detail of footing.

B. Cavity under new Navy Hospital. (Looking down.)

Site investigation: Obviously, cavities of the sizes just described -- large enough to be serious engineering problems -- cannot always be detected even by relatively closely spaced drilling. Holes on 25-feet centers should locate most large cavities, but not small, deep ones like that under the Navy Hospital. Geophysical means to detect shallow caverns are being developed, but are not readily available. The following procedures, then, are recommended to increase the probability of finding cavities, and to prevent concealed cavities from opening during or after construction.

A detailed map of the site under construction should be made, recording obvious fissures, joint systems, crushed zones, and, particularly, all closed depressions or pockets. Depressions are natural drains and in many places are underlain by cavities or solution pipes. The thickness of clay in the depressions should be determined by soils borings, and footing locations in or near depressions should be tested by drilling. Open channelways, or channels filled with clay may be concentrated around the peripheries, as well as in, surface depressions. Clay pockets or cavities exposed during preliminary clearing, stripping, excavating, and trenching should be particularly noted.

The construction area should be well drained to prevent large volumes of water from flowing into footing locations. If this is not done, unusually heavy rains may wash out and open up cavities in places where footing support normally is adequate. If drainage is kept away from footings, there is little likelihood of undiscovered cavities opening up; nevertheless, footings should be inspected periodically during and after construction.

Volcanic Rock Materials

General statement: The extents of the three volcanic rock units of engineering materials are, in general, coincident with those of the three principal geologic volcanic rock formations: Unit 4, volcanic tuff, consists mostly of the folded and faulted tuff and breccia of the Alutom formation; Unit 5, volcanic conglomerate, consists mostly of the massive pyroclastic breccia and conglomerate of the Bolanos conglomerate member of the Umatac formation; and Unit 6 consists mostly of the bedded flows of basalt, the pillow basalt, dikes, and interbedded calcareous tuff of the Facpi basalt member of the Umatac formation. Interpretations of engineering volcanic rock units are valid below the deep weathered zone to a depth of several hundred feet, and probably to sea level.

Construction materials: The volcanic rock materials on Guam generally are not as well suited for construction uses as are the limestone materials. Compact ledge rock for aggregate for concrete, base course, and wearing course is generally absent in the three volcanic units (although the Maemong limestone interbedded with the basalt of Unit 8 is a possible source). Further discussion of materials suitability and availability is included with the discussion of each unit.

Special engineering considerations: The principal problems of construction on the volcanic rock areas of Guam -- of roads, temporary installations, or permanent heavy installations -- result from, first, the great depth of weathered material upon the rocks; second, from the poor drainage of the weathered zone during times of excessive rainfall; and third, from the excessive erosion, mostly by slumping and gullying, of the weathered zone. Deep weathering, poor drainage, and excessive erosion are all interrelated, and all are common conditions in humid tropic lands.

Weathered material: The irregular thickness of the weathered mantle on the island prohibits prediction of its depth at any one place, so numerous soils borings are necessary to determine the depth to firm rock. Eight test holes were drilled (with a mobile power auger) to determine the depth of severely weathered volcanic rocks in the southern half of Guam. The following tabulation gives the depths of the holes, the depths to water, and the kind of materials drilled; the Engineering Geology map (pl. 44) gives the locations of the holes.

Site No.	Total depth (ft)	Kind of Material Drilled	Depth to water
1	19	Yellowish, brownish, grayish, and olive silty clay on weathered tuff and conglomerate at 6'.	16
2	64	Reddish-brown, firm, plastic clay on weathered dark grayish-green volcanic rock at 48'.	48
3	64	Reddish-brown to red silty clay over white to red, weathered tuffaceous shale. No bedrock.	--
4	79	Reddish-brown, plastic clay to brown plastic clay on weathered tuff at 30'.	--
5	35	Reddish, plastic silty clay on dark-gray, weathered tuff at 35'.	--
6	19	Reddish, brownish, yellowish, and gray silty clay on weathered tuff at 7'. No bedrock.	--
7	30	Reddish and brownish silty clay with Mn and Fe concretions on weathered tuff at 30'.	--
8	74	Reddish-brown, plastic clay over brown sticky clay at 52'. No bedrock.	68

The original weathering of the rocks was not uniform in depth, but probably ranged in thickness from about 25 feet to more than 100, averaging perhaps 75 feet. The weathered mantle has been thoroughly and irregularly dissected by erosion; in some places a thickness of 50 to 75 feet remains, in others the mantle is partly removed by sheet erosion or by slumping, and in still others it is nearly or completely removed. The residual weathered material is dominantly or entirely composed of clay minerals that preserve the structure of the fresh rock. This clay material is leached, porous, and permeable until it is reworked, at which time it becomes plastic and slippery.

The general properties of the weathered clayey mantle on volcanic rocks are given with the discussion of the volcanic rock units; additional detailed discussion is on the Engineering Soils map and tables.

Erosion: Soil creep, sheet erosion, headward erosion by gullying, and slumping and landsliding are severe on the volcanic rocks of Guam.

Soil creep, or slow downhill migration of the topsoil, is a dominant natural process on the island, but apparently it is not greatly accelerated by construction activities. Sheet erosion, or the removal of surface material by runoff on slopes lacking established drainageways, is normally severe; it is especially severe on swordgrass-covered slopes and becomes excessive when vegetation is stripped off during construction. Gullying is not severe on well vegetated slopes because of the generally high permeability of the soil, but becomes a serious problem even upon gentle slopes, however, when the cover of vegetation is removed or when the soil is reworked. Slumping and landsliding are common on Guam, usually involving a movement of the saturated mantle over fresh rock. Material 50 or more feet thick may slide, and larger slumps may involve hundreds of thousands of cubic yards of material. Many of the large erosion scars in the uplands of southern Guam were caused by slumps and slides initiated by excessive rainfall or by earthquakes. Sliding of a highway embankment on Route 5 is discussed under Unit 4 (see pl. 48).

Drainage: There are some perennial springs and numerous small perennial seeps in the volcanic rocks of Guam. The springs and seeps emerge from the base of limestone capping volcanic rock, from joints or bedding planes in volcanic rock, and from locally perched water in friable soil or weathered rock material overlying relatively impermeable volcanic rock. During the rainy season the ground becomes saturated and some fairly large springs and innumerable seeps develop.

Severe drainage problems may arise in an area that is naturally well drained even in the wet season, because of changes brought about by construction operations. Stripping the vegetation cover and reworking the upper few feet of soil by heavy equipment leads to ponding of drainage, and the consequent saturation of the mantle may result in instability of material even on gentle slopes. All construction should be planned with wet-season rainfall and soils conditions in mind. An area of ground that is firm with an apparently good footing at shallow depth during the dry season may change to a spongy quagmire, perhaps with standing water, during the rainy season. Even on well drained slopes the ground becomes saturated to considerable depth, and unstable soil conditions result. All diversion ditches should be planned to accommodate periodic excessive precipitation and flood conditions; they will require protective riprap.

The maximum rate of runoff in a given area will depend upon several factors, including the degree of saturation of the ground, the size and shape of the drainage basin, and the intensity of rainfall. Because the time of concentration (the time required for the rain falling on the farthest reaches of the basin to arrive at any given point) is measured in hours or minutes, the rate of rainfall per hour must be known in order to estimate flood peaks correctly. Rain gages may underregister as much as 50 percent (according to Weather Bureau figures) because the heaviest rains are accompanied by high winds; therefore, estimates of runoff based on rainfall data tend to be too small. The heaviest rainfall recorded by rain gage on Guam was October 15, 1953, when 25 inches fell in 24 hours, with a maximum recorded rate of 7.25 inches in $2\frac{1}{4}$ hours.

Continuous records of the stages of all the major streams on Guam have been collected at gaging stations since 1951. For a few stations, preliminary rating curves have been developed. The maximum, minimum, and mean flows at these stations have been estimated. Because of the inadequacy of rainfall data, as mentioned in the paragraph above, it is suggested that the formula $Q = c\sqrt{A}$ be used for design purposes. In this formula, Q = discharge in cubic feet per second, c = a constant, and A = drainage area in square miles. The constant, c, for Guam was computed on the basis of discharges obtained from preliminary rating curves for flood stages resulting from the storm of October 15, 1953. The values of the constant were modified and verified to a certain extent by comparison with values of c obtained in Japan and along the Gulf of Mexico from floods caused by typhoons and hurricanes. From these studies, formulas for estimating peak discharges from any size drainage area on Guam are as follows:

For peak discharge occurring on the average of once in 5 years:

$$Q = 3{,}000 \sqrt{A}$$

For peak discharge occurring on the average of once in 25 years:

$$Q = 4{,}000 \sqrt{A}$$

For the maximum peak discharge to be expected:

$$Q = 8{,}000 \sqrt{A}$$

Computed discharges are subject to large errors because the basic data from which the above constant is estimated are meager.

Unit 4: volcanic tuff:

Location and description: The volcanic rocks of Unit 4 make up the high mountainous terrain of central Guam; they crop out from the Pago Bay - Adelup Point fault zone south to Fena Basin (see pl. 4, in pocket), and from the fringing limestones of Unit 3 east of Apra Harbor to limestones of the same unit west of Yona and Talofofo.

High, broken, plateau-like uplands, asymmetrical elongate ridges, and steep slopes are typical of the landforms of Unit 4. Streams that begin in the interior of the plateau-like uplands have cut narrow winding valleys. Small ridges, hillocks, and gullies are on the upland terrain; ravines and gullies are cut into valley slopes. Steep dissected slopes border the plateau, except where it passes into uplands of Units 3 and 5. Mt. Santa Rosa and Mataguac Hill, two exposures of Unit 4 within an area of Unit 2, form dissected hills which rise above the surrounding limestones of the northern Guam plateau.

Unit 4 consists of about 70 percent of thick, bedded volcanic tuffs, 20 percent of interbedded volcanic conglomerates and breccias, and 10 percent of interbedded lava flows. All the rocks are basaltic or andesitic in composition. The fresh tuff is gray and fine-grained. The conglomerates and breccias consist of large to small boulders and small fragments in a sandy matrix. Most of the rocks contain some iron oxide and clay.

Weathered soft rock covers more than three-fourths of the area of hard rock in Unit 4. The weathered material has the general engineering properties of undisturbed firm, granular to slightly plastic clay; if wet and disturbed, it has the characteristics of plastic clay. Hillocks and ledges of indurated volcanic rock crop out irregularly from the mantle of weathered rock. Loose boulders and cobbles in clays are common in outcrops of the conglomerate beds. The weathered material includes Engineering Soils Units 6, 7, and 8 (Corps of Engineers Classification group (MH) in the upper part, and (SM) in the lower part).

The thickness of the weathered soft rock is variable, ranging to more than 50 feet, and at any given point can be determined only by boring. In Sasa Valley, fresh rock is at the surface in the stream bed and at depths as shallow as 15 feet in excavations; in the same area, however, highly weathered rock extends at least 50 feet below the surface. The most intense weathering is along faults, where ground water movement has accelerated decomposition, reducing fault breccias to clay (commonly with montmorillonite). Slumping and different rates of erosion are common on all rock types.

Individual beds in the rocks of Unit 4 range in thickness from less than one inch to several feet. Complex joint and fracture systems, and breccia zones are common; joint and fracture spacings range from less than one inch to several feet. At outcrops, the rocks break along joint planes into loose blocks; at depth, the tightness of the joints is poorly known, but evidence from drill cores indicates that it increases with depth. Some beds are horizontal, but locally they are complexly folded, faulted, and jointed, and the limbs of the numerous anticlines and synclines have dips as steep as vertical. Medium- to high-angle normal faults are common. Low- to medium-angle thrust faults are not common. The faults cause the lithology and dips of beds to vary within short distances. Fault zones contain breccias and clayey gouge with the characteristics of crushed rock.

Most of Unit 4 is coincident with the area of the Alutom formation (see pl. 4, in pocket); near Mt. Alifan, the unit is coincident with the Talisay formation.

<u>Excavation - method, facility, stability of slopes</u>: Soft rotten rock and residual clay at the surface of Unit 4 can be excavated by hand tools and power equipment. Much of the indurated tuff also can be excavated with power equipment, but harder rock and large basaltic boulders must be drilled and blasted. Blasting will reduce most of the rocks to angular blocks ranging in diameter from several inches to several feet; jointed tuffs probably will break along the joints; fault breccias may break up into sand and gravel sizes; unweathered, moderately jointed basalt and andesite probably will break into large, angular blocks. Relatively unconsolidated material in fault and clay zones can be excavated by earth-tunneling techniques. The rate of drilling and advance of headings will be variable in subsurface excavations because rocks of different resistances are interbedded.

Excavated weathered rock soon crumples; some unweathered tuffs become soft within a few months. Well indurated breccia and tuff, however, do not weather rapidly. Some hard tuffs become lighter in color after excavation, others show dark surface mottling which may be mineral stains or algal coatings.

Observed stable excavation slopes in soft, weathered clay range from 3:1 to 2:1; the steepest natural slopes in soft, weathered rock are about 3/4:1. Stable excavation slopes in hard rock range from 1:1 to more than ½:1 (fractured hard rock and breccias require slopes of about 1:1); the steepest natural slopes are vertical. Steeply inclined beds will induce slumping; slopes with structural planes dipping into the excavation in weathered rock must be benched. Excavation walls in wet clayey overburden slide on oversteepened slopes. Ravelling occurs in hard fractured rock and loose boulder conglomerates. Unprotected slopes in soft weathered rocks erode rapidly.

<u>Drainage</u>: During the dry season, perennial streams (which are common in Unit 4) are fed by seepage from aquifers. Wells into aquifers in Sasa Valley produce water throughout the year. Perched water occurs in the weathered material above hard rock.

Ground-water conditions in excavations will probably depend largely upon the number and sizes of aquifers cut, and upon the presence of fault zones which may concentrate the water. In faulted and folded rocks the ground-water conditions are liable to change within short distances. Subsurface drainage is slow in the weathered rocks, and slow to absent in compact hard rocks. Extensive drainage construction is necessary for excavations in Unit 4. Settling basins also may be necessary, for the water may carry a considerable load of fine sediment.

The pH of the soils is controlled by the position of the water table: the pH is 4.5 to 6.5 (acid), averaging 5.25, in the red lateritic upland soils above the water table; it is neutral to slightly alkaline in soils permanently below the water table. In general, the zone of corrosion is above the water table, but corrosion may be active in the zone of fluctuation of the pH from acid to basic; corrosion may not be a problem in excavations below the water table.

Tunneling: Suitable locations for adit entries are: 1) the seaward slopes of the Mt. Chachao - Mt. Tenjo ridge; 2) the southern and eastern slopes of the Mt. Tenjo - Mt. Alutom ridge; and 3) the northeast-trending ridge northeast of Mt. Alifan. The steep slopes in all three areas permit the construction of adits with deep natural cover.

The bridge-action period in rocks of this unit may range from several minutes to several days. In closely jointed and shattered zones, half-dome action may be large and rapid. If these overbreak properties are not considered before construction is designed, the volume of material actually excavated may greatly exceed the volume normally expected. Clay lenses in Unit 4 may squeeze, swell, or slake. Squeezing can cause an appreciable decrease in the volume of the excavated area; slaking generally takes place following a small amount of squeezing, and will cause clay to drop out of the roof. Roof supports should be installed to prevent roof collapse by slaking, or by swelling.

Rock pressures for the tuffaceous sandstones and shales of Unit 4 (calculated from an apparent specific gravity of 2.14, or 133 lbs per cubic foot) are as follows:

Rock Condition	Rock Pressure (lbs/sq ft)	Remarks
Very blocky and seamy	min. = 1,900 max. = 5,900	Little or no side pressure developed in this condition
Squeezing rock at moderate depth	min. = 5,900 max. =11,000	Heavy side pressure in this condition
Squeezing rock at great depth	min. =11,100 max. =23,800	Heavy side pressure in this condition
Swelling rock	up to 33,200	

(Rock pressures for conglomerates in Unit 4 will, in general, conform to those calculated for conglomerates in Unit 5, following.)

Rock pressures for the basalts and andesites of Unit 4 (calculated from an apparent specific gravity of 2.86, or 178 lbs per cubic foot) are as follows:

Rock Condition	Rock Pressure (lbs/sq ft)	Remarks
Massive moderately jointed	min. = 0 max. = 900	Loads may change erratically from place to place
Moderately blocky and seamy	min. = 900 max. = 2,500	No side pressure to be expected
Very blocky and seamy	min. = 2,500 max. = 7,900	Little or no side pressure
Squeezing rock at moderate depth	min. = 7,900 max. = 15,000	Heavy side pressure
Squeezing rock at great depth	up to 32,000	Heavy side pressure

Rock pressure will vary somewhat according to the angle between the strike of dipping rock strata and the centerline of the excavation. Moderately dipping beds may exert heavy side loads even though the roof loads may be small. Erratic dips in the areas of excavation will result in erratic loads over short distances.

Estimated volume percentages of rock conditions for the rocks of Unit 4 are as follows:

Intact to moderately blocky and seamy	15 %
Stratified to very blocky and seamy	75
Crushed	5
Squeezing and swelling	5

Pilot tunnels should be driven ahead of excavations to provide data on ground-water conditions, overbreak, squeezing and swelling ground, and bridge-action period. Tunneling and excavation conditions can be predicted from drill-hole samples if engineering test data for excavated rock are correlated with tunneling characteristics of the tested rock.

Foundation conditions for structures: Bearing capacity is generally very good on the hard rock of Unit 4, but only fair to good on brecciated and fractured rock. Bearing capacity is fair to poor on the widespread weathered rock. The best foundation sites on weathered rock are on broad, low hillocks at some distance from the edges of steep slopes, wet marsh depressions, or other natural drainage features. Tall, heavy towers on weathered rock must have spread footings. Footings on hard bedrock below the weathered zone and in the bottom part of the weathered zone must be protected from ground water; adequate drainage construction generally will preserve the footing support in soft weathered rock.

Road construction: The best road sites in Unit 4 are on upland terraces and along gentle slopes where there are good gradients, curves of long radius, and long alinements. Sites in rough, broken, steep terrain will have steep gradients, short-radius curves, and short alinements. Weathered rock can be removed with power equipment, but blast-

Highway embankment failure on Route 5.

ing is necessary to remove fresh rock. Some cut-and-fill is needed for roads on terraces and gentle slopes, and much is needed in rough, dissected terrain. Subgrade conditions on hard rock are excellent. Drainage construction is necessary where weathered subgrade or fill made of soft rock is adjacent to swampy areas. Roads over streams and gullies require bridging, or culverts with large weirs designed for maximum runoff. Roads across marshy depressions require stabilizing and adequate drainage of the subgrade.

Deep road cuts in soft weathered rock require benching and 2:1 slopes; lower slopes are adequate if the bedding dips toward the centerline of the road. Deep fills of soft weathered rock require 3:1 slopes. Vegetation or stabilization will prevent some slope erosion. Berms, side drains, and ditches on weathered slopes need protective riprap. Culverts in weathered subgrade must have wide headwalls with stable footings. Unit 4 will supply embankment and fill, and some hard rock for base course. (See Special engineering considerations, below, for description of a highway embankment failure.)

Airfield construction: The terrain of this unit is not suited for the construction of major airbases.

Special engineering considerations: The deep weathering, poor drainage, and excessive erosion common to all the volcanic rock materials is discussed briefly in the General Statement, and more fully in appropriate places within the discussions of volcanic rock units.

Highway embankment failure on Route 5: A highway embankment on Route 5 (engineering geology map Unit 4), failed on 15 October 1953. The terrain in the area comprises low hills with slopes of 5 to 15 percent. The foundation material was a hard calcareous tuff overlain, in turn, by a weathered tuff breccia and a red-brown clay soil. Surfaces within layers of the clay sloped downhill at about 5 degrees.

The heaviest rainfall recorded on Guam (25 inches in 24 hours) fell the day of the embankment failure. The failure was a slope slide apparently induced by saturation of the clay and breccia layers by infiltration of water from a drainage ditch on the uphill side of the road, and resulted in a mass movement of more than 100,000 cubic yards of surficial soil, clay, and breccia. About 250 feet of roadway surface was lowered 20 feet (pl. 48), and the slide disturbed the surface of the ground for a distance of about 450 feet downhill from the road.

Five test borings made after the failure by the Materials Testing Division, Base Development, ComNavMar, showed the sheared surface to be at the contact of the red clay soil with the weathered breccia. A thickness of 5 to 15 feet of breccia was churned up by the slide.

Unit 5: volcanic conglomerate:

Location and description: The volcanic rocks of Unit 5 crop out from the south end of Guam northward to the Fena basin, and from the Mt. Bolanos ridgeline eastward to the limestones that fringe the eastern coast of the island.

The principal landforms are steep dissected ridges and sharp peaks in the southern part of the area of the unit, and broken rolling uplands in the northern part. Steep, narrow valleys wind between the ridges and peaks, and small valleys and gullies have formed badlands in places on the uplands. Small scattered marshy areas are common on the uplands and along the coast. The Talofofo River, which has the largest drainage system on the island, extends across the northern part of Unit 5; about 10 percent of the area of the unit lies northeast of the floodplain of the river.

Unit 5 consists of about 65 percent of dark-gray massive volcanic conglomerate with included limestone fragments, and about 35 percent of massive and bedded, gray tuffaceous shales and sandstones. The conglomerate is made up of boulders, cobbles, and smaller fragments in a hard, impervious sandy matrix of tuffaceous materials; bedding planes are not numerous or well developed, and for engineering purposes the conglomerate may be considered to be massive rock. Beds of well stratified, intact to moderately blocky and seamy tuffaceous shales and sandstones lie upon and are interbedded with the conglomerate. The tuffaceous beds are most common along the southeast coast of Guam, where they are about 100 feet thick; they are common also in Fena basin, and are less common in rocks of Unit 5 exposed along the Mt. Bolanos ridgeline.

The principal outcrops of hard rock are in steep mountain areas and in stream beds; the rock, except for the included limestone, is basaltic to andesitic in composition. In the rolling uplands, which constitute about half of the unit, the hard rock is covered by about 50 feet of soft clayey weathered rock (with relict textures) and gray to reddish-brown residual clays. Partly weathered rock passes gradationally, both laterally and vertically, into residual clay. Hard residual cobbles of basalt in clay are common in weathered outcrops of the conglomerate. Thin, patchy overburden is common in the rugged stony terrain in the southern part of Unit 5.

The rocks of the unit are about 700 feet thick at the crest of Mt. Bolanos, where Unit 5 is above Unit 6. At its northern margin, Unit 5 is above Unit 4; in the west, Unit 5 is above and probably interfingers with Unit 6; on the Mt. Lamlam - Mt. Alifan ridges, Unit 2 is over Unit 5. Small patches of large hard, dense basalt boulders are scattered over the weathered outcrops of Unit 5 in the eastern uplands north of Inarajan.

The regional dip of the rocks of Unit 5 is 5 to 10 degrees eastward; locally, dips may be as steep as 45 degrees. No large regional folds are known, but there are small local folds, especially in the Fena basin and in the Dandan area. Folding presents no problems in construction on this unit. There are high-angle normal faults; and fault breccias that have the characteristics of crushed rock may be zones of caving ground. Joints and fracture zones in the tuffs are associated with faults. Folded tuffaceous shales and sandstones are moderately jointed in several directions. The massive conglomerate is cut locally by widely spaced joints, but lacks joints in many areas.

The rocks of engineering geology Unit 5 are those of the Bolanos conglomerate and Dandan basalt members of the Umatac formation, except near Mt. Almagosa where extensive thin basalt flows are mapped as Unit 6 (see pl. 4, in pocket).

Excavation - method, facility, stability of slopes: Factors affecting excavation rates in Unit 5 are the degree of induration of the rock, the number of fault zones and the condition of the rock in them, and the amount of stratification and jointing in the tuffaceous rocks. The soft weathered rock and residual clay, which are predominant in the unit, can be excavated with hand tools and power equipment; the limited amount of hard rock is more easily removed by drilling and blasting.

Well indurated rock will probably blast into irregular fragments; the more friable rock, such as crushed rock in fault zones, may be reduced to loose boulders and gravel.

Weathered rock crumbles easily after excavation; hard rock is relatively stable. Changes in color after excavation have not been observed.

Excavation slopes in soft weathered rock are stable at 3:1 to 2:1; benches may be needed in deep cuts. The steepest natural slopes in areas of weathered rock are about 3/4:1. The soft rock slides on oversteepened slopes if it is saturated, and it erodes easily on bare slopes. Excavation slopes in massive hard rock are stable at about $\frac{1}{2}$:1, and in fractured hard rock at about 1:1. The steepest natural slopes in hard rock are vertical, and no erosion of excavation slopes in hard rock was seen. Fractured and brecciated hard rock slumps on oversteepened slopes.

Drainage: The configuration of the water table in Unit 5 is not known in detail. In general, ground water in porous weathered material is perched above the relatively impermeable unweathered rock and feeds many of the perennial streams common in the unit. Seepage is slow in the weathered zone and very slow to absent in the hard conglomerates. Drainage construction is needed in excavations in both weathered and hard rock. The pH conditions are generally the same as those in Unit 4.

Tunneling: Steep cliffs and inland slopes suitable for adit entries, common in Unit 5, are 1) the upper parts of the high cliffs west of the Mt. Bolanos ridgeline, 2) the slopes of Mt. Schroeder, and 3) the dissected terrain west of the village of Inarajan. In steep, dissected areas, including those just mentioned, the weathered mantle is irregular in distribution and hard rock is exposed on ledges and scarps. Even the crests of Mt. Bolanos and Mt. Sasalaguan are weathered to clay to a depth of more than 50 feet in places.

Overbreak in massive conglomerate will be low and irregular; friable zones loosened by blasting have high and irregular overbreak. The massive conglomerate will have a definite bridge-action period. Overbreak in well stratified tuffaceous rocks with closely spaced bedding planes will be high and irregular, and will depend upon the spacing of joints and upon local variations in dip. The well bedded tuffaceous rocks may have a short and irregular bridge-action period. Backpacking and immediate roof support will be necessary in the stratified tuffaceous rocks.

Rock pressures for the rocks of Unit 5 (calculated from an apparent specific gravity of 2.72, or 170 lbs per cubic foot) are as follows:

Rock Condition	Estimated Volume Percent of Rock	Rock Pressure (lbs/sq ft)	Remarks
Intact	60	0	
Moderately blocky or seamy	35	min. = 850 max. = 7,500	No side pressure except where beds dip into the sides of excavations
Crushed	5	7,500	Considerable side pressure
Squeezing rock at moderate depth	?	min. = 7,500 max. = 14,000	
Swelling rock	?	up to 40,000	

Pilot tunnels in the rocks of Unit 5 may not be necessary in many areas if pre-excavation borings show no faults and no well stratified tuffaceous rocks or clay zones.

Road construction: The best road gradients and alinements in Unit 5 are on the rolling uplands in the northern part of the unit. Roads in the mountainous terrain of the southern part of the unit will have steep gradients, short-radius curves, and short or moderate alinements; trestle crossings and tunneling may also be necessary. Subgrade conditions on weathered rock are poor to unsatisfactory; bearing capacity on soft weathered rock is poor to fair. Deep road cuts in weathered rock need 2:1 benched slopes, and deep fills of weathered rock need 3:1 to 4:1 slopes, stabilized to prevent erosion. Subgrade conditions on hard rock are excellent. Slopes are stable in deep road cuts in hard rock at 1:1 to $\frac{1}{2}$:1, except in breccias and fractured zones, where less steep slopes are needed.

Unit 5 in the northern uplands will supply earth fill and embankment materials; steep rocky slopes and stream channels will provide poor base course. Excavation for roads on the upland generally can be made with power tools; drilling and blasting is necessary in areas of hard rock.

Airfield construction: The weathered rock uplands in Unit 5 are unsuitable for major airbase sites, although there is one possible site near Dandan. Deep cuts and extensive fills as much as 75 feet deep are necessary; fills exceed cuts throughout most of the unit. Most grading can be done with power equipment. Fills across swales must have drainage construction.

The bearing capacity of the weathered subgrade is equal to that of undisturbed firm granular clays, but careful moisture control is necessary in fill construction because the weathered rock becomes plastic if compacted while wet. Benches are needed on 2:1 slopes in deep cuts into soft rock; fill slopes of 3:1 or 4:1 must be stabilized to prevent erosion. Unit 5 will supply fill and embankment materials. (Good base course, aggregate, and wearing course are available from outcrops of adjacent Units 1 and 3.)

Special engineering considerations: See the general statement under volcanic rock materials for a discussion of the deep weathering, poor drainage, and excessive erosion common to Units 4, 5, and 6.

Unit 6: lava flows and dikes:

Location and description: The rocks of Unit 6 crop out along the southwest coast of Guam from south of Agat to Merizo. They underlie the limestone of Unit 2 on Mt. Lamlam, the conglomerate of Unit 5 along the Mt. Bolanos ridgeline, and they form the lower eastern slopes of Mt. Lamlam west of Fena basin.

Rough, steeply sloping terrain with dissected terraces and short, blunted valleys are common in the unit. Steep rock bluffs, deep ravines and gullies, and some badlands in highly weathered rock are common local features on the main seaward slopes. Sea cliffs are well developed around headlands, but are absent around the small embayments along the coast. Steep slopes or high cliffs are cut into the main slopes at the heads of blunted valleys. Small streams in Unit 6 empty into the embayments.

Unit 6 consists of about 70 percent of dark lava flows, 25 percent of grayish tuffs and volcanic conglomerates, and less than 5 percent of interbedded grayish limestones. The upper part of the unit consists of massive and bedded tuffaceous shales, sandstones, and conglomerates interbedded with basalt flows; the lower part, of thick, moderately hard pillow basalts and dikes. There is an extensive dike complex near Facpi Point. Limestone lenses of Unit 1 crop out in the middle part of the unit.

The hard rock of Unit 6 is basaltic to andesitic in composition, and the soft rock is mostly clay with preserved rock textures. Blocks of hard basalt, imbedded in clay, are common in weathered outcrops in the southern part of the unit. Zeolitic veinlets and amygdules of white zeolites, calcite, and quartz are common in the pillow basalts north of Umatac. Partly altered basalts contain some iron oxides and clay.

About three-fourths of the area of the unit is covered by soft weathered rock and residual clays that are more than 50 feet thick in places (figs. 18 and 19). The depth of the weathered zone on the rocks is variable; steep cliffs are less deeply weathered than is rolling land, and the depth of weathering generally decreases from the northern part of the unit southward. The slopes between the limestones capping the Mt. Alifan - Mt. Lamlam ridge and the west coast of the island are most deeply weathered; the depth of weathering exceeds 80 feet, and the rocks are reduced to soft, punky clays. The rocks west of Fena Dam also are deeply weathered. The sea cliffs along the west coast are cut into relatively fresh pillow basalts and the lower parts of the inland cliffs east of Umatac are cut into the fresh, massive, jointed basalt flows.

A thickness of about 1,100 feet of the volcanic rocks of Unit 6 is exposed above sea level at Mt. Lamlam, where the rocks are overlain by limestones of Unit 2. Unit 6 consists of lava flows and dikes of the Facpi basalt member of the Umatac formation (see pl. 4, in pocket).

The basalts in the unit are massively bedded, and dip 5 to 10 degrees to the west. The well stratified tuffaceous sandstones, shales, and limestones have erratic dips as steep as vertical. Numerous high-angle normal faults and associated breccia zones are common. Columnar jointing is common in dikes and in some basalt flows, and the tuffaceous beds generally are jointed in several directions; the degree of jointing is variable. Only small local folds are recognized in Unit 6, and these folds are concentrated mainly in Fena basin.

Excavation - method, facility, stability of slopes: Weathered rock of Unit 6 can be easily excavated with hand tools and power equipment; fault gouge can be excavated with power tools. Some drilling and blasting will expedite removal of hard rock; the massive unjointed basalts probably will break up into angular blocks if blasted, and the softer tuffaceous rocks may be reduced to gravel and sand sizes or, where the rocks are well jointed, to angular blocks. The rate of advance in massive basalts will vary according to the spacing of joints and the degree of weathering of the rock.

Soft weathered rock crumbles rapidly after excavation. Excavated hard rock becomes softer, and lighter in color, generally within a few months.

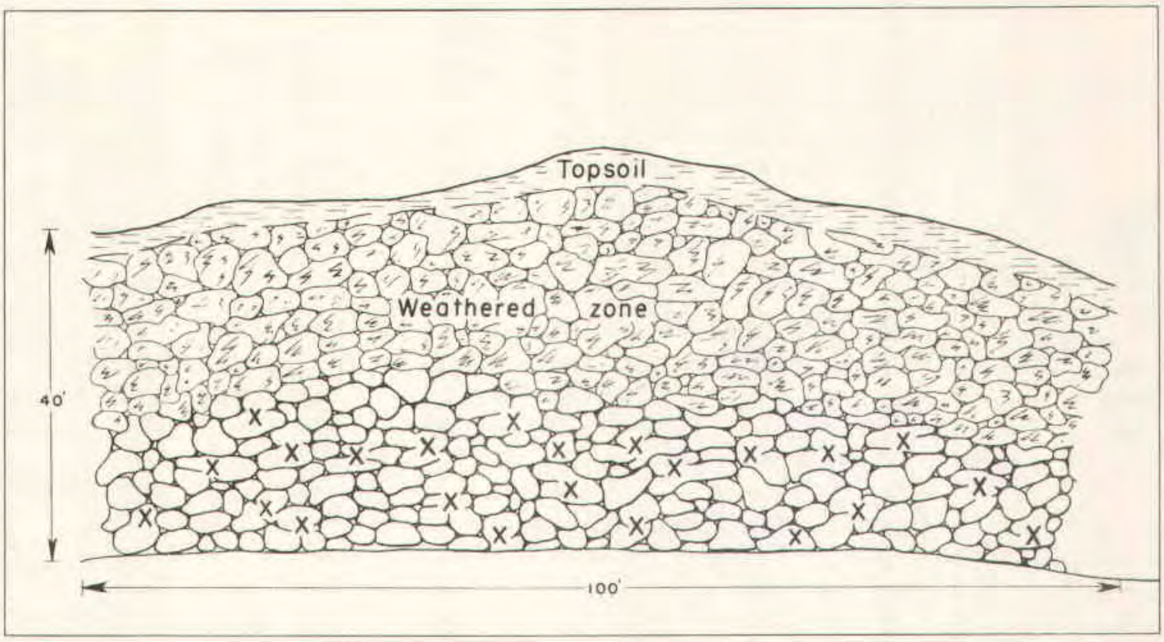


Figure 18. Hard pillow basalt of Engineering Geology Unit 6 in sea cliff near Facpi Point. x indicates places where loose pieces were broken off to obtain a composite sample of relatively fresh rock. Composite samples from two such sites (site 5C on Plate 44) were considered to be representative of the unit. Dikes were sampled separately; no samples were taken in the weathered zone.

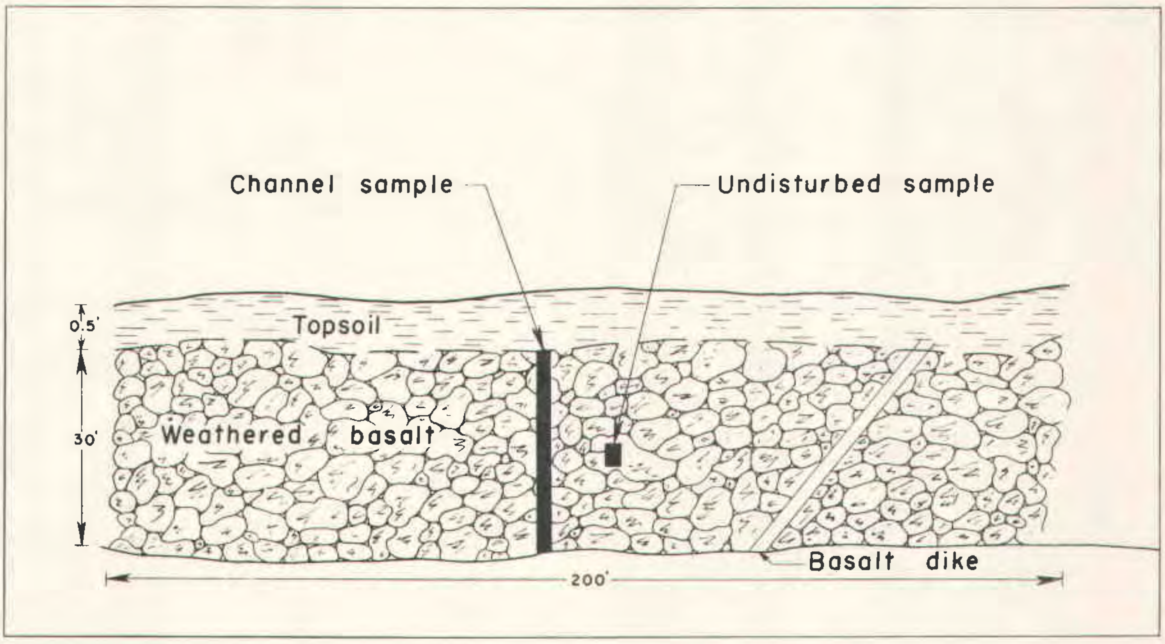


Figure 19. Weathered pillow basalt of Engineering Geology Unit 6 in roadcut near Mt. Lamlam. Sketch shows locations of channel sample and undisturbed sample; topsoil was not sampled.

Excavation slopes in weathered rock are stable at about 2:1 if slopes are benched; the steepest natural slopes are about 1:1. Saturated weathered rock slides on oversteepened slopes. Excavation slopes in hard rock probably are stable at 1:1 to 3/4:1 in the pillow basalts; the steepest natural slopes are nearly vertical. Jointed and shattered rock slumps on oversteepened excavation slopes. Erosion is rapid on bare excavation slopes in weathered rock, but is absent in hard rock excavations. Folding of the rocks does not constitute a serious problem in excavations in Unit 6.

Drainage: The numerous perennial streams on Unit 6 are fed, in part, by springs from aquifers and jointed zones, and by seeps from a saturated zone of variable depth in the porous weathered material above the hard rocks. Seepage is slow in the weathered rock and probably is slow to absent in the hard rock, except in joint and fracture zones. Seeps are common along the upper contacts of the relatively impermeable stratified tuffaceous sandstones and shales, and springs issue from slopes at the heads of blunted valleys. Many streams follow fault lines; the faults, therefore, are liable to be zones of groundwater concentration. Drainage construction is necessary in both the hard rock and weathered rock of Unit 6.

Chemical analyses of the ground water of the unit show that the hardness of the water is generally low; there is nothing to indicate corrosive conditions. (The general pH conditions in relation to the water table in volcanic rocks on Guam are discussed under Unit 4.)

Tunneling: Suitable locations for adit entries are 1) the steep cliffs east of Umatac, 2) the seaward slopes of the Mt. Lamlam - Mt. Alifan ridge, and 3) the eastern slopes of the Mt. Almagosa - Mt. Alifan ridge.

Overbreak in Unit 6 will depend upon the same factors as those listed for Unit 4. The pillow basalts, where the pillows are large and interlocking, probably will have low and regular overbreak; if the pillow basalts are well jointed and fractured, or if the pillows are small, the overbreak will increase. This rock may stand sell and probably will not require immediate roof support. Steeply dipping and well jointed dikes, as well as stratified tuffs which are generally jointed in several directions, will have high overbreak. The contacts between stratified rocks of erratic dip and the massively bedded basalts may be planes of high and irregular overbreak. The numerous high-angle faults in Unit 6 contain breccias in which high and irregular overbreak and caving may occur.

Wet, jointed stratified rocks and fault breccias probably will have a short and variable bridge-action period. Massive basalts probably will have a long bridge-action period. There may be squeezing, swelling, and slaking in zones of clayey fault gouge and weathered rock (see discussion of these phenomena under Unit 4).

Rock pressures for the tuffaceous sandstones and shales of Unit 6 (calculated from an apparent specific gravity of 2.14, or 133 lbs per cubic foot) are as follows:

Rock Condition	Rock Pressure (lbs/sq ft)	Remarks
Very blocky and seamy	min. = 1,900 max. = 5,900	Little or no side pressure except where beds dip into the sides of excavations
Crushed	5,900	Considerable side pressure

Rock pressures for the basalts of Unit 6 (calculated from an apparent specific gravity of 2.86, or 178 lbs per cubic foot) are as follows:

Rock Condition	Rock Pressure (lbs/sq ft)	Remarks
Intact	0	
Massive, moderate-jointed	min. = 0 max. = 900	Load may change erratically from place to place
Moderately blocky and seamy	min. = 900 max. = 2,500	No side pressure
Crushed	up to 7,900	

Estimated volume percentages of rock conditions for the rocks of Unit 6 are as follows:

Hard and intact	25 %
Massive moderately jointed to moderately blocky and seamy	50
Stratified and very blocky and seamy	20
Crushed	5

Pilot tunneling and drilling are recommended to detect waterbearing strata, fault zones, and strongly jointed rock.

Foundation conditions for structures: The bearing capacity of soft weathered rock is poor to fair. Footing support in weathered rock requires drainage construction because saturation of the rock reduces the bearing capacity; heavy towers on soft rotten rock need spread footings. The best foundations sites on weathered rock are on terraces, where slumping and creep are less common. The bearing capacity of massive hard rock is excellent, but the capacity of fractured or brecciated hard rock is less. Footings on buried hard rock require safeguards against ground water. Sites for heavy structures should be located away from fault and dike zones, and should be inland from the edges of cliffs and steep slopes where erosion may weaken footing support.

Road construction: Roads on terraces in weathered materials have gentle gradients, long-radius curves, and long alinements. Roads across steep terrain have steep gradients, short-radius curves, and alinements of variable lengths. Extensive cut-and-fill is necessary, except on terraces; cuts probably will equal fills in volume. Deep cuts in soft weathered rock require benched slopes at 2:1; fill slopes are stable at 3:1 to 4:1, and must be stabilized to prevent slope wash and sliding. Berms, side-drains, and ditches in weathered rock must be protected against erosion. Weathered rock has poor to fair bearing capacity as subgrade. Most excavations can be made with power equipment, but drilling and blasting are necessary wherever hard rock is uncovered. Unit 6 will supply fill and embankment materials, and selected hard dike rock for aggregate.

Airfield construction: The terrain of this unit is not suited for the construction of major airbases.

Special engineering considerations: See the general statement under volcanic rock materials for a discussion of the deep weathering, poor drainage, and excessive erosion common to Units 4, 5, and 6; see also the discussion of an embankment failure in Unit 4.

Unconsolidated Materials

General statement: The areas of the three units of unconsolidated engineering materials are coincident with the areas of the corresponding geologic formations (see pl. 4, in pocket).

Unit 7, beach sands and gravels, is a veneering deposit generally from 5 to 30 feet thick, with the water table 15 or less feet below the surface. Unit 8, lagoonal deposits, is entirely under 10 to 50 feet of water; few interpretations were made for this unit. Unit 9, deep clayey alluvium in river bottoms and in marshes, is generally 40 to 60 feet thick in interior basins and valleys.

Unit 7: Beach sands and gravels:

Location and description: Unit 7 is made up chiefly of discontinuous veneering beach and embayment deposits of unconsolidated limy granular materials along the coast from sea level to 20 feet above sea level. The embayment deposits are overlain by thin to moderately thick soils of clay or clayey silt.

Landforms include present beach slopes and ridges, discontinuous narrow coastal terraces or old raised beaches, and slightly buried embayments or old estuaries around the mouths of some streams and some of the coastal flats from Asan to Agat.

Unit 7 consists mainly of light-colored, fine to coarse limesand; the sand grains are angular to subrounded fragments of shells, algae, coral, and other reef detritus. Less than 2 percent of the unit is clay or fines, except in the upper part where clayey silt and vegetal detritus has accumulated. Volcanic detritus forms a significant part of beach deposits along volcanic rock coasts and at the mouths of streams. Olivine and magnetite grains are common constituents south of Facpi Point; one sand sample from a beach at Talofofo Bay contained 89 percent magnetite. Considerable amounts of gravel, cobbles, and large shells occur in sand at unprotected storm-swept beaches.

Beach deposits at the Tarague embayment are commonly coarse sand 4 to 12 feet thick over limestone bedrock; at Tumon Bay the sand is medium textured, as much as 33 feet thick; south of Apra Harbor the sands are mostly coarse. The beaches from Pago Bay south to Agat Point are coarse sand; boring at Pago Bay showed that the sands, lying upon limestone, are 19 feet thick and contain up to 4 percent fines. Unit 7 covers extensions of adjacent rock units. The beach deposits are generally equivalent to Engineering Soils Unit 12 (Corps of Engineers Classification group (SP)).

Present beaches are of clean sand; the sands of raised beaches have shallow (6 to 18 inches) dark-colored surface horizons with some humus and as much as 10 percent of fines; slightly buried coastal flats and embayments have 1 to 4 feet of highly organic clay overburden.

Excavation - method, facility, stability of slopes: The sands and gravels of Unit 7 are loose and easily excavated by hand tools and power equipment. The unit is too thin to tunnel in. Slight crusting was noted in a sand pit at Tumon, but the crusts were easily crushed by hand. Slopes in pits as deep as 10 feet stand at 1:1 above the water table; natural seaward slopes are gentle.

Drainage: The water table generally is at or near the surface; this high water table hinders excavation in embayments. In sands of raised beaches, however, the water table usually is from 5 to 15 feet below the surface, and as much as 25 feet below in a few places. Drainage is good above the water table. The water in the sands is brackish to saline.

Foundation conditions for structures: The bearing capacity of Unit 7 is fair to good on dry, confined sand. Detailed boring exploration is necessary wherever heavy permanent installations are planned, because clay and silt are interbedded with the sand and may lie under it around the mouths of streams and along the coast around the southern half of Guam. Drained and stabilized footing support or piling is needed on clayey sand. Flooding with rising water table, and high onshore storm waves are also hazards to structures on the unit.

Road construction: The best road locations in Unit 7 are on deposits of dry sand above bedrock; the sand has good bearing capacity and is self-draining. Road locations generally are poor on clayey estuarine beds, where the subgrade is highly organic clay overburden on interbedded sand and clay. Roads in the unit have level gradients, moderate curves, and alinements of variable lengths. All roads can be constructed easily with power equipment; little cut is needed, but considerable fill is necessary on estuarine beds to raise the grade above peak flood stage. Roads along low beaches are subject to washout by typhoon waves. Some bridging and culverts are required for road crossings over streams in the southern part of the unit. The sand of Unit 7 is satisfactory for embankment and fill in areas where torrential flooding is absent. Clayey estuarine beds do not contain materials suitable for fill.

Airfield construction: The terrain of this unit is not suitable for the construction of major airbases.

Special uses of materials: The sand is used locally for sandblasting in steel tank prime-coat preparation. It can be used for pipe or sewer tile cushioning, and is usable for mortar sand if washed and graded.

Unit 8: Lagoonal deposits:

Location and description: All lagoonal deposits are on the west side of Guam, under water, and are mapped in Apra Harbor, Tapungan Channel, and shoreward from Anae Island and Cocos Island.

Most of Unit 8 consists of limy, granular marine deposits 10 to 50 feet thick in the shallow basins of larger lagoons. The granular material ranges in size from silt to pebble and gravel to large coral boulders as much as 10 feet in diameter; the average size is sand and gravel, or cobbly gravel. The white to grayish-brown limy detritus generally is contaminated by clay and organic material. In places, the loose granular deposits are on reef limestones.

The maximum thickness of the lagoonal deposits is unknown, but it probably is more than 50 feet in deeper parts of large lagoons. No engineering tests were made of this material for this report; most of the fill areas around Apra Harbor, however, are made of lagoonal materials dredged from the harbor.

Excavation - method, facility, stability of slopes: Unconsolidated lagoonal deposits are easily excavated by hydraulic suction dredges, bucket line dredges, and barge-mounted dragline equipment. Shaped charges may be necessary to break up large boulders.

Little is known about submarine slopes in granular materials, especially if the materials are within the depths of wave and current action.

Foundation conditions for structures: Heavy structures require piling or anchored caissons for support.

Road construction: Causeways across Unit 8 will need reinforced underwater sub-base and subgrade. Alternately, cribbed stone and piling can be used to support roadways in quiet, shallow lagoons.

Airfield construction: Constructing airfields on Unit 8 would involve the considerations discussed under Road Constructions.

Unit 9: Alluvium:

Location and description: Alluvium is in nearly all valley bottoms, and on gently sloping alluvial fans and earthy floors in large basins in limestone terrain.

Landforms include nearly level to gently sloping sinuous floodplains in valleys, flattened alluvial fans in coastal coves, and basin floors on the limestone uplands. Deep, winding stream channels in the floodplains carry drainage seaward.

Alluvium consists mainly of clayey sediments 5 to 150 feet thick; near the Fena Valley dam, in the Talofofo River valley, unconsolidated Unit 9 materials are 200 feet thick. Below the topsoil are clays and silts that range in color from yellowish, brownish, and reddish to gray ish and black. The subsoils generally are firm to plastic when moist; soft, plastic, and sticky when wet; and very hard and cracked when dry. Overburden consists of a dark-colored topsoil zone 0.5 to 1.5 feet thick which contains a large amount of organic matter. No significant weathering effects were noted, except in weathered volcanic gravel. Unit 9 includes Engineering Soils Units 9, 10, and 11 (Corps of Engi neers Classification groups (MH) and (Pt)).

Excavation - method, facility, stability of slopes: Alluvium above the water table can be excavated easily with hand or machine tools; the feasibility of pumping and shoring excavations below the water table has not been tested.

Vertical excavation slopes above the water table will stand for a short time only, because ravelling, cracking, and slumping take place soon after excavation; maximum slopes of $\frac{1}{2}$:1 are stable in unshored excavations for a considerable length of time. Dikes or diversion ditches are necessary to prevent flooding in the wet seasons. Stream banks not subject to lateral wash stand vertically to heights of 10 to 15 feet. Vertical slopes exposed for more than a few days slump because of excessive swelling, shrinking, and cracking caused by alternate wetting and drying of the alluvial materials. Exposed material is subject to columnar-angular jointing; the joint blocks become very hard when dry, and firm to soft when wet.

Drainage: The water table ranges in depth from a few feet, near the coast, to a few tens of feet, inland; it is near the surface adjacent to small seepy or marshy areas. Valley flats and wide, low alluvial fans commonly are flooded during heavy rains in the wet seasons, and small marshy areas become ponded. Seepage may be slow to moderately rapid in such marshy places, and pumping may be inadequate unless the excavation is sealed off by retention walls or tight sheeting. The clays are soupy to viscous in saturated zones. Alluvial sediments cover extensions of adjacent volcanic and limestone units.

Foundation conditions for structures: The bearing capacity of the materials of Unit 9 is inadequate for heavy-design loadings. Subsurface exploration to determine the depth to buried bedrock is needed wherever heavy loadings are planned. Foundations for heavy permanent structures require adequate drainage and stabilized footing support. Piling support may be driven into bedrock under the alluvium if rock is within reach of piling lengths.

Road construction: Alluvium is generally poorly drained and poor in bearing capacity, and in valleys and basins is often saturated during the wet seasons. Roads generally have gentle gradients, moderate-radius curves, and alinements of variable lengths. During dry seasons the roads can be constructed easily with power equipment. Cuts are negligible in volume, but extensive fill from other units must be provided to raise roadbeds above the peak flood stage. Bridges and culverts need openings large enough to carry 100 percent runoff during climax flood conditions when the soil is saturated; especially large weirs are necessary over channels that carry drainage from steep-sided coves in engineering geology Units 4, 5, and 6. Road fills on sloping alluvial subgrade require drainage construction to prevent upslope ponding which produces saturation in the subgrade, thereby causing creeping or sliding downslope on the fluid soil in the subgrade. Unit 9 does not supply material suitable for road construction.

Airfield construction: The terrain of this unit is not suited for the construction of major airbases.

Recommendations for Site Investigation

A full understanding of the geologic conditions at a selected site must include the several investigations discussed below. The services of a geologist in pre-excavation mapping, drill-core logging and interpretation, and in making observations in exploratory tunneling will facilitate successful completion of construction projects.

Surface geologic mapping: The area immediately above a projected site, and as much of the area near the site as is feasible, should be mapped in as much detail as is possible. The geologic map should be on a scale of 1:1,000 or larger, and the contour interval should be no greater than 10 feet.

Drilling: Concurrently with surface mapping, drilling should be begun in a pattern appropriate to the design line of the proposed installation. Information from the drill holes and from the surface mapping may reveal local conditions, such as cavernous zones in limestone, areas of intense faulting, or deep weathering in volcanic rocks, which will require additional drilling. Some drilling should be extended below the invert grade of the proposed excavation to provide cores for testing foundation suitability.

Subsurface geologic mapping: Geologic cross-sections and an isometric projection of the subsurface geology at the proposed site should be prepared by correlating and combining the geologic information from the surface mapping and the drilling. These graphic representations of underground relationships will help to position the final design in the most suitable rock.

Materials testing: Tests should be run on drill-core materials to determine: 1) the presence of squeezing or swelling clays; 2) the specific gravities of the various rock types (for calculation of rock pressures); 3) the volume of rock that must be blasted, as compared to the volume removable by earth-tunneling techniques; and 4) the foundation suitability of the rock at the invert of the excavation.

Ground-water conditions: The depth to the water table and the configuration, porosity, and permeability of aquifers should be determined. In volcanic rocks a subsurface contour map (drawn from drill-hole data) showing the configuration of the base of the weathered zone may give significant information as to the channeling and concentration of ground water. Variation in saturation of the rocks in wet and in dry seasons must be inferred or determined. From these investigations, the volume of water to be pumped may be estimated.

Exploratory tunneling: Exploratory tunneling may be necessary to get detailed information on in-place characteristics of the rocks, and on the excavation characteristics of the rocks, such as overbreak conditions.

Engineering Soils

by

Carl H. Stensland

Conclusions

Engineering aspects of the soils of Guam are vitally related to an understanding of their genesis, landform, composition, and physical characteristics. Proper drainage and the control of moisture content in the soil used or affected by construction operations are regarded as the most important considerations.

Introduction

Organization of the section: Description of the engineering aspects of the soils is chiefly in tabular form. The Engineering Soils map (pl. 49, in pocket) contains the basic or pedological soil units with an explanation of their classification into groups according to their behavior characteristics for engineering use. The table on the map contains a brief summary of the physical characteristics and natural features of the soils, and outlines the important drainage and erosion features of the soils with applications to conditions encountered in the most common forms of engineering soil use -- excavations, embankments, and foundations. Table 20 (in pocket) contains further description of the Soil Conditions Affecting Construction and also an appraisal or interpretation of soils for their stability in slopes, suitability for natural and subgrade foundations, compaction characteristics, and bearing values. Table 21 (in pocket) contains Engineering Soils Test Data.

Comparison of soils and geologic methods: Emphasis in the Engineering Geology section is on the conditions encountered in solid bedrock and in the weathered rock; treatment of the weathered rock is gradationally less specific upward into the soil horizons; significant terrain and drainage features and conditions are described, and the soils are mentioned.

Emphasis in the Engineering Soils section is on the soils as physical units in the landscape -- each with a certain arrangement of horizons in profile, a certain set of physical characteristics in each horizon, certain drainage characteristics, and with defined ranges of prevailing surface gradients. Some of the soils, such as Guam clay (Unit 1), are so shallow that engineering considerations are chiefly those of the underlying bedrock; other soils are very deep, with C horizons or parent material extending 10 to 100 or more feet below the surface (Basic Soil Units 6, 7, and 8). These soils are described to bedrock where possible; below depths of 25 feet these descriptions become gradationally less specific as qualities of the underlying rock are approached, but the type and condition of underlying rock is mentioned at whatever depth it may occur, wherever identification is possible.

Pedological classification of the soils: Classification of the soils from the standpoint of their morphology and genesis is known as pedological classification. Morphology of the soils is affected by the principal genetic factors of climate, vegetation, parent material, slope (including relief and drainage), and time or age. Generally, a difference in kind or degree of any one of the genetic factors will result in a different soil. In this system, which is world-wide in scope and application, soil classes are divided into several categories; order (zonal, intrazonal, and azonal); suborder (soils with morphic effects of climate, vegetation, salinity, alkalinity, etc.); great soil groups; soil series; soil type, and soil type phase.

The pedological soil series: For engineering purposes, the soil series is probably the most significant category in the pedological system of soil classification. All of the soil types and phases in a named soil series have the same profile and the same genetic history; the soils have the same number of horizons of approximately the same depth, and the horizons were developed from the same kind of parent material under the same climate and native vegetation; they are developed in the same landform or landscape, and they are approximately of the same age. Each soil series is given a name, which is usually the proper name of some lake, city, stream, or other geographical entity near the place where the series was first found and scientifically described. Examples on Guam are the Shioya soils and Guam clay. The Shioya series was first identified and described near the village of Shioya, on Okinawa. Shioya loamy sand was mapped there in 1947 and 1948; other types of this series have been mapped on other islands in the western Pacific since that time; on Guam it was not differentiated into type of different surface textures. Guam clay has thus far been mapped only on Guam.

When a soil series has been established, which means that it has been appropriately described and named, that name is used to identify all soils fitting the description, wherever they may be encountered. For this reason, preservation of the identity of each soil series has been attempted, in the transition from the pedological soil units into the unified soil classification system.

The unified soil classification system: This system was originated by Dr. Arthur Casagrande of the Harvard University Graduate School of Engineering. It was adopted in 1942 by the Corps of Engineers, U.S. Army, for use in the large program of airfield construction occasioned by World War II. At that time it was called the "Airfield Classification" of soils. On the basis of experience gained in several other types of construction since that time, the original classification has been expanded and revised so that it applies not only to airfields but also to roads, embankments, foundations, and other engineering features.

The unified soil system is based upon only those textural and plasticity qualities of the soil which influence its behavior when it is used as an engineering construction material. This system is fully described in the Corps of Engineers, U.S. Army Technical Memorandum No. 3-357 (Waterways Experiment Station, March 1953). Its application to the use of soil in the construction of embankments, foundations, roads, and airfields is described in separate supplements to the above memorandum (Appendix A and Appendix B, of the same and later dates).

The concept of textural-plasticity terminology used in names for engineering soil groups in the unified soil classification system is somewhat different from that which governs textural terms in the pedological classification system. In the unified soil classification system the terms "silt" and "clay" are used to describe those soils with Atterberg limits plotting respectively below and above the "A" line on the plasticity chart (Waterways Experiment Station, 1953, vol. 1, pl. 2). In the engineering classification of the soils of Guam (pl. 49 and table 20) it is important that these terms not be confused with the purely textural classes of "silt" and "clay" as used in the basic or pedological soil classification (and as also used by the U.S. Department of Agriculture). The screened or sieved sizes of sand and gravel are also different in the two classifications.

Special Considerations

Reliability of the soil maps and engineering interpretations: As developed in this report, engineering interpretations or evaluations of the pedological soil classes are suitable for general planning purposes involving preliminary comparisons of proposed construction sites. In the pedological units composed of a single soil series or type, the original or pedological soils data may be regarded as relatively specific; in the pedological units composed of an association of two or more soil series the pedological information is regarded as valid concerning the series in the units, but the applications or interpretations derived from the units of combined soils is necessarily generalized.

Engineering evaluations of the pedological or basic soil components of the engineering soil groups are based on a minimum of engineering laboratory tests and are therefore unsuitable for specific planning or design at a construction site. They are regarded as useful, however, in a survey of the physical behaviour characteristics encountered in the different soils of Guam and should be applicable for planning purposes in the preliminary selection of construction sites. The engineering evaluations in Table 20 should also be useful in a survey of the preventive maintenance possibilities and requirements concerning erosion, flooding, seepage, and slumping or landsliding in the different soils over wide areas occupied by proposed or existing roads, pipelines, large installations or building sites.

Possibilities of extending or reenforcing the existing engineering evaluations: Enough information is presented in the basic or pedological soils section to afford a basis for more detailed mapping of some of the soil series --- especially those which are now mapped in associations of two or more series. This should be desirable from both the agricultural and engineering standpoints.

In the explanation of the Engineering Soils map (pl. 49) and in Table 22, a skeletal framework is provided for much further projection and refinement of engineering evaluations of the basic or pedological soils. This can be done by application of more testing data to the identified pedological series as a means of increasing the reliability of the engineering soil group evaluations. Some of this could be done immediately by applying to identifiable soil horizons some of the large mass of data that has been accumulated by the Pacific Islands Engineers in an extensive soil boring and testing program; the Navy soil testing laboratory on Guam also has an accumulation of soil testing data from various parts of the island which, with the assistance of a pedologist or an engineer with an understanding of the pedological classification system, might be used to refine and extend the type of tabular engineering evaluations initiated in this report.

Familiarity with the principles or fundamentals of the unified soil classification system is essential for anyone attempting to utilize or extend the type of soil engineering information contained in this report. This information can be obtained from the Corps of Engineers, U.S. Army technical memorandums previously cited (1953), and more recent ones.

Differences in soil behavior caused by differences in the soils: Differences in the physical behavior of soils when used for engineering construction materials may occur either between the over-all profiles of two basic soil series, or they may occur as differences in behavior of soil in different horizons of a single series or pedological type of soil. Engineering evaluations of the soils in this report are based largely upon the over-all or dominant characteristics in each of the pedological classes of soil that would affect ordinary engineering operations. Application of this technique to the significant, identifiable soil horizons within the profile of a single soil series is encouraged. This can be done within the framework of approach established in this report. (Experience indicates, however, that such an application within the units of Alluvial soils is sometimes extremely difficult or impossible because differences in the profile of an Alluvial soil are caused by heterogeneous differences in the stratification of sediments, rather than by well defined morphological differences resulting from the development of genetic horizons in a zonal soil.)

Differences in soil behavior caused by changes in the moisture content of a soil: Aside from the difference in behavior characteristics pointed out above, either between different classes of soil or differences among the horizons of a single kind of soil, one of the most important and significant differences that may occur in soil may be caused by a change or a series of changes in its moisture or water content, in a single horizon or in the whole profile of soil; the significant change in moisture or water content of a soil, sufficient to cause radical or disastrous changes in its physical behavior, may occur in soil used as natural foundations, or it may occur in a mass of soil that has been reworked in the process of engineering construction. Elaborate and expensive physical or engineering tests, which are usually performed upon soils at only one or two stages of specific moisture content, may be largely nullified by subsequent gradational or sudden changes of moisture or water content of the soil during or after its use in engineering construction. A lowering of the water table or pronounced reduction in the supply of water impounded behind an earth dam may cause excessive drying of the soil and the development of large cracks in the dam, which under certain circumstances could cause serious weakness or even failure in the structure. Conversely, the changes in external and internal drainage conditions of the soil caused by large construction operations, such as in a new building site or along a newly constructed highway, may cause enough change in the soil-water relationship, both in and upon the soil, so that serious failures or damage in the construction may result. Alteration in the natural configuration or condition of the surface soil at large construction sites may cause convergence or concentration of water flowing or standing on the soil. Serious erosion and washouts may result from convergence caused in the surface water runoff; uneven settling, slumping, or serious landsliding may result from neglected or prolonged imponding of even small amounts of water on or adjacent to natural soil foundations or large earth fills or embankments. The importance of engineering control of water in and upon construction soil can scarcely be overemphasized. The hiatus that exists between the data of soil mechanics textbooks and extensive engineering soil testing on the one hand, and the millions of dollars lost annually through failures in soil and earth construction on the other hand, is almost completely represented in a generally inadequate appreciation of the changes in physical behavior of the soil which are caused by changes in the soil-water relationships, both within and upon the soil.

<u>Adequate provisions for the flow of water upon the soil</u>: The determination of sizes for dam spillways or for adequate flow of water under bridges or through culvert openings is a problem in hydrology rather than in soil engineering. But it is mentioned here because of its extreme importance in connection with the construction of large earth fills or highway embankments. Spangler (1951, p. 344) writes: "In selecting the proper spillway capacity it is not enough to determine the greatest flood flow in recorded history and to apply an arbitrary factor of safety to this flow. It is better practice to study the maximum storms which have occurred within the climatic region in which the drainage area of the stream lies. Then, by transposing these storms to the drainage area under study, an idea of the maximum possible flood flow can be obtained. It is advisable to provide spillway (or bridge or culvert) capacity sufficiently large to handle the maximum possible flood flow thus determined with a generous margin of safety".

Special consideration of the drainage area in question should be given to large parts that may be periodically burned or that may have been disturbed or compacted during construction. Also there is a tendency to minimize such studies or considerations in places where the drainage areas appear to be small, when, in aggregate, the losses from failures in numerous small places may greatly exceed those in the fewer places which are large.

Excellent information concerning the effects of water flowing upon the soil and the control of accelerated erosion in large and small drainage areas can be obtained in literature of the U.S. Soil Conservation Service, the Bureau of Reclamation, and the Forest Service.

Adequate provisions for control of moisture or water in the soil: Fine-grained soils are materially weakened, both in bearing capacity and in resistance to shearing stresses, by high moisture content. A hard, dry clayey soil becomes soft and slippery after a rain. Earth bank cave-ins and landslides occur most commonly in clayey soils after heavy rainfall or an extended wet period.

Every possible precaution should be taken to prevent the accumulation of water on or adjacent to an engineering construction facility composed of soil or containing a soil foundation. Depressions which impound water above the slope line (or which saturate the porous soil along the slope line) of a foundation, cut, or embankment should be adequately drained. The possible saturation of soil foundations or embankment materials by seepage water should be explored very carefully. Artificial drains of sand, tile, or perforated pipe should be placed at suitable intervals along the base or contact of all sloping granular, porous soil which overlies the relatively impermeable, clayey volcanic saprolite of Basic Soil Units 6, 7, and 8. This need for adequate drainage control applies to all critical areas of soil, whether natural or emplaced, within or adjacent to a construction site.

Highway embankments which cut across natural drainageways in the volcanic soils (Basic Soil Units 6, 7, and 8) require careful attention to all aspects of drainage control. The need for adequate surface drainage has been emphasized; provisions for the control of underground or internal saturation and seepage are equally important. Plate 48 showing the highway embankment failure on Route No. 5 (15 October 1953) illustrates the effect of water saturation in a large mass of porous surface soil overlying volcanic saprolite in a small valley in Basic Soil Unit 7. The small valley floor was flat but inclined about 15 percent. The thickness of porous, granular, colluvial-alluvial sediments composing the valley fill ranges from 10 to 20 feet; the plane of contact of these sediments with underlying clayey bedrock or volcanic saprolite was also along a gradient of about 15 percent. Very heavy typhoon rains saturated a large mass of granular soil in the valley bottom across which the highway embankment was constructed; complete saturation in the base of the granular soil on the underlying relatively impermeable volcanic saprolite caused a drastic reduction in cohesion, friction, and consequent shearing resistance in the saturated contact zone. The resulting landslide moved about 100,000 cubic yards of the natural valley fill and a large segment of the highway embankment, causing a portion of the highway pavement about 250 feet long to collapse; vertical and horizontal displacement of the broken pavement averaged about 15 feet.

Landslides on Guam are most commonly in the soils of Units 6, 7, and 8; outside of these units, slumping or instability is most likely to occur in the soils of Units 2, 3, 4, 9, and 10.

After several years of study and research concerning the causes, classification, and prevention of landslides, the Highway Research Board (1958) includes the following among its conclusions (p. 126): "It is generally agreed, however, that for the majority of landslides ground water constitutes the most important single contributory cause; and in many areas of the country the most generally used successful methods for both prevention and correction of landslides consist entirely or partially of ground water control." In the *same report (p. 169) they again emphasize, "Drainage is without question the most generally applicable corrective treatment for slides".

Control of moisture in soil used for construction: Engineers on Guam have experienced difficulty in maintaining the moisture content required for optimum compaction of certain soils used in the construction of large earth fills or embankments. Basic Soil Units mentioned in the above paragraphs contain a large proportion of the clay mineral halloy site and the subsoils of Toto clay and Asan clay are predominantly of montmorillonite. Both of these mineral clays require careful attention in construction because of their excessive swelling and shrinking characteristics. Proper rolling and compaction of such soils used in embankments is also very difficult; only thin layers of these materials can be compacted during sunny weather and operations may have to be suspended when the conditions are such that optimum moisture content cannot be maintained.

Exposed cuts in these soils should be protected from extreme wetting and drying if cracking, spalling, and slumping are to be avoided. Protective blankets of asphalt, concrete, or other material may be required, as well as control of seepage and internal moisture in the natural soil of the cut.

GLOSSARY

Terms are defined as they are used in this report.

Aggregate, soil: A single mass or cluster of soil particles held together (such as a clod, prism, crumb, or granule).

Alluvial soils: A great soil group (taxonomic unit) which is comprised of azonal soils developed from transported and recently deposited alluvium characterized by weak or no modification of the original soil-forming processes.

amygdaloidal: A term applied to volcanic rocks that contain numerous cavities (vesicles) filled with secondary materials. The filled cavities are called amygdules.

andesite: A volcanic rock, generally porphyritic, composed essentially of plagioclase and one or more mafic minerals; commonly medium or dark colored, dense. Differs from basalt primarily in composition of the plagioclase feldspar.

argillaceous: An adjective meaning clayey; applied to all rocks or substances composed of clay, or having a notable proportion of clay in their composition.

associated soil: A group of soils, with or without common characteristics, geographically associated in an individual pattern. An association may include one or more catenas. If the individual members of the association are not separable on a map of the scale employed the association is considered a complex.

Azonal soils: Soils without well developed profile characteristics. Many soils on recent alluvial or colluvial deposits are azonal.

backpacking: The packing, with rock fragments, of the space between tunnel supports or lining and the roof or sides of the tunnel.

basalt: An extrusive igneous rock composed primarily of calcic plagioclase and pyroxene, with or without olivine; commonly dark colored, dense, and glassy.

beach: The zone of unconsolidated material that extends landward from the waterline to the place where there is a marked change in material, or physiographic form, or to the line of permanent vegetation, which is usually the effective limit of normal storm waves. The seaward limit of the beach, unless otherwise specified, is the mean low waterline. A beach includes foreshore and backshore.

bedrock: The more or less solid, undisturbed rock in place either at the surface or beneath superficial deposits of gravel, sand, or soil.

benthonic: Of or pertaining to sea-floor types of life or marine bottom-dwelling forms of life.

Bog soils: An intrazonal group of soils with a muck or peaty surface soil underlain by peat.

boulder: A rounded rock fragment more than 10 inches in diameter.

breccia: Angular fragments of volcanic rock cemented together by a matrix (generally volcanic dust, ash, or sand).

bridge-action period: The time which elapses between firing a round and the beginning of the breakdown of the unsupported part of the tunnel roof.

calcareous soil: Soil containing sufficient calcium carbonate, often with magnesium carbonate, to effervesce visibly when treated with hydrochloric acid. Soil alkaline in reaction, due to the presence of free calcium carbonate.

class, soil: Name given to the texture of a soil on the basis of the percentage of each of the soil separates. The basic classes are sand, loamy sand, silt, sandy loam, silt loam, loam, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay

colloid, soil: Both inorganic and organic matter of very small particle size and very large surface area per unit of mass. Many mineral colloids have a crystalline structure and are composed almost entirely of various kinds of clay minerals. Not all clay perticles are colloids; usually only the particles smaller than 0.002 or 0.001 mm are considered colloids.

complex, soil: A soil association composed of such an intimate mixture of areas of soil series, types, or phases that these cannot be indicated separately upon maps of the scale used so that the association is mapped as a unit.

concretions: Hardened local concentrations of certain chemical compounds, such as calcium carbonate and iron and manganese oxides, that form indurated grains or nodules of various sizes, shapes, and colors. Lime concretions consist of calcium carbonate and other included soil constituents. They vary in size from very small particles to particles as much as 2 feet in diameter. They take many shapes, with spheres, rough tubular or branched tubular, and rough plates being the common forms. Iron and manganese oxides, often called "shot", are commonly in the form of spherical pellets.

consistence, soil: The relative mutual attraction of the particles in the whole soil mass or their resistance to separation or deformation as evidenced in cohesion and plasticity. The terms for consistence used in soil descriptions as given in the Soil Survey Manual (U.S. Dept. of Agriculture, 1951, p. 232-234) follow:

When dry	When moist
loose	loose
soft	very friable
slightly hard	friable
hard	firm
very hard	very firm
extremely hard	extremely firm

When wet

plasticity	stickness
non-plastic	non-sticky
slightly plastic	slightly sticky
plastic	sticky
very plastic	very sticky

cropland: Land regularly used for crops (except forest crops). Cropland includes rotation pasture, cultivated summer fallow, or other land ordinarily used for crops but temporarily idle.

dendritic: Branching like a tree; applied to drainage patterns and to the forms of some mineral aggregates.

detritus: Loose material (especially rock fragments) resulting from rock disintegration or abrasion.

dike: In geology, a tabular body of igneous rock that cuts across the structure of adjacent rocks.

drainage, soil: Refers to the rapidity and extent of the removal of water from the soil, especially by surface runoff and by flow through the soil, in relation to additions.

drainage, soil, classes: A classification based on interpretation of combined effect of runoff, soil permeability, and internal soil drainage. The Soil Survey Manual (U.S. Dept. of Agriculture, 1951, p. 170-172) defines the following seven classes:

very poorly drained
poorly drained
imperfectly or somewhat poorly drained
moderately well drained
well drained
somewhat excessively drained
excessively drained

drainage, soil, internal: That quality of a soil that permits the downward flow of excess water through it. The Soil Survey Manual (U.S. Dept. of Agriculture, 1951, p. 168-169) defines the following six classes:

none
very slow
slow
medium
rapid
very rapid

eluviation: The movement of soil material from one place to another within the soil, in solution or suspension. Horizons that have lost material through eluviation are referred to as eluvial, and those that have received material as illuvial. The term generally refers to the movement of colloids.

Eocene: In the usage of the U.S. Geological Survey, the next to earliest of the epochs into which the Tertiary geologic period is divided; also the series of strata deposited at that time. Followed, in order of decreasing age, by the Oligocene, Miocene, and Pliocene epochs, and the Quaternary period.

epicenter: The point on the earth's surface directly above the place of origin of an earthquake.

facies: A lithologic or biologic variation of rocks within a geologic formation.

fault: A fracture or fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture. On a normal fault, the rocks above the fracture have moved downward relative to those below; on a reverse fault, the rocks above have moved upward. A thrust fault is a reverse fault whose plane of fracture is inclined only slightly from the horizontal.

fault gouge: Finely abraided and broken rock between the walls of a fault, a result of grinding during movement of the fault blocks; commonly soft, relatively permeable, and clayey.

fine fraction, soil: Fraction of a soil sample which passes through the mesh of a No. 200 (0.074 mm) sieve.

flow breccia: Angular fragments of solidified or partly solidified lava produced by explosion or movement within a lava flow with subsequent cementation by still-fluid lava of the same flow.

Foraminifera: A subdivision of the phylum Protozoa with skeletons (known as tests) which usually are microscopic in size, are commonly made of calcium carbonate, and which consist of one or more chambers.

forest: Land not in farms, bearing a stand of trees of any age or stature, including seedlings, but of species attaining a minimum average height of 6 feet at maturity; or land from which such a stand has been removed, which is not now restocking, and on which no other use has been substituted. Forest on farms is called farm woodland or farm forest.

fucoidal: A term applied to sediments, particularly limestone, upon which are indefinite, apparently biologic markings not referable to a known plant or animal.

Great Soil Group: A group of soils having common internal soil characteristics; includes one or more families of soils.

Half-bog soils: An intrazonal group of soils with mucky or peaty surface soil underlain by gray mineral soil; developed largely under swamp-forest types of vegetation, mostly in a humid or subhumid climate.

half-dome action: The formation of a half-dome (cave-like opening) between the supported portion of the roof and the working face; formed as a result of overbreak.

horizon, soil: A layer of soil approximately parallel to the land surface with characteristics produced by soil-forming processes.

- A_o horizon - Not strictly a part of the a horizon or the solum, it consists of a layer of partly decomposed or matted plant remains.

- A_p horizon - A plowed or otherwise mixed horizon, including more than the original A_1 horizon. The subscript letter p indicates disturbance.

- A horizon - The upper major horizon consisting of 1) one or more surface mineral horizons with maximum organic accumulations, or 2) horizons that have lost clay minerals, or 3) some combination of these conditions. The principal subhorizons are designated as A_1, A_2, and A_3.

B horizon - A major horizon characterized by 1) an accumulation of clay and oxides of iron or aluminum, or 2) more or less blocky, columnar, or prismatic structure, with development of stronger red or yellow colors, or 3) some combination of these characteristics. The principal subhorizons are designated as B_1, B_2, and B_3.

C horizon - The relatively unconsolidated parent material.

D horizon - Any stratum underlying the C, or the B if no C is present, which is unlike the C, or unlike the material from which the soil has been formed.

horst: A block of rock, generally much longer than it is wide, which has been uplifted along faults, relative to the rocks on each side; if faulting is recent, the block stands above its surroundings.

Hydromorphic soils: Soils that are developed in the presence of excess water, all or part of the time.

illuviation: The process of accumulation by deposition from percolating waters of material moved in suspension or solution.

immature soil: A young or imperfectly developed soil.

indurated: Hardened by heat, pressure, or cementation. The process by which rock is formed from unconsolidated materials.

Intrazonal soils: Any group of soils with well developed soil characteristics that reflect the dominating influence of some local factor of relief, parent material, or age over normal effect of the climate and vegetation. Often a condition of poor drainage is responsible.

joint: In geology, a fracture or parting in a rock mass; the rocks at each side have not moved along the plane of jointing.

kaolinite: One of three major groups of silicate clay minerals. The crystals are plate-like and roughly hexagonal, and are built up of flat crystal units composed of alternate layers of silica and alumina sheets; there is one alumina sheet for each silica sheet or a 1-to-1 lattice. The kaolinite crystals are the most stable of the layer-silicate clay minerals, the bonding between the units is firm, and they offer less surface area than the other clay minerals. The kaolinites exhibit few colloidal properties. (See montmorillonite.)

karst: A landform characterized by: many depressions of different sizes, such as sinkholes, caves; fluted limestone outcrops; and underground drainage developed by solution in limestone.

lapilli: Material ejected aerially from a volcano, ranging in size from 4 mm to 32 mm.

Latosols (Lateritic soils): A term proposed to comprehend all zonal soils in tropical and equatorial regions having their dominant characteristics associated with low silica-sesquioxide ratios of clay fractions, low base-exchange capacities, low activities of clays, low content of soluble constituents, a high degree of aggregate stability, and some red color.

ledge: A ridge or edge of hard rock projecting along a surface of softer material such as weathered rock or soil.

lithology: The study and description of rocks, usually from observation of the hand specimen or outcrop; also, the composition and texture of rocks.

Lithosols: An azonal group of soils having no clearly expressed soil morphology and consisting of freshly and imperfectly weathered mass of rock fragments largely confined to steeply sloping land.

loam: A soil that has roughly equal percentages of sand and silt, and a small amount of clay.

marl: A calcareous clay, or intimate mixture of clay and particles of calcareous materials, usually shell fragments.

marsh: Consists of wet, periodically flooded areas covered dominantly by grasses, cattails, rushes, or other herbaceous plants. Marsh is mainly covered by grasses and grasslike plants, while swamp is covered by trees.

matrix: In geology, the aggregate of glass or smaller size grains which surrounds distinctly larger grains, crystals, fossils, metals, etc.; the groundmass of porphyritic igneous rocks.

mature soil: A soil in equilibrium with its environment, with well developed characteristics produced by the natural processes of soil formation.

Miscellaneous land types: Land that has little or no natural soil or that is too nearly inaccessible for orderly examination, or where, for other reasons, it is not feasible to classify the soil.

montmorillonite: One of the three major groups of silicate clay minerals. The crystals are built of units alternating sheets, two silica sheets to an alumina, magnesium, or iron sheet, or a 2-10-1 lattice. The units are bonded together by weak oxygen-to-cation-to-oxygen linkages, which allow the crystal lattice to absorb water on the internal surfaces. This condition gives the montmorillonite high swelling and shrinkage properties. The crystals are much smaller than the crystals of illite and kaolinite. Montmorillonite is noted for its high plasticity and cohesion. (See kaolinite.)

morphology, soil: The physical constitution of the soil, including the texture, structure, porosity, consistence, and color of the various soil horizons, their thicknesses, and their arrangement in the soil profile.

mottled: Irregularly marked with spots of different colors.

muck: Well decomposed organic material -- decomposed enough so that identification of plant parts is impossible.

mullion structures: The larger grooves in a fault plane parallel to the direction of displacement along the fault.

neutral soil: A soil that is not acid or alkaline; practically, one having a pH between 6.6 and 7.3.

Order: The highest category of soil classification in the pedological system of classification. The three orders are: Zonal, Intrazonal, and Azonal soils.

organic soil: Any soil containing sufficient organic matter to dominate the soil characteristics. Usually the organic-matter content is above 20 percent. (Coming into use in the Great Soil Groups, in place of Bog Soil.)

overbreak: Rock that drops from the roof of an excavation, between the supported portion of the roof and working face, after a round is fired.

pandanus: A genus of tropical trees with very long, usually spiny, tough leaves.

parent material: The relatively unaltered, unconsolidated material beneath the solum, from which soil is formed.

peat; Organic matter consisting of undecomposed or slightly decomposed plant material accumulated under conditions of excessive moisture. The organic remains are sufficiently fresh to identify plant forms.

fibrous - Partially decomposed remains of mosses, sedges, reeds, and cat-tails, high in water-holding capacity.

woody - The partially decomposed remains of deciduous and coniferous trees and their undergrowth. Woody peat is usually loose and nonfibrous.

pelagic: Pertaining to communities of marine organisms which live free from direct dependence on bottom or shore; the two types are free-swimming forms (nektonic) and the floating forms (planktonic).

permeability: The capacity of rock or soil to transmit water under the influence of gravity or hydrostatic pressure.

pH: A notation used to designate the degree of alkalinity or acidity of a system; the common logarithm of the reciprocal of the hydrogen-ion concentration. (See reaction, soil.)

phase, soil: That part of a soil unit or soil type having minor variations in characteristics from those normal for the type. Although minor, these variations may be of great practical importance. The variations are chiefly in such external characteristics as relief, stoniness, or accelerated erosion.

phenocryst: A relatively large and ordinarily conspicuous crystal embedded in the finer-grained groundmass of an igneous rock. If phenocrysts are abundant, the rock is said to be porphyritic.

pillow lava: Lava which consists of rounded masses that resemble pillows, bolsters, or filled sacks. The rounded masses fit closely upon one another, the hollows of one matching the prominences of another, and intervening spaces usually are filled with sedimentary material.

pilot tunnel: A small tunnel driven ahead of the main excavation to determine rock and ground-water conditions.

Podzolic soils: Soils that have been formed wholly or partly under the influence of the podzolization process.

podzolization: A process, or processes, by which soils are depleted of bases, become acidic, and have developed eluvial A horizons and illuvial B horizons. Specifically, the process by which a podzol is developed, including the more rapid removal of iron and alumina than of silica from the surface horizons; but it is also used to include similar processes operative in the formation of certain other soils of humid regions.

porosity: The degree to which the soil mass is permeated with pores or cavities. It is expressed as the percentage of the whole volume of the soil that is unoccupied by solid particles.

porphyritic: A textural term describing igneous rocks in which larger crystals (phenocrysts) are set in a matrix of smaller crystals or glass (or both).

profile, soil: A vertical section of the soil through all its horizons and extending into the parent material.

pyroclastic: A general term applied to detrital volcanic materials that have been explosively or aerially ejected from a volcanic vent; also, a general term for the class of rocks made up of these materials.

ravelling: Dropping of chunks or flakes of material from exposed surfaces.

reaction, soil: The degree of acidity or alkalinity of the soil mass expressed in pH values, or in words as follows:

	pH
extremely acid	below 4.5
very strongly acid	4.5-5.0
strongly acid	5.1-5.5
medium acid	5.6-6.0
slightly acid	6.1-6.5
neutral	6.6-7.3
mildly alkaline	7.4-8.0
strongly alkaline	8.1-9.0
very strongly alkaline	9.1 and higher

regolith: All of the unconsolidated material above the bedrock.

Regosols: Azonal soils that consist mainly of soft or unconsolidated mineral materials in which there is no clearly developed soil morphology. They include relatively fresh glacial debris, beach sand, sand dunes, and recent accumulations of volcanic ash.

residual soil: Soil formed in place by the physical and chemical decomposition of bedrock.

rock condition: The type and intensity of rock defects. (Definitions below are taken from Proctor and White, 1946.)

intact rock - Contains neither joints nor hair cracks. Hence, it breaks across sound rock. On account of the injury to the rock due to blasting, spalls may drop off the roof several hours or days after blasting. This is known as spalling condition ....

stratified rock - Consists of individual strata with little or no resistance to separation along the boundaries between strata. The strata may or may not be weakened by traverse joints. In such rock the spalling condition is quite common.

moderately jointed rock - Contains joints and hair cracks, but the blocks between joints are locally grown together or so intimately interlocked that vertical walls do not require lateral support ....

blocky and seamy rock - Consists of chemically intact or almost intact rock fragments which are entirely separated from each other and imperfectly interlocked. In such rock vertical walls may require support.

crushed rock - If chemically intact, has the character of crusher run. If most or all of the fragments are as small as fine sand grains and no cementation has taken place, crushed rock below the water table exhibits the properties of a water-bearing sand.

squeezing rock - Slowly advances into the tunnel without perceptible volume increase. Prerequisite for squeeze is a high percentage of micaceous minerals or of clay minerals with a low swelling capacity.

swelling rock - Advances into the tunnel chiefly on account of expansion. The capacity to swell seems to be limited to those rocks which contain clay minerals with high swelling capacity, such as montmorillonite.

rock land: Areas having enough rock outcrop and very shallow soil to submerge other soil characteristics. The upper limit of rock outcrop is 90 percent of the mapped area and, unless the other features place the land in some other miscellaneous land type, the lower limit is ordinarily 25 percent. Several kinds of rock land are named according to the kind of rock material, including Limestone rock land.

rock pressure: The pressure exerted by surrounding rocks upon the supports of underground openings, including that due to weight of the overlying material, residual unrelieved stresses, and pressures associated with swelling clays.

calculation: the following formula (based on Proctor and White, 1946) was used in this report to calculate rock pressures for the limestones and volcanic rocks of Guam:

$$\text{Rock pressure} = V\,(B + H)\,w$$

in which: V is an empirical factor determined from studies on existing tunnels (its value varies according to the condition of the country rock - see definitions under Rock conditions, above) and has a maximum and minimum value for each rock condition; B is the width of the tunnel in feet; H is the height of the tunnel in feet; and w is the weight of the country rock in pounds per cubic foot.

For this report, the following values were assumed: B equals 20 feet; H equals 20 feet; and the tunnel depth below the ground surface is equal to or greater than 60 feet. Values for V were taken from tables in Proctor and White (1946). Apparent specific gravities of the rock types are those determined by the Base Development Laboratory of ComNavMar (see Engineering geology test data, table 18).

sand: See separate, soil.

savanna: A grassland containing scattered trees.

scarp: An escarpment, cliff, or steep slope of some extent along the margin of a plateau, mesa, terrace, or bench. A fault scarp is a cliff formed by faulting; a faultline scarp is a scarp that has been produced by differential erosion along an old fault line, rather than directly by movement along a fault.

sediments: Consolidated or unconsolidated materials deposited in water, on the land surface, or on the floors of streams, lakes, or the sea bottom; such materials deposited by wind.

separate, soil: A group of mineral particles of a specific size range. Most soil samples will contain more than one separate.

sand separate - Small rock or mineral fragments with diameters ranging from 0.05 to 2.0 mm.

silt separate - Small mineral soil grains with diameters ranging from 0.002 to 0.05 mm.

clay separate - The fine mineral soil grains with diameters less than 0.002 mm.

series, soil: A group of soils developed from the same parent material, having similar soil horizons and essentially the same characteristics throughout the profile except for the texture of the A, or surface, horizon.

sheetwash: Movement of surface water downslope as a thin, widespread sheet not concentrated into permanent channels.

silt: See separate, soil.

sinkhole: A depression in the land surface caused by water dissolving limestone along a joint or fracture.

slope, soil: Refers to the inclination of the surface of the soil area. Slope names and the ranges in slope percent are as follows:

Symbol	Slope Range	Slope Name
a	0 to 2 %	Nearly level
b	2 to 8 %	Gently sloping or undulating
c	8 to 15%	Sloping or rolling
d	15 to 25%	Moderately steep or hilly
e	25 to 45%	Steep
f	over 45%	Very steep

slope ratio: An expression of the inclination of a slope, generally in engineering usage, which relates to degrees and to percent of grade as follows:

ratio (horiz:vert)	degrees	grade percent (approx.)
4:1	14	30
3:1	18.5	40
2½:1	22	50
2:1	26.5	60
1½:1	33.5	75
1:1	45	100
3/4:1	53	120
½:1	63.5	140
¼:1	76	170
Vertical	90	-

solum: That part of the soil profile, above the parent material, in which the processes of soil formation are taking place. In mature soils, this includes the A and B horizons, and the character of the material may be greatly unlike that of the parent material.

structure, soil: The aggregation of soil particles into clusters of particles, which are separated from adjoining aggregates by surfaces of weakness.

blocky - The soil aggregates have a blocky shape, irregularly six-faced, and with the three dimensions nearly equal. The size of these aggregates ranges from a fraction of an inch to 3 or 4 inches in thickness. This structure is found in the B horizon of many soils. When the edges of the cubes are sharp and rectangular faces are distinct, the type is identified as blocky or angular blocky. If sub-rounding is apparent, the aggregates are identified as nutlike, nuciform, or subangular blocky.

columnar - Structure with the vertical axis of aggregates longer than the horizontal and with rounded tops. When the tops are level and clean cut the structure is identified as prismatic. Found in the B horizon.

crumb - Small, soft, porous aggregates irregular in shape and rarely larger than 1/3 inch. If the aggregates are relatively non-porous they are identified as granular. Both types are found in surface soils, especially those high in organic matter.

granular - See crumb.

laminated - Platy structure with the plates or very thin layers lying horizontal or parallel to the surface.

massive - Large uniform masses of cohesive soil, structureless.

prismatic - See columnar.

single-grain - No aggregation of the particles (such as dune sand).

subsoil: The horizon of soils with distinct profiles. In soils with weak profiles, it is the soil below the surface soil.

substratum: A material in or on which plants grow. Any layer below the solum, such as the C horizon, or a material distinctly different from the parent material of the soil (soil).

surface horizon, soil: The A horizon.

swamp: Consists of naturally wooded areas, all or most of which are covered by water much of the time. Differs from marsh by presence of trees.

tuff: Indurated volcanic ash or dust; grain size generally less than 4 mm.

tuff-breccia: A rock composed dominantly of tuff (that is, fine-grained volcanic material), but containing also a considerable proportion of large angular fragments.

type, soil: A subdivision of the soil series based upon the texture of the surface soil.

urban land: Land so altered or obscured by urban works and structures that identification of soils is not feasible.

Yellow Podzolic soils: A zonal group of soils having thin, organic and organic-mineral layers over a grayish-yellow, leached layer resting on a yellow horizon developed under the coniferous or mixed forest in a warm, temperate moist climate.

variant: A taxonomic soil unit closely related to another taxonomic unit (a soil series, for example) but departing from it in at least one differentiating characteristic at the series level, from which it derives its name as modified by the principal distinguishing feature. Some variants may later be recognized as new soil series.

vesicular: A term applied to rocks that contain numerous small, open cavities (vesicles). In volcanic rocks, the vesicles are formed by enclosed gas bubbles.

Zonal soils: Soils having well developed characteristics that reflect strong influence of climate and living organisms, mainly vegetation, in their formation.

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